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From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Fwd: Update
To: Frank Keutsch
Cc: Keith, David; Ronda Knott - NOAA Federal
Sent: October 27, 2020 10:25 PM (UTC-04:00)
Attached: Untitled attachment

Frank,

I hope this finds you doing well with the family in Germany.

DavidK and I invited you to a Friday v-meeting to catch up on CI matters. He will give me a brief download of his CDR ideas/perspective at the beginning at my request. So you could join late to miss that.

Let us know.
THanks
Dave

David W. Fahey, PhD
Director of the Earth System Research Laboratories (ESRL)
Director of the ESRL Chemical Sciences Laboratory
NOAA Earth System Research Laboratories
325 Broadway R/CSD
Boulder, CO 80305 USA
303-497-5277 -5822 fax
david.w.fahey@noaa.gov

Ronda Knott, Admin. Assistant
ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

Begin forwarded message:

From: Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
Subject: Re: Update
Date: October 26, 2020 at 7:51:29 PM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Cc: "Keith, David" (b) (6) [redacted]>

Hi Dave and David,

The meeting has been set for this Friday, October 30th at 7am MT and included Frank Kuetsch.
The connection details are:

Meeting ID
meet.google.com/zgb-gfnu-gdr
Phone Numbers
(US) +1 561-408-9337
PIN: 857 507 300#

Thank you,
Ronda

Ronda Knott
Executive Administrative Assistant to

Dr. David W. Fahey, Director

NOAA Chemical Sciences Laboratory
325 Broadway, R/CSL

Boulder CO 80305

I am currently teleworking, please call my cell: (b) (6)

303.497.4404 phone

303-497-5822 fax

ronda.knott@noaa.gov

On Mon, Oct 26, 2020 at 2:56 PM David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:

> David,
> 7Am Friday will work.
> Ronda can reach out to FrankK if you like. She will send a link to all.
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>
> D
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> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, October 24, 2020 6:29 PM
> **To:** Keith, David (b) (6) >
> **Cc:** Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
> **Subject:** Re: Update

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Thanks for the reply. I appreciate the perspective on Pierrehumbert; a bit frustrating. We will launch a webpage for the Earth Radiation Budget program (ie the Congressional funding) soon (albeit a bit late) that will explain NOAA's role and intent and in effect pushback on Pierrehumbert and others.

Thanks for your offer of a CDR debrief and catching up on other matters. My CDR meeting is 4 Nov so best would be next week sometime. Let me know if that might work (w/ or w/o Frank) and a preferred day/time.

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My management has asked me to inform them about CDR in an internal meeting. I am not very well prepared to do that and wondered if you had a presentation that you would be willing share to draw from for this purpose.

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http://www.esrl.noaa.gov/csd/

From: Keith, David (b) (6) [redacted] >
Subject: RE: Experimental research platform requirements
To: David Fahey - NOAA Federal
Cc: Smith, Wake; Keutsch, Frank N
Sent: February 3, 2021 9:59 AM (UTC-05:00)

Dave

Thanks. I think we see this about the same way.

From my perspective I came into this field working for Jim with all the excitement about Aurora's aircraft which ended up amounting to nothing. It took some years of my life. And yes, Global Hawk has been a big disappointment. So I definitely get the basis for skepticism.

On the other hand, there does seem to be a commercial-driven shakeup in the ability to develop low altitude aircraft. That's true from the new entrants into general aviation market through to the startups building off drone technology. So I'd like to understand whether this could apply to higher altitude light aircraft. I don't know, but if Wake spurs some interest I am open to find out more.

Have you had any conversations with these folks: Sceye | A new generation of HAPS | High Altitude Platform Stations? The head guy just reached out to me again and I will talk with.

David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Saturday, January 30, 2021 6:38 PM
To: Keith, David (b) (6) [redacted] >
Cc: Smith, Wake (b) (6) [redacted] >; Keutsch, Frank N (b) (6) [redacted] >
Subject: Re: Experimental research platform requirements

David,

Yes, I think if one has funding, then existing a/c become available. Certainly for the UT/LS, the WB-57s have been underutilized for years now and hence availability hasn't been an issue. Indeed a trip back to the boneyard was perhaps a growing threat.

I note that no one has ever built an aircraft for atmospheric chemistry, leaving the field to exploit as best they can existing a/c, which we have done very well. Thus, if there were runway a/c available that could do 30kg, 8hr, 79kft, the community would no doubt rush to use it. So the answer to your question is yes.

My problem with new-platforms-will-be-cheap is the issue of having truly operational a/c rather than experimental a/c. If one is trying to fly an experiment on an experimental a/c it reduces the probability of success by a large measure. Making an experimental a/c operational requires larger upfront and sustained investment by entities other than the science communities, creating the underwater part of the iceberg. This is why we don't have new operational a/c. And one can look to the Global Hawk and see that even starting at a high level (a mature platform) it failed to become operational because no one wants to pay the price, in this case neither NASA or NOAA. Now deeper pockets (DoD) have taken it over.

And to your final point about what payloads, yes, the new generation of lightweight instruments make 30kg interesting and valuable, and, yes, comprehensive chemistry payloads still want to be on heavy lift long-range a/c.

In reply to Wake's question about perturbation/monitoring a/c, hmmm, it depends. In the early days, perhaps they could be the same. Eventually the perturbations sought would be as large as possible per flight and not every flight would need diagnostics, so I think eventually they are different a/c. And monitoring a/c could be below the perturbation a/c altitudes and diagnose with lidar.

Interest above 70kft: in general because we would be deeper into the ozone layer. And perhaps the injection altitude would be there once we understand things better.

Regards
Dave

> On Jan 30, 2021, at 9:29 AM, Keith, David <(b) (6) [redacted]> wrote:
>
> Dave
>
> Interesting back-and-forth.
>
> I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.
>
> I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30 kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.
>
> I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.
>
> I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.
>
> Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.
>
> Interesting conversation. No simple answers.
>
> Cheers,
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Thursday, January 28, 2021 11:49 AM
> **To:** Smith, Wake (b) (6) [redacted]>

Cc: Keith, David <(b) (6)>; Keutsch, Frank N (b) (6)
Subject: Re: Experimental research platform requirements

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi-flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" <(b) (6)>
Cc: Frank Keutsch (b) (6)

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can't control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake <(b) (6) [redacted]> wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6) [redacted]

From: Kelly Wanser (b) (6) >
Subject: Nice job on the NOVA episode!
To: David Fahey - NOAA Federal; Frank Keutsch
Cc: John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:13 PM (UTC-04:00)

You were excellent and the piece came out great.
We'll promote it as we are able.

Best,
k.

--
Kelly Wanser
Executive Director, SilverLining | http://www.silverlining.ngo
Board Director, Dendra Systems | http://www.dendra.io
Advisor, University of Washington Marine Cloud Brightening Project | http://www.mcbproject.org
President's Circle, National Academy of Sciences | http://nas-sites.org/PC/
Phone: (b) (6)

TEDTalk: *Emergency Medicine for Our Climate Fever*
Report: *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: Graham Feingold - NOAA Federal <graham.feingold@noaa.gov>
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Andrea Smith; Simone Tilmes; Keutsch, Frank N; Smith, Wake; Karen Rosenlof - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:47 AM (UTC-04:00)

zoom link not working for me. is there something else i need to do?

On 9/17/21 11:06 AM, Andrea Smith wrote:

> Hello Frank, Wake and Graham,
>
> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>
> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
> Meeting ID: 816 4261 9898
> Passcode: 148321
>
> Please join 10 mins early to test tech and troubleshoot if needed.
>
> 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) [redacted] (preferably by Tuesday night):
>
> 3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.
>
> After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.
>
> Let me know if you have questions on any of the above.
>
> Thanks again, and see you next Wednesday.
>
> Andrea
>
> On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) [redacted]> wrote:
>
>> Hi Frank, Wake and Graham,
>> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>>
>> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
>>
>> 1. Frank Keutsch: ...
>> 2. Wake Smith:...
>> 3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening
>>
>> Here is Andreas rundown for logistics:
>>
>> -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
>> -send slide decks to Andrea by Tuesday (9/21) evening for backup purposes

> -arrive ~10 mins early so we can do quick test of screenshares
> -15 min talk length, w/ immediate clarifying question(s) and then ~30 mins broad discussion and questions at end
> -moderator will collect questions in chat window throughout and ask most pertinent ones for discussion
> -panelists and question askers encouraged to unmute & turn on camera
> -session will be recorded and posted later - we'll send a release form for them to complete
>
> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
>
> Cheers, Simone
>
> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6) [redacted]

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) [redacted] (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

--
Graham Feingold
NOAA Earth System Research Laboratories
Chemical Sciences Laboratory (R/CSL9)
325 Broadway
Boulder, Colorado 80305, USA
Tel: (303) 497-3098
Fax: (303) 497-5318

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Fwd: Update
To: Frank Keutsch
Cc: Keith, David; Ronda Knott - NOAA Federal
Sent: October 28, 2020 1:03 PM (UTC-04:00)
Attached: Untitled attachment

Great. Looking forward to it.

Begin forwarded message:

From: "Keutsch, Frank N" (b) (6) [redacted]>
Subject: Re: Update
Date: October 28, 2020 at 10:51:34 AM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>

Dave,

Thanks for your email. I will see how it goes. I have a number of deadlines looming over me, but will try to attend the whole meeting.

I hope you are doing well. Germany is going into a moderate lockdown!

All the best,

Frank

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Thank you,
Ronda

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>
> ---

Frank N. Keutsch
Stonington Professor of Engineering and Atmospheric Science

Harvard John A. Paulson School of Engineering and Applied Sciences
Department of Chemistry and Chemical Biology
Department of Earth and Planetary Sciences
Harvard University
12 Oxford Street
Cambridge, MA 02138
USA

E-mail:
(b) (6) [redacted]

Tel:+(b) (6)

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Nice job on the NOVA episode!
To: Kelly Wanser
Cc: Frank Keutsch; John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:19 PM (UTC-04:00)
Attached: Untitled attachment

Kelly,
I think you want to praise David K instead of me. I too thought they all did a great job.
Dave

> On Oct 29, 2020, at 1:12 PM, Kelly Wanser (b) (6) wrote:
>
> You were excellent and the piece came out great.
> We'll promote it as we are able.
>
> Best,
> k.
>
> --
> Kelly Wanser
> Executive Director, SilverLining | http://www.silverlining.ngo
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> Phone: (b) (6)
>
> **TEDTalk:** *Emergency Medicine for Our Climate Fever*
> **Report:** *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: Alan Robock ☮ (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin (b) (6) ; (b) (6) ; Karen Rosenlof - NOAA Federal; Katharine Ricke; (b) (6) Robert Wood; (b) (6) ; (b) (6) Daniele Visioni; Isla Simpson; Peter Irvine; Jonathan Proctor; (b) (6) ; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N
Cc: Trude Storelvmo; 'Simone Tilmes'; (b) (6)
Sent: July 15, 2021 5:37 PM (UTC-04:00)

Dear Doug and Trude,

I would like to give a talk. Thanks.

Alan

On 7/15/2021 11:06 AM, Douglas MacMartin wrote:

> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
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> As a start to our planning, could you let us know whether you would be interested in talking at the 2022 meeting? We would of course still love to hear from you, but schedules may not permit and research interests change (and, indeed, for some or many of you that may mean that the topic we were originally thinking you would talk about would no longer be what you are currently most excited by – the GRC is supposed to be cutting-edge current research, of course – so if you let us know we can start revising sessions and think about what gaps we'd like to fill). There are also some new people who are doing some great research too that we would like to hear from, so it's conceivable that – given the now 5 year gap since the last GRC – we might choose to slightly increase the number of talks and reduce the time available per talk.
>
> Thanks,
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> **From:** Douglas MacMartin
> **Sent:** Wednesday, February 19, 2020 10:27 AM
> **To:** (b) (6) ; (b) (6) ; Alan Robock (b) (6) ; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke (b) (6) ; (b) (6) ; Robert Wood (b) (6) (b) (6) ; (b) (6) (b) (6) ; Daniele Visioni (b) (6) ; (b) (6) ; Peter Irvine (b) (6) ; Jonathan Proctor (b) (6) ; (b) (6) Keith, David (b) (6) Kravitz, Ben (b) (6) Wake Smith (b) (6) ; Izidine Pinto (b) (6) Gabriel Chiodo (b) (6) ; Keutsch, Frank N (b) (6) >
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Thanks, and see you in June!
doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To:(b) (6) ;(b) (6) 'Jadwiga (Yaga) Richter' (b) (6) >; Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >;(b) (6) ; Robert Wood (b) (6) >;(b) (6) ;(b) (6) (b) (6) >; Daniele Visioni (b) (6) >;(b) (6) ; Peter Irvine (b) (6) ; Jonathan Proctor (b) (6) ; Govindasamy Bala (b) (6) >;(b) (6) Keith, David <(b) (6) ; Kravitz, Ben (b) (6) ; Wake Smith <(b) (6) >; Chris Field (b) (6)
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Douglas MacMartin
Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and
Faculty Fellow, Atkinson Center for a Sustainable Future
Cornell University
(b) (6) [redacted]
https://climate-engineering.mae.cornell.edu/

From: Douglas MacMartin (b) (6) >
Subject: RE: 2022 GRC program
To: Karen Rosenlof - NOAA Federal; Trude Storelvmo
Sent: July 19, 2021 10:15 AM (UTC-04:00)

Excellent! We should have a great conference ☺. (More later… probably not for a while.)

doug

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Sent: Thursday, July 15, 2021 5:04 PM
To: Douglas MacMartin (b) (6) Trude Storelvmo (b) (6)
Subject: Re: 2022 GRC program

Doug and Trude,
I should be available during that time frame, and would like to attend the test GRC. I'd be happy to adjust topics as you feel is needed.

Take care,

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
Boulder, CO 80305
office: 3A-121, DSRC
e-mail: Karen.H.Rosenlof@noaa.gov
phone: 303 497-7761
fax: 303 497-5373
----
while safer at home remains in effect, email is the most reliable contact

> On Jul 15, 2021, at 9:06 AM, Douglas MacMartin (b) (6) > wrote:
>
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>
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Proctor <(b) (6) >; Govindasamy Bala <(b) (6) >;(b) (6)
Keith, David (b) (6) >; Kravitz, Ben <bkravitz@iu.edu>; Wake Smith
<(b) (6) ; Chris Field (b) (6)
Cc: Lawrence, Mark (b) (6) >; valentina Aquila <(b) (6) Ulrike
Niemeier <(b) (6) >; Leisner, Thomas (IMK) <(b) (6) Olivier
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Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and
Faculty Fellow, Atkinson Center for a Sustainable Future
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(b) (6)
https://climate-engineering.mae.cornell.edu/

From: Kelly Wanser (b) (6) >
Subject: Re: Nice job on the NOVA episode!
To: David Fahey - NOAA Federal; David Keith
Cc: Frank Keutsch; John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:22 PM (UTC-04:00)

Ha, thanks, Dave. Adding David here.
Terrific piece, David!

Sent from my iPhone

> On Oct 29, 2020, at 1:19 PM, David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:
>
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> I think you want to praise David K instead of me. I too thought they all did a great job.
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From: Peter Irvine (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin
Cc: Piers Forster; (b) (6) Alan Robock; Karen Rosenlof - NOAA Federal; Katharine Ricke; Seneviratne Sonia Isabelle; Robert Wood; Helene Muri; (b) (6) Daniele Visioni; Isla Simpson; Jonathan Proctor; Ines Camilloni; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N; Trude Storelvmo; Simone Tilmes; Lohmann Ulrike
Sent: July 18, 2021 4:53 PM (UTC-04:00)

Hi Doug, Trude,

It's be happy to present in 2022, with the same title for now.

Cheers,

Pete

On Thu, Jul 15, 2021, 16:06 Douglas MacMartin (b) (6) > wrote:

> Hi all,
>
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Faculty Fellow, Atkinson Center for a Sustainable Future

Cornell University

(b) (6)

[redacted]

https://climate-engineering.mae.cornell.edu/

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Newsletter from Harvard's Solar Geoengineering Research Program
To: Keith, David
Cc: Frank Keutsch; Ronda Knott - NOAA Federal
Sent: December 28, 2020 11:44 AM (UTC-05:00)
Attached: Untitled attachment

David,
Good, yes let's talk on the 6th.
Ronda can arrange a time and link.
Happy New Year.
Dave

> On Dec 28, 2020, at 9:30 AM, Keith, David <(b) (6)> wrote:
>
> Dave
>
> Yes, we expect to fly POPS.
>
> Also, interesting developments on turbulence.
>
> Now that this mission seems to be (finally) coming together it would be good how about the three of us to touch base again about this and about the meeting to discuss future flight missions?
>
> How about Wednesday the 6th?
>
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, December 26, 2020 5:51 PM
> **To:** Keith, David (b) (6)
> **Subject:** Re: Newsletter from Harvard's Solar Geoengineering Research Program
>
> David,
>
> Thanks for the newsletter. I am impressed with your productivity.
>
> Good progress with Esrange launch plans and committee approval. Do you plan to fly POPS? It would be of value to get a high lat profile and adds to your flight data return. No communication with the device is needed since it records onboard. Let us know if you want assistance.
>
> We have prepared a POPS unit and backup to fly on the World View Stratollite in 2021 when they are able to resume launches.
>
> I hope you and yours are doing well enough this Holiday Season. We are OK.
> Regards
> Dave

On Dec 16, 2020, at 9:18 AM, David Keith (b) (6) [redacted] wrote:

Dear Readers,

As this strange year comes to a close, we wanted to share updates from Harvard's Solar Geoengineering Research Program (SGRP), which supports research at Harvard on the science, technology, and governance of solar geoengineering.

We hope everyone and their families are safe and well. We wish you a healthy new year.

Yours,
David Keith and Lizzie Burns
Faculty Director and Managing Director
Harvard's Solar Geoengineering Research Program

SCoPEx

SCoPEx Update

Led by Frank Keutsch, the Stratospheric Controlled Perturbation Experiment (SCoPEx) is a scientific experiment to advance understanding of stratospheric aerosols that could be relevant to solar geoengineering. It aims to reduce the uncertainty around specific science questions by making quantitative measurements of some of the aerosol microphysics and atmospheric chemistry required for estimating the risks and benefits of solar geoengineering in large atmospheric models.

The SCoPEx research team has asked the independent SCoPEx Advisory Committee to review our plans for a proposed platform test in Sweden in June 2021. This test would notbe the experiment itself, but rather a test of the SCoPEx platform without the release of any particles. Specifically, we would like to test the gondola's horizontal and vertical control using the winch system and propellers as well as the power, data, navigation, and communication systems. We would not release any aerosols, nor fly an aerosol injection/release system. Still, we will not proceed with this flight without a formal recommendation authorizing the flight from the Advisory Committee to Harvard management. We have asked the Advisory Committee if they can complete their review and reach a decision—be it positive or negative—about this platform test by February 15, 2021. You can learn more about this platform test here.

SCoPEx Advisory Committee

Recognizing the complex societal and governance issues surrounding solar geoengineering, Harvard has ensured the SCoPEx project has the guidance of an independent Advisory Committee, as noted above. The Advisory Committee has already begun to carry out a significant amount of work, including a financial review, legal review, and scientific and technical review, and they have proposed a draft process for a societal engagement review. You can learn more by visiting their website. We are grateful for the time the Committee members are volunteering and look forward to the work ahead.

Opportunities

SGRP Fellowship

SGRP is now accepting applications to its 2021 Fellowship Program, which offers short-term and long-term opportunities. Applications are due January 29, 2021. We are seeking applications from scholars in a range of disciplines, including the natural sciences, economics, law, government, public policy, public health, medicine, design, and the humanities. We also are looking for applicants who are new to the field of solar geoengineering and/or have critical views, and we strongly encourage applications from

women and minority candidates. More information can be found here.

We would also like to congratulate our current and future fellows who were accepted during our previous fellowship application process.

- Cody Floerchinger, (August 2019-July 2021) advised by Frank Keutsch, is using datasets from upcoming measurements campaigns to provide a comprehensive analysis of the state of our ability to model stratospheric plume dynamics and highlight areas where the community should focus its efforts when attempting to improve these model products (science).
- Yuanchao Fan, (October 2019-October 2021) advised by Kaighin McColl, is quantifying the impact of solar geoengineering on terrestrial ecosystems, including forests and agriculture, and their biophysical and biogeochemical feedbacks to climate. He is also collaborating with David Keith on a paper about geoengineering and food supply (science).
- Irina Bakalova (February 2021-April 2021) will be advised by Professor Rob Stavins, working closely to study the effectiveness and stability of potential international agreements on solar geoengineering (economics).
- Britta Clark (February 2021-June 2021) will be advised by Lucas Stanczyk and will analyze the intergenerational justice impacts of solar geoengineering as a mitigative strategy to address climate change (philosophy).
- Ermanno Napolitano (August 2021-July 2022) will be advised by Lucas Stanczyk and will catalogue and explore all of the existing international legal principles that are likely to have some bearing on the deployment of solar geoengineering (law).

Online Community for Junior Researchers

A group of junior scientists are organizing a diverse online community of young researchers new to the solar geoengineering field, designed to engage researchers with new perspectives. This group will provide young researchers the chance to informally present on their research, share ideas, receive feedback, and create a space for open and non-judgmental discussion on the topic. The first few sessions took place in November and December and were held live on Zoom. Graduate students and recent postdocs from across the globe, including from developing countries, discussed various publications containing alternate viewpoints on solar geoengineering. Future sessions scheduled include presentations by a former SGRP DECIMALS resident and other participants as well as discussion forums and networking opportunities on Slack. Undergraduate students, graduate students, and postdoctoral fellows within five years of completing their degree are welcome to join the group. If you are interested in participating, please email Selena Wallace: swallace@seas.harvard.edu.

Events

Due to COVID-19, we had to cancel in-person events beginning in March. Since that time, we have held countless Zoom conversations (like so many others). For example, in November we hosted a public health workshop at Harvard to try to broaden the diversity of researchers studying solar geoengineering on campus. We are also now in the process of building an exciting opportunity that will allow us to reach a broader audience outside of Harvard that will include experts, practitioners new to solar geoengineering, and the general public. We invite you to join us.

Public Health Roundtable

In November 2020, we held a virtual event with the Harvard Chan School of Public Health Center for Climate, Health, and the Global Environment where experts from both the geoengineering and the public health communities had the opportunity to discuss the potential public health challenges posed by solar geoengineering. Few studies to date have considered the public health implications of geoengineering, and those that have have been limited to mortality due to ambient air pollution and UV-induced malignant melanoma. This event discussion addressed questions of the risk factors that these studies might be omitting, the vast array of other public health issues that may arise, as well as the environmental justice implications of human interventions to the climate system such as geoengineering. The organizers of the event may publish a paper that summarizes the key points and questions to hopefully inspire other experts in the public health field to begin research on solar geoengineering. Overall, this event was significant because it not only signaled new interest from various public health experts who, years prior, had not yet engaged, but also because it will hopefully unlock even more new interest from a critical community that has yet to fully participate in solar geoengineering research.

Public Seminar Series

In the spring of 2020, we will launch a virtual seminars series to promote understanding and discussion of solar geoengineering and to enable audiences to learn from a broader set of perspectives in the area of solar geoengineering research and public policy. These seminars will contain a combination of practitioners and experts from around the world and will have a variety of formats including single speakers, moderated debate, and moderated panels. Previously, SGRP seminar attendance was limited to the Harvard community, but we are now able to extend the reach of this series to a global, public audience. We invite you to participate in these seminars. We will email this listserv when seminars are scheduled.

Publications, Video, and Audio Clips

The following written publications were funded all or in part by SGRP.

Recent Peer Reviewed Publications

Zhen Dai, Debra K. Weisenstein, Frank N. Keutsch, and David W. Keith. (2020). "Experimental reaction rates constrain estimates of ozone response to calcium carbonate geoengineering." Communications Earth and Environment 1, 63.

Jacob T. Seeley, Nicholas J. Lutsko, and David W. Keith. "Designing a radiative antidote to CO2." Geophysical Research Letters (Submitted).

Joshua B. Horton and Barbara Koromenos. (2020). "Steering and Influence in Transnational Climate Governance: Nonstate Engagement in Solar Geoengineering Research." Global Environmental Politics 20, 3: 93-111.

Nicholas J. Lutsko, Jacob T. Seeley, and David W. Keith. (2020). "Estimating Impacts and Trade-offs in Solar Geoengineering Scenarios With a Moist Energy Balance Model." Geophysical Research Letters 47, 9.

Joshua B. Horton, Penehuro Lefale, David Keith. (2020). "Parametric Insurance for Solar Geoengineering: Insights from the Pacific Catastrophe Risk Assessment and Financing Initiative." Global Policy, Special Issue.

David Keith and Peter Irvine. (2020). "Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards." Environmental Research Letters 15, 4.

Jesse Reynolds and Joshua Horton. (2020) "An earth system governance perspective on solar geoengineering." Earth System Governance, 3.

Other Publications

David W. Keith and John Deutch (2020) "Climate Policy Enters Four Dimensions." In *Securing our Economic Future,* edited by Amy Ganz and Melissa Kearney, Aspen Institute Press.

Cody Floerchinger, John Dykema, David Keith, and Frank Keutsch (2020) "A Need for In Situ Observations to Inform Nearfield Plume Transport and Aerosol Dynamics as well as Chemistry of Alternate Geoengineering Materials in the Stratosphere." Letter to the National Academy for Science.

David Keith, Frank Keutsch, and Cody Floerchinger (February 15, 2020) "Empirical methods to reduce uncertainty about solar geoengineering," public input to the National Academy Committee on *Climate Intervention Strategies that Reflect Sunlight to Cool Earth*.

Recent Video and Audio Recordings

AGU TV (December 2, 2020). “SCoPEx, Harvard University – New Frontiers in Climate Change Research.” WebsEdge Science.

Anthony Padilla (October 23, 2020) “I spent a day with climate change scientists” *Youtube*.

PBS Nova (October 16, 2020). "Can We Cool the Planet?" *WGBH*.

Harvard Magazine (October 16, 2020). “Daniel Schrag and David Keith: Can Solar Geoengineering Help Fight Climate Change?”

All Things Considered (July 22, 2020) “Harvard Scientists Plan First-Ever Field Experiment Related To Solar Geoengineering.” *WBUR*. (This aired again on Here & Now on December 4, 2020 as “Experiment To Help Researchers Understand Risk, Efficacy of Solar Geoengineering.”)

Harvard Museum of Natural History (December 12, 2019) “The Peril and Promise of Solar Geoengineering” *Youtube*.

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
OCEANIC AND ATMOSPHERIC RESEARCH
Silver Spring, MD 20910

April 25, 2024

Mr. Aaron Siri
Siri Glimstad
745 Fifth Avenue, Suite 500
New York, NY 10151

Re: FOIA Request DOC-NOAA-2023-010132

Dear Mr. Aaron Siri

This letter is in response to your Freedom of Information Act (FOIA) request which was received by our office on, on 06/22/2023. Your request tracking number is **DOC-NOAA-2023-010132**.

You requested:

> ***"All emails, including attachments, sent or received by Karen Rosenlof and/or David Fahey from January 1, 2010 through the date of the search which include Rob Wood, David Keith, Alan Robock, William Brennan, Ken Caldiera, and/or Frank Keutsch, and/or their email address(es), in the to, from, cc, and/or bcc lines. (Date Range for Record Search: From 1/1/2010 To 6/22/2023)"***
>
> ***On July 12, 2023, you modified the request to "Our client will modify the request to the seven-year time frame from 1/1/2016 to 6/22/2023."***

We have located **125** records responsive to your request. There are **20** of these records being released to you in their entirety.

We are also releasing **100** records responsive to your request that contain redactions under the 5 U.S.C. 552 (b)(6) which prohibits disclosure of records related solely to information that, if disclosed, would invade another individual's personal privacy. There is **one** record being withheld in full under 5 U.S.C. 552 (b)(4) which is information concerning business trade secrets or other confidential commercial or financial information, and **four** records are withheld in full under 5 U.S.C. 552 (b)(5) which is information concerning communications within or between agencies and are protected by legal privileges. Your request is now considered complete.

You have the right to file an administrative appeal if you are not satisfied with our response to your FOIA request. All appeals should include a statement of the reasons why you believe the FOIA response was not satisfactory. An appeal based on documents in this release must be received within 90 calendar days of the date of this response letter at the following address:

Assistant General Counsel for Employment, Litigation, and Information
U.S. Department of Commerce
Office of General Counsel
Room 5896
1401 Constitution Avenue, N.W.
Washington, D.C. 20230

An appeal may also be sent by e-mail to FOIAAppeals@doc.gov.

For your appeal to be complete, it must include the following items:

- a copy of the original request,
- our response to your request,
- a statement explaining why the withheld records should be made available, and why the
- denial of the records was in error.
- "Freedom of Information Act Appeal" must appear on your appeal letter. It should also be written on your envelope, or e-mail subject line.

FOIA appeals posted to the e-mail box or Office after normal business hours will be deemed received on the next business day. If the 90th calendar day for submitting an appeal falls on a Saturday, Sunday or legal public holiday, an appeal received by 5:00 p.m., Eastern Time, the next business day will be deemed timely. FOIA grants requesters the right to challenge an agency's final action in federal court. Before doing so, an adjudication of an administrative appeal is ordinarily required.

The Office of Government Information Services (OGIS), an office created within the National Archives and Records Administration, offers free mediation services to FOIA requesters. They may be contacted in any of the following ways:

Office of Government Information Services
National Archives and Records Administration
Room 2510
8601 Adelphi Road
College Park, MD 20740-6001

Email: ogis@nara.gov
Phone: 301-837-1996
Fax: 301-837-0348
Toll-free: 1-877-684-6448

If you have questions regarding this correspondence, please contact Sabrina Tucker at Sabrina.tucker@noaa.gov or the NOAA FOIA Public Liaison, Tony LaVoi, at 843-834-3516.

Sincerely,

Robin Burress

BURRESS.ROBIN.SURRETT.1365847696
Digitally signed by BURRESS.ROBIN.SURRETT.1365847696
Date: 2024.04.25 13:55:42 -04'00'

Robin Burress FOR
Mark Graff, NOAA FOIA Officer


NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

From: Andrea Smith (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Karen Rosenlof - NOAA Federal
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Graham Feingold - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:36 AM (UTC-04:00)

Good morning everyone,

If you haven't already done so, please reply here with slide decks or drop them in (b) (6) if large file size.

See you in 10-15 mins!

Cheers,

Andrea

On Fri, Sep 17, 2021 at 2:43 PM Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov> wrote:

> And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
> So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.
>
> Thanks!
>
> Karen
>
> --
> Karen Rosenlof
> NOAA Chemical Sciences Laboratory
> Mail Stop R/CSL8
> 325 Broadway
> Boulder, CO 80305
> office: 3A-121, DSRC
> e-mail: Karen.H.Rosenlof@noaa.gov
> phone: 303 497-7761
> fax: 303 497-5373
> --
> while safer at home remains in effect, email is the most reliable contact
>
>> On Sep 17, 2021, at 11:06 AM, Andrea Smith (b) (6) > wrote:
>>
>> Hello Frank, Wake and Graham,
>>
>> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>>
>> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
>> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
>> Meeting ID: 816 4261 9898
>> Passcode: 148321
>>
>> Please join 10 mins early to test tech and troubleshoot if needed.

2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) (preferably by Tuesday night):

3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.

After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.

Let me know if you have questions on any of the above.

Thanks again, and see you next Wednesday.

Andrea

On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) wrote:

> Hi Frank, Wake and Graham,
> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>
> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
>
> 1. Frank Keutsch: ...
> 2. Wake Smith:...
> 3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening
>
> Here is Andreas rundown for logistics:
>
> -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
> -send slide decks to Andrea by Tuesday (9/21) evening for backup purposes
> -arrive ~10 mins early so we can do quick test of screenshares
> -15 min talk length, w/ immediate clarifying question(s) and then ~30 mins broad discussion and questions at end
> -moderator will collect questions in chat window throughout and ask most pertinent ones for discussion
> -panelists and question askers encouraged to unmute & turn on camera
> -session will be recorded and posted later - we'll send a release form for them to complete
>
> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
>
> Cheers, Simone
>
> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*

> > *303-497-1400 (fax)*
> > (b) (6)
>
> --
> Andrea Smith
> Associate Scientist & Program Manager
> The COMET® Program
> University Corporation for Atmospheric Research
> 3085 Center Green Dr.
> Boulder, CO 80301
> 303-497-8320 (office)
> (b) (6) (cell)
>
> *My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.*
> <CCISspeaker_consent_form.pdf>

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Keith, David
Cc: Smith, Wake; Frank Keutsch
Sent: January 30, 2021 6:38 PM (UTC-05:00)
Attached: Untitled attachment

David,

Yes, I think if one has funding, then existing a/c become available. Certainly for the UT/LS, the WB-57s have been underutilized for years now and hence availability hasn't been an issue. Indeed a trip back to the boneyard was perhaps a growing threat.

I note that no one has ever built an aircraft for atmospheric chemistry, leaving the field to exploit as best they can existing a/c, which we have done very well. Thus, if there were runway a/c available that could do 30kg, 8hr, 79kft, the community would no doubt rush to use it. So the answer to your question is yes.

My problem with new-platforms-will-be-cheap is the issue of having truly operational a/c rather than experimental a/c. If one is trying to fly an experiment on an experimental a/c it reduces the probability of success by a large measure. Making an experimental a/c operational requires larger upfront and sustained investment by entities other than the science communities, creating the underwater part of the iceberg. This is why we don't have new operational a/c. And one can look to the Global Hawk and see that even starting at a high level (a mature platform) it failed to become operational because no one wants to pay the price, in this case neither NASA or NOAA. Now deeper pockets (DoD) have taken it over.

And to your final point about what payloads, yes, the new generation of lightweight instruments make 30kg interesting and valuable, and, yes, comprehensive chemistry payloads still want to be on heavy lift long-range a/c.

In reply to Wake's question about perturbation/monitoring a/c, hmmm, it depends. In the early days, perhaps they could be the same. Eventually the perturbations sought would be as large as possible per flight and not every flight would need diagnostics, so I think eventually they are different a/c. And monitoring a/c could be below the perturbation a/c altitudes and diagnose with lidar.

Interest above 70kft: in general because we would be deeper into the ozone layer. And perhaps the injection altitude would be there once we understand things better.

Regards
Dave

> On Jan 30, 2021, at 9:29 AM, Keith, David (b) (6) [redacted]> wrote:
>
> Dave
>
> Interesting back-and-forth.
>
> I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.
>
> I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30

kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.

I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.

I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.

Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.

Interesting conversation. No simple answers.

Cheers,
David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Thursday, January 28, 2021 11:49 AM
To: Smith, Wake (b) (6) [redacted] >
Cc: Keith, David <(b) (6) [redacted] >; Keutsch, Frank N (b) (6) [redacted]
Subject: Re: Experimental research platform requirements

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi-flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" (b) (6) >
Cc: Frank Keutsch <(b) (6)

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can't control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake (b) (6) > wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to

understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6) [redacted]

The Stratospheric Controlled Perturbation Experiment (SCoPEx)

Version 1.0

Executive Summary

Climate model studies of stratospheric solar radiation modification (SRM) depend, perhaps implicitly, on processes that take place in the near field of an injection plume. This is because materials delivered to the stratosphere by aircraft will form persistent, high aspect-ratio plumes with strong gradients before becoming well mixed, and processes within the plume will alter the large-scale, well-mixed aerosol and chemical properties that are simulated in global atmospheric models. All models ultimately depend on observations, yet we lack experimental data to assess some of the critical transport, microphysical, and chemical processes that directly control aerosol dynamics in the near-field that are important for understanding stratospheric SRM.

The scientific goal of the Stratospheric Controlled Perturbation Experiment (SCoPEx) is to improve process models that will, in turn, reduce uncertainties in global-scale models, thus reducing uncertainty in predictions of important SRM risks and benefits.

SCoPEx addresses questions in stratospheric aerosol injection (SAI) research that observations of existing analogues are incapable of addressing. For example, existing observational data do not include chemistry of alternate geoengineering materials specific to SAI, near-field particle microphysics of injection plumes, and relevant scales of atmospheric transport in the near-field. Yet these are needed to assess processes that control aerosol dynamics in the near field of an injection plume and that allow for the evaluation of alternate SAI materials, i.e., materials other than the naturally existing sulfate aerosol.

We first review why existing observations do not address the questions that SCoPEx will answer. We then give a description of the basic design of the platform and the concept of operations of SCoPEx. Finally, we describe the three specific science goals of SCoPEx, explain how they represent critical knowledge gaps in SAI research, and specify what measurements are needed to enable SCoPEx to provide quantitative answers to these questions. The three specific science goals are improving understanding of (i) turbulent mixing scales, (ii) aerosol microphysics with a focus on alternative SAI materials in the near-field of an injection, and (iii) process level chemical interactions of alternative SAI materials in the stratosphere.

We do not provide a detailed engineering document of the SCoPEx platform or its scientific instrumentation, nor do we provide a justification for the need for research on SRM via SAI in general. Rather, we focus specifically on the merits of SCoPEx itself.

1. Introduction

In this document we focus on the motivation and scientific merit of SCoPEx. We do not provide detailed engineering documentation of the SCoPEx platform or its scientific instrumentation. We also do not provide general justification for the need for research on solar radiation modification (SRM) via stratospheric aerosol injection (SAI), which can be found in many prior documents such as the 1992 NAS report that recommended the US government “Undertake research and development projects to improve our understanding of both the potential of geoengineering options to offset global warming and their possible side effects. This is not a recommendation that geoengineering options be undertaken at this time, but rather that we learn more about their likely advantages and disadvantages” (National Academy of Sciences et al., 1992) or the recent 2015 NAS report (National Research Council, 2015). Rather, we focus specifically on the need for small-scale field experiments such as SCoPEx, and the specific, critical SAI research needs that will be addressed by SCoPEx.

1.1. Role of and Need for Small-Scale Field Experiments

There is a vast array of science and engineering questions that have to be answered to achieve a better understanding of the risks, benefits and feasibility of SAI. The tools and topics that are needed to address these questions range from General Circulation Models (GCMs) all the way to detailed design of instrumentation to monitor or disperse aerosol. SCoPEx addresses a subset of questions that require small-scale field experiments for ground-truthing and that are aimed at improving the ability of models to predict the consequences of SAI.

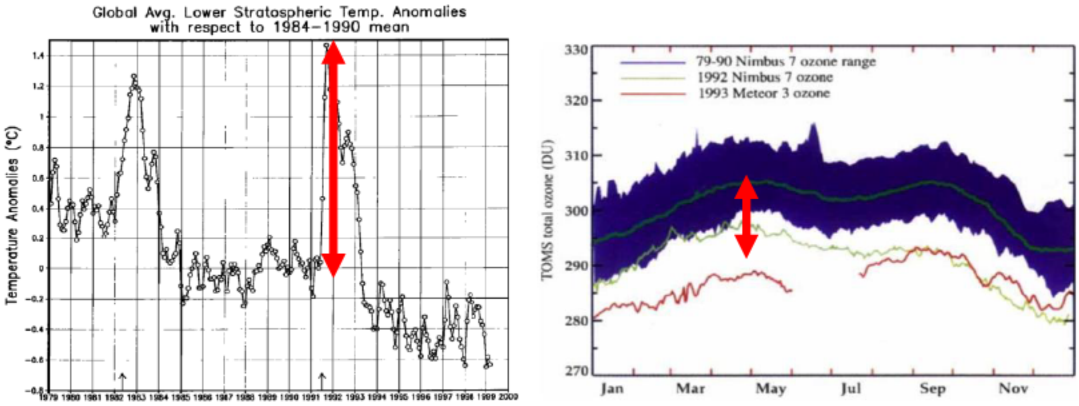

Figure 1: The two most important first-order stratospheric risks from sulfate SAI. The left panel shows stratospheric temperature anomalies from the El Chichon and Mount Pinatubo eruptions on top of background temperatures that are decreasing due to greenhouse gas emissions (Robock, 2000). The dynamical response of the stratosphere from such a short heating pulse likely is different than from sustained heating from longer-term SAI. The right panel shows that in the two years following the Mount Pinatubo reaction total ozone columns were lower than in the 1979-90 average as a result of increase sulfate aerosol surface area. Smaller eruptions also contributed to this. (McCormick et al., 1995)

There are numerous known risks associated with SAI, and SCoPEx focuses primarily on improving understanding of the first-order impacts in the stratosphere, i.e., risks and risk reduction associated with impacts of SAI within the stratosphere. There are many downstream / higher-order risks, e.g., impact on cloud formation as SAI particles leave the stratosphere (Cziczo et al., 2019), impacts on ecosystems via changes in the hydrological cycle (Bala et al., 2008; Russell et al., 2012; Tilmes et al., 2013), or the amount of direct

versus diffuse radiation (Gu et al., 2002; Farquhar & Roderick, 2003; Gu et al., 2003). Despite their importance, these impacts are not the direct target of this proposal although many of these are also influenced by stratospheric processes and properties of SAI aerosol. Two first-order risks are at the focus of this work: stratospheric ozone loss and the dynamic response resulting from stratospheric heating as a result of SAI.

Whereas stratospheric ozone chemistry is fairly well understood (World Meteorological Organization, 2019), there are still substantial uncertainties in the understanding and ability to model stratospheric dynamics (Figure 1). For example, models have only recently been able to reproduce the quasi-biennial oscillation without having it imposed (see Butchart et al., 2018 for a discussion of challenges). One approach taken in this work is to evaluate whether there are types of aerosols or methods of aerosol injection that can reduce first-order risks for a given amount of radiative forcing. It stands to reason that a reduction in the first-order stratospheric impacts will reduce downstream and higher-order risks. A case in point is the growing body of work that has been investigating the impacts of stratospheric heating on stratospheric water vapor and the dynamic response on regional climate (Simpson et al., 2019; Ferraro et al., 2015; Richter et al., 2018; Ji et al., 2018). It is important to note that the amount of stratospheric heating for a given material will be primarily driven by the total mass of aerosol, ozone destruction will be driven by the total surface area of aerosol, and the desired radiative forcing will be determined by the amount and size distribution of aerosol. Critically, both the aerosol mass required for a given desired radiative forcing *and* the resulting surface area are tied to this size distribution. Therefore, accurate models of the evolution of the size distribution of injected aerosol are critically needed. In addition, alternate materials with reduced stratospheric heating have to be investigated, as do injection methods for sulfate that minimize stratospheric heating and ozone loss for a given radiative forcing, as this will reduce risks associated with the dynamic response to this first-order perturbation.

2. Observational SAI Research Needs

Most of the rapidly growing body of literature on SAI rests on General Circulation Models (GCMs). We acknowledge the importance of GCM studies, but in the following we focus on research needs that require experiments and observations, and especially questions that can only be answered by conducting perturbative field experiments such as SCoPEx (see supplemental manuscripts Keith et al., 2020 and Floerchinger et al., 2020). In fact, SCoPEx will in the end inform GCMs by providing improved process level information that will be integrated in parameterizations used in GCMs. Below we review existing observational data sets and describe their utility for different SAI approaches, highlighting where they are unable to shed light on critical issues thus motivating studies like SCoPEx.

2.1. Field Experimental Needs for Sulfate SAI

Most studies that have sought to research SAI have assumed the addition of aerosol would take place by means of an injection of gas-phase SO_2, which is ultimately converted to H_2SO_4 and then to sulfate aerosol in the stratosphere on a timescale of approximately one month. The aerosol size distribution from this injection of gas phase precursor must be accurately predicted as it will control the shortwave (SW) scattering properties, the stratospheric lifetime of the aerosol, and ultimately be the driver for the radiative forcing (RF) efficiency per mass of injected sulfate. Some studies, such as Niemeier & Timmreck (2015), have suggested that with higher injection rates of SO_2, the resulting sulfate aerosol would be forced into a larger, coarse-mode size distribution and functionally reach a point of diminishing return. In this diminishing return scenario, the added amount of SW RF achieved per added mass of sulfate decreases exponentially.

Recent work by Pierce et al. (2010), Benduhn et al. (2016), and Vattioni et al. (2019) has highlighted the potential benefits of injecting H_2SO_4 aerosol directly into the accumulation mode (AM), i.e., aerosols with a radius of 0.1–1.0 µm, potentially by emitting H_2SO_4 vapor into an aircraft plume. This work has suggested better control of the resulting aerosol size distribution and thus the radiative forcing per unit mass sulfur injection, which would allow for the design of a system that maximizes the radiative forcing per mass of sulfate in a way that would not have the diminishing returns at high SO_2 injection rates. This would thus minimize the increase in the stratospheric sulfate burden and hence the risk of stratospheric heating which is driven by total mass whereas ozone loss is driven by surface area. While injecting AM–H_2SO_4 may represent the best possible approach for SAI with stratospheric sulfate, there is currently no proven way to introduce vapor phase AM–H_2SO_4 into the stratosphere. As AM–H_2SO_4 has not been studied, perturbative experiments are required to provide observational constraints on the aerosol size distributions predicted by models.

2.2. Field Experimental Needs for Alternate Aerosol Material SAI

Though sulfate aerosol does exist in the background stratosphere and there are some natural analogs of broad stratospheric sulfate injections (volcanic eruptions), it likely is not the optimal candidate for SAI. Alternative aerosol may be most appropriate in order to mitigate SAI risks (Teller et al., 1996; Crutzen, 2006; Ferraro et al., 2011; Ferraro et al., 2015; Weisenstein et al., 2015; Keith et al., 2016; Dykema et al., 2016; Weisenstein et al., 2015). These alternate aerosols could reduce the previously noted two major first-order stratospheric impacts, i.e., changes in ozone and stratospheric heating. Due to the uncertainties in the impacts of stratospheric heating, the study of materials with optical

properties that negate stratospheric heating is especially important. Materials such as calcium carbonate ($CaCO_3$), alumina (Al_2O_3), diamond (carbon), and several others, have been proposed as a way to minimize the inherent risks from SAI (Keith et al., 2016; Dykema et al., 2016; Weisenstein et al., 2015; Ferraro et al., 2015; Ferraro et al., 2011; Crutzen, 2006). Although model results of these aerosol species suggest that some of them possess optical properties that make them well suited to be used in a SRM scenario ($CaCO_3$, Al_2O_3, and diamond) (Dykema et al., 2016; Ferraro et al., 2011), the stratospheric aerosol microphysics of these compounds (especially coagulation) is poorly understood. As with AM–H_2SO_4 injections, there is a profound lack of in situ data to assess the ability to model the microphysics of alternative aerosols and the stratospheric chemistry of these materials. This is especially pertinent with respect to changes in ozone, and is exacerbated by the fact that these aerosols have no naturally existing analog in the stratosphere that could be studied. Because early studies suggest that these aerosols show much promise with respect to deploying SAI while mitigating the inherent risks of the deployment, it is imperative to design and execute in situ experiments in order to test our current understanding of the aerosol microphysics and observe the effects of alternative aerosol on the chemical composition and dynamics of the stratosphere.

2.3. Limitations in Existing Analogues

In this section we will review previous in situ studies of stratospheric plume processes, show how those datasets have contributed to our current understanding, and demonstrate the need for experiments such as SCoPEx to inform small-scale models of aerosol microphysics (nucleation and coagulation), plume transport and physical morphology, and chemical properties of new aerosol species that have thus far not been observed in the stratosphere. Because the nature of the injection scenarios (AM–H_2SO_4 or solid aerosols) are so complex compared to natural analogs, new experiments must be designed and implemented to provide observational constraints on our current nearfield modeling framework. Experimental data from carefully targeted small-scale studies would contribute to the development of nearfield-scale models that represent currently uncertain processes in detail.

We note that sub-grid scale processes do not represent the only unknowns in GCMs that are relevant to high-fidelity simulations of SRM scenarios, and that there are many large scale model phenomena which should be further assessed with observational evidence. However, here we focus on the need for in situ data to constrain sub-grid scale processes that can be addressed by SCoPEx and highlight the need for reducing the uncertainty in transport and aerosol dynamics and chemistry at this scale.

2.3.1. Limitations of Solid Rocket Motor Plume Observations

From 1996 to 2000 a number of rocket plumes were observed by high-altitude research aircraft. Generally, these missions involved a research team coordinating stratospheric sampling flights on either the NASA ER-2 or on the NASA WB-57 with coincident rocket launch events from either Cape Canaveral or Vandenberg Airforce Base. These studies sampled plumes from a host of rocket types including Titan IV, Space Shuttle (STS106, STS83, STS85), Delta II, Athena II, and Atlas IIAS.

Plumes were intercepted by the sampling aircraft between 5 and 125 minutes after emission from the rocket motor at stratospheric altitudes ranging from 11 to 19.8km (Voigt et al., 2013). The main science objective of these missions was to assess the stratospheric

ozone depletion potential of space exploration by understanding the halogen chemistry occurring as a result of the high-altitude rocket burn. However, in studying the effects on the ozone layer, this era of stratospheric sampling provided a unique set of plume measurements to study nearfield processes of chemical injections into the stratosphere.

While measuring the plumes from the Titan IV rocket (as a part of the United States Airforce Rocket Impacts on Stratospheric Ozone (RISO) Campaign) and attempting to develop a plume chemistry model to solve for the Cl_2 concentration in a rocket plume as it evolves shortly after its emission, Ross et al. (1997) noted the many assumptions that had to be made about the plume morphology in order to simulate the mixing and diffusion that the rocket plume had with the surrounding stratosphere. Their model solved for the Cl_2 concentration of a circular nighttime plume as it expanded in diameter along an isentropic surface. Subsequent aircraft measurements showed that plumes contained more than twice the predicted concentration of Cl_2 despite the plume being intercepted during the day time (when the Cl_2 reservoir should be somewhat depleted by the photolysis reaction $Cl_2 + h\nu \rightarrow 2Cl$), suggesting that there may be an error in the assumption of a circular plume morphology on the short transport time scales observed in this study ($\sim 28 min$).

Ross went on to publish a second study as a part of the RISO project in 1999, this time looking to quantify the size distribution of alumina aerosols emitted from the rocket engines which contained particulate alumina (Al_2O_3) (Ross et al.,1999). They compared measured aerosol size distributions from the WB-57F plume interceptions to results from an aerosol coagulation model and highlighted a massive discrepancy. The model predicted a much smaller aerosol size distribution with 1-10% of the aerosol mass being in the smallest (0.005μm) mode and the aircraft observed only fractions (<0.05%) of the model estimate in that same small mode. At the same time, over 99% of the aerosol mass sampled by the aircraft was found in the coarsest mode (2 μm), which the model was unable to predict. It is most likely that the model used in Ross et al. (1999) did not well account for the effects of ion mediated nucleation as described by Yu & Turco (1997). However, the data from Ross et al. (1999) was some of the first in situ data to highlight the uncertainty in stratospheric aerosol coagulation models. Alumina aerosol, as well as other solid aerosols, in contrast to liquid sulfate aerosol, have since been investigated as a candidate for use in SAI (Weisenstein et al., 2015). Therefore, it is imperative that we understand the chemical, coagulation, and accumulation properties of these and other solid aerosols in a stratospheric environment.

2.3.2. Limitations of Previous Stratospheric Aircraft Wake Crossing Observations

We can look to the few times high-altitude aircraft wake plumes have been sampled in situ for another example of stratospheric plume measurements. In the early 1990s the popularity and capability of the Concorde spurred discussions of a large fleet of High Speed Civil Transport (HSCT) aircraft that would operate in the lower stratosphere between 16 and 23 km. Scientists became concerned with the effects of high-altitude aircraft and high-altitude supersonic aircraft on stratospheric ozone destruction via the creation of a large NOx source in the lower stratosphere. NASA then launched several field campaigns using the ER-2 to study the exhaust profiles of high-altitude aircraft. In 1992 NASA commissioned the Stratospheric Photochemistry Aerosols and Dynamics Expedition (SPADE) to look at the effects of HSCTs. As a part of SPADE the ER2 sampled its own plume on several occasions by making a hairpin turn and heading into its original path, therefore measuring its own wake

(Figure 2). SPADE resulted in at least 11 published studies and some of these can inform us about the mixing and aerosol dynamics that may be relevant to an SAI scenario (Stolarski & Wesoky, 1993).

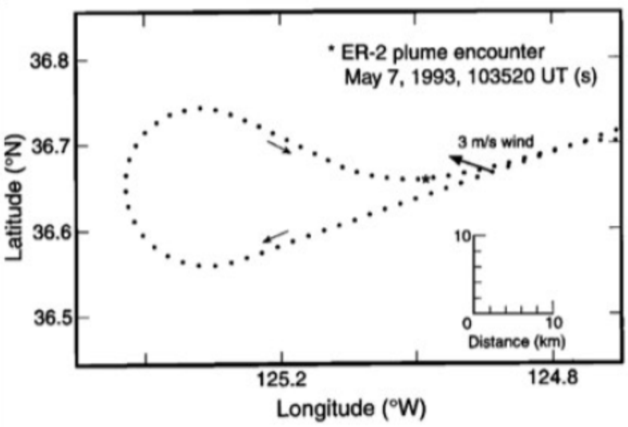

Figure 2: Shows the ER-2 flight track on a typical wake crossing trajectory (adapted from Fahey et al. 1995).

Fahey et al. (1995a) described measurements made of condensation nuclei (CN) present in the ER-2's exhaust plume from the emission of aerosol carbon and of sulfur compounds during one of its SPADE wake crossing events. Because the main focus of this study was to quantify the emission indices (EIs) of various compounds measured by the ER-2 that may have ozone depletion implications, they focused mainly on gas phase compounds. However, for the three wake crossings that the study focused on, they observed large variability in their EI measurements for CN. They noted that this is likely due to differences in mixing history of the encountered air parcels and noted that a full explanation of CN coagulation required more in-depth study and further measurements (Fahey et al, 1995b).

In another study published by Fahey et al. (1995b), they used a similar wake crossing technique to measure the exhaust of the Concorde aircraft and developed an aerosol coagulation model to predict particle formation and size as a function of the time since emission from the aircraft. The coagulation model was initialized at the observed conditions from the one-hour old Concord transect. The results from this model estimated that from 0 to 10 hr since emission from the engine, the mean particle diameter remained fairly constant at 0.06 µm before growing exponentially to a factor of 3 times its initial value over the next 1,000hr. The model predicted exponential mean particle diameter growth continuing right until the of the simulation at 1,000 hr (Fahey et al., 1995a).

Yu & Turco (1997) attempted to model the observed aerosol plume during the Concorde wake crossings with the goal of determining the driving factor for the large aerosol size distributions observed by the ER-2 in the exhaust which had not yet been explained by models. Yu proposed that aerosol formation was being aided by ion-mediated nucleation (IMN), that is, charged particles formed by chemi-ionization processes within the aircraft engines provide charged centers (H_2SO_4 [S(VI)]) around which molecular clusters rapidly coalesce. "The resulting charged micro-particles exhibit enhanced growth due to condensation and coagulation aided by electrostatic effects" (Yu & Turco, 1997). It is likely that IMN is the reason previous particle coagulation modeling of solid rocket motor plumes had overestimated the amount of aerosol in the small size ranges when compared to the in situ data, though this has not since been tested. Because of these effects, and the fact that specific size distributions of aerosol are desired to obtain the optimal radiative

forcing effects for SAI (nominally smaller than observed in rocket or aircraft plumes), we must understand the aerosol nucleation and coagulation dynamics in an unperturbed stratosphere.

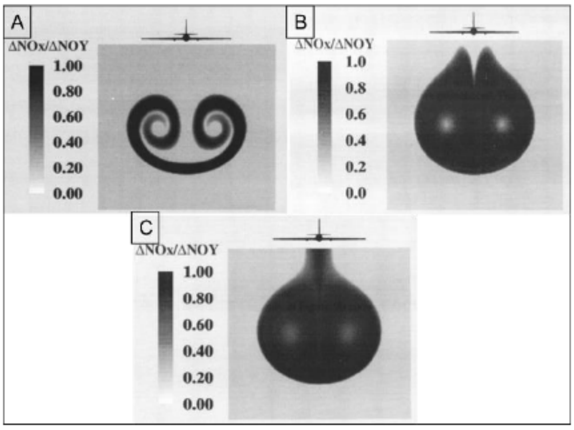

Figure 3: Shows the chemical and morphological evolution of an ER-2 plume during SPADE at 1.7 km (A), 4.8 km (B), and 7.9 km (C). (adapted from Anderson et al. (1996))

As a part of the SPADE project, Anderson et al. (1996) computed the flow field and chemical kinetics of the ER-2 aircraft exhaust using the Aerodyne Research Inc. UNIWAKE model. Their calculations address the effects of complex plume morphology on in-plume chemistry as a function of dilution time since emission from the aircraft engine. They showed that the plume morphology is highly variable out to about 5 km post emission Figure 3 and estimated that the stability of the wing vortex pair begins to break up at roughly 20 km post emission. Although this study was completed in the mid 1990s, it is still one of the only studies that attempts to compute nearfield chemistry within a dynamic stratospheric plume. However, particles were not considered as part of this study.

2.3.3. Limitations of Stratospheric Wake Crossings

Previous stratospheric plume studies of solid rocket motors and aircraft wake crossings have laid the foundation for our understanding of stratospheric plume chemical, aerosol, and mixing dynamics on transport scales of 0→100 km. These studies highlight the types of processes we must be aware of when considering the logistics of SAI. However, the violent initial conditions of engine exhaust plumes (such as temperatures of 700K, IMN) make it difficult to relate these observations to other systems. Because the engines drive the mixing and transport in the nearfield, and the ionic injection conditions of the plume create electrostatic forces that introduce complex nucleation affinities (IMN), understanding individual parameters can become analogous to finding a needle in a haystack. Moreover, because the radiative properties of any stratospheric aerosol that may be used for SRM depend on the diameter of the particle, we must understand the coagulation of that aerosol in the nearfield after the injection, which means that we must also understand the plume morphology that dictates the concentrations of that aerosol. Currently there have been no in situ data gathered that help us understand nearfield aerosol nucleation and plume dynamics in the absence of a very disruptive source. These conditions are necessary to understand as SAI may require that we mitigate the effect of IMN in order to obtain an aerosol size distribution that is small enough to provide the desired radiative properties.

2.3.4. Limitations of Naturally Occurring Analogs

Another source of useful in situ data on plume dynamics in the stratosphere can be found in literature addressing the fate and transport of convective overshooting events that often occur at the top of a Mesoscale Convective Complex (MCC). These events drive brief airmass exchange with the troposphere and often end up resulting in a plume-like parcel of tropospheric air being injected into the stratosphere.

Measurements of convective systems and upper troposphere-lower stratosphere exchange, as a means to interrogate stratospheric plume transport, have provided valuable in situ datasets that help us understand mid-field (10 to >1000 km) plume dynamics in the lower stratosphere. Similar to convective overshooting events, volcanic eruptions have provided an immense amount of in situ data that has informed us about regional and even global transport of stratospheric injections (Robock, 2000). Although their data are applicable in some sense to the transport of an SAI plume after its initial injection, the turbulent nature of a convective storm makes it difficult to measure these events at points near their injection source. Additionally, the storm conditions themselves dramatically complicate the system in the lower stratosphere such that is difficult to see through the effects of the induced turbulence in the nearfield. Indeed, an important limitation of these type of natural analogs is the spatial extent of their perturbation, which does not allow for near-field observations analogous to that of a point source. This also arises from the violent nature of these events which does not allow airborne platforms, such as the ER-2, to sample the initial conditions of the injection. We also note that volcanic eruptions are limited in their utility to evaluate dynamic response to stratospheric heating from sulfate aerosol, as they represent a perturbative pulse rather than the long-term heating one would expect from SAI.

In addition, these natural analogues provide extremely limited ability to study alternate materials, although organic and mineral dust aerosol injections into the lowermost stratosphere have been documented from convective overshoots. However, the complexity of the massive perturbations of both gas- and particle-phase preclude a study focusing on the impact on stratospheric composition and aerosol evolution that would result from SAI of a single material.

3. SCoPEx Short Overview

This section provides a brief overview of the engineering and operational aspects of SCoPEx. We first describe the platform, the instruments, and the concept of operations before describing the rationale for the overall SCoPEx design choices.

3.1. SCoPEx Platform

The SCoPEx gondola (Figure 4) is a balloon-born new research platform being developed at Harvard by the engineering and science staff within the Anderson/Keith/Keutsch laboratory group. The development builds on four decades of stratospheric research on aircraft, balloon, and rocket platforms that has focused on understanding the environmental chemistry of the ozone layer. The SCoPEx experiment was first described by Dykema et al. (2014). While many details of the design have changed, that paper still succinctly describes the advantages of choosing a balloon born platform over an aircraft, particularly for studying perturbations like solar geoengineering, and several of the limits of laboratory experiments that that could be addressed in a perturbative experiment like SCoPEx.

The gondola has three primary features: the frame, the ascender, and the propellers. The aluminum and carbon fiber frame contains two decks and a ballast hopper for coarse altitude control. One deck is primarily dedicated to platform support (power and flight control) and one deck is primarily dedicated to instruments. At the top of the gondola is an ascender and rope which allows the distance between the bottom of the balloon train and the gondola to vary from 0 to 150 m, which provides fine altitude control of the gondola. The ascender has been developed and tested by Atlas (Chelmsford, MA) building on their previous hardware in collaboration with the Harvard engineering team. The propellers serve two purposes: to create a well-mixed volume of air where observations of the aerosols and perturbed gas-phase can be made, and to reposition the gondola within the evolving aerosol plume. While the trajectory of the balloon and gondola system will be dictated by the balloon, the propellers allow for repositioning relative to the prevailing winds.

The ascender makes it impossible to have cables and other physical connections between the flight operations equipment and the gondola. Thus, the platform will handle its own communications and power. The SCoPEx platform will be powered using 28 V and 100 V DC power supplies which will power all operations on the platform including the propellers, ascender, and instruments. Elements of the flight platform are listed in Table 1. The gondola flight, flight safety, recovery parachute, and recovery operations will be managed by the balloon operator (in contrast to the SCoPEx team itself). Because the absolute velocity and distance capability of the gondola are so small compared to balloon drift, the trajectory will be determined by the balloon operator as if it was a passive nonpowered payload. During operations, the detailed float altitude will be jointly managed by the balloon operator via control of the balloon vents and the Harvard team via control of the ballast and ascender.

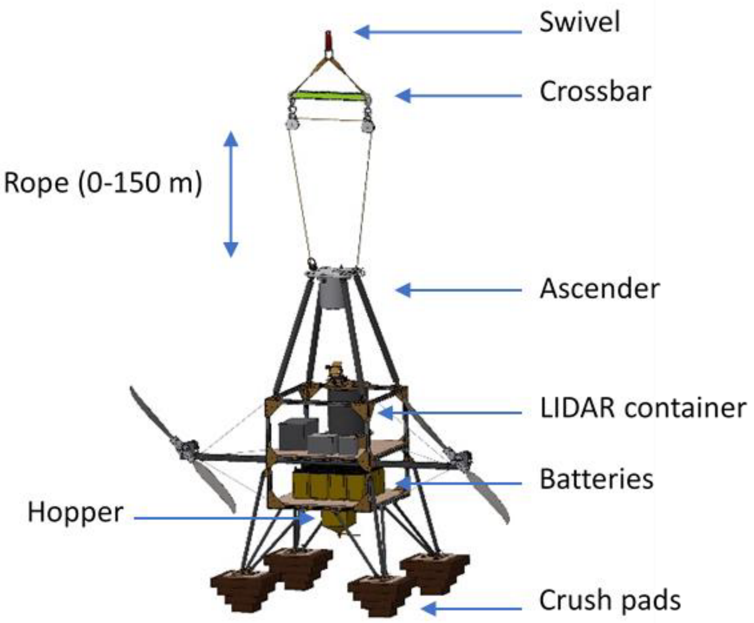

Figure 4: A representation of the SCoPEx flight platform. The final configuration may have subsystems packaged differently.

Parameter	Description
Total mass (Frame, all subsystems, hopper with ballast)	600 kg
Interface to balloon	Crosby 5-S-2 jaw & jaw swivel
Ascender	13 mm diameter rope Range of motion: 0-150 m Max speed: 10 m/min
Gondola propulsion	Twin propellers, 1.88 m diameter 32 N thrust each Max airspeed: 3 m/s
Power	28 V and 100 V DC power supplies with 24 MJ and 10 MJ total energy when fully charged
Communications	Satellite phone for communication between ground equipment and payload
Maximum termination shock	10 g

Table 1: Elements of the SCoPEx flight platform.

3.2. Instruments for First Science Flights (Science Goals 1 and 2)

The proposed instruments for the first science flight, addressing science Goals 1 and 2, are listed in Table 2. The corresponding science goals that motivate their inclusion are detailed in Section 4.

Measurement	Instruments	Rationale	Corresponding Science Goal
Wind speed measurement	Wind pendulum	Gondola and plume movement relative to balloon	Platform operation
Meteorology	Commercial off-the-shelf instrument	Temperature and pressure measurement throughout the flight	1, 2, 3
Wind turbulence	Constant temperature anemometer	Stratospheric mixing and modeling evolution of aerosol size distribution	1, 2
Particle dispersal	Solid Aerosolizer	Injects monodispersed particles for measurement and study	2, 3
Plume tracking	LIDAR	Tracking plume and navigation back into plume	2, 3
Particle sizer	POPS	Aerosol size distribution measurement for comparison with microphysics models of near-field evolution	2, 3
Light Scattering	Radiometer	Comparison of aerosol scattering with model prediction	2

Table 2: Instruments for first SCoPEx science flight.

Wind Pendulum: Understanding differential wind speed measurements between the balloon and payload will be important for plume evolution relative to the balloon trajectory and navigating the payload back into the plume. Commercial equipment to measure wind speed is typically not designed for the low densities found in the stratosphere. SCoPEx will therefore use a pendulum-based instrument and model to extract wind speed measurements. A camera will track a pendulum bob with high surface area and low mass, light enough to be perturbed by low winds in the stratosphere. Using the location and tilt data from the payload and a 3-dimentail kinetic model, the wind speed will be extracted from photos of the pendulum bob.

Commercial Meteorology Instrument: Commercial off-the-shelf instruments will be used for meteorological measurements on SCoPEx. They will record pressures and temperatures of the ambient stratosphere.

Constant Temperature Anemometer: A constant temperature anemometer (CTA) uses convective cooling caused by air flowing across a heated thin wire to measure flow velocity. LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere) (Gerding et al., 2009; Theuerkauf et al., 2010) used such a measurement to study stratospheric turbulence up to 29 km. LITOS consisted of a 5 μm diameter and 1.25 mm long tungsten wire CTA and a 16 bit ADC with 2000 samples per second to collect measurements with a vertical resolution of 2.5 mm at 5 m/s ascent speed. The anemometer data was analyzed by performing a spectral

analysis on the voltage signal to retrieve the spectral slope of the observed variation. A similar instrument will be used on SCoPEx to measure stratospheric turbulence. Air flow around the device will be simulated using CFD tools. The CFD runs will provide a means to identify key flow characteristics that drive sensor performance (sensitivity and accuracy), and to drive detailed sensor design.

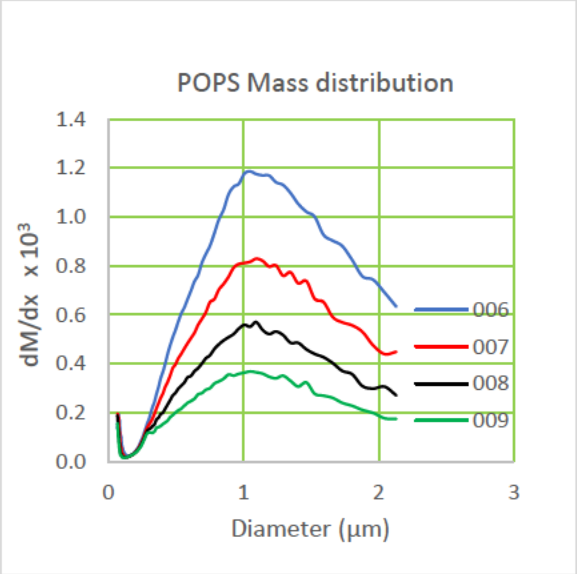

Figure 5: Successive measurements of sprayed $CaCO_3$ using an optical particle spectrometer. 006-009 indicate numbered time intervals spaced 4 minutes apart with 006 being the earliest measurement. $CaCO_3$ was sprayed using a 200 µm nozzle. In this laboratory experiment there was no significant variation in the shape of the distribution over time. (personal communication A Neukermans and team)

Solid Aerosolizer: The solid particle aerosolizer has been developed by a team lead by Armand Neukermans. For SCoPEx, the goal is to spray roughly monodisperse ~0.5 µm diameter precipitated calcium carbonate powder, the first candidate for solid SAI, through a 1-2 mm nozzle using the expansion of powder suspended in high pressure liquid CO_2. The aerosolizer would use a 1:4 weight ratio of $CaCO_3$ to CO_2. For 1 kg of $CaCO_3$ this would require a 5-7 L pressurized container. This concept has already been demonstrated in the lab. Figure 5 shows successive measurements of sprayed $CaCO_3$ with a size distribution centered at 1 µm diameter. Measurements were taken every 4 minutes using POPS (see below). In this case, total particle count decreased over time but there was no significant variation in the shape of the size distribution.

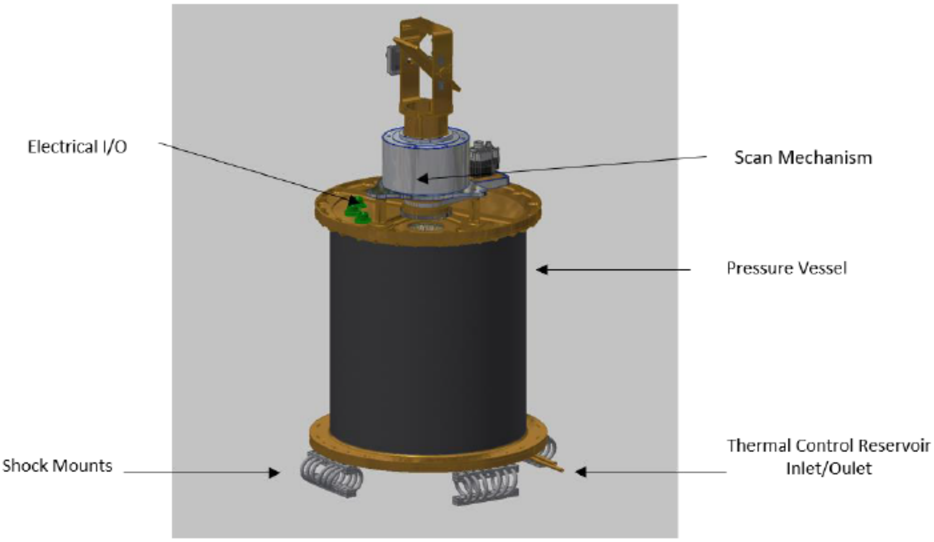

Figure 6: LIDAR pressure vessel provides safe storage and operating environment and support equipment.

LIDAR: The LIDAR is used to track the plume and allow navigation back into it. The core of the LIDAR system is an off-the-shelf eye-safe visible LIDAR, purchased from Sigma Space (now owned and operated by Droplet Measurement Technologies). This LIDAR produces 4 µJ pulses of 532 nm light at a repetition rate of 532 nm. The light that is backscattered by molecules and aerosols is collected by an 80 mm telescope and detected with a high-speed, high-sensitivity photodiode.

We have integrated this LIDAR in a pressure vessel (Figure 6) to provide a near-1 atm pressure environment with adequate temperature stability to ensure safe operation of the LIDAR at float altitude and safe storage on launch, ascent, descent, and recovery. This pressure vessel includes equipment for electrical and mechanical support, including command, data handling, and shock mounting. The LIDAR requires a scan capability to search the nearby atmosphere for the extent and geometry of the plume. The tilt and pan functions of the scan capability allows the LIDAR to be scanned over a set of angles that define the plausible location of the plume.

Portable Optical Particle Spectrometer (POPS): The POPS instrument will provide the aerosol size distribution measurements for studying aerosol formation and agglomeration. POPS is a light-weight instrument that directly samples the aerosol. It was built by and provided to SCoPEx through a collaboration with NOAA. The particles are illuminated with a 405 nm diode laser and the scattered light is collected onto a photomultiplier tube. The particle size is determined by the intensity of the scattered light. It has both the detection limit and size range (0.13 – 3 µm) to measure background stratospheric aerosol, which is more than sufficient for SCoPEx needs (Gao et al., 2016).

The Keutsch Group has already developed and extensively characterized a POPS instrument in preparation for the NASA-EVS3 Dynamics and Chemistry of the Summer Stratosphere field campaign on board the NASA-ER2, for which Keutsch is the deputy-PI. The POPS instrument tests include extensive thermal vacuum chamber characterizations to ensure operation under harsh stratospheric conditions. Compared to the ER-2, operation for SCoPEx will be simpler due to the insignificant air speed of the balloon and a much simpler operational pressure regime (on the ER-2 there is a large range of external pressures for both sampling and exhaust).

Radiometer: The aerosol plume can also be detected using a narrowband, narrow field of view radiometer with azimuthal/zenith pointing capability. The relationship between measurements of scattered solar radiation and the physical characteristics of atmospheric aerosols has been studied for more than two decades. Sky scanning measurements at multiple wavelengths between 300 nm and 1200 nm have been obtained using robotically pointed ground-based spectral radiometers deployed worldwide (Holben et al., 1998). The theory of these measurements has been refined and validated as a function of viewing geometry to provide a strong basis for inferring aerosol microphysics from radiometer data (Torres et al., 2014). The success of these approaches has motivated the development of compact sky scanning radiometers suitable for deployment on unsteady platforms like unmanned aerial vehicles (UAVs) and SCoPEx. One such design, reported by NOAA (Murphy et al., 2016), measures at 4 wavelengths (460 nm, 550 nm , 670 nm, and 860 nm) with a field of view of 0.006 sr (equivalent to 2.5° half-angle) and a circular limiting aperture of 1.1 mm diameter. A radiometer like this one deployed on SCoPEx would be capable of observing a SCoPEx plume, based on Golja et al. (2020), formed by a 0.1 g s^{-1} injection of calcite from a distance of 200 m with an approximate signal-to-noise ratio of 6000 for a 1 ms signal accumulation.

3.3. Instruments for Future Science Flights (Science Goal 3)

The additional instruments listed in Table 3 are candidates for future SCoPEx flights beyond the initial science flight, i.e., addressing science goal 3. They have not yet been adapted to fly on the SCoPEx platform. Instrument choices will be refined based on experiences in the first science flights. The corresponding science goals that motivate their inclusion are detailed in Section 4.

Measurement	Candidate Instrument	Rationale	Corresponding science goal
Aerosol composition	Drum Sampler	Collecting aerosols for offline analysis	3
Water Vapor	IR Absorption or Frost Point	H_2O outgassing of platform, Influence on coagulation and heterogenous chemistry	2, 3
Atmospheric trace gas concentrations (ex: HCl, NOx)	Spectroscopic trace gas instruments	For measuring concentrations of various atmospheric trace gases before and after addition of solid ASI material	3

Table 3: Potential instrument for future SCoPEx science flights.

Aerosol Composition: Aerosol composition can be analyzed via the collection of aerosol with a drum sampler followed by offline analysis in the laboratory using standard offline methods. Aerosol sampling has been done numerous times aboard stratospheric platforms.

Water Vapor: Gas-phase water vapor measurements are important as relative humidity likely has a large impact on the heterogeneous reactivity of solid SAI material. The balloon and gondola can outgas significant amounts of water and thus an initial experiment will characterize how long, if at all, this outgassing perturbs the SCoPEx plume. As mentioned previously, the goal of SCoPEx is to ideally minimize the perturbation to only the introduction of calcium carbonate. Water vapor measurements are common on many stratospheric platforms.

Hydrogen Chloride: HCl can be measured via infrared absorption spectroscopy. The Anderson group at Harvard, which shares a laboratory with the Keutsch group, has developed a stratospheric HCl instrument and thus has extensive experience with the design of stratospheric HCl instrumentation. In addition, the Keutsch group has designed multiple spectroscopic trace gas measurements. The much lower air speeds of the balloon compared to aircraft favor the design of an open path system, which eliminates the notorious wall effects that can make HCl measurements challenging.

NOx: For NOx there exist a number of good instrumentation options. Recently, a compact NO-LIF instrument has been designed that has spectacular detection limits in the low ppt range, more than sufficient for the needs of SCoPEx. The instrument is a close analogue of the fiber-laser based formaldehyde LIF instrument that the Keutsch Group developed, so there is a high degree of expertise available for such an instrument. There are also sensitive cavity enhanced techniques available usually in the visible range of the spectrum.

3.4. SCoPEx Concept of Operations

Flights will proceed in the following manner. The payload would be launched with the ascender retracted such that there is minimal distance between the crossbar and platform. Once the balloon reaches the float altitude, the rope will be let out through the ascender such that there is 100 m between the crossbar and platform. The platform will then be ready to perform experiments and execute maneuvers. Figure 7 illustrates a proposed flight maneuver. The platform will initially travel in a straight line laying out a plume, after which it will maneuver back through the plume to make measurements. During these maneuvers the ascender can be used to fine tune the altitude of the platform and instruments. Several series of such maneuvers can be performed within each flight. At the conclusion of the experiments the ascender retracts the rope before the descent.

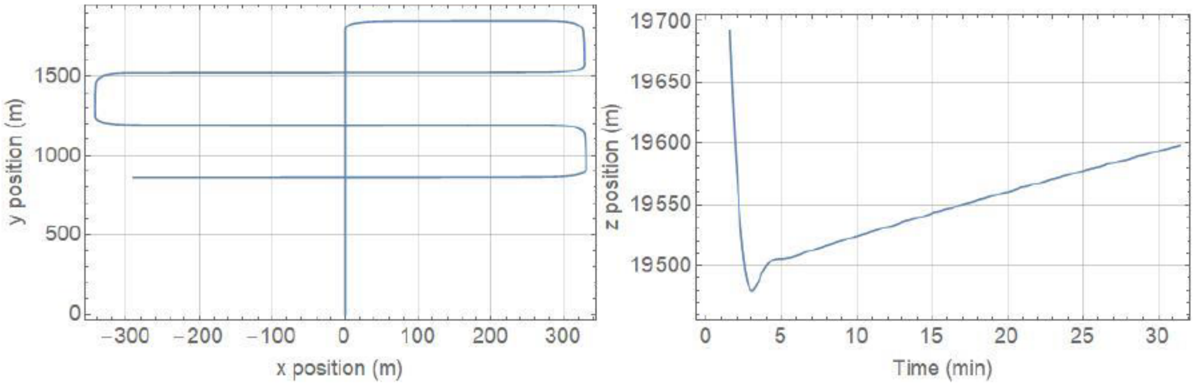

Figure 7: (left) A top down view of the proposed flight maneuvers over a 35-minute window. x and y are in the horizontal plane. The platform begins at (0,0). (right) The vertical position expected without any ascender or hopper vertical trimming over the same 35-minute platform maneuver.

4. SCoPEx Goals

In this section we describe the three long-term SCoPEx science goals. For each goal we describe the scientific problem, the need for SCoPEx, and the measurements required. The first phase of science flights targets the first two science goals. The design of the flights for the third goal will be informed by an understanding of the evolution of particle size distribution in the plume and the plume size. Thus, if later stage science flights move forward, they will be refined based on the results of the first science flights and the most up-to-date knowledge within the solar geoengineering and stratospheric science research communities.

4.1. Goal 1: Measurements of Turbulence for Small-Scale Mixing

4.1.1. The Importance of Plume-Scale Turbulence

Stratospheric turbulence influences the evolution of aerosol distribution from plume to regional to global scale. The mixing of air masses (of differing composition) in the stratosphere is a combination of two processes (Nakamura, 1996; Schoeberl & Bacmeister, 1993). The first process is strain, the distortion of streamline flow that brings air masses of differing composition adjacent to one another (Prather& Jaffe, 1990). Sometimes this is also referred to as “stirring” (Haynes, 2005). The second process occurs when air masses of differing composition are transported across the streamlines. This second process is the true “mixing” process.

In the stratosphere, mixing ultimately occurs because of molecular diffusion. This happens at the length scale of molecular viscosity. It is accelerated by turbulence, which can dramatically enhance the rate at which differing air masses are deformed to small enough spatial scales for molecular diffusion to mix them efficiently. Stratospheric turbulence is, however, highly intermittent (Vanneste, 2004). Understanding the mechanisms of stratospheric turbulence production is essential to understanding the spatial inhomogeneity and effective rate of mixing on spatial scales of 10-500 m (Schneider et al., 2017).

An understanding of this role of turbulence is of interest to stratospheric science because studies suggest that more accurate representations of mixing influence tracer distributions (Hoppe et al., 2014). Measurements of long-lived tracers are the strongest observational constraint on the stratospheric age of air, a key measure of the stratospheric large-scale circulation. Turbulence also modifies the character of kinetic energy fluxes. The magnitude and variability of these energy fluxes determine the rate of frictional dissipation in the atmosphere. This dissipation is represented in global models by a damping parameter and is the primary determinant of the mesoscale atmospheric kinetic energy spectrum. The uncertainty in kinetic spectrum is important to the understanding of the large-scale circulation of the middle atmosphere (Jablonowski & Williamson, 2011).

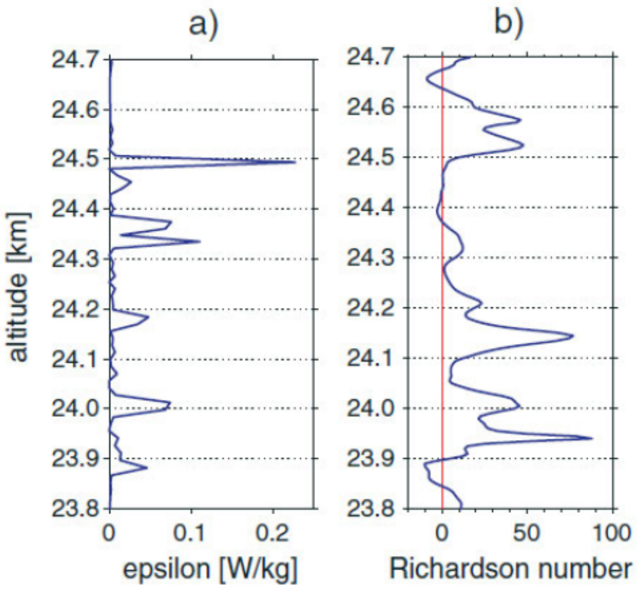

Figure 8: LITOS balloon-borne high-speed anemometer measurements reveal that models of atmospheric turbulence do not explain observed stratospheric turbulence. Physical models predict that a low Richardson number (buoyancy/shear ratio) implies turbulence, but high values of epsilon (turbulent dissipation) should be correlated with low Richardson number, which is not observed. (Haack et al., 2014)

Physical models predict that a low buoyancy/shear ratio (Richardson number) implies turbulence, and that high values of turbulent dissipation should be correlated with low Richardson number (Figure 8). However, recent balloon born measurements during the LITOS campaign did not agree with this, with numerous instances of high values of turbulent dissipation occurring at high Richardson numbers (Haack et al., 2014). As detailed above, both the impact of turbulence on mixing and the associated dissipation of energy are important for general stratospheric science. The point at which viscous fluid forces dominate atmospheric motion is the point where atmospheric motions become purely statistical and is called the dissipation scale. At this scale, models no longer require computationally expensive deterministic modeling. Furthermore, these viscous forces are also responsible for the dissipation of turbulent kinetic energy. Therefore, measurements which resolve the winds at the dissipation scale will allow numerical models to realistically close the atmospheric kinetic energy budget, an important metric of model fidelity.

4.1.2. Importance of Small-Scale Mixing for SAI and SCoPEx

From an SAI and SCoPEx perspective, plume-scale turbulence influences the frequency of collisions of monomer particles within the SCoPEx plume, which determines the rate of formation of fractal, larger aggregates. While Van der Waals forces finally determine whether particles that collide stick together and remain as a fractal aggregate (Sukhodolov et al., 2018), the collision rate is a critical quantity in determining total coagulation rate. Therefore, it is essential to know the frequency of collisions. This frequency is controlled by the wind variability at small spatial scales, i.e., the power spectrum. Intuitively, inertial forcing of particles by wind is much stronger than thermal forcing (e.g. Boltzmann distribution of velocity for ~1 μm particles at ~220 K). Fractal aggregates have a shorter lifetime in the stratosphere and are less effective at scattering light on a per mass basis (Weisenstein et al., 2015), so being able to model the formation

rate of fractal aggregates is an important aspect of SAI, especially with alternate SAI materials.

Improved knowledge of collision rates from wind measurements will allow for the selection of the appropriate mathematical representation of particle coagulation, the coagulation kernel. An accurate kernel is essential for numerical models to correctly simulate aerosol microphysical processes that determine the size distribution and residence time of solid aerosol particles. Adding wind and turbulence measurements to the SCoPEx payload will therefore address the major sources of uncertainty in aerosol microphysics under real atmospheric conditions, which include small-scale fluid flow, particle composition, and humidity.

4.1.3. Experimental Methods to Measure Turbulence in the Stratosphere

Multiple technologies are possible to achieve wind measurements with the necessary spatial resolution under stratospheric conditions. Current state of the art options include pitot tubes (with high sensitivity micro-pirani pressure sensors), hot wire anemometers, and acoustic anemometers. An existing stratospheric program has utilized hot wire anemometers to make measurements that are a close analog to what is necessary for SCoPEx. The program developed LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere), an instrument which made measurements of stratospheric turbulence up to 29 km (Gerding et al., 2009; Theuerkauf et al., 2011). The LITOS instrument has undergone significant calibration and has been compared against radiosondes (Schneider et al., 2015). One drawback of its deployment on a balloon has been the contamination of its wind measurements due to the influence of the balloon’s wake. In contrast, SCoPEx is engineered so that the wind environment of the instrument payload is well separated from the balloon wake when SCoPEx is traveling horizontally. For this reason, SCoPEx could provide significantly more data per flight at a chosen float altitude. In this way, SCoPEx and LITOS would be very complementary. The horizontal flight path of SCoPEx, combined with measurements of the wind power spectrum, would provide an excellent complement to the LITOS observations, which are only obtained along a vertical profile. These power spectra obtained by SCoPEx would contribute to improved micrometeorology understanding relevant both to stratospheric aerosol injection and to fundamental atmospheric science.

Additionally, air flow through the turbulence instrument will be simulated using CFD tools. The CFD runs will provide a means to identify key flow characteristics that drive sensor performance (sensitivity and accuracy) and detailed sensor design. This application of the SCoPEx platform would therefore constitute a nonperturbative means to obtain necessary turbulence measurements that have, to date, eluded the scientific community. This information is important for understanding stratospheric dynamics, including the response to climate change or stratospheric heating from SAI. As no injection of particles is needed, these could be among the first scientific measurements to be conducted.

4.2. Goal 2: Evaluation of Aerosol Microphysics of AM-Sulfate and Alternative SAI Materials

One of the goals for which there are insufficient observational analogues is the near-field evolution of particles injected from a point source in the stratosphere. Specifically, observations of the temporal and spatial evolution of the aerosol size distribution (number and volume) of solid, alternate SAI materials or AM-H_2SO_4 injected form a point source can

only be compared with plume model predictions via a perturbative experiment such as SCoPEx. In the following we describe a plume model by Golja et al. (2020) specifically designed for SCoPEx. We also explain the results from the model and the SCoPEx experimental approach for comparing observations with model results.

4.2.1. Plume Model

Golja et al. (2020) incorporated the SCoPEx design features in their model to study the injection of a solid aerosol and vapor-phase sulfuric acid from a balloon payload. To provide observations relevant to SAI, SCoPEx needs to produce downstream aerosols with radii within the range of roughly 0.2 to 1.0 μm. For calcium carbonate, the objective is to maintain a high fraction of the aerosol in monomer form, while for sulfate an ideal distribution would have a peak diameter of 0.6 μm (Dykema et al., 2016). The generation of largely smaller than ideal particles, while imperfect for assessing radiative efficiency relevant to SAI, does not serve to increase particle sedimentation rates within the plume. Such smaller sizes may, however, result in a larger surface to volume ratio, which can strongly influence stratospheric composition as heterogeneous chemistry is directly related to surface area. Distributions centered on small particle sizes in the near field may, however, continue to evolve beyond the domain of the study.

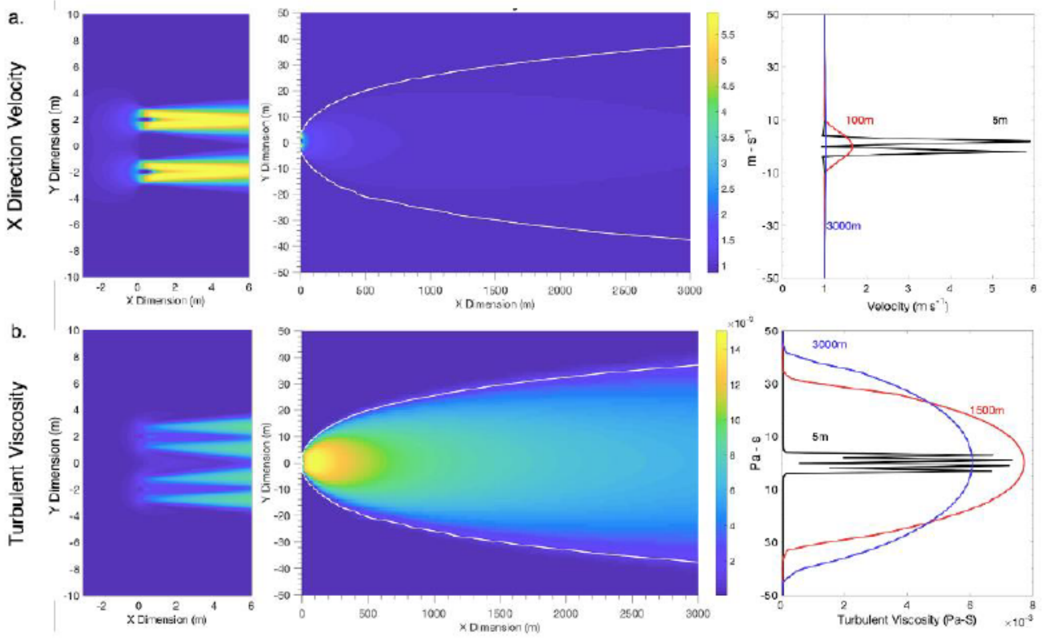

Figure 9 : ANSYS Fluent Velocity and Turbulence Fields. Shown above are the steady state x-direction velocity, u, and turbulent viscosity fields generated by ANSYS Fluent. Left panels show the genesis of disruptions to background X direction flow of 1 ms^{-1}, where propeller features are imposed at locations of 0,2) and (0,-2) meters. The center panel shows the entire domain, from 0 to 3 km, where the imposed red line contours 1 ms^{-1} in plot A, and contours 10% of the absolute maximum turbulent viscosity in plot B. Note Y direction scaling differs between the center and left panels. The right panel shows cross sections of velocity (A) and turbulent viscosity (B) through the Y plane at varying X locations. (Golja et al. 2020)

The velocity and turbulent viscosity fields from Fluent are shown in Figure 9. These fields form the basis of the simulation environment and are instructive in achieving an understanding of SCoPEx and the perturbation it achieves. Peaks in the x-direction velocity, u, are found directly downstream from the modeled propeller centers with an absolute maximum value of 6.3 ms^{-1}. By 1500 m downstream from the inlet locations, the velocity is reduced to the imposed background flow of 1 ms^{-1}. Turbulent viscosity, used as a measure

of particle mixing with background air, exhibits a narrow distribution of peak values ~10 m downstream from simulated propellers. With increasing distance downstream, the turbulent velocity spatial distribution widens, attaining a full width half maximum (FWHM) of 60 m by 1500 m downstream. The wake of the balloon itself is not visible, as it is sufficiently far from the payload to avoid wake crossing/interaction. Additionally, this simulation assumes a laminar stratospheric background flow, neglecting the potential impacts of breaking gravity waves.

For SCoPEx, precipitated calcium carbonate powder with roughly monodisperse size distribution centered at ~0.5 mm diameter will be aerosolized using the expansion of powder suspended in high pressure CO_2 through a 1-2 mm nozzle (see description in Section 3). The model injects aerosol as a 3D gaussian distribution of mass flux into the model grid, where the size of that distribution represents the scale of which the high velocity jet from the nozzle mixes with ambient air. The model considered two injection scenarios: scenario 1 (S1), a single point injection between the propellers; and scenario 2 (S2), injection from the center of each propeller. The model plume diameter at 3 km is, however, insensitive to the injection scenario for injection of both AM-H_2SO_4 and calcium carbonate. This suggests that injection at or between the propellers does not significantly alter the characteristics of the particles' experienced velocity field, and scenario S1 is the one selected for testing the model of plume evolution on SCoPEx. This is also important for the SCoPEx experiment as it necessitates only one sprayer that can be more easily placed in the equipment gondola.

4.2.2. Modelled Mass Injection Rate Dependence of Aerosol Size Distribution

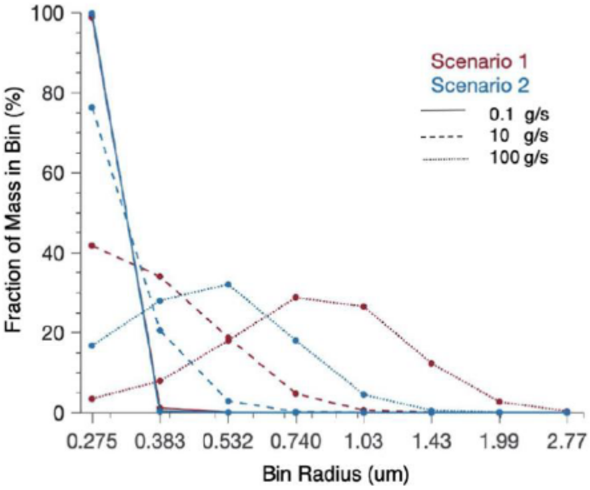

Figure 10: Calcium carbonate aerosol size distributions. Fraction of total mass in each sectional bin where the x-axis markers represent the central radius of each sectional size bin. These distributions represent the percent of total aerosol mass in the final 100 m of the plume across the full domain. Results are shown for three injection rates, 0.1 g s^{-1}, 10 gs^{-1}, and 100 gs^{-1}, for injection scenario 1 (red) and 2 (blue). (Golja et al. 2020)

Mass injection rates of 0.1, 10, and 100 g s^{-1} (0.36, 36, and 360 kg hr^{-1}) were used to test the influence of initial particle number density on the final plume aerosol size distribution. Although some of these are high, their use in the model is instructive as it can answer how different a short burst of high injection rate (much less than an hour) is from a slower but longer injection for the same total mass. Increasing calcium carbonate injection rates from 0.1 to 100 g s^{-1} reduces the share of monomer particles and increases undesired multi-monomer fractal aggregates. Figure 10 shows calcium carbonate's size distribution in the final 100 m of the modeled plume, i.e., the percent in each bin for the three different

injection rates of 0.275 μm radius particles. The low calcium carbonate injection rate of 0.1 g s^{-1} is the most desirable, maintaining 99% of the total mass in the final 100 m of the plume in monomer form. Increasing mass injection rate to 10 g s^{-1} and 100 g s^{-1}, with an S1 injection, shifts peak mass loading to favor particles of radii 0.5 and 0.75 um, respectively, corresponding to fractal "dimers" and "trimers".

Golja et al. (2020) also evaluated whether, in addition to the very sensitive in-situ optical particle counting aerosol size distribution instrument which originally was designed to measure background stratospheric aerosol size distributions (Murphy et al., 2016), the plumes could also be detected optically via scattered light. It should be emphasized that this does not refer to measurements from the ground but rather from close to the plume, e.g., when the equipment gondola is in close vicinity to the plume. Measuring the scattering from one view angle gives the product of the scattering phase at that angle and the scattering efficiency. This is closely related to the radiative forcing, but it does not uniquely determine the radiative forcing. By measuring at multiple angles, we could obtain enough information to quantify the radiative forcing. For example, we could measure from the side and below to obtain the forward scatter fraction, then calculate backscatter by flux conservation.

In the model, the extinction optical depth was calculated using Mie scattering theory and vertically integrating down columns in the y-z plane. Figure 11 shows the relative optical thickness of a sulphate and calcite aerosol plume formed via scenario 1 with an injection rate of 0.1 g s^{-1}. Calcite exhibits greater optical thickness by an order of magnitude at 550 nm, with an average value of 8.6×10^{-4} and maximum of 0.014 across the domain, as compared to sulphate, with an average of 9.4×10^{-5} and maximum 0.001. From these values, Golja et al. calculated that we expect adequate SNR to confidently detect the plume with a fast-scanning radiometer via the solar radiation it scatters. This calculation assumed an altitude of 21 km, solar elevation angle of 60°, an observing instrument situated on the payload gondola, and the gondola 200 m away from the edge of the plume and 1 km downstream of the termination of a scenario 1 type injection of calcite aerosol. Details of this calculation can be found in Golja et al. (2020).

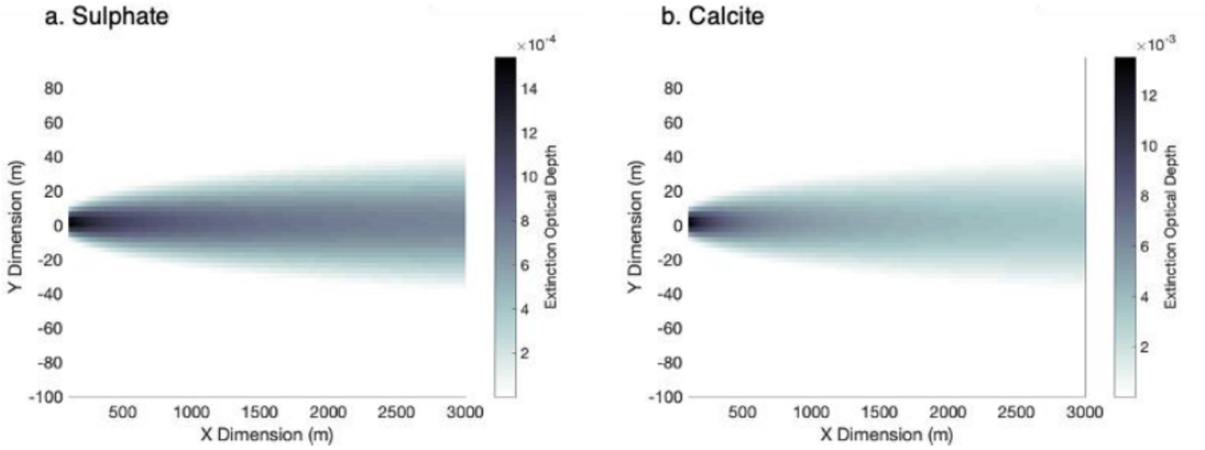

Figure 11: Extinction optical depth integrated vertically through all columns in the plume from 100-3000 m. Plots a and b show results for 0.1 gs^{-1} injections of condensable H_2SO_4 and calcite, respectively. The resulting number density of calcite aerosol is 490 cm^{-3} on the centerline at a downstream distance of 1000 m, predominantly as monomers. Aerosol optical depths were derived from Mie scattering theory at 550 nm, using refractive indices for sulphate and calcite stated in Dykema et al. (2016). (Golja et al. 2020)

4.2.3. SCoPEx Experimental Design and Analysis of Plume Evolution

For this goal, SCoPEx will follow the standard concept of operations, first spraying calcium carbonate at an injection rate suggested by the model analysis. It is desirable to maximize the contrast with the background stratosphere, both with respect to the aerosol concentration and the potential resulting chemical changes, while also maintaining calcium carbonate as monodisperse aerosol. To this end, additional models will be run at injection rates between 0.1 and 10 gs^{-1}. Based on these results, an injection rate will be chosen for the actual SCoPEx experiment. In addition to the basic components of the SCoPEx platform (gondola, ascender, propulsion, power, flight computer, communication, and wind), the calcium carbonate sprayer as well as the LIDAR and POPS instrument are critical for this science goal; without these components, there would not be a way to make and find the plume or measure the aerosol size distribution. While the turbulence measurement from goal 1 is desirable, it is, at least initially, not necessary. Similar studies of AM-H_2SO_4 injection would also be extremely useful. Our current plan is to conduct these after the calcium carbonate injection studies, as initially calcium carbonate is easier to handle than sulfuric acid and its precursors (see next section for motivation of calcium carbonate).

The aerosol size distribution measurements will be compared with the model predictions. In combination with turbulence measurements, discrepancies between the observed and modeled aerosol size distributions can be used to identify issues within the aerosol microphysical scheme or highlight misrepresentations of the velocity and turbulence field of the payload. The results of these studies will provide critical observational constraints on the aerosol microphysics and plume evolution of an injection with solid particles. It will be unique data that is ideal for testing the model of plume evolution as SCoPEx does not have to address problems resulting from the much more violent injection regime associated with injection from airplanes. Clearly, such studies are also needed, but SCoPEx represents a feasible and compelling first step in a sequence of new studies that more comprehensively investigate the aerosol microphysics of point source injections.

4.3. Goal 3: Evaluation of Process Level Chemical Models of Stratospheric Chemistry of Sulfate and Alternative SAI Materials

4.3.1. Need for Alternative SAI Materials

As previously discussed, the two largest first-order stratospheric risks of SAI with sulfate aerosol are ozone depletion and stratospheric heating. For sulfate aerosol the relative magnitude of these two risks can be adjusted if the size distribution can be controlled, e.g., via the AM-H_2SO_4 approach. It is worth noting that the impact on stratospheric ozone may be greatly reduced in the future if reactive halogen concentrations are lower. In contrast, the impact of stratospheric heating will not change. This represents a risk with a poorer understanding of its consequences, which makes it highly desirable to minimize stratospheric heating and resulting dynamic response. Therefore, it is important to investigate alternative SAI materials.

The properties of the “ideal” SAI material is (i) no absorption of radiation, i.e., purely scattering aerosol both fresh and aged, (ii) chemically inert, i.e., no direct impact of this material on stratospheric composition, and (iii) minimal down-stream effects, i.e., no impact on cirrus or other clouds, no environmental impact on deposition on the ground, etc. In reality, it is unlikely that a material with no impacts exists and rather the question is which materials can minimize these impacts. There have been a number of studies investigating

SAI materials in this context. High refractive index materials have been suggested as they reduce the mass of material that have to be lofted (Ferraro et al., 2015; Ferraro et al., 2011; Pope et al., 2012; Keith et al., 2016; Dai et al., 2020; Weisenstein et al., 2015). This largely cost-driven perspective is not a motivation for our work. In contrast, one of the goals of SCoPEx is to decrease the uncertainty in SRM models that use calcium carbonate SAI. The rationale for the choice of calcium carbonate as well as the approach to evaluate some of these risks is described in the following sections.

4.3.2. Unreactive Alternative SAI Materials

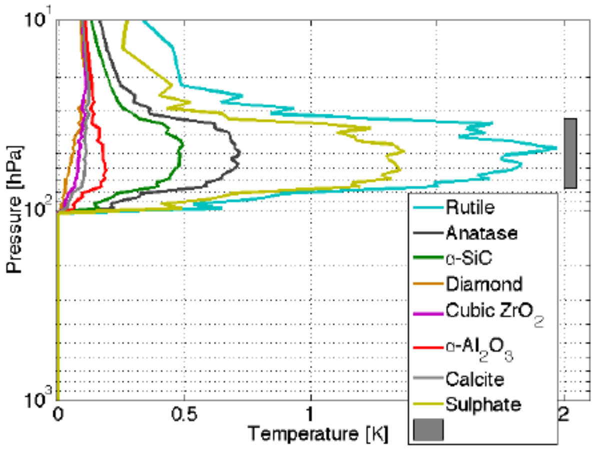

Figure 12: Comparison of stratospheric heating for different materials. Diamond has the lowest impact, although cubic zirconia and calcite are very similar. Sulfate and rutile result in much larger heating. (Dykema et al., 2016)

Diamond is probably the material with the best properties for SAI from a purely stratospheric perspective. Diamond has no absorption features in the solar or terrestrial spectrum and thus triggers the minimal possible dynamical response Figure 12. In addition, diamond should have ideal chemical properties. Hydrogen-terminated diamond surfaces are extremely inert and hydrophobic, precluding the ozone destroying chemistry initiated on sulfuric acid surfaces. The surface itself is also resistant to concentrated sulfuric acid. Exposure to OH radicals would probably slowly make the surface more hydrophilic. From a purely stratospheric perspective the only first-order risk of diamond would be increased ozone loss from the increased sulfuric acid surface area resulting from coagulation with background sulfate aerosol.

4.3.3. Reactive Alternative SAI Materials: The Case for Calcium Carbonate

Although the impact on cloud properties and the risk to Earth's surface from deposition of SAI diamond is likely very low, it could be preferable to have a material that dissolved easily in water, hence not persisting for long times outside of the stratosphere. It would also be preferable to have a material that is naturally abundant at Earth's surface. In addition, it would be ideal to overcome increased ozone loss due to coagulation by using a reactive aerosol. We therefore propose calcium carbonate as a prototype alternate SAI material for the following reasons: First, its optical properties are nearly equal to diamond and stratospheric heating and resulting dynamic response should be negligible compared to sulfate (Figure 12). Second, carbonates are typically quite reactive with acids, especially with concentrated sulfuric acid (Figure 13). Hence, calcium carbonate will neutralize upon

coagulation with sulfate aerosol eliminating the acidic surfaces resulting from coagulation of diamond and sulfate aerosol. Of course, the reactivity of calcium carbonate also makes model predictions with calcium carbonate more complex. The evolution of chemical and optical aerosol properties has to be modeled over its stratospheric lifetimes. One of the key research questions that SCoPEx will help address is whether the reactivity of calcium carbonate and the evolution of its chemical and optical properties and those of the surrounding gas-phase correspond to the detailed hypothesis laid out below. To this end, SCoPEx will compare observations of the chemical evolution of calcium carbonate, as well as the gas-phase, with those of a model based on known properties of calcium carbonate and recent laboratory experiments (Dai et al., 2020). This will provide a real-world evaluation of kinetic parameters, such as heterogeneous uptake coefficients derived from the laboratory studies, that will enable GCMs to include reliable parameterizations of the stratospheric impacts of calcium carbonate SAI.

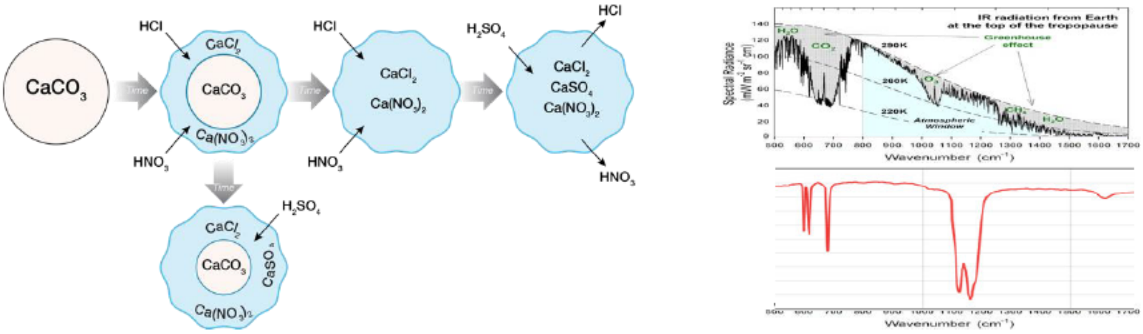

Figure 13: The left panel shows schematic of potential chemical reactivity of calcium carbonate in the stratosphere. The right panel shows the atmospheric windows in the terrestrial infrared (top) as well as the infrared absorption spectrum of calcium sulfate (bottom). The position of the 1150 cm^{-1} sulfate in part explains the stratospheric heating effect of sulfuric acid.

4.3.3.1. Optical Properties

Based on well-established chemistry, the reaction of sulfuric acid aerosol with calcium carbonate can be assumed to go to completion, i.e., be reagent limited. The optical properties of calcium sulfate in the terrestrial infrared are similar to those of sulfuric acid with only slight differences in relative band intensities and wavelengths (Figure 13 right hand inset). This is important as it implies that there will be no large first-order changes in stratospheric heating from changing background sulfuric acid to calcium sulfate. There are higher order impacts due to slight differences in the absorption of sulfuric acid, which has some liquid water compared to calcium sulfate. There are also numerous forms of calcium sulfate (anhydrite, bassanite, gypsum, etc.). However, the resulting differences are much smaller than introducing an absorbing material via SAI.

4.3.3.2. Chemical Properties

Predicting the evolution of the chemical properties of calcium carbonate under stratospheric conditions is more challenging. It is certain that calcium carbonate does not have the same heterogeneous reactions that activate ozone destroying substances as sulfuric acid. Figure 13 shows a schematic of the expected reactivity. Calcium carbonate is expected to react with acidic substances neutralizing them, forming salts and carbon dioxide. These acid neutralizing reactions can deplete gas-phase HNO_3, HCl, etc. There are a large number of ozone destroying catalytic cycles involving NOx, chlorine and other

halogens, which are altitude (and latitude) dependent. NOx can be produced via HNO_3 photolysis and lost via heterogeneous reaction of N_2O_5. It participates both in ozone destroying catalytic cycles and is important for deactivation of ozone destroying halogen radicals. Thus, knowledge of the heterogeneous reaction rates of numerous substances with calcium carbonate are required to predict the impact it will have on stratospheric composition.

However, until the recent study by Dai et al. in our laboratory, no heterogeneous chemistry studies of calcium carbonate under stratospheric conditions had been conducted, to our knowledge, although there exists a rich data set under tropospheric conditions (Dai et al., 2020). This work, as well as the work of Dai et al., highlights that reactive solid aerosols are indeed more complex than liquid sulfuric acid: The authors observed moderate initial uptake of the gas-phase acids HCl and HNO_3 on fresh calcium carbonate, as the dry stratospheric conditions already make uptake coefficients lower than under typical tropospheric conditions. An additional large difference to liquid aerosol is that the surface of the solid calcium carbonate passivates, drastically reducing the uptake coefficients of HCl and HNO_3. Hence, based on the Dai et al. laboratory study, calcium carbonate rapidly becomes effectively unreactive with respect to uptake of these gas-phase acids, an important finding that confirms calcium carbonate as a good candidate as alternate SAI material. In addition, calcium carbonate particles are abundant at Earth's surface due to windblown mineral dust. And the small calcium carbonate SAI particles should dissolve rapidly in water. This does not exclude risks associated with the deposition of calcium carbonate SAI particles or impacts on clouds (Cziczo et al., 2019). However, due to its abundance at the Earth's surface, there already exists a large knowledge base for its environmental impacts in contrast to, e.g., diamond. Further laboratory work is required to study especially the $ClONO_2$ + HCl and N_2O_5 hydrolysis reactions on fresh and aged calcium carbonate. However, the existing results prepare the stage for studying them in the real stratospheric environment as outlined below. Figure 14 shows results of the AER 2-D chemistry-transport-aerosol model for annual average ozone column changes of calcium carbonate SAI compared to a control for 2040. Ignoring the passivation of calcium carbonate (thk-ind) results in increases in ozone columns from calcium carbonate SAI whereas the inclusion of passivation can either result in very little ozone column change or losses in the Southern Hemisphere, depending how the $ClONO_2$+HCl is parameterized. Either of the two, more realistic, passivation scenarios result in significantly lower ozone loss than the equivalent amount of sulfate SAI, consistent with the hypothesis.

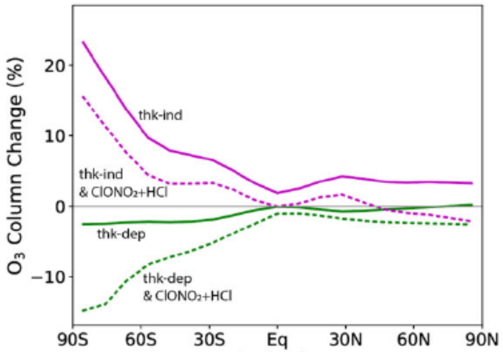

Figure 14: Shows the role of passivation and the heterogeneous $ClONO_2$+HCl reaction on ozone column change using the AER 2-D model taken from Dai et al. 2020. Inclusion of this reaction with the same rate as measured for Al_2O_3 results in a substantial reduction in ozone for scenarios including, thk-ind, or excluding passivation, thk-dep.

4.3.4. Need for SCoPEx Calcium Carbonate Plume Studies

One of the challenges for alternate SAI aerosol is the lack of materials such as calcium carbonate in the stratosphere. The only way to then study these materials in the actual stratosphere is via deliberate stratospheric injection of a small amount of these materials. In environmental studies, including stratospheric studies, it is not possible to rely purely on laboratory studies. For example, flights on the NASA ER-2 into the polar vortex over Antarctica provided the ability to test whether laboratory-derived reaction mechanisms were able to capture real-world ozone destruction chemistry. Without these flights, the level of confidence in the model predictions would have been much lower, and for good reason. It is not clear that a given experimental setup in the laboratory can faithfully capture the entire complexity of the real stratosphere; only field observations are able to provide this. For a number of natural stratospheric processes, remote observations can provide important information in addition to in situ aircraft or balloon. However, these are only possible when large-scale phenomena are at work.

Since there are no natural calcium carbonate plumes in the stratosphere that would even allow for in situ observations, intentional injection is necessary to perform these studies. Calcium carbonate injections will allow SCoPEx to provide invaluable observations as it will quantitively test the mechanisms determined in the laboratory. As stated above, there is a need for more laboratory studies, however, there is good reason to proceed with the planning of SCoPEx calcium carbonate experiments. First, by the time of the first injection experiments, additional studies should have been conducted. In addition, N_2O_5 uptake coefficients used in the model are likely a very good estimation as similar values have been found for different solid materials, e.g., Al_2O_3 and SiO_2 (Molina et al., 1997). In addition, even with these additional lab determined mechanisms, the same type of experiments as proposed here will still have to be conducted, as we expect these reactions to not make a significant difference. In other words, they will not be a deciding factor about the viability of calcium carbonate as an alternate SAI material. Only field experiments will help shed insight into these questions. In summary, there is a critical need for evaluating not just the aerosol microphysics (goal 2) but also the stratospheric chemistry of calcium carbonate due to the promise it holds as a lower risk SAI material.

4.3.5. SCoPEx Experimental Design and Analysis of Chemical Calcium Carbonate Plume Evolution

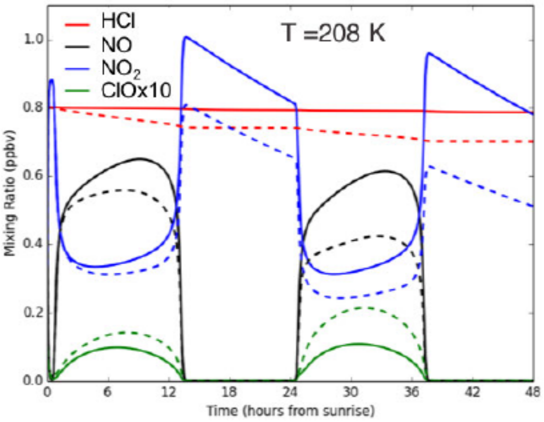

Figure 15: Solid lines: background $2\mu m^2\ cm^{-3}$ sulfate $5ppm_v$ H_2O. Dashed lines: plume $15\mu m^2\ cm^{-3}$ sulfate 10 ppm_v H_2O.

The experiments will again follow the standard concept of operations as under goal 2. In order to determine optimal injection rates, we will include chemical reactions in the plume model, updated with the newest mechanisms available at that time. Figure 15 shows the evolution of an air mass perturbed by a sulfate aerosol injection over multiple days, i.e., significantly longer than the initial SCoPEx experiments. Significant changes in HCl and NOx can be observed already over short time periods and these are easily detectable with existing instrumentation. For this science goal, it is desirable to measure aerosol composition and size distribution as well as key gas-phase chemical species, especially HCl, NOx and water. Therefore, this science goal requires a much larger set of instruments. In addition, the equivalent model to Figure 15 for calcium carbonate is informed by the results of science goal 2. The work of Dai et al. provides kinetic parameters needed for this model, and reactions for which there are no laboratory data to date are parameterized using close analogues and conditions, e.g., $ClONO_2$ + HCl are parameterized using the results for alumina (and silica) from Molina et al. (1997). One key question is whether the changes in HCl and NOx will indeed be smaller for calcium carbonate than those for sulfate shown in the figure above, which would confirm the hypothesis for calcium carbonate as a potential alternate SAI material.

In summary, SCoPEx experiments using calcium carbonate injections will provide a unique evaluation as to whether calcium carbonate indeed is an alternate SAI material that could substantially reduce risk from SAI compared to sulfate. Follow-up studies will be needed. For example, improved chemical and aerosol microphysics models will provide improved models of the chemical and physical evolution of calcium carbonate, which likely will motivate specific laboratory investigations. These will provide information for SCoPEx studies using “stratospherically aged” calcium carbonate as precursor for injection that can then be used to compare whether the laboratory mechanisms of this aged calcium carbonate agree with that found in the real stratospheric environment.

5. Data Management Plan and Dissemination of Results

Products of the research. The data generated during this project consists of meteorological, navigational, telemetry, and a variety of instrumentation data, in particular aerosol size distributions as well as chemical composition data during later science flights. In addition, there will be model data on plume chemical evolution.

Access to data, data sharing practices, and policies and dissemination of results. Data relevant for scientific analysis will be made public within 60 days of the end of flight. This taw data will be made public with appropriate warnings that it has not undergone QA/QC. The email address of users will be recorded so that they can be automatically notified when revised versions become available. Based on previous experiences with stratospheric airborne campaigns, this is typically 6-15 months after the flight depending on the type of data, e.g., the amount of calibration and data workup required. We have chosen to make raw data available rapidly—going far beyond what is typical for stratospheric science missions—because of the public scrutiny of SCoPEx and because of the broad commitment to Open Access data principles articulated by Harvard's Solar Geoengineering Research Program which is funding SCoPEx.

Principal Investigators (PI) and their groups have an excellent track record with presenting their work at major national and international conferences and workshops. All data that go into key analyses and figures in the group's publications will be made publicly available via the PI's group website. All publications resulting from this project will be posted on the PI's webpage (https://projects.iq.harvard.edu/keutschgroup/publications). Preprints of manuscripts submitted for publication as well as the underlying data will also be posted on Harvard's Dash manuscript repository. Publications will be made in open access formats.

Archiving of data. All data acquisition/storage computers in the PI's group are automatically backed up daily, both wirelessly to a server elsewhere on campus, and/or to a cloud server. Both of these processes ensure that data will not be lost and enable rapid access to the data. The file naming system used for all software (which includes the date of the experiment) ensures straightforward retrieval and use of archived data. Group laptops are also backed up daily, ensuring that analyzed data are archived as well.

6. SCoPEx Research Team Biographies

Frank Keutsch (b) (6) [redacted]

David Keith (b) (6) [redacted]

(b) (6) [redacted]

Norton Allen (b) (6) [redacted]

John Dykema (b) (6) [redacted]

Mike Greenberg (b) (6) [redacted]

Michael Litchfield (b) (6) [redacted]

(b) (6) [redacted]

Craig Mascarenhas (b) (6) [redacted]

Terry Martin (b) (6) [redacted]

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From: Smith, Wake (b) (6)
Subject: RE: CCIS webinar Wednesday Sept 22nd
To: Karen Rosenlof - NOAA Federal
Sent: September 18, 2021 7:59 AM (UTC-04:00)

Will do.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6)

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Sent: Friday, September 17, 2021 4:44 PM
To: Andrea Smith (b) (6)
Cc: Simone Tilmes (b) (6) ; Keutsch, Frank N (b) (6) >; Smith, Wake <(b) (6) ; Graham Feingold - NOAA Federal <Graham.Feingold@noaa.gov>; Brian Medeiros (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd

And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.

Thanks!

Karen

Karen Rosenlof
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while safer at home remains in effect, email is the most reliable contact

> On Sep 17, 2021, at 11:06 AM, Andrea Smith (b) (6) > wrote:
>
> Hello Frank, Wake and Graham,
>
> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>
> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
> Meeting ID: 816 4261 9898
> Passcode: 148321

Please join 10 mins early to test tech and troubleshoot if needed.

2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) [redacted] (preferably by Tuesday night):

3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.

After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.

Let me know if you have questions on any of the above.

Thanks again, and see you next Wednesday.

Andrea

On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) [redacted]> wrote:

> Hi Frank, Wake and Graham,
> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>
> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
>
> 1. Frank Keutsch: ...
> 2. Wake Smith:...
> 3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening
>
> Here is Andreas rundown for logistics:
>
> -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
> -send slide decks to Andrea by Tuesday (9/21) evening for backup purposes
> -arrive ~10 mins early so we can do quick test of screenshares
> -15 min talk length, w/ immediate clarifying question(s) and then ~30 mins broad discussion and questions at end
> -moderator will collect questions in chat window throughout and ask most pertinent ones for discussion
> -panelists and question askers encouraged to unmute & turn on camera
> -session will be recorded and posted later - we'll send a release form for them to complete
>
> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
>
> Cheers, Simone

> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6)

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.
<CCISspeaker_consent_form.pdf>

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Andrea Smith
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Graham Feingold - NOAA Federal; Brian Medeiros
Sent: September 17, 2021 4:44 PM (UTC-04:00)
Attached: Untitled attachment

And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.

Thanks!

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
Boulder, CO 80305
office: 3A-121, DSRC
e-mail: Karen.H.Rosenlof@noaa.gov
phone: 303 497-7761
fax: 303 497-5373
----
while safer at home remains in effect, email is the most reliable contact

> On Sep 17, 2021, at 11:06 AM, Andrea Smith (b) (6) [redacted]> wrote:
>
> Hello Frank, Wake and Graham,
>
> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>
> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
> Meeting ID: 816 4261 9898
> Passcode: 148321
>
> Please join 10 mins early to test tech and troubleshoot if needed.
>
> 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) [redacted] (preferably by Tuesday night):
>
> 3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.

After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.

Let me know if you have questions on any of the above.

Thanks again, and see you next Wednesday.

Andrea

On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) [redacted] wrote:

> Hi Frank, Wake and Graham,
> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>
> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
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> 1. Frank Keutsch: ...
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> -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
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>
> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
>
> Cheers, Simone
>
> --
> *Simone Tilmes,*
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> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6) [redacted]

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.

Boulder, CO 80301
303-497-8320 (office)
(b) (6)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.
<CCISspeaker_consent_form.pdf>

From: Keith, David (b) (6) [redacted] >
Subject: RE: Experimental research platform requirements
To: David Fahey - NOAA Federal
Cc: Smith, Wake; Keutsch, Frank N
Sent: February 3, 2021 9:59 AM (UTC-05:00)

Dave

Thanks. I think we see this about the same way.

From my perspective I came into this field working for Jim with all the excitement about Aurora's aircraft which ended up amounting to nothing. It took some years of my life. And yes, Global Hawk has been a big disappointment. So I definitely get the basis for skepticism.

On the other hand, there does seem to be a commercial-driven shakeup in the ability to develop low altitude aircraft. That's true from the new entrants into general aviation market through to the startups building off drone technology. So I'd like to understand whether this could apply to higher altitude light aircraft. I don't know, but if Wake spurs some interest I am open to find out more.

Have you had any conversations with these folks: Sceye | A new generation of HAPS | High Altitude Platform Stations? The head guy just reached out to me again and I will talk with.

David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Saturday, January 30, 2021 6:38 PM
To: Keith, David (b) (6) [redacted] >
Cc: Smith, Wake (b) (6) [redacted] >; Keutsch, Frank N (b) (6) [redacted] >
Subject: Re: Experimental research platform requirements

David,

Yes, I think if one has funding, then existing a/c become available. Certainly for the UT/LS, the WB-57s have been underutilized for years now and hence availability hasn't been an issue. Indeed a trip back to the boneyard was perhaps a growing threat.

I note that no one has ever built an aircraft for atmospheric chemistry, leaving the field to exploit as best they can existing a/c, which we have done very well. Thus, if there were runway a/c available that could do 30kg, 8hr, 79kft, the community would no doubt rush to use it. So the answer to your question is yes.

My problem with new-platforms-will-be-cheap is the issue of having truly operational a/c rather than experimental a/c. If one is trying to fly an experiment on an experimental a/c it reduces the probability of success by a large measure. Making an experimental a/c operational requires larger upfront and sustained investment by entities other than the science communities, creating the underwater part of the iceberg. This is why we don't have new operational a/c. And one can look to the Global Hawk and see that even starting at a high level (a mature platform) it failed to become operational because no one wants to pay the price, in this case neither NASA or NOAA. Now deeper pockets (DoD) have taken it over.

And to your final point about what payloads, yes, the new generation of lightweight instruments make 30kg interesting and valuable, and, yes, comprehensive chemistry payloads still want to be on heavy lift long-range a/c.

In reply to Wake's question about perturbation/monitoring a/c, hmmm, it depends. In the early days, perhaps they could be the same. Eventually the perturbations sought would be as large as possible per flight and not every flight would need diagnostics, so I think eventually they are different a/c. And monitoring a/c could be below the perturbation a/c altitudes and diagnose with lidar.

Interest above 70kft: in general because we would be deeper into the ozone layer. And perhaps the injection altitude would be there once we understand things better.

Regards
Dave

> On Jan 30, 2021, at 9:29 AM, Keith, David <(b) (6) [redacted]> wrote:
>
> Dave
>
> Interesting back-and-forth.
>
> I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.
>
> I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30 kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.
>
> I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.
>
> I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.
>
> Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.
>
> Interesting conversation. No simple answers.
>
> Cheers,
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Thursday, January 28, 2021 11:49 AM
> **To:** Smith, Wake (b) (6) [redacted]>

Cc: Keith, David <(b) (6) [redacted]>; Keutsch, Frank N (b) (6) [redacted]
Subject: Re: Experimental research platform requirements

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi-flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" <(b) (6) [redacted]>
Cc: Frank Keutsch (b) (6) [redacted]

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can't control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake <(b) (6) [redacted]> wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6) [redacted]

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Fwd: Update
To: Frank Keutsch
Cc: Keith, David; Ronda Knott - NOAA Federal
Sent: October 28, 2020 1:03 PM (UTC-04:00)
Attached: Untitled attachment

Great. Looking forward to it.

> Begin forwarded message:
>
> **From:** "Keutsch, Frank N" (b) (6) [redacted]>
> **Subject: Re: Update**
> **Date:** October 28, 2020 at 10:51:34 AM MDT
> **To:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
>
> Dave,
>
> Thanks for your email. I will see how it goes. I have a number of deadlines looming over me, but will try to attend the whole meeting.
>
> I hope you are doing well. Germany is going into a moderate lockdown!
>
> All the best,
>
> Frank
>
>> On Oct 28, 2020, at 3:25 AM, David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:
>>
>> Frank,
>>
>> I hope this finds you doing well with the family in Germany.
>>
>> DavidK and I invited you to a Friday v-meeting to catch up on CI matters. He will give me a brief download of his CDR ideas/perspective at the beginning at my request. So you could join late to miss that.
>>
>> Let us know.
>> THanks
>> Dave
>>
>> ---
>>
>> David W. Fahey, PhD
>> Director of the Earth System Research Laboratories (ESRL)
>> Director of the ESRL Chemical Sciences Laboratory
>> NOAA Earth System Research Laboratories
>> 325 Broadway R/CSD
>> Boulder, CO 80305 USA

303-497-5277   -5822 fax
david.w.fahey@noaa.gov

Ronda Knott, Admin. Assistant
ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

Begin forwarded message:

From: Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
Subject: Re: Update
Date: October 26, 2020 at 7:51:29 PM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Cc: "Keith, David" <(b) (6) [redacted]>

Hi Dave and David,

The meeting has been set for this Friday, October 30th at 7am MT and included Frank Kuetsch.
The connection details are:

Meeting ID
meet.google.com/zgb-gfnu-gdr
Phone Numbers
(US) +1 561-408-9337
PIN: 857 507 300#

Thank you,
Ronda

Ronda Knott
Executive Administrative Assistant to

Dr. David W. Fahey, Director

NOAA Chemical Sciences Laboratory
325 Broadway, R/CSL

Boulder CO 80305

I am currently teleworking, please call my cell: (b) (6) [redacted]

303.497.4404 phone

303-497-5822 fax

ronda.knott@noaa.gov

On Mon, Oct 26, 2020 at 2:56 PM David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:

> David,
> 7Am Friday will work.
> Ronda can reach out to FrankK if you like. She will send a link to all.
> Thanks
> Dave
>
> On Oct 25, 2020, at 9:17 PM, Keith, David (b) (6) [redacted] > wrote:
>
> How about 8:30 AM MT on Friday the 30th? (I can do any time from 7:00 to 10:00) MT that AM. Suggest we choose a time, then I will see if Frank can join (he can miss the CDR part).
>
> D
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, October 24, 2020 6:29 PM
> **To:** Keith, David (b) (6) [redacted]
> **Cc:** Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
> **Subject:** Re: Update
>
> David,
>
> Thanks for the reply. I appreciate the perspective on Pierrehumbert; a bit frustrating. We will launch a webpage for the Earth Radiation Budget program (ie the Congressional funding) soon (albeit a bit late) that will explain NOAA's role and intent and in effect pushback on Pierrehumbert and others.
>
> Thanks for your offer of a CDR debrief and catching up on other matters. My CDR meeting is 4 Nov so best would be next week sometime. Let me know if that might work (w/ or w/o Frank) and a preferred day/time.
>
> Regards
> Dave
> PS Canmore seems like a good faraway place to get fresh air devoid of C-19.

On Oct 21, 2020, at 2:13 PM, Keith, David
(b) (6) [redacted] wrote:

Dave

Thanks. Yet, I'm particularly frustrating because Ray repeats the idea that doing it at all commits us to doing it for a thousand years, yet I think he knows that's not true. When he was at Harvard and from the public audience we challenged him on that pointing out that you could always taper off slowly even if you didn't have carbon removal and so the net result would be a reduction in the rate of change even if it didn't change the ultimate endpoint. He agreed. Yet he keeps coming back to this claim.

I don't have an overview on CDR. I step back because of the conflict of interest after starting Carbon Engineering (the air capture company). In fact I think that CDR is a bit overhyped and I have been trying to figure out how to say that without frustrating people at Carbon Engineering too much. I have fragments of talks and some opinions. I could dump these on you in a short (15 minutes) conversation which might be helpful to me because I'm trying to polish the stuff.

I think you catch up with you, me and Frank would make sense. I'm thinking early November at that point we will of got science plan out to the SCoPEx committee and have made the next step towards reality on a spring flight.

It's beautiful and snowy up here in Canmore Alberta.

David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Wednesday, October 21, 2020 1:23 PM
To: Keith, David (b) (6) [redacted] >
Subject: Update

David,

Very good article in Globe. Pierrehumbert's article

> is frustrating since he attacks CI and calls out people like me yet at the end says there might be an appropriate role for CI, something he has done in other articles.
>
> My management has asked me to inform them about CDR in an internal meeting. I am not very well prepared to do that and wondered if you had a presentation that you would be willing share to draw from for this purpose.
>
> A call to catch up with Frank would be welcome.
>
> Regards
> Dave
>
> ___
>
> David W. Fahey, PhD
> Director of the Earth System Research Laboratories (ESRL)
> Director of the ESRL Chemical Sciences Laboratory
> NOAA Earth System Research Laboratories
> 325 Broadway R/CSD
> Boulder, CO 80305 USA
> 303-497-5277   -5822 fax
> david.w.fahey@noaa.gov
>
> Ronda Knott, Admin. Assistant
> ronda.knott@noaa.gov, 303-497-4404
> http://www.esrl.noaa.gov/csd/
>
> ___

Frank N. Keutsch
Stonington Professor of Engineering and Atmospheric Science

Harvard John A. Paulson School of Engineering and Applied Sciences
Department of Chemistry and Chemical Biology
Department of Earth and Planetary Sciences
Harvard University
12 Oxford Street
Cambridge, MA 02138
USA

E-mail:
(b) (6) [redacted]

Tel:+(b) (6)

Siri | Glimstad

NEW YORK | LOS ANGELES | MIAMI
PHOENIX | DETROIT | DENVER | AUSTIN

745 Fifth Ave, Suite 500, New York, NY 10151
sirillp.com | P: (212) 532-1091 | F: (646) 417-5967

NOAA FREEDOM OF INFORMATION ACT REQUEST

VIA ONLINE PORTAL June 6, 2023

Mark Graff
FOIA Officer
NOAA FOIA Office, Room 9719 (SOU 10000)
1315 East-West Highway
Silver Spring, MD 20910
FOIA@noaa.gov

Re: Karen Rosenlof and/or David Fahey Emails Which Include Rob Wood, David Keith, Alan Robock, William Brennan, Ken Caldiera, and/or Frank Keutsch (IR#13023C)

Dear Sir or Madam:

This firm represents Informed Consent Action Network ("**ICAN**"). On behalf of ICAN, please provide the following records to ear@sirillp.com in electronic form:

> **All emails, including attachments, sent or received by Karen Rosenlof and/or David Fahey from January 1, 2010 through the date of the search which include Rob Wood, David Keith, Alan Robock, William Brennan, Ken Caldiera, and/or Frank Keutsch, and/or their email address(es), in the to, from, cc, and/or bcc lines.**

We ask that you waive any and all fees or charges pursuant to 5 U.S.C. § 552(a)(4)(A)(iii). ICAN is a not-for-profit news media organization whose mission is to raise public awareness about vaccine safety, other medical treatments, and overall health choices, and to provide the public with information needed in order to give informed consent. (**Attachment A**.) As part of its mission, ICAN actively investigates and disseminates scientifically-based health information regarding the safety of vaccines, other medical treatments, and governmental activities for free through its website,[1] a weekly health news and talk show,[2] and through press events and releases. ICAN is seeking the information in this FOIA request to allow it to contribute to the public understanding of government programs and any potential effects of same on public health. The information ICAN is requesting will not contribute to any commercial activities. Therefore, ICAN should be properly categorized as a media requester, and it is entitled to the search and processing privileges

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[1] https://www.icandecide.org/.

[2] https://thehighwire.com/.

associated with such a category designation. Accordingly, ICAN will be forced to challenge any agency decision that categorizes it as any other category of requester.

Please note that the FOIA provides that if only portions of a requested file are exempted from release, the remainder must still be released. We therefore request that we be provided with all non-exempt portions which are reasonably segregable. We further request that you describe any deleted or withheld material in detail and specify the statutory basis for the denial as well as your reasons for believing that the alleged statutory justification applies. Please also separately state your reasons for not invoking your discretionary powers to release the requested documents in the public interest. Such statements may help to avoid unnecessary appeal and litigation. ICAN reserves all rights to appeal the withholding or deletion of any information.

Access to the requested records should be granted within twenty (20) business days from the date of your receipt of this letter. Failure to respond in a timely manner shall be viewed as a denial of this request and ICAN may immediately take further administrative or legal action.

Furthermore, we specifically request that the agency provide us with an estimated date of completion for this request.

If you would like to discuss our request or any issues raised in this letter, please feel free to contact us at (212) 532-1091 or ear@sirillp.com during normal business hours. Thank you for your time and attention to this matter.

Very truly yours,

/s/ Aaron Siri
Aaron Siri, Esq.

Attachment A

DECLARATION OF CATHARINE LAYTON

STATE OF TEXAS

COUNTY OF Hays

I, Catharine Layton, being duly sworn on oath do say:

1. I am the Chief Operating Officer of the Informed Consent Action Network (ICAN), a not-for-profit 501(c)(3) organization whose mission is to disseminate scientific health information to the public.

2. I have been an officer of ICAN since its founding in 2016. I oversee all day-to-day operations of the organization and all ICAN's programs. Together with our CEO and Board, I ensure that all efforts are focused on our mission statement and ensure that ICAN stays in compliance with all required rules and regulations.

3. In pursuit of its mission, ICAN relies primarily on its own investigative reporting. ICAN is both instrumental in orchestrating cutting edge investigations into the safety of various medical products, as well as widely disseminating its findings through various media channels. Most notably, ICAN's popular website hosts the organization's largest education program, The HighWire with Del Bigtree. Utilizing its media teams' 40+ years of experience in TV production and investigative journalism, The HighWire provides hours of new video content to the public each week for free.

4. The HighWire website has approximately 3.4 million weekly visitors. On Twitter, The HighWire has approximately 140,000 followers and 1 to 2.5 million impressions in a 28-day period. Between Rumble and Bitchute, The HighWire has approximately 60,000 followers and growing. Additionally, ICAN has 29,000 text subscribers and 194,245 email subscribers.

5. The size of ICAN's audience and subscribers continues to grow and is illustrative of the wide public interest in the subject of health and medical safety. Moreover, critical to ICAN's mission is its proven ability to find and review critical scientific and governmental records and meaningfully report about their social impacts.

6. One of the tools ICAN uses to gather the raw material it uses in its popular investigative reporting is the Freedom of Information Act (FOIA).

7. ICAN uses records it obtains from its FOIA requests to carry out its public mission and support its role as a non-profit news-media organization in the field of health and medical safety, but as a non-profit, ICAN does not have a commercial interest in the records it seeks through FOIA.

8. Based on what I know as the Chief Operating Officer, as well what has been demonstrated by ICAN's past and current investigative reporting, for purposes of FOIA's Fee Waiver provisions, ICAN certainly qualifies as a "representative of the news media."

Signed 3 day of May 2022

Signature of Catharine Layton

I, Amy Blackwell Notary public for the state of Texas witnessed said Catharine Layton sign the above statement this 3 day of May (month), 2022

Notary Public for

AMY MARIE BLACKWELL
Notary ID #132597493
My Commission Expires
July 30, 2024

From: Andrea Smith (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Graham Feingold - NOAA Federal
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Karen Rosenlof - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:49 AM (UTC-04:00)

https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09

Do you need to use the web client? NOAA or other government users can use Zoom's government-approved web client

Try that, let me know how it goes.

A

On Wed, Sep 22, 2021 at 8:47 AM Graham Feingold - NOAA Federal <graham.feingold@noaa.gov> wrote:

> zoom link not working for me. is there something else i need to do?
>
> On 9/17/21 11:06 AM, Andrea Smith wrote:
>
>> Hello Frank, Wake and Graham,
>>
>> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>>
>> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
>> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
>> Meeting ID: 816 4261 9898
>> Passcode: 148321
>>
>> Please join 10 mins early to test tech and troubleshoot if needed.
>>
>> 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) (preferably by Tuesday night):
>>
>> 3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.
>>
>> After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.
>>
>> Let me know if you have questions on any of the above.
>>
>> Thanks again, and see you next Wednesday.
>>
>> Andrea
>>
>> On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) > wrote:
>>
>>> Hi Frank, Wake and Graham,
>>> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>>>
>>> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see

> below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
>
> 1. Frank Keutsch: ...
> 2. Wake Smith:...
> 3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening
>
> Here is Andreas rundown for logistics:
>
> -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
> -send slide decks to Andrea by Tuesday (9/21) evening for backup purposes
> -arrive ~10 mins early so we can do quick test of screenshares
> -15 min talk length, w/ immediate clarifying question(s) and then ~30 mins broad discussion and questions at end
> -moderator will collect questions in chat window throughout and ask most pertinent ones for discussion
> -panelists and question askers encouraged to unmute & turn on camera
> -session will be recorded and posted later - we'll send a release form for them to complete
>
> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
>
> Cheers, Simone
>
> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6) [redacted]

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) [redacted] (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

--
Graham Feingold
NOAA Earth System Research Laboratories
Chemical Sciences Laboratory (R/CSL9)
325 Broadway
Boulder, Colorado 80305, USA

> Tel: (303) 497-3098
> Fax: (303) 497-5318

--

Andrea Smith
Associate Scientist & Program Manager
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3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Keith, David
Cc: Smith, Wake; Frank Keutsch
Sent: February 3, 2021 6:41 PM (UTC-05:00)
Attached: Untitled attachment

David,

Yes, the Perseus a/c was a big distraction that I was only on the edge of fortunately.

I will remain skeptical about the likelihood of new non-military a/c but want to be first in line to use them. We were first in line and funded to use the new Boeing/Aurora a/c, Odysseus, when the plug was pulled.

Yes we have had conversations with the Sceye folks and would like to have a chance to use when the day comes.

BTW, the CU group here apparently demonstrated a 1.5km reel down from a balloon quite recently. No other details.

Regards
Dave

> On Feb 3, 2021, at 7:59 AM, Keith, David (b) (6) [redacted]> wrote:
>
> Dave
>
> Thanks. I think we see this about the same way.
>
> From my perspective I came into this field working for Jim with all the excitement about Aurora's aircraft which ended up amounting to nothing. It took some years of my life. And yes, Global Hawk has been a big disappointment. So I definitely get the basis for skepticism.
>
> On the other hand, there does seem to be a commercial-driven shakeup in the ability to develop low altitude aircraft. That's true from the new entrants into general aviation market through to the startups building off drone technology. So I'd like to understand whether this could apply to higher altitude light aircraft. I don't know, but if Wake spurs some interest I am open to find out more.
>
> Have you had any conversations with these folks: Sceye | A new generation of HAPS | High Altitude Platform Stations? The head guy just reached out to me again and I will talk with.
>
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, January 30, 2021 6:38 PM
> **To:** Keith, David (b) (6) [redacted]>
> **Cc:** Smith, Wake (b) (6) [redacted]; Keutsch, Frank N (b) (6) [redacted]

Subject: Re: Experimental research platform requirements

David,

Yes, I think if one has funding, then existing a/c become available. Certainly for the UT/LS, the WB-57s have been underutilized for years now and hence availability hasn't been an issue. Indeed a trip back to the boneyard was perhaps a growing threat.

I note that no one has ever built an aircraft for atmospheric chemistry, leaving the field to exploit as best they can existing a/c, which we have done very well. Thus, if there were runway a/c available that could do 30kg, 8hr, 79kft, the community would no doubt rush to use it. So the answer to your question is yes.

My problem with new-platforms-will-be-cheap is the issue of having truly operational a/c rather than experimental a/c. If one is trying to fly an experiment on an experimental a/c it reduces the probability of success by a large measure. Making an experimental a/c operational requires larger upfront and sustained investment by entities other than the science communities, creating the underwater part of the iceberg. This is why we don't have new operational a/c. And one can look to the Global Hawk and see that even starting at a high level (a mature platform) it failed to become operational because no one wants to pay the price, in this case neither NASA or NOAA. Now deeper pockets (DoD) have taken it over.

And to your final point about what payloads, yes, the new generation of lightweight instruments make 30kg interesting and valuable, and, yes, comprehensive chemistry payloads still want to be on heavy lift long-range a/c.

In reply to Wake's question about perturbation/monitoring a/c, hmmm, it depends. In the early days, perhaps they could be the same. Eventually the perturbations sought would be as large as possible per flight and not every flight would need diagnostics, so I think eventually they are different a/c. And monitoring a/c could be below the perturbation a/c altitudes and diagnose with lidar.

Interest above 70kft: in general because we would be deeper into the ozone layer. And perhaps the injection altitude would be there once we understand things better.

Regards
Dave

> On Jan 30, 2021, at 9:29 AM, Keith, David (b) (6) [redacted]> wrote:
>
> Dave
>
> Interesting back-and-forth.
>
> I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.
>
> I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30 kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.

I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.

I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.

Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.

Interesting conversation. No simple answers.

Cheers,
David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Thursday, January 28, 2021 11:49 AM
To: Smith, Wake <(b) (6) [redacted]
Cc: Keith, David (b) (6) [redacted] Keutsch, Frank N
(b) (6) [redacted]
Subject: Re: Experimental research platform requirements

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi- flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" <(b) (6) [redacted]>
Cc: Frank Keutsch <(b) (6) [redacted]>

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can't control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake <(b) (6) [redacted]> wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I

understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School & Lecturer in Yale College
(b) (6)

From: Douglas MacMartin (b) (6) [redacted]>
Subject: RE: 2022 GRC program
To: Karen Rosenlof - NOAA Federal; Trude Storelvmo
Sent: July 19, 2021 10:15 AM (UTC-04:00)

Excellent! We should have a great conference ☺. (More later… probably not for a while.)

doug

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Sent: Thursday, July 15, 2021 5:04 PM
To: Douglas MacMartin (b) (6) [redacted] Trude Storelvmo (b) (6) [redacted]
Subject: Re: 2022 GRC program

Doug and Trude,

I should be available during that time frame, and would like to attend the test GRC. I'd be happy to adjust topics as you feel is needed.

Take care,

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
Boulder, CO 80305
office: 3A-121, DSRC
e-mail: Karen.H.Rosenlof@noaa.gov
phone: 303 497-7761
fax: 303 497-5373
----
while safer at home remains in effect, email is the most reliable contact

> On Jul 15, 2021, at 9:06 AM, Douglas MacMartin (b) (6) [redacted]> wrote:
>
> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
>
> As a start to our planning, could you let us know whether you would be interested in talking at the 2022 meeting? We would of course still love to hear from you, but schedules may not permit and research interests change (and, indeed, for some or many of you that may mean that the topic we were originally thinking you would talk about would no longer be what you are currently most excited by – the GRC is supposed to be cutting-edge current research, of course – so if you let us know we can start revising sessions and think about what gaps we'd like to fill). There are also some new people who are doing some great research too that we would like to hear from, so it's conceivable that – given the now 5 year gap since the last GRC – we might choose to slightly increase the number of talks and reduce the time available per talk.

Thanks,
Doug & Trude

From: Douglas MacMartin
Sent: Wednesday, February 19, 2020 10:27 AM
To: (b) (6) ; (b) (6) ; Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke (b) (6) >; (b) (6) ; Robert Wood <(b) (6) ; (b) (6) (b) (6) <(b) (6) ; Daniele Visioni <(b) (6) >; (b) (6) ; Peter Irvine <(b) (6) >; Jonathan Proctor (b) (6) ; (b) (6) ; Keith, David (b) (6) >; Kravitz, Ben (b) (6) >; Wake Smith <(b) (6) >; Izidine Pinto (b) (6) ; Gabriel Chiodo (b) (6) >; Keutsch, Frank N <(b) (6) >
Cc: Lawrence, Mark <(b) (6) >; valentina Aquila (b) (6) ; Ulrike Niemeier (b) (6) >; Leisner, Thomas (IMK) (b) (6) >; Olivier Boucher <(b) (6) >; Schrag, Daniel P. <(b) (6) >; TAYLOR,Michael <(b) (6) >; (b) (6) Trude Storelvmo <(b) (6) >; 'Simone Tilmes' (b) (6) >; (b) (6) Jim Hurrell (b) (6)
Subject: RE: 2020 GRC program

Hi all,

Just a reminder that if you haven't sent me a title yet, to do so (otherwise I'll have to make something up; GRC needs us to upload our "final" program by the end of this month) I have titles for about half of you (though some of those are draft titles you sent quite some time ago, e.g. for Pete, Isla, Danny).

And, if you haven't responded yet regarding need for travel support, let me know (about half of you have). For those of you who haven't been to a GRC before, there's a bus from Boston airport, and from Portland Maine airport.

If you've already both sent me a title and responded regarding travel, then you can ignore this email.

Also, regarding format, this year we're explicitly including 10-15 minutes for the discussion leader to make some remarks to help frame each session (taking 5 minutes from each speaker's time), and rather than having a lengthy discussion after each talk, we'll have a shorter 10-minute discussion after each talk and a 20-minute general session discussion at the end (that's as long as GRC will allow) with everyone from a given session.

Thanks, and see you in June!
doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) ; (b) (6) 'Jadwiga (Yaga) Richter' (b) (6) >; Alan Robock (b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >; (b) (6) ; Robert Wood (b) (6) >; (b) (6) ; (b) (6) <(b) (6) >; Daniele Visioni <(b) (6) >; (b) (6) Peter Irvine <(b) (6) >; Jonathan

Proctor <(b) (6) >; Govindasamy Bala <(b) (6) >; (b) (6) Keith, David (b) (6) >; Kravitz, Ben <bkravitz@iu.edu>; Wake Smith <(b) (6) ; Chris Field (b) (6)
Cc: Lawrence, Mark (b) (6) >; valentina Aquila <(b) (6) Ulrike Niemeier <(b) (6) >; Leisner, Thomas (IMK) <(b) (6) Olivier Boucher (b) (6) >; Schrag, Daniel P. (b) (6) ; TAYLOR,Michael (b) (6) ;(b) (6) ; Lynn Russell (b) (6) Trude Storelvmo <(b) (6) 'Simone Tilmes' (b) (6) >; (b) (6)
Subject: 2020 GRC program

Hi all,

Happy New Year!

The full program for GRC is due on February 28; if you haven't sent us a title for your talk (or if you did and want to revise it), please do so before the end of February so I have time to enter everything into the conference management system online.

The cc-line has discussion leaders for each session.

Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin
Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and
Faculty Fellow, Atkinson Center for a Sustainable Future
Cornell University
(b) (6)
https://climate-engineering.mae.cornell.edu/

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Smith, Wake
Cc: Keith, David; Frank Keutsch
Sent: January 28, 2021 11:49 AM (UTC-05:00)
Attached: Untitled attachment

Wake,

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I am happy to discuss further.

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Dave

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Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" <(b) (6)
Cc: Frank Keutsch <(b) (6)

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Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

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Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6) [redacted]

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Fwd: Update
To: Frank Keutsch
Cc: Keith, David; Ronda Knott - NOAA Federal
Sent: October 27, 2020 10:25 PM (UTC-04:00)
Attached: Untitled attachment

Frank,

I hope this finds you doing well with the family in Germany.

DavidK and I invited you to a Friday v-meeting to catch up on CI matters. He will give me a brief download of his CDR ideas/perspective at the beginning at my request. So you could join late to miss that.

Let us know.
THanks
Dave

David W. Fahey, PhD
Director of the Earth System Research Laboratories (ESRL)
Director of the ESRL Chemical Sciences Laboratory
NOAA Earth System Research Laboratories
325 Broadway R/CSD
Boulder, CO 80305 USA
303-497-5277 -5822 fax
david.w.fahey@noaa.gov

Ronda Knott, Admin. Assistant
ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

Begin forwarded message:

From: Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
Subject: Re: Update
Date: October 26, 2020 at 7:51:29 PM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Cc: "Keith, David" (b) (6) [redacted]>

Hi Dave and David,

The meeting has been set for this Friday, October 30th at 7am MT and included Frank Kuetsch.
The connection details are:

Meeting ID
meet.google.com/zgb-gfnu-gdr
Phone Numbers
(US) +1 561-408-9337
PIN: 857 507 300#

Thank you,
Ronda

Ronda Knott
Executive Administrative Assistant to

Dr. David W. Fahey, Director

NOAA Chemical Sciences Laboratory
325 Broadway, R/CSL

Boulder CO 80305

I am currently teleworking, please call my cell: (b) (6)

303.497.4404 phone

303-497-5822 fax

ronda.knott@noaa.gov

On Mon, Oct 26, 2020 at 2:56 PM David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:

> David,
> 7Am Friday will work.
> Ronda can reach out to FrankK if you like. She will send a link to all.
> Thanks
> Dave
>
> On Oct 25, 2020, at 9:17 PM, Keith, David (b) (6) > wrote:
>
> How about 8:30 AM MT on Friday the 30th? (I can do any time from 7:00 to 10:00) MT that AM. Suggest we choose a time, then I will see if Frank can join (he can miss the CDR part).
>
> D
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, October 24, 2020 6:29 PM
> **To:** Keith, David (b) (6) >
> **Cc:** Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
> **Subject:** Re: Update

David,

Thanks for the reply. I appreciate the perspective on Pierrehumbert; a bit frustrating. We will launch a webpage for the Earth Radiation Budget program (ie the Congressional funding) soon (albeit a bit late) that will explain NOAA's role and intent and in effect pushback on Pierrehumbert and others.

Thanks for your offer of a CDR debrief and catching up on other matters. My CDR meeting is 4 Nov so best would be next week sometime. Let me know if that might work (w/ or w/o Frank) and a preferred day/time.

Regards
Dave
PS Canmore seems like a good faraway place to get fresh air devoid of C-19.

> On Oct 21, 2020, at 2:13 PM, Keith, David (b) (6) [redacted] wrote:
>
> Dave
>
> Thanks. Yet, I'm particularly frustrating because Ray repeats the idea that doing it at all commits us to doing it for a thousand years, yet I think he knows that's not true. When he was at Harvard and from the public audience we challenged him on that pointing out that you could always taper off slowly even if you didn't have carbon removal and so the net result would be a reduction in the rate of change even if it didn't change the ultimate endpoint. He agreed. Yet he keeps coming back to this claim.
>
> I don't have an overview on CDR. I step back because of the conflict of interest after starting Carbon Engineering (the air capture company). In fact I think that CDR is a bit overhyped and I have been trying to figure out how to say that without frustrating people at Carbon Engineering too much. I have fragments of talks and some opinions. I could dump these on you in a short (15 minutes) conversation which might be helpful to me because I'm trying to polish the stuff.
>
> I think you catch up with you, me and Frank would make sense. I'm thinking early November at that point we will of got science plan out to the SCoPEx committee and have made the next step towards reality on a spring flight.
>
> It's beautiful and snowy up here in Canmore Alberta.
>
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>

Sent: Wednesday, October 21, 2020 1:23 PM
To: Keith, David <(b) (6)
Subject: Update

David,

Very good article in Globe. Pierrehumbert's article is frustrating since he attacks CI and calls out people like me yet at the end says there might be an appropriate role for CI, something he has done in other articles.

My management has asked me to inform them about CDR in an internal meeting. I am not very well prepared to do that and wondered if you had a presentation that you would be willing share to draw from for this purpose.

A call to catch up with Frank would be welcome.

Regards
Dave

David W. Fahey, PhD
Director of the Earth System Research Laboratories (ESRL)
Director of the ESRL Chemical Sciences Laboratory
NOAA Earth System Research Laboratories
325 Broadway R/CSD
Boulder, CO 80305 USA
303-497-5277 -5822 fax
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Ronda Knott, Admin. Assistant
ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

From: Kelly Wanser (b) (6) >
Subject: Nice job on the NOVA episode!
To: David Fahey - NOAA Federal; Frank Keutsch
Cc: John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:13 PM (UTC-04:00)

You were excellent and the piece came out great.
We'll promote it as we are able.

Best,
k.

--
Kelly Wanser
Executive Director, SilverLining | http://www.silverlining.ngo
Board Director, Dendra Systems | http://www.dendra.io
Advisor, University of Washington Marine Cloud Brightening Project | http://www.mcbproject.org
President's Circle, National Academy of Sciences | http://nas-sites.org/PC/
Phone: (b) (6)

TEDTalk: *Emergency Medicine for Our Climate Fever*
Report: *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: Graham Feingold - NOAA Federal <graham.feingold@noaa.gov>
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Andrea Smith; Simone Tilmes; Keutsch, Frank N; Smith, Wake; Karen Rosenlof - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:47 AM (UTC-04:00)

zoom link not working for me. is there something else i need to do?

On 9/17/21 11:06 AM, Andrea Smith wrote:

> Hello Frank, Wake and Graham,
>
> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>
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> Let me know if you have questions on any of the above.
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> Thanks again, and see you next Wednesday.
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> *National Center for Atmospheric Research*
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> (b) (6) [redacted]

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Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) [redacted] (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

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Graham Feingold
NOAA Earth System Research Laboratories
Chemical Sciences Laboratory (R/CSL9)
325 Broadway
Boulder, Colorado 80305, USA
Tel: (303) 497-3098
Fax: (303) 497-5318

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Newsletter from Harvard's Solar Geoengineering Research Program
To: Keith, David
Cc: Frank Keutsch; Ronda Knott - NOAA Federal
Sent: December 28, 2020 11:44 AM (UTC-05:00)
Attached: Untitled attachment

David,
Good, yes let's talk on the 6th.
Ronda can arrange a time and link.
Happy New Year.
Dave

> On Dec 28, 2020, at 9:30 AM, Keith, David <(b) (6) [redacted]> wrote:
>
> Dave
>
> Yes, we expect to fly POPS.
>
> Also, interesting developments on turbulence.
>
> Now that this mission seems to be (finally) coming together it would be good how about the three of us to touch base again about this and about the meeting to discuss future flight missions?
>
> How about Wednesday the 6th?
>
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, December 26, 2020 5:51 PM
> **To:** Keith, David (b) (6) [redacted]
> **Subject:** Re: Newsletter from Harvard's Solar Geoengineering Research Program
>
> David,
>
> Thanks for the newsletter. I am impressed with your productivity.
>
> Good progress with Esrange launch plans and committee approval. Do you plan to fly POPS? It would be of value to get a high lat profile and adds to your flight data return. No communication with the device is needed since it records onboard. Let us know if you want assistance.
>
> We have prepared a POPS unit and backup to fly on the World View Stratollite in 2021 when they are able to resume launches.
>
> I hope you and yours are doing well enough this Holiday Season. We are OK.
> Regards
> Dave

On Dec 16, 2020, at 9:18 AM, David Keith (b) (6) wrote:

Dear Readers,

As this strange year comes to a close, we wanted to share updates from Harvard's Solar Geoengineering Research Program (SGRP), which supports research at Harvard on the science, technology, and governance of solar geoengineering.

We hope everyone and their families are safe and well. We wish you a healthy new year.

Yours,
David Keith and Lizzie Burns
Faculty Director and Managing Director
Harvard's Solar Geoengineering Research Program

SCoPEx

SCoPEx Update

Led by Frank Keutsch, the Stratospheric Controlled Perturbation Experiment (SCoPEx) is a scientific experiment to advance understanding of stratospheric aerosols that could be relevant to solar geoengineering. It aims to reduce the uncertainty around specific science questions by making quantitative measurements of some of the aerosol microphysics and atmospheric chemistry required for estimating the risks and benefits of solar geoengineering in large atmospheric models.

The SCoPEx research team has asked the independent SCoPEx Advisory Committee to review our plans for a proposed platform test in Sweden in June 2021. This test would notbe the experiment itself, but rather a test of the SCoPEx platform without the release of any particles. Specifically, we would like to test the gondola's horizontal and vertical control using the winch system and propellers as well as the power, data, navigation, and communication systems. We would not release any aerosols, nor fly an aerosol injection/release system. Still, we will not proceed with this flight without a formal recommendation authorizing the flight from the Advisory Committee to Harvard management. We have asked the Advisory Committee if they can complete their review and reach a decision—be it positive or negative—about this platform test by February 15, 2021. You can learn more about this platform test here.

SCoPEx Advisory Committee

Recognizing the complex societal and governance issues surrounding solar geoengineering, Harvard has ensured the SCoPEx project has the guidance of an independent Advisory Committee, as noted above. The Advisory Committee has already begun to carry out a significant amount of work, including a financial review, legal review, and scientific and technical review, and they have proposed a draft process for a societal engagement review. You can learn more by visiting their website. We are grateful for the time the Committee members are volunteering and look forward to the work ahead.

Opportunities

SGRP Fellowship

SGRP is now accepting applications to its 2021 Fellowship Program, which offers short-term and long-term opportunities. Applications are due January 29, 2021. We are seeking applications from scholars in a range of disciplines, including the natural sciences, economics, law, government, public policy, public health, medicine, design, and the humanities. We also are looking for applicants who are new to the field of solar geoengineering and/or have critical views, and we strongly encourage applications from

women and minority candidates. More information can be found here.

We would also like to congratulate our current and future fellows who were accepted during our previous fellowship application process.

- Cody Floerchinger, (August 2019-July 2021) advised by Frank Keutsch, is using datasets from upcoming measurements campaigns to provide a comprehensive analysis of the state of our ability to model stratospheric plume dynamics and highlight areas where the community should focus its efforts when attempting to improve these model products (science).
- Yuanchao Fan, (October 2019-October 2021) advised by Kaighin McColl, is quantifying the impact of solar geoengineering on terrestrial ecosystems, including forests and agriculture, and their biophysical and biogeochemical feedbacks to climate. He is also collaborating with David Keith on a paper about geoengineering and food supply (science).
- Irina Bakalova (February 2021-April 2021) will be advised by Professor Rob Stavins, working closely to study the effectiveness and stability of potential international agreements on solar geoengineering (economics).
- Britta Clark (February 2021-June 2021) will be advised by Lucas Stanczyk and will analyze the intergenerational justice impacts of solar geoengineering as a mitigative strategy to address climate change (philosophy).
- Ermanno Napolitano (August 2021-July 2022) will be advised by Lucas Stanczyk and will catalogue and explore all of the existing international legal principles that are likely to have some bearing on the deployment of solar geoengineering (law).

Online Community for Junior Researchers

A group of junior scientists are organizing a diverse online community of young researchers new to the solar geoengineering field, designed to engage researchers with new perspectives. This group will provide young researchers the chance to informally present on their research, share ideas, receive feedback, and create a space for open and non-judgmental discussion on the topic. The first few sessions took place in November and December and were held live on Zoom. Graduate students and recent postdocs from across the globe, including from developing countries, discussed various publications containing alternate viewpoints on solar geoengineering. Future sessions scheduled include presentations by a former SGRP DECIMALS resident and other participants as well as discussion forums and networking opportunities on Slack. Undergraduate students, graduate students, and postdoctoral fellows within five years of completing their degree are welcome to join the group. If you are interested in participating, please email Selena Wallace: swallace@seas.harvard.edu.

Events

Due to COVID-19, we had to cancel in-person events beginning in March. Since that time, we have held countless Zoom conversations (like so many others). For example, in November we hosted a public health workshop at Harvard to try to broaden the diversity of researchers studying solar geoengineering on campus. We are also now in the process of building an exciting opportunity that will allow us to reach a broader audience outside of Harvard that will include experts, practitioners new to solar geoengineering, and the general public. We invite you to join us.

Public Health Roundtable

In November 2020, we held a virtual event with the Harvard Chan School of Public Health Center for Climate, Health, and the Global Environment where experts from both the geoengineering and the public health communities had the opportunity to discuss the potential public health challenges posed by solar geoengineering. Few studies to date have considered the public health implications of geoengineering, and those that have have been limited to mortality due to ambient air pollution and UV-induced malignant melanoma. This event discussion addressed questions of the risk factors that these studies might be omitting, the vast array of other public health issues that may arise, as well as the environmental justice implications of human interventions to the climate system such as geoengineering. The organizers of the event may publish a paper that summarizes the key points and questions to hopefully inspire other experts in the public health field to begin research on solar geoengineering. Overall, this event was significant because it not only signaled new interest from various public health experts who, years prior, had not yet engaged, but also because it will hopefully unlock even more new interest from a critical community that has yet to fully participate in solar geoengineering research.

Public Seminar Series

In the spring of 2020, we will launch a virtual seminars series to promote understanding and discussion of solar geoengineering and to enable audiences to learn from a broader set of perspectives in the area of solar geoengineering research and public policy. These seminars will contain a combination of practitioners and experts from around the world and will have a variety of formats including single speakers, moderated debate, and moderated panels. Previously, SGRP seminar attendance was limited to the Harvard community, but we are now able to extend the reach of this series to a global, public audience. We invite you to participate in these seminars. We will email this listserv when seminars are scheduled.

Publications, Video, and Audio Clips

The following written publications were funded all or in part by SGRP.

Recent Peer Reviewed Publications

Zhen Dai, Debra K. Weisenstein, Frank N. Keutsch, and David W. Keith. (2020). "Experimental reaction rates constrain estimates of ozone response to calcium carbonate geoengineering." Communications Earth and Environment 1, 63.

Jacob T. Seeley, Nicholas J. Lutsko, and David W. Keith. "Designing a radiative antidote to CO2." Geophysical Research Letters (Submitted).

Joshua B. Horton and Barbara Koromenos. (2020). "Steering and Influence in Transnational Climate Governance: Nonstate Engagement in Solar Geoengineering Research." Global Environmental Politics 20, 3: 93-111.

Nicholas J. Lutsko, Jacob T. Seeley, and David W. Keith. (2020). "Estimating Impacts and Trade-offs in Solar Geoengineering Scenarios With a Moist Energy Balance Model." Geophysical Research Letters 47, 9.

Joshua B. Horton, Penehuro Lefale, David Keith. (2020). "Parametric Insurance for Solar Geoengineering: Insights from the Pacific Catastrophe Risk Assessment and Financing Initiative." Global Policy, Special Issue.

David Keith and Peter Irvine. (2020). "Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards." Environmental Research Letters 15, 4.

Jesse Reynolds and Joshua Horton. (2020) "An earth system governance perspective on solar geoengineering." Earth System Governance, 3.

Other Publications

David W. Keith and John Deutch (2020) "Climate Policy Enters Four Dimensions." In *Securing our Economic Future,* edited by Amy Ganz and Melissa Kearney, Aspen Institute Press.

Cody Floerchinger, John Dykema, David Keith, and Frank Keutsch (2020) "A Need for In Situ Observations to Inform Nearfield Plume Transport and Aerosol Dynamics as well as Chemistry of Alternate Geoengineering Materials in the Stratosphere." Letter to the National Academy for Science.

David Keith, Frank Keutsch, and Cody Floerchinger (February 15, 2020) "Empirical methods to reduce uncertainty about solar geoengineering," public input to the National Academy Committee on *Climate Intervention Strategies that Reflect Sunlight to Cool Earth*.

Recent Video and Audio Recordings

AGU TV (December 2, 2020). “SCoPEx, Harvard University – New Frontiers in Climate Change Research.” WebsEdge Science.

Anthony Padilla (October 23, 2020) “I spent a day with climate change scientists” *Youtube*.

PBS Nova (October 16, 2020). "Can We Cool the Planet?" *WGBH*.

Harvard Magazine (October 16, 2020). “Daniel Schrag and David Keith: Can Solar Geoengineering Help Fight Climate Change?”

All Things Considered (July 22, 2020) “Harvard Scientists Plan First-Ever Field Experiment Related To Solar Geoengineering.” *WBUR*. (This aired again on Here & Now on December 4, 2020 as “Experiment To Help Researchers Understand Risk, Efficacy of Solar Geoengineering.”)

Harvard Museum of Natural History (December 12, 2019) “The Peril and Promise of Solar Geoengineering” *Youtube*.

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Subject: Re: Nice job on the NOVA episode!
To: David Fahey - NOAA Federal; David Keith
Cc: Frank Keutsch; John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:22 PM (UTC-04:00)

Ha, thanks, Dave. Adding David here.
Terrific piece, David!

Sent from my iPhone

> On Oct 29, 2020, at 1:19 PM, David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:
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> Kelly,
> I think you want to praise David K instead of me. I too thought they all did a great job.
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TEDTalk: *Emergency Medicine for Our Climate Fever*
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From: Smith, Wake (b) (6)
Subject: RE: CCIS webinar Wednesday Sept 22nd
To: Karen Rosenlof - NOAA Federal
Sent: September 18, 2021 7:59 AM (UTC-04:00)

Will do.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6)

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Sent: Friday, September 17, 2021 4:44 PM
To: Andrea Smith (b) (6)
Cc: Simone Tilmes (b) (6) ; Keutsch, Frank N (b) (6) >; Smith, Wake <(b) (6) ; Graham Feingold - NOAA Federal <Graham.Feingold@noaa.gov>; Brian Medeiros (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd

And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.

Thanks!

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
Boulder, CO 80305
office: 3A-121, DSRC
e-mail: Karen.H.Rosenlof@noaa.gov
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> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
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<CCISspeaker_consent_form.pdf>

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Associate Scientist & Program Manager
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(b) (6)

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From: Robert Wood (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin
Cc: (b) (6); (b) (6); Alan Robock; Karen Rosenlof - NOAA Federal; Katharine Ricke; (b) (6) (b) (6); (b) (6) Daniele Visioni; Isla Simpson; Peter Irvine; Jonathan Proctor; (b) (6); Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N; Trude Storelvmo; Simone Tilmes; (b) (6)
Sent: July 15, 2021 3:52 PM (UTC-04:00)

Hi Doug and Trude,

Thank you for the offer to present at next year's GRC. I am still interested.

Regards

Rob

Robert Wood
Professor, Atmospheric Sciences
Department of Atmospheric Sciences,
718 ATG Building
University of Washington, Seattle
WA 98195-1640

Tel: 206-267-8343 (cell); 206-543-1203 (office)
Web: atmos.washington.edu/~robwood
Email: (b) (6)
[redacted]

On Thu, Jul 15, 2021 at 8:11 AM Douglas MacMartin <(b) (6)> wrote:

> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
>
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Doug & Trude

From: Douglas MacMartin
Sent: Wednesday, February 19, 2020 10:27 AM
To: (b) (6) ; (b) (6) ; Alan Robock (b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >; (b) (6) ; Robert Wood (b) (6) >; (b) (6) (b) (6) <(b) (6) >; Daniele Visioni (b) (6) >; (b) (6) ; Peter Irvine (b) (6) >; Jonathan Proctor (b) (6) >; (b) (6) ; Keith, David <(b) (6) >; Kravitz, Ben <(b) (6) >; Wake Smith (b) (6) >; Izidine Pinto (b) (6) >; Gabriel Chiodo <(b) (6) ; Keutsch, Frank N (b) (6) >
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doug

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Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) (b) (6) ; 'Jadwiga (Yaga) Richter' <(b) (6) >;
Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>;
Katharine Ricke <(b) (6) >; (b) (6) ; Robert Wood <(b) (6) >;
(b) (6) ; (b) (6) <(b) (6) >; Daniele Visioni
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Douglas MacMartin

Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and

Faculty Fellow, Atkinson Center for a Sustainable Future

Cornell University

(b) (6)

(b) (6)

https://climate-engineering.mae.cornell.edu/

From: Andrea Smith (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Karen Rosenlof - NOAA Federal
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Graham Feingold - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:36 AM (UTC-04:00)

Good morning everyone,

If you haven't already done so, please reply here with slide decks or drop them in (b) (6) . if large file size.

See you in 10-15 mins!

Cheers,

Andrea

On Fri, Sep 17, 2021 at 2:43 PM Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov> wrote:

> And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
> So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.
>
> Thanks!
>
> Karen
>
> --
> Karen Rosenlof
> NOAA Chemical Sciences Laboratory
> Mail Stop R/CSL8
> 325 Broadway
> Boulder, CO 80305
> office: 3A-121, DSRC
> e-mail: Karen.H.Rosenlof@noaa.gov
> phone: 303 497-7761
> fax: 303 497-5373
> --
> while safer at home remains in effect, email is the most reliable contact
>
>> On Sep 17, 2021, at 11:06 AM, Andrea Smith (b) (6) > wrote:
>>
>> Hello Frank, Wake and Graham,
>>
>> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>>
>> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
>> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
>> Meeting ID: 816 4261 9898
>> Passcode: 148321
>>
>> Please join 10 mins early to test tech and troubleshoot if needed.

2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) [redacted] (preferably by Tuesday night):

3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.

After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.

Let me know if you have questions on any of the above.

Thanks again, and see you next Wednesday.

Andrea

On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) [redacted] wrote:

> Hi Frank, Wake and Graham,
> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>
> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
>
> 1. Frank Keutsch: ...
> 2. Wake Smith:...
> 3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening
>
> Here is Andreas rundown for logistics:
>
> -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
> -send slide decks to Andrea by Tuesday (9/21) evening for backup purposes
> -arrive ~10 mins early so we can do quick test of screenshares
> -15 min talk length, w/ immediate clarifying question(s) and then ~30 mins broad discussion and questions at end
> -moderator will collect questions in chat window throughout and ask most pertinent ones for discussion
> -panelists and question askers encouraged to unmute & turn on camera
> -session will be recorded and posted later - we'll send a release form for them to complete
>
> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
>
> Cheers, Simone
>
> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*

> > *303-497-1400 (fax)*
> > (b) (6)
>
> --
> Andrea Smith
> Associate Scientist & Program Manager
> The COMET® Program
> University Corporation for Atmospheric Research
> 3085 Center Green Dr.
> Boulder, CO 80301
> 303-497-8320 (office)
> (b) (6) (cell)
>
> *My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.*
> <CCISspeaker_consent_form.pdf>

--
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From: Alan Robock ☮ (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin;(b) (6) ;(b) (6) ; Karen Rosenlof - NOAA Federal; Katharine Ricke; (b) (6) Robert Wood; (b) (6) ; (b) (6) Daniele Visioni; Isla Simpson; Peter Irvine; Jonathan Proctor; (b) (6) ; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N
Cc: Trude Storelvmo; 'Simone Tilmes'; (b) (6)
Sent: July 15, 2021 5:37 PM (UTC-04:00)

Dear Doug and Trude,

I would like to give a talk. Thanks.

Alan

On 7/15/2021 11:06 AM, Douglas MacMartin wrote:

> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
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Thanks, and see you in June!
doug

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Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) ;(b) (6) 'Jadwiga (Yaga) Richter' (b) (6) >; Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >;(b) (6) ; Robert Wood (b) (6) >;(b) (6) ;(b) (6) (b) (6) >; Daniele Visioni (b) (6) >;(b) (6) ; Peter Irvine (b) (6) ; Jonathan Proctor (b) (6) ; Govindasamy Bala (b) (6) >;(b) (6) Keith, David <(b) (6) ; Kravitz, Ben (b) (6) ; Wake Smith <(b) (6) >; Chris Field (b) (6)
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Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and
Faculty Fellow, Atkinson Center for a Sustainable Future
Cornell University
(b) (6)
https://climate-engineering.mae.cornell.edu/

From: Peter Irvine (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin
Cc: Piers Forster; (b) (6) Alan Robock; Karen Rosenlof - NOAA Federal; Katharine Ricke; Seneviratne Sonia Isabelle; Robert Wood; Helene Muri; (b) (6) Daniele Visioni; Isla Simpson; Jonathan Proctor; Ines Camilloni; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N; Trude Storelvmo; Simone Tilmes; Lohmann Ulrike
Sent: July 18, 2021 4:53 PM (UTC-04:00)

Hi Doug, Trude,

It's be happy to present in 2022, with the same title for now.

Cheers,

Pete

On Thu, Jul 15, 2021, 16:06 Douglas MacMartin (b) (6) > wrote:

> Hi all,
>
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Cornell University

(b) (6)

[redacted]

https://climate-engineering.mae.cornell.edu/

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Keith, David
Cc: Smith, Wake; Frank Keutsch
Sent: January 30, 2021 6:38 PM (UTC-05:00)
Attached: Untitled attachment

David,

Yes, I think if one has funding, then existing a/c become available. Certainly for the UT/LS, the WB-57s have been underutilized for years now and hence availability hasn't been an issue. Indeed a trip back to the boneyard was perhaps a growing threat.

I note that no one has ever built an aircraft for atmospheric chemistry, leaving the field to exploit as best they can existing a/c, which we have done very well. Thus, if there were runway a/c available that could do 30kg, 8hr, 79kft, the community would no doubt rush to use it. So the answer to your question is yes.

My problem with new-platforms-will-be-cheap is the issue of having truly operational a/c rather than experimental a/c. If one is trying to fly an experiment on an experimental a/c it reduces the probability of success by a large measure. Making an experimental a/c operational requires larger upfront and sustained investment by entities other than the science communities, creating the underwater part of the iceberg. This is why we don't have new operational a/c. And one can look to the Global Hawk and see that even starting at a high level (a mature platform) it failed to become operational because no one wants to pay the price, in this case neither NASA or NOAA. Now deeper pockets (DoD) have taken it over.

And to your final point about what payloads, yes, the new generation of lightweight instruments make 30kg interesting and valuable, and, yes, comprehensive chemistry payloads still want to be on heavy lift long-range a/c.

In reply to Wake's question about perturbation/monitoring a/c, hmmm, it depends. In the early days, perhaps they could be the same. Eventually the perturbations sought would be as large as possible per flight and not every flight would need diagnostics, so I think eventually they are different a/c. And monitoring a/c could be below the perturbation a/c altitudes and diagnose with lidar.

Interest above 70kft: in general because we would be deeper into the ozone layer. And perhaps the injection altitude would be there once we understand things better.

Regards
Dave

> On Jan 30, 2021, at 9:29 AM, Keith, David (b) (6) > wrote:
>
> Dave
>
> Interesting back-and-forth.
>
> I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.
>
> I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30

kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.

I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.

I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.

Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.

Interesting conversation. No simple answers.

Cheers,
David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Thursday, January 28, 2021 11:49 AM
To: Smith, Wake (b) (6) >
Cc: Keith, David <(b) (6) >; Keutsch, Frank N (b) (6)
Subject: Re: Experimental research platform requirements

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi-flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" (b) (6) [redacted]>
Cc: Frank Keutsch <(b) (6) [redacted]

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can't control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake (b) (6) [redacted] > wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to

understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6)

From: Robert Wood (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin
Cc: (b) (6) ; (b) (6) ; Alan Robock; Karen Rosenlof - NOAA Federal; Katharine Ricke; (b) (6) (b) (6) ; (b) (6) Daniele Visioni; Isla Simpson; Peter Irvine; Jonathan Proctor; (b) (6) ; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N; Trude Storelvmo; Simone Tilmes; (b) (6)
Sent: July 15, 2021 3:52 PM (UTC-04:00)

Hi Doug and Trude,

Thank you for the offer to present at next year's GRC. I am still interested.

Regards

Rob

Robert Wood
Professor, Atmospheric Sciences
Department of Atmospheric Sciences,
718 ATG Building
University of Washington, Seattle
WA 98195-1640

Tel: 206-267-8343 (cell); 206-543-1203 (office)
Web: atmos.washington.edu/~robwood
Email: (b) (6)
[redacted]

On Thu, Jul 15, 2021 at 8:11 AM Douglas MacMartin <(b) (6) > wrote:

> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
>
> As a start to our planning, could you let us know whether you would be interested in talking at the 2022 meeting? We would of course still love to hear from you, but schedules may not permit and research interests change (and, indeed, for some or many of you that may mean that the topic we were originally thinking you would talk about would no longer be what you are currently most excited by – the GRC is supposed to be cutting-edge current research, of course – so if you let us know we can start revising sessions and think about what gaps we'd like to fill). There are also some new people who are doing some great research too that we would like to hear from, so it's conceivable that – given the now 5 year gap since the last GRC – we might choose to slightly increase the number of talks and reduce the time available per talk.
>
> Thanks,

Doug & Trude

From: Douglas MacMartin
Sent: Wednesday, February 19, 2020 10:27 AM
To: (b) (6) ; (b) (6) ; Alan Robock (b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >; (b) (6) ; Robert Wood (b) (6) >; (b) (6) (b) (6) <(b) (6) >; Daniele Visioni (b) (6) >; (b) (6) ; Peter Irvine (b) (6) >; Jonathan Proctor (b) (6) >; (b) (6) ; Keith, David <(b) (6) >; Kravitz, Ben <(b) (6) >; Wake Smith (b) (6) >; Izidine Pinto (b) (6) >; Gabriel Chiodo <(b) (6) ; Keutsch, Frank N (b) (6) >
Cc: Lawrence, Mark <(b) (6) >; valentina Aquila (b) (6) >; Ulrike Niemeier <(b) (6) >; Leisner, Thomas (IMK) (b) (6) >; Olivier Boucher <(b) (6) >; Schrag, Daniel P. (b) (6) >; TAYLOR,Michael (b) (6) >; (b) (6) Trude Storelvmo <(b) (6) ; 'Simone Tilmes' (b) (6) ; (b) (6) Jim Hurrell (b) (6) >
Subject: RE: 2020 GRC program

Hi all,

Just a reminder that if you haven't sent me a title yet, to do so (otherwise I'll have to make something up; GRC needs us to upload our "final" program by the end of this month) I have titles for about half of you (though some of those are draft titles you sent quite some time ago, e.g. for Pete, Isla, Danny).

And, if you haven't responded yet regarding need for travel support, let me know (about half of you have). For those of you who haven't been to a GRC before, there's a bus from Boston airport, and from Portland Maine airport.

If you've already both sent me a title and responded regarding travel, then you can ignore this email.

Also, regarding format, this year we're explicitly including 10-15 minutes for the discussion leader to make some remarks to help frame each session (taking 5 minutes from each speaker's time), and rather than having a lengthy discussion after each talk, we'll have a shorter 10-minute discussion after each talk and a 20-minute general session discussion at the end (that's as long as GRC will allow) with everyone from a given session.

Thanks, and see you in June!

doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) (b) (6) ; 'Jadwiga (Yaga) Richter' <(b) (6) >; Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >;(b) (6) ; Robert Wood <(b) (6) >; (b) (6) ;(b) (6) <(b) (6) >; Daniele Visioni <(b) (6) >;(b) (6) ; Peter Irvine <(b) (6) >; Jonathan Proctor <(b) (6) >; Govindasamy Bala <(b) (6) >;(b) (6) ; Keith, David <(b) (6) >; Kravitz, Ben <(b) (6) >; Wake Smith <(b) (6) >; Chris Field <(b) (6) >
Cc: Lawrence, Mark <(b) (6) >; valentina Aquila <(b) (6) >; Ulrike Niemeier <(b) (6) >; Leisner, Thomas (IMK) <(b) (6) >; Olivier Boucher (b) (6) >; Schrag, Daniel P. <(b) (6) >; TAYLOR,Michael (b) (6) >;(b) (6) ; Lynn Russell (b) (6) >; Trude Storelvmo <(b) (6) >; 'Simone Tilmes' (b) (6) >;(b) (6)
Subject: 2020 GRC program

Hi all,

Happy New Year!

The full program for GRC is due on February 28; if you haven't sent us a title for your talk (or if you did and want to revise it), please do so before the end of February so I have time to enter everything into the conference management system online.

The cc-line has discussion leaders for each session.

Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin

Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and

Faculty Fellow, Atkinson Center for a Sustainable Future

Cornell University

(b) (6)

(b) (6)

https://climate-engineering.mae.cornell.edu/

From: Andrea Smith (b) (6) [redacted]
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Graham Feingold - NOAA Federal
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Karen Rosenlof - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:49 AM (UTC-04:00)

https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09

Do you need to use the web client? NOAA or other government users can use Zoom's government-approved web client

Try that, let me know how it goes.

A

On Wed, Sep 22, 2021 at 8:47 AM Graham Feingold - NOAA Federal <graham.feingold@noaa.gov> wrote:

> zoom link not working for me. is there something else i need to do?
>
> On 9/17/21 11:06 AM, Andrea Smith wrote:
>
>> Hello Frank, Wake and Graham,
>>
>> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>>
>> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
>> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
>> Meeting ID: 816 4261 9898
>> Passcode: 148321
>>
>> Please join 10 mins early to test tech and troubleshoot if needed.
>>
>> 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) [redacted] (preferably by Tuesday night):
>>
>> 3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.
>>
>> After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.
>>
>> Let me know if you have questions on any of the above.
>>
>> Thanks again, and see you next Wednesday.
>>
>> Andrea
>>
>> On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) [redacted] > wrote:
>>
>>> Hi Frank, Wake and Graham,
>>> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>>>
>>> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see

below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?

1. Frank Keutsch: ...
2. Wake Smith:...
3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening

Here is Andreas rundown for logistics:

-please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
-send slide decks to Andrea by Tuesday (9/21) evening for backup purposes
-arrive ~10 mins early so we can do quick test of screenshares
-15 min talk length, w/ immediate clarifying question(s) and then ~30 mins broad discussion and questions at end
-moderator will collect questions in chat window throughout and ask most pertinent ones for discussion
-panelists and question askers encouraged to unmute & turn on camera
-session will be recorded and posted later - we'll send a release form for them to complete

Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,

Cheers, Simone

--
Simone Tilmes,
Atmospheric Chemistry, Observations & Modeling Lab
National Center for Atmospheric Research
PO Box 3000
Boulder, Colorado 80307-3000
303-497-1445
303-497-1400 (fax)
(b) (6) [redacted]

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Andrea Smith
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My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

--
Graham Feingold
NOAA Earth System Research Laboratories
Chemical Sciences Laboratory (R/CSL9)
325 Broadway
Boulder, Colorado 80305, USA

> Tel: (303) 497-3098
> Fax: (303) 497-5318

--
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My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

The Stratospheric Controlled Perturbation Experiment (SCoPEx)

Version 1.0

Executive Summary

Climate model studies of stratospheric solar radiation modification (SRM) depend, perhaps implicitly, on processes that take place in the near field of an injection plume. This is because materials delivered to the stratosphere by aircraft will form persistent, high aspect-ratio plumes with strong gradients before becoming well mixed, and processes within the plume will alter the large-scale, well-mixed aerosol and chemical properties that are simulated in global atmospheric models. All models ultimately depend on observations, yet we lack experimental data to assess some of the critical transport, microphysical, and chemical processes that directly control aerosol dynamics in the near-field that are important for understanding stratospheric SRM.

The scientific goal of the Stratospheric Controlled Perturbation Experiment (SCoPEx) is to improve process models that will, in turn, reduce uncertainties in global-scale models, thus reducing uncertainty in predictions of important SRM risks and benefits.

SCoPEx addresses questions in stratospheric aerosol injection (SAI) research that observations of existing analogues are incapable of addressing. For example, existing observational data do not include chemistry of alternate geoengineering materials specific to SAI, near-field particle microphysics of injection plumes, and relevant scales of atmospheric transport in the near-field. Yet these are needed to assess processes that control aerosol dynamics in the near field of an injection plume and that allow for the evaluation of alternate SAI materials, i.e., materials other than the naturally existing sulfate aerosol.

We first review why existing observations do not address the questions that SCoPEx will answer. We then give a description of the basic design of the platform and the concept of operations of SCoPEx. Finally, we describe the three specific science goals of SCoPEx, explain how they represent critical knowledge gaps in SAI research, and specify what measurements are needed to enable SCoPEx to provide quantitative answers to these questions. The three specific science goals are improving understanding of (i) turbulent mixing scales, (ii) aerosol microphysics with a focus on alternative SAI materials in the near-field of an injection, and (iii) process level chemical interactions of alternative SAI materials in the stratosphere.

We do not provide a detailed engineering document of the SCoPEx platform or its scientific instrumentation, nor do we provide a justification for the need for research on SRM via SAI in general. Rather, we focus specifically on the merits of SCoPEx itself.

1. Introduction

In this document we focus on the motivation and scientific merit of SCoPEx. We do not provide detailed engineering documentation of the SCoPEx platform or its scientific instrumentation. We also do not provide general justification for the need for research on solar radiation modification (SRM) via stratospheric aerosol injection (SAI), which can be found in many prior documents such as the 1992 NAS report that recommended the US government "Undertake research and development projects to improve our understanding of both the potential of geoengineering options to offset global warming and their possible side effects. This is not a recommendation that geoengineering options be undertaken at this time, but rather that we learn more about their likely advantages and disadvantages" (National Academy of Sciences et al., 1992) or the recent 2015 NAS report (National Research Council, 2015). Rather, we focus specifically on the need for small-scale field experiments such as SCoPEx, and the specific, critical SAI research needs that will be addressed by SCoPEx.

1.1. Role of and Need for Small-Scale Field Experiments

There is a vast array of science and engineering questions that have to be answered to achieve a better understanding of the risks, benefits and feasibility of SAI. The tools and topics that are needed to address these questions range from General Circulation Models (GCMs) all the way to detailed design of instrumentation to monitor or disperse aerosol. SCoPEx addresses a subset of questions that require small-scale field experiments for ground-truthing and that are aimed at improving the ability of models to predict the consequences of SAI.

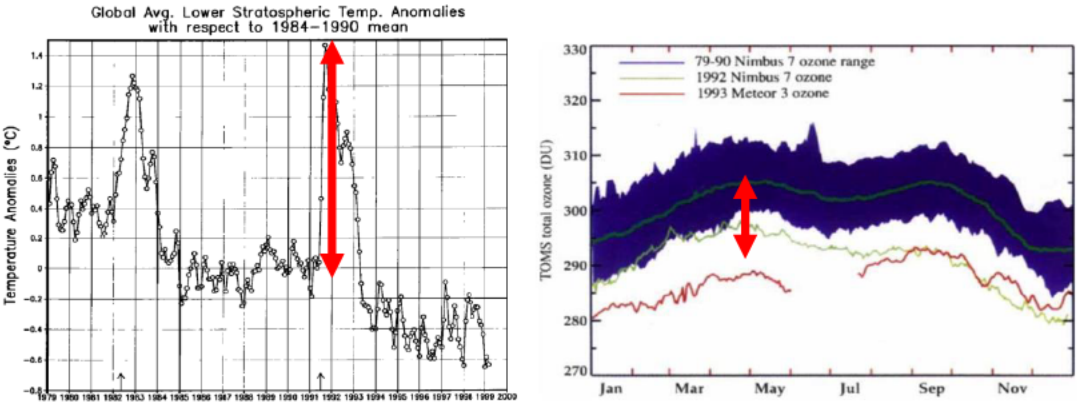

Figure 1: The two most important first-order stratospheric risks from sulfate SAI. The left panel shows stratospheric temperature anomalies from the El Chichon and Mount Pinatubo eruptions on top of background temperatures that are decreasing due to greenhouse gas emissions (Robock, 2000). The dynamical response of the stratosphere from such a short heating pulse likely is different than from sustained heating from longer-term SAI. The right panel shows that in the two years following the Mount Pinatubo reaction total ozone columns were lower than in the 1979-90 average as a result of increase sulfate aerosol surface area. Smaller eruptions also contributed to this. (McCormick et al., 1995)

There are numerous known risks associated with SAI, and SCoPEx focuses primarily on improving understanding of the first-order impacts in the stratosphere, i.e., risks and risk reduction associated with impacts of SAI within the stratosphere. There are many downstream / higher-order risks, e.g., impact on cloud formation as SAI particles leave the stratosphere (Cziczo et al., 2019), impacts on ecosystems via changes in the hydrological cycle (Bala et al., 2008; Russell et al., 2012; Tilmes et al., 2013), or the amount of direct

versus diffuse radiation (Gu et al., 2002; Farquhar & Roderick, 2003; Gu et al., 2003). Despite their importance, these impacts are not the direct target of this proposal although many of these are also influenced by stratospheric processes and properties of SAI aerosol. Two first-order risks are at the focus of this work: stratospheric ozone loss and the dynamic response resulting from stratospheric heating as a result of SAI.

Whereas stratospheric ozone chemistry is fairly well understood (World Meteorological Organization, 2019), there are still substantial uncertainties in the understanding and ability to model stratospheric dynamics (Figure 1). For example, models have only recently been able to reproduce the quasi-biennial oscillation without having it imposed (see Butchart et al., 2018 for a discussion of challenges). One approach taken in this work is to evaluate whether there are types of aerosols or methods of aerosol injection that can reduce first-order risks for a given amount of radiative forcing. It stands to reason that a reduction in the first-order stratospheric impacts will reduce downstream and higher-order risks. A case in point is the growing body of work that has been investigating the impacts of stratospheric heating on stratospheric water vapor and the dynamic response on regional climate (Simpson et al., 2019; Ferraro et al., 2015; Richter et al., 2018; Ji et al., 2018). It is important to note that the amount of stratospheric heating for a given material will be primarily driven by the total mass of aerosol, ozone destruction will be driven by the total surface area of aerosol, and the desired radiative forcing will be determined by the amount and size distribution of aerosol. Critically, both the aerosol mass required for a given desired radiative forcing *and* the resulting surface area are tied to this size distribution. Therefore, accurate models of the evolution of the size distribution of injected aerosol are critically needed. In addition, alternate materials with reduced stratospheric heating have to be investigated, as do injection methods for sulfate that minimize stratospheric heating and ozone loss for a given radiative forcing, as this will reduce risks associated with the dynamic response to this first-order perturbation.

2. Observational SAI Research Needs

Most of the rapidly growing body of literature on SAI rests on General Circulation Models (GCMs). We acknowledge the importance of GCM studies, but in the following we focus on research needs that require experiments and observations, and especially questions that can only be answered by conducting perturbative field experiments such as SCoPEx (see supplemental manuscripts Keith et al., 2020 and Floerchinger et al., 2020). In fact, SCoPEx will in the end inform GCMs by providing improved process level information that will be integrated in parameterizations used in GCMs. Below we review existing observational data sets and describe their utility for different SAI approaches, highlighting where they are unable to shed light on critical issues thus motivating studies like SCoPEx.

2.1. Field Experimental Needs for Sulfate SAI

Most studies that have sought to research SAI have assumed the addition of aerosol would take place by means of an injection of gas-phase SO_2, which is ultimately converted to H_2SO_4 and then to sulfate aerosol in the stratosphere on a timescale of approximately one month. The aerosol size distribution from this injection of gas phase precursor must be accurately predicted as it will control the shortwave (SW) scattering properties, the stratospheric lifetime of the aerosol, and ultimately be the driver for the radiative forcing (RF) efficiency per mass of injected sulfate. Some studies, such as Niemeier & Timmreck (2015), have suggested that with higher injection rates of SO_2, the resulting sulfate aerosol would be forced into a larger, coarse-mode size distribution and functionally reach a point of diminishing return. In this diminishing return scenario, the added amount of SW RF achieved per added mass of sulfate decreases exponentially.

Recent work by Pierce et al. (2010), Benduhn et al. (2016), and Vattioni et al. (2019) has highlighted the potential benefits of injecting H_2SO_4 aerosol directly into the accumulation mode (AM), i.e., aerosols with a radius of 0.1–1.0 µm, potentially by emitting H_2SO_4 vapor into an aircraft plume. This work has suggested better control of the resulting aerosol size distribution and thus the radiative forcing per unit mass sulfur injection, which would allow for the design of a system that maximizes the radiative forcing per mass of sulfate in a way that would not have the diminishing returns at high SO_2 injection rates. This would thus minimize the increase in the stratospheric sulfate burden and hence the risk of stratospheric heating which is driven by total mass whereas ozone loss is driven by surface area. While injecting AM–H_2SO_4 may represent the best possible approach for SAI with stratospheric sulfate, there is currently no proven way to introduce vapor phase AM–H_2SO_4 into the stratosphere. As AM–H_2SO_4 has not been studied, perturbative experiments are required to provide observational constraints on the aerosol size distributions predicted by models.

2.2. Field Experimental Needs for Alternate Aerosol Material SAI

Though sulfate aerosol does exist in the background stratosphere and there are some natural analogs of broad stratospheric sulfate injections (volcanic eruptions), it likely is not the optimal candidate for SAI. Alternative aerosol may be most appropriate in order to mitigate SAI risks (Teller et al., 1996; Crutzen, 2006; Ferraro et al., 2011; Ferraro et al., 2015; Weisenstein et al., 2015; Keith et al., 2016; Dykema et al., 2016; Weisenstein et al., 2015). These alternate aerosols could reduce the previously noted two major first-order stratospheric impacts, i.e., changes in ozone and stratospheric heating. Due to the uncertainties in the impacts of stratospheric heating, the study of materials with optical

properties that negate stratospheric heating is especially important. Materials such as calcium carbonate ($CaCO_3$), alumina (Al_2O_3), diamond (carbon), and several others, have been proposed as a way to minimize the inherent risks from SAI (Keith et al., 2016; Dykema et al., 2016; Weisenstein et al., 2015; Ferraro et al., 2015; Ferraro et al., 2011; Crutzen, 2006). Although model results of these aerosol species suggest that some of them possess optical properties that make them well suited to be used in a SRM scenario ($CaCO_3$, Al_2O_3, and diamond) (Dykema et al., 2016; Ferraro et al., 2011), the stratospheric aerosol microphysics of these compounds (especially coagulation) is poorly understood. As with AM–H_2SO_4 injections, there is a profound lack of in situ data to assess the ability to model the microphysics of alternative aerosols and the stratospheric chemistry of these materials. This is especially pertinent with respect to changes in ozone, and is exacerbated by the fact that these aerosols have no naturally existing analog in the stratosphere that could be studied. Because early studies suggest that these aerosols show much promise with respect to deploying SAI while mitigating the inherent risks of the deployment, it is imperative to design and execute in situ experiments in order to test our current understanding of the aerosol microphysics and observe the effects of alternative aerosol on the chemical composition and dynamics of the stratosphere.

2.3. Limitations in Existing Analogues

In this section we will review previous in situ studies of stratospheric plume processes, show how those datasets have contributed to our current understanding, and demonstrate the need for experiments such as SCoPEx to inform small-scale models of aerosol microphysics (nucleation and coagulation), plume transport and physical morphology, and chemical properties of new aerosol species that have thus far not been observed in the stratosphere. Because the nature of the injection scenarios (AM–H_2SO_4 or solid aerosols) are so complex compared to natural analogs, new experiments must be designed and implemented to provide observational constraints on our current nearfield modeling framework. Experimental data from carefully targeted small-scale studies would contribute to the development of nearfield-scale models that represent currently uncertain processes in detail.

We note that sub-grid scale processes do not represent the only unknowns in GCMs that are relevant to high-fidelity simulations of SRM scenarios, and that there are many large scale model phenomena which should be further assessed with observational evidence. However, here we focus on the need for in situ data to constrain sub-grid scale processes that can be addressed by SCoPEx and highlight the need for reducing the uncertainty in transport and aerosol dynamics and chemistry at this scale.

2.3.1. Limitations of Solid Rocket Motor Plume Observations

From 1996 to 2000 a number of rocket plumes were observed by high-altitude research aircraft. Generally, these missions involved a research team coordinating stratospheric sampling flights on either the NASA ER-2 or on the NASA WB-57 with coincident rocket launch events from either Cape Canaveral or Vandenberg Airforce Base. These studies sampled plumes from a host of rocket types including Titan IV, Space Shuttle (STS106, STS83, STS85), Delta II, Athena II, and Atlas IIAS.

Plumes were intercepted by the sampling aircraft between 5 and 125 minutes after emission from the rocket motor at stratospheric altitudes ranging from 11 to 19.8km (Voigt et al., 2013). The main science objective of these missions was to assess the stratospheric

ozone depletion potential of space exploration by understanding the halogen chemistry occurring as a result of the high-altitude rocket burn. However, in studying the effects on the ozone layer, this era of stratospheric sampling provided a unique set of plume measurements to study nearfield processes of chemical injections into the stratosphere.

While measuring the plumes from the Titan IV rocket (as a part of the United States Airforce Rocket Impacts on Stratospheric Ozone (RISO) Campaign) and attempting to develop a plume chemistry model to solve for the Cl_2 concentration in a rocket plume as it evolves shortly after its emission, Ross et al. (1997) noted the many assumptions that had to be made about the plume morphology in order to simulate the mixing and diffusion that the rocket plume had with the surrounding stratosphere. Their model solved for the Cl_2 concentration of a circular nighttime plume as it expanded in diameter along an isentropic surface. Subsequent aircraft measurements showed that plumes contained more than twice the predicted concentration of Cl_2 despite the plume being intercepted during the day time (when the Cl_2 reservoir should be somewhat depleted by the photolysis reaction $Cl_2 + h\nu \rightarrow 2Cl$), suggesting that there may be an error in the assumption of a circular plume morphology on the short transport time scales observed in this study ($\sim 28min$).

Ross went on to publish a second study as a part of the RISO project in 1999, this time looking to quantify the size distribution of alumina aerosols emitted from the rocket engines which contained particulate alumina (Al_2O_3) (Ross et al.,1999). They compared measured aerosol size distributions from the WB-57F plume interceptions to results from an aerosol coagulation model and highlighted a massive discrepancy. The model predicted a much smaller aerosol size distribution with 1-10% of the aerosol mass being in the smallest (0.005μm) mode and the aircraft observed only fractions (<0.05%) of the model estimate in that same small mode. At the same time, over 99% of the aerosol mass sampled by the aircraft was found in the coarsest mode (2 μm), which the model was unable to predict. It is most likely that the model used in Ross et al. (1999) did not well account for the effects of ion mediated nucleation as described by Yu & Turco (1997). However, the data from Ross et al. (1999) was some of the first in situ data to highlight the uncertainty in stratospheric aerosol coagulation models. Alumina aerosol, as well as other solid aerosols, in contrast to liquid sulfate aerosol, have since been investigated as a candidate for use in SAI (Weisenstein et al., 2015). Therefore, it is imperative that we understand the chemical, coagulation, and accumulation properties of these and other solid aerosols in a stratospheric environment.

2.3.2. Limitations of Previous Stratospheric Aircraft Wake Crossing Observations

We can look to the few times high-altitude aircraft wake plumes have been sampled in situ for another example of stratospheric plume measurements. In the early 1990s the popularity and capability of the Concorde spurred discussions of a large fleet of High Speed Civil Transport (HSCT) aircraft that would operate in the lower stratosphere between 16 and 23 km. Scientists became concerned with the effects of high-altitude aircraft and high-altitude supersonic aircraft on stratospheric ozone destruction via the creation of a large NOx source in the lower stratosphere. NASA then launched several field campaigns using the ER-2 to study the exhaust profiles of high-altitude aircraft. In 1992 NASA commissioned the Stratospheric Photochemistry Aerosols and Dynamics Expedition (SPADE) to look at the effects of HSCTs. As a part of SPADE the ER2 sampled its own plume on several occasions by making a hairpin turn and heading into its original path, therefore measuring its own wake

(Figure 2). SPADE resulted in at least 11 published studies and some of these can inform us about the mixing and aerosol dynamics that may be relevant to an SAI scenario (Stolarski & Wesoky, 1993).

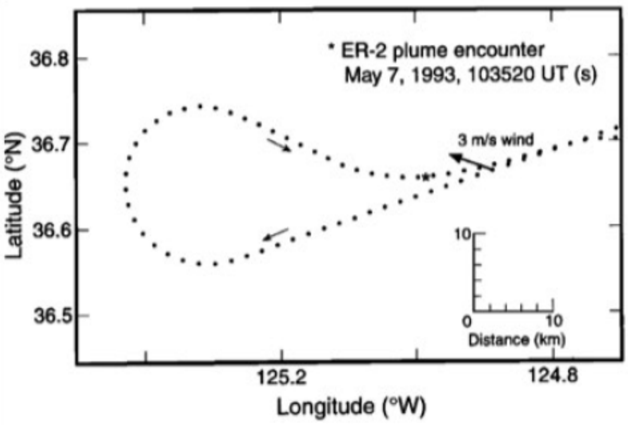

Figure 2: Shows the ER-2 flight track on a typical wake crossing trajectory (adapted from Fahey et al. 1995).

Fahey et al. (1995a) described measurements made of condensation nuclei (CN) present in the ER-2's exhaust plume from the emission of aerosol carbon and of sulfur compounds during one of its SPADE wake crossing events. Because the main focus of this study was to quantify the emission indices (EIs) of various compounds measured by the ER-2 that may have ozone depletion implications, they focused mainly on gas phase compounds. However, for the three wake crossings that the study focused on, they observed large variability in their EI measurements for CN. They noted that this is likely due to differences in mixing history of the encountered air parcels and noted that a full explanation of CN coagulation required more in-depth study and further measurements (Fahey et al, 1995b).

In another study published by Fahey et al. (1995b), they used a similar wake crossing technique to measure the exhaust of the Concorde aircraft and developed an aerosol coagulation model to predict particle formation and size as a function of the time since emission from the aircraft. The coagulation model was initialized at the observed conditions from the one-hour old Concord transect. The results from this model estimated that from 0 to 10 hr since emission from the engine, the mean particle diameter remained fairly constant at 0.06 μm before growing exponentially to a factor of 3 times its initial value over the next 1,000hr. The model predicted exponential mean particle diameter growth continuing right until the of the simulation at 1,000 hr (Fahey et al., 1995a).

Yu & Turco (1997) attempted to model the observed aerosol plume during the Concorde wake crossings with the goal of determining the driving factor for the large aerosol size distributions observed by the ER-2 in the exhaust which had not yet been explained by models. Yu proposed that aerosol formation was being aided by ion-mediated nucleation (IMN), that is, charged particles formed by chemi-ionization processes within the aircraft engines provide charged centers (H_2SO_4 [S(VI)]) around which molecular clusters rapidly coalesce. "The resulting charged micro-particles exhibit enhanced growth due to condensation and coagulation aided by electrostatic effects" (Yu & Turco, 1997). It is likely that IMN is the reason previous particle coagulation modeling of solid rocket motor plumes had overestimated the amount of aerosol in the small size ranges when compared to the in situ data, though this has not since been tested. Because of these effects, and the fact that specific size distributions of aerosol are desired to obtain the optimal radiative

forcing effects for SAI (nominally smaller than observed in rocket or aircraft plumes), we must understand the aerosol nucleation and coagulation dynamics in an unperturbed stratosphere.

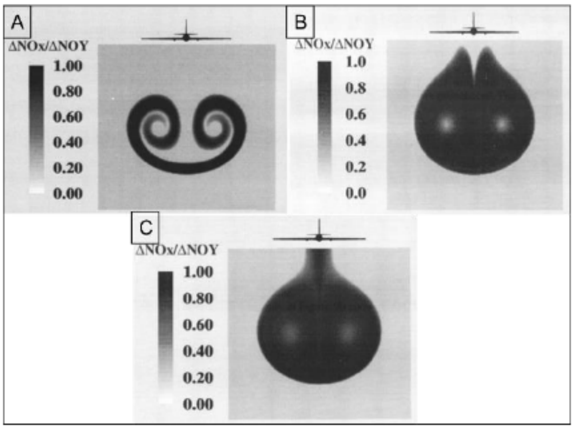

Figure 3: Shows the chemical and morphological evolution of an ER-2 plume during SPADE at 1.7 km (A), 4.8 km (B), and 7.9 km (C). (adapted from Anderson et al. (1996))

As a part of the SPADE project, Anderson et al. (1996) computed the flow field and chemical kinetics of the ER-2 aircraft exhaust using the Aerodyne Research Inc. UNIWAKE model. Their calculations address the effects of complex plume morphology on in-plume chemistry as a function of dilution time since emission from the aircraft engine. They showed that the plume morphology is highly variable out to about 5 km post emission Figure 3 and estimated that the stability of the wing vortex pair begins to break up at roughly 20 km post emission. Although this study was completed in the mid 1990s, it is still one of the only studies that attempts to compute nearfield chemistry within a dynamic stratospheric plume. However, particles were not considered as part of this study.

2.3.3. Limitations of Stratospheric Wake Crossings

Previous stratospheric plume studies of solid rocket motors and aircraft wake crossings have laid the foundation for our understanding of stratospheric plume chemical, aerosol, and mixing dynamics on transport scales of 0→100 km. These studies highlight the types of processes we must be aware of when considering the logistics of SAI. However, the violent initial conditions of engine exhaust plumes (such as temperatures of 700K, IMN) make it difficult to relate these observations to other systems. Because the engines drive the mixing and transport in the nearfield, and the ionic injection conditions of the plume create electrostatic forces that introduce complex nucleation affinities (IMN), understanding individual parameters can become analogous to finding a needle in a haystack. Moreover, because the radiative properties of any stratospheric aerosol that may be used for SRM depend on the diameter of the particle, we must understand the coagulation of that aerosol in the nearfield after the injection, which means that we must also understand the plume morphology that dictates the concentrations of that aerosol. Currently there have been no in situ data gathered that help us understand nearfield aerosol nucleation and plume dynamics in the absence of a very disruptive source. These conditions are necessary to understand as SAI may require that we mitigate the effect of IMN in order to obtain an aerosol size distribution that is small enough to provide the desired radiative properties.

2.3.4. Limitations of Naturally Occurring Analogs

Another source of useful in situ data on plume dynamics in the stratosphere can be found in literature addressing the fate and transport of convective overshooting events that often occur at the top of a Mesoscale Convective Complex (MCC). These events drive brief airmass exchange with the troposphere and often end up resulting in a plume-like parcel of tropospheric air being injected into the stratosphere.

Measurements of convective systems and upper troposphere-lower stratosphere exchange, as a means to interrogate stratospheric plume transport, have provided valuable in situ datasets that help us understand mid-field (10 to >1000 km) plume dynamics in the lower stratosphere. Similar to convective overshooting events, volcanic eruptions have provided an immense amount of in situ data that has informed us about regional and even global transport of stratospheric injections (Robock, 2000). Although their data are applicable in some sense to the transport of an SAI plume after its initial injection, the turbulent nature of a convective storm makes it difficult to measure these events at points near their injection source. Additionally, the storm conditions themselves dramatically complicate the system in the lower stratosphere such that is difficult to see through the effects of the induced turbulence in the nearfield. Indeed, an important limitation of these type of natural analogs is the spatial extent of their perturbation, which does not allow for near-field observations analogous to that of a point source. This also arises from the violent nature of these events which does not allow airborne platforms, such as the ER-2, to sample the initial conditions of the injection. We also note that volcanic eruptions are limited in their utility to evaluate dynamic response to stratospheric heating from sulfate aerosol, as they represent a perturbative pulse rather than the long-term heating one would expect from SAI.

In addition, these natural analogues provide extremely limited ability to study alternate materials, although organic and mineral dust aerosol injections into the lowermost stratosphere have been documented from convective overshoots. However, the complexity of the massive perturbations of both gas- and particle-phase preclude a study focusing on the impact on stratospheric composition and aerosol evolution that would result from SAI of a single material.

3. SCoPEx Short Overview

This section provides a brief overview of the engineering and operational aspects of SCoPEx. We first describe the platform, the instruments, and the concept of operations before describing the rationale for the overall SCoPEx design choices.

3.1. SCoPEx Platform

The SCoPEx gondola (Figure 4) is a balloon-born new research platform being developed at Harvard by the engineering and science staff within the Anderson/Keith/Keutsch laboratory group. The development builds on four decades of stratospheric research on aircraft, balloon, and rocket platforms that has focused on understanding the environmental chemistry of the ozone layer. The SCoPEx experiment was first described by Dykema et al. (2014). While many details of the design have changed, that paper still succinctly describes the advantages of choosing a balloon born platform over an aircraft, particularly for studying perturbations like solar geoengineering, and several of the limits of laboratory experiments that that could be addressed in a perturbative experiment like SCoPEx.

The gondola has three primary features: the frame, the ascender, and the propellers. The aluminum and carbon fiber frame contains two decks and a ballast hopper for coarse altitude control. One deck is primarily dedicated to platform support (power and flight control) and one deck is primarily dedicated to instruments. At the top of the gondola is an ascender and rope which allows the distance between the bottom of the balloon train and the gondola to vary from 0 to 150 m, which provides fine altitude control of the gondola. The ascender has been developed and tested by Atlas (Chelmsford, MA) building on their previous hardware in collaboration with the Harvard engineering team. The propellers serve two purposes: to create a well-mixed volume of air where observations of the aerosols and perturbed gas-phase can be made, and to reposition the gondola within the evolving aerosol plume. While the trajectory of the balloon and gondola system will be dictated by the balloon, the propellers allow for repositioning relative to the prevailing winds.

The ascender makes it impossible to have cables and other physical connections between the flight operations equipment and the gondola. Thus, the platform will handle its own communications and power. The SCoPEx platform will be powered using 28 V and 100 V DC power supplies which will power all operations on the platform including the propellers, ascender, and instruments. Elements of the flight platform are listed in Table 1. The gondola flight, flight safety, recovery parachute, and recovery operations will be managed by the balloon operator (in contrast to the SCoPEx team itself). Because the absolute velocity and distance capability of the gondola are so small compared to balloon drift, the trajectory will be determined by the balloon operator as if it was a passive nonpowered payload. During operations, the detailed float altitude will be jointly managed by the balloon operator via control of the balloon vents and the Harvard team via control of the ballast and ascender.

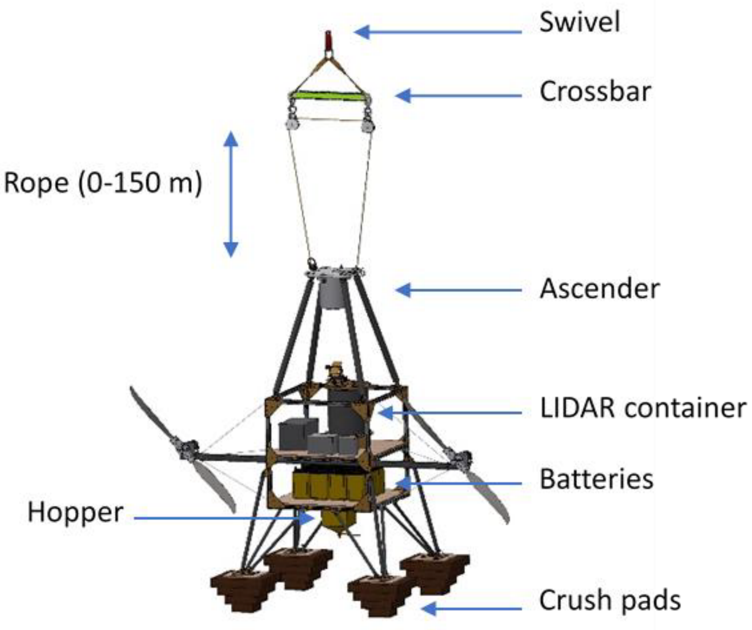

Figure 4: A representation of the SCoPEx flight platform. The final configuration may have subsystems packaged differently.

Parameter	**Description**
Total mass (Frame, all subsystems, hopper with ballast)	600 kg
Interface to balloon	Crosby 5-S-2 jaw & jaw swivel
Ascender	13 mm diameter rope Range of motion: 0-150 m Max speed: 10 m/min
Gondola propulsion	Twin propellers, 1.88 m diameter 32 N thrust each Max airspeed: 3 m/s
Power	28 V and 100 V DC power supplies with 24 MJ and 10 MJ total energy when fully charged
Communications	Satellite phone for communication between ground equipment and payload
Maximum termination shock	10 g

Table 1: Elements of the SCoPEx flight platform.

3.2. Instruments for First Science Flights (Science Goals 1 and 2)

The proposed instruments for the first science flight, addressing science Goals 1 and 2, are listed in Table 2. The corresponding science goals that motivate their inclusion are detailed in Section 4.

Measurement	Instruments	Rationale	Corresponding Science Goal
Wind speed measurement	Wind pendulum	Gondola and plume movement relative to balloon	Platform operation
Meteorology	Commercial off-the-shelf instrument	Temperature and pressure measurement throughout the flight	1, 2, 3
Wind turbulence	Constant temperature anemometer	Stratospheric mixing and modeling evolution of aerosol size distribution	1, 2
Particle dispersal	Solid Aerosolizer	Injects monodispersed particles for measurement and study	2, 3
Plume tracking	LIDAR	Tracking plume and navigation back into plume	2, 3
Particle sizer	POPS	Aerosol size distribution measurement for comparison with microphysics models of near-field evolution	2, 3
Light Scattering	Radiometer	Comparison of aerosol scattering with model prediction	2

Table 2: Instruments for first SCoPEx science flight.

Wind Pendulum: Understanding differential wind speed measurements between the balloon and payload will be important for plume evolution relative to the balloon trajectory and navigating the payload back into the plume. Commercial equipment to measure wind speed is typically not designed for the low densities found in the stratosphere. SCoPEx will therefore use a pendulum-based instrument and model to extract wind speed measurements. A camera will track a pendulum bob with high surface area and low mass, light enough to be perturbed by low winds in the stratosphere. Using the location and tilt data from the payload and a 3-dimentail kinetic model, the wind speed will be extracted from photos of the pendulum bob.

Commercial Meteorology Instrument: Commercial off-the-shelf instruments will be used for meteorological measurements on SCoPEx. They will record pressures and temperatures of the ambient stratosphere.

Constant Temperature Anemometer: A constant temperature anemometer (CTA) uses convective cooling caused by air flowing across a heated thin wire to measure flow velocity. LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere) (Gerding et al., 2009; Theuerkauf et al., 2010) used such a measurement to study stratospheric turbulence up to 29 km. LITOS consisted of a 5 μm diameter and 1.25 mm long tungsten wire CTA and a 16 bit ADC with 2000 samples per second to collect measurements with a vertical resolution of 2.5 mm at 5 m/s ascent speed. The anemometer data was analyzed by performing a spectral

analysis on the voltage signal to retrieve the spectral slope of the observed variation. A similar instrument will be used on SCoPEx to measure stratospheric turbulence. Air flow around the device will be simulated using CFD tools. The CFD runs will provide a means to identify key flow characteristics that drive sensor performance (sensitivity and accuracy), and to drive detailed sensor design.

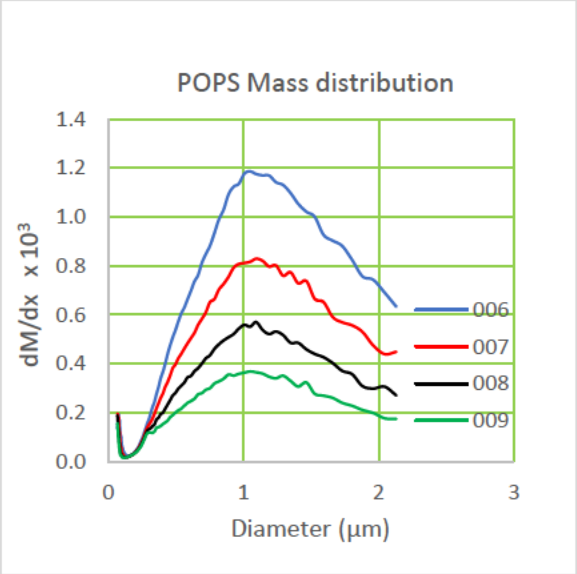

Figure 5: Successive measurements of sprayed $CaCO_3$ using an optical particle spectrometer. 006-009 indicate numbered time intervals spaced 4 minutes apart with 006 being the earliest measurement. $CaCO_3$ was sprayed using a 200 µm nozzle. In this laboratory experiment there was no significant variation in the shape of the distribution over time. (personal communication A Neukermans and team)

Solid Aerosolizer: The solid particle aerosolizer has been developed by a team lead by Armand Neukermans. For SCoPEx, the goal is to spray roughly monodisperse ~0.5 μm diameter precipitated calcium carbonate powder, the first candidate for solid SAI, through a 1-2 mm nozzle using the expansion of powder suspended in high pressure liquid CO_2. The aerosolizer would use a 1:4 weight ratio of $CaCO_3$ to CO_2. For 1 kg of $CaCO_3$ this would require a 5-7 L pressurized container. This concept has already been demonstrated in the lab. Figure 5 shows successive measurements of sprayed $CaCO_3$ with a size distribution centered at 1 μm diameter. Measurements were taken every 4 minutes using POPS (see below). In this case, total particle count decreased over time but there was no significant variation in the shape of the size distribution.

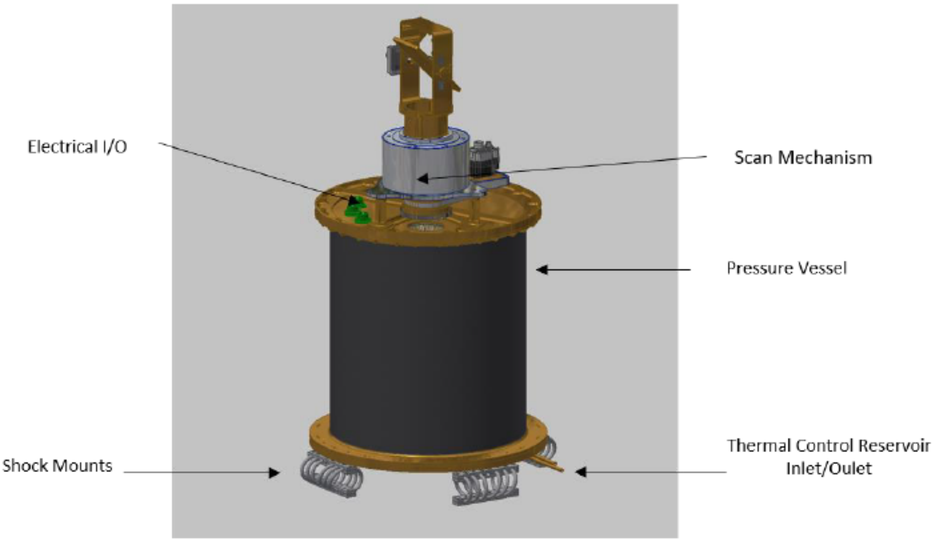

Figure 6: LIDAR pressure vessel provides safe storage and operating environment and support equipment.

LIDAR: The LIDAR is used to track the plume and allow navigation back into it. The core of the LIDAR system is an off-the-shelf eye-safe visible LIDAR, purchased from Sigma Space (now owned and operated by Droplet Measurement Technologies). This LIDAR produces 4 µJ pulses of 532 nm light at a repetition rate of 532 nm. The light that is backscattered by molecules and aerosols is collected by an 80 mm telescope and detected with a high-speed, high-sensitivity photodiode.

We have integrated this LIDAR in a pressure vessel (Figure 6) to provide a near-1 atm pressure environment with adequate temperature stability to ensure safe operation of the LIDAR at float altitude and safe storage on launch, ascent, descent, and recovery. This pressure vessel includes equipment for electrical and mechanical support, including command, data handling, and shock mounting. The LIDAR requires a scan capability to search the nearby atmosphere for the extent and geometry of the plume. The tilt and pan functions of the scan capability allows the LIDAR to be scanned over a set of angles that define the plausible location of the plume.

Portable Optical Particle Spectrometer (POPS): The POPS instrument will provide the aerosol size distribution measurements for studying aerosol formation and agglomeration. POPS is a light-weight instrument that directly samples the aerosol. It was built by and provided to SCoPEx through a collaboration with NOAA. The particles are illuminated with a 405 nm diode laser and the scattered light is collected onto a photomultiplier tube. The particle size is determined by the intensity of the scattered light. It has both the detection limit and size range (0.13 – 3 µm) to measure background stratospheric aerosol, which is more than sufficient for SCoPEx needs (Gao et al., 2016).

The Keutsch Group has already developed and extensively characterized a POPS instrument in preparation for the NASA-EVS3 Dynamics and Chemistry of the Summer Stratosphere field campaign on board the NASA-ER2, for which Keutsch is the deputy-PI. The POPS instrument tests include extensive thermal vacuum chamber characterizations to ensure operation under harsh stratospheric conditions. Compared to the ER-2, operation for SCoPEx will be simpler due to the insignificant air speed of the balloon and a much simpler operational pressure regime (on the ER-2 there is a large range of external pressures for both sampling and exhaust).

Radiometer: The aerosol plume can also be detected using a narrowband, narrow field of view radiometer with azimuthal/zenith pointing capability. The relationship between measurements of scattered solar radiation and the physical characteristics of atmospheric aerosols has been studied for more than two decades. Sky scanning measurements at multiple wavelengths between 300 nm and 1200 nm have been obtained using robotically pointed ground-based spectral radiometers deployed worldwide (Holben et al., 1998). The theory of these measurements has been refined and validated as a function of viewing geometry to provide a strong basis for inferring aerosol microphysics from radiometer data (Torres et al., 2014). The success of these approaches has motivated the development of compact sky scanning radiometers suitable for deployment on unsteady platforms like unmanned aerial vehicles (UAVs) and SCoPEx. One such design, reported by NOAA (Murphy et al., 2016), measures at 4 wavelengths (460 nm, 550 nm , 670 nm, and 860 nm) with a field of view of 0.006 sr (equivalent to 2.5° half-angle) and a circular limiting aperture of 1.1 mm diameter. A radiometer like this one deployed on SCoPEx would be capable of observing a SCoPEx plume, based on Golja et al. (2020), formed by a 0.1 g s^{-1} injection of calcite from a distance of 200 m with an approximate signal-to-noise ratio of 6000 for a 1 ms signal accumulation.

3.3. Instruments for Future Science Flights (Science Goal 3)

The additional instruments listed in Table 3 are candidates for future SCoPEx flights beyond the initial science flight, i.e., addressing science goal 3. They have not yet been adapted to fly on the SCoPEx platform. Instrument choices will be refined based on experiences in the first science flights. The corresponding science goals that motivate their inclusion are detailed in Section 4.

Measurement	Candidate Instrument	Rationale	Corresponding science goal
Aerosol composition	Drum Sampler	Collecting aerosols for offline analysis	3
Water Vapor	IR Absorption or Frost Point	H_2O outgassing of platform, Influence on coagulation and heterogenous chemistry	2, 3
Atmospheric trace gas concentrations (ex: HCl, NOx)	Spectroscopic trace gas instruments	For measuring concentrations of various atmospheric trace gases before and after addition of solid ASI material	3

Table 3: Potential instrument for future SCoPEx science flights.

Aerosol Composition: Aerosol composition can be analyzed via the collection of aerosol with a drum sampler followed by offline analysis in the laboratory using standard offline methods. Aerosol sampling has been done numerous times aboard stratospheric platforms.

Water Vapor: Gas-phase water vapor measurements are important as relative humidity likely has a large impact on the heterogeneous reactivity of solid SAI material. The balloon and gondola can outgas significant amounts of water and thus an initial experiment will characterize how long, if at all, this outgassing perturbs the SCoPEx plume. As mentioned previously, the goal of SCoPEx is to ideally minimize the perturbation to only the introduction of calcium carbonate. Water vapor measurements are common on many stratospheric platforms.

Hydrogen Chloride: HCl can be measured via infrared absorption spectroscopy. The Anderson group at Harvard, which shares a laboratory with the Keutsch group, has developed a stratospheric HCl instrument and thus has extensive experience with the design of stratospheric HCl instrumentation. In addition, the Keutsch group has designed multiple spectroscopic trace gas measurements. The much lower air speeds of the balloon compared to aircraft favor the design of an open path system, which eliminates the notorious wall effects that can make HCl measurements challenging.

NOx: For NOx there exist a number of good instrumentation options. Recently, a compact NO-LIF instrument has been designed that has spectacular detection limits in the low ppt range, more than sufficient for the needs of SCoPEx. The instrument is a close analogue of the fiber-laser based formaldehyde LIF instrument that the Keutsch Group developed, so there is a high degree of expertise available for such an instrument. There are also sensitive cavity enhanced techniques available usually in the visible range of the spectrum.

3.4. SCoPEx Concept of Operations

Flights will proceed in the following manner. The payload would be launched with the ascender retracted such that there is minimal distance between the crossbar and platform. Once the balloon reaches the float altitude, the rope will be let out through the ascender such that there is 100 m between the crossbar and platform. The platform will then be ready to perform experiments and execute maneuvers. Figure 7 illustrates a proposed flight maneuver. The platform will initially travel in a straight line laying out a plume, after which it will maneuver back through the plume to make measurements. During these maneuvers the ascender can be used to fine tune the altitude of the platform and instruments. Several series of such maneuvers can be performed within each flight. At the conclusion of the experiments the ascender retracts the rope before the descent.

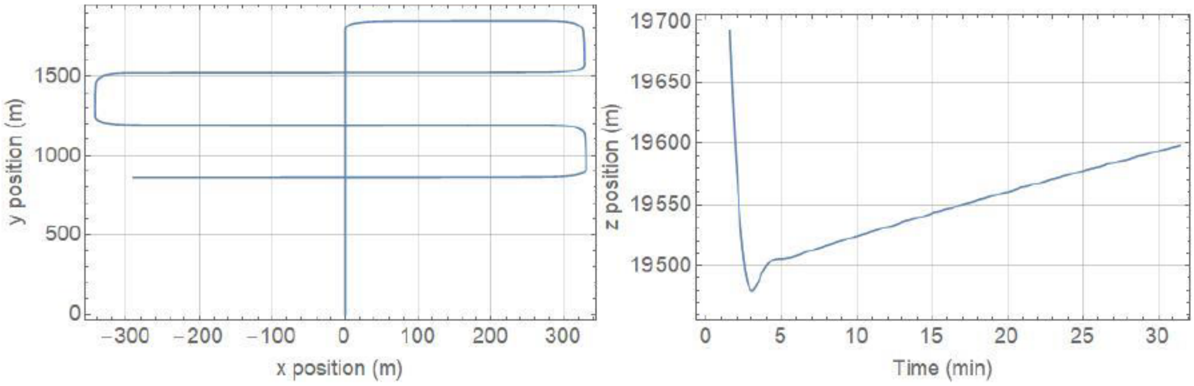

Figure 7: (left) A top down view of the proposed flight maneuvers over a 35-minute window. x and y are in the horizontal plane. The platform begins at (0,0). (right) The vertical position expected without any ascender or hopper vertical trimming over the same 35-minute platform maneuver.

4. SCoPEx Goals

In this section we describe the three long-term SCoPEx science goals. For each goal we describe the scientific problem, the need for SCoPEx, and the measurements required. The first phase of science flights targets the first two science goals. The design of the flights for the third goal will be informed by an understanding of the evolution of particle size distribution in the plume and the plume size. Thus, if later stage science flights move forward, they will be refined based on the results of the first science flights and the most up-to-date knowledge within the solar geoengineering and stratospheric science research communities.

4.1. Goal 1: Measurements of Turbulence for Small-Scale Mixing

4.1.1. The Importance of Plume-Scale Turbulence

Stratospheric turbulence influences the evolution of aerosol distribution from plume to regional to global scale. The mixing of air masses (of differing composition) in the stratosphere is a combination of two processes (Nakamura, 1996; Schoeberl & Bacmeister, 1993). The first process is strain, the distortion of streamline flow that brings air masses of differing composition adjacent to one another (Prather& Jaffe, 1990). Sometimes this is also referred to as “stirring” (Haynes, 2005). The second process occurs when air masses of differing composition are transported across the streamlines. This second process is the true “mixing” process.

In the stratosphere, mixing ultimately occurs because of molecular diffusion. This happens at the length scale of molecular viscosity. It is accelerated by turbulence, which can dramatically enhance the rate at which differing air masses are deformed to small enough spatial scales for molecular diffusion to mix them efficiently. Stratospheric turbulence is, however, highly intermittent (Vanneste, 2004). Understanding the mechanisms of stratospheric turbulence production is essential to understanding the spatial inhomogeneity and effective rate of mixing on spatial scales of 10-500 m (Schneider et al., 2017).

An understanding of this role of turbulence is of interest to stratospheric science because studies suggest that more accurate representations of mixing influence tracer distributions (Hoppe et al., 2014). Measurements of long-lived tracers are the strongest observational constraint on the stratospheric age of air, a key measure of the stratospheric large-scale circulation. Turbulence also modifies the character of kinetic energy fluxes. The magnitude and variability of these energy fluxes determine the rate of frictional dissipation in the atmosphere. This dissipation is represented in global models by a damping parameter and is the primary determinant of the mesoscale atmospheric kinetic energy spectrum. The uncertainty in kinetic spectrum is important to the understanding of the large-scale circulation of the middle atmosphere (Jablonowski & Williamson, 2011).

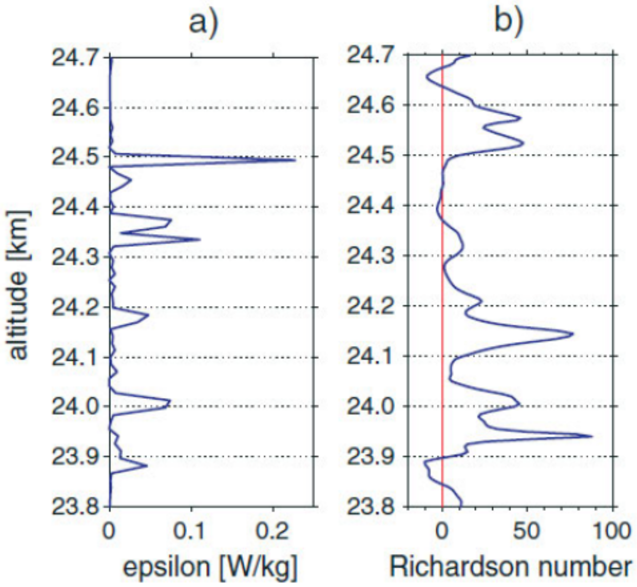

Figure 8: LITOS balloon-borne high-speed anemometer measurements reveal that models of atmospheric turbulence do not explain observed stratospheric turbulence. Physical models predict that a low Richardson number (buoyancy/shear ratio) implies turbulence, but high values of epsilon (turbulent dissipation) should be correlated with low Richardson number, which is not observed. (Haack et al., 2014)

Physical models predict that a low buoyancy/shear ratio (Richardson number) implies turbulence, and that high values of turbulent dissipation should be correlated with low Richardson number (Figure 8). However, recent balloon born measurements during the LITOS campaign did not agree with this, with numerous instances of high values of turbulent dissipation occurring at high Richardson numbers (Haack et al., 2014). As detailed above, both the impact of turbulence on mixing and the associated dissipation of energy are important for general stratospheric science. The point at which viscous fluid forces dominate atmospheric motion is the point where atmospheric motions become purely statistical and is called the dissipation scale. At this scale, models no longer require computationally expensive deterministic modeling. Furthermore, these viscous forces are also responsible for the dissipation of turbulent kinetic energy. Therefore, measurements which resolve the winds at the dissipation scale will allow numerical models to realistically close the atmospheric kinetic energy budget, an important metric of model fidelity.

4.1.2. Importance of Small-Scale Mixing for SAI and SCoPEx

From an SAI and SCoPEx perspective, plume-scale turbulence influences the frequency of collisions of monomer particles within the SCoPEx plume, which determines the rate of formation of fractal, larger aggregates. While Van der Waals forces finally determine whether particles that collide stick together and remain as a fractal aggregate (Sukhodolov et al., 2018), the collision rate is a critical quantity in determining total coagulation rate. Therefore, it is essential to know the frequency of collisions. This frequency is controlled by the wind variability at small spatial scales, i.e., the power spectrum. Intuitively, inertial forcing of particles by wind is much stronger than thermal forcing (e.g. Boltzmann distribution of velocity for ~1 µm particles at ~220 K). Fractal aggregates have a shorter lifetime in the stratosphere and are less effective at scattering light on a per mass basis (Weisenstein et al., 2015), so being able to model the formation

rate of fractal aggregates is an important aspect of SAI, especially with alternate SAI materials.

Improved knowledge of collision rates from wind measurements will allow for the selection of the appropriate mathematical representation of particle coagulation, the coagulation kernel. An accurate kernel is essential for numerical models to correctly simulate aerosol microphysical processes that determine the size distribution and residence time of solid aerosol particles. Adding wind and turbulence measurements to the SCoPEx payload will therefore address the major sources of uncertainty in aerosol microphysics under real atmospheric conditions, which include small-scale fluid flow, particle composition, and humidity.

4.1.3. Experimental Methods to Measure Turbulence in the Stratosphere

Multiple technologies are possible to achieve wind measurements with the necessary spatial resolution under stratospheric conditions. Current state of the art options include pitot tubes (with high sensitivity micro-pirani pressure sensors), hot wire anemometers, and acoustic anemometers. An existing stratospheric program has utilized hot wire anemometers to make measurements that are a close analog to what is necessary for SCoPEx. The program developed LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere), an instrument which made measurements of stratospheric turbulence up to 29 km (Gerding et al., 2009; Theuerkauf et al., 2011). The LITOS instrument has undergone significant calibration and has been compared against radiosondes (Schneider et al., 2015). One drawback of its deployment on a balloon has been the contamination of its wind measurements due to the influence of the balloon's wake. In contrast, SCoPEx is engineered so that the wind environment of the instrument payload is well separated from the balloon wake when SCoPEx is traveling horizontally. For this reason, SCoPEx could provide significantly more data per flight at a chosen float altitude. In this way, SCoPEx and LITOS would be very complementary. The horizontal flight path of SCoPEx, combined with measurements of the wind power spectrum, would provide an excellent complement to the LITOS observations, which are only obtained along a vertical profile. These power spectra obtained by SCoPEx would contribute to improved micrometeorology understanding relevant both to stratospheric aerosol injection and to fundamental atmospheric science.

Additionally, air flow through the turbulence instrument will be simulated using CFD tools. The CFD runs will provide a means to identify key flow characteristics that drive sensor performance (sensitivity and accuracy) and detailed sensor design. This application of the SCoPEx platform would therefore constitute a nonperturbative means to obtain necessary turbulence measurements that have, to date, eluded the scientific community. This information is important for understanding stratospheric dynamics, including the response to climate change or stratospheric heating from SAI. As no injection of particles is needed, these could be among the first scientific measurements to be conducted.

4.2. Goal 2: Evaluation of Aerosol Microphysics of AM-Sulfate and Alternative SAI Materials

One of the goals for which there are insufficient observational analogues is the near-field evolution of particles injected from a point source in the stratosphere. Specifically, observations of the temporal and spatial evolution of the aerosol size distribution (number and volume) of solid, alternate SAI materials or AM-H_2SO_4 injected form a point source can

only be compared with plume model predictions via a perturbative experiment such as SCoPEx. In the following we describe a plume model by Golja et al. (2020) specifically designed for SCoPEx. We also explain the results from the model and the SCoPEx experimental approach for comparing observations with model results.

4.2.1. Plume Model

Golja et al. (2020) incorporated the SCoPEx design features in their model to study the injection of a solid aerosol and vapor-phase sulfuric acid from a balloon payload. To provide observations relevant to SAI, SCoPEx needs to produce downstream aerosols with radii within the range of roughly 0.2 to 1.0 µm. For calcium carbonate, the objective is to maintain a high fraction of the aerosol in monomer form, while for sulfate an ideal distribution would have a peak diameter of 0.6 µm (Dykema et al., 2016). The generation of largely smaller than ideal particles, while imperfect for assessing radiative efficiency relevant to SAI, does not serve to increase particle sedimentation rates within the plume. Such smaller sizes may, however, result in a larger surface to volume ratio, which can strongly influence stratospheric composition as heterogeneous chemistry is directly related to surface area. Distributions centered on small particle sizes in the near field may, however, continue to evolve beyond the domain of the study.

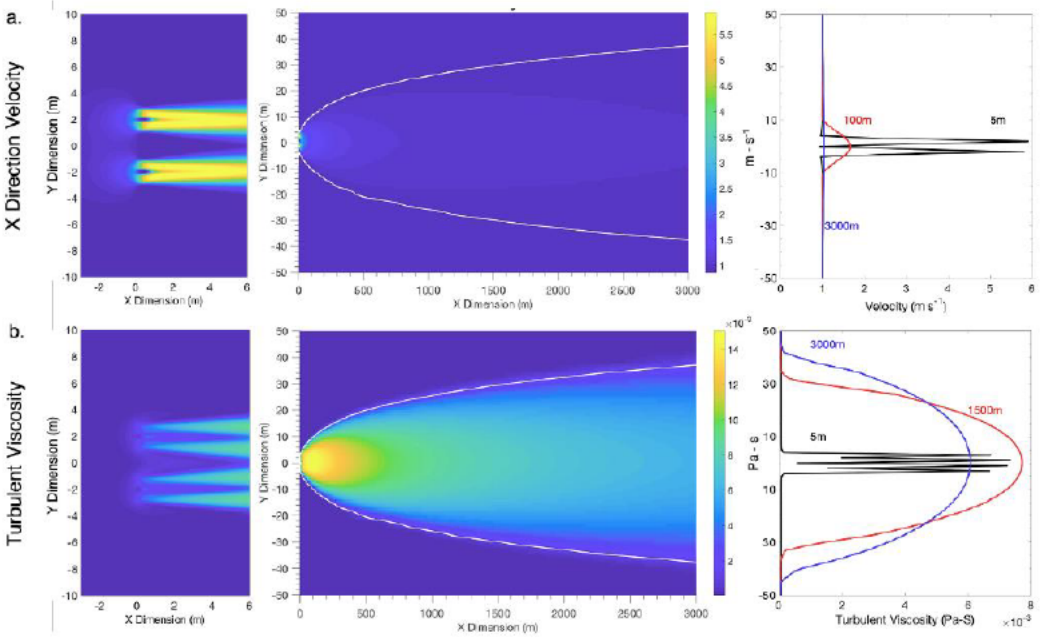

Figure 9 : ANSYS Fluent Velocity and Turbulence Fields. Shown above are the steady state x-direction velocity, u, and turbulent viscosity fields generated by ANSYS Fluent. Left panels show the genesis of disruptions to background X direction flow of 1 ms^{-1}, where propeller features are imposed at locations of 0,2) and (0,-2) meters. The center panel shows the entire domain, from 0 to 3 km, where the imposed red line contours 1 ms^{-1} in plot A, and contours 10% of the absolute maximum turbulent viscosity in plot B. Note Y direction scaling differs between the center and left panels. The right panel shows cross sections of velocity (A) and turbulent viscosity (B) through the Y plane at varying X locations. (Golja et al. 2020)

The velocity and turbulent viscosity fields from Fluent are shown in Figure 9. These fields form the basis of the simulation environment and are instructive in achieving an understanding of SCoPEx and the perturbation it achieves. Peaks in the x-direction velocity, u, are found directly downstream from the modeled propeller centers with an absolute maximum value of 6.3 ms^{-1}. By 1500 m downstream from the inlet locations, the velocity is reduced to the imposed background flow of 1 ms^{-1}. Turbulent viscosity, used as a measure

of particle mixing with background air, exhibits a narrow distribution of peak values ~10 m downstream from simulated propellers. With increasing distance downstream, the turbulent velocity spatial distribution widens, attaining a full width half maximum (FWHM) of 60 m by 1500 m downstream. The wake of the balloon itself is not visible, as it is sufficiently far from the payload to avoid wake crossing/interaction. Additionally, this simulation assumes a laminar stratospheric background flow, neglecting the potential impacts of breaking gravity waves.

For SCoPEx, precipitated calcium carbonate powder with roughly monodisperse size distribution centered at ~0.5 mm diameter will be aerosolized using the expansion of powder suspended in high pressure CO_2 through a 1-2 mm nozzle (see description in Section 3). The model injects aerosol as a 3D gaussian distribution of mass flux into the model grid, where the size of that distribution represents the scale of which the high velocity jet from the nozzle mixes with ambient air. The model considered two injection scenarios: scenario 1 (S1), a single point injection between the propellers; and scenario 2 (S2), injection from the center of each propeller. The model plume diameter at 3 km is, however, insensitive to the injection scenario for injection of both AM-H_2SO_4 and calcium carbonate. This suggests that injection at or between the propellers does not significantly alter the characteristics of the particles' experienced velocity field, and scenario S1 is the one selected for testing the model of plume evolution on SCoPEx. This is also important for the SCoPEx experiment as it necessitates only one sprayer that can be more easily placed in the equipment gondola.

4.2.2. Modelled Mass Injection Rate Dependence of Aerosol Size Distribution

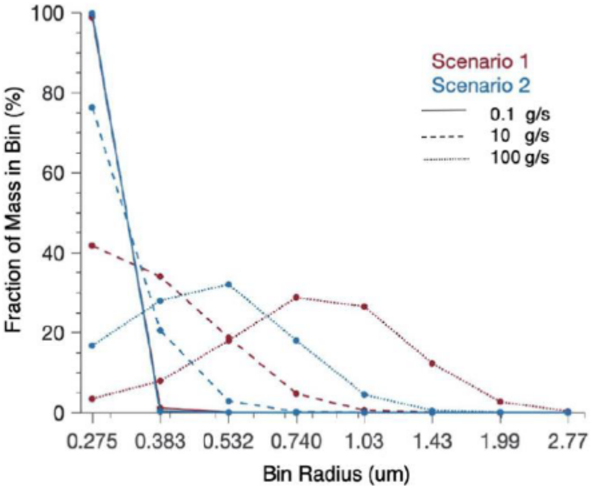

Figure 10: Calcium carbonate aerosol size distributions. Fraction of total mass in each sectional bin where the x-axis markers represent the central radius of each sectional size bin. These distributions represent the percent of total aerosol mass in the final 100 m of the plume across the full domain. Results are shown for three injection rates, 0.1 g s^{-1}, 10 gs^{-1}, and 100 gs^{-1}, for injection scenario 1 (red) and 2 (blue). (Golja et al. 2020)

Mass injection rates of 0.1, 10, and 100 g s^{-1} (0.36, 36, and 360 kg hr^{-1}) were used to test the influence of initial particle number density on the final plume aerosol size distribution. Although some of these are high, their use in the model is instructive as it can answer how different a short burst of high injection rate (much less than an hour) is from a slower but longer injection for the same total mass. Increasing calcium carbonate injection rates from 0.1 to 100 g s^{-1} reduces the share of monomer particles and increases undesired multi-monomer fractal aggregates. Figure 10 shows calcium carbonate's size distribution in the final 100 m of the modeled plume, i.e., the percent in each bin for the three different

injection rates of 0.275 μm radius particles. The low calcium carbonate injection rate of 0.1 g s^{-1} is the most desirable, maintaining 99% of the total mass in the final 100 m of the plume in monomer form. Increasing mass injection rate to 10 g s^{-1} and 100 g s^{-1}, with an S1 injection, shifts peak mass loading to favor particles of radii 0.5 and 0.75 um, respectively, corresponding to fractal "dimers" and "trimers".

Golja et al. (2020) also evaluated whether, in addition to the very sensitive in-situ optical particle counting aerosol size distribution instrument which originally was designed to measure background stratospheric aerosol size distributions (Murphy et al., 2016), the plumes could also be detected optically via scattered light. It should be emphasized that this does not refer to measurements from the ground but rather from close to the plume, e.g., when the equipment gondola is in close vicinity to the plume. Measuring the scattering from one view angle gives the product of the scattering phase at that angle and the scattering efficiency. This is closely related to the radiative forcing, but it does not uniquely determine the radiative forcing. By measuring at multiple angles, we could obtain enough information to quantify the radiative forcing. For example, we could measure from the side and below to obtain the forward scatter fraction, then calculate backscatter by flux conservation.

In the model, the extinction optical depth was calculated using Mie scattering theory and vertically integrating down columns in the y-z plane. Figure 11 shows the relative optical thickness of a sulphate and calcite aerosol plume formed via scenario 1 with an injection rate of 0.1 g s^{-1}. Calcite exhibits greater optical thickness by an order of magnitude at 550 nm, with an average value of 8.6×10^{-4} and maximum of 0.014 across the domain, as compared to sulphate, with an average of 9.4×10^{-5} and maximum 0.001. From these values, Golja et al. calculated that we expect adequate SNR to confidently detect the plume with a fast-scanning radiometer via the solar radiation it scatters. This calculation assumed an altitude of 21 km, solar elevation angle of 60°, an observing instrument situated on the payload gondola, and the gondola 200 m away from the edge of the plume and 1 km downstream of the termination of a scenario 1 type injection of calcite aerosol. Details of this calculation can be found in Golja et al. (2020).

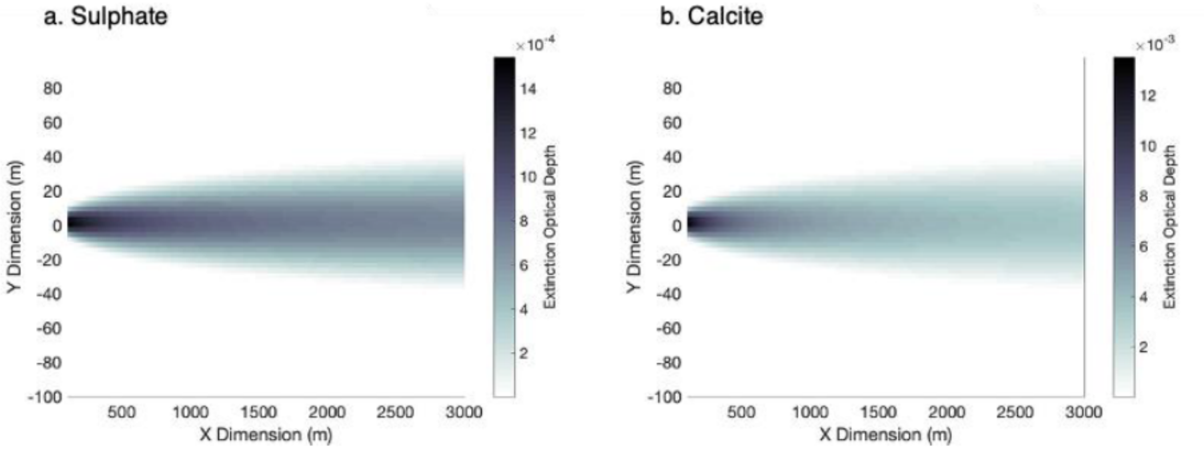

Figure 11: Extinction optical depth integrated vertically through all columns in the plume from 100-3000 m. Plots a and b show results for 0.1 gs^{-1} injections of condensable H_2SO_4 and calcite, respectively. The resulting number density of calcite aerosol is 490 cm^{-3} on the centerline at a downstream distance of 1000 m, predominantly as monomers. Aerosol optical depths were derived from Mie scattering theory at 550 nm, using refractive indices for sulphate and calcite stated in Dykema et al. (2016). (Golja et al. 2020)

4.2.3. SCoPEx Experimental Design and Analysis of Plume Evolution

For this goal, SCoPEx will follow the standard concept of operations, first spraying calcium carbonate at an injection rate suggested by the model analysis. It is desirable to maximize the contrast with the background stratosphere, both with respect to the aerosol concentration and the potential resulting chemical changes, while also maintaining calcium carbonate as monodisperse aerosol. To this end, additional models will be run at injection rates between 0.1 and 10 gs^{-1}. Based on these results, an injection rate will be chosen for the actual SCoPEx experiment. In addition to the basic components of the SCoPEx platform (gondola, ascender, propulsion, power, flight computer, communication, and wind), the calcium carbonate sprayer as well as the LIDAR and POPS instrument are critical for this science goal; without these components, there would not be a way to make and find the plume or measure the aerosol size distribution. While the turbulence measurement from goal 1 is desirable, it is, at least initially, not necessary. Similar studies of AM-H_2SO_4 injection would also be extremely useful. Our current plan is to conduct these after the calcium carbonate injection studies, as initially calcium carbonate is easier to handle than sulfuric acid and its precursors (see next section for motivation of calcium carbonate).

The aerosol size distribution measurements will be compared with the model predictions. In combination with turbulence measurements, discrepancies between the observed and modeled aerosol size distributions can be used to identify issues within the aerosol microphysical scheme or highlight misrepresentations of the velocity and turbulence field of the payload. The results of these studies will provide critical observational constraints on the aerosol microphysics and plume evolution of an injection with solid particles. It will be unique data that is ideal for testing the model of plume evolution as SCoPEx does not have to address problems resulting from the much more violent injection regime associated with injection from airplanes. Clearly, such studies are also needed, but SCoPEx represents a feasible and compelling first step in a sequence of new studies that more comprehensively investigate the aerosol microphysics of point source injections.

4.3. Goal 3: Evaluation of Process Level Chemical Models of Stratospheric Chemistry of Sulfate and Alternative SAI Materials

4.3.1. Need for Alternative SAI Materials

As previously discussed, the two largest first-order stratospheric risks of SAI with sulfate aerosol are ozone depletion and stratospheric heating. For sulfate aerosol the relative magnitude of these two risks can be adjusted if the size distribution can be controlled, e.g., via the AM-H_2SO_4 approach. It is worth noting that the impact on stratospheric ozone may be greatly reduced in the future if reactive halogen concentrations are lower. In contrast, the impact of stratospheric heating will not change. This represents a risk with a poorer understanding of its consequences, which makes it highly desirable to minimize stratospheric heating and resulting dynamic response. Therefore, it is important to investigate alternative SAI materials.

The properties of the “ideal” SAI material is (i) no absorption of radiation, i.e., purely scattering aerosol both fresh and aged, (ii) chemically inert, i.e., no direct impact of this material on stratospheric composition, and (iii) minimal down-stream effects, i.e., no impact on cirrus or other clouds, no environmental impact on deposition on the ground, etc. In reality, it is unlikely that a material with no impacts exists and rather the question is which materials can minimize these impacts. There have been a number of studies investigating

SAI materials in this context. High refractive index materials have been suggested as they reduce the mass of material that have to be lofted (Ferraro et al., 2015; Ferraro et al., 2011; Pope et al., 2012; Keith et al., 2016; Dai et al., 2020; Weisenstein et al., 2015). This largely cost-driven perspective is not a motivation for our work. In contrast, one of the goals of SCoPEx is to decrease the uncertainty in SRM models that use calcium carbonate SAI. The rationale for the choice of calcium carbonate as well as the approach to evaluate some of these risks is described in the following sections.

4.3.2. Unreactive Alternative SAI Materials

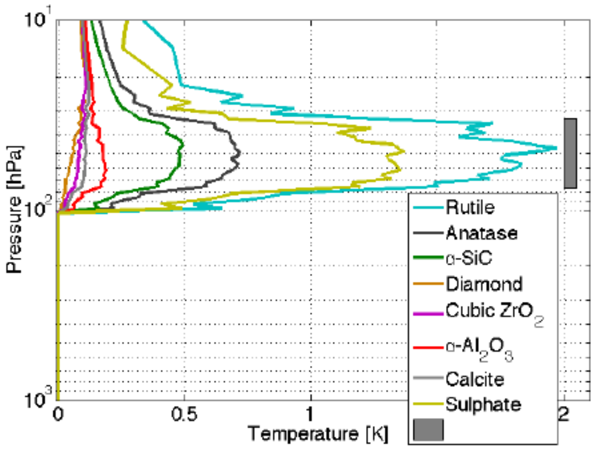

Figure 12: Comparison of stratospheric heating for different materials. Diamond has the lowest impact, although cubic zirconia and calcite are very similar. Sulfate and rutile result in much larger heating. (Dykema et al., 2016)

Diamond is probably the material with the best properties for SAI from a purely stratospheric perspective. Diamond has no absorption features in the solar or terrestrial spectrum and thus triggers the minimal possible dynamical response Figure 12. In addition, diamond should have ideal chemical properties. Hydrogen-terminated diamond surfaces are extremely inert and hydrophobic, precluding the ozone destroying chemistry initiated on sulfuric acid surfaces. The surface itself is also resistant to concentrated sulfuric acid. Exposure to OH radicals would probably slowly make the surface more hydrophilic. From a purely stratospheric perspective the only first-order risk of diamond would be increased ozone loss from the increased sulfuric acid surface area resulting from coagulation with background sulfate aerosol.

4.3.3. Reactive Alternative SAI Materials: The Case for Calcium Carbonate

Although the impact on cloud properties and the risk to Earth’s surface from deposition of SAI diamond is likely very low, it could be preferable to have a material that dissolved easily in water, hence not persisting for long times outside of the stratosphere. It would also be preferable to have a material that is naturally abundant at Earth’s surface. In addition, it would be ideal to overcome increased ozone loss due to coagulation by using a reactive aerosol. We therefore propose calcium carbonate as a prototype alternate SAI material for the following reasons: First, its optical properties are nearly equal to diamond and stratospheric heating and resulting dynamic response should be negligible compared to sulfate (Figure 12). Second, carbonates are typically quite reactive with acids, especially with concentrated sulfuric acid (Figure 13). Hence, calcium carbonate will neutralize upon

coagulation with sulfate aerosol eliminating the acidic surfaces resulting from coagulation of diamond and sulfate aerosol. Of course, the reactivity of calcium carbonate also makes model predictions with calcium carbonate more complex. The evolution of chemical and optical aerosol properties has to be modeled over its stratospheric lifetimes. One of the key research questions that SCoPEx will help address is whether the reactivity of calcium carbonate and the evolution of its chemical and optical properties and those of the surrounding gas-phase correspond to the detailed hypothesis laid out below. To this end, SCoPEx will compare observations of the chemical evolution of calcium carbonate, as well as the gas-phase, with those of a model based on known properties of calcium carbonate and recent laboratory experiments (Dai et al., 2020). This will provide a real-world evaluation of kinetic parameters, such as heterogeneous uptake coefficients derived from the laboratory studies, that will enable GCMs to include reliable parameterizations of the stratospheric impacts of calcium carbonate SAI.

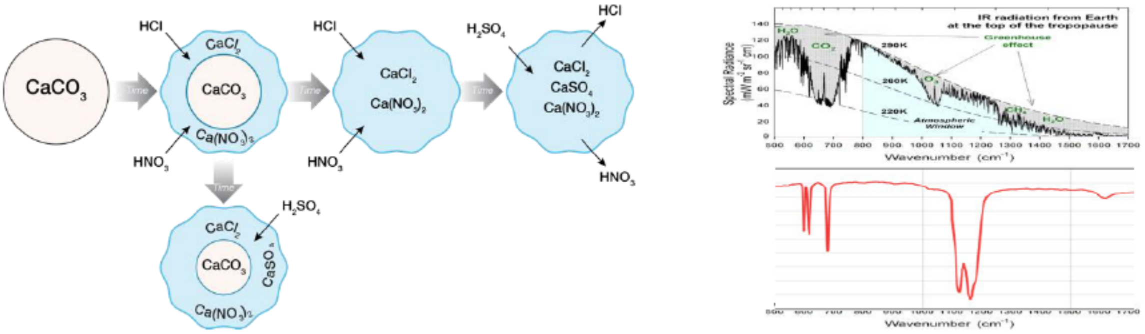

Figure 13: The left panel shows schematic of potential chemical reactivity of calcium carbonate in the stratosphere. The right panel shows the atmospheric windows in the terrestrial infrared (top) as well as the infrared absorption spectrum of calcium sulfate (bottom). The position of the 1150 cm^{-1} sulfate in part explains the stratospheric heating effect of sulfuric acid.

4.3.3.1. Optical Properties

Based on well-established chemistry, the reaction of sulfuric acid aerosol with calcium carbonate can be assumed to go to completion, i.e., be reagent limited. The optical properties of calcium sulfate in the terrestrial infrared are similar to those of sulfuric acid with only slight differences in relative band intensities and wavelengths (Figure 13 right hand inset). This is important as it implies that there will be no large first-order changes in stratospheric heating from changing background sulfuric acid to calcium sulfate. There are higher order impacts due to slight differences in the absorption of sulfuric acid, which has some liquid water compared to calcium sulfate. There are also numerous forms of calcium sulfate (anhydrite, bassanite, gypsum, etc.). However, the resulting differences are much smaller than introducing an absorbing material via SAI.

4.3.3.2. Chemical Properties

Predicting the evolution of the chemical properties of calcium carbonate under stratospheric conditions is more challenging. It is certain that calcium carbonate does not have the same heterogeneous reactions that activate ozone destroying substances as sulfuric acid. Figure 13 shows a schematic of the expected reactivity. Calcium carbonate is expected to react with acidic substances neutralizing them, forming salts and carbon dioxide. These acid neutralizing reactions can deplete gas-phase HNO_3, HCl, etc. There are a large number of ozone destroying catalytic cycles involving NOx, chlorine and other

halogens, which are altitude (and latitude) dependent. NOx can be produced via HNO_3 photolysis and lost via heterogeneous reaction of N_2O_5. It participates both in ozone destroying catalytic cycles and is important for deactivation of ozone destroying halogen radicals. Thus, knowledge of the heterogeneous reaction rates of numerous substances with calcium carbonate are required to predict the impact it will have on stratospheric composition.

However, until the recent study by Dai et al. in our laboratory, no heterogeneous chemistry studies of calcium carbonate under stratospheric conditions had been conducted, to our knowledge, although there exists a rich data set under tropospheric conditions (Dai et al., 2020). This work, as well as the work of Dai et al., highlights that reactive solid aerosols are indeed more complex than liquid sulfuric acid: The authors observed moderate initial uptake of the gas-phase acids HCl and HNO_3 on fresh calcium carbonate, as the dry stratospheric conditions already make uptake coefficients lower than under typical tropospheric conditions. An additional large difference to liquid aerosol is that the surface of the solid calcium carbonate passivates, drastically reducing the uptake coefficients of HCl and HNO_3. Hence, based on the Dai et al. laboratory study, calcium carbonate rapidly becomes effectively unreactive with respect to uptake of these gas-phase acids, an important finding that confirms calcium carbonate as a good candidate as alternate SAI material. In addition, calcium carbonate particles are abundant at Earth's surface due to windblown mineral dust. And the small calcium carbonate SAI particles should dissolve rapidly in water. This does not exclude risks associated with the deposition of calcium carbonate SAI particles or impacts on clouds (Cziczo et al., 2019). However, due to its abundance at the Earth's surface, there already exists a large knowledge base for its environmental impacts in contrast to, e.g., diamond. Further laboratory work is required to study especially the $ClONO_2$ + HCl and N_2O_5 hydrolysis reactions on fresh and aged calcium carbonate. However, the existing results prepare the stage for studying them in the real stratospheric environment as outlined below. Figure 14 shows results of the AER 2-D chemistry-transport-aerosol model for annual average ozone column changes of calcium carbonate SAI compared to a control for 2040. Ignoring the passivation of calcium carbonate (thk-ind) results in increases in ozone columns from calcium carbonate SAI whereas the inclusion of passivation can either result in very little ozone column change or losses in the Southern Hemisphere, depending how the $ClONO_2$+HCl is parameterized. Either of the two, more realistic, passivation scenarios result in significantly lower ozone loss than the equivalent amount of sulfate SAI, consistent with the hypothesis.

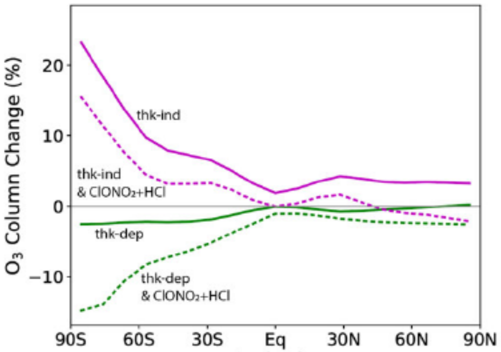

Figure 14: Shows the role of passivation and the heterogeneous $ClONO_2$+HCl reaction on ozone column change using the AER 2-D model taken from Dai et al. 2020. Inclusion of this reaction with the same rate as measured for Al_2O_3 results in a substantial reduction in ozone for scenarios including, thk-ind, or excluding passivation, thk-dep.

4.3.4. Need for SCoPEx Calcium Carbonate Plume Studies

One of the challenges for alternate SAI aerosol is the lack of materials such as calcium carbonate in the stratosphere. The only way to then study these materials in the actual stratosphere is via deliberate stratospheric injection of a small amount of these materials. In environmental studies, including stratospheric studies, it is not possible to rely purely on laboratory studies. For example, flights on the NASA ER-2 into the polar vortex over Antarctica provided the ability to test whether laboratory-derived reaction mechanisms were able to capture real-world ozone destruction chemistry. Without these flights, the level of confidence in the model predictions would have been much lower, and for good reason. It is not clear that a given experimental setup in the laboratory can faithfully capture the entire complexity of the real stratosphere; only field observations are able to provide this. For a number of natural stratospheric processes, remote observations can provide important information in addition to in situ aircraft or balloon. However, these are only possible when large-scale phenomena are at work.

Since there are no natural calcium carbonate plumes in the stratosphere that would even allow for in situ observations, intentional injection is necessary to perform these studies. Calcium carbonate injections will allow SCoPEx to provide invaluable observations as it will quantitively test the mechanisms determined in the laboratory. As stated above, there is a need for more laboratory studies, however, there is good reason to proceed with the planning of SCoPEx calcium carbonate experiments. First, by the time of the first injection experiments, additional studies should have been conducted. In addition, N_2O_5 uptake coefficients used in the model are likely a very good estimation as similar values have been found for different solid materials, e.g., Al_2O_3 and SiO_2 (Molina et al., 1997). In addition, even with these additional lab determined mechanisms, the same type of experiments as proposed here will still have to be conducted, as we expect these reactions to not make a significant difference. In other words, they will not be a deciding factor about the viability of calcium carbonate as an alternate SAI material. Only field experiments will help shed insight into these questions. In summary, there is a critical need for evaluating not just the aerosol microphysics (goal 2) but also the stratospheric chemistry of calcium carbonate due to the promise it holds as a lower risk SAI material.

4.3.5. SCoPEx Experimental Design and Analysis of Chemical Calcium Carbonate Plume Evolution

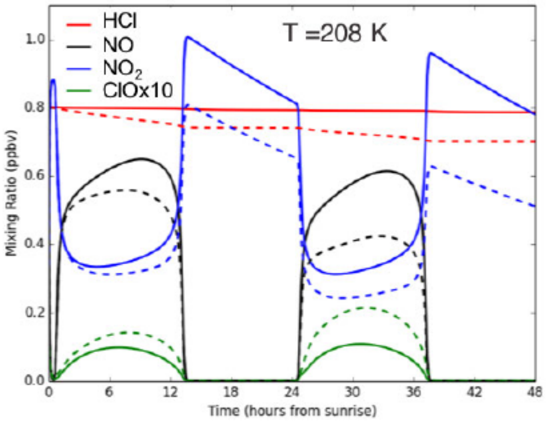

Figure 15: Solid lines: background $2\mu m^2\ cm^{-3}$ sulfate $5ppm_v$ H_2O. Dashed lines: plume $15\mu m^2\ cm^{-3}$ sulfate 10 ppm_v H_2O.

The experiments will again follow the standard concept of operations as under goal 2. In order to determine optimal injection rates, we will include chemical reactions in the plume model, updated with the newest mechanisms available at that time. Figure 15 shows the evolution of an air mass perturbed by a sulfate aerosol injection over multiple days, i.e., significantly longer than the initial SCoPEx experiments. Significant changes in HCl and NOx can be observed already over short time periods and these are easily detectable with existing instrumentation. For this science goal, it is desirable to measure aerosol composition and size distribution as well as key gas-phase chemical species, especially HCl, NOx and water. Therefore, this science goal requires a much larger set of instruments. In addition, the equivalent model to Figure 15 for calcium carbonate is informed by the results of science goal 2. The work of Dai et al. provides kinetic parameters needed for this model, and reactions for which there are no laboratory data to date are parameterized using close analogues and conditions, e.g., $ClONO_2$ + HCl are parameterized using the results for alumina (and silica) from Molina et al. (1997). One key question is whether the changes in HCl and NOx will indeed be smaller for calcium carbonate than those for sulfate shown in the figure above, which would confirm the hypothesis for calcium carbonate as a potential alternate SAI material.

In summary, SCoPEx experiments using calcium carbonate injections will provide a unique evaluation as to whether calcium carbonate indeed is an alternate SAI material that could substantially reduce risk from SAI compared to sulfate. Follow-up studies will be needed. For example, improved chemical and aerosol microphysics models will provide improved models of the chemical and physical evolution of calcium carbonate, which likely will motivate specific laboratory investigations. These will provide information for SCoPEx studies using "stratospherically aged" calcium carbonate as precursor for injection that can then be used to compare whether the laboratory mechanisms of this aged calcium carbonate agree with that found in the real stratospheric environment.

5. Data Management Plan and Dissemination of Results

Products of the research. The data generated during this project consists of meteorological, navigational, telemetry, and a variety of instrumentation data, in particular aerosol size distributions as well as chemical composition data during later science flights. In addition, there will be model data on plume chemical evolution.

Access to data, data sharing practices, and policies and dissemination of results. Data relevant for scientific analysis will be made public within 60 days of the end of flight. This taw data will be made public with appropriate warnings that it has not undergone QA/QC. The email address of users will be recorded so that they can be automatically notified when revised versions become available. Based on previous experiences with stratospheric airborne campaigns, this is typically 6-15 months after the flight depending on the type of data, e.g., the amount of calibration and data workup required. We have chosen to make raw data available rapidly—going far beyond what is typical for stratospheric science missions—because of the public scrutiny of SCoPEx and because of the broad commitment to Open Access data principles articulated by Harvard’s Solar Geoengineering Research Program which is funding SCoPEx.

Principal Investigators (PI) and their groups have an excellent track record with presenting their work at major national and international conferences and workshops. All data that go into key analyses and figures in the group’s publications will be made publicly available via the PI’s group website. All publications resulting from this project will be posted on the PI’s webpage (https://projects.iq.harvard.edu/keutschgroup/publications). Preprints of manuscripts submitted for publication as well as the underlying data will also be posted on Harvard’s Dash manuscript repository. Publications will be made in open access formats.

Archiving of data. All data acquisition/storage computers in the PI’s group are automatically backed up daily, both wirelessly to a server elsewhere on campus, and/or to a cloud server. Both of these processes ensure that data will not be lost and enable rapid access to the data. The file naming system used for all software (which includes the date of the experiment) ensures straightforward retrieval and use of archived data. Group laptops are also backed up daily, ensuring that analyzed data are archived as well.

6. SCoPEx Research Team Biographies

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From: Keith, David (b) (6) [redacted]>
Subject: RE: Experimental research platform requirements
To: David Fahey - NOAA Federal
Cc: Smith, Wake; Keutsch, Frank N
Sent: February 3, 2021 9:59 AM (UTC-05:00)

Dave

Thanks. I think we see this about the same way.

From my perspective I came into this field working for Jim with all the excitement about Aurora's aircraft which ended up amounting to nothing. It took some years of my life. And yes, Global Hawk has been a big disappointment. So I definitely get the basis for skepticism.

On the other hand, there does seem to be a commercial-driven shakeup in the ability to develop low altitude aircraft. That's true from the new entrants into general aviation market through to the startups building off drone technology. So I'd like to understand whether this could apply to higher altitude light aircraft. I don't know, but if Wake spurs some interest I am open to find out more.

Have you had any conversations with these folks: Sceye | A new generation of HAPS | High Altitude Platform Stations? The head guy just reached out to me again and I will talk with.

David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Saturday, January 30, 2021 6:38 PM
To: Keith, David (b) (6) [redacted]>
Cc: Smith, Wake (b) (6) [redacted]>; Keutsch, Frank N (b) (6) [redacted]>
Subject: Re: Experimental research platform requirements

David,

Yes, I think if one has funding, then existing a/c become available. Certainly for the UT/LS, the WB-57s have been underutilized for years now and hence availability hasn't been an issue. Indeed a trip back to the boneyard was perhaps a growing threat.

I note that no one has ever built an aircraft for atmospheric chemistry, leaving the field to exploit as best they can existing a/c, which we have done very well. Thus, if there were runway a/c available that could do 30kg, 8hr, 79kft, the community would no doubt rush to use it. So the answer to your question is yes.

My problem with new-platforms-will-be-cheap is the issue of having truly operational a/c rather than experimental a/c. If one is trying to fly an experiment on an experimental a/c it reduces the probability of success by a large measure. Making an experimental a/c operational requires larger upfront and sustained investment by entities other than the science communities, creating the underwater part of the iceberg. This is why we don't have new operational a/c. And one can look to the Global Hawk and see that even starting at a high level (a mature platform) it failed to become operational because no one wants to pay the price, in this case neither NASA or NOAA. Now deeper pockets (DoD) have taken it over.

And to your final point about what payloads, yes, the new generation of lightweight instruments make 30kg interesting and valuable, and, yes, comprehensive chemistry payloads still want to be on heavy lift long-range a/c.

In reply to Wake’s question about perturbation/monitoring a/c, hmmm, it depends. In the early days, perhaps they could be the same. Eventually the perturbations sought would be as large as possible per flight and not every flight would need diagnostics, so I think eventually they are different a/c. And monitoring a/c could be below the perturbation a/c altitudes and diagnose with lidar.

Interest above 70kft: in general because we would be deeper into the ozone layer. And perhaps the injection altitude would be there once we understand things better.

Regards
Dave

On Jan 30, 2021, at 9:29 AM, Keith, David <(b) (6)> wrote:

Dave

Interesting back-and-forth.

I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.

I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30 kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.

I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.

I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.

Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.

Interesting conversation. No simple answers.

Cheers,
David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Thursday, January 28, 2021 11:49 AM
To: Smith, Wake (b) (6) >

Cc: Keith, David <(b) (6) [redacted]>; Keutsch, Frank N (b) (6) [redacted]
Subject: Re: Experimental research platform requirements

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi-flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" <(b) (6) [redacted]>
Cc: Frank Keutsch (b) (6) [redacted]

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can’t control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake <(b) (6) [redacted]> wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6) [redacted]

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Fwd: Update
To: Frank Keutsch
Cc: Keith, David; Ronda Knott - NOAA Federal
Sent: October 28, 2020 1:03 PM (UTC-04:00)
Attached: Untitled attachment

Great. Looking forward to it.

Begin forwarded message:

From: "Keutsch, Frank N" (b) (6) >
Subject: Re: Update
Date: October 28, 2020 at 10:51:34 AM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>

Dave,

Thanks for your email. I will see how it goes. I have a number of deadlines looming over me, but will try to attend the whole meeting.

I hope you are doing well. Germany is going into a moderate lockdown!

All the best,

Frank

> On Oct 28, 2020, at 3:25 AM, David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:
>
> Frank,
>
> I hope this finds you doing well with the family in Germany.
>
> DavidK and I invited you to a Friday v-meeting to catch up on CI matters. He will give me a brief download of his CDR ideas/perspective at the beginning at my request. So you could join late to miss that.
>
> Let us know.
> THanks
> Dave
>
> ---
>
> David W. Fahey, PhD
> Director of the Earth System Research Laboratories (ESRL)
> Director of the ESRL Chemical Sciences Laboratory
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Ronda Knott, Admin. Assistant
ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

Begin forwarded message:

From: Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
Subject: Re: Update
Date: October 26, 2020 at 7:51:29 PM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Cc: "Keith, David" <(b) (6) [redacted]>

Hi Dave and David,

The meeting has been set for this Friday, October 30th at 7am MT and included Frank Kuetsch.
The connection details are:

Meeting ID
meet.google.com/zgb-gfnu-gdr
Phone Numbers
(US) +1 561-408-9337
PIN: 857 507 300#

Thank you,
Ronda

Ronda Knott
Executive Administrative Assistant to

Dr. David W. Fahey, Director

NOAA Chemical Sciences Laboratory
325 Broadway, R/CSL

Boulder CO 80305

I am currently teleworking, please call my cell: (b) (6) [redacted]

303.497.4404 phone

303-497-5822 fax

ronda.knott@noaa.gov

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> > PS Canmore seems like a good faraway place to get fresh air devoid of C-19.

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It's beautiful and snowy up here in Canmore Alberta.

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From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Wednesday, October 21, 2020 1:23 PM
To: Keith, David (b) (6) [redacted] >
Subject: Update

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> David W. Fahey, PhD
> Director of the Earth System Research Laboratories (ESRL)
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> 325 Broadway R/CSD
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>
> Ronda Knott, Admin. Assistant
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> http://www.esrl.noaa.gov/csd/

Frank N. Keutsch
Stonington Professor of Engineering and Atmospheric Science

Harvard John A. Paulson School of Engineering and Applied Sciences
Department of Chemistry and Chemical Biology
Department of Earth and Planetary Sciences
Harvard University
12 Oxford Street
Cambridge, MA 02138
USA

E-mail:
(b) (6)

Tel:+(b) (6)

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Smith, Wake
Cc: Keith, David; Frank Keutsch
Sent: January 28, 2021 11:49 AM (UTC-05:00)
Attached: Untitled attachment

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi- flyers to carry small payloads to 70kft. So we are already there.

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Subject: Re: Small stratospheric aircraft
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Cc: Frank Keutsch <(b) (6) [redacted]

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In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6)

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Fwd: Update
To: Frank Keutsch
Cc: Keith, David; Ronda Knott - NOAA Federal
Sent: October 27, 2020 10:25 PM (UTC-04:00)
Attached: Untitled attachment

Frank,

I hope this finds you doing well with the family in Germany.

DavidK and I invited you to a Friday v-meeting to catch up on CI matters. He will give me a brief download of his CDR ideas/perspective at the beginning at my request. So you could join late to miss that.

Let us know.
THanks
Dave

David W. Fahey, PhD
Director of the Earth System Research Laboratories (ESRL)
Director of the ESRL Chemical Sciences Laboratory
NOAA Earth System Research Laboratories
325 Broadway R/CSD
Boulder, CO 80305 USA
303-497-5277 -5822 fax
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Ronda Knott, Admin. Assistant
ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

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From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Keith, David
Cc: Smith, Wake; Frank Keutsch
Sent: February 3, 2021 6:41 PM (UTC-05:00)
Attached: Untitled attachment

David,

Yes, the Perseus a/c was a big distraction that I was only on the edge of fortunately.

I will remain skeptical about the likelihood of new non-military a/c but want to be first in line to use them. We were first in line and funded to use the new Boeing/Aurora a/c, Odysseus, when the plug was pulled.

Yes we have had conversations with the Sceye folks and would like to have a chance to use when the day comes.

BTW, the CU group here apparently demonstrated a 1.5km reel down from a balloon quite recently. No other details.

Regards
Dave

On Feb 3, 2021, at 7:59 AM, Keith, David (b) (6) [redacted]> wrote:

Dave

Thanks. I think we see this about the same way.

From my perspective I came into this field working for Jim with all the excitement about Aurora's aircraft which ended up amounting to nothing. It took some years of my life. And yes, Global Hawk has been a big disappointment. So I definitely get the basis for skepticism.

On the other hand, there does seem to be a commercial-driven shakeup in the ability to develop low altitude aircraft. That's true from the new entrants into general aviation market through to the startups building off drone technology. So I'd like to understand whether this could apply to higher altitude light aircraft. I don't know, but if Wake spurs some interest I am open to find out more.

Have you had any conversations with these folks: Sceye | A new generation of HAPS | High Altitude Platform Stations? The head guy just reached out to me again and I will talk with.

David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Saturday, January 30, 2021 6:38 PM
To: Keith, David (b) (6) [redacted]>
Cc: Smith, Wake (b) (6) [redacted]; Keutsch, Frank N (b) (6) [redacted]

Subject: Re: Experimental research platform requirements

David,

Yes, I think if one has funding, then existing a/c become available. Certainly for the UT/LS, the WB-57s have been underutilized for years now and hence availability hasn't been an issue. Indeed a trip back to the boneyard was perhaps a growing threat.

I note that no one has ever built an aircraft for atmospheric chemistry, leaving the field to exploit as best they can existing a/c, which we have done very well. Thus, if there were runway a/c available that could do 30kg, 8hr, 79kft, the community would no doubt rush to use it. So the answer to your question is yes.

My problem with new-platforms-will-be-cheap is the issue of having truly operational a/c rather than experimental a/c. If one is trying to fly an experiment on an experimental a/c it reduces the probability of success by a large measure. Making an experimental a/c operational requires larger upfront and sustained investment by entities other than the science communities, creating the underwater part of the iceberg. This is why we don't have new operational a/c. And one can look to the Global Hawk and see that even starting at a high level (a mature platform) it failed to become operational because no one wants to pay the price, in this case neither NASA or NOAA. Now deeper pockets (DoD) have taken it over.

And to your final point about what payloads, yes, the new generation of lightweight instruments make 30kg interesting and valuable, and, yes, comprehensive chemistry payloads still want to be on heavy lift long-range a/c.

In reply to Wake's question about perturbation/monitoring a/c, hmmm, it depends. In the early days, perhaps they could be the same. Eventually the perturbations sought would be as large as possible per flight and not every flight would need diagnostics, so I think eventually they are different a/c. And monitoring a/c could be below the perturbation a/c altitudes and diagnose with lidar.

Interest above 70kft: in general because we would be deeper into the ozone layer. And perhaps the injection altitude would be there once we understand things better.

Regards
Dave

> On Jan 30, 2021, at 9:29 AM, Keith, David (b) (6) [redacted] > wrote:
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> Interesting back-and-forth.
>
> I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.
>
> I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30 kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.

I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.

I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.

Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.

Interesting conversation. No simple answers.

Cheers,
David

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Sent: Thursday, January 28, 2021 11:49 AM
To: Smith, Wake <(b) (6)
Cc: Keith, David (b) (6) Keutsch, Frank N
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Subject: Re: Experimental research platform requirements

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Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School & Lecturer in Yale College
(b) (6)

From: Kelly Wanser (b) (6) >
Subject: Nice job on the NOVA episode!
To: David Fahey - NOAA Federal; Frank Keutsch
Cc: John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:13 PM (UTC-04:00)

You were excellent and the piece came out great.
We'll promote it as we are able.

Best,
k.

--
Kelly Wanser
Executive Director, SilverLining | http://www.silverlining.ngo
Board Director, Dendra Systems | http://www.dendra.io
Advisor, University of Washington Marine Cloud Brightening Project | http://www.mcbproject.org
President's Circle, National Academy of Sciences | http://nas-sites.org/PC/
Phone: (b) (6)

TEDTalk: *Emergency Medicine for Our Climate Fever*
Report: *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Newsletter from Harvard's Solar Geoengineering Research Program
To: Keith, David
Cc: Frank Keutsch; Ronda Knott - NOAA Federal
Sent: December 28, 2020 11:44 AM (UTC-05:00)
Attached: Untitled attachment

David,
Good, yes let's talk on the 6th.
Ronda can arrange a time and link.
Happy New Year.
Dave

> On Dec 28, 2020, at 9:30 AM, Keith, David <(b) (6)> wrote:
>
> Dave
>
> Yes, we expect to fly POPS.
>
> Also, interesting developments on turbulence.
>
> Now that this mission seems to be (finally) coming together it would be good how about the three of us to touch base again about this and about the meeting to discuss future flight missions?
>
> How about Wednesday the 6th?
>
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, December 26, 2020 5:51 PM
> **To:** Keith, David (b) (6)
> **Subject:** Re: Newsletter from Harvard's Solar Geoengineering Research Program
>
> David,
>
> Thanks for the newsletter. I am impressed with your productivity.
>
> Good progress with Esrange launch plans and committee approval. Do you plan to fly POPS? It would be of value to get a high lat profile and adds to your flight data return. No communication with the device is needed since it records onboard. Let us know if you want assistance.
>
> We have prepared a POPS unit and backup to fly on the World View Stratollite in 2021 when they are able to resume launches.
>
> I hope you and yours are doing well enough this Holiday Season. We are OK.
> Regards
> Dave

On Dec 16, 2020, at 9:18 AM, David Keith (b) (6) wrote:

Dear Readers,

As this strange year comes to a close, we wanted to share updates from Harvard's Solar Geoengineering Research Program (SGRP), which supports research at Harvard on the science, technology, and governance of solar geoengineering.

We hope everyone and their families are safe and well. We wish you a healthy new year.

Yours,
David Keith and Lizzie Burns
Faculty Director and Managing Director
Harvard's Solar Geoengineering Research Program

SCoPEx

SCoPEx Update

Led by Frank Keutsch, the Stratospheric Controlled Perturbation Experiment (SCoPEx) is a scientific experiment to advance understanding of stratospheric aerosols that could be relevant to solar geoengineering. It aims to reduce the uncertainty around specific science questions by making quantitative measurements of some of the aerosol microphysics and atmospheric chemistry required for estimating the risks and benefits of solar geoengineering in large atmospheric models.

The SCoPEx research team has asked the independent SCoPEx Advisory Committee to review our plans for a proposed platform test in Sweden in June 2021. This test would notbe the experiment itself, but rather a test of the SCoPEx platform without the release of any particles. Specifically, we would like to test the gondola's horizontal and vertical control using the winch system and propellers as well as the power, data, navigation, and communication systems. We would not release any aerosols, nor fly an aerosol injection/release system. Still, we will not proceed with this flight without a formal recommendation authorizing the flight from the Advisory Committee to Harvard management. We have asked the Advisory Committee if they can complete their review and reach a decision—be it positive or negative—about this platform test by February 15, 2021. You can learn more about this platform test here.

SCoPEx Advisory Committee

Recognizing the complex societal and governance issues surrounding solar geoengineering, Harvard has ensured the SCoPEx project has the guidance of an independent Advisory Committee, as noted above. The Advisory Committee has already begun to carry out a significant amount of work, including a financial review, legal review, and scientific and technical review, and they have proposed a draft process for a societal engagement review. You can learn more by visiting their website. We are grateful for the time the Committee members are volunteering and look forward to the work ahead.

Opportunities

SGRP Fellowship

SGRP is now accepting applications to its 2021 Fellowship Program, which offers short-term and long-term opportunities. Applications are due January 29, 2021. We are seeking applications from scholars in a range of disciplines, including the natural sciences, economics, law, government, public policy, public health, medicine, design, and the humanities. We also are looking for applicants who are new to the field of solar geoengineering and/or have critical views, and we strongly encourage applications from

women and minority candidates. More information can be found here.

We would also like to congratulate our current and future fellows who were accepted during our previous fellowship application process.

- Cody Floerchinger, (August 2019-July 2021) advised by Frank Keutsch, is using datasets from upcoming measurements campaigns to provide a comprehensive analysis of the state of our ability to model stratospheric plume dynamics and highlight areas where the community should focus its efforts when attempting to improve these model products (science).
- Yuanchao Fan, (October 2019-October 2021) advised by Kaighin McColl, is quantifying the impact of solar geoengineering on terrestrial ecosystems, including forests and agriculture, and their biophysical and biogeochemical feedbacks to climate. He is also collaborating with David Keith on a paper about geoengineering and food supply (science).
- Irina Bakalova (February 2021-April 2021) will be advised by Professor Rob Stavins, working closely to study the effectiveness and stability of potential international agreements on solar geoengineering (economics).
- Britta Clark (February 2021-June 2021) will be advised by Lucas Stanczyk and will analyze the intergenerational justice impacts of solar geoengineering as a mitigative strategy to address climate change (philosophy).
- Ermanno Napolitano (August 2021-July 2022) will be advised by Lucas Stanczyk and will catalogue and explore all of the existing international legal principles that are likely to have some bearing on the deployment of solar geoengineering (law).

Online Community for Junior Researchers

A group of junior scientists are organizing a diverse online community of young researchers new to the solar geoengineering field, designed to engage researchers with new perspectives. This group will provide young researchers the chance to informally present on their research, share ideas, receive feedback, and create a space for open and non-judgmental discussion on the topic. The first few sessions took place in November and December and were held live on Zoom. Graduate students and recent postdocs from across the globe, including from developing countries, discussed various publications containing alternate viewpoints on solar geoengineering. Future sessions scheduled include presentations by a former SGRP DECIMALS resident and other participants as well as discussion forums and networking opportunities on Slack. Undergraduate students, graduate students, and postdoctoral fellows within five years of completing their degree are welcome to join the group. If you are interested in participating, please email Selena Wallace: swallace@seas.harvard.edu.

Events

Due to COVID-19, we had to cancel in-person events beginning in March. Since that time, we have held countless Zoom conversations (like so many others). For example, in November we hosted a public health workshop at Harvard to try to broaden the diversity of researchers studying solar geoengineering on campus. We are also now in the process of building an exciting opportunity that will allow us to reach a broader audience outside of Harvard that will include experts, practitioners new to solar geoengineering, and the general public. We invite you to join us.

Public Health Roundtable

In November 2020, we held a virtual event with the Harvard Chan School of Public Health Center for Climate, Health, and the Global Environment where experts from both the geoengineering and the public health communities had the opportunity to discuss the potential public health challenges posed by solar geoengineering. Few studies to date have considered the public health implications of geoengineering, and those that have have been limited to mortality due to ambient air pollution and UV-induced malignant melanoma. This event discussion addressed questions of the risk factors that these studies might be omitting, the vast array of other public health issues that may arise, as well as the environmental justice implications of human interventions to the climate system such as geoengineering. The organizers of the event may publish a paper that summarizes the key points and questions to hopefully inspire other experts in the public health field to begin research on solar geoengineering. Overall, this event was significant because it not only signaled new interest from various public health experts who, years prior, had not yet engaged, but also because it will hopefully unlock even more new interest from a critical community that has yet to fully participate in solar geoengineering research.

Public Seminar Series

In the spring of 2020, we will launch a virtual seminars series to promote understanding and discussion of solar geoengineering and to enable audiences to learn from a broader set of perspectives in the area of solar geoengineering research and public policy. These seminars will contain a combination of practitioners and experts from around the world and will have a variety of formats including single speakers, moderated debate, and moderated panels. Previously, SGRP seminar attendance was limited to the Harvard community, but we are now able to extend the reach of this series to a global, public audience. We invite you to participate in these seminars. We will email this listserv when seminars are scheduled.

Publications, Video, and Audio Clips

The following written publications were funded all or in part by SGRP.

Recent Peer Reviewed Publications

Zhen Dai, Debra K. Weisenstein, Frank N. Keutsch, and David W. Keith. (2020). "Experimental reaction rates constrain estimates of ozone response to calcium carbonate geoengineering." Communications Earth and Environment 1, 63.

Jacob T. Seeley, Nicholas J. Lutsko, and David W. Keith. "Designing a radiative antidote to CO2." Geophysical Research Letters (Submitted).

Joshua B. Horton and Barbara Koromenos. (2020). "Steering and Influence in Transnational Climate Governance: Nonstate Engagement in Solar Geoengineering Research." Global Environmental Politics 20, 3: 93-111.

Nicholas J. Lutsko, Jacob T. Seeley, and David W. Keith. (2020). "Estimating Impacts and Trade-offs in Solar Geoengineering Scenarios With a Moist Energy Balance Model." Geophysical Research Letters 47, 9.

Joshua B. Horton, Penehuro Lefale, David Keith. (2020). "Parametric Insurance for Solar Geoengineering: Insights from the Pacific Catastrophe Risk Assessment and Financing Initiative." Global Policy, Special Issue.

David Keith and Peter Irvine. (2020). "Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards." Environmental Research Letters 15, 4.

Jesse Reynolds and Joshua Horton. (2020) "An earth system governance perspective on solar geoengineering." Earth System Governance, 3.

Other Publications

David W. Keith and John Deutch (2020) "Climate Policy Enters Four Dimensions." In *Securing our Economic Future,* edited by Amy Ganz and Melissa Kearney, Aspen Institute Press.

Cody Floerchinger, John Dykema, David Keith, and Frank Keutsch (2020) "A Need for In Situ Observations to Inform Nearfield Plume Transport and Aerosol Dynamics as well as Chemistry of Alternate Geoengineering Materials in the Stratosphere." Letter to the National Academy for Science.

David Keith, Frank Keutsch, and Cody Floerchinger (February 15, 2020) "Empirical methods to reduce uncertainty about solar geoengineering," public input to the National Academy Committee on *Climate Intervention Strategies that Reflect Sunlight to Cool Earth*.

Recent Video and Audio Recordings

AGU TV (December 2, 2020). “SCoPEx, Harvard University – New Frontiers in Climate Change Research.” WebsEdge Science.

Anthony Padilla (October 23, 2020) “I spent a day with climate change scientists” *Youtube*.

PBS Nova (October 16, 2020). "Can We Cool the Planet?" *WGBH*.

Harvard Magazine (October 16, 2020). “Daniel Schrag and David Keith: Can Solar Geoengineering Help Fight Climate Change?”

All Things Considered (July 22, 2020) “Harvard Scientists Plan First-Ever Field Experiment Related To Solar Geoengineering.” *WBUR*. (This aired again on Here & Now on December 4, 2020 as “Experiment To Help Researchers Understand Risk, Efficacy of Solar Geoengineering.”)

Harvard Museum of Natural History (December 12, 2019) “The Peril and Promise of Solar Geoengineering” *Youtube*.

From: Graham Feingold - NOAA Federal <graham.feingold@noaa.gov>
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Andrea Smith; Simone Tilmes; Keutsch, Frank N; Smith, Wake; Karen Rosenlof - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:47 AM (UTC-04:00)

zoom link not working for me. is there something else i need to do?

On 9/17/21 11:06 AM, Andrea Smith wrote:

> Hello Frank, Wake and Graham,
>
> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>
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> Meeting ID: 816 4261 9898
> Passcode: 148321
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> Please join 10 mins early to test tech and troubleshoot if needed.
>
> 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) [redacted] (preferably by Tuesday night):
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> Let me know if you have questions on any of the above.
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> Thanks again, and see you next Wednesday.
>
> Andrea
>
> On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) [redacted]> wrote:
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> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
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> Cheers, Simone
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> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6) [redacted]

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) [redacted] (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

--
Graham Feingold
NOAA Earth System Research Laboratories
Chemical Sciences Laboratory (R/CSL9)
325 Broadway
Boulder, Colorado 80305, USA
Tel: (303) 497-3098
Fax: (303) 497-5318

From: Kelly Wanser (b) (6) [redacted] >
Subject: Re: Nice job on the NOVA episode!
To: David Fahey - NOAA Federal; David Keith
Cc: Frank Keutsch; John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:22 PM (UTC-04:00)

Ha, thanks, Dave. Adding David here.
Terrific piece, David!

Sent from my iPhone

> On Oct 29, 2020, at 1:19 PM, David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:
>
> Kelly,
> I think you want to praise David K instead of me. I too thought they all did a great job.
> Dave
>
>> On Oct 29, 2020, at 1:12 PM, Kelly Wanser <(b) (6) [redacted] > wrote:
>>
>> You were excellent and the piece came out great.
>> We'll promote it as we are able.
>>
>> Best,
>> k.
>>
>> --
>> Kelly Wanser
>> Executive Director, SilverLining | http://www.silverlining.ngo
>> Board Director, Dendra Systems | http://www.dendra.io
>> Advisor, University of Washington Marine Cloud Brightening Project | http://www.mcbproject.org
>> President's Circle, National Academy of Sciences | http://nas-sites.org/PC/
>> Phone: (b) (6) [redacted]
>>
>> **TEDTalk:** *Emergency Medicine for Our Climate Fever*
>> **Report:** *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: Andrea Smith (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Karen Rosenlof - NOAA Federal
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Graham Feingold - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:36 AM (UTC-04:00)

Good morning everyone,

If you haven't already done so, please reply here with slide decks or drop them in (b) (6) if large file size.

See you in 10-15 mins!

Cheers,

Andrea

On Fri, Sep 17, 2021 at 2:43 PM Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov> wrote:

> And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
> So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.
>
> Thanks!
>
> Karen
>
> --
> Karen Rosenlof
> NOAA Chemical Sciences Laboratory
> Mail Stop R/CSL8
> 325 Broadway
> Boulder, CO 80305
> office: 3A-121, DSRC
> e-mail: Karen.H.Rosenlof@noaa.gov
> phone: 303 497-7761
> fax: 303 497-5373
> --
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After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.

Let me know if you have questions on any of the above.

Thanks again, and see you next Wednesday.

Andrea

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> <CCISspeaker_consent_form.pdf>

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From: Douglas MacMartin (b) (6) [redacted] >
Subject: RE: 2022 GRC program
To: Karen Rosenlof - NOAA Federal; Trude Storelvmo
Sent: July 19, 2021 10:15 AM (UTC-04:00)

Excellent! We should have a great conference ☺. (More later… probably not for a while.)

doug

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Sent: Thursday, July 15, 2021 5:04 PM
To: Douglas MacMartin (b) (6) [redacted] Trude Storelvmo (b) (6) [redacted]
Subject: Re: 2022 GRC program

Doug and Trude,
I should be available during that time frame, and would like to attend the test GRC. I'd be happy to adjust topics as you feel is needed.

Take care,

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
Boulder, CO 80305
office: 3A-121, DSRC
e-mail: Karen.H.Rosenlof@noaa.gov
phone: 303 497-7761
fax: 303 497-5373
----
while safer at home remains in effect, email is the most reliable contact

> On Jul 15, 2021, at 9:06 AM, Douglas MacMartin (b) (6) [redacted] > wrote:
>
> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
>
> As a start to our planning, could you let us know whether you would be interested in talking at the 2022 meeting? We would of course still love to hear from you, but schedules may not permit and research interests change (and, indeed, for some or many of you that may mean that the topic we were originally thinking you would talk about would no longer be what you are currently most excited by – the GRC is supposed to be cutting-edge current research, of course – so if you let us know we can start revising sessions and think about what gaps we'd like to fill). There are also some new people who are doing some great research too that we would like to hear from, so it's conceivable that – given the now 5 year gap since the last GRC – we might choose to slightly increase the number of talks and reduce the time available per talk.

Thanks,
Doug & Trude

From: Douglas MacMartin
Sent: Wednesday, February 19, 2020 10:27 AM
To: (b) (6) ; (b) (6) ; Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke (b) (6) >; (b) (6) ; Robert Wood <(b) (6) ; (b) (6) (b) (6) <(b) (6) ; Daniele Visioni <(b) (6) >; (b) (6) ; Peter Irvine <(b) (6) >; Jonathan Proctor (b) (6) ; (b) (6) ; Keith, David (b) (6) >; Kravitz, Ben (b) (6) >; Wake Smith <(b) (6) >; Izidine Pinto (b) (6) ; Gabriel Chiodo (b) (6) >; Keutsch, Frank N <(b) (6) >
Cc: Lawrence, Mark <(b) (6) >; valentina Aquila (b) (6) ; Ulrike Niemeier (b) (6) >; Leisner, Thomas (IMK) (b) (6) >; Olivier Boucher <(b) (6) >; Schrag, Daniel P. <(b) (6) >; TAYLOR,Michael <(b) (6) >; (b) (6) Trude Storelvmo <(b) (6) >; 'Simone Tilmes' (b) (6) >; (b) (6) Jim Hurrell (b) (6)
Subject: RE: 2020 GRC program

Hi all,

Just a reminder that if you haven't sent me a title yet, to do so (otherwise I'll have to make something up; GRC needs us to upload our "final" program by the end of this month) I have titles for about half of you (though some of those are draft titles you sent quite some time ago, e.g. for Pete, Isla, Danny).

And, if you haven't responded yet regarding need for travel support, let me know (about half of you have). For those of you who haven't been to a GRC before, there's a bus from Boston airport, and from Portland Maine airport.

If you've already both sent me a title and responded regarding travel, then you can ignore this email.

Also, regarding format, this year we're explicitly including 10-15 minutes for the discussion leader to make some remarks to help frame each session (taking 5 minutes from each speaker's time), and rather than having a lengthy discussion after each talk, we'll have a shorter 10-minute discussion after each talk and a 20-minute general session discussion at the end (that's as long as GRC will allow) with everyone from a given session.

Thanks, and see you in June!
doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) ; (b) (6) 'Jadwiga (Yaga) Richter' (b) (6) >; Alan Robock (b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >; (b) (6) ; Robert Wood (b) (6) >; (b) (6) ; (b) (6) <(b) (6) >; Daniele Visioni <(b) (6) >; (b) (6) Peter Irvine <(b) (6) >; Jonathan

Proctor <(b) (6) >; Govindasamy Bala <(b) (6) >;(b) (6)
Keith, David (b) (6) >; Kravitz, Ben <bkravitz@iu.edu>; Wake Smith
<(b) (6) ; Chris Field (b) (6)
Cc: Lawrence, Mark (b) (6) >; valentina Aquila <(b) (6) Ulrike
Niemeier <(b) (6) >; Leisner, Thomas (IMK) <(b) (6) Olivier
Boucher (b) (6) >; Schrag, Daniel P. (b) (6) ; TAYLOR,Michael
(b) (6) ;(b) (6) ; Lynn Russell (b) (6) Trude Storelvmo
<(b) (6) 'Simone Tilmes' (b) (6) >;(b) (6)
Subject: 2020 GRC program

Hi all,

Happy New Year!

The full program for GRC is due on February 28; if you haven't sent us a title for your talk (or if you did and want to revise it), please do so before the end of February so I have time to enter everything into the conference management system online.

The cc-line has discussion leaders for each session.

Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin
Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and
Faculty Fellow, Atkinson Center for a Sustainable Future
Cornell University
(b) (6)
https://climate-engineering.mae.cornell.edu/

From: Smith, Wake (b) (6)
Subject: RE: CCIS webinar Wednesday Sept 22nd
To: Karen Rosenlof - NOAA Federal
Sent: September 18, 2021 7:59 AM (UTC-04:00)

Will do.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6)

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Sent: Friday, September 17, 2021 4:44 PM
To: Andrea Smith (b) (6)
Cc: Simone Tilmes (b) (6); Keutsch, Frank N (b) (6)>; Smith, Wake <(b) (6); Graham Feingold - NOAA Federal <Graham.Feingold@noaa.gov>; Brian Medeiros (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd

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So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.

Thanks!

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
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> (b) (6)

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Andrea Smith
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<CCISspeaker_consent_form.pdf>

From: Peter Irvine (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin
Cc: Piers Forster; (b) (6) Alan Robock; Karen Rosenlof - NOAA Federal; Katharine Ricke; Seneviratne Sonia Isabelle; Robert Wood; Helene Muri; (b) (6) Daniele Visioni; Isla Simpson; Jonathan Proctor; Ines Camilloni; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N; Trude Storelvmo; Simone Tilmes; Lohmann Ulrike
Sent: July 18, 2021 4:53 PM (UTC-04:00)

Hi Doug, Trude,

It's be happy to present in 2022, with the same title for now.

Cheers,

Pete

On Thu, Jul 15, 2021, 16:06 Douglas MacMartin (b) (6) > wrote:

> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
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>
> Thanks,
>
> Doug & Trude
>
> ---
>
> **From:** Douglas MacMartin
> **Sent:** Wednesday, February 19, 2020 10:27 AM
> **To:** (b) (6) (b) (6) ; Alan Robock (b) (6) >;
> Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke (b) (6) ;
> (b) (6) ; Robert Wood (b) (6) >; (b) (6) ;
> (b) (6) (b) (6) >; Daniele Visioni (b) (6) >;
> (b) (6) Peter Irvine (b) (6) >; Jonathan Proctor (b) (6) >;

(b) (6) Keith, David <(b) (6) >; Kravitz, Ben (b) (6) >; Wake Smith (b) (6) >; Izidine Pinto <(b) (6) >; Gabriel Chiodo <(b) (6) >; Keutsch, Frank N (b) (6)
Cc: Lawrence, Mark <(b) (6) >; valentina Aquila <(b) (6) ; Ulrike Niemeier <(b) (6) >; Leisner, Thomas (IMK) <(b) (6) >; Olivier Boucher <(b) (6) >; Schrag, Daniel P. <(b) (6) >; TAYLOR,Michael <(b) (6) >;(b) (6) Trude Storelvmo (b) (6) >; 'Simone Tilmes' <(b) (6) >;(b) (6) ; Jim Hurrell (b) (6) >
Subject: RE: 2020 GRC program

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Also, regarding format, this year we're explicitly including 10-15 minutes for the discussion leader to make some remarks to help frame each session (taking 5 minutes from each speaker's time), and rather than having a lengthy discussion after each talk, we'll have a shorter 10-minute discussion after each talk and a 20-minute general session discussion at the end (that's as long as GRC will allow) with everyone from a given session.

Thanks, and see you in June!

doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) ;(b) (6) ; 'Jadwiga (Yaga) Richter' <(b) (6) >; Alan Robock (b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >;(b) (6) ; Robert Wood <(b) (6) >; (b) (6) ;(b) (6) (b) (6) >; Daniele Visioni <(b) (6) >;(b) (6) ; Peter Irvine (b) (6) >; Jonathan Proctor (b) (6) >; Govindasamy Bala (b) (6) ;(b) (6) ; Keith, David <(b) (6) >; Kravitz, Ben (b) (6) >; Wake Smith (b) (6) >; Chris Field <(b) (6) >

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Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin

Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and

Faculty Fellow, Atkinson Center for a Sustainable Future

Cornell University

(b) (6)

[redacted]

https://climate-engineering.mae.cornell.edu/

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Nice job on the NOVA episode!
To: Kelly Wanser
Cc: Frank Keutsch; John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:19 PM (UTC-04:00)
Attached: Untitled attachment

Kelly,
I think you want to praise David K instead of me. I too thought they all did a great job.
Dave

On Oct 29, 2020, at 1:12 PM, Kelly Wanser (b) (6) wrote:

You were excellent and the piece came out great.
We'll promote it as we are able.

Best,
k.

--
Kelly Wanser
Executive Director, SilverLining | http://www.silverlining.ngo
Board Director, Dendra Systems | http://www.dendra.io
Advisor, University of Washington Marine Cloud Brightening Project | http://www.mcbproject.org
President's Circle, National Academy of Sciences | http://nas-sites.org/PC/
Phone: (b) (6)

TEDTalk: *Emergency Medicine for Our Climate Fever*
Report: *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: Alan Robock ☮ (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin; (b) (6); (b) (6); Karen Rosenlof - NOAA Federal; Katharine Ricke; (b) (6) Robert Wood; (b) (6); (b) (6) Daniele Visioni; Isla Simpson; Peter Irvine; Jonathan Proctor; (b) (6); Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N
Cc: Trude Storelvmo; 'Simone Tilmes'; (b) (6)
Sent: July 15, 2021 5:37 PM (UTC-04:00)

Dear Doug and Trude,

I would like to give a talk. Thanks.

Alan

On 7/15/2021 11:06 AM, Douglas MacMartin wrote:

> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
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Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and
Faculty Fellow, Atkinson Center for a Sustainable Future
Cornell University
(b) (6)
https://climate-engineering.mae.cornell.edu/

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Keith, David
Cc: Smith, Wake; Frank Keutsch
Sent: January 30, 2021 6:38 PM (UTC-05:00)
Attached: Untitled attachment

David,

Yes, I think if one has funding, then existing a/c become available. Certainly for the UT/LS, the WB-57s have been underutilized for years now and hence availability hasn't been an issue. Indeed a trip back to the boneyard was perhaps a growing threat.

I note that no one has ever built an aircraft for atmospheric chemistry, leaving the field to exploit as best they can existing a/c, which we have done very well. Thus, if there were runway a/c available that could do 30kg, 8hr, 79kft, the community would no doubt rush to use it. So the answer to your question is yes.

My problem with new-platforms-will-be-cheap is the issue of having truly operational a/c rather than experimental a/c. If one is trying to fly an experiment on an experimental a/c it reduces the probability of success by a large measure. Making an experimental a/c operational requires larger upfront and sustained investment by entities other than the science communities, creating the underwater part of the iceberg. This is why we don't have new operational a/c. And one can look to the Global Hawk and see that even starting at a high level (a mature platform) it failed to become operational because no one wants to pay the price, in this case neither NASA or NOAA. Now deeper pockets (DoD) have taken it over.

And to your final point about what payloads, yes, the new generation of lightweight instruments make 30kg interesting and valuable, and, yes, comprehensive chemistry payloads still want to be on heavy lift long-range a/c.

In reply to Wake's question about perturbation/monitoring a/c, hmmm, it depends. In the early days, perhaps they could be the same. Eventually the perturbations sought would be as large as possible per flight and not every flight would need diagnostics, so I think eventually they are different a/c. And monitoring a/c could be below the perturbation a/c altitudes and diagnose with lidar.

Interest above 70kft: in general because we would be deeper into the ozone layer. And perhaps the injection altitude would be there once we understand things better.

Regards
Dave

> On Jan 30, 2021, at 9:29 AM, Keith, David (b) (6) [redacted]> wrote:
>
> Dave
>
> Interesting back-and-forth.
>
> I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.
>
> I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30

kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.

I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.

I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.

Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.

Interesting conversation. No simple answers.

Cheers,
David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Thursday, January 28, 2021 11:49 AM
To: Smith, Wake (b) (6) >
Cc: Keith, David <(b) (6) >; Keutsch, Frank N (b) (6)
Subject: Re: Experimental research platform requirements

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi-flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" (b) (6) >
Cc: Frank Keutsch <(b) (6)

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can't control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake (b) (6) > wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to

understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6)

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Andrea Smith
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Graham Feingold - NOAA Federal; Brian Medeiros
Sent: September 17, 2021 4:44 PM (UTC-04:00)
Attached: Untitled attachment

And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.

Thanks!

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
Boulder, CO 80305
office: 3A-121, DSRC
e-mail: Karen.H.Rosenlof@noaa.gov
phone: 303 497-7761
fax: 303 497-5373
----
while safer at home remains in effect, email is the most reliable contact

> On Sep 17, 2021, at 11:06 AM, Andrea Smith (b) (6) > wrote:
>
> Hello Frank, Wake and Graham,
>
> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>
> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
> Meeting ID: 816 4261 9898
> Passcode: 148321
>
> Please join 10 mins early to test tech and troubleshoot if needed.
>
> 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) (preferably by Tuesday night):
>
> 3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.

After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.

Let me know if you have questions on any of the above.

Thanks again, and see you next Wednesday.

Andrea

On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) [redacted] wrote:

> Hi Frank, Wake and Graham,
> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>
> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
>
> 1. Frank Keutsch: ...
> 2. Wake Smith:...
> 3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening
>
> Here is Andreas rundown for logistics:
>
> -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
> -send slide decks to Andrea by Tuesday (9/21) evening for backup purposes
> -arrive ~10 mins early so we can do quick test of screenshares
> -15 min talk length, w/ immediate clarifying question(s) and then ~30 mins broad discussion and questions at end
> -moderator will collect questions in chat window throughout and ask most pertinent ones for discussion
> -panelists and question askers encouraged to unmute & turn on camera
> -session will be recorded and posted later - we'll send a release form for them to complete
>
> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
>
> Cheers, Simone
>
> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6) [redacted]

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.

Boulder, CO 80301
303-497-8320 (office)
(b) (6)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.
<CCISspeaker_consent_form.pdf>

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Keith, David
Cc: Smith, Wake; Frank Keutsch
Sent: February 3, 2021 6:41 PM (UTC-05:00)
Attached: Untitled attachment

David,

Yes, the Perseus a/c was a big distraction that I was only on the edge of fortunately.

I will remain skeptical about the likelihood of new non-military a/c but want to be first in line to use them. We were first in line and funded to use the new Boeing/Aurora a/c, Odysseus, when the plug was pulled.

Yes we have had conversations with the Sceye folks and would like to have a chance to use when the day comes.

BTW, the CU group here apparently demonstrated a 1.5km reel down from a balloon quite recently. No other details.

Regards
Dave

> On Feb 3, 2021, at 7:59 AM, Keith, David (b) (6) [redacted] > wrote:
>
> Dave
>
> Thanks. I think we see this about the same way.
>
> From my perspective I came into this field working for Jim with all the excitement about Aurora's aircraft which ended up amounting to nothing. It took some years of my life. And yes, Global Hawk has been a big disappointment. So I definitely get the basis for skepticism.
>
> On the other hand, there does seem to be a commercial-driven shakeup in the ability to develop low altitude aircraft. That's true from the new entrants into general aviation market through to the startups building off drone technology. So I'd like to understand whether this could apply to higher altitude light aircraft. I don't know, but if Wake spurs some interest I am open to find out more.
>
> Have you had any conversations with these folks: Sceye | A new generation of HAPS | High Altitude Platform Stations? The head guy just reached out to me again and I will talk with.
>
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, January 30, 2021 6:38 PM
> **To:** Keith, David (b) (6) [redacted] >
> **Cc:** Smith, Wake (b) (6) [redacted]; Keutsch, Frank N (b) (6) [redacted]

Subject: Re: Experimental research platform requirements

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> Interesting back-and-forth.
>
> I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.
>
> I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30 kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.

I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.

I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.

Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.

Interesting conversation. No simple answers.

Cheers,
David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Thursday, January 28, 2021 11:49 AM
To: Smith, Wake <(b) (6)
Cc: Keith, David (b) (6) Keutsch, Frank N
(b) (6)
Subject: Re: Experimental research platform requirements

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi- flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" <(b) (6)>
Cc: Frank Keutsch <(b) (6)>

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can’t control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can’t have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today’s technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake <(b) (6)> wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I

understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School & Lecturer in Yale College
(b) (6) [redacted]

The Stratospheric Controlled Perturbation Experiment (SCoPEx)

Version 1.0

Executive Summary

Climate model studies of stratospheric solar radiation modification (SRM) depend, perhaps implicitly, on processes that take place in the near field of an injection plume. This is because materials delivered to the stratosphere by aircraft will form persistent, high aspect-ratio plumes with strong gradients before becoming well mixed, and processes within the plume will alter the large-scale, well-mixed aerosol and chemical properties that are simulated in global atmospheric models. All models ultimately depend on observations, yet we lack experimental data to assess some of the critical transport, microphysical, and chemical processes that directly control aerosol dynamics in the near-field that are important for understanding stratospheric SRM.

The scientific goal of the Stratospheric Controlled Perturbation Experiment (SCoPEx) is to improve process models that will, in turn, reduce uncertainties in global-scale models, thus reducing uncertainty in predictions of important SRM risks and benefits.

SCoPEx addresses questions in stratospheric aerosol injection (SAI) research that observations of existing analogues are incapable of addressing. For example, existing observational data do not include chemistry of alternate geoengineering materials specific to SAI, near-field particle microphysics of injection plumes, and relevant scales of atmospheric transport in the near-field. Yet these are needed to assess processes that control aerosol dynamics in the near field of an injection plume and that allow for the evaluation of alternate SAI materials, i.e., materials other than the naturally existing sulfate aerosol.

We first review why existing observations do not address the questions that SCoPEx will answer. We then give a description of the basic design of the platform and the concept of operations of SCoPEx. Finally, we describe the three specific science goals of SCoPEx, explain how they represent critical knowledge gaps in SAI research, and specify what measurements are needed to enable SCoPEx to provide quantitative answers to these questions. The three specific science goals are improving understanding of (i) turbulent mixing scales, (ii) aerosol microphysics with a focus on alternative SAI materials in the near-field of an injection, and (iii) process level chemical interactions of alternative SAI materials in the stratosphere.

We do not provide a detailed engineering document of the SCoPEx platform or its scientific instrumentation, nor do we provide a justification for the need for research on SRM via SAI in general. Rather, we focus specifically on the merits of SCoPEx itself.

1. Introduction

In this document we focus on the motivation and scientific merit of SCoPEx. We do not provide detailed engineering documentation of the SCoPEx platform or its scientific instrumentation. We also do not provide general justification for the need for research on solar radiation modification (SRM) via stratospheric aerosol injection (SAI), which can be found in many prior documents such as the 1992 NAS report that recommended the US government "Undertake research and development projects to improve our understanding of both the potential of geoengineering options to offset global warming and their possible side effects. This is not a recommendation that geoengineering options be undertaken at this time, but rather that we learn more about their likely advantages and disadvantages" (National Academy of Sciences et al., 1992) or the recent 2015 NAS report (National Research Council, 2015). Rather, we focus specifically on the need for small-scale field experiments such as SCoPEx, and the specific, critical SAI research needs that will be addressed by SCoPEx.

1.1. Role of and Need for Small-Scale Field Experiments

There is a vast array of science and engineering questions that have to be answered to achieve a better understanding of the risks, benefits and feasibility of SAI. The tools and topics that are needed to address these questions range from General Circulation Models (GCMs) all the way to detailed design of instrumentation to monitor or disperse aerosol. SCoPEx addresses a subset of questions that require small-scale field experiments for ground-truthing and that are aimed at improving the ability of models to predict the consequences of SAI.

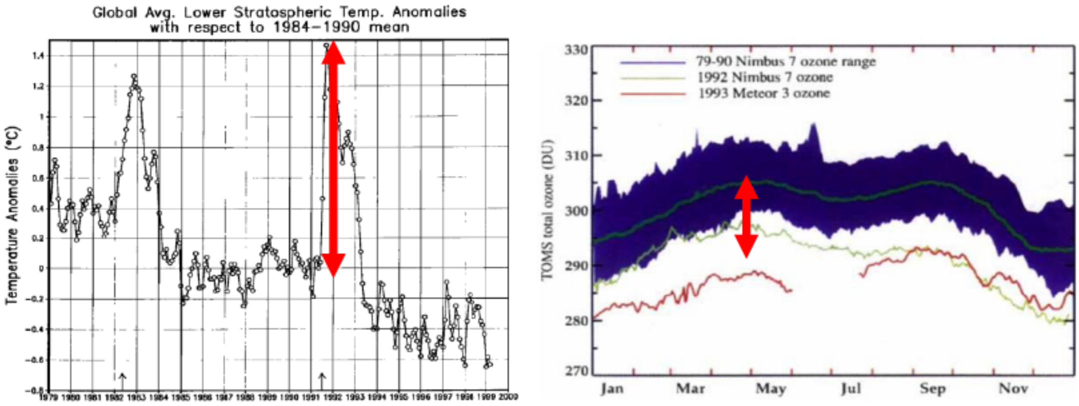

Figure 1: The two most important first-order stratospheric risks from sulfate SAI. The left panel shows stratospheric temperature anomalies from the El Chichon and Mount Pinatubo eruptions on top of background temperatures that are decreasing due to greenhouse gas emissions (Robock, 2000). The dynamical response of the stratosphere from such a short heating pulse likely is different than from sustained heating from longer-term SAI. The right panel shows that in the two years following the Mount Pinatubo reaction total ozone columns were lower than in the 1979-90 average as a result of increase sulfate aerosol surface area. Smaller eruptions also contributed to this. (McCormick et al., 1995)

There are numerous known risks associated with SAI, and SCoPEx focuses primarily on improving understanding of the first-order impacts in the stratosphere, i.e., risks and risk reduction associated with impacts of SAI within the stratosphere. There are many downstream / higher-order risks, e.g., impact on cloud formation as SAI particles leave the stratosphere (Cziczo et al., 2019), impacts on ecosystems via changes in the hydrological cycle (Bala et al., 2008; Russell et al., 2012; Tilmes et al., 2013), or the amount of direct

versus diffuse radiation (Gu et al., 2002; Farquhar & Roderick, 2003; Gu et al., 2003). Despite their importance, these impacts are not the direct target of this proposal although many of these are also influenced by stratospheric processes and properties of SAI aerosol. Two first-order risks are at the focus of this work: stratospheric ozone loss and the dynamic response resulting from stratospheric heating as a result of SAI.

Whereas stratospheric ozone chemistry is fairly well understood (World Meteorological Organization, 2019), there are still substantial uncertainties in the understanding and ability to model stratospheric dynamics (Figure 1). For example, models have only recently been able to reproduce the quasi-biennial oscillation without having it imposed (see Butchart et al., 2018 for a discussion of challenges). One approach taken in this work is to evaluate whether there are types of aerosols or methods of aerosol injection that can reduce first-order risks for a given amount of radiative forcing. It stands to reason that a reduction in the first-order stratospheric impacts will reduce downstream and higher-order risks. A case in point is the growing body of work that has been investigating the impacts of stratospheric heating on stratospheric water vapor and the dynamic response on regional climate (Simpson et al., 2019; Ferraro et al., 2015; Richter et al., 2018; Ji et al., 2018). It is important to note that the amount of stratospheric heating for a given material will be primarily driven by the total mass of aerosol, ozone destruction will be driven by the total surface area of aerosol, and the desired radiative forcing will be determined by the amount and size distribution of aerosol. Critically, both the aerosol mass required for a given desired radiative forcing *and* the resulting surface area are tied to this size distribution. Therefore, accurate models of the evolution of the size distribution of injected aerosol are critically needed. In addition, alternate materials with reduced stratospheric heating have to be investigated, as do injection methods for sulfate that minimize stratospheric heating and ozone loss for a given radiative forcing, as this will reduce risks associated with the dynamic response to this first-order perturbation.

2. Observational SAI Research Needs

Most of the rapidly growing body of literature on SAI rests on General Circulation Models (GCMs). We acknowledge the importance of GCM studies, but in the following we focus on research needs that require experiments and observations, and especially questions that can only be answered by conducting perturbative field experiments such as SCoPEx (see supplemental manuscripts Keith et al., 2020 and Floerchinger et al., 2020). In fact, SCoPEx will in the end inform GCMs by providing improved process level information that will be integrated in parameterizations used in GCMs. Below we review existing observational data sets and describe their utility for different SAI approaches, highlighting where they are unable to shed light on critical issues thus motivating studies like SCoPEx.

2.1. Field Experimental Needs for Sulfate SAI

Most studies that have sought to research SAI have assumed the addition of aerosol would take place by means of an injection of gas-phase SO_2, which is ultimately converted to H_2SO_4 and then to sulfate aerosol in the stratosphere on a timescale of approximately one month. The aerosol size distribution from this injection of gas phase precursor must be accurately predicted as it will control the shortwave (SW) scattering properties, the stratospheric lifetime of the aerosol, and ultimately be the driver for the radiative forcing (RF) efficiency per mass of injected sulfate. Some studies, such as Niemeier & Timmreck (2015), have suggested that with higher injection rates of SO_2, the resulting sulfate aerosol would be forced into a larger, coarse-mode size distribution and functionally reach a point of diminishing return. In this diminishing return scenario, the added amount of SW RF achieved per added mass of sulfate decreases exponentially.

Recent work by Pierce et al. (2010), Benduhn et al. (2016), and Vattioni et al. (2019) has highlighted the potential benefits of injecting H_2SO_4 aerosol directly into the accumulation mode (AM), i.e., aerosols with a radius of 0.1–1.0 µm, potentially by emitting H_2SO_4 vapor into an aircraft plume. This work has suggested better control of the resulting aerosol size distribution and thus the radiative forcing per unit mass sulfur injection, which would allow for the design of a system that maximizes the radiative forcing per mass of sulfate in a way that would not have the diminishing returns at high SO_2 injection rates. This would thus minimize the increase in the stratospheric sulfate burden and hence the risk of stratospheric heating which is driven by total mass whereas ozone loss is driven by surface area. While injecting AM–H_2SO_4 may represent the best possible approach for SAI with stratospheric sulfate, there is currently no proven way to introduce vapor phase AM–H_2SO_4 into the stratosphere. As AM–H_2SO_4 has not been studied, perturbative experiments are required to provide observational constraints on the aerosol size distributions predicted by models.

2.2. Field Experimental Needs for Alternate Aerosol Material SAI

Though sulfate aerosol does exist in the background stratosphere and there are some natural analogs of broad stratospheric sulfate injections (volcanic eruptions), it likely is not the optimal candidate for SAI. Alternative aerosol may be most appropriate in order to mitigate SAI risks (Teller et al., 1996; Crutzen, 2006; Ferraro et al., 2011; Ferraro et al., 2015; Weisenstein et al., 2015; Keith et al., 2016; Dykema et al., 2016; Weisenstein et al., 2015). These alternate aerosols could reduce the previously noted two major first-order stratospheric impacts, i.e., changes in ozone and stratospheric heating. Due to the uncertainties in the impacts of stratospheric heating, the study of materials with optical

properties that negate stratospheric heating is especially important. Materials such as calcium carbonate ($CaCO_3$), alumina (Al_2O_3), diamond (carbon), and several others, have been proposed as a way to minimize the inherent risks from SAI (Keith et al., 2016; Dykema et al., 2016; Weisenstein et al., 2015; Ferraro et al., 2015; Ferraro et al., 2011; Crutzen, 2006). Although model results of these aerosol species suggest that some of them possess optical properties that make them well suited to be used in a SRM scenario ($CaCO_3$, Al_2O_3, and diamond) (Dykema et al., 2016; Ferraro et al., 2011), the stratospheric aerosol microphysics of these compounds (especially coagulation) is poorly understood. As with AM–H_2SO_4 injections, there is a profound lack of in situ data to assess the ability to model the microphysics of alternative aerosols and the stratospheric chemistry of these materials. This is especially pertinent with respect to changes in ozone, and is exacerbated by the fact that these aerosols have no naturally existing analog in the stratosphere that could be studied. Because early studies suggest that these aerosols show much promise with respect to deploying SAI while mitigating the inherent risks of the deployment, it is imperative to design and execute in situ experiments in order to test our current understanding of the aerosol microphysics and observe the effects of alternative aerosol on the chemical composition and dynamics of the stratosphere.

2.3. Limitations in Existing Analogues

In this section we will review previous in situ studies of stratospheric plume processes, show how those datasets have contributed to our current understanding, and demonstrate the need for experiments such as SCoPEx to inform small-scale models of aerosol microphysics (nucleation and coagulation), plume transport and physical morphology, and chemical properties of new aerosol species that have thus far not been observed in the stratosphere. Because the nature of the injection scenarios (AM–H_2SO_4 or solid aerosols) are so complex compared to natural analogs, new experiments must be designed and implemented to provide observational constraints on our current nearfield modeling framework. Experimental data from carefully targeted small-scale studies would contribute to the development of nearfield-scale models that represent currently uncertain processes in detail.

We note that sub-grid scale processes do not represent the only unknowns in GCMs that are relevant to high-fidelity simulations of SRM scenarios, and that there are many large scale model phenomena which should be further assessed with observational evidence. However, here we focus on the need for in situ data to constrain sub-grid scale processes that can be addressed by SCoPEx and highlight the need for reducing the uncertainty in transport and aerosol dynamics and chemistry at this scale.

2.3.1. Limitations of Solid Rocket Motor Plume Observations

From 1996 to 2000 a number of rocket plumes were observed by high-altitude research aircraft. Generally, these missions involved a research team coordinating stratospheric sampling flights on either the NASA ER-2 or on the NASA WB-57 with coincident rocket launch events from either Cape Canaveral or Vandenberg Airforce Base. These studies sampled plumes from a host of rocket types including Titan IV, Space Shuttle (STS106, STS83, STS85), Delta II, Athena II, and Atlas IIAS.

Plumes were intercepted by the sampling aircraft between 5 and 125 minutes after emission from the rocket motor at stratospheric altitudes ranging from 11 to 19.8km (Voigt et al., 2013). The main science objective of these missions was to assess the stratospheric

ozone depletion potential of space exploration by understanding the halogen chemistry occurring as a result of the high-altitude rocket burn. However, in studying the effects on the ozone layer, this era of stratospheric sampling provided a unique set of plume measurements to study nearfield processes of chemical injections into the stratosphere.

While measuring the plumes from the Titan IV rocket (as a part of the United States Airforce Rocket Impacts on Stratospheric Ozone (RISO) Campaign) and attempting to develop a plume chemistry model to solve for the Cl_2 concentration in a rocket plume as it evolves shortly after its emission, Ross et al. (1997) noted the many assumptions that had to be made about the plume morphology in order to simulate the mixing and diffusion that the rocket plume had with the surrounding stratosphere. Their model solved for the Cl_2 concentration of a circular nighttime plume as it expanded in diameter along an isentropic surface. Subsequent aircraft measurements showed that plumes contained more than twice the predicted concentration of Cl_2 despite the plume being intercepted during the day time (when the Cl_2 reservoir should be somewhat depleted by the photolysis reaction $Cl_2 + h\nu \rightarrow 2Cl$), suggesting that there may be an error in the assumption of a circular plume morphology on the short transport time scales observed in this study ($\sim 28min$).

Ross went on to publish a second study as a part of the RISO project in 1999, this time looking to quantify the size distribution of alumina aerosols emitted from the rocket engines which contained particulate alumina (Al_2O_3) (Ross et al.,1999). They compared measured aerosol size distributions from the WB-57F plume interceptions to results from an aerosol coagulation model and highlighted a massive discrepancy. The model predicted a much smaller aerosol size distribution with 1-10% of the aerosol mass being in the smallest (0.005μm) mode and the aircraft observed only fractions (<0.05%) of the model estimate in that same small mode. At the same time, over 99% of the aerosol mass sampled by the aircraft was found in the coarsest mode (2 μm), which the model was unable to predict. It is most likely that the model used in Ross et al. (1999) did not well account for the effects of ion mediated nucleation as described by Yu & Turco (1997). However, the data from Ross et al. (1999) was some of the first in situ data to highlight the uncertainty in stratospheric aerosol coagulation models. Alumina aerosol, as well as other solid aerosols, in contrast to liquid sulfate aerosol, have since been investigated as a candidate for use in SAI (Weisenstein et al., 2015). Therefore, it is imperative that we understand the chemical, coagulation, and accumulation properties of these and other solid aerosols in a stratospheric environment.

2.3.2. Limitations of Previous Stratospheric Aircraft Wake Crossing Observations

We can look to the few times high-altitude aircraft wake plumes have been sampled in situ for another example of stratospheric plume measurements. In the early 1990s the popularity and capability of the Concorde spurred discussions of a large fleet of High Speed Civil Transport (HSCT) aircraft that would operate in the lower stratosphere between 16 and 23 km. Scientists became concerned with the effects of high-altitude aircraft and high-altitude supersonic aircraft on stratospheric ozone destruction via the creation of a large NOx source in the lower stratosphere. NASA then launched several field campaigns using the ER-2 to study the exhaust profiles of high-altitude aircraft. In 1992 NASA commissioned the Stratospheric Photochemistry Aerosols and Dynamics Expedition (SPADE) to look at the effects of HSCTs. As a part of SPADE the ER2 sampled its own plume on several occasions by making a hairpin turn and heading into its original path, therefore measuring its own wake

(Figure 2). SPADE resulted in at least 11 published studies and some of these can inform us about the mixing and aerosol dynamics that may be relevant to an SAI scenario (Stolarski & Wesoky, 1993).

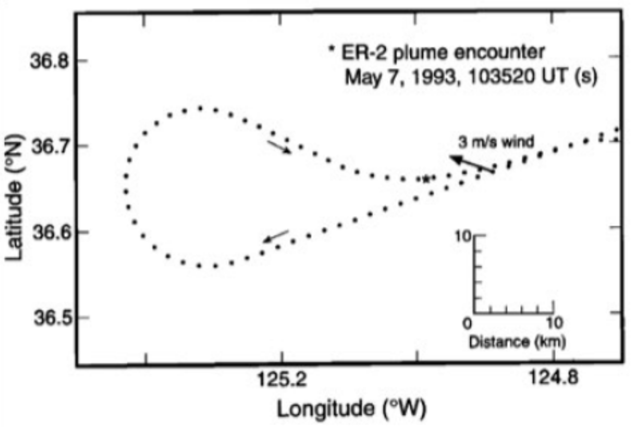

Figure 2: Shows the ER-2 flight track on a typical wake crossing trajectory (adapted from Fahey et al. 1995).

Fahey et al. (1995a) described measurements made of condensation nuclei (CN) present in the ER-2's exhaust plume from the emission of aerosol carbon and of sulfur compounds during one of its SPADE wake crossing events. Because the main focus of this study was to quantify the emission indices (EIs) of various compounds measured by the ER-2 that may have ozone depletion implications, they focused mainly on gas phase compounds. However, for the three wake crossings that the study focused on, they observed large variability in their EI measurements for CN. They noted that this is likely due to differences in mixing history of the encountered air parcels and noted that a full explanation of CN coagulation required more in-depth study and further measurements (Fahey et al, 1995b).

In another study published by Fahey et al. (1995b), they used a similar wake crossing technique to measure the exhaust of the Concorde aircraft and developed an aerosol coagulation model to predict particle formation and size as a function of the time since emission from the aircraft. The coagulation model was initialized at the observed conditions from the one-hour old Concord transect. The results from this model estimated that from 0 to 10 hr since emission from the engine, the mean particle diameter remained fairly constant at 0.06 μm before growing exponentially to a factor of 3 times its initial value over the next 1,000hr. The model predicted exponential mean particle diameter growth continuing right until the of the simulation at 1,000 hr (Fahey et al., 1995a).

Yu & Turco (1997) attempted to model the observed aerosol plume during the Concorde wake crossings with the goal of determining the driving factor for the large aerosol size distributions observed by the ER-2 in the exhaust which had not yet been explained by models. Yu proposed that aerosol formation was being aided by ion-mediated nucleation (IMN), that is, charged particles formed by chemi-ionization processes within the aircraft engines provide charged centers (H_2SO_4 [S(VI)]) around which molecular clusters rapidly coalesce. "The resulting charged micro-particles exhibit enhanced growth due to condensation and coagulation aided by electrostatic effects" (Yu & Turco, 1997). It is likely that IMN is the reason previous particle coagulation modeling of solid rocket motor plumes had overestimated the amount of aerosol in the small size ranges when compared to the in situ data, though this has not since been tested. Because of these effects, and the fact that specific size distributions of aerosol are desired to obtain the optimal radiative

forcing effects for SAI (nominally smaller than observed in rocket or aircraft plumes), we must understand the aerosol nucleation and coagulation dynamics in an unperturbed stratosphere.

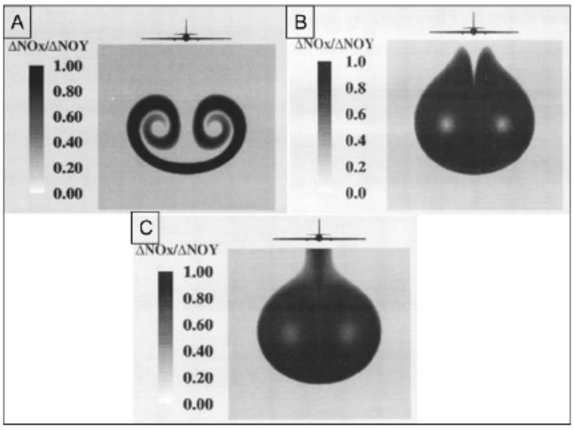

Figure 3: Shows the chemical and morphological evolution of an ER-2 plume during SPADE at 1.7 km (A), 4.8 km (B), and 7.9 km (C). (adapted from Anderson et al. (1996))

As a part of the SPADE project, Anderson et al. (1996) computed the flow field and chemical kinetics of the ER-2 aircraft exhaust using the Aerodyne Research Inc. UNIWAKE model. Their calculations address the effects of complex plume morphology on in-plume chemistry as a function of dilution time since emission from the aircraft engine. They showed that the plume morphology is highly variable out to about 5 km post emission Figure 3 and estimated that the stability of the wing vortex pair begins to break up at roughly 20 km post emission. Although this study was completed in the mid 1990s, it is still one of the only studies that attempts to compute nearfield chemistry within a dynamic stratospheric plume. However, particles were not considered as part of this study.

2.3.3. Limitations of Stratospheric Wake Crossings

Previous stratospheric plume studies of solid rocket motors and aircraft wake crossings have laid the foundation for our understanding of stratospheric plume chemical, aerosol, and mixing dynamics on transport scales of 0→100 km. These studies highlight the types of processes we must be aware of when considering the logistics of SAI. However, the violent initial conditions of engine exhaust plumes (such as temperatures of 700K, IMN) make it difficult to relate these observations to other systems. Because the engines drive the mixing and transport in the nearfield, and the ionic injection conditions of the plume create electrostatic forces that introduce complex nucleation affinities (IMN), understanding individual parameters can become analogous to finding a needle in a haystack. Moreover, because the radiative properties of any stratospheric aerosol that may be used for SRM depend on the diameter of the particle, we must understand the coagulation of that aerosol in the nearfield after the injection, which means that we must also understand the plume morphology that dictates the concentrations of that aerosol. Currently there have been no in situ data gathered that help us understand nearfield aerosol nucleation and plume dynamics in the absence of a very disruptive source. These conditions are necessary to understand as SAI may require that we mitigate the effect of IMN in order to obtain an aerosol size distribution that is small enough to provide the desired radiative properties.

2.3.4. Limitations of Naturally Occurring Analogs

Another source of useful in situ data on plume dynamics in the stratosphere can be found in literature addressing the fate and transport of convective overshooting events that often occur at the top of a Mesoscale Convective Complex (MCC). These events drive brief airmass exchange with the troposphere and often end up resulting in a plume-like parcel of tropospheric air being injected into the stratosphere.

Measurements of convective systems and upper troposphere-lower stratosphere exchange, as a means to interrogate stratospheric plume transport, have provided valuable in situ datasets that help us understand mid-field (10 to >1000 km) plume dynamics in the lower stratosphere. Similar to convective overshooting events, volcanic eruptions have provided an immense amount of in situ data that has informed us about regional and even global transport of stratospheric injections (Robock, 2000). Although their data are applicable in some sense to the transport of an SAI plume after its initial injection, the turbulent nature of a convective storm makes it difficult to measure these events at points near their injection source. Additionally, the storm conditions themselves dramatically complicate the system in the lower stratosphere such that is difficult to see through the effects of the induced turbulence in the nearfield. Indeed, an important limitation of these type of natural analogs is the spatial extent of their perturbation, which does not allow for near-field observations analogous to that of a point source. This also arises from the violent nature of these events which does not allow airborne platforms, such as the ER-2, to sample the initial conditions of the injection. We also note that volcanic eruptions are limited in their utility to evaluate dynamic response to stratospheric heating from sulfate aerosol, as they represent a perturbative pulse rather than the long-term heating one would expect from SAI.

In addition, these natural analogues provide extremely limited ability to study alternate materials, although organic and mineral dust aerosol injections into the lowermost stratosphere have been documented from convective overshoots. However, the complexity of the massive perturbations of both gas- and particle-phase preclude a study focusing on the impact on stratospheric composition and aerosol evolution that would result from SAI of a single material.

3. SCoPEx Short Overview

This section provides a brief overview of the engineering and operational aspects of SCoPEx. We first describe the platform, the instruments, and the concept of operations before describing the rationale for the overall SCoPEx design choices.

3.1. SCoPEx Platform

The SCoPEx gondola (Figure 4) is a balloon-born new research platform being developed at Harvard by the engineering and science staff within the Anderson/Keith/Keutsch laboratory group. The development builds on four decades of stratospheric research on aircraft, balloon, and rocket platforms that has focused on understanding the environmental chemistry of the ozone layer. The SCoPEx experiment was first described by Dykema et al. (2014). While many details of the design have changed, that paper still succinctly describes the advantages of choosing a balloon born platform over an aircraft, particularly for studying perturbations like solar geoengineering, and several of the limits of laboratory experiments that that could be addressed in a perturbative experiment like SCoPEx.

The gondola has three primary features: the frame, the ascender, and the propellers. The aluminum and carbon fiber frame contains two decks and a ballast hopper for coarse altitude control. One deck is primarily dedicated to platform support (power and flight control) and one deck is primarily dedicated to instruments. At the top of the gondola is an ascender and rope which allows the distance between the bottom of the balloon train and the gondola to vary from 0 to 150 m, which provides fine altitude control of the gondola. The ascender has been developed and tested by Atlas (Chelmsford, MA) building on their previous hardware in collaboration with the Harvard engineering team. The propellers serve two purposes: to create a well-mixed volume of air where observations of the aerosols and perturbed gas-phase can be made, and to reposition the gondola within the evolving aerosol plume. While the trajectory of the balloon and gondola system will be dictated by the balloon, the propellers allow for repositioning relative to the prevailing winds.

The ascender makes it impossible to have cables and other physical connections between the flight operations equipment and the gondola. Thus, the platform will handle its own communications and power. The SCoPEx platform will be powered using 28 V and 100 V DC power supplies which will power all operations on the platform including the propellers, ascender, and instruments. Elements of the flight platform are listed in Table 1. The gondola flight, flight safety, recovery parachute, and recovery operations will be managed by the balloon operator (in contrast to the SCoPEx team itself). Because the absolute velocity and distance capability of the gondola are so small compared to balloon drift, the trajectory will be determined by the balloon operator as if it was a passive nonpowered payload. During operations, the detailed float altitude will be jointly managed by the balloon operator via control of the balloon vents and the Harvard team via control of the ballast and ascender.

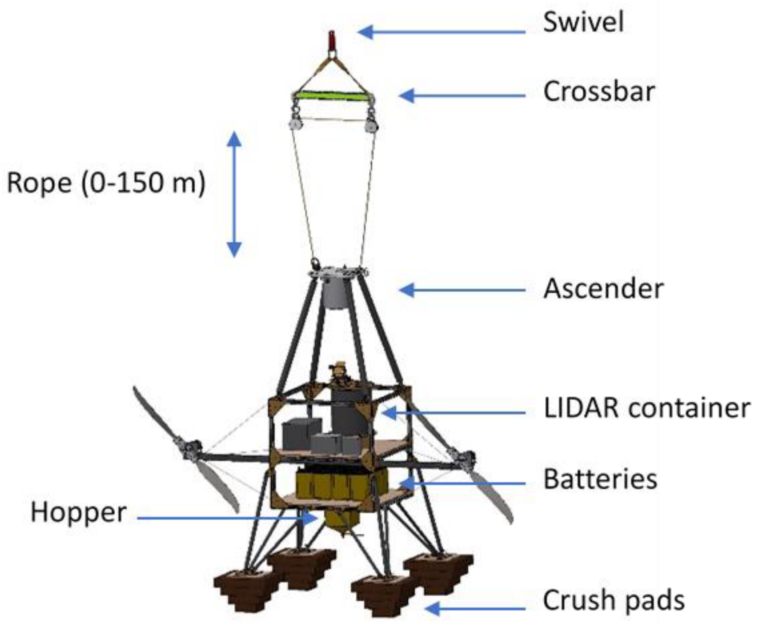

Figure 4: A representation of the SCoPEx flight platform. The final configuration may have subsystems packaged differently.

Parameter	Description
Total mass (Frame, all subsystems, hopper with ballast)	600 kg
Interface to balloon	Crosby 5-S-2 jaw & jaw swivel
Ascender	13 mm diameter rope Range of motion: 0-150 m Max speed: 10 m/min
Gondola propulsion	Twin propellers, 1.88 m diameter 32 N thrust each Max airspeed: 3 m/s
Power	28 V and 100 V DC power supplies with 24 MJ and 10 MJ total energy when fully charged
Communications	Satellite phone for communication between ground equipment and payload
Maximum termination shock	10 g

Table 1: Elements of the SCoPEx flight platform.

3.2. Instruments for First Science Flights (Science Goals 1 and 2)

The proposed instruments for the first science flight, addressing science Goals 1 and 2, are listed in Table 2. The corresponding science goals that motivate their inclusion are detailed in Section 4.

Measurement	Instruments	Rationale	Corresponding Science Goal
Wind speed measurement	Wind pendulum	Gondola and plume movement relative to balloon	Platform operation
Meteorology	Commercial off-the-shelf instrument	Temperature and pressure measurement throughout the flight	1, 2, 3
Wind turbulence	Constant temperature anemometer	Stratospheric mixing and modeling evolution of aerosol size distribution	1, 2
Particle dispersal	Solid Aerosolizer	Injects monodispersed particles for measurement and study	2, 3
Plume tracking	LIDAR	Tracking plume and navigation back into plume	2, 3
Particle sizer	POPS	Aerosol size distribution measurement for comparison with microphysics models of near-field evolution	2, 3
Light Scattering	Radiometer	Comparison of aerosol scattering with model prediction	2

Table 2: Instruments for first SCoPEx science flight.

Wind Pendulum: Understanding differential wind speed measurements between the balloon and payload will be important for plume evolution relative to the balloon trajectory and navigating the payload back into the plume. Commercial equipment to measure wind speed is typically not designed for the low densities found in the stratosphere. SCoPEx will therefore use a pendulum-based instrument and model to extract wind speed measurements. A camera will track a pendulum bob with high surface area and low mass, light enough to be perturbed by low winds in the stratosphere. Using the location and tilt data from the payload and a 3-dimentail kinetic model, the wind speed will be extracted from photos of the pendulum bob.

Commercial Meteorology Instrument: Commercial off-the-shelf instruments will be used for meteorological measurements on SCoPEx. They will record pressures and temperatures of the ambient stratosphere.

Constant Temperature Anemometer: A constant temperature anemometer (CTA) uses convective cooling caused by air flowing across a heated thin wire to measure flow velocity. LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere) (Gerding et al., 2009; Theuerkauf et al., 2010) used such a measurement to study stratospheric turbulence up to 29 km. LITOS consisted of a 5 μm diameter and 1.25 mm long tungsten wire CTA and a 16 bit ADC with 2000 samples per second to collect measurements with a vertical resolution of 2.5 mm at 5 m/s ascent speed. The anemometer data was analyzed by performing a spectral

analysis on the voltage signal to retrieve the spectral slope of the observed variation. A similar instrument will be used on SCoPEx to measure stratospheric turbulence. Air flow around the device will be simulated using CFD tools. The CFD runs will provide a means to identify key flow characteristics that drive sensor performance (sensitivity and accuracy), and to drive detailed sensor design.

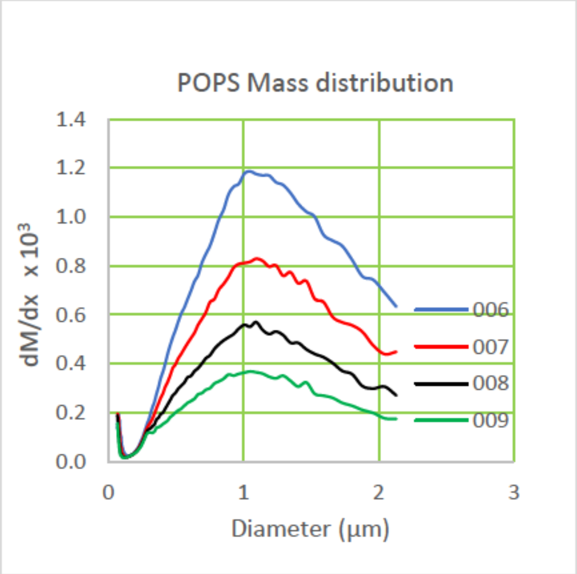

Figure 5: Successive measurements of sprayed $CaCO_3$ using an optical particle spectrometer. 006-009 indicate numbered time intervals spaced 4 minutes apart with 006 being the earliest measurement. $CaCO_3$ was sprayed using a 200 µm nozzle. In this laboratory experiment there was no significant variation in the shape of the distribution over time. (personal communication A Neukermans and team)

Solid Aerosolizer: The solid particle aerosolizer has been developed by a team lead by Armand Neukermans. For SCoPEx, the goal is to spray roughly monodisperse ~0.5 µm diameter precipitated calcium carbonate powder, the first candidate for solid SAI, through a 1-2 mm nozzle using the expansion of powder suspended in high pressure liquid CO_2. The aerosolizer would use a 1:4 weight ratio of $CaCO_3$ to CO_2. For 1 kg of $CaCO_3$ this would require a 5-7 L pressurized container. This concept has already been demonstrated in the lab. Figure 5 shows successive measurements of sprayed $CaCO_3$ with a size distribution centered at 1 µm diameter. Measurements were taken every 4 minutes using POPS (see below). In this case, total particle count decreased over time but there was no significant variation in the shape of the size distribution.

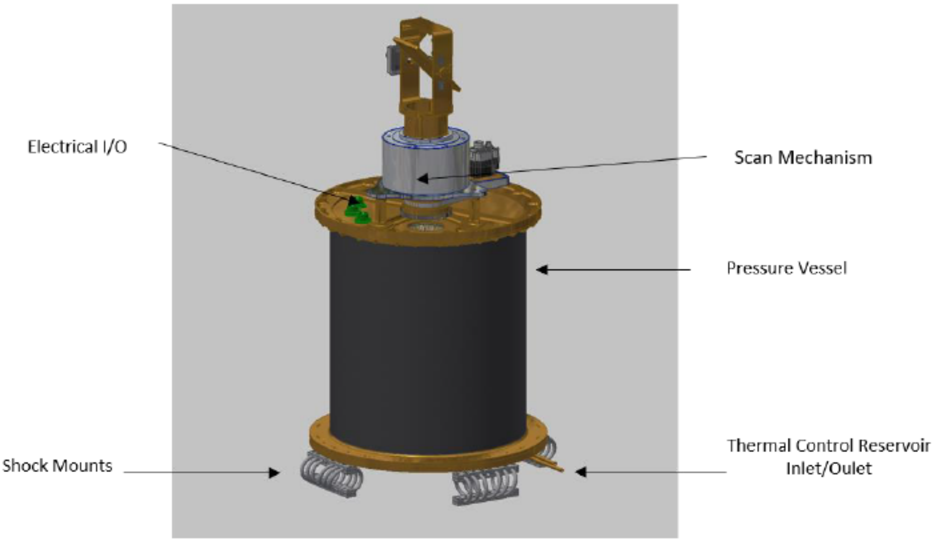

Figure 6: LIDAR pressure vessel provides safe storage and operating environment and support equipment.

LIDAR: The LIDAR is used to track the plume and allow navigation back into it. The core of the LIDAR system is an off-the-shelf eye-safe visible LIDAR, purchased from Sigma Space (now owned and operated by Droplet Measurement Technologies). This LIDAR produces 4 µJ pulses of 532 nm light at a repetition rate of 532 nm. The light that is backscattered by molecules and aerosols is collected by an 80 mm telescope and detected with a high-speed, high-sensitivity photodiode.

We have integrated this LIDAR in a pressure vessel (Figure 6) to provide a near-1 atm pressure environment with adequate temperature stability to ensure safe operation of the LIDAR at float altitude and safe storage on launch, ascent, descent, and recovery. This pressure vessel includes equipment for electrical and mechanical support, including command, data handling, and shock mounting. The LIDAR requires a scan capability to search the nearby atmosphere for the extent and geometry of the plume. The tilt and pan functions of the scan capability allows the LIDAR to be scanned over a set of angles that define the plausible location of the plume.

Portable Optical Particle Spectrometer (POPS): The POPS instrument will provide the aerosol size distribution measurements for studying aerosol formation and agglomeration. POPS is a light-weight instrument that directly samples the aerosol. It was built by and provided to SCoPEx through a collaboration with NOAA. The particles are illuminated with a 405 nm diode laser and the scattered light is collected onto a photomultiplier tube. The particle size is determined by the intensity of the scattered light. It has both the detection limit and size range (0.13 – 3 µm) to measure background stratospheric aerosol, which is more than sufficient for SCoPEx needs (Gao et al., 2016).

The Keutsch Group has already developed and extensively characterized a POPS instrument in preparation for the NASA-EVS3 Dynamics and Chemistry of the Summer Stratosphere field campaign on board the NASA-ER2, for which Keutsch is the deputy-PI. The POPS instrument tests include extensive thermal vacuum chamber characterizations to ensure operation under harsh stratospheric conditions. Compared to the ER-2, operation for SCoPEx will be simpler due to the insignificant air speed of the balloon and a much simpler operational pressure regime (on the ER-2 there is a large range of external pressures for both sampling and exhaust).

Radiometer: The aerosol plume can also be detected using a narrowband, narrow field of view radiometer with azimuthal/zenith pointing capability. The relationship between measurements of scattered solar radiation and the physical characteristics of atmospheric aerosols has been studied for more than two decades. Sky scanning measurements at multiple wavelengths between 300 nm and 1200 nm have been obtained using robotically pointed ground-based spectral radiometers deployed worldwide (Holben et al., 1998). The theory of these measurements has been refined and validated as a function of viewing geometry to provide a strong basis for inferring aerosol microphysics from radiometer data (Torres et al., 2014). The success of these approaches has motivated the development of compact sky scanning radiometers suitable for deployment on unsteady platforms like unmanned aerial vehicles (UAVs) and SCoPEx. One such design, reported by NOAA (Murphy et al., 2016), measures at 4 wavelengths (460 nm, 550 nm , 670 nm, and 860 nm) with a field of view of 0.006 sr (equivalent to 2.5° half-angle) and a circular limiting aperture of 1.1 mm diameter. A radiometer like this one deployed on SCoPEx would be capable of observing a SCoPEx plume, based on Golja et al. (2020), formed by a 0.1 g s^{-1} injection of calcite from a distance of 200 m with an approximate signal-to-noise ratio of 6000 for a 1 ms signal accumulation.

3.3. Instruments for Future Science Flights (Science Goal 3)

The additional instruments listed in Table 3 are candidates for future SCoPEx flights beyond the initial science flight, i.e., addressing science goal 3. They have not yet been adapted to fly on the SCoPEx platform. Instrument choices will be refined based on experiences in the first science flights. The corresponding science goals that motivate their inclusion are detailed in Section 4.

Measurement	Candidate Instrument	Rationale	Corresponding science goal
Aerosol composition	Drum Sampler	Collecting aerosols for offline analysis	3
Water Vapor	IR Absorption or Frost Point	H_2O outgassing of platform, Influence on coagulation and heterogenous chemistry	2, 3
Atmospheric trace gas concentrations (ex: HCl, NOx)	Spectroscopic trace gas instruments	For measuring concentrations of various atmospheric trace gases before and after addition of solid ASI material	3

Table 3: Potential instrument for future SCoPEx science flights.

Aerosol Composition: Aerosol composition can be analyzed via the collection of aerosol with a drum sampler followed by offline analysis in the laboratory using standard offline methods. Aerosol sampling has been done numerous times aboard stratospheric platforms.

Water Vapor: Gas-phase water vapor measurements are important as relative humidity likely has a large impact on the heterogeneous reactivity of solid SAI material. The balloon and gondola can outgas significant amounts of water and thus an initial experiment will characterize how long, if at all, this outgassing perturbs the SCoPEx plume. As mentioned previously, the goal of SCoPEx is to ideally minimize the perturbation to only the introduction of calcium carbonate. Water vapor measurements are common on many stratospheric platforms.

Hydrogen Chloride: HCl can be measured via infrared absorption spectroscopy. The Anderson group at Harvard, which shares a laboratory with the Keutsch group, has developed a stratospheric HCl instrument and thus has extensive experience with the design of stratospheric HCl instrumentation. In addition, the Keutsch group has designed multiple spectroscopic trace gas measurements. The much lower air speeds of the balloon compared to aircraft favor the design of an open path system, which eliminates the notorious wall effects that can make HCl measurements challenging.

NOx: For NOx there exist a number of good instrumentation options. Recently, a compact NO-LIF instrument has been designed that has spectacular detection limits in the low ppt range, more than sufficient for the needs of SCoPEx. The instrument is a close analogue of the fiber-laser based formaldehyde LIF instrument that the Keutsch Group developed, so there is a high degree of expertise available for such an instrument. There are also sensitive cavity enhanced techniques available usually in the visible range of the spectrum.

3.4. SCoPEx Concept of Operations

Flights will proceed in the following manner. The payload would be launched with the ascender retracted such that there is minimal distance between the crossbar and platform. Once the balloon reaches the float altitude, the rope will be let out through the ascender such that there is 100 m between the crossbar and platform. The platform will then be ready to perform experiments and execute maneuvers. Figure 7 illustrates a proposed flight maneuver. The platform will initially travel in a straight line laying out a plume, after which it will maneuver back through the plume to make measurements. During these maneuvers the ascender can be used to fine tune the altitude of the platform and instruments. Several series of such maneuvers can be performed within each flight. At the conclusion of the experiments the ascender retracts the rope before the descent.

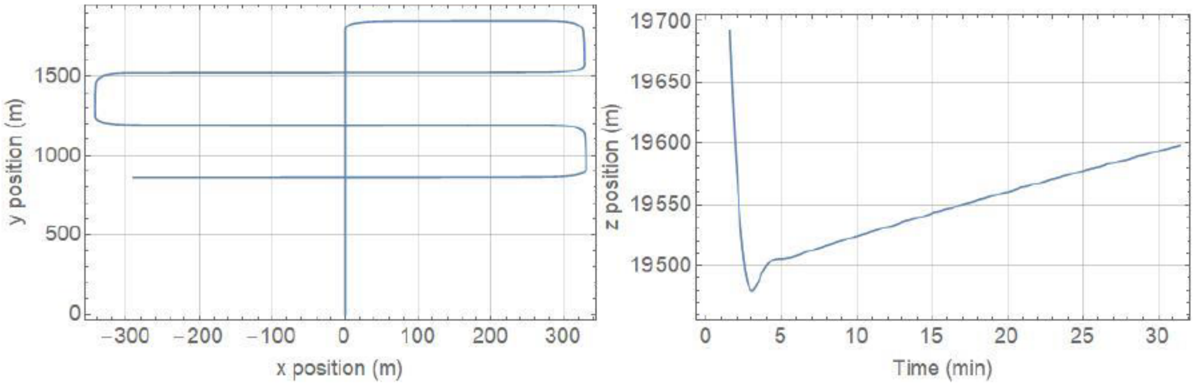

Figure 7: (left) A top down view of the proposed flight maneuvers over a 35-minute window. x and y are in the horizontal plane. The platform begins at (0,0). (right) The vertical position expected without any ascender or hopper vertical trimming over the same 35-minute platform maneuver.

4. SCoPEx Goals

In this section we describe the three long-term SCoPEx science goals. For each goal we describe the scientific problem, the need for SCoPEx, and the measurements required. The first phase of science flights targets the first two science goals. The design of the flights for the third goal will be informed by an understanding of the evolution of particle size distribution in the plume and the plume size. Thus, if later stage science flights move forward, they will be refined based on the results of the first science flights and the most up-to-date knowledge within the solar geoengineering and stratospheric science research communities.

4.1. Goal 1: Measurements of Turbulence for Small-Scale Mixing

4.1.1. The Importance of Plume-Scale Turbulence

Stratospheric turbulence influences the evolution of aerosol distribution from plume to regional to global scale. The mixing of air masses (of differing composition) in the stratosphere is a combination of two processes (Nakamura, 1996; Schoeberl & Bacmeister, 1993). The first process is strain, the distortion of streamline flow that brings air masses of differing composition adjacent to one another (Prather& Jaffe, 1990). Sometimes this is also referred to as “stirring” (Haynes, 2005). The second process occurs when air masses of differing composition are transported across the streamlines. This second process is the true “mixing” process.

In the stratosphere, mixing ultimately occurs because of molecular diffusion. This happens at the length scale of molecular viscosity. It is accelerated by turbulence, which can dramatically enhance the rate at which differing air masses are deformed to small enough spatial scales for molecular diffusion to mix them efficiently. Stratospheric turbulence is, however, highly intermittent (Vanneste, 2004). Understanding the mechanisms of stratospheric turbulence production is essential to understanding the spatial inhomogeneity and effective rate of mixing on spatial scales of 10-500 m (Schneider et al., 2017).

An understanding of this role of turbulence is of interest to stratospheric science because studies suggest that more accurate representations of mixing influence tracer distributions (Hoppe et al., 2014). Measurements of long-lived tracers are the strongest observational constraint on the stratospheric age of air, a key measure of the stratospheric large-scale circulation. Turbulence also modifies the character of kinetic energy fluxes. The magnitude and variability of these energy fluxes determine the rate of frictional dissipation in the atmosphere. This dissipation is represented in global models by a damping parameter and is the primary determinant of the mesoscale atmospheric kinetic energy spectrum. The uncertainty in kinetic spectrum is important to the understanding of the large-scale circulation of the middle atmosphere (Jablonowski & Williamson, 2011).

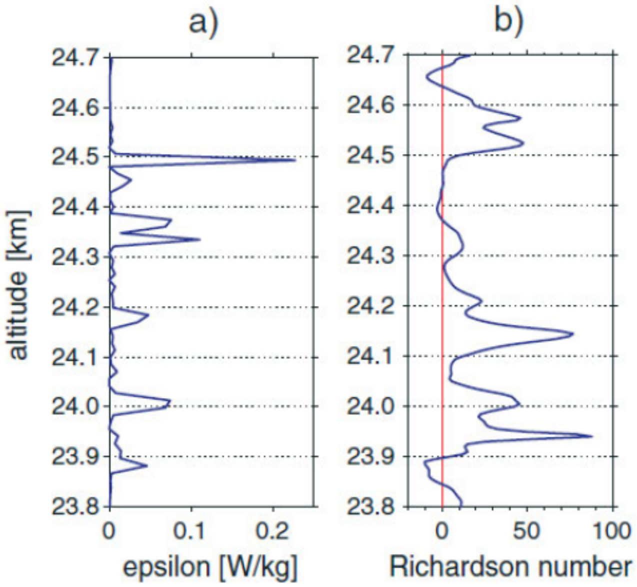

Figure 8: LITOS balloon-borne high-speed anemometer measurements reveal that models of atmospheric turbulence do not explain observed stratospheric turbulence. Physical models predict that a low Richardson number (buoyancy/shear ratio) implies turbulence, but high values of epsilon (turbulent dissipation) should be correlated with low Richardson number, which is not observed. (Haack et al., 2014)

Physical models predict that a low buoyancy/shear ratio (Richardson number) implies turbulence, and that high values of turbulent dissipation should be correlated with low Richardson number (Figure 8). However, recent balloon born measurements during the LITOS campaign did not agree with this, with numerous instances of high values of turbulent dissipation occurring at high Richardson numbers (Haack et al., 2014). As detailed above, both the impact of turbulence on mixing and the associated dissipation of energy are important for general stratospheric science. The point at which viscous fluid forces dominate atmospheric motion is the point where atmospheric motions become purely statistical and is called the dissipation scale. At this scale, models no longer require computationally expensive deterministic modeling. Furthermore, these viscous forces are also responsible for the dissipation of turbulent kinetic energy. Therefore, measurements which resolve the winds at the dissipation scale will allow numerical models to realistically close the atmospheric kinetic energy budget, an important metric of model fidelity.

4.1.2. Importance of Small-Scale Mixing for SAI and SCoPEx

From an SAI and SCoPEx perspective, plume-scale turbulence influences the frequency of collisions of monomer particles within the SCoPEx plume, which determines the rate of formation of fractal, larger aggregates. While Van der Waals forces finally determine whether particles that collide stick together and remain as a fractal aggregate (Sukhodolov et al., 2018), the collision rate is a critical quantity in determining total coagulation rate. Therefore, it is essential to know the frequency of collisions. This frequency is controlled by the wind variability at small spatial scales, i.e., the power spectrum. Intuitively, inertial forcing of particles by wind is much stronger than thermal forcing (e.g. Boltzmann distribution of velocity for ~1 µm particles at ~220 K). Fractal aggregates have a shorter lifetime in the stratosphere and are less effective at scattering light on a per mass basis (Weisenstein et al., 2015), so being able to model the formation

rate of fractal aggregates is an important aspect of SAI, especially with alternate SAI materials.

Improved knowledge of collision rates from wind measurements will allow for the selection of the appropriate mathematical representation of particle coagulation, the coagulation kernel. An accurate kernel is essential for numerical models to correctly simulate aerosol microphysical processes that determine the size distribution and residence time of solid aerosol particles. Adding wind and turbulence measurements to the SCoPEx payload will therefore address the major sources of uncertainty in aerosol microphysics under real atmospheric conditions, which include small-scale fluid flow, particle composition, and humidity.

4.1.3. Experimental Methods to Measure Turbulence in the Stratosphere

Multiple technologies are possible to achieve wind measurements with the necessary spatial resolution under stratospheric conditions. Current state of the art options include pitot tubes (with high sensitivity micro-pirani pressure sensors), hot wire anemometers, and acoustic anemometers. An existing stratospheric program has utilized hot wire anemometers to make measurements that are a close analog to what is necessary for SCoPEx. The program developed LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere), an instrument which made measurements of stratospheric turbulence up to 29 km (Gerding et al., 2009; Theuerkauf et al., 2011). The LITOS instrument has undergone significant calibration and has been compared against radiosondes (Schneider et al., 2015). One drawback of its deployment on a balloon has been the contamination of its wind measurements due to the influence of the balloon's wake. In contrast, SCoPEx is engineered so that the wind environment of the instrument payload is well separated from the balloon wake when SCoPEx is traveling horizontally. For this reason, SCoPEx could provide significantly more data per flight at a chosen float altitude. In this way, SCoPEx and LITOS would be very complementary. The horizontal flight path of SCoPEx, combined with measurements of the wind power spectrum, would provide an excellent complement to the LITOS observations, which are only obtained along a vertical profile. These power spectra obtained by SCoPEx would contribute to improved micrometeorology understanding relevant both to stratospheric aerosol injection and to fundamental atmospheric science.

Additionally, air flow through the turbulence instrument will be simulated using CFD tools. The CFD runs will provide a means to identify key flow characteristics that drive sensor performance (sensitivity and accuracy) and detailed sensor design. This application of the SCoPEx platform would therefore constitute a nonperturbative means to obtain necessary turbulence measurements that have, to date, eluded the scientific community. This information is important for understanding stratospheric dynamics, including the response to climate change or stratospheric heating from SAI. As no injection of particles is needed, these could be among the first scientific measurements to be conducted.

4.2. Goal 2: Evaluation of Aerosol Microphysics of AM-Sulfate and Alternative SAI Materials

One of the goals for which there are insufficient observational analogues is the near-field evolution of particles injected from a point source in the stratosphere. Specifically, observations of the temporal and spatial evolution of the aerosol size distribution (number and volume) of solid, alternate SAI materials or AM-H_2SO_4 injected form a point source can

only be compared with plume model predictions via a perturbative experiment such as SCoPEx. In the following we describe a plume model by Golja et al. (2020) specifically designed for SCoPEx. We also explain the results from the model and the SCoPEx experimental approach for comparing observations with model results.

4.2.1. Plume Model

Golja et al. (2020) incorporated the SCoPEx design features in their model to study the injection of a solid aerosol and vapor-phase sulfuric acid from a balloon payload. To provide observations relevant to SAI, SCoPEx needs to produce downstream aerosols with radii within the range of roughly 0.2 to 1.0 µm. For calcium carbonate, the objective is to maintain a high fraction of the aerosol in monomer form, while for sulfate an ideal distribution would have a peak diameter of 0.6 µm (Dykema et al., 2016). The generation of largely smaller than ideal particles, while imperfect for assessing radiative efficiency relevant to SAI, does not serve to increase particle sedimentation rates within the plume. Such smaller sizes may, however, result in a larger surface to volume ratio, which can strongly influence stratospheric composition as heterogeneous chemistry is directly related to surface area. Distributions centered on small particle sizes in the near field may, however, continue to evolve beyond the domain of the study.

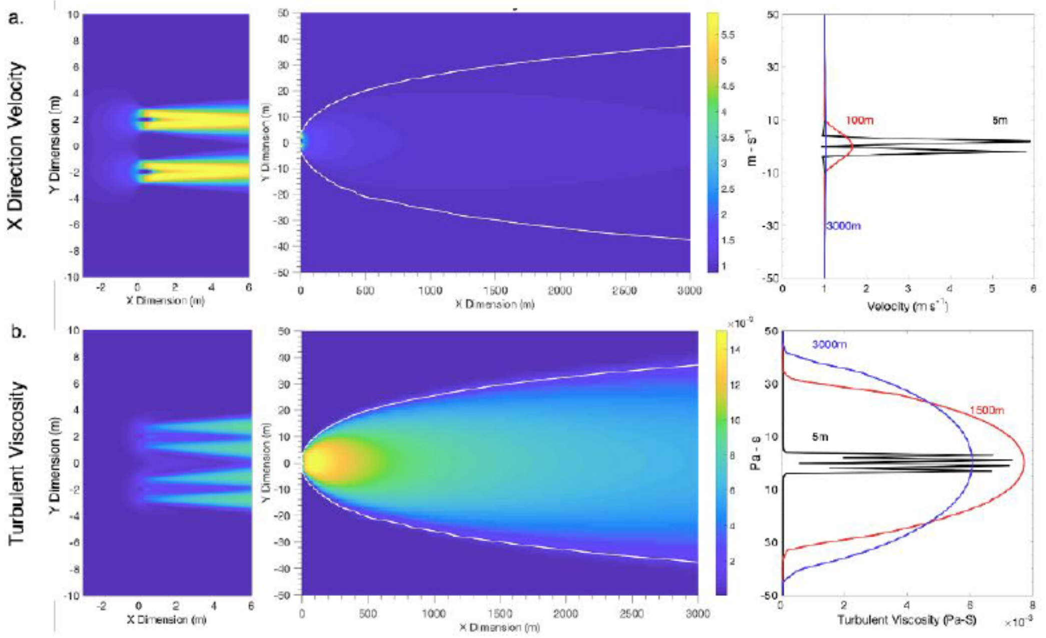

Figure 9 : ANSYS Fluent Velocity and Turbulence Fields. Shown above are the steady state x-direction velocity, u, and turbulent viscosity fields generated by ANSYS Fluent. Left panels show the genesis of disruptions to background X direction flow of 1 ms^{-1}, where propeller features are imposed at locations of 0,2) and (0,-2) meters. The center panel shows the entire domain, from 0 to 3 km, where the imposed red line contours 1 ms^{-1} in plot A, and contours 10% of the absolute maximum turbulent viscosity in plot B. Note Y direction scaling differs between the center and left panels. The right panel shows cross sections of velocity (A) and turbulent viscosity (B) through the Y plane at varying X locations. (Golja et al. 2020)

The velocity and turbulent viscosity fields from Fluent are shown in Figure 9. These fields form the basis of the simulation environment and are instructive in achieving an understanding of SCoPEx and the perturbation it achieves. Peaks in the x-direction velocity, u, are found directly downstream from the modeled propeller centers with an absolute maximum value of 6.3 ms^{-1}. By 1500 m downstream from the inlet locations, the velocity is reduced to the imposed background flow of 1 ms^{-1}. Turbulent viscosity, used as a measure

of particle mixing with background air, exhibits a narrow distribution of peak values ~10 m downstream from simulated propellers. With increasing distance downstream, the turbulent velocity spatial distribution widens, attaining a full width half maximum (FWHM) of 60 m by 1500 m downstream. The wake of the balloon itself is not visible, as it is sufficiently far from the payload to avoid wake crossing/interaction. Additionally, this simulation assumes a laminar stratospheric background flow, neglecting the potential impacts of breaking gravity waves.

For SCoPEx, precipitated calcium carbonate powder with roughly monodisperse size distribution centered at ~0.5 mm diameter will be aerosolized using the expansion of powder suspended in high pressure CO_2 through a 1-2 mm nozzle (see description in Section 3). The model injects aerosol as a 3D gaussian distribution of mass flux into the model grid, where the size of that distribution represents the scale of which the high velocity jet from the nozzle mixes with ambient air. The model considered two injection scenarios: scenario 1 (S1), a single point injection between the propellers; and scenario 2 (S2), injection from the center of each propeller. The model plume diameter at 3 km is, however, insensitive to the injection scenario for injection of both AM-H_2SO_4 and calcium carbonate. This suggests that injection at or between the propellers does not significantly alter the characteristics of the particles' experienced velocity field, and scenario S1 is the one selected for testing the model of plume evolution on SCoPEx. This is also important for the SCoPEx experiment as it necessitates only one sprayer that can be more easily placed in the equipment gondola.

4.2.2. Modelled Mass Injection Rate Dependence of Aerosol Size Distribution

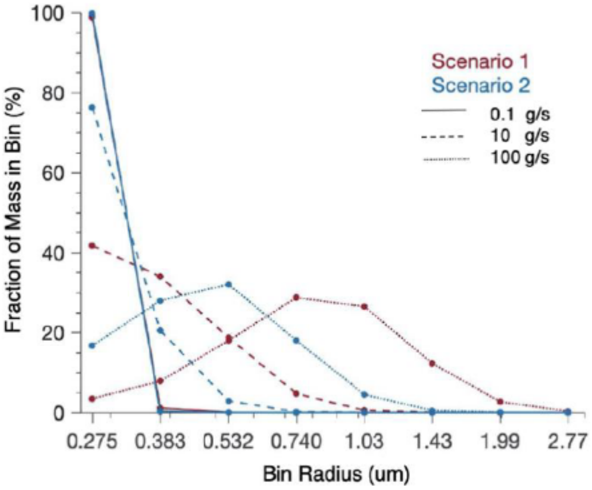

Figure 10: Calcium carbonate aerosol size distributions. Fraction of total mass in each sectional bin where the x-axis markers represent the central radius of each sectional size bin. These distributions represent the percent of total aerosol mass in the final 100 m of the plume across the full domain. Results are shown for three injection rates, 0.1 g s^{-1}, 10 gs^{-1}, and 100 gs^{-1}, for injection scenario 1 (red) and 2 (blue). (Golja et al. 2020)

Mass injection rates of 0.1, 10, and 100 g s^{-1} (0.36, 36, and 360 kg hr^{-1}) were used to test the influence of initial particle number density on the final plume aerosol size distribution. Although some of these are high, their use in the model is instructive as it can answer how different a short burst of high injection rate (much less than an hour) is from a slower but longer injection for the same total mass. Increasing calcium carbonate injection rates from 0.1 to 100 g s^{-1} reduces the share of monomer particles and increases undesired multi-monomer fractal aggregates. Figure 10 shows calcium carbonate's size distribution in the final 100 m of the modeled plume, i.e., the percent in each bin for the three different

injection rates of 0.275 μm radius particles. The low calcium carbonate injection rate of 0.1 g s^{-1} is the most desirable, maintaining 99% of the total mass in the final 100 m of the plume in monomer form. Increasing mass injection rate to 10 g s^{-1} and 100 g s^{-1}, with an S1 injection, shifts peak mass loading to favor particles of radii 0.5 and 0.75 um, respectively, corresponding to fractal "dimers" and "trimers".

Golja et al. (2020) also evaluated whether, in addition to the very sensitive in-situ optical particle counting aerosol size distribution instrument which originally was designed to measure background stratospheric aerosol size distributions (Murphy et al., 2016), the plumes could also be detected optically via scattered light. It should be emphasized that this does not refer to measurements from the ground but rather from close to the plume, e.g., when the equipment gondola is in close vicinity to the plume. Measuring the scattering from one view angle gives the product of the scattering phase at that angle and the scattering efficiency. This is closely related to the radiative forcing, but it does not uniquely determine the radiative forcing. By measuring at multiple angles, we could obtain enough information to quantify the radiative forcing. For example, we could measure from the side and below to obtain the forward scatter fraction, then calculate backscatter by flux conservation.

In the model, the extinction optical depth was calculated using Mie scattering theory and vertically integrating down columns in the y-z plane. Figure 11 shows the relative optical thickness of a sulphate and calcite aerosol plume formed via scenario 1 with an injection rate of 0.1 g s^{-1}. Calcite exhibits greater optical thickness by an order of magnitude at 550 nm, with an average value of 8.6×10^{-4} and maximum of 0.014 across the domain, as compared to sulphate, with an average of 9.4×10^{-5} and maximum 0.001. From these values, Golja et al. calculated that we expect adequate SNR to confidently detect the plume with a fast-scanning radiometer via the solar radiation it scatters. This calculation assumed an altitude of 21 km, solar elevation angle of 60°, an observing instrument situated on the payload gondola, and the gondola 200 m away from the edge of the plume and 1 km downstream of the termination of a scenario 1 type injection of calcite aerosol. Details of this calculation can be found in Golja et al. (2020).

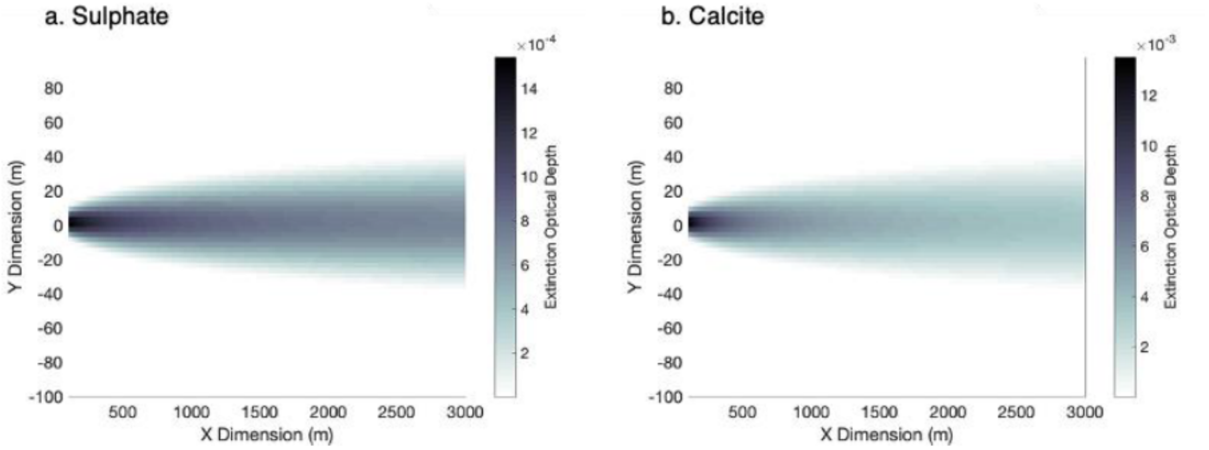

Figure 11: Extinction optical depth integrated vertically through all columns in the plume from 100-3000 m. Plots a and b show results for 0.1 gs^{-1} injections of condensable H_2SO_4 and calcite, respectively. The resulting number density of calcite aerosol is 490 cm^{-3} on the centerline at a downstream distance of 1000 m, predominantly as monomers. Aerosol optical depths were derived from Mie scattering theory at 550 nm, using refractive indices for sulphate and calcite stated in Dykema et al. (2016). (Golja et al. 2020)

4.2.3. SCoPEx Experimental Design and Analysis of Plume Evolution

For this goal, SCoPEx will follow the standard concept of operations, first spraying calcium carbonate at an injection rate suggested by the model analysis. It is desirable to maximize the contrast with the background stratosphere, both with respect to the aerosol concentration and the potential resulting chemical changes, while also maintaining calcium carbonate as monodisperse aerosol. To this end, additional models will be run at injection rates between 0.1 and 10 gs^{-1}. Based on these results, an injection rate will be chosen for the actual SCoPEx experiment. In addition to the basic components of the SCoPEx platform (gondola, ascender, propulsion, power, flight computer, communication, and wind), the calcium carbonate sprayer as well as the LIDAR and POPS instrument are critical for this science goal; without these components, there would not be a way to make and find the plume or measure the aerosol size distribution. While the turbulence measurement from goal 1 is desirable, it is, at least initially, not necessary. Similar studies of AM-H_2SO_4 injection would also be extremely useful. Our current plan is to conduct these after the calcium carbonate injection studies, as initially calcium carbonate is easier to handle than sulfuric acid and its precursors (see next section for motivation of calcium carbonate).

The aerosol size distribution measurements will be compared with the model predictions. In combination with turbulence measurements, discrepancies between the observed and modeled aerosol size distributions can be used to identify issues within the aerosol microphysical scheme or highlight misrepresentations of the velocity and turbulence field of the payload. The results of these studies will provide critical observational constraints on the aerosol microphysics and plume evolution of an injection with solid particles. It will be unique data that is ideal for testing the model of plume evolution as SCoPEx does not have to address problems resulting from the much more violent injection regime associated with injection from airplanes. Clearly, such studies are also needed, but SCoPEx represents a feasible and compelling first step in a sequence of new studies that more comprehensively investigate the aerosol microphysics of point source injections.

4.3. Goal 3: Evaluation of Process Level Chemical Models of Stratospheric Chemistry of Sulfate and Alternative SAI Materials

4.3.1. Need for Alternative SAI Materials

As previously discussed, the two largest first-order stratospheric risks of SAI with sulfate aerosol are ozone depletion and stratospheric heating. For sulfate aerosol the relative magnitude of these two risks can be adjusted if the size distribution can be controlled, e.g., via the AM-H_2SO_4 approach. It is worth noting that the impact on stratospheric ozone may be greatly reduced in the future if reactive halogen concentrations are lower. In contrast, the impact of stratospheric heating will not change. This represents a risk with a poorer understanding of its consequences, which makes it highly desirable to minimize stratospheric heating and resulting dynamic response. Therefore, it is important to investigate alternative SAI materials.

The properties of the “ideal” SAI material is (i) no absorption of radiation, i.e., purely scattering aerosol both fresh and aged, (ii) chemically inert, i.e., no direct impact of this material on stratospheric composition, and (iii) minimal down-stream effects, i.e., no impact on cirrus or other clouds, no environmental impact on deposition on the ground, etc. In reality, it is unlikely that a material with no impacts exists and rather the question is which materials can minimize these impacts. There have been a number of studies investigating

SAI materials in this context. High refractive index materials have been suggested as they reduce the mass of material that have to be lofted (Ferraro et al., 2015; Ferraro et al., 2011; Pope et al., 2012; Keith et al., 2016; Dai et al., 2020; Weisenstein et al., 2015). This largely cost-driven perspective is not a motivation for our work. In contrast, one of the goals of SCoPEx is to decrease the uncertainty in SRM models that use calcium carbonate SAI. The rationale for the choice of calcium carbonate as well as the approach to evaluate some of these risks is described in the following sections.

4.3.2. Unreactive Alternative SAI Materials

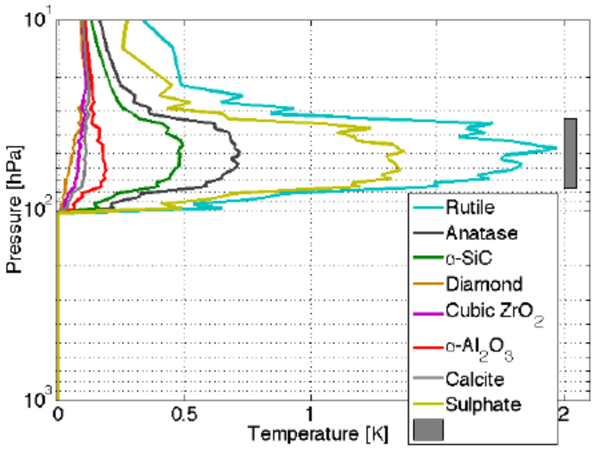

Figure 12: Comparison of stratospheric heating for different materials. Diamond has the lowest impact, although cubic zirconia and calcite are very similar. Sulfate and rutile result in much larger heating. (Dykema et al., 2016)

Diamond is probably the material with the best properties for SAI from a purely stratospheric perspective. Diamond has no absorption features in the solar or terrestrial spectrum and thus triggers the minimal possible dynamical response Figure 12. In addition, diamond should have ideal chemical properties. Hydrogen-terminated diamond surfaces are extremely inert and hydrophobic, precluding the ozone destroying chemistry initiated on sulfuric acid surfaces. The surface itself is also resistant to concentrated sulfuric acid. Exposure to OH radicals would probably slowly make the surface more hydrophilic. From a purely stratospheric perspective the only first-order risk of diamond would be increased ozone loss from the increased sulfuric acid surface area resulting from coagulation with background sulfate aerosol.

4.3.3. Reactive Alternative SAI Materials: The Case for Calcium Carbonate

Although the impact on cloud properties and the risk to Earth's surface from deposition of SAI diamond is likely very low, it could be preferable to have a material that dissolved easily in water, hence not persisting for long times outside of the stratosphere. It would also be preferable to have a material that is naturally abundant at Earth's surface. In addition, it would be ideal to overcome increased ozone loss due to coagulation by using a reactive aerosol. We therefore propose calcium carbonate as a prototype alternate SAI material for the following reasons: First, its optical properties are nearly equal to diamond and stratospheric heating and resulting dynamic response should be negligible compared to sulfate (Figure 12). Second, carbonates are typically quite reactive with acids, especially with concentrated sulfuric acid (Figure 13). Hence, calcium carbonate will neutralize upon

coagulation with sulfate aerosol eliminating the acidic surfaces resulting from coagulation of diamond and sulfate aerosol. Of course, the reactivity of calcium carbonate also makes model predictions with calcium carbonate more complex. The evolution of chemical and optical aerosol properties has to be modeled over its stratospheric lifetimes. One of the key research questions that SCoPEx will help address is whether the reactivity of calcium carbonate and the evolution of its chemical and optical properties and those of the surrounding gas-phase correspond to the detailed hypothesis laid out below. To this end, SCoPEx will compare observations of the chemical evolution of calcium carbonate, as well as the gas-phase, with those of a model based on known properties of calcium carbonate and recent laboratory experiments (Dai et al., 2020). This will provide a real-world evaluation of kinetic parameters, such as heterogeneous uptake coefficients derived from the laboratory studies, that will enable GCMs to include reliable parameterizations of the stratospheric impacts of calcium carbonate SAI.

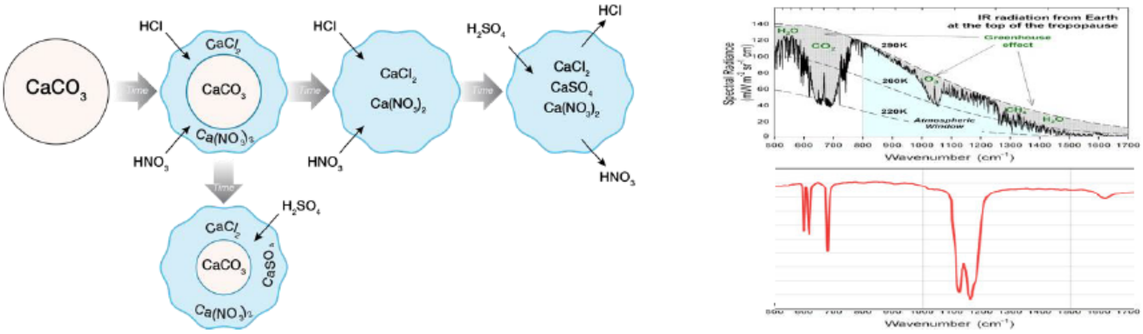

Figure 13: The left panel shows schematic of potential chemical reactivity of calcium carbonate in the stratosphere. The right panel shows the atmospheric windows in the terrestrial infrared (top) as well as the infrared absorption spectrum of calcium sulfate (bottom). The position of the 1150 cm^{-1} sulfate in part explains the stratospheric heating effect of sulfuric acid.

4.3.3.1. Optical Properties

Based on well-established chemistry, the reaction of sulfuric acid aerosol with calcium carbonate can be assumed to go to completion, i.e., be reagent limited. The optical properties of calcium sulfate in the terrestrial infrared are similar to those of sulfuric acid with only slight differences in relative band intensities and wavelengths (Figure 13 right hand inset). This is important as it implies that there will be no large first-order changes in stratospheric heating from changing background sulfuric acid to calcium sulfate. There are higher order impacts due to slight differences in the absorption of sulfuric acid, which has some liquid water compared to calcium sulfate. There are also numerous forms of calcium sulfate (anhydrite, bassanite, gypsum, etc.). However, the resulting differences are much smaller than introducing an absorbing material via SAI.

4.3.3.2. Chemical Properties

Predicting the evolution of the chemical properties of calcium carbonate under stratospheric conditions is more challenging. It is certain that calcium carbonate does not have the same heterogeneous reactions that activate ozone destroying substances as sulfuric acid. Figure 13 shows a schematic of the expected reactivity. Calcium carbonate is expected to react with acidic substances neutralizing them, forming salts and carbon dioxide. These acid neutralizing reactions can deplete gas-phase HNO_3, HCl, etc. There are a large number of ozone destroying catalytic cycles involving NOx, chlorine and other

halogens, which are altitude (and latitude) dependent. NOx can be produced via HNO_3 photolysis and lost via heterogeneous reaction of N_2O_5. It participates both in ozone destroying catalytic cycles and is important for deactivation of ozone destroying halogen radicals. Thus, knowledge of the heterogeneous reaction rates of numerous substances with calcium carbonate are required to predict the impact it will have on stratospheric composition.

However, until the recent study by Dai et al. in our laboratory, no heterogeneous chemistry studies of calcium carbonate under stratospheric conditions had been conducted, to our knowledge, although there exists a rich data set under tropospheric conditions (Dai et al., 2020). This work, as well as the work of Dai et al., highlights that reactive solid aerosols are indeed more complex than liquid sulfuric acid: The authors observed moderate initial uptake of the gas-phase acids HCl and HNO_3 on fresh calcium carbonate, as the dry stratospheric conditions already make uptake coefficients lower than under typical tropospheric conditions. An additional large difference to liquid aerosol is that the surface of the solid calcium carbonate passivates, drastically reducing the uptake coefficients of HCl and HNO_3. Hence, based on the Dai et al. laboratory study, calcium carbonate rapidly becomes effectively unreactive with respect to uptake of these gas-phase acids, an important finding that confirms calcium carbonate as a good candidate as alternate SAI material. In addition, calcium carbonate particles are abundant at Earth's surface due to windblown mineral dust. And the small calcium carbonate SAI particles should dissolve rapidly in water. This does not exclude risks associated with the deposition of calcium carbonate SAI particles or impacts on clouds (Cziczo et al., 2019). However, due to its abundance at the Earth's surface, there already exists a large knowledge base for its environmental impacts in contrast to, e.g., diamond. Further laboratory work is required to study especially the $ClONO_2$ + HCl and N_2O_5 hydrolysis reactions on fresh and aged calcium carbonate. However, the existing results prepare the stage for studying them in the real stratospheric environment as outlined below. Figure 14 shows results of the AER 2-D chemistry-transport-aerosol model for annual average ozone column changes of calcium carbonate SAI compared to a control for 2040. Ignoring the passivation of calcium carbonate (thk-ind) results in increases in ozone columns from calcium carbonate SAI whereas the inclusion of passivation can either result in very little ozone column change or losses in the Southern Hemisphere, depending how the $ClONO_2$+HCl is parameterized. Either of the two, more realistic, passivation scenarios result in significantly lower ozone loss than the equivalent amount of sulfate SAI, consistent with the hypothesis.

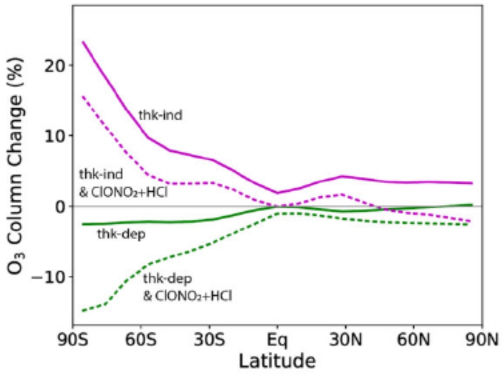

Figure 14: Shows the role of passivation and the heterogeneous $ClONO_2$+HCl reaction on ozone column change using the AER 2-D model taken from Dai et al. 2020. Inclusion of this reaction with the same rate as measured for Al_2O_3 results in a substantial reduction in ozone for scenarios including, thk-ind, or excluding passivation, thk-dep.

4.3.4. Need for SCoPEx Calcium Carbonate Plume Studies

One of the challenges for alternate SAI aerosol is the lack of materials such as calcium carbonate in the stratosphere. The only way to then study these materials in the actual stratosphere is via deliberate stratospheric injection of a small amount of these materials. In environmental studies, including stratospheric studies, it is not possible to rely purely on laboratory studies. For example, flights on the NASA ER-2 into the polar vortex over Antarctica provided the ability to test whether laboratory-derived reaction mechanisms were able to capture real-world ozone destruction chemistry. Without these flights, the level of confidence in the model predictions would have been much lower, and for good reason. It is not clear that a given experimental setup in the laboratory can faithfully capture the entire complexity of the real stratosphere; only field observations are able to provide this. For a number of natural stratospheric processes, remote observations can provide important information in addition to in situ aircraft or balloon. However, these are only possible when large-scale phenomena are at work.

Since there are no natural calcium carbonate plumes in the stratosphere that would even allow for in situ observations, intentional injection is necessary to perform these studies. Calcium carbonate injections will allow SCoPEx to provide invaluable observations as it will quantitively test the mechanisms determined in the laboratory. As stated above, there is a need for more laboratory studies, however, there is good reason to proceed with the planning of SCoPEx calcium carbonate experiments. First, by the time of the first injection experiments, additional studies should have been conducted. In addition, N_2O_5 uptake coefficients used in the model are likely a very good estimation as similar values have been found for different solid materials, e.g., Al_2O_3 and SiO_2 (Molina et al., 1997). In addition, even with these additional lab determined mechanisms, the same type of experiments as proposed here will still have to be conducted, as we expect these reactions to not make a significant difference. In other words, they will not be a deciding factor about the viability of calcium carbonate as an alternate SAI material. Only field experiments will help shed insight into these questions. In summary, there is a critical need for evaluating not just the aerosol microphysics (goal 2) but also the stratospheric chemistry of calcium carbonate due to the promise it holds as a lower risk SAI material.

4.3.5. SCoPEx Experimental Design and Analysis of Chemical Calcium Carbonate Plume Evolution

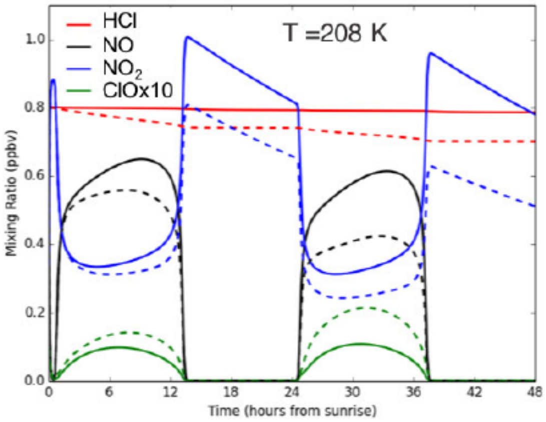

Figure 15: Solid lines: background 2µm^2 cm^{-3} sulfate 5ppm_v H_2O. Dashed lines: plume 15µm^2 cm^{-3} sulfate 10 ppm_v H_2O.

The experiments will again follow the standard concept of operations as under goal 2. In order to determine optimal injection rates, we will include chemical reactions in the plume model, updated with the newest mechanisms available at that time. Figure 15 shows the evolution of an air mass perturbed by a sulfate aerosol injection over multiple days, i.e., significantly longer than the initial SCoPEx experiments. Significant changes in HCl and NOx can be observed already over short time periods and these are easily detectable with existing instrumentation. For this science goal, it is desirable to measure aerosol composition and size distribution as well as key gas-phase chemical species, especially HCl, NOx and water. Therefore, this science goal requires a much larger set of instruments. In addition, the equivalent model to Figure 15 for calcium carbonate is informed by the results of science goal 2. The work of Dai et al. provides kinetic parameters needed for this model, and reactions for which there are no laboratory data to date are parameterized using close analogues and conditions, e.g., $ClONO_2$ + HCl are parameterized using the results for alumina (and silica) from Molina et al. (1997). One key question is whether the changes in HCl and NOx will indeed be smaller for calcium carbonate than those for sulfate shown in the figure above, which would confirm the hypothesis for calcium carbonate as a potential alternate SAI material.

In summary, SCoPEx experiments using calcium carbonate injections will provide a unique evaluation as to whether calcium carbonate indeed is an alternate SAI material that could substantially reduce risk from SAI compared to sulfate. Follow-up studies will be needed. For example, improved chemical and aerosol microphysics models will provide improved models of the chemical and physical evolution of calcium carbonate, which likely will motivate specific laboratory investigations. These will provide information for SCoPEx studies using “stratospherically aged” calcium carbonate as precursor for injection that can then be used to compare whether the laboratory mechanisms of this aged calcium carbonate agree with that found in the real stratospheric environment.

5. Data Management Plan and Dissemination of Results

Products of the research. The data generated during this project consists of meteorological, navigational, telemetry, and a variety of instrumentation data, in particular aerosol size distributions as well as chemical composition data during later science flights. In addition, there will be model data on plume chemical evolution.

Access to data, data sharing practices, and policies and dissemination of results. Data relevant for scientific analysis will be made public within 60 days of the end of flight. This taw data will be made public with appropriate warnings that it has not undergone QA/QC. The email address of users will be recorded so that they can be automatically notified when revised versions become available. Based on previous experiences with stratospheric airborne campaigns, this is typically 6-15 months after the flight depending on the type of data, e.g., the amount of calibration and data workup required. We have chosen to make raw data available rapidly—going far beyond what is typical for stratospheric science missions—because of the public scrutiny of SCoPEx and because of the broad commitment to Open Access data principles articulated by Harvard's Solar Geoengineering Research Program which is funding SCoPEx.

Principal Investigators (PI) and their groups have an excellent track record with presenting their work at major national and international conferences and workshops. All data that go into key analyses and figures in the group's publications will be made publicly available via the PI's group website. All publications resulting from this project will be posted on the PI's webpage (https://projects.iq.harvard.edu/keutschgroup/publications). Preprints of manuscripts submitted for publication as well as the underlying data will also be posted on Harvard's Dash manuscript repository. Publications will be made in open access formats.

Archiving of data. All data acquisition/storage computers in the PI's group are automatically backed up daily, both wirelessly to a server elsewhere on campus, and/or to a cloud server. Both of these processes ensure that data will not be lost and enable rapid access to the data. The file naming system used for all software (which includes the date of the experiment) ensures straightforward retrieval and use of archived data. Group laptops are also backed up daily, ensuring that analyzed data are archived as well.

6. SCoPEx Research Team Biographies

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From: Robert Wood (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin
Cc: (b) (6) ; (b) (6) ; Alan Robock; Karen Rosenlof - NOAA Federal; Katharine Ricke; (b) (6) (b) (6) ; (b) (6) Daniele Visioni; Isla Simpson; Peter Irvine; Jonathan Proctor; (b) (6) ; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N; Trude Storelvmo; Simone Tilmes; (b) (6)
Sent: July 15, 2021 3:52 PM (UTC-04:00)

Hi Doug and Trude,

Thank you for the offer to present at next year's GRC. I am still interested.

Regards

Rob

Robert Wood
Professor, Atmospheric Sciences
Department of Atmospheric Sciences,
718 ATG Building
University of Washington, Seattle
WA 98195-1640

Tel: 206-267-8343 (cell); 206-543-1203 (office)
Web: atmos.washington.edu/~robwood
Email: (b) (6)
[redacted]

On Thu, Jul 15, 2021 at 8:11 AM Douglas MacMartin <(b) (6) > wrote:

> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
>
> As a start to our planning, could you let us know whether you would be interested in talking at the 2022 meeting? We would of course still love to hear from you, but schedules may not permit and research interests change (and, indeed, for some or many of you that may mean that the topic we were originally thinking you would talk about would no longer be what you are currently most excited by – the GRC is supposed to be cutting-edge current research, of course – so if you let us know we can start revising sessions and think about what gaps we'd like to fill). There are also some new people who are doing some great research too that we would like to hear from, so it's conceivable that – given the now 5 year gap since the last GRC – we might choose to slightly increase the number of talks and reduce the time available per talk.
>
> Thanks,

Doug & Trude

From: Douglas MacMartin
Sent: Wednesday, February 19, 2020 10:27 AM
To: (b) (6) ; (b) (6) ; Alan Robock (b) (6) >;
Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >;
(b) (6) ; Robert Wood (b) (6) >; (b) (6)
(b) (6) <(b) (6) >; Daniele Visioni (b) (6) >;
(b) (6) ; Peter Irvine (b) (6) >; Jonathan Proctor (b) (6) >;
(b) (6) ; Keith, David <(b) (6) >; Kravitz, Ben <(b) (6) >; Wake Smith
(b) (6) >; Izidine Pinto (b) (6) >; Gabriel Chiodo
<(b) (6) ; Keutsch, Frank N (b) (6) >
Cc: Lawrence, Mark <(b) (6) >; valentina Aquila (b) (6) >; Ulrike
Niemeier <(b) (6) >; Leisner, Thomas (IMK) (b) (6) >; Olivier Boucher
<(b) (6) >; Schrag, Daniel P. (b) (6) >; TAYLOR,Michael
(b) (6) >; (b) (6) Trude Storelvmo <(b) (6) ; 'Simone
Tilmes' (b) (6) ; (b) (6) Jim Hurrell (b) (6) >
Subject: RE: 2020 GRC program

Hi all,

Just a reminder that if you haven't sent me a title yet, to do so (otherwise I'll have to make something up; GRC needs us to upload our "final" program by the end of this month) I have titles for about half of you (though some of those are draft titles you sent quite some time ago, e.g. for Pete, Isla, Danny).

And, if you haven't responded yet regarding need for travel support, let me know (about half of you have). For those of you who haven't been to a GRC before, there's a bus from Boston airport, and from Portland Maine airport.

If you've already both sent me a title and responded regarding travel, then you can ignore this email.

Also, regarding format, this year we're explicitly including 10-15 minutes for the discussion leader to make some remarks to help frame each session (taking 5 minutes from each speaker's time), and rather than having a lengthy discussion after each talk, we'll have a shorter 10-minute discussion after each talk and a 20-minute general session discussion at the end (that's as long as GRC will allow) with everyone from a given session.

Thanks, and see you in June!

doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) (b) (6) ; 'Jadwiga (Yaga) Richter' <(b) (6) >;
Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>;
Katharine Ricke <(b) (6) >;(b) (6) ; Robert Wood <(b) (6) >;
(b) (6) ;(b) (6) <(b) (6) >; Daniele Visioni
<(b) (6) >;(b) (6) ; Peter Irvine <(b) (6) >; Jonathan Proctor
<(b) (6) >; Govindasamy Bala <(b) (6) >;(b) (6) ; Keith, David
<(b) (6) >; Kravitz, Ben <(b) (6) >; Wake Smith <(b) (6) >; Chris Field
<(b) (6) >
Cc: Lawrence, Mark <(b) (6) >; valentina Aquila <(b) (6) >; Ulrike
Niemeier <(b) (6) >; Leisner, Thomas (IMK) <(b) (6) >; Olivier Boucher
(b) (6) >; Schrag, Daniel P. <(b) (6) >; TAYLOR,Michael
(b) (6) >;(b) (6) ; Lynn Russell (b) (6) >; Trude Storelvmo
<(b) (6) >; 'Simone Tilmes' (b) (6) >;(b) (6)
Subject: 2020 GRC program

Hi all,

Happy New Year!

The full program for GRC is due on February 28; if you haven't sent us a title for your talk (or if you did and want to revise it), please do so before the end of February so I have time to enter everything into the conference management system online.

The cc-line has discussion leaders for each session.

Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin

Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and

Faculty Fellow, Atkinson Center for a Sustainable Future

Cornell University

(b) (6)

(b) (6)

https://climate-engineering.mae.cornell.edu/

From: Andrea Smith (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Graham Feingold - NOAA Federal
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Karen Rosenlof - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:49 AM (UTC-04:00)

https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09

Do you need to use the web client? NOAA or other government users can use Zoom's government-approved web client

Try that, let me know how it goes.

A

On Wed, Sep 22, 2021 at 8:47 AM Graham Feingold - NOAA Federal <graham.feingold@noaa.gov> wrote:

> zoom link not working for me. is there something else i need to do?
>
> On 9/17/21 11:06 AM, Andrea Smith wrote:
>
>> Hello Frank, Wake and Graham,
>>
>> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>>
>> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
>> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
>> Meeting ID: 816 4261 9898
>> Passcode: 148321
>>
>> Please join 10 mins early to test tech and troubleshoot if needed.
>>
>> 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) (preferably by Tuesday night):
>>
>> 3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.
>>
>> After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.
>>
>> Let me know if you have questions on any of the above.
>>
>> Thanks again, and see you next Wednesday.
>>
>> Andrea
>>
>> On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) > wrote:
>>
>>> Hi Frank, Wake and Graham,
>>> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>>>
>>> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see

> below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
>
> 1. Frank Keutsch: ...
> 2. Wake Smith:...
> 3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening
>
> Here is Andreas rundown for logistics:
>
> -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
> -send slide decks to Andrea by Tuesday (9/21) evening for backup purposes
> -arrive ~10 mins early so we can do quick test of screenshares
> -15 min talk length, w/ immediate clarifying question(s) and then ~30 mins broad discussion and questions at end
> -moderator will collect questions in chat window throughout and ask most pertinent ones for discussion
> -panelists and question askers encouraged to unmute & turn on camera
> -session will be recorded and posted later - we'll send a release form for them to complete
>
> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
>
> Cheers, Simone
>
> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6) [redacted]

--
Andrea Smith
Associate Scientist & Program Manager
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University Corporation for Atmospheric Research
3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) [redacted] (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

--
Graham Feingold
NOAA Earth System Research Laboratories
Chemical Sciences Laboratory (R/CSL9)
325 Broadway
Boulder, Colorado 80305, USA

> Tel: (303) 497-3098
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My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Smith, Wake
Cc: Keith, David; Frank Keutsch
Sent: January 28, 2021 11:49 AM (UTC-05:00)
Attached: Untitled attachment

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi- flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" <(b) (6)
Cc: Frank Keutsch <(b) (6)

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can't control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake (b) (6) [redacted] wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6) [redacted]

From: Keith, David (b) (6) [redacted] >
Subject: RE: Experimental research platform requirements
To: David Fahey - NOAA Federal
Cc: Smith, Wake; Keutsch, Frank N
Sent: February 3, 2021 9:59 AM (UTC-05:00)

Dave

Thanks. I think we see this about the same way.

From my perspective I came into this field working for Jim with all the excitement about Aurora's aircraft which ended up amounting to nothing. It took some years of my life. And yes, Global Hawk has been a big disappointment. So I definitely get the basis for skepticism.

On the other hand, there does seem to be a commercial-driven shakeup in the ability to develop low altitude aircraft. That's true from the new entrants into general aviation market through to the startups building off drone technology. So I'd like to understand whether this could apply to higher altitude light aircraft. I don't know, but if Wake spurs some interest I am open to find out more.

Have you had any conversations with these folks: Sceye | A new generation of HAPS | High Altitude Platform Stations? The head guy just reached out to me again and I will talk with.

David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Saturday, January 30, 2021 6:38 PM
To: Keith, David (b) (6) [redacted] >
Cc: Smith, Wake (b) (6) [redacted] >; Keutsch, Frank N (b) (6) [redacted] >
Subject: Re: Experimental research platform requirements

David,

Yes, I think if one has funding, then existing a/c become available. Certainly for the UT/LS, the WB-57s have been underutilized for years now and hence availability hasn't been an issue. Indeed a trip back to the boneyard was perhaps a growing threat.

I note that no one has ever built an aircraft for atmospheric chemistry, leaving the field to exploit as best they can existing a/c, which we have done very well. Thus, if there were runway a/c available that could do 30kg, 8hr, 79kft, the community would no doubt rush to use it. So the answer to your question is yes.

My problem with new-platforms-will-be-cheap is the issue of having truly operational a/c rather than experimental a/c. If one is trying to fly an experiment on an experimental a/c it reduces the probability of success by a large measure. Making an experimental a/c operational requires larger upfront and sustained investment by entities other than the science communities, creating the underwater part of the iceberg. This is why we don't have new operational a/c. And one can look to the Global Hawk and see that even starting at a high level (a mature platform) it failed to become operational because no one wants to pay the price, in this case neither NASA or NOAA. Now deeper pockets (DoD) have taken it over.

And to your final point about what payloads, yes, the new generation of lightweight instruments make 30kg interesting and valuable, and, yes, comprehensive chemistry payloads still want to be on heavy lift long-range a/c.

In reply to Wake's question about perturbation/monitoring a/c, hmmm, it depends. In the early days, perhaps they could be the same. Eventually the perturbations sought would be as large as possible per flight and not every flight would need diagnostics, so I think eventually they are different a/c. And monitoring a/c could be below the perturbation a/c altitudes and diagnose with lidar.

Interest above 70kft: in general because we would be deeper into the ozone layer. And perhaps the injection altitude would be there once we understand things better.

Regards
Dave

> On Jan 30, 2021, at 9:29 AM, Keith, David <(b) (6)> wrote:
>
> Dave
>
> Interesting back-and-forth.
>
> I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.
>
> I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30 kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.
>
> I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.
>
> I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.
>
> Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.
>
> Interesting conversation. No simple answers.
>
> Cheers,
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Thursday, January 28, 2021 11:49 AM
> **To:** Smith, Wake(b) (6)>

Cc: Keith, David <(b) (6) [redacted]>; Keutsch, Frank N (b) (6) [redacted]
Subject: Re: Experimental research platform requirements

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi-flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" <(b) (6) [redacted]>
Cc: Frank Keutsch (b) (6) [redacted]

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can't control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake <(b) (6)> wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6)

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Fwd: Update
To: Frank Keutsch
Cc: Keith, David; Ronda Knott - NOAA Federal
Sent: October 27, 2020 10:25 PM (UTC-04:00)
Attached: Untitled attachment

Frank,

I hope this finds you doing well with the family in Germany.

DavidK and I invited you to a Friday v-meeting to catch up on CI matters. He will give me a brief download of his CDR ideas/perspective at the beginning at my request. So you could join late to miss that.

Let us know.
THanks
Dave

David W. Fahey, PhD
Director of the Earth System Research Laboratories (ESRL)
Director of the ESRL Chemical Sciences Laboratory
NOAA Earth System Research Laboratories
325 Broadway R/CSD
Boulder, CO 80305 USA
303-497-5277 -5822 fax
david.w.fahey@noaa.gov

Ronda Knott, Admin. Assistant
ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

Begin forwarded message:

From: Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
Subject: Re: Update
Date: October 26, 2020 at 7:51:29 PM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Cc: "Keith, David" (b) (6) >

Hi Dave and David,

The meeting has been set for this Friday, October 30th at 7am MT and included Frank Kuetsch.
The connection details are:

Meeting ID
meet.google.com/zgb-gfnu-gdr
Phone Numbers
(US) +1 561-408-9337
PIN: 857 507 300#

Thank you,
Ronda

Ronda Knott
Executive Administrative Assistant to

Dr. David W. Fahey, Director

NOAA Chemical Sciences Laboratory
325 Broadway, R/CSL

Boulder CO 80305

I am currently teleworking, please call my cell: (b) (6)

303.497.4404 phone

303-497-5822 fax

ronda.knott@noaa.gov

On Mon, Oct 26, 2020 at 2:56 PM David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:

> David,
> 7Am Friday will work.
> Ronda can reach out to FrankK if you like. She will send a link to all.
> Thanks
> Dave
>
> On Oct 25, 2020, at 9:17 PM, Keith, David (b) (6) > wrote:
>
> How about 8:30 AM MT on Friday the 30th? (I can do any time from 7:00 to 10:00) MT that AM. Suggest we choose a time, then I will see if Frank can join (he can miss the CDR part).
>
> D
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, October 24, 2020 6:29 PM
> **To:** Keith, David (b) (6) >
> **Cc:** Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
> **Subject:** Re: Update

David,

Thanks for the reply. I appreciate the perspective on Pierrehumbert; a bit frustrating. We will launch a webpage for the Earth Radiation Budget program (ie the Congressional funding) soon (albeit a bit late) that will explain NOAA's role and intent and in effect pushback on Pierrehumbert and others.

Thanks for your offer of a CDR debrief and catching up on other matters. My CDR meeting is 4 Nov so best would be next week sometime. Let me know if that might work (w/ or w/o Frank) and a preferred day/time.

Regards
Dave
PS Canmore seems like a good faraway place to get fresh air devoid of C-19.

> On Oct 21, 2020, at 2:13 PM, Keith, David (b) (6) wrote:
>
> Dave
>
> Thanks. Yet, I'm particularly frustrating because Ray repeats the idea that doing it at all commits us to doing it for a thousand years, yet I think he knows that's not true. When he was at Harvard and from the public audience we challenged him on that pointing out that you could always taper off slowly even if you didn't have carbon removal and so the net result would be a reduction in the rate of change even if it didn't change the ultimate endpoint. He agreed. Yet he keeps coming back to this claim.
>
> I don't have an overview on CDR. I step back because of the conflict of interest after starting Carbon Engineering (the air capture company). In fact I think that CDR is a bit overhyped and I have been trying to figure out how to say that without frustrating people at Carbon Engineering too much. I have fragments of talks and some opinions. I could dump these on you in a short (15 minutes) conversation which might be helpful to me because I'm trying to polish the stuff.
>
> I think you catch up with you, me and Frank would make sense. I'm thinking early November at that point we will of got science plan out to the SCoPEx committee and have made the next step towards reality on a spring flight.
>
> It's beautiful and snowy up here in Canmore Alberta.
>
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>

Sent: Wednesday, October 21, 2020 1:23 PM
To: Keith, David <(b) (6) [redacted]
Subject: Update

David,

Very good article in Globe. Pierrehumbert's article is frustrating since he attacks CI and calls out people like me yet at the end says there might be an appropriate role for CI, something he has done in other articles.

My management has asked me to inform them about CDR in an internal meeting. I am not very well prepared to do that and wondered if you had a presentation that you would be willing share to draw from for this purpose.

A call to catch up with Frank would be welcome.

Regards
Dave

David W. Fahey, PhD
Director of the Earth System Research Laboratories (ESRL)
Director of the ESRL Chemical Sciences Laboratory
NOAA Earth System Research Laboratories
325 Broadway R/CSD
Boulder, CO 80305 USA
303-497-5277   -5822 fax
david.w.fahey@noaa.gov

Ronda Knott, Admin. Assistant
ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Fwd: Update
To: Frank Keutsch
Cc: Keith, David; Ronda Knott - NOAA Federal
Sent: October 28, 2020 1:03 PM (UTC-04:00)
Attached: Untitled attachment

Great. Looking forward to it.

Begin forwarded message:

From: "Keutsch, Frank N" (b) (6) [redacted]>
Subject: Re: Update
Date: October 28, 2020 at 10:51:34 AM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>

Dave,

Thanks for your email. I will see how it goes. I have a number of deadlines looming over me, but will try to attend the whole meeting.

I hope you are doing well. Germany is going into a moderate lockdown!

All the best,

Frank

> On Oct 28, 2020, at 3:25 AM, David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:
>
> Frank,
>
> I hope this finds you doing well with the family in Germany.
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> Let us know.
> THanks
> Dave
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> David W. Fahey, PhD
> Director of the Earth System Research Laboratories (ESRL)
> Director of the ESRL Chemical Sciences Laboratory
> NOAA Earth System Research Laboratories
> 325 Broadway R/CSD
> Boulder, CO 80305 USA

303-497-5277   -5822 fax
david.w.fahey@noaa.gov

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ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

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From: Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
Subject: Re: Update
Date: October 26, 2020 at 7:51:29 PM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Cc: "Keith, David" <(b) (6) [redacted]>

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Ronda Knott
Executive Administrative Assistant to

Dr. David W. Fahey, Director

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Boulder CO 80305

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303.497.4404 phone

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> **Sent:** Saturday, October 24, 2020 6:29 PM
> **To:** Keith, David (b) (6)
> **Cc:** Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
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> Dave
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David

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To: Keith, David (b) (6) [redacted] >
Subject: Update

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>
> ---

Frank N. Keutsch
Stonington Professor of Engineering and Atmospheric Science

Harvard John A. Paulson School of Engineering and Applied Sciences
Department of Chemistry and Chemical Biology
Department of Earth and Planetary Sciences
Harvard University
12 Oxford Street
Cambridge, MA 02138
USA

E-mail:
(b) (6) [redacted]

Tel:+(b) (6)

From: Kelly Wanser (b) (6) [redacted] >
Subject: Nice job on the NOVA episode!
To: David Fahey - NOAA Federal; Frank Keutsch
Cc: John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:13 PM (UTC-04:00)

You were excellent and the piece came out great.
We'll promote it as we are able.

Best,
k.

--
Kelly Wanser
Executive Director, SilverLining | http://www.silverlining.ngo
Board Director, Dendra Systems | http://www.dendra.io
Advisor, University of Washington Marine Cloud Brightening Project | http://www.mcbproject.org
President's Circle, National Academy of Sciences | http://nas-sites.org/PC/
Phone: (b) (6) [redacted]

TEDTalk: *Emergency Medicine for Our Climate Fever*
Report: *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: Alan Robock ☮ (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin;(b) (6) ;(b) (6) ; Karen Rosenlof - NOAA Federal; Katharine Ricke; (b) (6) Robert Wood; (b) (6) ; (b) (6) Daniele Visioni; Isla Simpson; Peter Irvine; Jonathan Proctor; (b) (6) ; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N
Cc: Trude Storelvmo; 'Simone Tilmes'; (b) (6)
Sent: July 15, 2021 5:37 PM (UTC-04:00)

Dear Doug and Trude,

I would like to give a talk. Thanks.

Alan

On 7/15/2021 11:06 AM, Douglas MacMartin wrote:

> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
>
> As a start to our planning, could you let us know whether you would be interested in talking at the 2022 meeting? We would of course still love to hear from you, but schedules may not permit and research interests change (and, indeed, for some or many of you that may mean that the topic we were originally thinking you would talk about would no longer be what you are currently most excited by – the GRC is supposed to be cutting-edge current research, of course – so if you let us know we can start revising sessions and think about what gaps we'd like to fill). There are also some new people who are doing some great research too that we would like to hear from, so it's conceivable that – given the now 5 year gap since the last GRC – we might choose to slightly increase the number of talks and reduce the time available per talk.
>
> Thanks,
> Doug & Trude
>
> ---
>
> **From:** Douglas MacMartin
> **Sent:** Wednesday, February 19, 2020 10:27 AM
> **To:**(b) (6) ;(b) (6) ; Alan Robock (b) (6) ; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke(b) (6) ;(b) (6) ; Robert Wood(b) (6) (b) (6) ;(b) (6) (b) (6) ; Daniele Visioni (b) (6) ;(b) (6) ; Peter Irvine(b) (6) ; Jonathan Proctor (b) (6) ;(b) (6) Keith, David(b) (6) Kravitz, Ben (b) (6) Wake Smith(b) (6) ; Izidine Pinto(b) (6) Gabriel Chiodo(b) (6) ; Keutsch, Frank N(b) (6) >
> **Cc:** Lawrence, Mark(b) (6) ; valentina Aquila(b) (6) >; Ulrike Niemeier(b) (6) >; Leisner, Thomas (IMK)(b) (6) Olivier Boucher(b) (6) Schrag, Daniel P.(b) (6) TAYLOR,Michael (b) (6) (b) (6) Trude Storelvmo(b) (6) ;

'Simone Tilmes'(b) (6) ;(b) (6) Jim Hurrell (b) (6)
Subject: RE: 2020 GRC program

Hi all,

Just a reminder that if you haven't sent me a title yet, to do so (otherwise I'll have to make something up; GRC needs us to upload our "final" program by the end of this month) I have titles for about half of you (though some of those are draft titles you sent quite some time ago, e.g. for Pete, Isla, Danny).

And, if you haven't responded yet regarding need for travel support, let me know (about half of you have). For those of you who haven't been to a GRC before, there's a bus from Boston airport, and from Portland Maine airport.

If you've already both sent me a title and responded regarding travel, then you can ignore this email.

Also, regarding format, this year we're explicitly including 10-15 minutes for the discussion leader to make some remarks to help frame each session (taking 5 minutes from each speaker's time), and rather than having a lengthy discussion after each talk, we'll have a shorter 10-minute discussion after each talk and a 20-minute general session discussion at the end (that's as long as GRC will allow) with everyone from a given session.

Thanks, and see you in June!
doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To:(b) (6) ;(b) (6) 'Jadwiga (Yaga) Richter' (b) (6) >; Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >;(b) (6) ; Robert Wood (b) (6) >;(b) (6) ;(b) (6) (b) (6) >; Daniele Visioni (b) (6) >;(b) (6) ; Peter Irvine (b) (6) ; Jonathan Proctor (b) (6) ; Govindasamy Bala (b) (6) >;(b) (6) Keith, David <(b) (6) ; Kravitz, Ben (b) (6) ; Wake Smith <(b) (6) >; Chris Field (b) (6)
Cc: Lawrence, Mark (b) (6) >; valentina Aquila (b) (6) >; Ulrike Niemeier (b) (6) ; Leisner, Thomas (IMK) (b) (6) ; Olivier Boucher (b) (6) ; Schrag, Daniel P. (b) (6) ; TAYLOR,Michael (b) (6) >;(b) (6) ; Lynn Russell (b) (6) >; Trude Storelvmo (b) (6) >; 'Simone Tilmes' (b) (6) >;(b) (6)
Subject: 2020 GRC program

Hi all,

Happy New Year!

The full program for GRC is due on February 28; if you haven't sent us a title for your talk (or if you did and want to revise it), please do so before the end of February so I have time to enter everything into the conference management system online.

The cc-line has discussion leaders for each session.

Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin
Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and
Faculty Fellow, Atkinson Center for a Sustainable Future
Cornell University
(b) (6)
https://climate-engineering.mae.cornell.edu/

From: Graham Feingold - NOAA Federal <graham.feingold@noaa.gov>
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Andrea Smith; Simone Tilmes; Keutsch, Frank N; Smith, Wake; Karen Rosenlof - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:47 AM (UTC-04:00)

zoom link not working for me. is there something else i need to do?

On 9/17/21 11:06 AM, Andrea Smith wrote:

> Hello Frank, Wake and Graham,
>
> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>
> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
> Meeting ID: 816 4261 9898
> Passcode: 148321
>
> Please join 10 mins early to test tech and troubleshoot if needed.
>
> 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) [redacted] (preferably by Tuesday night):
>
> 3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.
>
> After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.
>
> Let me know if you have questions on any of the above.
>
> Thanks again, and see you next Wednesday.
>
> Andrea
>
> On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) [redacted]> wrote:
>
> > Hi Frank, Wake and Graham,
> > thanks for joining our meeting on Friday, and here is a little summary and a todo list:
> >
> > First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
> >
> > 1. Frank Keutsch: ...
> > 2. Wake Smith:...
> > 3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening
> >
> > Here is Andreas rundown for logistics:
> >
> > -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
> > -send slide decks to Andrea by Tuesday (9/21) evening for backup purposes

> -arrive ~10 mins early so we can do quick test of screenshares
> -15 min talk length, w/ immediate clarifying question(s) and then ~30 mins broad discussion and questions at end
> -moderator will collect questions in chat window throughout and ask most pertinent ones for discussion
> -panelists and question askers encouraged to unmute & turn on camera
> -session will be recorded and posted later - we'll send a release form for them to complete
>
> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
>
> Cheers, Simone
>
> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6) [redacted]

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) [redacted] (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

--
Graham Feingold
NOAA Earth System Research Laboratories
Chemical Sciences Laboratory (R/CSL9)
325 Broadway
Boulder, Colorado 80305, USA
Tel: (303) 497-3098
Fax: (303) 497-5318

From: Douglas MacMartin (b) (6) >
Subject: RE: 2022 GRC program
To: Karen Rosenlof - NOAA Federal; Trude Storelvmo
Sent: July 19, 2021 10:15 AM (UTC-04:00)

Excellent! We should have a great conference ☺. (More later… probably not for a while.)

doug

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Sent: Thursday, July 15, 2021 5:04 PM
To: Douglas MacMartin (b) (6) Trude Storelvmo (b) (6)
Subject: Re: 2022 GRC program

Doug and Trude,
I should be available during that time frame, and would like to attend the test GRC. I'd be happy to adjust topics as you feel is needed.

Take care,

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
Boulder, CO 80305
office: 3A-121, DSRC
e-mail: Karen.H.Rosenlof@noaa.gov
phone: 303 497-7761
fax: 303 497-5373
----
while safer at home remains in effect, email is the most reliable contact

> On Jul 15, 2021, at 9:06 AM, Douglas MacMartin (b) (6) > wrote:
>
> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
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Thanks,
Doug & Trude

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Sent: Wednesday, February 19, 2020 10:27 AM
To: (b) (6) ;(b) (6) ; Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke (b) (6) >;(b) (6) ; Robert Wood <(b) (6) ;(b) (6) (b) (6) <(b) (6) ; Daniele Visioni <(b) (6) >;(b) (6) ; Peter Irvine <(b) (6) >; Jonathan Proctor (b) (6) ;(b) (6) ; Keith, David (b) (6) >; Kravitz, Ben (b) (6) >; Wake Smith <(b) (6) >; Izidine Pinto (b) (6) ; Gabriel Chiodo (b) (6) >; Keutsch, Frank N <(b) (6) >
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Subject: RE: 2020 GRC program

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Thanks, and see you in June!
doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) ;(b) (6) 'Jadwiga (Yaga) Richter' (b) (6) >; Alan Robock (b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >;(b) (6) ; Robert Wood (b) (6) >;(b) (6) ;(b) (6) <(b) (6) >; Daniele Visioni <(b) (6) >;(b) (6) Peter Irvine <(b) (6) >; Jonathan

Proctor <(b) (6) >; Govindasamy Bala <(b) (6) >; (b) (6)
Keith, David (b) (6) >; Kravitz, Ben <bkravitz@iu.edu>; Wake Smith
<(b) (6) ; Chris Field (b) (6)
Cc: Lawrence, Mark (b) (6) >; valentina Aquila <(b) (6) Ulrike
Niemeier <(b) (6) >; Leisner, Thomas (IMK) <(b) (6) Olivier
Boucher (b) (6) >; Schrag, Daniel P. (b) (6) ; TAYLOR,Michael
(b) (6) ;(b) (6) ; Lynn Russell (b) (6) Trude Storelvmo
<(b) (6) 'Simone Tilmes' (b) (6) >; (b) (6)
Subject: 2020 GRC program

Hi all,

Happy New Year!

The full program for GRC is due on February 28; if you haven't sent us a title for your talk (or if you did and want to revise it), please do so before the end of February so I have time to enter everything into the conference management system online.

The cc-line has discussion leaders for each session.

Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin
Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and
Faculty Fellow, Atkinson Center for a Sustainable Future
Cornell University
(b) (6)
https://climate-engineering.mae.cornell.edu/

From: Andrea Smith (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Karen Rosenlof - NOAA Federal
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Graham Feingold - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:36 AM (UTC-04:00)

Good morning everyone,

If you haven't already done so, please reply here with slide decks or drop them in (b) (6) if large file size.

See you in 10-15 mins!

Cheers,

Andrea

On Fri, Sep 17, 2021 at 2:43 PM Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov> wrote:

> And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
> So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.
>
> Thanks!
>
> Karen
>
> --
> Karen Rosenlof
> NOAA Chemical Sciences Laboratory
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> 325 Broadway
> Boulder, CO 80305
> office: 3A-121, DSRC
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>>
>> Please join 10 mins early to test tech and troubleshoot if needed.

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3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.

After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.

Let me know if you have questions on any of the above.

Thanks again, and see you next Wednesday.

Andrea

On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) wrote:

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> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>
> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
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> 1. Frank Keutsch: ...
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> Here is Andreas rundown for logistics:
>
> -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
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>
> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
>
> Cheers, Simone
>
> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*

> > *303-497-1400 (fax)*
> > (b) (6)
>
> --
> Andrea Smith
> Associate Scientist & Program Manager
> The COMET® Program
> University Corporation for Atmospheric Research
> 3085 Center Green Dr.
> Boulder, CO 80301
> 303-497-8320 (office)
> (b) (6) (cell)
>
> *My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.*
> <CCISspeaker_consent_form.pdf>

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From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Nice job on the NOVA episode!
To: Kelly Wanser
Cc: Frank Keutsch; John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:19 PM (UTC-04:00)
Attached: Untitled attachment

Kelly,
I think you want to praise David K instead of me. I too thought they all did a great job.
Dave

> On Oct 29, 2020, at 1:12 PM, Kelly Wanser (b) (6) wrote:
>
> You were excellent and the piece came out great.
> We'll promote it as we are able.
>
> Best,
> k.
>
> --
> Kelly Wanser
> Executive Director, SilverLining | http://www.silverlining.ngo
> Board Director, Dendra Systems | http://www.dendra.io
> Advisor, University of Washington Marine Cloud Brightening Project | http://www.mcbproject.org
> President's Circle, National Academy of Sciences | http://nas-sites.org/PC/
> Phone: (b) (6)
>
> **TEDTalk:** *Emergency Medicine for Our Climate Fever*
> **Report:** *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: Peter Irvine (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin
Cc: Piers Forster; (b) (6) Alan Robock; Karen Rosenlof - NOAA Federal; Katharine Ricke; Seneviratne Sonia Isabelle; Robert Wood; Helene Muri; (b) (6) Daniele Visioni; Isla Simpson; Jonathan Proctor; Ines Camilloni; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N; Trude Storelvmo; Simone Tilmes; Lohmann Ulrike
Sent: July 18, 2021 4:53 PM (UTC-04:00)

Hi Doug, Trude,

It's be happy to present in 2022, with the same title for now.

Cheers,

Pete

On Thu, Jul 15, 2021, 16:06 Douglas MacMartin (b) (6) > wrote:

> Hi all,
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Faculty Fellow, Atkinson Center for a Sustainable Future

Cornell University

(b) (6)

[redacted]

https://climate-engineering.mae.cornell.edu/

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To: David Fahey - NOAA Federal; David Keith
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Sent: October 29, 2020 3:22 PM (UTC-04:00)

Ha, thanks, Dave. Adding David here.
Terrific piece, David!

Sent from my iPhone

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>> Phone: (b) (6)
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From: Smith, Wake (b) (6) [redacted]
Subject: RE: CCIS webinar Wednesday Sept 22nd
To: Karen Rosenlof - NOAA Federal
Sent: September 18, 2021 7:59 AM (UTC-04:00)

Will do.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6) [redacted]

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Sent: Friday, September 17, 2021 4:44 PM
To: Andrea Smith (b) (6) [redacted]
Cc: Simone Tilmes (b) (6) [redacted]; Keutsch, Frank N (b) (6) [redacted]>; Smith, Wake <(b) (6) [redacted]; Graham Feingold - NOAA Federal <Graham.Feingold@noaa.gov>; Brian Medeiros (b) (6) [redacted]
Subject: Re: CCIS webinar Wednesday Sept 22nd

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So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.

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> *National Center for Atmospheric Research*
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> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6)

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<CCISspeaker_consent_form.pdf>

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Newsletter from Harvard's Solar Geoengineering Research Program
To: Keith, David
Cc: Frank Keutsch; Ronda Knott - NOAA Federal
Sent: December 28, 2020 11:44 AM (UTC-05:00)
Attached: Untitled attachment

David,
Good, yes let's talk on the 6th.
Ronda can arrange a time and link.
Happy New Year.
Dave

> On Dec 28, 2020, at 9:30 AM, Keith, David <(b) (6) [redacted]> wrote:
>
> Dave
>
> Yes, we expect to fly POPS.
>
> Also, interesting developments on turbulence.
>
> Now that this mission seems to be (finally) coming together it would be good how about the three of us to touch base again about this and about the meeting to discuss future flight missions?
>
> How about Wednesday the 6th?
>
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, December 26, 2020 5:51 PM
> **To:** Keith, David (b) (6) [redacted]
> **Subject:** Re: Newsletter from Harvard's Solar Geoengineering Research Program
>
> David,
>
> Thanks for the newsletter. I am impressed with your productivity.
>
> Good progress with Esrange launch plans and committee approval. Do you plan to fly POPS? It would be of value to get a high lat profile and adds to your flight data return. No communication with the device is needed since it records onboard. Let us know if you want assistance.
>
> We have prepared a POPS unit and backup to fly on the World View Stratollite in 2021 when they are able to resume launches.
>
> I hope you and yours are doing well enough this Holiday Season. We are OK.
> Regards
> Dave

On Dec 16, 2020, at 9:18 AM, David Keith (b) (6) wrote:

Dear Readers,

As this strange year comes to a close, we wanted to share updates from Harvard's Solar Geoengineering Research Program (SGRP), which supports research at Harvard on the science, technology, and governance of solar geoengineering.

We hope everyone and their families are safe and well. We wish you a healthy new year.

Yours,
David Keith and Lizzie Burns
Faculty Director and Managing Director
Harvard's Solar Geoengineering Research Program

SCoPEx

SCoPEx Update

Led by Frank Keutsch, the Stratospheric Controlled Perturbation Experiment (SCoPEx) is a scientific experiment to advance understanding of stratospheric aerosols that could be relevant to solar geoengineering. It aims to reduce the uncertainty around specific science questions by making quantitative measurements of some of the aerosol microphysics and atmospheric chemistry required for estimating the risks and benefits of solar geoengineering in large atmospheric models.

The SCoPEx research team has asked the independent SCoPEx Advisory Committee to review our plans for a proposed platform test in Sweden in June 2021. This test would notbe the experiment itself, but rather a test of the SCoPEx platform without the release of any particles. Specifically, we would like to test the gondola's horizontal and vertical control using the winch system and propellers as well as the power, data, navigation, and communication systems. We would not release any aerosols, nor fly an aerosol injection/release system. Still, we will not proceed with this flight without a formal recommendation authorizing the flight from the Advisory Committee to Harvard management. We have asked the Advisory Committee if they can complete their review and reach a decision—be it positive or negative—about this platform test by February 15, 2021. You can learn more about this platform test here.

SCoPEx Advisory Committee

Recognizing the complex societal and governance issues surrounding solar geoengineering, Harvard has ensured the SCoPEx project has the guidance of an independent Advisory Committee, as noted above. The Advisory Committee has already begun to carry out a significant amount of work, including a financial review, legal review, and scientific and technical review, and they have proposed a draft process for a societal engagement review. You can learn more by visiting their website. We are grateful for the time the Committee members are volunteering and look forward to the work ahead.

Opportunities

SGRP Fellowship

SGRP is now accepting applications to its 2021 Fellowship Program, which offers short-term and long-term opportunities. Applications are due January 29, 2021. We are seeking applications from scholars in a range of disciplines, including the natural sciences, economics, law, government, public policy, public health, medicine, design, and the humanities. We also are looking for applicants who are new to the field of solar geoengineering and/or have critical views, and we strongly encourage applications from

women and minority candidates. More information can be found here.

We would also like to congratulate our current and future fellows who were accepted during our previous fellowship application process.

- Cody Floerchinger, (August 2019-July 2021) advised by Frank Keutsch, is using datasets from upcoming measurements campaigns to provide a comprehensive analysis of the state of our ability to model stratospheric plume dynamics and highlight areas where the community should focus its efforts when attempting to improve these model products (science).
- Yuanchao Fan, (October 2019-October 2021) advised by Kaighin McColl, is quantifying the impact of solar geoengineering on terrestrial ecosystems, including forests and agriculture, and their biophysical and biogeochemical feedbacks to climate. He is also collaborating with David Keith on a paper about geoengineering and food supply (science).
- Irina Bakalova (February 2021-April 2021) will be advised by Professor Rob Stavins, working closely to study the effectiveness and stability of potential international agreements on solar geoengineering (economics).
- Britta Clark (February 2021-June 2021) will be advised by Lucas Stanczyk and will analyze the intergenerational justice impacts of solar geoengineering as a mitigative strategy to address climate change (philosophy).
- Ermanno Napolitano (August 2021-July 2022) will be advised by Lucas Stanczyk and will catalogue and explore all of the existing international legal principles that are likely to have some bearing on the deployment of solar geoengineering (law).

Online Community for Junior Researchers

A group of junior scientists are organizing a diverse online community of young researchers new to the solar geoengineering field, designed to engage researchers with new perspectives. This group will provide young researchers the chance to informally present on their research, share ideas, receive feedback, and create a space for open and non-judgmental discussion on the topic. The first few sessions took place in November and December and were held live on Zoom. Graduate students and recent postdocs from across the globe, including from developing countries, discussed various publications containing alternate viewpoints on solar geoengineering. Future sessions scheduled include presentations by a former SGRP DECIMALS resident and other participants as well as discussion forums and networking opportunities on Slack. Undergraduate students, graduate students, and postdoctoral fellows within five years of completing their degree are welcome to join the group. If you are interested in participating, please email Selena Wallace: swallace@seas.harvard.edu.

Events

Due to COVID-19, we had to cancel in-person events beginning in March. Since that time, we have held countless Zoom conversations (like so many others). For example, in November we hosted a public health workshop at Harvard to try to broaden the diversity of researchers studying solar geoengineering on campus. We are also now in the process of building an exciting opportunity that will allow us to reach a broader audience outside of Harvard that will include experts, practitioners new to solar geoengineering, and the general public. We invite you to join us.

Public Health Roundtable

In November 2020, we held a virtual event with the Harvard Chan School of Public Health Center for Climate, Health, and the Global Environment where experts from both the geoengineering and the public health communities had the opportunity to discuss the potential public health challenges posed by solar geoengineering. Few studies to date have considered the public health implications of geoengineering, and those that have have been limited to mortality due to ambient air pollution and UV-induced malignant melanoma. This event discussion addressed questions of the risk factors that these studies might be omitting, the vast array of other public health issues that may arise, as well as the environmental justice implications of human interventions to the climate system such as geoengineering. The organizers of the event may publish a paper that summarizes the key points and questions to hopefully inspire other experts in the public health field to begin research on solar geoengineering. Overall, this event was significant because it not only signaled new interest from various public health experts who, years prior, had not yet engaged, but also because it will hopefully unlock even more new interest from a critical community that has yet to fully participate in solar geoengineering research.

Public Seminar Series

In the spring of 2020, we will launch a virtual seminars series to promote understanding and discussion of solar geoengineering and to enable audiences to learn from a broader set of perspectives in the area of solar geoengineering research and public policy. These seminars will contain a combination of practitioners and experts from around the world and will have a variety of formats including single speakers, moderated debate, and moderated panels. Previously, SGRP seminar attendance was limited to the Harvard community, but we are now able to extend the reach of this series to a global, public audience. We invite you to participate in these seminars. We will email this listserv when seminars are scheduled.

Publications, Video, and Audio Clips

The following written publications were funded all or in part by SGRP.

Recent Peer Reviewed Publications

Zhen Dai, Debra K. Weisenstein, Frank N. Keutsch, and David W. Keith. (2020). "Experimental reaction rates constrain estimates of ozone response to calcium carbonate geoengineering." Communications Earth and Environment 1, 63.

Jacob T. Seeley, Nicholas J. Lutsko, and David W. Keith. "Designing a radiative antidote to CO2." Geophysical Research Letters (Submitted).

Joshua B. Horton and Barbara Koromenos. (2020). "Steering and Influence in Transnational Climate Governance: Nonstate Engagement in Solar Geoengineering Research." Global Environmental Politics 20, 3: 93-111.

Nicholas J. Lutsko, Jacob T. Seeley, and David W. Keith. (2020). "Estimating Impacts and Trade-offs in Solar Geoengineering Scenarios With a Moist Energy Balance Model." Geophysical Research Letters 47, 9.

Joshua B. Horton, Penehuro Lefale, David Keith. (2020). "Parametric Insurance for Solar Geoengineering: Insights from the Pacific Catastrophe Risk Assessment and Financing Initiative." Global Policy, Special Issue.

David Keith and Peter Irvine. (2020). "Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards." Environmental Research Letters 15, 4.

Jesse Reynolds and Joshua Horton. (2020) "An earth system governance perspective on solar geoengineering." Earth System Governance, 3.

Other Publications

David W. Keith and John Deutch (2020) "Climate Policy Enters Four Dimensions." In *Securing our Economic Future,* edited by Amy Ganz and Melissa Kearney, Aspen Institute Press.

Cody Floerchinger, John Dykema, David Keith, and Frank Keutsch (2020) "A Need for In Situ Observations to Inform Nearfield Plume Transport and Aerosol Dynamics as well as Chemistry of Alternate Geoengineering Materials in the Stratosphere." Letter to the National Academy for Science.

David Keith, Frank Keutsch, and Cody Floerchinger (February 15, 2020) "Empirical methods to reduce uncertainty about solar geoengineering," public input to the National Academy Committee on *Climate Intervention Strategies that Reflect Sunlight to Cool Earth*.

Recent Video and Audio Recordings

AGU TV (December 2, 2020). "SCoPEx, Harvard University – New Frontiers in Climate Change Research." WebsEdge Science.

Anthony Padilla (October 23, 2020) "I spent a day with climate change scientists" *Youtube*.

PBS Nova (October 16, 2020). "Can We Cool the Planet?" *WGBH*.

Harvard Magazine (October 16, 2020). "Daniel Schrag and David Keith: Can Solar Geoengineering Help Fight Climate Change?"

All Things Considered (July 22, 2020) "Harvard Scientists Plan First-Ever Field Experiment Related To Solar Geoengineering." *WBUR*. (This aired again on Here & Now on December 4, 2020 as "Experiment To Help Researchers Understand Risk, Efficacy of Solar Geoengineering.")

Harvard Museum of Natural History (December 12, 2019) "The Peril and Promise of Solar Geoengineering" *Youtube*.

From: Andrea Smith (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Graham Feingold - NOAA Federal
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Karen Rosenlof - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:49 AM (UTC-04:00)

https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09

Do you need to use the web client? NOAA or other government users can use Zoom’s government-approved web client

Try that, let me know how it goes.

A

On Wed, Sep 22, 2021 at 8:47 AM Graham Feingold - NOAA Federal <graham.feingold@noaa.gov> wrote:

> zoom link not working for me. is there something else i need to do?
>
> On 9/17/21 11:06 AM, Andrea Smith wrote:
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> > Hello Frank, Wake and Graham,
> >
> > Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
> >
> > 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
> > https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
> > Meeting ID: 816 4261 9898
> > Passcode: 148321
> >
> > Please join 10 mins early to test tech and troubleshoot if needed.
> >
> > 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) (preferably by Tuesday night):
> >
> > 3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.
> >
> > After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.
> >
> > Let me know if you have questions on any of the above.
> >
> > Thanks again, and see you next Wednesday.
> >
> > Andrea
> >
> > On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) > wrote:
> >
> > > Hi Frank, Wake and Graham,
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> 1. Frank Keutsch: ...
> 2. Wake Smith:...
> 3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening
>
> Here is Andreas rundown for logistics:
>
> -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
> -send slide decks to Andrea by Tuesday (9/21) evening for backup purposes
> -arrive ~10 mins early so we can do quick test of screenshares
> -15 min talk length, w/ immediate clarifying question(s) and then ~30 mins broad discussion and questions at end
> -moderator will collect questions in chat window throughout and ask most pertinent ones for discussion
> -panelists and question askers encouraged to unmute & turn on camera
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> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
>
> Cheers, Simone
>
> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6) [redacted]

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) [redacted] (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

--
Graham Feingold
NOAA Earth System Research Laboratories
Chemical Sciences Laboratory (R/CSL9)
325 Broadway
Boulder, Colorado 80305, USA

> Tel: (303) 497-3098
> Fax: (303) 497-5318

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From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Andrea Smith
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Graham Feingold - NOAA Federal; Brian Medeiros
Sent: September 17, 2021 4:44 PM (UTC-04:00)
Attached: Untitled attachment

And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.

Thanks!

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
Boulder, CO 80305
office: 3A-121, DSRC
e-mail: Karen.H.Rosenlof@noaa.gov
phone: 303 497-7761
fax: 303 497-5373

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while safer at home remains in effect, email is the most reliable contact

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>
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(b) (6)

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<CCISspeaker_consent_form.pdf>

The Stratospheric Controlled Perturbation Experiment (SCoPEx)

Version 1.0

Executive Summary

Climate model studies of stratospheric solar radiation modification (SRM) depend, perhaps implicitly, on processes that take place in the near field of an injection plume. This is because materials delivered to the stratosphere by aircraft will form persistent, high aspect-ratio plumes with strong gradients before becoming well mixed, and processes within the plume will alter the large-scale, well-mixed aerosol and chemical properties that are simulated in global atmospheric models. All models ultimately depend on observations, yet we lack experimental data to assess some of the critical transport, microphysical, and chemical processes that directly control aerosol dynamics in the near-field that are important for understanding stratospheric SRM.

The scientific goal of the Stratospheric Controlled Perturbation Experiment (SCoPEx) is to improve process models that will, in turn, reduce uncertainties in global-scale models, thus reducing uncertainty in predictions of important SRM risks and benefits.

SCoPEx addresses questions in stratospheric aerosol injection (SAI) research that observations of existing analogues are incapable of addressing. For example, existing observational data do not include chemistry of alternate geoengineering materials specific to SAI, near-field particle microphysics of injection plumes, and relevant scales of atmospheric transport in the near-field. Yet these are needed to assess processes that control aerosol dynamics in the near field of an injection plume and that allow for the evaluation of alternate SAI materials, i.e., materials other than the naturally existing sulfate aerosol.

We first review why existing observations do not address the questions that SCoPEx will answer. We then give a description of the basic design of the platform and the concept of operations of SCoPEx. Finally, we describe the three specific science goals of SCoPEx, explain how they represent critical knowledge gaps in SAI research, and specify what measurements are needed to enable SCoPEx to provide quantitative answers to these questions. The three specific science goals are improving understanding of (i) turbulent mixing scales, (ii) aerosol microphysics with a focus on alternative SAI materials in the near-field of an injection, and (iii) process level chemical interactions of alternative SAI materials in the stratosphere.

We do not provide a detailed engineering document of the SCoPEx platform or its scientific instrumentation, nor do we provide a justification for the need for research on SRM via SAI in general. Rather, we focus specifically on the merits of SCoPEx itself.

1. Introduction

In this document we focus on the motivation and scientific merit of SCoPEx. We do not provide detailed engineering documentation of the SCoPEx platform or its scientific instrumentation. We also do not provide general justification for the need for research on solar radiation modification (SRM) via stratospheric aerosol injection (SAI), which can be found in many prior documents such as the 1992 NAS report that recommended the US government "Undertake research and development projects to improve our understanding of both the potential of geoengineering options to offset global warming and their possible side effects. This is not a recommendation that geoengineering options be undertaken at this time, but rather that we learn more about their likely advantages and disadvantages" (National Academy of Sciences et al., 1992) or the recent 2015 NAS report (National Research Council, 2015). Rather, we focus specifically on the need for small-scale field experiments such as SCoPEx, and the specific, critical SAI research needs that will be addressed by SCoPEx.

1.1. Role of and Need for Small-Scale Field Experiments

There is a vast array of science and engineering questions that have to be answered to achieve a better understanding of the risks, benefits and feasibility of SAI. The tools and topics that are needed to address these questions range from General Circulation Models (GCMs) all the way to detailed design of instrumentation to monitor or disperse aerosol. SCoPEx addresses a subset of questions that require small-scale field experiments for ground-truthing and that are aimed at improving the ability of models to predict the consequences of SAI.

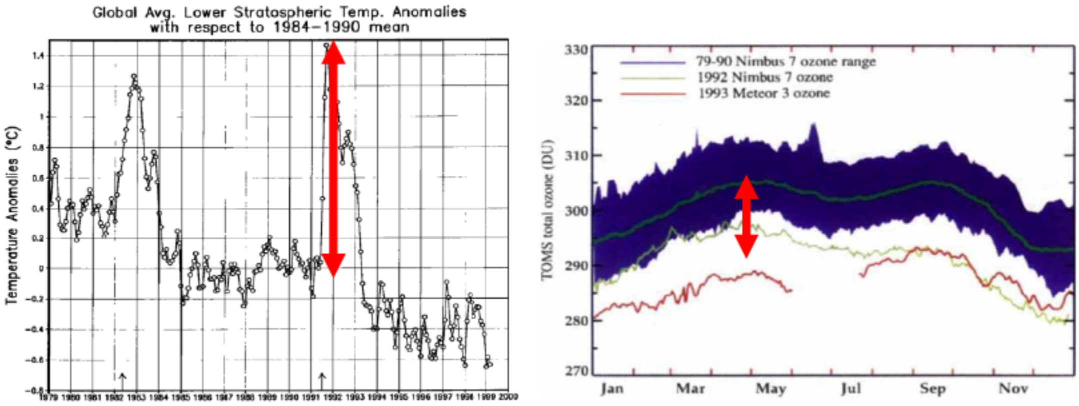


Figure 1: The two most important first-order stratospheric risks from sulfate SAI. The left panel shows stratospheric temperature anomalies from the El Chichon and Mount Pinatubo eruptions on top of background temperatures that are decreasing due to greenhouse gas emissions (Robock, 2000). The dynamical response of the stratosphere from such a short heating pulse likely is different than from sustained heating from longer-term SAI. The right panel shows that in the two years following the Mount Pinatubo reaction total ozone columns were lower than in the 1979-90 average as a result of increase sulfate aerosol surface area. Smaller eruptions also contributed to this. (McCormick et al., 1995)

There are numerous known risks associated with SAI, and SCoPEx focuses primarily on improving understanding of the first-order impacts in the stratosphere, i.e., risks and risk reduction associated with impacts of SAI within the stratosphere. There are many downstream / higher-order risks, e.g., impact on cloud formation as SAI particles leave the stratosphere (Cziczo et al., 2019), impacts on ecosystems via changes in the hydrological cycle (Bala et al., 2008; Russell et al., 2012; Tilmes et al., 2013), or the amount of direct

versus diffuse radiation (Gu et al., 2002; Farquhar & Roderick, 2003; Gu et al., 2003). Despite their importance, these impacts are not the direct target of this proposal although many of these are also influenced by stratospheric processes and properties of SAI aerosol. Two first-order risks are at the focus of this work: stratospheric ozone loss and the dynamic response resulting from stratospheric heating as a result of SAI.

Whereas stratospheric ozone chemistry is fairly well understood (World Meteorological Organization, 2019), there are still substantial uncertainties in the understanding and ability to model stratospheric dynamics (Figure 1). For example, models have only recently been able to reproduce the quasi-biennial oscillation without having it imposed (see Butchart et al., 2018 for a discussion of challenges). One approach taken in this work is to evaluate whether there are types of aerosols or methods of aerosol injection that can reduce first-order risks for a given amount of radiative forcing. It stands to reason that a reduction in the first-order stratospheric impacts will reduce downstream and higher-order risks. A case in point is the growing body of work that has been investigating the impacts of stratospheric heating on stratospheric water vapor and the dynamic response on regional climate (Simpson et al., 2019; Ferraro et al., 2015; Richter et al., 2018; Ji et al., 2018). It is important to note that the amount of stratospheric heating for a given material will be primarily driven by the total mass of aerosol, ozone destruction will be driven by the total surface area of aerosol, and the desired radiative forcing will be determined by the amount and size distribution of aerosol. Critically, both the aerosol mass required for a given desired radiative forcing *and* the resulting surface area are tied to this size distribution. Therefore, accurate models of the evolution of the size distribution of injected aerosol are critically needed. In addition, alternate materials with reduced stratospheric heating have to be investigated, as do injection methods for sulfate that minimize stratospheric heating and ozone loss for a given radiative forcing, as this will reduce risks associated with the dynamic response to this first-order perturbation.

2. Observational SAI Research Needs

Most of the rapidly growing body of literature on SAI rests on General Circulation Models (GCMs). We acknowledge the importance of GCM studies, but in the following we focus on research needs that require experiments and observations, and especially questions that can only be answered by conducting perturbative field experiments such as SCoPEx (see supplemental manuscripts Keith et al., 2020 and Floerchinger et al., 2020). In fact, SCoPEx will in the end inform GCMs by providing improved process level information that will be integrated in parameterizations used in GCMs. Below we review existing observational data sets and describe their utility for different SAI approaches, highlighting where they are unable to shed light on critical issues thus motivating studies like SCoPEx.

2.1. Field Experimental Needs for Sulfate SAI

Most studies that have sought to research SAI have assumed the addition of aerosol would take place by means of an injection of gas-phase SO_2, which is ultimately converted to H_2SO_4 and then to sulfate aerosol in the stratosphere on a timescale of approximately one month. The aerosol size distribution from this injection of gas phase precursor must be accurately predicted as it will control the shortwave (SW) scattering properties, the stratospheric lifetime of the aerosol, and ultimately be the driver for the radiative forcing (RF) efficiency per mass of injected sulfate. Some studies, such as Niemeier & Timmreck (2015), have suggested that with higher injection rates of SO_2, the resulting sulfate aerosol would be forced into a larger, coarse-mode size distribution and functionally reach a point of diminishing return. In this diminishing return scenario, the added amount of SW RF achieved per added mass of sulfate decreases exponentially.

Recent work by Pierce et al. (2010), Benduhn et al. (2016), and Vattioni et al. (2019) has highlighted the potential benefits of injecting H_2SO_4 aerosol directly into the accumulation mode (AM), i.e., aerosols with a radius of 0.1–1.0 µm, potentially by emitting H_2SO_4 vapor into an aircraft plume. This work has suggested better control of the resulting aerosol size distribution and thus the radiative forcing per unit mass sulfur injection, which would allow for the design of a system that maximizes the radiative forcing per mass of sulfate in a way that would not have the diminishing returns at high SO_2 injection rates. This would thus minimize the increase in the stratospheric sulfate burden and hence the risk of stratospheric heating which is driven by total mass whereas ozone loss is driven by surface area. While injecting AM–H_2SO_4 may represent the best possible approach for SAI with stratospheric sulfate, there is currently no proven way to introduce vapor phase AM–H_2SO_4 into the stratosphere. As AM–H_2SO_4 has not been studied, perturbative experiments are required to provide observational constraints on the aerosol size distributions predicted by models.

2.2. Field Experimental Needs for Alternate Aerosol Material SAI

Though sulfate aerosol does exist in the background stratosphere and there are some natural analogs of broad stratospheric sulfate injections (volcanic eruptions), it likely is not the optimal candidate for SAI. Alternative aerosol may be most appropriate in order to mitigate SAI risks (Teller et al., 1996; Crutzen, 2006; Ferraro et al., 2011; Ferraro et al., 2015; Weisenstein et al., 2015; Keith et al., 2016; Dykema et al., 2016; Weisenstein et al., 2015). These alternate aerosols could reduce the previously noted two major first-order stratospheric impacts, i.e., changes in ozone and stratospheric heating. Due to the uncertainties in the impacts of stratospheric heating, the study of materials with optical

properties that negate stratospheric heating is especially important. Materials such as calcium carbonate ($CaCO_3$), alumina (Al_2O_3), diamond (carbon), and several others, have been proposed as a way to minimize the inherent risks from SAI (Keith et al., 2016; Dykema et al., 2016; Weisenstein et al., 2015; Ferraro et al., 2015; Ferraro et al., 2011; Crutzen, 2006). Although model results of these aerosol species suggest that some of them possess optical properties that make them well suited to be used in a SRM scenario ($CaCO_3$, Al_2O_3, and diamond) (Dykema et al., 2016; Ferraro et al., 2011), the stratospheric aerosol microphysics of these compounds (especially coagulation) is poorly understood. As with AM–H_2SO_4 injections, there is a profound lack of in situ data to assess the ability to model the microphysics of alternative aerosols and the stratospheric chemistry of these materials. This is especially pertinent with respect to changes in ozone, and is exacerbated by the fact that these aerosols have no naturally existing analog in the stratosphere that could be studied. Because early studies suggest that these aerosols show much promise with respect to deploying SAI while mitigating the inherent risks of the deployment, it is imperative to design and execute in situ experiments in order to test our current understanding of the aerosol microphysics and observe the effects of alternative aerosol on the chemical composition and dynamics of the stratosphere.

2.3. Limitations in Existing Analogues

In this section we will review previous in situ studies of stratospheric plume processes, show how those datasets have contributed to our current understanding, and demonstrate the need for experiments such as SCoPEx to inform small-scale models of aerosol microphysics (nucleation and coagulation), plume transport and physical morphology, and chemical properties of new aerosol species that have thus far not been observed in the stratosphere. Because the nature of the injection scenarios (AM–H_2SO_4 or solid aerosols) are so complex compared to natural analogs, new experiments must be designed and implemented to provide observational constraints on our current nearfield modeling framework. Experimental data from carefully targeted small-scale studies would contribute to the development of nearfield-scale models that represent currently uncertain processes in detail.

We note that sub-grid scale processes do not represent the only unknowns in GCMs that are relevant to high-fidelity simulations of SRM scenarios, and that there are many large scale model phenomena which should be further assessed with observational evidence. However, here we focus on the need for in situ data to constrain sub-grid scale processes that can be addressed by SCoPEx and highlight the need for reducing the uncertainty in transport and aerosol dynamics and chemistry at this scale.

2.3.1. Limitations of Solid Rocket Motor Plume Observations

From 1996 to 2000 a number of rocket plumes were observed by high-altitude research aircraft. Generally, these missions involved a research team coordinating stratospheric sampling flights on either the NASA ER-2 or on the NASA WB-57 with coincident rocket launch events from either Cape Canaveral or Vandenberg Airforce Base. These studies sampled plumes from a host of rocket types including Titan IV, Space Shuttle (STS106, STS83, STS85), Delta II, Athena II, and Atlas IIAS.

Plumes were intercepted by the sampling aircraft between 5 and 125 minutes after emission from the rocket motor at stratospheric altitudes ranging from 11 to 19.8km (Voigt et al., 2013). The main science objective of these missions was to assess the stratospheric

ozone depletion potential of space exploration by understanding the halogen chemistry occurring as a result of the high-altitude rocket burn. However, in studying the effects on the ozone layer, this era of stratospheric sampling provided a unique set of plume measurements to study nearfield processes of chemical injections into the stratosphere.

While measuring the plumes from the Titan IV rocket (as a part of the United States Airforce Rocket Impacts on Stratospheric Ozone (RISO) Campaign) and attempting to develop a plume chemistry model to solve for the Cl_2 concentration in a rocket plume as it evolves shortly after its emission, Ross et al. (1997) noted the many assumptions that had to be made about the plume morphology in order to simulate the mixing and diffusion that the rocket plume had with the surrounding stratosphere. Their model solved for the Cl_2 concentration of a circular nighttime plume as it expanded in diameter along an isentropic surface. Subsequent aircraft measurements showed that plumes contained more than twice the predicted concentration of Cl_2 despite the plume being intercepted during the day time (when the Cl_2 reservoir should be somewhat depleted by the photolysis reaction $Cl_2 + h\nu \rightarrow 2Cl$), suggesting that there may be an error in the assumption of a circular plume morphology on the short transport time scales observed in this study ($\sim 28 min$).

Ross went on to publish a second study as a part of the RISO project in 1999, this time looking to quantify the size distribution of alumina aerosols emitted from the rocket engines which contained particulate alumina (Al_2O_3) (Ross et al.,1999). They compared measured aerosol size distributions from the WB-57F plume interceptions to results from an aerosol coagulation model and highlighted a massive discrepancy. The model predicted a much smaller aerosol size distribution with 1-10% of the aerosol mass being in the smallest (0.005μm) mode and the aircraft observed only fractions (<0.05%) of the model estimate in that same small mode. At the same time, over 99% of the aerosol mass sampled by the aircraft was found in the coarsest mode (2 μm), which the model was unable to predict. It is most likely that the model used in Ross et al. (1999) did not well account for the effects of ion mediated nucleation as described by Yu & Turco (1997). However, the data from Ross et al. (1999) was some of the first in situ data to highlight the uncertainty in stratospheric aerosol coagulation models. Alumina aerosol, as well as other solid aerosols, in contrast to liquid sulfate aerosol, have since been investigated as a candidate for use in SAI (Weisenstein et al., 2015). Therefore, it is imperative that we understand the chemical, coagulation, and accumulation properties of these and other solid aerosols in a stratospheric environment.

2.3.2. Limitations of Previous Stratospheric Aircraft Wake Crossing Observations

We can look to the few times high-altitude aircraft wake plumes have been sampled in situ for another example of stratospheric plume measurements. In the early 1990s the popularity and capability of the Concorde spurred discussions of a large fleet of High Speed Civil Transport (HSCT) aircraft that would operate in the lower stratosphere between 16 and 23 km. Scientists became concerned with the effects of high-altitude aircraft and high-altitude supersonic aircraft on stratospheric ozone destruction via the creation of a large NOx source in the lower stratosphere. NASA then launched several field campaigns using the ER-2 to study the exhaust profiles of high-altitude aircraft. In 1992 NASA commissioned the Stratospheric Photochemistry Aerosols and Dynamics Expedition (SPADE) to look at the effects of HSCTs. As a part of SPADE the ER2 sampled its own plume on several occasions by making a hairpin turn and heading into its original path, therefore measuring its own wake

(Figure 2). SPADE resulted in at least 11 published studies and some of these can inform us about the mixing and aerosol dynamics that may be relevant to an SAI scenario (Stolarski & Wesoky, 1993).

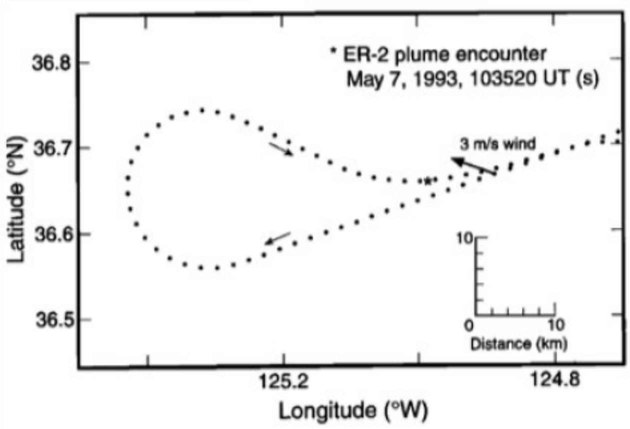


Figure 2: Shows the ER-2 flight track on a typical wake crossing trajectory (adapted from Fahey et al. 1995).

Fahey et al. (1995a) described measurements made of condensation nuclei (CN) present in the ER-2's exhaust plume from the emission of aerosol carbon and of sulfur compounds during one of its SPADE wake crossing events. Because the main focus of this study was to quantify the emission indices (EIs) of various compounds measured by the ER-2 that may have ozone depletion implications, they focused mainly on gas phase compounds. However, for the three wake crossings that the study focused on, they observed large variability in their EI measurements for CN. They noted that this is likely due to differences in mixing history of the encountered air parcels and noted that a full explanation of CN coagulation required more in-depth study and further measurements (Fahey et al, 1995b).

In another study published by Fahey et al. (1995b), they used a similar wake crossing technique to measure the exhaust of the Concorde aircraft and developed an aerosol coagulation model to predict particle formation and size as a function of the time since emission from the aircraft. The coagulation model was initialized at the observed conditions from the one-hour old Concord transect. The results from this model estimated that from 0 to 10 hr since emission from the engine, the mean particle diameter remained fairly constant at 0.06 µm before growing exponentially to a factor of 3 times its initial value over the next 1,000hr. The model predicted exponential mean particle diameter growth continuing right until the of the simulation at 1,000 hr (Fahey et al., 1995a).

Yu & Turco (1997) attempted to model the observed aerosol plume during the Concorde wake crossings with the goal of determining the driving factor for the large aerosol size distributions observed by the ER-2 in the exhaust which had not yet been explained by models. Yu proposed that aerosol formation was being aided by ion-mediated nucleation (IMN), that is, charged particles formed by chemi-ionization processes within the aircraft engines provide charged centers (H_2SO_4 [S(VI)]) around which molecular clusters rapidly coalesce. "The resulting charged micro-particles exhibit enhanced growth due to condensation and coagulation aided by electrostatic effects" (Yu & Turco, 1997). It is likely that IMN is the reason previous particle coagulation modeling of solid rocket motor plumes had overestimated the amount of aerosol in the small size ranges when compared to the in situ data, though this has not since been tested. Because of these effects, and the fact that specific size distributions of aerosol are desired to obtain the optimal radiative

forcing effects for SAI (nominally smaller than observed in rocket or aircraft plumes), we must understand the aerosol nucleation and coagulation dynamics in an unperturbed stratosphere.

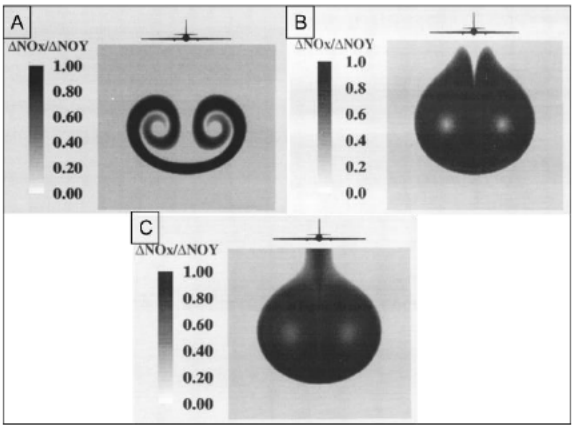


Figure 3: Shows the chemical and morphological evolution of an ER-2 plume during SPADE at 1.7 km (A), 4.8 km (B), and 7.9 km (C). (adapted from Anderson et al. (1996))

As a part of the SPADE project, Anderson et al. (1996) computed the flow field and chemical kinetics of the ER-2 aircraft exhaust using the Aerodyne Research Inc. UNIWAKE model. Their calculations address the effects of complex plume morphology on in-plume chemistry as a function of dilution time since emission from the aircraft engine. They showed that the plume morphology is highly variable out to about 5 km post emission Figure 3 and estimated that the stability of the wing vortex pair begins to break up at roughly 20 km post emission. Although this study was completed in the mid 1990s, it is still one of the only studies that attempts to compute nearfield chemistry within a dynamic stratospheric plume. However, particles were not considered as part of this study.

2.3.3. Limitations of Stratospheric Wake Crossings

Previous stratospheric plume studies of solid rocket motors and aircraft wake crossings have laid the foundation for our understanding of stratospheric plume chemical, aerosol, and mixing dynamics on transport scales of 0→100 km. These studies highlight the types of processes we must be aware of when considering the logistics of SAI. However, the violent initial conditions of engine exhaust plumes (such as temperatures of 700K, IMN) make it difficult to relate these observations to other systems. Because the engines drive the mixing and transport in the nearfield, and the ionic injection conditions of the plume create electrostatic forces that introduce complex nucleation affinities (IMN), understanding individual parameters can become analogous to finding a needle in a haystack. Moreover, because the radiative properties of any stratospheric aerosol that may be used for SRM depend on the diameter of the particle, we must understand the coagulation of that aerosol in the nearfield after the injection, which means that we must also understand the plume morphology that dictates the concentrations of that aerosol. Currently there have been no in situ data gathered that help us understand nearfield aerosol nucleation and plume dynamics in the absence of a very disruptive source. These conditions are necessary to understand as SAI may require that we mitigate the effect of IMN in order to obtain an aerosol size distribution that is small enough to provide the desired radiative properties.

2.3.4. Limitations of Naturally Occurring Analogs

Another source of useful in situ data on plume dynamics in the stratosphere can be found in literature addressing the fate and transport of convective overshooting events that often occur at the top of a Mesoscale Convective Complex (MCC). These events drive brief airmass exchange with the troposphere and often end up resulting in a plume-like parcel of tropospheric air being injected into the stratosphere.

Measurements of convective systems and upper troposphere-lower stratosphere exchange, as a means to interrogate stratospheric plume transport, have provided valuable in situ datasets that help us understand mid-field (10 to >1000 km) plume dynamics in the lower stratosphere. Similar to convective overshooting events, volcanic eruptions have provided an immense amount of in situ data that has informed us about regional and even global transport of stratospheric injections (Robock, 2000). Although their data are applicable in some sense to the transport of an SAI plume after its initial injection, the turbulent nature of a convective storm makes it difficult to measure these events at points near their injection source. Additionally, the storm conditions themselves dramatically complicate the system in the lower stratosphere such that is difficult to see through the effects of the induced turbulence in the nearfield. Indeed, an important limitation of these type of natural analogs is the spatial extent of their perturbation, which does not allow for near-field observations analogous to that of a point source. This also arises from the violent nature of these events which does not allow airborne platforms, such as the ER-2, to sample the initial conditions of the injection. We also note that volcanic eruptions are limited in their utility to evaluate dynamic response to stratospheric heating from sulfate aerosol, as they represent a perturbative pulse rather than the long-term heating one would expect from SAI.

In addition, these natural analogues provide extremely limited ability to study alternate materials, although organic and mineral dust aerosol injections into the lowermost stratosphere have been documented from convective overshoots. However, the complexity of the massive perturbations of both gas- and particle-phase preclude a study focusing on the impact on stratospheric composition and aerosol evolution that would result from SAI of a single material.

3. SCoPEx Short Overview

This section provides a brief overview of the engineering and operational aspects of SCoPEx. We first describe the platform, the instruments, and the concept of operations before describing the rationale for the overall SCoPEx design choices.

3.1. SCoPEx Platform

The SCoPEx gondola (Figure 4) is a balloon-born new research platform being developed at Harvard by the engineering and science staff within the Anderson/Keith/Keutsch laboratory group. The development builds on four decades of stratospheric research on aircraft, balloon, and rocket platforms that has focused on understanding the environmental chemistry of the ozone layer. The SCoPEx experiment was first described by Dykema et al. (2014). While many details of the design have changed, that paper still succinctly describes the advantages of choosing a balloon born platform over an aircraft, particularly for studying perturbations like solar geoengineering, and several of the limits of laboratory experiments that that could be addressed in a perturbative experiment like SCoPEx.

The gondola has three primary features: the frame, the ascender, and the propellers. The aluminum and carbon fiber frame contains two decks and a ballast hopper for coarse altitude control. One deck is primarily dedicated to platform support (power and flight control) and one deck is primarily dedicated to instruments. At the top of the gondola is an ascender and rope which allows the distance between the bottom of the balloon train and the gondola to vary from 0 to 150 m, which provides fine altitude control of the gondola. The ascender has been developed and tested by Atlas (Chelmsford, MA) building on their previous hardware in collaboration with the Harvard engineering team. The propellers serve two purposes: to create a well-mixed volume of air where observations of the aerosols and perturbed gas-phase can be made, and to reposition the gondola within the evolving aerosol plume. While the trajectory of the balloon and gondola system will be dictated by the balloon, the propellers allow for repositioning relative to the prevailing winds.

The ascender makes it impossible to have cables and other physical connections between the flight operations equipment and the gondola. Thus, the platform will handle its own communications and power. The SCoPEx platform will be powered using 28 V and 100 V DC power supplies which will power all operations on the platform including the propellers, ascender, and instruments. Elements of the flight platform are listed in Table 1. The gondola flight, flight safety, recovery parachute, and recovery operations will be managed by the balloon operator (in contrast to the SCoPEx team itself). Because the absolute velocity and distance capability of the gondola are so small compared to balloon drift, the trajectory will be determined by the balloon operator as if it was a passive nonpowered payload. During operations, the detailed float altitude will be jointly managed by the balloon operator via control of the balloon vents and the Harvard team via control of the ballast and ascender.

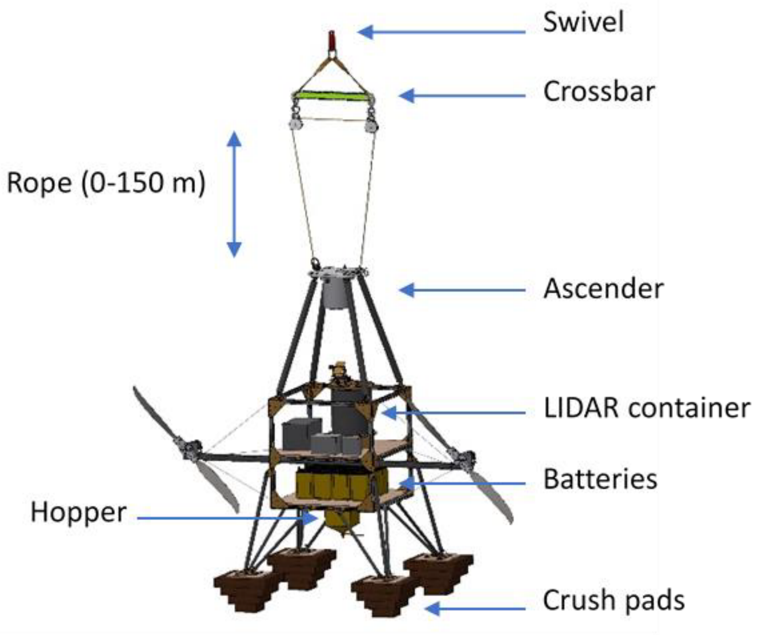


Figure 4: A representation of the SCoPEx flight platform. The final configuration may have subsystems packaged differently.

Parameter	Description
Total mass (Frame, all subsystems, hopper with ballast)	600 kg
Interface to balloon	Crosby 5-S-2 jaw & jaw swivel
Ascender	13 mm diameter rope Range of motion: 0-150 m Max speed: 10 m/min
Gondola propulsion	Twin propellers, 1.88 m diameter 32 N thrust each Max airspeed: 3 m/s
Power	28 V and 100 V DC power supplies with 24 MJ and 10 MJ total energy when fully charged
Communications	Satellite phone for communication between ground equipment and payload
Maximum termination shock	10 g

Table 1: Elements of the SCoPEx flight platform.

3.2. Instruments for First Science Flights (Science Goals 1 and 2)

The proposed instruments for the first science flight, addressing science Goals 1 and 2, are listed in Table 2. The corresponding science goals that motivate their inclusion are detailed in Section 4.

Measurement	Instruments	Rationale	Corresponding Science Goal
Wind speed measurement	Wind pendulum	Gondola and plume movement relative to balloon	Platform operation
Meteorology	Commercial off-the-shelf instrument	Temperature and pressure measurement throughout the flight	1, 2, 3
Wind turbulence	Constant temperature anemometer	Stratospheric mixing and modeling evolution of aerosol size distribution	1, 2
Particle dispersal	Solid Aerosolizer	Injects monodispersed particles for measurement and study	2, 3
Plume tracking	LIDAR	Tracking plume and navigation back into plume	2, 3
Particle sizer	POPS	Aerosol size distribution measurement for comparison with microphysics models of near-field evolution	2, 3
Light Scattering	Radiometer	Comparison of aerosol scattering with model prediction	2

Table 2: Instruments for first SCoPEx science flight.

Wind Pendulum: Understanding differential wind speed measurements between the balloon and payload will be important for plume evolution relative to the balloon trajectory and navigating the payload back into the plume. Commercial equipment to measure wind speed is typically not designed for the low densities found in the stratosphere. SCoPEx will therefore use a pendulum-based instrument and model to extract wind speed measurements. A camera will track a pendulum bob with high surface area and low mass, light enough to be perturbed by low winds in the stratosphere. Using the location and tilt data from the payload and a 3-dimentail kinetic model, the wind speed will be extracted from photos of the pendulum bob.

Commercial Meteorology Instrument: Commercial off-the-shelf instruments will be used for meteorological measurements on SCoPEx. They will record pressures and temperatures of the ambient stratosphere.

Constant Temperature Anemometer: A constant temperature anemometer (CTA) uses convective cooling caused by air flowing across a heated thin wire to measure flow velocity. LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere) (Gerding et al., 2009; Theuerkauf et al., 2010) used such a measurement to study stratospheric turbulence up to 29 km. LITOS consisted of a 5 μm diameter and 1.25 mm long tungsten wire CTA and a 16 bit ADC with 2000 samples per second to collect measurements with a vertical resolution of 2.5 mm at 5 m/s ascent speed. The anemometer data was analyzed by performing a spectral

analysis on the voltage signal to retrieve the spectral slope of the observed variation. A similar instrument will be used on SCoPEx to measure stratospheric turbulence. Air flow around the device will be simulated using CFD tools. The CFD runs will provide a means to identify key flow characteristics that drive sensor performance (sensitivity and accuracy), and to drive detailed sensor design.

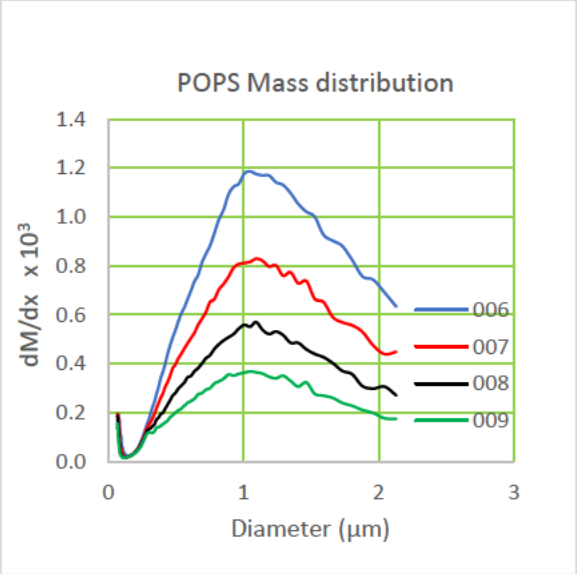


Figure 5: Successive measurements of sprayed $CaCO_3$ using an optical particle spectrometer. 006-009 indicate numbered time intervals spaced 4 minutes apart with 006 being the earliest measurement. $CaCO_3$ was sprayed using a 200 µm nozzle. In this laboratory experiment there was no significant variation in the shape of the distribution over time. (personal communication A Neukermans and team)

Solid Aerosolizer: The solid particle aerosolizer has been developed by a team lead by Armand Neukermans. For SCoPEx, the goal is to spray roughly monodisperse ~0.5 µm diameter precipitated calcium carbonate powder, the first candidate for solid SAI, through a 1-2 mm nozzle using the expansion of powder suspended in high pressure liquid CO_2. The aerosolizer would use a 1:4 weight ratio of $CaCO_3$ to CO_2. For 1 kg of $CaCO_3$ this would require a 5-7 L pressurized container. This concept has already been demonstrated in the lab. Figure 5 shows successive measurements of sprayed $CaCO_3$ with a size distribution centered at 1 µm diameter. Measurements were taken every 4 minutes using POPS (see below). In this case, total particle count decreased over time but there was no significant variation in the shape of the size distribution.

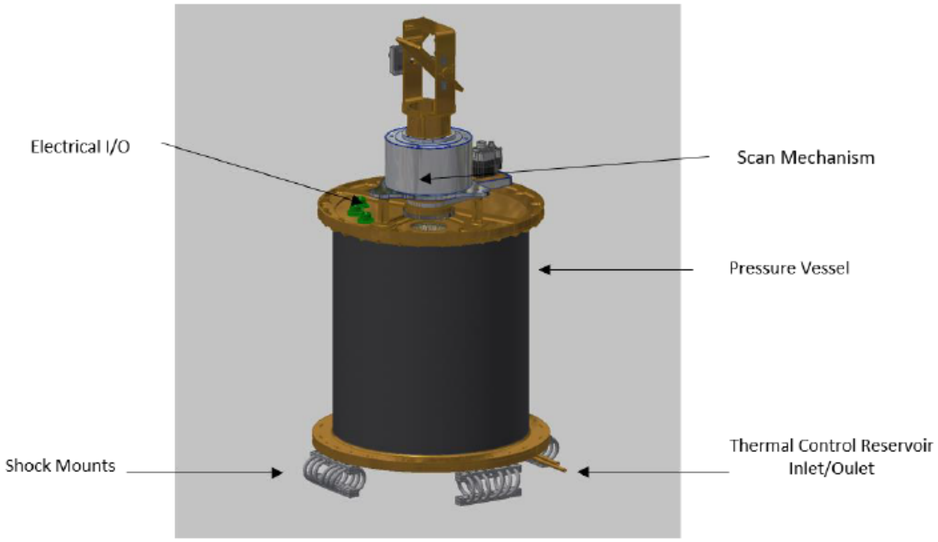


Figure 6: LIDAR pressure vessel provides safe storage and operating environment and support equipment.

LIDAR: The LIDAR is used to track the plume and allow navigation back into it. The core of the LIDAR system is an off-the-shelf eye-safe visible LIDAR, purchased from Sigma Space (now owned and operated by Droplet Measurement Technologies). This LIDAR produces 4 µJ pulses of 532 nm light at a repetition rate of 532 nm. The light that is backscattered by molecules and aerosols is collected by an 80 mm telescope and detected with a high-speed, high-sensitivity photodiode.

We have integrated this LIDAR in a pressure vessel (Figure 6) to provide a near-1 atm pressure environment with adequate temperature stability to ensure safe operation of the LIDAR at float altitude and safe storage on launch, ascent, descent, and recovery. This pressure vessel includes equipment for electrical and mechanical support, including command, data handling, and shock mounting. The LIDAR requires a scan capability to search the nearby atmosphere for the extent and geometry of the plume. The tilt and pan functions of the scan capability allows the LIDAR to be scanned over a set of angles that define the plausible location of the plume.

Portable Optical Particle Spectrometer (POPS): The POPS instrument will provide the aerosol size distribution measurements for studying aerosol formation and agglomeration. POPS is a light-weight instrument that directly samples the aerosol. It was built by and provided to SCoPEx through a collaboration with NOAA. The particles are illuminated with a 405 nm diode laser and the scattered light is collected onto a photomultiplier tube. The particle size is determined by the intensity of the scattered light. It has both the detection limit and size range (0.13 – 3 µm) to measure background stratospheric aerosol, which is more than sufficient for SCoPEx needs (Gao et al., 2016).

The Keutsch Group has already developed and extensively characterized a POPS instrument in preparation for the NASA-EVS3 Dynamics and Chemistry of the Summer Stratosphere field campaign on board the NASA-ER2, for which Keutsch is the deputy-PI. The POPS instrument tests include extensive thermal vacuum chamber characterizations to ensure operation under harsh stratospheric conditions. Compared to the ER-2, operation for SCoPEx will be simpler due to the insignificant air speed of the balloon and a much simpler operational pressure regime (on the ER-2 there is a large range of external pressures for both sampling and exhaust).

Radiometer: The aerosol plume can also be detected using a narrowband, narrow field of view radiometer with azimuthal/zenith pointing capability. The relationship between measurements of scattered solar radiation and the physical characteristics of atmospheric aerosols has been studied for more than two decades. Sky scanning measurements at multiple wavelengths between 300 nm and 1200 nm have been obtained using robotically pointed ground-based spectral radiometers deployed worldwide (Holben et al., 1998). The theory of these measurements has been refined and validated as a function of viewing geometry to provide a strong basis for inferring aerosol microphysics from radiometer data (Torres et al., 2014). The success of these approaches has motivated the development of compact sky scanning radiometers suitable for deployment on unsteady platforms like unmanned aerial vehicles (UAVs) and SCoPEx. One such design, reported by NOAA (Murphy et al., 2016), measures at 4 wavelengths (460 nm, 550 nm , 670 nm, and 860 nm) with a field of view of 0.006 sr (equivalent to 2.5° half-angle) and a circular limiting aperture of 1.1 mm diameter. A radiometer like this one deployed on SCoPEx would be capable of observing a SCoPEx plume, based on Golja et al. (2020), formed by a 0.1 g s^{-1} injection of calcite from a distance of 200 m with an approximate signal-to-noise ratio of 6000 for a 1 ms signal accumulation.

3.3. Instruments for Future Science Flights (Science Goal 3)

The additional instruments listed in Table 3 are candidates for future SCoPEx flights beyond the initial science flight, i.e., addressing science goal 3. They have not yet been adapted to fly on the SCoPEx platform. Instrument choices will be refined based on experiences in the first science flights. The corresponding science goals that motivate their inclusion are detailed in Section 4.

Measurement	Candidate Instrument	Rationale	Corresponding science goal
Aerosol composition	Drum Sampler	Collecting aerosols for offline analysis	3
Water Vapor	IR Absorption or Frost Point	H_2O outgassing of platform, Influence on coagulation and heterogenous chemistry	2, 3
Atmospheric trace gas concentrations (ex: HCl, NOx)	Spectroscopic trace gas instruments	For measuring concentrations of various atmospheric trace gases before and after addition of solid ASI material	3

Table 3: Potential instrument for future SCoPEx science flights.

Aerosol Composition: Aerosol composition can be analyzed via the collection of aerosol with a drum sampler followed by offline analysis in the laboratory using standard offline methods. Aerosol sampling has been done numerous times aboard stratospheric platforms.

Water Vapor: Gas-phase water vapor measurements are important as relative humidity likely has a large impact on the heterogeneous reactivity of solid SAI material. The balloon and gondola can outgas significant amounts of water and thus an initial experiment will characterize how long, if at all, this outgassing perturbs the SCoPEx plume. As mentioned previously, the goal of SCoPEx is to ideally minimize the perturbation to only the introduction of calcium carbonate. Water vapor measurements are common on many stratospheric platforms.

Hydrogen Chloride: HCl can be measured via infrared absorption spectroscopy. The Anderson group at Harvard, which shares a laboratory with the Keutsch group, has developed a stratospheric HCl instrument and thus has extensive experience with the design of stratospheric HCl instrumentation. In addition, the Keutsch group has designed multiple spectroscopic trace gas measurements. The much lower air speeds of the balloon compared to aircraft favor the design of an open path system, which eliminates the notorious wall effects that can make HCl measurements challenging.

NOx: For NOx there exist a number of good instrumentation options. Recently, a compact NO-LIF instrument has been designed that has spectacular detection limits in the low ppt range, more than sufficient for the needs of SCoPEx. The instrument is a close analogue of the fiber-laser based formaldehyde LIF instrument that the Keutsch Group developed, so there is a high degree of expertise available for such an instrument. There are also sensitive cavity enhanced techniques available usually in the visible range of the spectrum.

3.4. SCoPEx Concept of Operations

Flights will proceed in the following manner. The payload would be launched with the ascender retracted such that there is minimal distance between the crossbar and platform. Once the balloon reaches the float altitude, the rope will be let out through the ascender such that there is 100 m between the crossbar and platform. The platform will then be ready to perform experiments and execute maneuvers. Figure 7 illustrates a proposed flight maneuver. The platform will initially travel in a straight line laying out a plume, after which it will maneuver back through the plume to make measurements. During these maneuvers the ascender can be used to fine tune the altitude of the platform and instruments. Several series of such maneuvers can be performed within each flight. At the conclusion of the experiments the ascender retracts the rope before the descent.

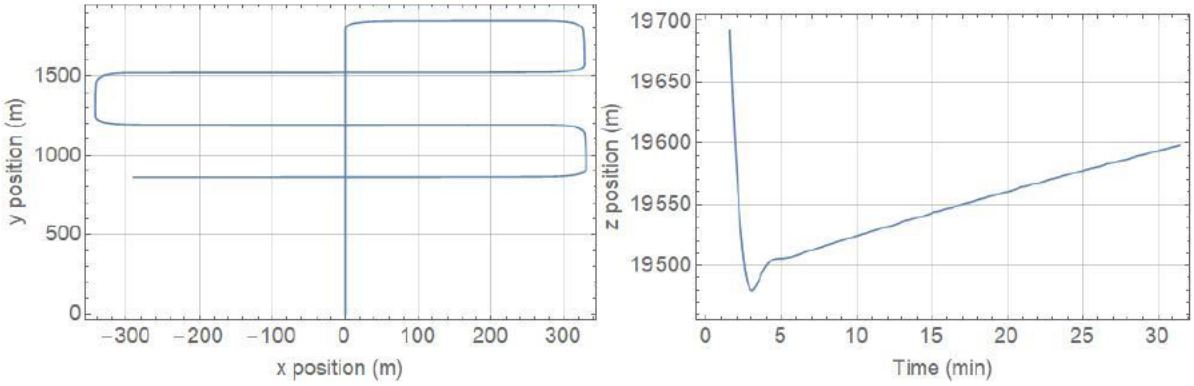


Figure 7: (left) A top down view of the proposed flight maneuvers over a 35-minute window. x and y are in the horizontal plane. The platform begins at (0,0). (right) The vertical position expected without any ascender or hopper vertical trimming over the same 35-minute platform maneuver.

4. SCoPEx Goals

In this section we describe the three long-term SCoPEx science goals. For each goal we describe the scientific problem, the need for SCoPEx, and the measurements required. The first phase of science flights targets the first two science goals. The design of the flights for the third goal will be informed by an understanding of the evolution of particle size distribution in the plume and the plume size. Thus, if later stage science flights move forward, they will be refined based on the results of the first science flights and the most up-to-date knowledge within the solar geoengineering and stratospheric science research communities.

4.1. Goal 1: Measurements of Turbulence for Small-Scale Mixing

4.1.1. The Importance of Plume-Scale Turbulence

Stratospheric turbulence influences the evolution of aerosol distribution from plume to regional to global scale. The mixing of air masses (of differing composition) in the stratosphere is a combination of two processes (Nakamura, 1996; Schoeberl & Bacmeister, 1993). The first process is strain, the distortion of streamline flow that brings air masses of differing composition adjacent to one another (Prather& Jaffe, 1990). Sometimes this is also referred to as “stirring” (Haynes, 2005). The second process occurs when air masses of differing composition are transported across the streamlines. This second process is the true “mixing” process.

In the stratosphere, mixing ultimately occurs because of molecular diffusion. This happens at the length scale of molecular viscosity. It is accelerated by turbulence, which can dramatically enhance the rate at which differing air masses are deformed to small enough spatial scales for molecular diffusion to mix them efficiently. Stratospheric turbulence is, however, highly intermittent (Vanneste, 2004). Understanding the mechanisms of stratospheric turbulence production is essential to understanding the spatial inhomogeneity and effective rate of mixing on spatial scales of 10-500 m (Schneider et al., 2017).

An understanding of this role of turbulence is of interest to stratospheric science because studies suggest that more accurate representations of mixing influence tracer distributions (Hoppe et al., 2014). Measurements of long-lived tracers are the strongest observational constraint on the stratospheric age of air, a key measure of the stratospheric large-scale circulation. Turbulence also modifies the character of kinetic energy fluxes. The magnitude and variability of these energy fluxes determine the rate of frictional dissipation in the atmosphere. This dissipation is represented in global models by a damping parameter and is the primary determinant of the mesoscale atmospheric kinetic energy spectrum. The uncertainty in kinetic spectrum is important to the understanding of the large-scale circulation of the middle atmosphere (Jablonowski & Williamson, 2011).

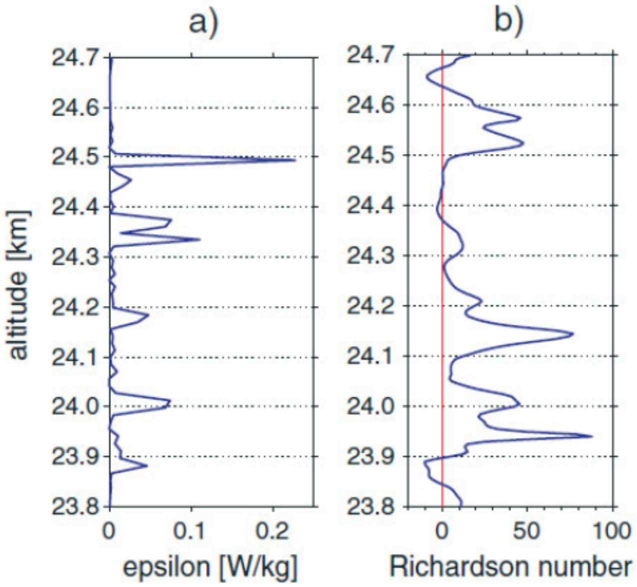


Figure 8: LITOS balloon-borne high-speed anemometer measurements reveal that models of atmospheric turbulence do not explain observed stratospheric turbulence. Physical models predict that a low Richardson number (buoyancy/shear ratio) implies turbulence, but high values of epsilon (turbulent dissipation) should be correlated with low Richardson number, which is not observed. (Haack et al., 2014)

Physical models predict that a low buoyancy/shear ratio (Richardson number) implies turbulence, and that high values of turbulent dissipation should be correlated with low Richardson number (Figure 8). However, recent balloon born measurements during the LITOS campaign did not agree with this, with numerous instances of high values of turbulent dissipation occurring at high Richardson numbers (Haack et al., 2014). As detailed above, both the impact of turbulence on mixing and the associated dissipation of energy are important for general stratospheric science. The point at which viscous fluid forces dominate atmospheric motion is the point where atmospheric motions become purely statistical and is called the dissipation scale. At this scale, models no longer require computationally expensive deterministic modeling. Furthermore, these viscous forces are also responsible for the dissipation of turbulent kinetic energy. Therefore, measurements which resolve the winds at the dissipation scale will allow numerical models to realistically close the atmospheric kinetic energy budget, an important metric of model fidelity.

4.1.2. Importance of Small-Scale Mixing for SAI and SCoPEx

From an SAI and SCoPEx perspective, plume-scale turbulence influences the frequency of collisions of monomer particles within the SCoPEx plume, which determines the rate of formation of fractal, larger aggregates. While Van der Waals forces finally determine whether particles that collide stick together and remain as a fractal aggregate (Sukhodolov et al., 2018), the collision rate is a critical quantity in determining total coagulation rate. Therefore, it is essential to know the frequency of collisions. This frequency is controlled by the wind variability at small spatial scales, i.e., the power spectrum. Intuitively, inertial forcing of particles by wind is much stronger than thermal forcing (e.g. Boltzmann distribution of velocity for ~1 µm particles at ~220 K). Fractal aggregates have a shorter lifetime in the stratosphere and are less effective at scattering light on a per mass basis (Weisenstein et al., 2015), so being able to model the formation

rate of fractal aggregates is an important aspect of SAI, especially with alternate SAI materials.

Improved knowledge of collision rates from wind measurements will allow for the selection of the appropriate mathematical representation of particle coagulation, the coagulation kernel. An accurate kernel is essential for numerical models to correctly simulate aerosol microphysical processes that determine the size distribution and residence time of solid aerosol particles. Adding wind and turbulence measurements to the SCoPEx payload will therefore address the major sources of uncertainty in aerosol microphysics under real atmospheric conditions, which include small-scale fluid flow, particle composition, and humidity.

4.1.3. Experimental Methods to Measure Turbulence in the Stratosphere

Multiple technologies are possible to achieve wind measurements with the necessary spatial resolution under stratospheric conditions. Current state of the art options include pitot tubes (with high sensitivity micro-pirani pressure sensors), hot wire anemometers, and acoustic anemometers. An existing stratospheric program has utilized hot wire anemometers to make measurements that are a close analog to what is necessary for SCoPEx. The program developed LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere), an instrument which made measurements of stratospheric turbulence up to 29 km (Gerding et al., 2009; Theuerkauf et al., 2011). The LITOS instrument has undergone significant calibration and has been compared against radiosondes (Schneider et al., 2015). One drawback of its deployment on a balloon has been the contamination of its wind measurements due to the influence of the balloon’s wake. In contrast, SCoPEx is engineered so that the wind environment of the instrument payload is well separated from the balloon wake when SCoPEx is traveling horizontally. For this reason, SCoPEx could provide significantly more data per flight at a chosen float altitude. In this way, SCoPEx and LITOS would be very complementary. The horizontal flight path of SCoPEx, combined with measurements of the wind power spectrum, would provide an excellent complement to the LITOS observations, which are only obtained along a vertical profile. These power spectra obtained by SCoPEx would contribute to improved micrometeorology understanding relevant both to stratospheric aerosol injection and to fundamental atmospheric science.

Additionally, air flow through the turbulence instrument will be simulated using CFD tools. The CFD runs will provide a means to identify key flow characteristics that drive sensor performance (sensitivity and accuracy) and detailed sensor design. This application of the SCoPEx platform would therefore constitute a nonperturbative means to obtain necessary turbulence measurements that have, to date, eluded the scientific community. This information is important for understanding stratospheric dynamics, including the response to climate change or stratospheric heating from SAI. As no injection of particles is needed, these could be among the first scientific measurements to be conducted.

4.2. Goal 2: Evaluation of Aerosol Microphysics of AM-Sulfate and Alternative SAI Materials

One of the goals for which there are insufficient observational analogues is the near-field evolution of particles injected from a point source in the stratosphere. Specifically, observations of the temporal and spatial evolution of the aerosol size distribution (number and volume) of solid, alternate SAI materials or AM-H_2SO_4 injected form a point source can

only be compared with plume model predictions via a perturbative experiment such as SCoPEx. In the following we describe a plume model by Golja et al. (2020) specifically designed for SCoPEx. We also explain the results from the model and the SCoPEx experimental approach for comparing observations with model results.

4.2.1. Plume Model

Golja et al. (2020) incorporated the SCoPEx design features in their model to study the injection of a solid aerosol and vapor-phase sulfuric acid from a balloon payload. To provide observations relevant to SAI, SCoPEx needs to produce downstream aerosols with radii within the range of roughly 0.2 to 1.0 µm. For calcium carbonate, the objective is to maintain a high fraction of the aerosol in monomer form, while for sulfate an ideal distribution would have a peak diameter of 0.6 μm (Dykema et al., 2016). The generation of largely smaller than ideal particles, while imperfect for assessing radiative efficiency relevant to SAI, does not serve to increase particle sedimentation rates within the plume. Such smaller sizes may, however, result in a larger surface to volume ratio, which can strongly influence stratospheric composition as heterogeneous chemistry is directly related to surface area. Distributions centered on small particle sizes in the near field may, however, continue to evolve beyond the domain of the study.

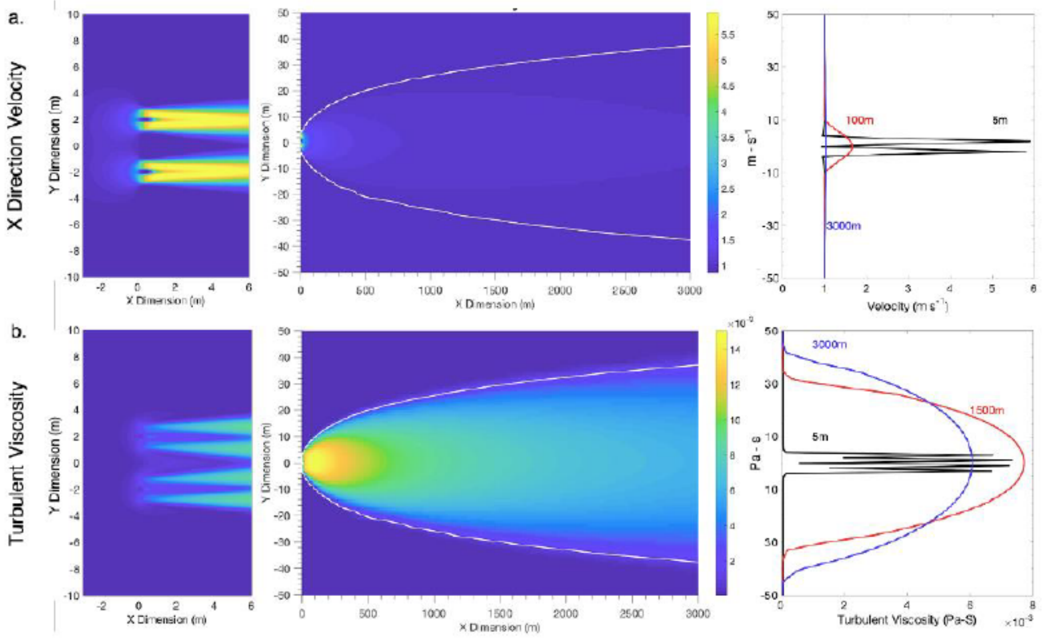


Figure 9 : ANSYS Fluent Velocity and Turbulence Fields. Shown above are the steady state x-direction velocity, u, and turbulent viscosity fields generated by ANSYS Fluent. Left panels show the genesis of disruptions to background X direction flow of 1 ms^{-1}, where propeller features are imposed at locations of 0,2) and (0,-2) meters. The center panel shows the entire domain, from 0 to 3 km, where the imposed red line contours 1 ms^{-1} in plot A, and contours 10% of the absolute maximum turbulent viscosity in plot B. Note Y direction scaling differs between the center and left panels. The right panel shows cross sections of velocity (A) and turbulent viscosity (B) through the Y plane at varying X locations. (Golja et al. 2020)

The velocity and turbulent viscosity fields from Fluent are shown in Figure 9. These fields form the basis of the simulation environment and are instructive in achieving an understanding of SCoPEx and the perturbation it achieves. Peaks in the x-direction velocity, u, are found directly downstream from the modeled propeller centers with an absolute maximum value of 6.3 ms^{-1}. By 1500 m downstream from the inlet locations, the velocity is reduced to the imposed background flow of 1 ms^{-1}. Turbulent viscosity, used as a measure

of particle mixing with background air, exhibits a narrow distribution of peak values ~10 m downstream from simulated propellers. With increasing distance downstream, the turbulent velocity spatial distribution widens, attaining a full width half maximum (FWHM) of 60 m by 1500 m downstream. The wake of the balloon itself is not visible, as it is sufficiently far from the payload to avoid wake crossing/interaction. Additionally, this simulation assumes a laminar stratospheric background flow, neglecting the potential impacts of breaking gravity waves.

For SCoPEx, precipitated calcium carbonate powder with roughly monodisperse size distribution centered at ~0.5 mm diameter will be aerosolized using the expansion of powder suspended in high pressure CO_2 through a 1-2 mm nozzle (see description in Section 3). The model injects aerosol as a 3D gaussian distribution of mass flux into the model grid, where the size of that distribution represents the scale of which the high velocity jet from the nozzle mixes with ambient air. The model considered two injection scenarios: scenario 1 (S1), a single point injection between the propellers; and scenario 2 (S2), injection from the center of each propeller. The model plume diameter at 3 km is, however, insensitive to the injection scenario for injection of both AM-H_2SO_4 and calcium carbonate. This suggests that injection at or between the propellers does not significantly alter the characteristics of the particles' experienced velocity field, and scenario S1 is the one selected for testing the model of plume evolution on SCoPEx. This is also important for the SCoPEx experiment as it necessitates only one sprayer that can be more easily placed in the equipment gondola.

4.2.2. Modelled Mass Injection Rate Dependence of Aerosol Size Distribution

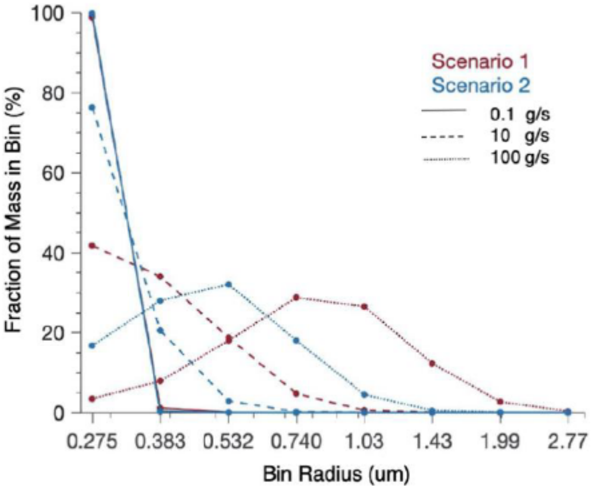


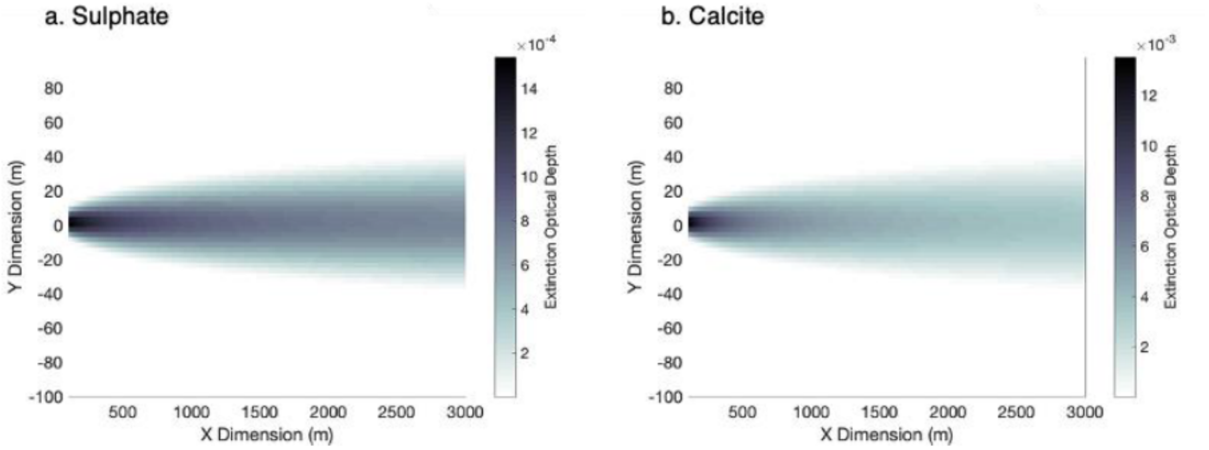
Figure 10: Calcium carbonate aerosol size distributions. Fraction of total mass in each sectional bin where the x-axis markers represent the central radius of each sectional size bin. These distributions represent the percent of total aerosol mass in the final 100 m of the plume across the full domain. Results are shown for three injection rates, 0.1 g s^{-1}, 10 gs^{-1}, and 100 gs^{-1}, for injection scenario 1 (red) and 2 (blue). (Golja et al. 2020)

Mass injection rates of 0.1, 10, and 100 g s^{-1} (0.36, 36, and 360 kg hr^{-1}) were used to test the influence of initial particle number density on the final plume aerosol size distribution. Although some of these are high, their use in the model is instructive as it can answer how different a short burst of high injection rate (much less than an hour) is from a slower but longer injection for the same total mass. Increasing calcium carbonate injection rates from 0.1 to 100 g s^{-1} reduces the share of monomer particles and increases undesired multi-monomer fractal aggregates. Figure 10 shows calcium carbonate's size distribution in the final 100 m of the modeled plume, i.e., the percent in each bin for the three different

injection rates of 0.275 μm radius particles. The low calcium carbonate injection rate of 0.1 g s^{-1} is the most desirable, maintaining 99% of the total mass in the final 100 m of the plume in monomer form. Increasing mass injection rate to 10 g s^{-1} and 100 g s^{-1}, with an S1 injection, shifts peak mass loading to favor particles of radii 0.5 and 0.75 um, respectively, corresponding to fractal "dimers" and "trimers".

Golja et al. (2020) also evaluated whether, in addition to the very sensitive in-situ optical particle counting aerosol size distribution instrument which originally was designed to measure background stratospheric aerosol size distributions (Murphy et al., 2016), the plumes could also be detected optically via scattered light. It should be emphasized that this does not refer to measurements from the ground but rather from close to the plume, e.g., when the equipment gondola is in close vicinity to the plume. Measuring the scattering from one view angle gives the product of the scattering phase at that angle and the scattering efficiency. This is closely related to the radiative forcing, but it does not uniquely determine the radiative forcing. By measuring at multiple angles, we could obtain enough information to quantify the radiative forcing. For example, we could measure from the side and below to obtain the forward scatter fraction, then calculate backscatter by flux conservation.

In the model, the extinction optical depth was calculated using Mie scattering theory and vertically integrating down columns in the y-z plane. Figure 11 shows the relative optical thickness of a sulphate and calcite aerosol plume formed via scenario 1 with an injection rate of 0.1 g s^{-1}. Calcite exhibits greater optical thickness by an order of magnitude at 550 nm, with an average value of 8.6x10^{-4} and maximum of 0.014 across the domain, as compared to sulphate, with an average of 9.4x10^{-5} and maximum 0.001. From these values, Golja et al. calculated that we expect adequate SNR to confidently detect the plume with a fast-scanning radiometer via the solar radiation it scatters. This calculation assumed an altitude of 21 km, solar elevation angle of 60°, an observing instrument situated on the payload gondola, and the gondola 200 m away from the edge of the plume and 1 km downstream of the termination of a scenario 1 type injection of calcite aerosol. Details of this calculation can be found in Golja et al. (2020).


a. Sulphate

b. Calcite

Figure 11: Extinction optical depth integrated vertically through all columns in the plume from 100-3000 m. Plots a and b show results for 0.1 gs^{-1} injections of condensable H_2SO_4 and calcite, respectively. The resulting number density of calcite aerosol is 490 cm^{-3} on the centerline at a downstream distance of 1000 m, predominantly as monomers. Aerosol optical depths were derived from Mie scattering theory at 550 nm, using refractive indices for sulphate and calcite stated in Dykema et al. (2016). (Golja et al. 2020)

4.2.3. SCoPEx Experimental Design and Analysis of Plume Evolution

For this goal, SCoPEx will follow the standard concept of operations, first spraying calcium carbonate at an injection rate suggested by the model analysis. It is desirable to maximize the contrast with the background stratosphere, both with respect to the aerosol concentration and the potential resulting chemical changes, while also maintaining calcium carbonate as monodisperse aerosol. To this end, additional models will be run at injection rates between 0.1 and 10 gs^{-1}. Based on these results, an injection rate will be chosen for the actual SCoPEx experiment. In addition to the basic components of the SCoPEx platform (gondola, ascender, propulsion, power, flight computer, communication, and wind), the calcium carbonate sprayer as well as the LIDAR and POPS instrument are critical for this science goal; without these components, there would not be a way to make and find the plume or measure the aerosol size distribution. While the turbulence measurement from goal 1 is desirable, it is, at least initially, not necessary. Similar studies of AM-H_2SO_4 injection would also be extremely useful. Our current plan is to conduct these after the calcium carbonate injection studies, as initially calcium carbonate is easier to handle than sulfuric acid and its precursors (see next section for motivation of calcium carbonate).

The aerosol size distribution measurements will be compared with the model predictions. In combination with turbulence measurements, discrepancies between the observed and modeled aerosol size distributions can be used to identify issues within the aerosol microphysical scheme or highlight misrepresentations of the velocity and turbulence field of the payload. The results of these studies will provide critical observational constraints on the aerosol microphysics and plume evolution of an injection with solid particles. It will be unique data that is ideal for testing the model of plume evolution as SCoPEx does not have to address problems resulting from the much more violent injection regime associated with injection from airplanes. Clearly, such studies are also needed, but SCoPEx represents a feasible and compelling first step in a sequence of new studies that more comprehensively investigate the aerosol microphysics of point source injections.

4.3. Goal 3: Evaluation of Process Level Chemical Models of Stratospheric Chemistry of Sulfate and Alternative SAI Materials

4.3.1. Need for Alternative SAI Materials

As previously discussed, the two largest first-order stratospheric risks of SAI with sulfate aerosol are ozone depletion and stratospheric heating. For sulfate aerosol the relative magnitude of these two risks can be adjusted if the size distribution can be controlled, e.g., via the AM-H_2SO_4 approach. It is worth noting that the impact on stratospheric ozone may be greatly reduced in the future if reactive halogen concentrations are lower. In contrast, the impact of stratospheric heating will not change. This represents a risk with a poorer understanding of its consequences, which makes it highly desirable to minimize stratospheric heating and resulting dynamic response. Therefore, it is important to investigate alternative SAI materials.

The properties of the “ideal” SAI material is (i) no absorption of radiation, i.e., purely scattering aerosol both fresh and aged, (ii) chemically inert, i.e., no direct impact of this material on stratospheric composition, and (iii) minimal down-stream effects, i.e., no impact on cirrus or other clouds, no environmental impact on deposition on the ground, etc. In reality, it is unlikely that a material with no impacts exists and rather the question is which materials can minimize these impacts. There have been a number of studies investigating

SAI materials in this context. High refractive index materials have been suggested as they reduce the mass of material that have to be lofted (Ferraro et al., 2015; Ferraro et al., 2011; Pope et al., 2012; Keith et al., 2016; Dai et al., 2020; Weisenstein et al., 2015). This largely cost-driven perspective is not a motivation for our work. In contrast, one of the goals of SCoPEx is to decrease the uncertainty in SRM models that use calcium carbonate SAI. The rationale for the choice of calcium carbonate as well as the approach to evaluate some of these risks is described in the following sections.

4.3.2. Unreactive Alternative SAI Materials

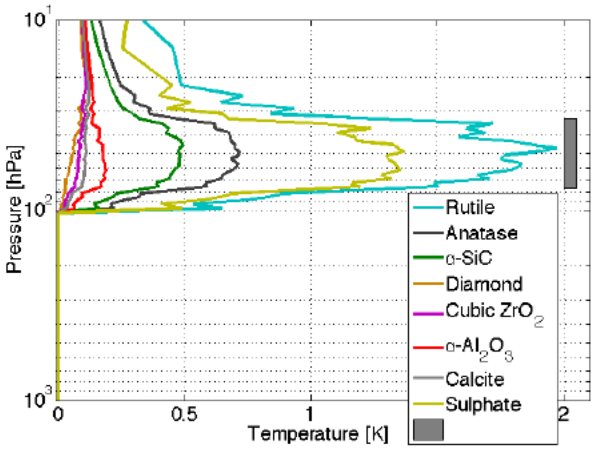


Figure 12: Comparison of stratospheric heating for different materials. Diamond has the lowest impact, although cubic zirconia and calcite are very similar. Sulfate and rutile result in much larger heating. (Dykema et al., 2016)

Diamond is probably the material with the best properties for SAI from a purely stratospheric perspective. Diamond has no absorption features in the solar or terrestrial spectrum and thus triggers the minimal possible dynamical response Figure 12. In addition, diamond should have ideal chemical properties. Hydrogen-terminated diamond surfaces are extremely inert and hydrophobic, precluding the ozone destroying chemistry initiated on sulfuric acid surfaces. The surface itself is also resistant to concentrated sulfuric acid. Exposure to OH radicals would probably slowly make the surface more hydrophilic. From a purely stratospheric perspective the only first-order risk of diamond would be increased ozone loss from the increased sulfuric acid surface area resulting from coagulation with background sulfate aerosol.

4.3.3. Reactive Alternative SAI Materials: The Case for Calcium Carbonate

Although the impact on cloud properties and the risk to Earth's surface from deposition of SAI diamond is likely very low, it could be preferable to have a material that dissolved easily in water, hence not persisting for long times outside of the stratosphere. It would also be preferable to have a material that is naturally abundant at Earth's surface. In addition, it would be ideal to overcome increased ozone loss due to coagulation by using a reactive aerosol. We therefore propose calcium carbonate as a prototype alternate SAI material for the following reasons: First, its optical properties are nearly equal to diamond and stratospheric heating and resulting dynamic response should be negligible compared to sulfate (Figure 12). Second, carbonates are typically quite reactive with acids, especially with concentrated sulfuric acid (Figure 13). Hence, calcium carbonate will neutralize upon

coagulation with sulfate aerosol eliminating the acidic surfaces resulting from coagulation of diamond and sulfate aerosol. Of course, the reactivity of calcium carbonate also makes model predictions with calcium carbonate more complex. The evolution of chemical and optical aerosol properties has to be modeled over its stratospheric lifetimes. One of the key research questions that SCoPEx will help address is whether the reactivity of calcium carbonate and the evolution of its chemical and optical properties and those of the surrounding gas-phase correspond to the detailed hypothesis laid out below. To this end, SCoPEx will compare observations of the chemical evolution of calcium carbonate, as well as the gas-phase, with those of a model based on known properties of calcium carbonate and recent laboratory experiments (Dai et al., 2020). This will provide a real-world evaluation of kinetic parameters, such as heterogeneous uptake coefficients derived from the laboratory studies, that will enable GCMs to include reliable parameterizations of the stratospheric impacts of calcium carbonate SAI.

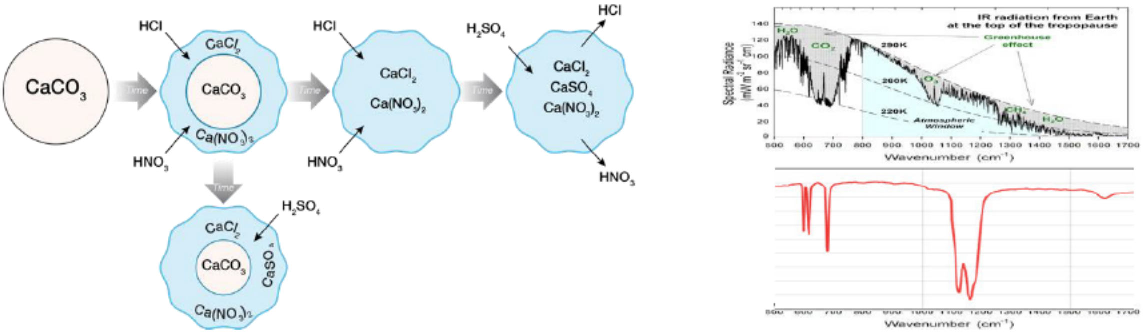


Figure 13: The left panel shows schematic of potential chemical reactivity of calcium carbonate in the stratosphere. The right panel shows the atmospheric windows in the terrestrial infrared (top) as well as the infrared absorption spectrum of calcium sulfate (bottom). The position of the 1150 cm^{-1} sulfate in part explains the stratospheric heating effect of sulfuric acid.

4.3.3.1. Optical Properties

Based on well-established chemistry, the reaction of sulfuric acid aerosol with calcium carbonate can be assumed to go to completion, i.e., be reagent limited. The optical properties of calcium sulfate in the terrestrial infrared are similar to those of sulfuric acid with only slight differences in relative band intensities and wavelengths (Figure 13 right hand inset). This is important as it implies that there will be no large first-order changes in stratospheric heating from changing background sulfuric acid to calcium sulfate. There are higher order impacts due to slight differences in the absorption of sulfuric acid, which has some liquid water compared to calcium sulfate. There are also numerous forms of calcium sulfate (anhydrite, bassanite, gypsum, etc.). However, the resulting differences are much smaller than introducing an absorbing material via SAI.

4.3.3.2. Chemical Properties

Predicting the evolution of the chemical properties of calcium carbonate under stratospheric conditions is more challenging. It is certain that calcium carbonate does not have the same heterogeneous reactions that activate ozone destroying substances as sulfuric acid. Figure 13 shows a schematic of the expected reactivity. Calcium carbonate is expected to react with acidic substances neutralizing them, forming salts and carbon dioxide. These acid neutralizing reactions can deplete gas-phase HNO_3, HCl, etc. There are a large number of ozone destroying catalytic cycles involving NOx, chlorine and other

halogens, which are altitude (and latitude) dependent. NOx can be produced via HNO_3 photolysis and lost via heterogeneous reaction of N_2O_5. It participates both in ozone destroying catalytic cycles and is important for deactivation of ozone destroying halogen radicals. Thus, knowledge of the heterogeneous reaction rates of numerous substances with calcium carbonate are required to predict the impact it will have on stratospheric composition.

However, until the recent study by Dai et al. in our laboratory, no heterogeneous chemistry studies of calcium carbonate under stratospheric conditions had been conducted, to our knowledge, although there exists a rich data set under tropospheric conditions (Dai et al., 2020). This work, as well as the work of Dai et al., highlights that reactive solid aerosols are indeed more complex than liquid sulfuric acid: The authors observed moderate initial uptake of the gas-phase acids HCl and HNO_3 on fresh calcium carbonate, as the dry stratospheric conditions already make uptake coefficients lower than under typical tropospheric conditions. An additional large difference to liquid aerosol is that the surface of the solid calcium carbonate passivates, drastically reducing the uptake coefficients of HCl and HNO_3. Hence, based on the Dai et al. laboratory study, calcium carbonate rapidly becomes effectively unreactive with respect to uptake of these gas-phase acids, an important finding that confirms calcium carbonate as a good candidate as alternate SAI material. In addition, calcium carbonate particles are abundant at Earth's surface due to windblown mineral dust. And the small calcium carbonate SAI particles should dissolve rapidly in water. This does not exclude risks associated with the deposition of calcium carbonate SAI particles or impacts on clouds (Cziczo et al., 2019). However, due to its abundance at the Earth's surface, there already exists a large knowledge base for its environmental impacts in contrast to, e.g., diamond. Further laboratory work is required to study especially the $ClONO_2$ + HCl and N_2O_5 hydrolysis reactions on fresh and aged calcium carbonate. However, the existing results prepare the stage for studying them in the real stratospheric environment as outlined below. Figure 14 shows results of the AER 2-D chemistry-transport-aerosol model for annual average ozone column changes of calcium carbonate SAI compared to a control for 2040. Ignoring the passivation of calcium carbonate (thk-ind) results in increases in ozone columns from calcium carbonate SAI whereas the inclusion of passivation can either result in very little ozone column change or losses in the Southern Hemisphere, depending how the $ClONO_2$+HCl is parameterized. Either of the two, more realistic, passivation scenarios result in significantly lower ozone loss than the equivalent amount of sulfate SAI, consistent with the hypothesis.

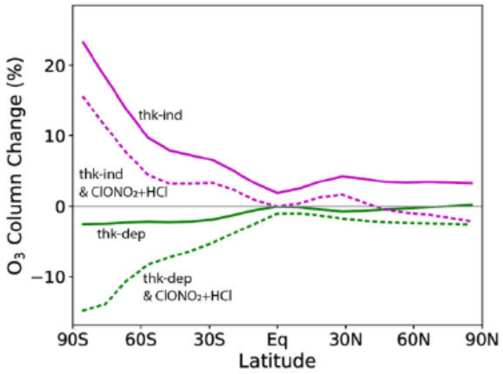


Figure 14: Shows the role of passivation and the heterogeneous $ClONO_2$+HCl reaction on ozone column change using the AER 2-D model taken from Dai et al. 2020. Inclusion of this reaction with the same rate as measured for Al_2O_3 results in a substantial reduction in ozone for scenarios including, thk-ind, or excluding passivation, thk-dep.

4.3.4. Need for SCoPEx Calcium Carbonate Plume Studies

One of the challenges for alternate SAI aerosol is the lack of materials such as calcium carbonate in the stratosphere. The only way to then study these materials in the actual stratosphere is via deliberate stratospheric injection of a small amount of these materials. In environmental studies, including stratospheric studies, it is not possible to rely purely on laboratory studies. For example, flights on the NASA ER-2 into the polar vortex over Antarctica provided the ability to test whether laboratory-derived reaction mechanisms were able to capture real-world ozone destruction chemistry. Without these flights, the level of confidence in the model predictions would have been much lower, and for good reason. It is not clear that a given experimental setup in the laboratory can faithfully capture the entire complexity of the real stratosphere; only field observations are able to provide this. For a number of natural stratospheric processes, remote observations can provide important information in addition to in situ aircraft or balloon. However, these are only possible when large-scale phenomena are at work.

Since there are no natural calcium carbonate plumes in the stratosphere that would even allow for in situ observations, intentional injection is necessary to perform these studies. Calcium carbonate injections will allow SCoPEx to provide invaluable observations as it will quantitively test the mechanisms determined in the laboratory. As stated above, there is a need for more laboratory studies, however, there is good reason to proceed with the planning of SCoPEx calcium carbonate experiments. First, by the time of the first injection experiments, additional studies should have been conducted. In addition, N_2O_5 uptake coefficients used in the model are likely a very good estimation as similar values have been found for different solid materials, e.g., Al_2O_3 and SiO_2 (Molina et al., 1997). In addition, even with these additional lab determined mechanisms, the same type of experiments as proposed here will still have to be conducted, as we expect these reactions to not make a significant difference. In other words, they will not be a deciding factor about the viability of calcium carbonate as an alternate SAI material. Only field experiments will help shed insight into these questions. In summary, there is a critical need for evaluating not just the aerosol microphysics (goal 2) but also the stratospheric chemistry of calcium carbonate due to the promise it holds as a lower risk SAI material.

4.3.5. SCoPEx Experimental Design and Analysis of Chemical Calcium Carbonate Plume Evolution

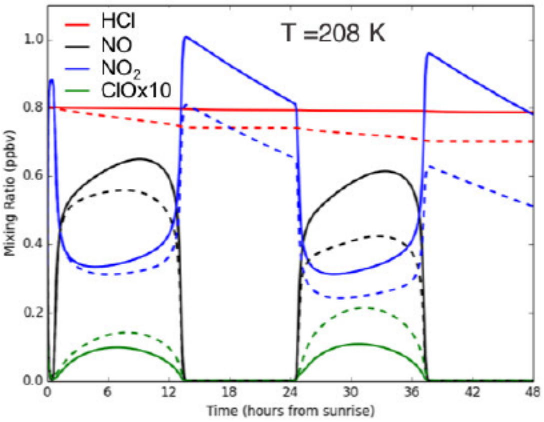


Figure 15: Solid lines: background 2μm^2 cm^{-3} sulfate 5ppm$_v$ H_2O. Dashed lines: plume 15μm^2 cm^{-3} sulfate 10 ppm$_v$ H_2O.

The experiments will again follow the standard concept of operations as under goal 2. In order to determine optimal injection rates, we will include chemical reactions in the plume model, updated with the newest mechanisms available at that time. Figure 15 shows the evolution of an air mass perturbed by a sulfate aerosol injection over multiple days, i.e., significantly longer than the initial SCoPEx experiments. Significant changes in HCl and NOx can be observed already over short time periods and these are easily detectable with existing instrumentation. For this science goal, it is desirable to measure aerosol composition and size distribution as well as key gas-phase chemical species, especially HCl, NOx and water. Therefore, this science goal requires a much larger set of instruments. In addition, the equivalent model to Figure 15 for calcium carbonate is informed by the results of science goal 2. The work of Dai et al. provides kinetic parameters needed for this model, and reactions for which there are no laboratory data to date are parameterized using close analogues and conditions, e.g., $ClONO_2$ + HCl are parameterized using the results for alumina (and silica) from Molina et al. (1997). One key question is whether the changes in HCl and NOx will indeed be smaller for calcium carbonate than those for sulfate shown in the figure above, which would confirm the hypothesis for calcium carbonate as a potential alternate SAI material.

In summary, SCoPEx experiments using calcium carbonate injections will provide a unique evaluation as to whether calcium carbonate indeed is an alternate SAI material that could substantially reduce risk from SAI compared to sulfate. Follow-up studies will be needed. For example, improved chemical and aerosol microphysics models will provide improved models of the chemical and physical evolution of calcium carbonate, which likely will motivate specific laboratory investigations. These will provide information for SCoPEx studies using “stratospherically aged” calcium carbonate as precursor for injection that can then be used to compare whether the laboratory mechanisms of this aged calcium carbonate agree with that found in the real stratospheric environment.

5. Data Management Plan and Dissemination of Results

Products of the research. The data generated during this project consists of meteorological, navigational, telemetry, and a variety of instrumentation data, in particular aerosol size distributions as well as chemical composition data during later science flights. In addition, there will be model data on plume chemical evolution.

Access to data, data sharing practices, and policies and dissemination of results. Data relevant for scientific analysis will be made public within 60 days of the end of flight. This taw data will be made public with appropriate warnings that it has not undergone QA/QC. The email address of users will be recorded so that they can be automatically notified when revised versions become available. Based on previous experiences with stratospheric airborne campaigns, this is typically 6-15 months after the flight depending on the type of data, e.g., the amount of calibration and data workup required. We have chosen to make raw data available rapidly—going far beyond what is typical for stratospheric science missions—because of the public scrutiny of SCoPEx and because of the broad commitment to Open Access data principles articulated by Harvard’s Solar Geoengineering Research Program which is funding SCoPEx.

Principal Investigators (PI) and their groups have an excellent track record with presenting their work at major national and international conferences and workshops. All data that go into key analyses and figures in the group’s publications will be made publicly available via the PI’s group website. All publications resulting from this project will be posted on the PI’s webpage (https://projects.iq.harvard.edu/keutschgroup/publications). Preprints of manuscripts submitted for publication as well as the underlying data will also be posted on Harvard’s Dash manuscript repository. Publications will be made in open access formats.

Archiving of data. All data acquisition/storage computers in the PI’s group are automatically backed up daily, both wirelessly to a server elsewhere on campus, and/or to a cloud server. Both of these processes ensure that data will not be lost and enable rapid access to the data. The file naming system used for all software (which includes the date of the experiment) ensures straightforward retrieval and use of archived data. Group laptops are also backed up daily, ensuring that analyzed data are archived as well.

6. SCoPEx Research Team Biographies

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From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Fwd: Update
To: Frank Keutsch
Cc: Keith, David; Ronda Knott - NOAA Federal
Sent: October 27, 2020 10:25 PM (UTC-04:00)
Attached: Untitled attachment

Frank,

I hope this finds you doing well with the family in Germany.

DavidK and I invited you to a Friday v-meeting to catch up on CI matters. He will give me a brief download of his CDR ideas/perspective at the beginning at my request. So you could join late to miss that.

Let us know.
THanks
Dave

David W. Fahey, PhD
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Ronda Knott, Admin. Assistant
ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

> Begin forwarded message:
>
> **From:** Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
> **Subject: Re: Update**
> **Date:** October 26, 2020 at 7:51:29 PM MDT
> **To:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Cc:** "Keith, David" (b) (6) [redacted]>
>
> Hi Dave and David,

The meeting has been set for this Friday, October 30th at 7am MT and included Frank Kuetsch. The connection details are:

Meeting ID
meet.google.com/zgb-gfnu-gdr
Phone Numbers
(US) +1 561-408-9337
PIN: 857 507 300#

Thank you,
Ronda

Ronda Knott
Executive Administrative Assistant to

Dr. David W. Fahey, Director

NOAA Chemical Sciences Laboratory
325 Broadway, R/CSL

Boulder CO 80305

I am currently teleworking, please call my cell: (b) (6)

303.497.4404 phone

303-497-5822 fax

ronda.knott@noaa.gov

On Mon, Oct 26, 2020 at 2:56 PM David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:

> David,
> 7Am Friday will work.
> Ronda can reach out to FrankK if you like. She will send a link to all.
> Thanks
> Dave
>
> On Oct 25, 2020, at 9:17 PM, Keith, David (b) (6) > wrote:
>
> How about 8:30 AM MT on Friday the 30th? (I can do any time from 7:00 to 10:00) MT that AM. Suggest we choose a time, then I will see if Frank can join (he can miss the CDR part).
>
> D
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, October 24, 2020 6:29 PM
> **To:** Keith, David (b) (6) >
> **Cc:** Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
> **Subject:** Re: Update

David,

Thanks for the reply. I appreciate the perspective on Pierrehumbert; a bit frustrating. We will launch a webpage for the Earth Radiation Budget program (ie the Congressional funding) soon (albeit a bit late) that will explain NOAA's role and intent and in effect pushback on Pierrehumbert and others.

Thanks for your offer of a CDR debrief and catching up on other matters. My CDR meeting is 4 Nov so best would be next week sometime. Let me know if that might work (w/ or w/o Frank) and a preferred day/time.

Regards
Dave
PS Canmore seems like a good faraway place to get fresh air devoid of C-19.

> On Oct 21, 2020, at 2:13 PM, Keith, David (b) (6) [redacted] wrote:
>
> Dave
>
> Thanks. Yet, I'm particularly frustrating because Ray repeats the idea that doing it at all commits us to doing it for a thousand years, yet I think he knows that's not true. When he was at Harvard and from the public audience we challenged him on that pointing out that you could always taper off slowly even if you didn't have carbon removal and so the net result would be a reduction in the rate of change even if it didn't change the ultimate endpoint. He agreed. Yet he keeps coming back to this claim.
>
> I don't have an overview on CDR. I step back because of the conflict of interest after starting Carbon Engineering (the air capture company). In fact I think that CDR is a bit overhyped and I have been trying to figure out how to say that without frustrating people at Carbon Engineering too much. I have fragments of talks and some opinions. I could dump these on you in a short (15 minutes) conversation which might be helpful to me because I'm trying to polish the stuff.
>
> I think you catch up with you, me and Frank would make sense. I'm thinking early November at that point we will of got science plan out to the SCoPEx committee and have made the next step towards reality on a spring flight.
>
> It's beautiful and snowy up here in Canmore Alberta.
>
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>

Sent: Wednesday, October 21, 2020 1:23 PM
To: Keith, David <(b) (6) [redacted]
Subject: Update

David,

Very good article in Globe. Pierrehumbert's article is frustrating since he attacks CI and calls out people like me yet at the end says there might be an appropriate role for CI, something he has done in other articles.

My management has asked me to inform them about CDR in an internal meeting. I am not very well prepared to do that and wondered if you had a presentation that you would be willing share to draw from for this purpose.

A call to catch up with Frank would be welcome.

Regards
Dave

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ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

From: Keith, David (b) (6) [redacted] >
Subject: RE: Experimental research platform requirements
To: David Fahey - NOAA Federal
Cc: Smith, Wake; Keutsch, Frank N
Sent: February 3, 2021 9:59 AM (UTC-05:00)

Dave

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Sent: Saturday, January 30, 2021 6:38 PM
To: Keith, David (b) (6) [redacted] >
Cc: Smith, Wake (b) (6) [redacted] >; Keutsch, Frank N (b) (6) [redacted] >
Subject: Re: Experimental research platform requirements

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Attached: Untitled attachment

David,

Yes, the Perseus a/c was a big distraction that I was only on the edge of fortunately.

I will remain skeptical about the likelihood of new non-military a/c but want to be first in line to use them. We were first in line and funded to use the new Boeing/Aurora a/c, Odysseus, when the plug was pulled.

Yes we have had conversations with the Sceye folks and would like to have a chance to use when the day comes.

BTW, the CU group here apparently demonstrated a 1.5km reel down from a balloon quite recently. No other details.

Regards
Dave

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From: Douglas MacMartin (b) (6) [redacted]>
Subject: RE: 2022 GRC program
To: Karen Rosenlof - NOAA Federal; Trude Storelvmo
Sent: July 19, 2021 10:15 AM (UTC-04:00)

Excellent! We should have a great conference ☺. (More later… probably not for a while.)

doug

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Sent: Thursday, July 15, 2021 5:04 PM
To: Douglas MacMartin (b) (6) [redacted] Trude Storelvmo (b) (6) [redacted]
Subject: Re: 2022 GRC program

Doug and Trude,
I should be available during that time frame, and would like to attend the test GRC. I'd be happy to adjust topics as you feel is needed.

Take care,

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
Boulder, CO 80305
office: 3A-121, DSRC
e-mail: Karen.H.Rosenlof@noaa.gov
phone: 303 497-7761
fax: 303 497-5373
----
while safer at home remains in effect, email is the most reliable contact

> On Jul 15, 2021, at 9:06 AM, Douglas MacMartin (b) (6) [redacted]> wrote:
>
> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
>
> As a start to our planning, could you let us know whether you would be interested in talking at the 2022 meeting? We would of course still love to hear from you, but schedules may not permit and research interests change (and, indeed, for some or many of you that may mean that the topic we were originally thinking you would talk about would no longer be what you are currently most excited by – the GRC is supposed to be cutting-edge current research, of course – so if you let us know we can start revising sessions and think about what gaps we'd like to fill). There are also some new people who are doing some great research too that we would like to hear from, so it's conceivable that – given the now 5 year gap since the last GRC – we might choose to slightly increase the number of talks and reduce the time available per talk.

Thanks,
Doug & Trude

From: Douglas MacMartin
Sent: Wednesday, February 19, 2020 10:27 AM
To: (b) (6) ; (b) (6) ; Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke (b) (6) >; (b) (6) ; Robert Wood <(b) (6) ; (b) (6) (b) (6) <(b) (6) ; Daniele Visioni <(b) (6) >; (b) (6) ; Peter Irvine <(b) (6) >; Jonathan Proctor (b) (6) ; (b) (6) ; Keith, David (b) (6) >; Kravitz, Ben (b) (6) >; Wake Smith <(b) (6) >; Izidine Pinto (b) (6) ; Gabriel Chiodo (b) (6) >; Keutsch, Frank N <(b) (6) >
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Subject: RE: 2020 GRC program

Hi all,

Just a reminder that if you haven’t sent me a title yet, to do so (otherwise I’ll have to make something up; GRC needs us to upload our “final” program by the end of this month) I have titles for about half of you (though some of those are draft titles you sent quite some time ago, e.g. for Pete, Isla, Danny).

And, if you haven’t responded yet regarding need for travel support, let me know (about half of you have). For those of you who haven’t been to a GRC before, there’s a bus from Boston airport, and from Portland Maine airport.

If you’ve already both sent me a title and responded regarding travel, then you can ignore this email.

Also, regarding format, this year we’re explicitly including 10-15 minutes for the discussion leader to make some remarks to help frame each session (taking 5 minutes from each speaker’s time), and rather than having a lengthy discussion after each talk, we’ll have a shorter 10-minute discussion after each talk and a 20-minute general session discussion at the end (that’s as long as GRC will allow) with everyone from a given session.

Thanks, and see you in June!
doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) ; (b) (6) 'Jadwiga (Yaga) Richter' (b) (6) >; Alan Robock (b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >; (b) (6) ; Robert Wood (b) (6) >; (b) (6) ; (b) (6) <(b) (6) >; Daniele Visioni <(b) (6) >; (b) (6) Peter Irvine <(b) (6) >; Jonathan

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Cc: Lawrence, Mark (b) (6) >; valentina Aquila <(b) (6) Ulrike
Niemeier <(b) (6) >; Leisner, Thomas (IMK) <(b) (6) Olivier
Boucher (b) (6) >; Schrag, Daniel P. (b) (6) ; TAYLOR,Michael
(b) (6) ;(b) (6) ; Lynn Russell (b) (6) Trude Storelvmo
<(b) (6) 'Simone Tilmes' (b) (6) >;(b) (6)
Subject: 2020 GRC program

Hi all,

Happy New Year!

The full program for GRC is due on February 28; if you haven’t sent us a title for your talk (or if you did and want to revise it), please do so before the end of February so I have time to enter everything into the conference management system online.

The cc-line has discussion leaders for each session.

Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin
Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and
Faculty Fellow, Atkinson Center for a Sustainable Future
Cornell University
(b) (6)
https://climate-engineering.mae.cornell.edu/

From: Robert Wood (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin
Cc: (b) (6); (b) (6); Alan Robock; Karen Rosenlof - NOAA Federal; Katharine Ricke; (b) (6) (b) (6); (b) (6) Daniele Visioni; Isla Simpson; Peter Irvine; Jonathan Proctor; (b) (6); Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N; Trude Storelvmo; Simone Tilmes; (b) (6)
Sent: July 15, 2021 3:52 PM (UTC-04:00)

Hi Doug and Trude,

Thank you for the offer to present at next year's GRC. I am still interested.

Regards

Rob

Robert Wood
Professor, Atmospheric Sciences
Department of Atmospheric Sciences,
718 ATG Building
University of Washington, Seattle
WA 98195-1640

Tel: 206-267-8343 (cell); 206-543-1203 (office)
Web: atmos.washington.edu/~robwood
Email: (b) (6)
[redacted]

On Thu, Jul 15, 2021 at 8:11 AM Douglas MacMartin <(b) (6)> wrote:

> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
>
> As a start to our planning, could you let us know whether you would be interested in talking at the 2022 meeting? We would of course still love to hear from you, but schedules may not permit and research interests change (and, indeed, for some or many of you that may mean that the topic we were originally thinking you would talk about would no longer be what you are currently most excited by – the GRC is supposed to be cutting-edge current research, of course – so if you let us know we can start revising sessions and think about what gaps we'd like to fill). There are also some new people who are doing some great research too that we would like to hear from, so it's conceivable that – given the now 5 year gap since the last GRC – we might choose to slightly increase the number of talks and reduce the time available per talk.
>
> Thanks,

Doug & Trude

From: Douglas MacMartin
Sent: Wednesday, February 19, 2020 10:27 AM
To: (b) (6) ; (b) (6) ; Alan Robock (b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >; (b) (6) ; Robert Wood (b) (6) >; (b) (6) (b) (6) <(b) (6) >; Daniele Visioni (b) (6) >; (b) (6) ; Peter Irvine (b) (6) >; Jonathan Proctor (b) (6) >; (b) (6) ; Keith, David <(b) (6) >; Kravitz, Ben <(b) (6) >; Wake Smith (b) (6) >; Izidine Pinto (b) (6) >; Gabriel Chiodo <(b) (6) ; Keutsch, Frank N (b) (6) >
Cc: Lawrence, Mark <(b) (6) >; valentina Aquila (b) (6) >; Ulrike Niemeier <(b) (6) >; Leisner, Thomas (IMK) (b) (6) >; Olivier Boucher <(b) (6) >; Schrag, Daniel P. (b) (6) >; TAYLOR,Michael (b) (6) >; (b) (6) Trude Storelvmo <(b) (6) ; 'Simone Tilmes' (b) (6) ; (b) (6) Jim Hurrell (b) (6) >
Subject: RE: 2020 GRC program

Hi all,

Just a reminder that if you haven't sent me a title yet, to do so (otherwise I'll have to make something up; GRC needs us to upload our "final" program by the end of this month) I have titles for about half of you (though some of those are draft titles you sent quite some time ago, e.g. for Pete, Isla, Danny).

And, if you haven't responded yet regarding need for travel support, let me know (about half of you have). For those of you who haven't been to a GRC before, there's a bus from Boston airport, and from Portland Maine airport.

If you've already both sent me a title and responded regarding travel, then you can ignore this email.

Also, regarding format, this year we're explicitly including 10-15 minutes for the discussion leader to make some remarks to help frame each session (taking 5 minutes from each speaker's time), and rather than having a lengthy discussion after each talk, we'll have a shorter 10-minute discussion after each talk and a 20-minute general session discussion at the end (that's as long as GRC will allow) with everyone from a given session.

Thanks, and see you in June!

doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) (b) (6) ; 'Jadwiga (Yaga) Richter' <(b) (6) >; Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >; (b) (6) ; Robert Wood <(b) (6) >; (b) (6) ; (b) (6) <(b) (6) >; Daniele Visioni <(b) (6) >; (b) (6) ; Peter Irvine <(b) (6) >; Jonathan Proctor <(b) (6) >; Govindasamy Bala <(b) (6) >; (b) (6) ; Keith, David <(b) (6) >; Kravitz, Ben <(b) (6) >; Wake Smith <(b) (6) >; Chris Field <(b) (6) >
Cc: Lawrence, Mark <(b) (6) >; valentina Aquila <(b) (6) >; Ulrike Niemeier <(b) (6) >; Leisner, Thomas (IMK) <(b) (6) >; Olivier Boucher (b) (6) >; Schrag, Daniel P. <(b) (6) >; TAYLOR,Michael (b) (6) >; (b) (6) ; Lynn Russell (b) (6) >; Trude Storelvmo <(b) (6) >; 'Simone Tilmes' (b) (6) >; (b) (6)
Subject: 2020 GRC program

Hi all,

Happy New Year!

The full program for GRC is due on February 28; if you haven't sent us a title for your talk (or if you did and want to revise it), please do so before the end of February so I have time to enter everything into the conference management system online.

The cc-line has discussion leaders for each session.

Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin

Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and

Faculty Fellow, Atkinson Center for a Sustainable Future

Cornell University

(b) (6)

(b) (6)

https://climate-engineering.mae.cornell.edu/

From: Kelly Wanser (b) (6) >
Subject: Nice job on the NOVA episode!
To: David Fahey - NOAA Federal; Frank Keutsch
Cc: John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:13 PM (UTC-04:00)

You were excellent and the piece came out great.
We'll promote it as we are able.

Best,
k.

--
Kelly Wanser
Executive Director, SilverLining | http://www.silverlining.ngo
Board Director, Dendra Systems | http://www.dendra.io
Advisor, University of Washington Marine Cloud Brightening Project | http://www.mcbproject.org
President's Circle, National Academy of Sciences | http://nas-sites.org/PC/
Phone: (b) (6)

TEDTalk: *Emergency Medicine for Our Climate Fever*
Report: *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Newsletter from Harvard's Solar Geoengineering Research Program
To: Keith, David
Cc: Frank Keutsch; Ronda Knott - NOAA Federal
Sent: December 28, 2020 11:44 AM (UTC-05:00)
Attached: Untitled attachment

David,
Good, yes let's talk on the 6th.
Ronda can arrange a time and link.
Happy New Year.
Dave

> On Dec 28, 2020, at 9:30 AM, Keith, David <(b) (6)> wrote:
>
> Dave
>
> Yes, we expect to fly POPS.
>
> Also, interesting developments on turbulence.
>
> Now that this mission seems to be (finally) coming together it would be good how about the three of us to touch base again about this and about the meeting to discuss future flight missions?
>
> How about Wednesday the 6th?
>
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, December 26, 2020 5:51 PM
> **To:** Keith, David (b) (6)
> **Subject:** Re: Newsletter from Harvard's Solar Geoengineering Research Program
>
> David,
>
> Thanks for the newsletter. I am impressed with your productivity.
>
> Good progress with Esrange launch plans and committee approval. Do you plan to fly POPS? It would be of value to get a high lat profile and adds to your flight data return. No communication with the device is needed since it records onboard. Let us know if you want assistance.
>
> We have prepared a POPS unit and backup to fly on the World View Stratollite in 2021 when they are able to resume launches.
>
> I hope you and yours are doing well enough this Holiday Season. We are OK.
> Regards
> Dave

On Dec 16, 2020, at 9:18 AM, David Keith (b) (6) wrote:

Dear Readers,

As this strange year comes to a close, we wanted to share updates from Harvard's Solar Geoengineering Research Program (SGRP), which supports research at Harvard on the science, technology, and governance of solar geoengineering.

We hope everyone and their families are safe and well. We wish you a healthy new year.

Yours,
David Keith and Lizzie Burns
Faculty Director and Managing Director
Harvard's Solar Geoengineering Research Program

SCoPEx

SCoPEx Update

Led by Frank Keutsch, the Stratospheric Controlled Perturbation Experiment (SCoPEx) is a scientific experiment to advance understanding of stratospheric aerosols that could be relevant to solar geoengineering. It aims to reduce the uncertainty around specific science questions by making quantitative measurements of some of the aerosol microphysics and atmospheric chemistry required for estimating the risks and benefits of solar geoengineering in large atmospheric models.

The SCoPEx research team has asked the independent SCoPEx Advisory Committee to review our plans for a proposed platform test in Sweden in June 2021. This test would notbe the experiment itself, but rather a test of the SCoPEx platform without the release of any particles. Specifically, we would like to test the gondola's horizontal and vertical control using the winch system and propellers as well as the power, data, navigation, and communication systems. We would not release any aerosols, nor fly an aerosol injection/release system. Still, we will not proceed with this flight without a formal recommendation authorizing the flight from the Advisory Committee to Harvard management. We have asked the Advisory Committee if they can complete their review and reach a decision—be it positive or negative—about this platform test by February 15, 2021. You can learn more about this platform test here.

SCoPEx Advisory Committee

Recognizing the complex societal and governance issues surrounding solar geoengineering, Harvard has ensured the SCoPEx project has the guidance of an independent Advisory Committee, as noted above. The Advisory Committee has already begun to carry out a significant amount of work, including a financial review, legal review, and scientific and technical review, and they have proposed a draft process for a societal engagement review. You can learn more by visiting their website. We are grateful for the time the Committee members are volunteering and look forward to the work ahead.

Opportunities

SGRP Fellowship

SGRP is now accepting applications to its 2021 Fellowship Program, which offers short-term and long-term opportunities. Applications are due January 29, 2021. We are seeking applications from scholars in a range of disciplines, including the natural sciences, economics, law, government, public policy, public health, medicine, design, and the humanities. We also are looking for applicants who are new to the field of solar geoengineering and/or have critical views, and we strongly encourage applications from

women and minority candidates. More information can be found here.

We would also like to congratulate our current and future fellows who were accepted during our previous fellowship application process.

- Cody Floerchinger, (August 2019-July 2021) advised by Frank Keutsch, is using datasets from upcoming measurements campaigns to provide a comprehensive analysis of the state of our ability to model stratospheric plume dynamics and highlight areas where the community should focus its efforts when attempting to improve these model products (science).
- Yuanchao Fan, (October 2019-October 2021) advised by Kaighin McColl, is quantifying the impact of solar geoengineering on terrestrial ecosystems, including forests and agriculture, and their biophysical and biogeochemical feedbacks to climate. He is also collaborating with David Keith on a paper about geoengineering and food supply (science).
- Irina Bakalova (February 2021-April 2021) will be advised by Professor Rob Stavins, working closely to study the effectiveness and stability of potential international agreements on solar geoengineering (economics).
- Britta Clark (February 2021-June 2021) will be advised by Lucas Stanczyk and will analyze the intergenerational justice impacts of solar geoengineering as a mitigative strategy to address climate change (philosophy).
- Ermanno Napolitano (August 2021-July 2022) will be advised by Lucas Stanczyk and will catalogue and explore all of the existing international legal principles that are likely to have some bearing on the deployment of solar geoengineering (law).

Online Community for Junior Researchers

A group of junior scientists are organizing a diverse online community of young researchers new to the solar geoengineering field, designed to engage researchers with new perspectives. This group will provide young researchers the chance to informally present on their research, share ideas, receive feedback, and create a space for open and non-judgmental discussion on the topic. The first few sessions took place in November and December and were held live on Zoom. Graduate students and recent postdocs from across the globe, including from developing countries, discussed various publications containing alternate viewpoints on solar geoengineering. Future sessions scheduled include presentations by a former SGRP DECIMALS resident and other participants as well as discussion forums and networking opportunities on Slack. Undergraduate students, graduate students, and postdoctoral fellows within five years of completing their degree are welcome to join the group. If you are interested in participating, please email Selena Wallace: swallace@seas.harvard.edu.

Events

Due to COVID-19, we had to cancel in-person events beginning in March. Since that time, we have held countless Zoom conversations (like so many others). For example, in November we hosted a public health workshop at Harvard to try to broaden the diversity of researchers studying solar geoengineering on campus. We are also now in the process of building an exciting opportunity that will allow us to reach a broader audience outside of Harvard that will include experts, practitioners new to solar geoengineering, and the general public. We invite you to join us.

Public Health Roundtable

In November 2020, we held a virtual event with the Harvard Chan School of Public Health Center for Climate, Health, and the Global Environment where experts from both the geoengineering and the public health communities had the opportunity to discuss the potential public health challenges posed by solar geoengineering. Few studies to date have considered the public health implications of geoengineering, and those that have have been limited to mortality due to ambient air pollution and UV-induced malignant melanoma. This event discussion addressed questions of the risk factors that these studies might be omitting, the vast array of other public health issues that may arise, as well as the environmental justice implications of human interventions to the climate system such as geoengineering. The organizers of the event may publish a paper that summarizes the key points and questions to hopefully inspire other experts in the public health field to begin research on solar geoengineering. Overall, this event was significant because it not only signaled new interest from various public health experts who, years prior, had not yet engaged, but also because it will hopefully unlock even more new interest from a critical community that has yet to fully participate in solar geoengineering research.

Public Seminar Series

In the spring of 2020, we will launch a virtual seminars series to promote understanding and discussion of solar geoengineering and to enable audiences to learn from a broader set of perspectives in the area of solar geoengineering research and public policy. These seminars will contain a combination of practitioners and experts from around the world and will have a variety of formats including single speakers, moderated debate, and moderated panels. Previously, SGRP seminar attendance was limited to the Harvard community, but we are now able to extend the reach of this series to a global, public audience. We invite you to participate in these seminars. We will email this listserv when seminars are scheduled.

Publications, Video, and Audio Clips

The following written publications were funded all or in part by SGRP.

Recent Peer Reviewed Publications

Zhen Dai, Debra K. Weisenstein, Frank N. Keutsch, and David W. Keith. (2020). "Experimental reaction rates constrain estimates of ozone response to calcium carbonate geoengineering." Communications Earth and Environment 1, 63.

Jacob T. Seeley, Nicholas J. Lutsko, and David W. Keith. "Designing a radiative antidote to CO2." Geophysical Research Letters (Submitted).

Joshua B. Horton and Barbara Koromenos. (2020). "Steering and Influence in Transnational Climate Governance: Nonstate Engagement in Solar Geoengineering Research." Global Environmental Politics 20, 3: 93-111.

Nicholas J. Lutsko, Jacob T. Seeley, and David W. Keith. (2020). "Estimating Impacts and Trade-offs in Solar Geoengineering Scenarios With a Moist Energy Balance Model." Geophysical Research Letters 47, 9.

Joshua B. Horton, Penehuro Lefale, David Keith. (2020). "Parametric Insurance for Solar Geoengineering: Insights from the Pacific Catastrophe Risk Assessment and Financing Initiative." Global Policy, Special Issue.

David Keith and Peter Irvine. (2020). "Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards." Environmental Research Letters 15, 4.

Jesse Reynolds and Joshua Horton. (2020) "An earth system governance perspective on solar geoengineering." Earth System Governance, 3.

Other Publications

David W. Keith and John Deutch (2020) "Climate Policy Enters Four Dimensions." In *Securing our Economic Future,* edited by Amy Ganz and Melissa Kearney, Aspen Institute Press.

Cody Floerchinger, John Dykema, David Keith, and Frank Keutsch (2020) "A Need for In Situ Observations to Inform Nearfield Plume Transport and Aerosol Dynamics as well as Chemistry of Alternate Geoengineering Materials in the Stratosphere." Letter to the National Academy for Science.

David Keith, Frank Keutsch, and Cody Floerchinger (February 15, 2020) "Empirical methods to reduce uncertainty about solar geoengineering," public input to the National Academy Committee on *Climate Intervention Strategies that Reflect Sunlight to Cool Earth*.

Recent Video and Audio Recordings

AGU TV (December 2, 2020). “SCoPEx, Harvard University – New Frontiers in Climate Change Research.” WebsEdge Science.

Anthony Padilla (October 23, 2020) “I spent a day with climate change scientists” *Youtube*.

PBS Nova (October 16, 2020). "Can We Cool the Planet?" *WGBH*.

Harvard Magazine (October 16, 2020). “Daniel Schrag and David Keith: Can Solar Geoengineering Help Fight Climate Change?”

All Things Considered (July 22, 2020) “Harvard Scientists Plan First-Ever Field Experiment Related To Solar Geoengineering.” *WBUR*. (This aired again on Here & Now on December 4, 2020 as “Experiment To Help Researchers Understand Risk, Efficacy of Solar Geoengineering.”)

Harvard Museum of Natural History (December 12, 2019) “The Peril and Promise of Solar Geoengineering” *Youtube*.

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Fwd: Update
To: Frank Keutsch
Cc: Keith, David; Ronda Knott - NOAA Federal
Sent: October 28, 2020 1:03 PM (UTC-04:00)
Attached: Untitled attachment

Great. Looking forward to it.

Begin forwarded message:

From: "Keutsch, Frank N" (b) (6) >
Subject: Re: Update
Date: October 28, 2020 at 10:51:34 AM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>

Dave,

Thanks for your email. I will see how it goes. I have a number of deadlines looming over me, but will try to attend the whole meeting.

I hope you are doing well. Germany is going into a moderate lockdown!

All the best,

Frank

> On Oct 28, 2020, at 3:25 AM, David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:
>
> Frank,
>
> I hope this finds you doing well with the family in Germany.
>
> DavidK and I invited you to a Friday v-meeting to catch up on CI matters. He will give me a brief download of his CDR ideas/perspective at the beginning at my request. So you could join late to miss that.
>
> Let us know.
> THanks
> Dave
>
> ---
>
> David W. Fahey, PhD
> Director of the Earth System Research Laboratories (ESRL)
> Director of the ESRL Chemical Sciences Laboratory
> NOAA Earth System Research Laboratories
> 325 Broadway R/CSD
> Boulder, CO 80305 USA

303-497-5277   -5822 fax
david.w.fahey@noaa.gov

Ronda Knott, Admin. Assistant
ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

Begin forwarded message:

From: Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
Subject: Re: Update
Date: October 26, 2020 at 7:51:29 PM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Cc: "Keith, David" <(b) (6) [redacted]>

Hi Dave and David,

The meeting has been set for this Friday, October 30th at 7am MT and included Frank Kuetsch.
The connection details are:

Meeting ID
meet.google.com/zgb-gfnu-gdr
Phone Numbers
(US) +1 561-408-9337
PIN: 857 507 300#

Thank you,
Ronda

Ronda Knott
Executive Administrative Assistant to

Dr. David W. Fahey, Director

NOAA Chemical Sciences Laboratory
325 Broadway, R/CSL

Boulder CO 80305

I am currently teleworking, please call my cell: (b) (6) [redacted]

303.497.4404 phone

303-497-5822 fax

ronda.knott@noaa.gov

On Mon, Oct 26, 2020 at 2:56 PM David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:

> David,
> 7Am Friday will work.
> Ronda can reach out to FrankK if you like. She will send a link to all.
> Thanks
> Dave
>
> On Oct 25, 2020, at 9:17 PM, Keith, David (b) (6) > wrote:
>
> How about 8:30 AM MT on Friday the 30th? (I can do any time from 7:00 to 10:00) MT that AM. Suggest we choose a time, then I will see if Frank can join (he can miss the CDR part).
>
> D
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, October 24, 2020 6:29 PM
> **To:** Keith, David (b) (6)
> **Cc:** Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
> **Subject:** Re: Update
>
> David,
>
> Thanks for the reply. I appreciate the perspective on Pierrehumbert; a bit frustrating. We will launch a webpage for the Earth Radiation Budget program (ie the Congressional funding) soon (albeit a bit late) that will explain NOAA's role and intent and in effect pushback on Pierrehumbert and others.
>
> Thanks for your offer of a CDR debrief and catching up on other matters. My CDR meeting is 4 Nov so best would be next week sometime. Let me know if that might work (w/ or w/o Frank) and a preferred day/time.
>
> Regards
> Dave
> PS Canmore seems like a good faraway place to get fresh air devoid of C-19.

On Oct 21, 2020, at 2:13 PM, Keith, David
(b) (6) [redacted] wrote:

Dave

Thanks. Yet, I'm particularly frustrating because Ray repeats the idea that doing it at all commits us to doing it for a thousand years, yet I think he knows that's not true. When he was at Harvard and from the public audience we challenged him on that pointing out that you could always taper off slowly even if you didn't have carbon removal and so the net result would be a reduction in the rate of change even if it didn't change the ultimate endpoint. He agreed. Yet he keeps coming back to this claim.

I don't have an overview on CDR. I step back because of the conflict of interest after starting Carbon Engineering (the air capture company). In fact I think that CDR is a bit overhyped and I have been trying to figure out how to say that without frustrating people at Carbon Engineering too much. I have fragments of talks and some opinions. I could dump these on you in a short (15 minutes) conversation which might be helpful to me because I'm trying to polish the stuff.

I think you catch up with you, me and Frank would make sense. I'm thinking early November at that point we will of got science plan out to the SCoPEx committee and have made the next step towards reality on a spring flight.

It's beautiful and snowy up here in Canmore Alberta.

David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Wednesday, October 21, 2020 1:23 PM
To: Keith, David (b) (6) [redacted] >
Subject: Update

David,

Very good article in Globe. Pierrehumbert's article

> is frustrating since he attacks CI and calls out people like me yet at the end says there might be an appropriate role for CI, something he has done in other articles.
>
> My management has asked me to inform them about CDR in an internal meeting. I am not very well prepared to do that and wondered if you had a presentation that you would be willing share to draw from for this purpose.
>
> A call to catch up with Frank would be welcome.
>
> Regards
> Dave
>
> ---
>
> David W. Fahey, PhD
> Director of the Earth System Research Laboratories (ESRL)
> Director of the ESRL Chemical Sciences Laboratory
> NOAA Earth System Research Laboratories
> 325 Broadway R/CSD
> Boulder, CO 80305 USA
> 303-497-5277 -5822 fax
> david.w.fahey@noaa.gov
>
> Ronda Knott, Admin. Assistant
> ronda.knott@noaa.gov, 303-497-4404
> http://www.esrl.noaa.gov/csd/
>
> ---

Frank N. Keutsch
Stonington Professor of Engineering and Atmospheric Science

Harvard John A. Paulson School of Engineering and Applied Sciences
Department of Chemistry and Chemical Biology
Department of Earth and Planetary Sciences
Harvard University
12 Oxford Street
Cambridge, MA 02138
USA

E-mail:
(b) (6) [redacted]

Tel:+(b) (6)

From: Graham Feingold - NOAA Federal <graham.feingold@noaa.gov>
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Andrea Smith; Simone Tilmes; Keutsch, Frank N; Smith, Wake; Karen Rosenlof - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:47 AM (UTC-04:00)

zoom link not working for me. is there something else i need to do?

On 9/17/21 11:06 AM, Andrea Smith wrote:

> Hello Frank, Wake and Graham,
>
> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>
> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
> Meeting ID: 816 4261 9898
> Passcode: 148321
>
> Please join 10 mins early to test tech and troubleshoot if needed.
>
> 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) [redacted] (preferably by Tuesday night):
>
> 3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.
>
> After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.
>
> Let me know if you have questions on any of the above.
>
> Thanks again, and see you next Wednesday.
>
> Andrea
>
> On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) [redacted] > wrote:
>
>> Hi Frank, Wake and Graham,
>> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>>
>> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
>>
>> 1. Frank Keutsch: ...
>> 2. Wake Smith:...
>> 3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening
>>
>> Here is Andreas rundown for logistics:
>>
>> -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
>> -send slide decks to Andrea by Tuesday (9/21) evening for backup purposes

> -arrive ~10 mins early so we can do quick test of screenshares
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> -panelists and question askers encouraged to unmute & turn on camera
> -session will be recorded and posted later - we'll send a release form for them to complete
>
> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
>
> Cheers, Simone
>
> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6) [redacted]

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) [redacted] (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

--
Graham Feingold
NOAA Earth System Research Laboratories
Chemical Sciences Laboratory (R/CSL9)
325 Broadway
Boulder, Colorado 80305, USA
Tel: (303) 497-3098
Fax: (303) 497-5318

From: Alan Robock ☮ (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin;(b) (6) ;(b) (6) ; Karen Rosenlof - NOAA Federal; Katharine Ricke; (b) (6) Robert Wood; (b) (6) ; (b) (6) Daniele Visioni; Isla Simpson; Peter Irvine; Jonathan Proctor; (b) (6) ; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N
Cc: Trude Storelvmo; 'Simone Tilmes'; (b) (6)
Sent: July 15, 2021 5:37 PM (UTC-04:00)

Dear Doug and Trude,

I would like to give a talk. Thanks.

Alan

On 7/15/2021 11:06 AM, Douglas MacMartin wrote:

> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
>
> As a start to our planning, could you let us know whether you would be interested in talking at the 2022 meeting? We would of course still love to hear from you, but schedules may not permit and research interests change (and, indeed, for some or many of you that may mean that the topic we were originally thinking you would talk about would no longer be what you are currently most excited by – the GRC is supposed to be cutting-edge current research, of course – so if you let us know we can start revising sessions and think about what gaps we'd like to fill). There are also some new people who are doing some great research too that we would like to hear from, so it's conceivable that – given the now 5 year gap since the last GRC – we might choose to slightly increase the number of talks and reduce the time available per talk.
>
> Thanks,
> Doug & Trude
>
> ---
>
> **From:** Douglas MacMartin
> **Sent:** Wednesday, February 19, 2020 10:27 AM
> **To:** (b) (6) ;(b) (6) ; Alan Robock (b) (6) ; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke (b) (6) ;(b) (6) ; Robert Wood (b) (6) (b) (6) ;(b) (6) (b) (6) ; Daniele Visioni (b) (6) ;(b) (6) ; Peter Irvine (b) (6) ; Jonathan Proctor (b) (6) ;(b) (6) Keith, David (b) (6) Kravitz, Ben (b) (6) Wake Smith (b) (6) ; Izidine Pinto (b) (6) Gabriel Chiodo (b) (6) ; Keutsch, Frank N (b) (6) >
> **Cc:** Lawrence, Mark (b) (6) ; valentina Aquila (b) (6) >; Ulrike Niemeier (b) (6) >; Leisner, Thomas (IMK) (b) (6) Olivier Boucher (b) (6) Schrag, Daniel P. (b) (6) TAYLOR,Michael (b) (6) (b) (6) Trude Storelvmo (b) (6) ;

'Simone Tilmes'(b) (6) ;(b) (6) Jim Hurrell
(b) (6)
Subject: RE: 2020 GRC program

Hi all,

Just a reminder that if you haven't sent me a title yet, to do so (otherwise I'll have to make something up; GRC needs us to upload our "final" program by the end of this month) I have titles for about half of you (though some of those are draft titles you sent quite some time ago, e.g. for Pete, Isla, Danny).

And, if you haven't responded yet regarding need for travel support, let me know (about half of you have). For those of you who haven't been to a GRC before, there's a bus from Boston airport, and from Portland Maine airport.

If you've already both sent me a title and responded regarding travel, then you can ignore this email.

Also, regarding format, this year we're explicitly including 10-15 minutes for the discussion leader to make some remarks to help frame each session (taking 5 minutes from each speaker's time), and rather than having a lengthy discussion after each talk, we'll have a shorter 10-minute discussion after each talk and a 20-minute general session discussion at the end (that's as long as GRC will allow) with everyone from a given session.

Thanks, and see you in June!
doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To:(b) (6) ;(b) (6) 'Jadwiga (Yaga) Richter'
(b) (6) >; Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal
<karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >;(b) (6) ; Robert
Wood (b) (6) >;(b) (6) ;(b) (6)
(b) (6) >; Daniele Visioni (b) (6) >;(b) (6) ; Peter Irvine
(b) (6) ; Jonathan Proctor (b) (6) ; Govindasamy Bala
(b) (6) >;(b) (6) Keith, David <(b) (6) ; Kravitz, Ben
(b) (6) ; Wake Smith <(b) (6) >; Chris Field (b) (6)
Cc: Lawrence, Mark (b) (6) >; valentina Aquila (b) (6) >; Ulrike
Niemeier (b) (6) ; Leisner, Thomas (IMK) (b) (6) ; Olivier
Boucher (b) (6) ; Schrag, Daniel P. (b) (6) ; TAYLOR,Michael
(b) (6) >;(b) (6) ; Lynn Russell (b) (6) >; Trude Storelvmo
(b) (6) >; 'Simone Tilmes' (b) (6) >;(b) (6)
Subject: 2020 GRC program

Hi all,

Happy New Year!

The full program for GRC is due on February 28; if you haven't sent us a title for your talk (or if you did and want to revise it), please do so before the end of February so I have time to enter everything into the conference management system online.

The cc-line has discussion leaders for each session.

Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin
Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and
Faculty Fellow, Atkinson Center for a Sustainable Future
Cornell University
(b) (6) [redacted]
https://climate-engineering.mae.cornell.edu/

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Nice job on the NOVA episode!
To: Kelly Wanser
Cc: Frank Keutsch; John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:19 PM (UTC-04:00)
Attached: Untitled attachment

Kelly,
I think you want to praise David K instead of me. I too thought they all did a great job.
Dave

> On Oct 29, 2020, at 1:12 PM, Kelly Wanser (b) (6) wrote:
>
> You were excellent and the piece came out great.
> We'll promote it as we are able.
>
> Best,
> k.
>
> --
> Kelly Wanser
> Executive Director, SilverLining | http://www.silverlining.ngo
> Board Director, Dendra Systems | http://www.dendra.io
> Advisor, University of Washington Marine Cloud Brightening Project | http://www.mcbproject.org
> President's Circle, National Academy of Sciences | http://nas-sites.org/PC/
> Phone: (b) (6)
>
> **TEDTalk:** *Emergency Medicine for Our Climate Fever*
> **Report:** *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: Kelly Wanser (b) (6) [redacted] >
Subject: Re: Nice job on the NOVA episode!
To: David Fahey - NOAA Federal; David Keith
Cc: Frank Keutsch; John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:22 PM (UTC-04:00)

Ha, thanks, Dave. Adding David here.
Terrific piece, David!

Sent from my iPhone

> On Oct 29, 2020, at 1:19 PM, David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:
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>> **TEDTalk:** *Emergency Medicine for Our Climate Fever*
>> **Report:** *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: Andrea Smith (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Karen Rosenlof - NOAA Federal
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Graham Feingold - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:36 AM (UTC-04:00)

Good morning everyone,

If you haven't already done so, please reply here with slide decks or drop them in (b) (6) if large file size.

See you in 10-15 mins!

Cheers,

Andrea

On Fri, Sep 17, 2021 at 2:43 PM Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov> wrote:

> And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
> So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.
>
> Thanks!
>
> Karen
>
> --
> Karen Rosenlof
> NOAA Chemical Sciences Laboratory
> Mail Stop R/CSL8
> 325 Broadway
> Boulder, CO 80305
> office: 3A-121, DSRC
> e-mail: Karen.H.Rosenlof@noaa.gov
> phone: 303 497-7761
> fax: 303 497-5373
> --
> while safer at home remains in effect, email is the most reliable contact
>
> > On Sep 17, 2021, at 11:06 AM, Andrea Smith (b) (6) > wrote:
> >
> > Hello Frank, Wake and Graham,
> >
> > Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
> >
> > 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
> > https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
> > Meeting ID: 816 4261 9898
> > Passcode: 148321
> >
> > Please join 10 mins early to test tech and troubleshoot if needed.

2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) (preferably by Tuesday night):

3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.

After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.

Let me know if you have questions on any of the above.

Thanks again, and see you next Wednesday.

Andrea

On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) wrote:

> Hi Frank, Wake and Graham,
> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>
> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
>
> 1. Frank Keutsch: ...
> 2. Wake Smith:...
> 3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening
>
> Here is Andreas rundown for logistics:
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> -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
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> > *303-497-1400 (fax)*
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>
> --
> Andrea Smith
> Associate Scientist & Program Manager
> The COMET® Program
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> (b) (6) (cell)
>
> *My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.*
> <CCISspeaker_consent_form.pdf>

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Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
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3085 Center Green Dr.
Boulder, CO 80301
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(b) (6) (cell)

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From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Keith, David
Cc: Smith, Wake; Frank Keutsch
Sent: January 30, 2021 6:38 PM (UTC-05:00)
Attached: Untitled attachment

David,

Yes, I think if one has funding, then existing a/c become available. Certainly for the UT/LS, the WB-57s have been underutilized for years now and hence availability hasn't been an issue. Indeed a trip back to the boneyard was perhaps a growing threat.

I note that no one has ever built an aircraft for atmospheric chemistry, leaving the field to exploit as best they can existing a/c, which we have done very well. Thus, if there were runway a/c available that could do 30kg, 8hr, 79kft, the community would no doubt rush to use it. So the answer to your question is yes.

My problem with new-platforms-will-be-cheap is the issue of having truly operational a/c rather than experimental a/c. If one is trying to fly an experiment on an experimental a/c it reduces the probability of success by a large measure. Making an experimental a/c operational requires larger upfront and sustained investment by entities other than the science communities, creating the underwater part of the iceberg. This is why we don't have new operational a/c. And one can look to the Global Hawk and see that even starting at a high level (a mature platform) it failed to become operational because no one wants to pay the price, in this case neither NASA or NOAA. Now deeper pockets (DoD) have taken it over.

And to your final point about what payloads, yes, the new generation of lightweight instruments make 30kg interesting and valuable, and, yes, comprehensive chemistry payloads still want to be on heavy lift long-range a/c.

In reply to Wake's question about perturbation/monitoring a/c, hmmm, it depends. In the early days, perhaps they could be the same. Eventually the perturbations sought would be as large as possible per flight and not every flight would need diagnostics, so I think eventually they are different a/c. And monitoring a/c could be below the perturbation a/c altitudes and diagnose with lidar.

Interest above 70kft: in general because we would be deeper into the ozone layer. And perhaps the injection altitude would be there once we understand things better.

Regards
Dave

> On Jan 30, 2021, at 9:29 AM, Keith, David (b) (6)> wrote:
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> I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.
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> I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30

kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.

I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.

I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.

Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.

Interesting conversation. No simple answers.

Cheers,
David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Thursday, January 28, 2021 11:49 AM
To: Smith, Wake (b) (6) >
Cc: Keith, David <(b) (6) >; Keutsch, Frank N (b) (6)
Subject: Re: Experimental research platform requirements

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi-flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" (b) (6) [redacted] >
Cc: Frank Keutsch <(b) (6) [redacted]

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can't control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake (b) (6) [redacted] > wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to

understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6)

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Keith, David
Cc: Smith, Wake; Frank Keutsch
Sent: February 3, 2021 6:41 PM (UTC-05:00)
Attached: Untitled attachment

David,

Yes, the Perseus a/c was a big distraction that I was only on the edge of fortunately.

I will remain skeptical about the likelihood of new non-military a/c but want to be first in line to use them. We were first in line and funded to use the new Boeing/Aurora a/c, Odysseus, when the plug was pulled.

Yes we have had conversations with the Sceye folks and would like to have a chance to use when the day comes.

BTW, the CU group here apparently demonstrated a 1.5km reel down from a balloon quite recently. No other details.

Regards
Dave

On Feb 3, 2021, at 7:59 AM, Keith, David (b) (6) [redacted]> wrote:

Dave

Thanks. I think we see this about the same way.

From my perspective I came into this field working for Jim with all the excitement about Aurora's aircraft which ended up amounting to nothing. It took some years of my life. And yes, Global Hawk has been a big disappointment. So I definitely get the basis for skepticism.

On the other hand, there does seem to be a commercial-driven shakeup in the ability to develop low altitude aircraft. That's true from the new entrants into general aviation market through to the startups building off drone technology. So I'd like to understand whether this could apply to higher altitude light aircraft. I don't know, but if Wake spurs some interest I am open to find out more.

Have you had any conversations with these folks: [Sceye | A new generation of HAPS | High Altitude Platform Stations](#)? The head guy just reached out to me again and I will talk with.

David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Saturday, January 30, 2021 6:38 PM
To: Keith, David (b) (6) [redacted]>
Cc: Smith, Wake (b) (6) [redacted]; Keutsch, Frank N (b) (6) [redacted]

Subject: Re: Experimental research platform requirements

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David

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Sent: Thursday, January 28, 2021 11:49 AM
To: Smith, Wake <(b) (6)
Cc: Keith, David (b) (6) Keutsch, Frank N
(b) (6)
Subject: Re: Experimental research platform requirements

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From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" <(b) (6) [redacted]>
Cc: Frank Keutsch <(b) (6) [redacted]>

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can't control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake <(b) (6) [redacted]> wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I

understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School & Lecturer in Yale College
(b) (6)

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Andrea Smith
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Graham Feingold - NOAA Federal; Brian Medeiros
Sent: September 17, 2021 4:44 PM (UTC-04:00)
Attached: Untitled attachment

And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.

Thanks!

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
Boulder, CO 80305
office: 3A-121, DSRC
e-mail: Karen.H.Rosenlof@noaa.gov
phone: 303 497-7761
fax: 303 497-5373
----
while safer at home remains in effect, email is the most reliable contact

> On Sep 17, 2021, at 11:06 AM, Andrea Smith (b) (6) [redacted]> wrote:
>
> Hello Frank, Wake and Graham,
>
> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>
> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
> Meeting ID: 816 4261 9898
> Passcode: 148321
>
> Please join 10 mins early to test tech and troubleshoot if needed.
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> 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) [redacted] (preferably by Tuesday night):
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> 3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.

After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.

Let me know if you have questions on any of the above.

Thanks again, and see you next Wednesday.

Andrea

On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) [redacted] wrote:

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> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>
> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
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> 2. Wake Smith:...
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> Cheers, Simone
>
> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6) [redacted]

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.

Boulder, CO 80301
303-497-8320 (office)
(b) (6)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.
<CCISspeaker_consent_form.pdf>

From: Smith, Wake (b) (6)
Subject: RE: CCIS webinar Wednesday Sept 22nd
To: Karen Rosenlof - NOAA Federal
Sent: September 18, 2021 7:59 AM (UTC-04:00)

Will do.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6)

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Sent: Friday, September 17, 2021 4:44 PM
To: Andrea Smith (b) (6)
Cc: Simone Tilmes (b) (6) ; Keutsch, Frank N (b) (6) >; Smith, Wake <(b) (6) ; Graham Feingold - NOAA Federal <Graham.Feingold@noaa.gov>; Brian Medeiros (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd

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So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.

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Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
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Please join 10 mins early to test tech and troubleshoot if needed.

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(b) (6) (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.
<CCISspeaker_consent_form.pdf>

From: Peter Irvine (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin
Cc: Piers Forster; (b) (6) Alan Robock; Karen Rosenlof - NOAA Federal; Katharine Ricke; Seneviratne Sonia Isabelle; Robert Wood; Helene Muri; (b) (6) Daniele Visioni; Isla Simpson; Jonathan Proctor; Ines Camilloni; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N; Trude Storelvmo; Simone Tilmes; Lohmann Ulrike
Sent: July 18, 2021 4:53 PM (UTC-04:00)

Hi Doug, Trude,

It's be happy to present in 2022, with the same title for now.

Cheers,

Pete

On Thu, Jul 15, 2021, 16:06 Douglas MacMartin (b) (6) > wrote:

> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
>
> As a start to our planning, could you let us know whether you would be interested in talking at the 2022 meeting? We would of course still love to hear from you, but schedules may not permit and research interests change (and, indeed, for some or many of you that may mean that the topic we were originally thinking you would talk about would no longer be what you are currently most excited by – the GRC is supposed to be cutting-edge current research, of course – so if you let us know we can start revising sessions and think about what gaps we'd like to fill). There are also some new people who are doing some great research too that we would like to hear from, so it's conceivable that – given the now 5 year gap since the last GRC – we might choose to slightly increase the number of talks and reduce the time available per talk.
>
> Thanks,
>
> Doug & Trude
>
> ---
>
> **From:** Douglas MacMartin
> **Sent:** Wednesday, February 19, 2020 10:27 AM
> **To:** (b) (6) (b) (6) ; Alan Robock (b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke (b) (6) ; (b) (6) ; Robert Wood (b) (6) >; (b) (6) ; (b) (6) (b) (6) >; Daniele Visioni (b) (6) >; (b) (6) Peter Irvine (b) (6) >; Jonathan Proctor (b) (6) >;

(b) (6) Keith, David <(b) (6) >; Kravitz, Ben (b) (6) >; Wake Smith
(b) (6) >; Izidine Pinto <(b) (6) >; Gabriel Chiodo
<(b) (6) >; Keutsch, Frank N (b) (6)
Cc: Lawrence, Mark <(b) (6) >; valentina Aquila <(b) (6) ; Ulrike
Niemeier <(b) (6) >; Leisner, Thomas (IMK) <(b) (6) >; Olivier Boucher
<(b) (6) >; Schrag, Daniel P. <(b) (6) >; TAYLOR,Michael
<(b) (6) >;(b) (6) Trude Storelvmo (b) (6) >; 'Simone
Tilmes' <(b) (6) >;(b) (6) ; Jim Hurrell (b) (6) >
Subject: RE: 2020 GRC program

Hi all,

Just a reminder that if you haven't sent me a title yet, to do so (otherwise I'll have to make something up; GRC needs us to upload our "final" program by the end of this month) I have titles for about half of you (though some of those are draft titles you sent quite some time ago, e.g. for Pete, Isla, Danny).

And, if you haven't responded yet regarding need for travel support, let me know (about half of you have). For those of you who haven't been to a GRC before, there's a bus from Boston airport, and from Portland Maine airport.

If you've already both sent me a title and responded regarding travel, then you can ignore this email.

Also, regarding format, this year we're explicitly including 10-15 minutes for the discussion leader to make some remarks to help frame each session (taking 5 minutes from each speaker's time), and rather than having a lengthy discussion after each talk, we'll have a shorter 10-minute discussion after each talk and a 20-minute general session discussion at the end (that's as long as GRC will allow) with everyone from a given session.

Thanks, and see you in June!

doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) ;(b) (6) ; 'Jadwiga (Yaga) Richter' <(b) (6) >;
Alan Robock (b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>;
Katharine Ricke <(b) (6) >;(b) (6) ; Robert Wood <(b) (6) >;
(b) (6) ;(b) (6) (b) (6) >; Daniele Visioni
<(b) (6) >;(b) (6) ; Peter Irvine (b) (6) >; Jonathan Proctor
(b) (6) >; Govindasamy Bala (b) (6) ;(b) (6) ; Keith, David
<(b) (6) >; Kravitz, Ben (b) (6) >; Wake Smith (b) (6) >; Chris Field
<(b) (6) >

Cc: Lawrence, Mark <(b) (6) >; valentina Aquila (b) (6) >; Ulrike Niemeier <(b) (6) Leisner, Thomas (IMK) (b) (6) >; Olivier Boucher <(b) (6) ; Schrag, Daniel P. <(b) (6) >; TAYLOR,Michael (b) (6) >;(b) (6) ; Lynn Russell (b) (6) ; Trude Storelvmo <(b) (6) >; 'Simone Tilmes' <(b) (6) >;(b) (6)
Subject: 2020 GRC program

Hi all,

Happy New Year!

The full program for GRC is due on February 28; if you haven't sent us a title for your talk (or if you did and want to revise it), please do so before the end of February so I have time to enter everything into the conference management system online.

The cc-line has discussion leaders for each session.

Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin

Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and

Faculty Fellow, Atkinson Center for a Sustainable Future

Cornell University

(b) (6)

[redacted]

https://climate-engineering.mae.cornell.edu/

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Smith, Wake
Cc: Keith, David; Frank Keutsch
Sent: January 28, 2021 11:49 AM (UTC-05:00)
Attached: Untitled attachment

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi- flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

> Begin forwarded message:
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Subject: Re: Small stratospheric aircraft**
> **Date:** January 22, 2021 at 8:56:59 AM MST
> **To:** "Keith, David" <(b) (6)
> **Cc:** Frank Keutsch <(b) (6)
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Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
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Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6)

From: Andrea Smith (b) (6) [redacted]
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Graham Feingold - NOAA Federal
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Karen Rosenlof - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:49 AM (UTC-04:00)

https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09

Do you need to use the web client? NOAA or other government users can use Zoom's government-approved web client

Try that, let me know how it goes.

A

On Wed, Sep 22, 2021 at 8:47 AM Graham Feingold - NOAA Federal <graham.feingold@noaa.gov> wrote:

> zoom link not working for me. is there something else i need to do?
>
> On 9/17/21 11:06 AM, Andrea Smith wrote:
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3085 Center Green Dr.
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```
Graham Feingold
NOAA Earth System Research Laboratories
Chemical Sciences Laboratory (R/CSL9)
325 Broadway
Boulder, Colorado 80305, USA
```

> Tel: (303) 497-3098
> Fax: (303) 497-5318

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From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Fwd: Update
To: Frank Keutsch
Cc: Keith, David; Ronda Knott - NOAA Federal
Sent: October 28, 2020 1:03 PM (UTC-04:00)
Attached: Untitled attachment

Great. Looking forward to it.

Begin forwarded message:

From: "Keutsch, Frank N" (b) (6) [redacted]>
Subject: Re: Update
Date: October 28, 2020 at 10:51:34 AM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>

Dave,

Thanks for your email. I will see how it goes. I have a number of deadlines looming over me, but will try to attend the whole meeting.

I hope you are doing well. Germany is going into a moderate lockdown!

All the best,

Frank

> On Oct 28, 2020, at 3:25 AM, David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:
>
> Frank,
>
> I hope this finds you doing well with the family in Germany.
>
> DavidK and I invited you to a Friday v-meeting to catch up on CI matters. He will give me a brief download of his CDR ideas/perspective at the beginning at my request. So you could join late to miss that.
>
> Let us know.
> THanks
> Dave
>
> ---
>
> David W. Fahey, PhD
> Director of the Earth System Research Laboratories (ESRL)
> Director of the ESRL Chemical Sciences Laboratory
> NOAA Earth System Research Laboratories
> 325 Broadway R/CSD
> Boulder, CO 80305 USA

303-497-5277   -5822 fax
david.w.fahey@noaa.gov

Ronda Knott, Admin. Assistant
ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

Begin forwarded message:

From: Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
Subject: Re: Update
Date: October 26, 2020 at 7:51:29 PM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Cc: "Keith, David" <(b) (6) [redacted]>

Hi Dave and David,

The meeting has been set for this Friday, October 30th at 7am MT and included Frank Kuetsch.
The connection details are:

Meeting ID
meet.google.com/zgb-gfnu-gdr
Phone Numbers
(US) +1 561-408-9337
PIN: 857 507 300#

Thank you,
Ronda

Ronda Knott
Executive Administrative Assistant to

Dr. David W. Fahey, Director

NOAA Chemical Sciences Laboratory
325 Broadway, R/CSL

Boulder CO 80305

I am currently teleworking, please call my cell: (b) (6) [redacted]

303.497.4404 phone

303-497-5822 fax

ronda.knott@noaa.gov

On Mon, Oct 26, 2020 at 2:56 PM David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:

> David,
> 7Am Friday will work.
> Ronda can reach out to FrankK if you like. She will send a link to all.
> Thanks
> Dave
>
> On Oct 25, 2020, at 9:17 PM, Keith, David (b) (6) [redacted] > wrote:
>
> How about 8:30 AM MT on Friday the 30th? (I can do any time from 7:00 to 10:00) MT that AM. Suggest we choose a time, then I will see if Frank can join (he can miss the CDR part).
>
> D
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, October 24, 2020 6:29 PM
> **To:** Keith, David (b) (6) [redacted]
> **Cc:** Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
> **Subject:** Re: Update
>
> David,
>
> Thanks for the reply. I appreciate the perspective on Pierrehumbert; a bit frustrating. We will launch a webpage for the Earth Radiation Budget program (ie the Congressional funding) soon (albeit a bit late) that will explain NOAA's role and intent and in effect pushback on Pierrehumbert and others.
>
> Thanks for your offer of a CDR debrief and catching up on other matters. My CDR meeting is 4 Nov so best would be next week sometime. Let me know if that might work (w/ or w/o Frank) and a preferred day/time.
>
> Regards
> Dave
> PS Canmore seems like a good faraway place to get fresh air devoid of C-19.

On Oct 21, 2020, at 2:13 PM, Keith, David
(b) (6) wrote:

Dave

Thanks. Yet, I'm particularly frustrating because Ray repeats the idea that doing it at all commits us to doing it for a thousand years, yet I think he knows that's not true. When he was at Harvard and from the public audience we challenged him on that pointing out that you could always taper off slowly even if you didn't have carbon removal and so the net result would be a reduction in the rate of change even if it didn't change the ultimate endpoint. He agreed. Yet he keeps coming back to this claim.

I don't have an overview on CDR. I step back because of the conflict of interest after starting Carbon Engineering (the air capture company). In fact I think that CDR is a bit overhyped and I have been trying to figure out how to say that without frustrating people at Carbon Engineering too much. I have fragments of talks and some opinions. I could dump these on you in a short (15 minutes) conversation which might be helpful to me because I'm trying to polish the stuff.

I think you catch up with you, me and Frank would make sense. I'm thinking early November at that point we will of got science plan out to the SCoPEx committee and have made the next step towards reality on a spring flight.

It's beautiful and snowy up here in Canmore Alberta.

David

From: David Fahey - NOAA Federal
<david.w.fahey@noaa.gov>
Sent: Wednesday, October 21, 2020 1:23 PM
To: Keith, David (b) (6) >
Subject: Update

David,

Very good article in Globe. Pierrehumbert’s article

> is frustrating since he attacks CI and calls out people like me yet at the end says there might be an appropriate role for CI, something he has done in other articles.
>
> My management has asked me to inform them about CDR in an internal meeting. I am not very well prepared to do that and wondered if you had a presentation that you would be willing share to draw from for this purpose.
>
> A call to catch up with Frank would be welcome.
>
> Regards
> Dave
>
> ---
>
> David W. Fahey, PhD
> Director of the Earth System Research Laboratories (ESRL)
> Director of the ESRL Chemical Sciences Laboratory
> NOAA Earth System Research Laboratories
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> Boulder, CO 80305 USA
> 303-497-5277 -5822 fax
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>
> Ronda Knott, Admin. Assistant
> ronda.knott@noaa.gov, 303-497-4404
> http://www.esrl.noaa.gov/csd/
>
> ---

Frank N. Keutsch
Stonington Professor of Engineering and Atmospheric Science

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The Stratospheric Controlled Perturbation Experiment (SCoPEx)

Version 1.0

Executive Summary

Climate model studies of stratospheric solar radiation modification (SRM) depend, perhaps implicitly, on processes that take place in the near field of an injection plume. This is because materials delivered to the stratosphere by aircraft will form persistent, high aspect-ratio plumes with strong gradients before becoming well mixed, and processes within the plume will alter the large-scale, well-mixed aerosol and chemical properties that are simulated in global atmospheric models. All models ultimately depend on observations, yet we lack experimental data to assess some of the critical transport, microphysical, and chemical processes that directly control aerosol dynamics in the near-field that are important for understanding stratospheric SRM.

The scientific goal of the Stratospheric Controlled Perturbation Experiment (SCoPEx) is to improve process models that will, in turn, reduce uncertainties in global-scale models, thus reducing uncertainty in predictions of important SRM risks and benefits.

SCoPEx addresses questions in stratospheric aerosol injection (SAI) research that observations of existing analogues are incapable of addressing. For example, existing observational data do not include chemistry of alternate geoengineering materials specific to SAI, near-field particle microphysics of injection plumes, and relevant scales of atmospheric transport in the near-field. Yet these are needed to assess processes that control aerosol dynamics in the near field of an injection plume and that allow for the evaluation of alternate SAI materials, i.e., materials other than the naturally existing sulfate aerosol.

We first review why existing observations do not address the questions that SCoPEx will answer. We then give a description of the basic design of the platform and the concept of operations of SCoPEx. Finally, we describe the three specific science goals of SCoPEx, explain how they represent critical knowledge gaps in SAI research, and specify what measurements are needed to enable SCoPEx to provide quantitative answers to these questions. The three specific science goals are improving understanding of (i) turbulent mixing scales, (ii) aerosol microphysics with a focus on alternative SAI materials in the near-field of an injection, and (iii) process level chemical interactions of alternative SAI materials in the stratosphere.

We do not provide a detailed engineering document of the SCoPEx platform or its scientific instrumentation, nor do we provide a justification for the need for research on SRM via SAI in general. Rather, we focus specifically on the merits of SCoPEx itself.

1. Introduction

In this document we focus on the motivation and scientific merit of SCoPEx. We do not provide detailed engineering documentation of the SCoPEx platform or its scientific instrumentation. We also do not provide general justification for the need for research on solar radiation modification (SRM) via stratospheric aerosol injection (SAI), which can be found in many prior documents such as the 1992 NAS report that recommended the US government "Undertake research and development projects to improve our understanding of both the potential of geoengineering options to offset global warming and their possible side effects. This is not a recommendation that geoengineering options be undertaken at this time, but rather that we learn more about their likely advantages and disadvantages" (National Academy of Sciences et al., 1992) or the recent 2015 NAS report (National Research Council, 2015). Rather, we focus specifically on the need for small-scale field experiments such as SCoPEx, and the specific, critical SAI research needs that will be addressed by SCoPEx.

1.1. Role of and Need for Small-Scale Field Experiments

There is a vast array of science and engineering questions that have to be answered to achieve a better understanding of the risks, benefits and feasibility of SAI. The tools and topics that are needed to address these questions range from General Circulation Models (GCMs) all the way to detailed design of instrumentation to monitor or disperse aerosol. SCoPEx addresses a subset of questions that require small-scale field experiments for ground-truthing and that are aimed at improving the ability of models to predict the consequences of SAI.

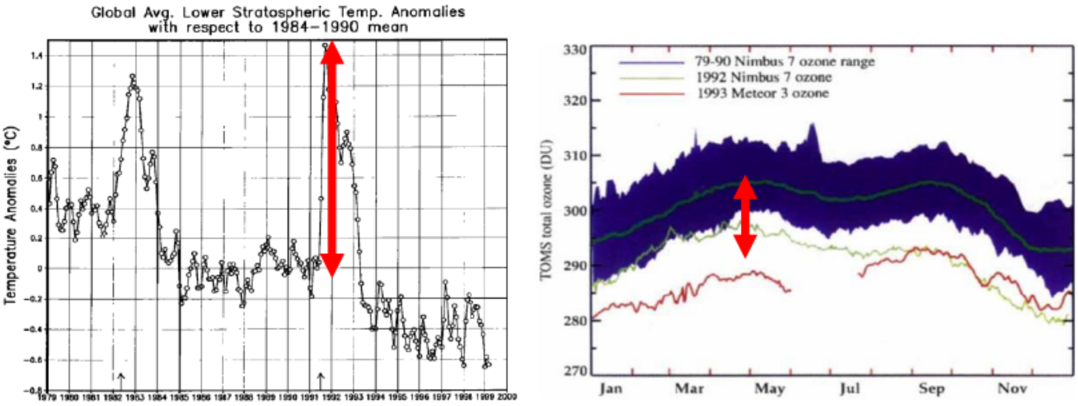

Figure 1: The two most important first-order stratospheric risks from sulfate SAI. The left panel shows stratospheric temperature anomalies from the El Chichon and Mount Pinatubo eruptions on top of background temperatures that are decreasing due to greenhouse gas emissions (Robock, 2000). The dynamical response of the stratosphere from such a short heating pulse likely is different than from sustained heating from longer-term SAI. The right panel shows that in the two years following the Mount Pinatubo reaction total ozone columns were lower than in the 1979-90 average as a result of increase sulfate aerosol surface area. Smaller eruptions also contributed to this. (McCormick et al., 1995)

There are numerous known risks associated with SAI, and SCoPEx focuses primarily on improving understanding of the first-order impacts in the stratosphere, i.e., risks and risk reduction associated with impacts of SAI within the stratosphere. There are many downstream / higher-order risks, e.g., impact on cloud formation as SAI particles leave the stratosphere (Cziczo et al., 2019), impacts on ecosystems via changes in the hydrological cycle (Bala et al., 2008; Russell et al., 2012; Tilmes et al., 2013), or the amount of direct

versus diffuse radiation (Gu et al., 2002; Farquhar & Roderick, 2003; Gu et al., 2003). Despite their importance, these impacts are not the direct target of this proposal although many of these are also influenced by stratospheric processes and properties of SAI aerosol. Two first-order risks are at the focus of this work: stratospheric ozone loss and the dynamic response resulting from stratospheric heating as a result of SAI.

Whereas stratospheric ozone chemistry is fairly well understood (World Meteorological Organization, 2019), there are still substantial uncertainties in the understanding and ability to model stratospheric dynamics (Figure 1). For example, models have only recently been able to reproduce the quasi-biennial oscillation without having it imposed (see Butchart et al., 2018 for a discussion of challenges). One approach taken in this work is to evaluate whether there are types of aerosols or methods of aerosol injection that can reduce first-order risks for a given amount of radiative forcing. It stands to reason that a reduction in the first-order stratospheric impacts will reduce downstream and higher-order risks. A case in point is the growing body of work that has been investigating the impacts of stratospheric heating on stratospheric water vapor and the dynamic response on regional climate (Simpson et al., 2019; Ferraro et al., 2015; Richter et al., 2018; Ji et al., 2018). It is important to note that the amount of stratospheric heating for a given material will be primarily driven by the total mass of aerosol, ozone destruction will be driven by the total surface area of aerosol, and the desired radiative forcing will be determined by the amount and size distribution of aerosol. Critically, both the aerosol mass required for a given desired radiative forcing *and* the resulting surface area are tied to this size distribution. Therefore, accurate models of the evolution of the size distribution of injected aerosol are critically needed. In addition, alternate materials with reduced stratospheric heating have to be investigated, as do injection methods for sulfate that minimize stratospheric heating and ozone loss for a given radiative forcing, as this will reduce risks associated with the dynamic response to this first-order perturbation.

2. Observational SAI Research Needs

Most of the rapidly growing body of literature on SAI rests on General Circulation Models (GCMs). We acknowledge the importance of GCM studies, but in the following we focus on research needs that require experiments and observations, and especially questions that can only be answered by conducting perturbative field experiments such as SCoPEx (see supplemental manuscripts Keith et al., 2020 and Floerchinger et al., 2020). In fact, SCoPEx will in the end inform GCMs by providing improved process level information that will be integrated in parameterizations used in GCMs. Below we review existing observational data sets and describe their utility for different SAI approaches, highlighting where they are unable to shed light on critical issues thus motivating studies like SCoPEx.

2.1. Field Experimental Needs for Sulfate SAI

Most studies that have sought to research SAI have assumed the addition of aerosol would take place by means of an injection of gas-phase SO_2, which is ultimately converted to H_2SO_4 and then to sulfate aerosol in the stratosphere on a timescale of approximately one month. The aerosol size distribution from this injection of gas phase precursor must be accurately predicted as it will control the shortwave (SW) scattering properties, the stratospheric lifetime of the aerosol, and ultimately be the driver for the radiative forcing (RF) efficiency per mass of injected sulfate. Some studies, such as Niemeier & Timmreck (2015), have suggested that with higher injection rates of SO_2, the resulting sulfate aerosol would be forced into a larger, coarse-mode size distribution and functionally reach a point of diminishing return. In this diminishing return scenario, the added amount of SW RF achieved per added mass of sulfate decreases exponentially.

Recent work by Pierce et al. (2010), Benduhn et al. (2016), and Vattioni et al. (2019) has highlighted the potential benefits of injecting H_2SO_4 aerosol directly into the accumulation mode (AM), i.e., aerosols with a radius of 0.1–1.0 µm, potentially by emitting H_2SO_4 vapor into an aircraft plume. This work has suggested better control of the resulting aerosol size distribution and thus the radiative forcing per unit mass sulfur injection, which would allow for the design of a system that maximizes the radiative forcing per mass of sulfate in a way that would not have the diminishing returns at high SO_2 injection rates. This would thus minimize the increase in the stratospheric sulfate burden and hence the risk of stratospheric heating which is driven by total mass whereas ozone loss is driven by surface area. While injecting AM–H_2SO_4 may represent the best possible approach for SAI with stratospheric sulfate, there is currently no proven way to introduce vapor phase AM–H_2SO_4 into the stratosphere. As AM–H_2SO_4 has not been studied, perturbative experiments are required to provide observational constraints on the aerosol size distributions predicted by models.

2.2. Field Experimental Needs for Alternate Aerosol Material SAI

Though sulfate aerosol does exist in the background stratosphere and there are some natural analogs of broad stratospheric sulfate injections (volcanic eruptions), it likely is not the optimal candidate for SAI. Alternative aerosol may be most appropriate in order to mitigate SAI risks (Teller et al., 1996; Crutzen, 2006; Ferraro et al., 2011; Ferraro et al., 2015; Weisenstein et al., 2015; Keith et al., 2016; Dykema et al., 2016; Weisenstein et al., 2015). These alternate aerosols could reduce the previously noted two major first-order stratospheric impacts, i.e., changes in ozone and stratospheric heating. Due to the uncertainties in the impacts of stratospheric heating, the study of materials with optical

properties that negate stratospheric heating is especially important. Materials such as calcium carbonate ($CaCO_3$), alumina (Al_2O_3), diamond (carbon), and several others, have been proposed as a way to minimize the inherent risks from SAI (Keith et al., 2016; Dykema et al., 2016; Weisenstein et al., 2015; Ferraro et al., 2015; Ferraro et al., 2011; Crutzen, 2006). Although model results of these aerosol species suggest that some of them possess optical properties that make them well suited to be used in a SRM scenario ($CaCO_3$, Al_2O_3, and diamond) (Dykema et al., 2016; Ferraro et al., 2011), the stratospheric aerosol microphysics of these compounds (especially coagulation) is poorly understood. As with AM–H_2SO_4 injections, there is a profound lack of in situ data to assess the ability to model the microphysics of alternative aerosols and the stratospheric chemistry of these materials. This is especially pertinent with respect to changes in ozone, and is exacerbated by the fact that these aerosols have no naturally existing analog in the stratosphere that could be studied. Because early studies suggest that these aerosols show much promise with respect to deploying SAI while mitigating the inherent risks of the deployment, it is imperative to design and execute in situ experiments in order to test our current understanding of the aerosol microphysics and observe the effects of alternative aerosol on the chemical composition and dynamics of the stratosphere.

2.3. Limitations in Existing Analogues

In this section we will review previous in situ studies of stratospheric plume processes, show how those datasets have contributed to our current understanding, and demonstrate the need for experiments such as SCoPEx to inform small-scale models of aerosol microphysics (nucleation and coagulation), plume transport and physical morphology, and chemical properties of new aerosol species that have thus far not been observed in the stratosphere. Because the nature of the injection scenarios (AM–H_2SO_4 or solid aerosols) are so complex compared to natural analogs, new experiments must be designed and implemented to provide observational constraints on our current nearfield modeling framework. Experimental data from carefully targeted small-scale studies would contribute to the development of nearfield-scale models that represent currently uncertain processes in detail.

We note that sub-grid scale processes do not represent the only unknowns in GCMs that are relevant to high-fidelity simulations of SRM scenarios, and that there are many large scale model phenomena which should be further assessed with observational evidence. However, here we focus on the need for in situ data to constrain sub-grid scale processes that can be addressed by SCoPEx and highlight the need for reducing the uncertainty in transport and aerosol dynamics and chemistry at this scale.

2.3.1. Limitations of Solid Rocket Motor Plume Observations

From 1996 to 2000 a number of rocket plumes were observed by high-altitude research aircraft. Generally, these missions involved a research team coordinating stratospheric sampling flights on either the NASA ER-2 or on the NASA WB-57 with coincident rocket launch events from either Cape Canaveral or Vandenberg Airforce Base. These studies sampled plumes from a host of rocket types including Titan IV, Space Shuttle (STS106, STS83, STS85), Delta II, Athena II, and Atlas IIAS.

Plumes were intercepted by the sampling aircraft between 5 and 125 minutes after emission from the rocket motor at stratospheric altitudes ranging from 11 to 19.8km (Voigt et al., 2013). The main science objective of these missions was to assess the stratospheric

ozone depletion potential of space exploration by understanding the halogen chemistry occurring as a result of the high-altitude rocket burn. However, in studying the effects on the ozone layer, this era of stratospheric sampling provided a unique set of plume measurements to study nearfield processes of chemical injections into the stratosphere.

While measuring the plumes from the Titan IV rocket (as a part of the United States Airforce Rocket Impacts on Stratospheric Ozone (RISO) Campaign) and attempting to develop a plume chemistry model to solve for the Cl_2 concentration in a rocket plume as it evolves shortly after its emission, Ross et al. (1997) noted the many assumptions that had to be made about the plume morphology in order to simulate the mixing and diffusion that the rocket plume had with the surrounding stratosphere. Their model solved for the Cl_2 concentration of a circular nighttime plume as it expanded in diameter along an isentropic surface. Subsequent aircraft measurements showed that plumes contained more than twice the predicted concentration of Cl_2 despite the plume being intercepted during the day time (when the Cl_2 reservoir should be somewhat depleted by the photolysis reaction $Cl_2 + h\nu \rightarrow 2Cl$), suggesting that there may be an error in the assumption of a circular plume morphology on the short transport time scales observed in this study ($\sim 28 min$).

Ross went on to publish a second study as a part of the RISO project in 1999, this time looking to quantify the size distribution of alumina aerosols emitted from the rocket engines which contained particulate alumina (Al_2O_3) (Ross et al.,1999). They compared measured aerosol size distributions from the WB-57F plume interceptions to results from an aerosol coagulation model and highlighted a massive discrepancy. The model predicted a much smaller aerosol size distribution with 1-10% of the aerosol mass being in the smallest (0.005μm) mode and the aircraft observed only fractions (<0.05%) of the model estimate in that same small mode. At the same time, over 99% of the aerosol mass sampled by the aircraft was found in the coarsest mode (2 μm), which the model was unable to predict. It is most likely that the model used in Ross et al. (1999) did not well account for the effects of ion mediated nucleation as described by Yu & Turco (1997). However, the data from Ross et al. (1999) was some of the first in situ data to highlight the uncertainty in stratospheric aerosol coagulation models. Alumina aerosol, as well as other solid aerosols, in contrast to liquid sulfate aerosol, have since been investigated as a candidate for use in SAI (Weisenstein et al., 2015). Therefore, it is imperative that we understand the chemical, coagulation, and accumulation properties of these and other solid aerosols in a stratospheric environment.

2.3.2. Limitations of Previous Stratospheric Aircraft Wake Crossing Observations

We can look to the few times high-altitude aircraft wake plumes have been sampled in situ for another example of stratospheric plume measurements. In the early 1990s the popularity and capability of the Concorde spurred discussions of a large fleet of High Speed Civil Transport (HSCT) aircraft that would operate in the lower stratosphere between 16 and 23 km. Scientists became concerned with the effects of high-altitude aircraft and high-altitude supersonic aircraft on stratospheric ozone destruction via the creation of a large NOx source in the lower stratosphere. NASA then launched several field campaigns using the ER-2 to study the exhaust profiles of high-altitude aircraft. In 1992 NASA commissioned the Stratospheric Photochemistry Aerosols and Dynamics Expedition (SPADE) to look at the effects of HSCTs. As a part of SPADE the ER2 sampled its own plume on several occasions by making a hairpin turn and heading into its original path, therefore measuring its own wake

(Figure 2). SPADE resulted in at least 11 published studies and some of these can inform us about the mixing and aerosol dynamics that may be relevant to an SAI scenario (Stolarski & Wesoky, 1993).

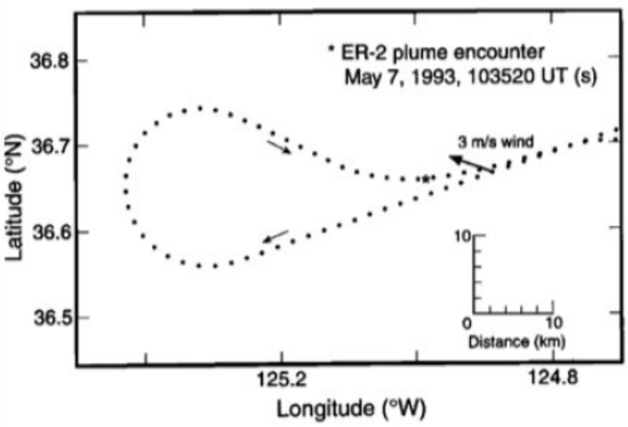

Figure 2: Shows the ER-2 flight track on a typical wake crossing trajectory (adapted from Fahey et al. 1995).

Fahey et al. (1995a) described measurements made of condensation nuclei (CN) present in the ER-2's exhaust plume from the emission of aerosol carbon and of sulfur compounds during one of its SPADE wake crossing events. Because the main focus of this study was to quantify the emission indices (EIs) of various compounds measured by the ER-2 that may have ozone depletion implications, they focused mainly on gas phase compounds. However, for the three wake crossings that the study focused on, they observed large variability in their EI measurements for CN. They noted that this is likely due to differences in mixing history of the encountered air parcels and noted that a full explanation of CN coagulation required more in-depth study and further measurements (Fahey et al, 1995b).

In another study published by Fahey et al. (1995b), they used a similar wake crossing technique to measure the exhaust of the Concorde aircraft and developed an aerosol coagulation model to predict particle formation and size as a function of the time since emission from the aircraft. The coagulation model was initialized at the observed conditions from the one-hour old Concord transect. The results from this model estimated that from 0 to 10 hr since emission from the engine, the mean particle diameter remained fairly constant at 0.06 µm before growing exponentially to a factor of 3 times its initial value over the next 1,000hr. The model predicted exponential mean particle diameter growth continuing right until the of the simulation at 1,000 hr (Fahey et al., 1995a).

Yu & Turco (1997) attempted to model the observed aerosol plume during the Concorde wake crossings with the goal of determining the driving factor for the large aerosol size distributions observed by the ER-2 in the exhaust which had not yet been explained by models. Yu proposed that aerosol formation was being aided by ion-mediated nucleation (IMN), that is, charged particles formed by chemi-ionization processes within the aircraft engines provide charged centers (H_2SO_4 [S(VI)]) around which molecular clusters rapidly coalesce. "The resulting charged micro-particles exhibit enhanced growth due to condensation and coagulation aided by electrostatic effects" (Yu & Turco, 1997). It is likely that IMN is the reason previous particle coagulation modeling of solid rocket motor plumes had overestimated the amount of aerosol in the small size ranges when compared to the in situ data, though this has not since been tested. Because of these effects, and the fact that specific size distributions of aerosol are desired to obtain the optimal radiative

forcing effects for SAI (nominally smaller than observed in rocket or aircraft plumes), we must understand the aerosol nucleation and coagulation dynamics in an unperturbed stratosphere.

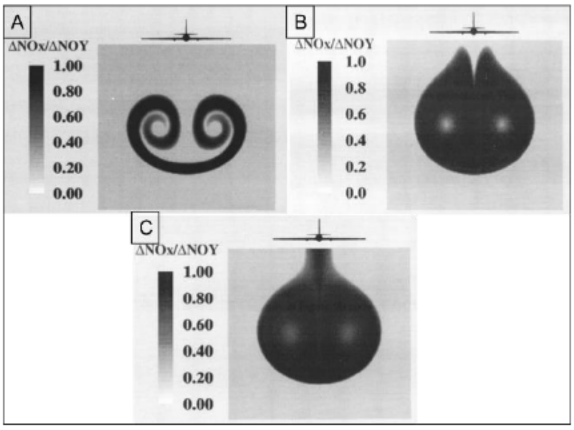

Figure 3: Shows the chemical and morphological evolution of an ER-2 plume during SPADE at 1.7 km (A), 4.8 km (B), and 7.9 km (C). (adapted from Anderson et al. (1996))

As a part of the SPADE project, Anderson et al. (1996) computed the flow field and chemical kinetics of the ER-2 aircraft exhaust using the Aerodyne Research Inc. UNIWAKE model. Their calculations address the effects of complex plume morphology on in-plume chemistry as a function of dilution time since emission from the aircraft engine. They showed that the plume morphology is highly variable out to about 5 km post emission Figure 3 and estimated that the stability of the wing vortex pair begins to break up at roughly 20 km post emission. Although this study was completed in the mid 1990s, it is still one of the only studies that attempts to compute nearfield chemistry within a dynamic stratospheric plume. However, particles were not considered as part of this study.

2.3.3. Limitations of Stratospheric Wake Crossings

Previous stratospheric plume studies of solid rocket motors and aircraft wake crossings have laid the foundation for our understanding of stratospheric plume chemical, aerosol, and mixing dynamics on transport scales of 0→100 km. These studies highlight the types of processes we must be aware of when considering the logistics of SAI. However, the violent initial conditions of engine exhaust plumes (such as temperatures of 700K, IMN) make it difficult to relate these observations to other systems. Because the engines drive the mixing and transport in the nearfield, and the ionic injection conditions of the plume create electrostatic forces that introduce complex nucleation affinities (IMN), understanding individual parameters can become analogous to finding a needle in a haystack. Moreover, because the radiative properties of any stratospheric aerosol that may be used for SRM depend on the diameter of the particle, we must understand the coagulation of that aerosol in the nearfield after the injection, which means that we must also understand the plume morphology that dictates the concentrations of that aerosol. Currently there have been no in situ data gathered that help us understand nearfield aerosol nucleation and plume dynamics in the absence of a very disruptive source. These conditions are necessary to understand as SAI may require that we mitigate the effect of IMN in order to obtain an aerosol size distribution that is small enough to provide the desired radiative properties.

2.3.4. Limitations of Naturally Occurring Analogs

Another source of useful in situ data on plume dynamics in the stratosphere can be found in literature addressing the fate and transport of convective overshooting events that often occur at the top of a Mesoscale Convective Complex (MCC). These events drive brief airmass exchange with the troposphere and often end up resulting in a plume-like parcel of tropospheric air being injected into the stratosphere.

Measurements of convective systems and upper troposphere-lower stratosphere exchange, as a means to interrogate stratospheric plume transport, have provided valuable in situ datasets that help us understand mid-field (10 to >1000 km) plume dynamics in the lower stratosphere. Similar to convective overshooting events, volcanic eruptions have provided an immense amount of in situ data that has informed us about regional and even global transport of stratospheric injections (Robock, 2000). Although their data are applicable in some sense to the transport of an SAI plume after its initial injection, the turbulent nature of a convective storm makes it difficult to measure these events at points near their injection source. Additionally, the storm conditions themselves dramatically complicate the system in the lower stratosphere such that is difficult to see through the effects of the induced turbulence in the nearfield. Indeed, an important limitation of these type of natural analogs is the spatial extent of their perturbation, which does not allow for near-field observations analogous to that of a point source. This also arises from the violent nature of these events which does not allow airborne platforms, such as the ER-2, to sample the initial conditions of the injection. We also note that volcanic eruptions are limited in their utility to evaluate dynamic response to stratospheric heating from sulfate aerosol, as they represent a perturbative pulse rather than the long-term heating one would expect from SAI.

In addition, these natural analogues provide extremely limited ability to study alternate materials, although organic and mineral dust aerosol injections into the lowermost stratosphere have been documented from convective overshoots. However, the complexity of the massive perturbations of both gas- and particle-phase preclude a study focusing on the impact on stratospheric composition and aerosol evolution that would result from SAI of a single material.

3. SCoPEx Short Overview

This section provides a brief overview of the engineering and operational aspects of SCoPEx. We first describe the platform, the instruments, and the concept of operations before describing the rationale for the overall SCoPEx design choices.

3.1. SCoPEx Platform

The SCoPEx gondola (Figure 4) is a balloon-born new research platform being developed at Harvard by the engineering and science staff within the Anderson/Keith/Keutsch laboratory group. The development builds on four decades of stratospheric research on aircraft, balloon, and rocket platforms that has focused on understanding the environmental chemistry of the ozone layer. The SCoPEx experiment was first described by Dykema et al. (2014). While many details of the design have changed, that paper still succinctly describes the advantages of choosing a balloon born platform over an aircraft, particularly for studying perturbations like solar geoengineering, and several of the limits of laboratory experiments that that could be addressed in a perturbative experiment like SCoPEx.

The gondola has three primary features: the frame, the ascender, and the propellers. The aluminum and carbon fiber frame contains two decks and a ballast hopper for coarse altitude control. One deck is primarily dedicated to platform support (power and flight control) and one deck is primarily dedicated to instruments. At the top of the gondola is an ascender and rope which allows the distance between the bottom of the balloon train and the gondola to vary from 0 to 150 m, which provides fine altitude control of the gondola. The ascender has been developed and tested by Atlas (Chelmsford, MA) building on their previous hardware in collaboration with the Harvard engineering team. The propellers serve two purposes: to create a well-mixed volume of air where observations of the aerosols and perturbed gas-phase can be made, and to reposition the gondola within the evolving aerosol plume. While the trajectory of the balloon and gondola system will be dictated by the balloon, the propellers allow for repositioning relative to the prevailing winds.

The ascender makes it impossible to have cables and other physical connections between the flight operations equipment and the gondola. Thus, the platform will handle its own communications and power. The SCoPEx platform will be powered using 28 V and 100 V DC power supplies which will power all operations on the platform including the propellers, ascender, and instruments. Elements of the flight platform are listed in Table 1. The gondola flight, flight safety, recovery parachute, and recovery operations will be managed by the balloon operator (in contrast to the SCoPEx team itself). Because the absolute velocity and distance capability of the gondola are so small compared to balloon drift, the trajectory will be determined by the balloon operator as if it was a passive nonpowered payload. During operations, the detailed float altitude will be jointly managed by the balloon operator via control of the balloon vents and the Harvard team via control of the ballast and ascender.

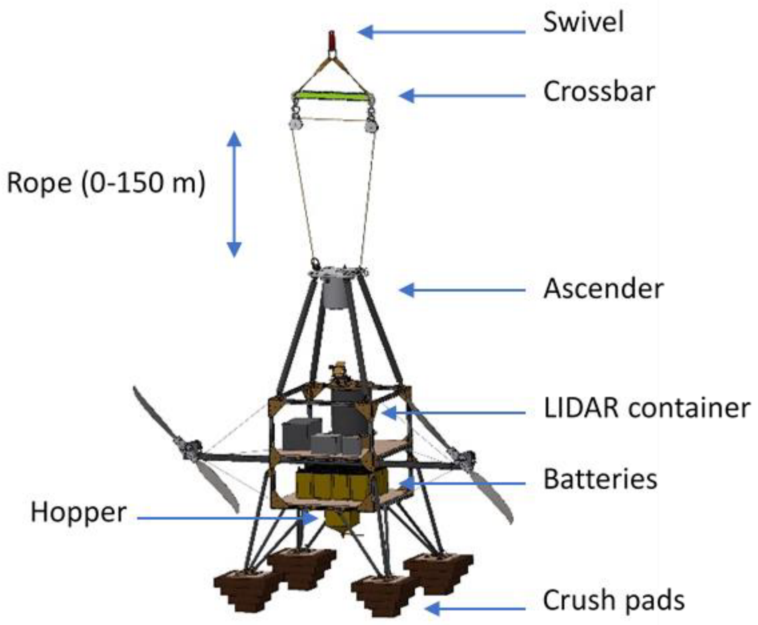

Figure 4: A representation of the SCoPEx flight platform. The final configuration may have subsystems packaged differently.

Parameter	**Description**
Total mass (Frame, all subsystems, hopper with ballast)	600 kg
Interface to balloon	Crosby 5-S-2 jaw & jaw swivel
Ascender	13 mm diameter rope Range of motion: 0-150 m Max speed: 10 m/min
Gondola propulsion	Twin propellers, 1.88 m diameter 32 N thrust each Max airspeed: 3 m/s
Power	28 V and 100 V DC power supplies with 24 MJ and 10 MJ total energy when fully charged
Communications	Satellite phone for communication between ground equipment and payload
Maximum termination shock	10 g

Table 1: Elements of the SCoPEx flight platform.

3.2. Instruments for First Science Flights (Science Goals 1 and 2)

The proposed instruments for the first science flight, addressing science Goals 1 and 2, are listed in Table 2. The corresponding science goals that motivate their inclusion are detailed in Section 4.

Measurement	Instruments	Rationale	Corresponding Science Goal
Wind speed measurement	Wind pendulum	Gondola and plume movement relative to balloon	Platform operation
Meteorology	Commercial off-the-shelf instrument	Temperature and pressure measurement throughout the flight	1, 2, 3
Wind turbulence	Constant temperature anemometer	Stratospheric mixing and modeling evolution of aerosol size distribution	1, 2
Particle dispersal	Solid Aerosolizer	Injects monodispersed particles for measurement and study	2, 3
Plume tracking	LIDAR	Tracking plume and navigation back into plume	2, 3
Particle sizer	POPS	Aerosol size distribution measurement for comparison with microphysics models of near-field evolution	2, 3
Light Scattering	Radiometer	Comparison of aerosol scattering with model prediction	2

Table 2: Instruments for first SCoPEx science flight.

Wind Pendulum: Understanding differential wind speed measurements between the balloon and payload will be important for plume evolution relative to the balloon trajectory and navigating the payload back into the plume. Commercial equipment to measure wind speed is typically not designed for the low densities found in the stratosphere. SCoPEx will therefore use a pendulum-based instrument and model to extract wind speed measurements. A camera will track a pendulum bob with high surface area and low mass, light enough to be perturbed by low winds in the stratosphere. Using the location and tilt data from the payload and a 3-dimentail kinetic model, the wind speed will be extracted from photos of the pendulum bob.

Commercial Meteorology Instrument: Commercial off-the-shelf instruments will be used for meteorological measurements on SCoPEx. They will record pressures and temperatures of the ambient stratosphere.

Constant Temperature Anemometer: A constant temperature anemometer (CTA) uses convective cooling caused by air flowing across a heated thin wire to measure flow velocity. LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere) (Gerding et al., 2009; Theuerkauf et al., 2010) used such a measurement to study stratospheric turbulence up to 29 km. LITOS consisted of a 5 μm diameter and 1.25 mm long tungsten wire CTA and a 16 bit ADC with 2000 samples per second to collect measurements with a vertical resolution of 2.5 mm at 5 m/s ascent speed. The anemometer data was analyzed by performing a spectral

analysis on the voltage signal to retrieve the spectral slope of the observed variation. A similar instrument will be used on SCoPEx to measure stratospheric turbulence. Air flow around the device will be simulated using CFD tools. The CFD runs will provide a means to identify key flow characteristics that drive sensor performance (sensitivity and accuracy), and to drive detailed sensor design.

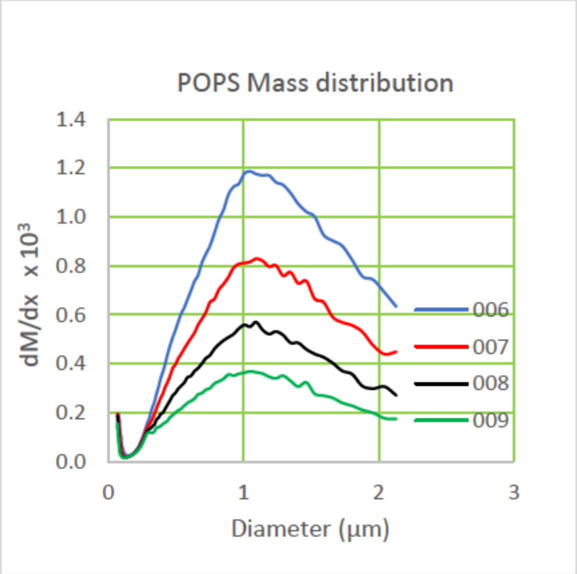

Figure 5: Successive measurements of sprayed $CaCO_3$ using an optical particle spectrometer. 006-009 indicate numbered time intervals spaced 4 minutes apart with 006 being the earliest measurement. $CaCO_3$ was sprayed using a 200 µm nozzle. In this laboratory experiment there was no significant variation in the shape of the distribution over time. (personal communication A Neukermans and team)

Solid Aerosolizer: The solid particle aerosolizer has been developed by a team lead by Armand Neukermans. For SCoPEx, the goal is to spray roughly monodisperse ~0.5 µm diameter precipitated calcium carbonate powder, the first candidate for solid SAI, through a 1-2 mm nozzle using the expansion of powder suspended in high pressure liquid CO_2. The aerosolizer would use a 1:4 weight ratio of $CaCO_3$ to CO_2. For 1 kg of $CaCO_3$ this would require a 5-7 L pressurized container. This concept has already been demonstrated in the lab. Figure 5 shows successive measurements of sprayed $CaCO_3$ with a size distribution centered at 1 µm diameter. Measurements were taken every 4 minutes using POPS (see below). In this case, total particle count decreased over time but there was no significant variation in the shape of the size distribution.

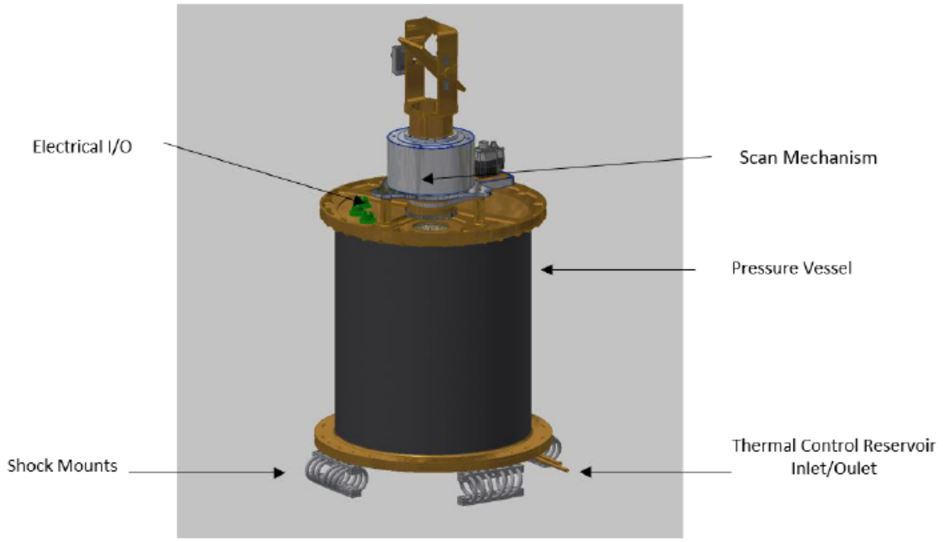

Figure 6: LIDAR pressure vessel provides safe storage and operating environment and support equipment.

LIDAR: The LIDAR is used to track the plume and allow navigation back into it. The core of the LIDAR system is an off-the-shelf eye-safe visible LIDAR, purchased from Sigma Space (now owned and operated by Droplet Measurement Technologies). This LIDAR produces 4 μJ pulses of 532 nm light at a repetition rate of 532 nm. The light that is backscattered by molecules and aerosols is collected by an 80 mm telescope and detected with a high-speed, high-sensitivity photodiode.

We have integrated this LIDAR in a pressure vessel (Figure 6) to provide a near-1 atm pressure environment with adequate temperature stability to ensure safe operation of the LIDAR at float altitude and safe storage on launch, ascent, descent, and recovery. This pressure vessel includes equipment for electrical and mechanical support, including command, data handling, and shock mounting. The LIDAR requires a scan capability to search the nearby atmosphere for the extent and geometry of the plume. The tilt and pan functions of the scan capability allows the LIDAR to be scanned over a set of angles that define the plausible location of the plume.

Portable Optical Particle Spectrometer (POPS): The POPS instrument will provide the aerosol size distribution measurements for studying aerosol formation and agglomeration. POPS is a light-weight instrument that directly samples the aerosol. It was built by and provided to SCoPEx through a collaboration with NOAA. The particles are illuminated with a 405 nm diode laser and the scattered light is collected onto a photomultiplier tube. The particle size is determined by the intensity of the scattered light. It has both the detection limit and size range (0.13 – 3 μm) to measure background stratospheric aerosol, which is more than sufficient for SCoPEx needs (Gao et al., 2016).

The Keutsch Group has already developed and extensively characterized a POPS instrument in preparation for the NASA-EVS3 Dynamics and Chemistry of the Summer Stratosphere field campaign on board the NASA-ER2, for which Keutsch is the deputy-PI. The POPS instrument tests include extensive thermal vacuum chamber characterizations to ensure operation under harsh stratospheric conditions. Compared to the ER-2, operation for SCoPEx will be simpler due to the insignificant air speed of the balloon and a much simpler operational pressure regime (on the ER-2 there is a large range of external pressures for both sampling and exhaust).

Radiometer: The aerosol plume can also be detected using a narrowband, narrow field of view radiometer with azimuthal/zenith pointing capability. The relationship between measurements of scattered solar radiation and the physical characteristics of atmospheric aerosols has been studied for more than two decades. Sky scanning measurements at multiple wavelengths between 300 nm and 1200 nm have been obtained using robotically pointed ground-based spectral radiometers deployed worldwide (Holben et al., 1998). The theory of these measurements has been refined and validated as a function of viewing geometry to provide a strong basis for inferring aerosol microphysics from radiometer data (Torres et al., 2014). The success of these approaches has motivated the development of compact sky scanning radiometers suitable for deployment on unsteady platforms like unmanned aerial vehicles (UAVs) and SCoPEx. One such design, reported by NOAA (Murphy et al., 2016), measures at 4 wavelengths (460 nm, 550 nm , 670 nm, and 860 nm) with a field of view of 0.006 sr (equivalent to 2.5° half-angle) and a circular limiting aperture of 1.1 mm diameter. A radiometer like this one deployed on SCoPEx would be capable of observing a SCoPEx plume, based on Golja et al. (2020), formed by a 0.1 g s^{-1} injection of calcite from a distance of 200 m with an approximate signal-to-noise ratio of 6000 for a 1 ms signal accumulation.

3.3. Instruments for Future Science Flights (Science Goal 3)

The additional instruments listed in Table 3 are candidates for future SCoPEx flights beyond the initial science flight, i.e., addressing science goal 3. They have not yet been adapted to fly on the SCoPEx platform. Instrument choices will be refined based on experiences in the first science flights. The corresponding science goals that motivate their inclusion are detailed in Section 4.

Measurement	Candidate Instrument	Rationale	Corresponding science goal
Aerosol composition	Drum Sampler	Collecting aerosols for offline analysis	3
Water Vapor	IR Absorption or Frost Point	H_2O outgassing of platform, Influence on coagulation and heterogenous chemistry	2, 3
Atmospheric trace gas concentrations (ex: HCl, NOx)	Spectroscopic trace gas instruments	For measuring concentrations of various atmospheric trace gases before and after addition of solid ASI material	3

Table 3: Potential instrument for future SCoPEx science flights.

Aerosol Composition: Aerosol composition can be analyzed via the collection of aerosol with a drum sampler followed by offline analysis in the laboratory using standard offline methods. Aerosol sampling has been done numerous times aboard stratospheric platforms.

Water Vapor: Gas-phase water vapor measurements are important as relative humidity likely has a large impact on the heterogeneous reactivity of solid SAI material. The balloon and gondola can outgas significant amounts of water and thus an initial experiment will characterize how long, if at all, this outgassing perturbs the SCoPEx plume. As mentioned previously, the goal of SCoPEx is to ideally minimize the perturbation to only the introduction of calcium carbonate. Water vapor measurements are common on many stratospheric platforms.

Hydrogen Chloride: HCl can be measured via infrared absorption spectroscopy. The Anderson group at Harvard, which shares a laboratory with the Keutsch group, has developed a stratospheric HCl instrument and thus has extensive experience with the design of stratospheric HCl instrumentation. In addition, the Keutsch group has designed multiple spectroscopic trace gas measurements. The much lower air speeds of the balloon compared to aircraft favor the design of an open path system, which eliminates the notorious wall effects that can make HCl measurements challenging.

NOx: For NOx there exist a number of good instrumentation options. Recently, a compact NO-LIF instrument has been designed that has spectacular detection limits in the low ppt range, more than sufficient for the needs of SCoPEx. The instrument is a close analogue of the fiber-laser based formaldehyde LIF instrument that the Keutsch Group developed, so there is a high degree of expertise available for such an instrument. There are also sensitive cavity enhanced techniques available usually in the visible range of the spectrum.

3.4. SCoPEx Concept of Operations

Flights will proceed in the following manner. The payload would be launched with the ascender retracted such that there is minimal distance between the crossbar and platform. Once the balloon reaches the float altitude, the rope will be let out through the ascender such that there is 100 m between the crossbar and platform. The platform will then be ready to perform experiments and execute maneuvers. Figure 7 illustrates a proposed flight maneuver. The platform will initially travel in a straight line laying out a plume, after which it will maneuver back through the plume to make measurements. During these maneuvers the ascender can be used to fine tune the altitude of the platform and instruments. Several series of such maneuvers can be performed within each flight. At the conclusion of the experiments the ascender retracts the rope before the descent.

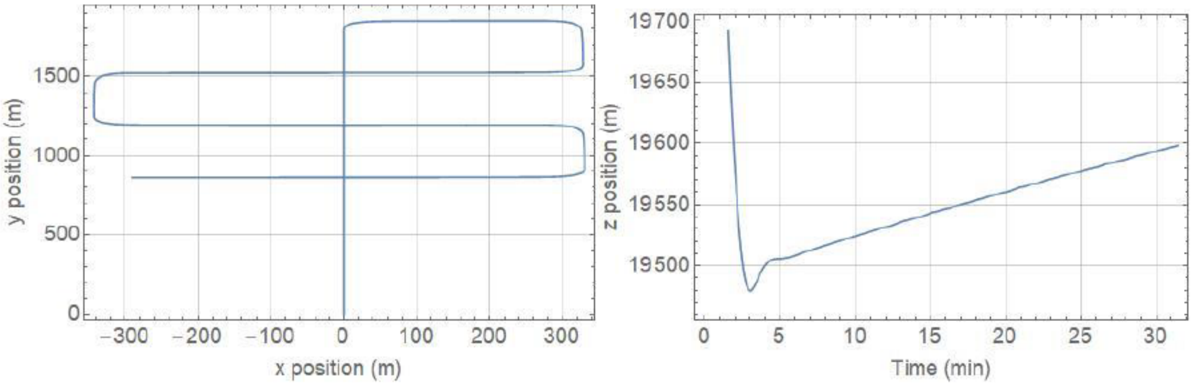

Figure 7: (left) A top down view of the proposed flight maneuvers over a 35-minute window. x and y are in the horizontal plane. The platform begins at (0,0). (right) The vertical position expected without any ascender or hopper vertical trimming over the same 35-minute platform maneuver.

4. SCoPEx Goals

In this section we describe the three long-term SCoPEx science goals. For each goal we describe the scientific problem, the need for SCoPEx, and the measurements required. The first phase of science flights targets the first two science goals. The design of the flights for the third goal will be informed by an understanding of the evolution of particle size distribution in the plume and the plume size. Thus, if later stage science flights move forward, they will be refined based on the results of the first science flights and the most up-to-date knowledge within the solar geoengineering and stratospheric science research communities.

4.1. Goal 1: Measurements of Turbulence for Small-Scale Mixing

4.1.1. The Importance of Plume-Scale Turbulence

Stratospheric turbulence influences the evolution of aerosol distribution from plume to regional to global scale. The mixing of air masses (of differing composition) in the stratosphere is a combination of two processes (Nakamura, 1996; Schoeberl & Bacmeister, 1993). The first process is strain, the distortion of streamline flow that brings air masses of differing composition adjacent to one another (Prather& Jaffe, 1990). Sometimes this is also referred to as “stirring” (Haynes, 2005). The second process occurs when air masses of differing composition are transported across the streamlines. This second process is the true “mixing” process.

In the stratosphere, mixing ultimately occurs because of molecular diffusion. This happens at the length scale of molecular viscosity. It is accelerated by turbulence, which can dramatically enhance the rate at which differing air masses are deformed to small enough spatial scales for molecular diffusion to mix them efficiently. Stratospheric turbulence is, however, highly intermittent (Vanneste, 2004). Understanding the mechanisms of stratospheric turbulence production is essential to understanding the spatial inhomogeneity and effective rate of mixing on spatial scales of 10-500 m (Schneider et al., 2017).

An understanding of this role of turbulence is of interest to stratospheric science because studies suggest that more accurate representations of mixing influence tracer distributions (Hoppe et al., 2014). Measurements of long-lived tracers are the strongest observational constraint on the stratospheric age of air, a key measure of the stratospheric large-scale circulation. Turbulence also modifies the character of kinetic energy fluxes. The magnitude and variability of these energy fluxes determine the rate of frictional dissipation in the atmosphere. This dissipation is represented in global models by a damping parameter and is the primary determinant of the mesoscale atmospheric kinetic energy spectrum. The uncertainty in kinetic spectrum is important to the understanding of the large-scale circulation of the middle atmosphere (Jablonowski & Williamson, 2011).

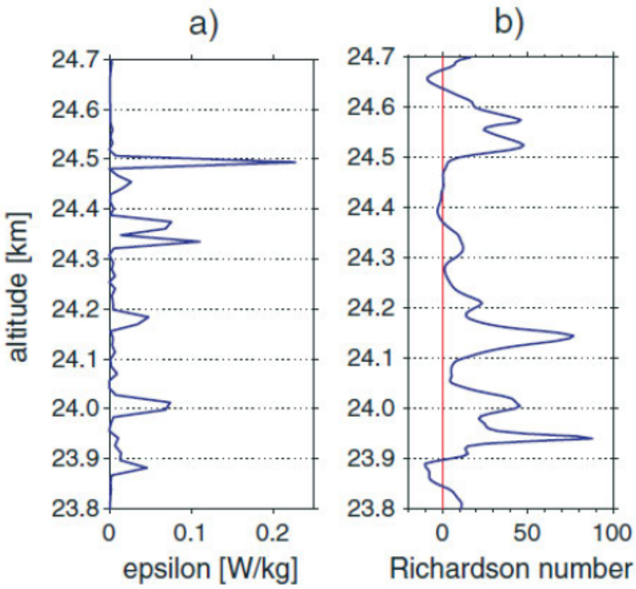

Figure 8: LITOS balloon-borne high-speed anemometer measurements reveal that models of atmospheric turbulence do not explain observed stratospheric turbulence. Physical models predict that a low Richardson number (buoyancy/shear ratio) implies turbulence, but high values of epsilon (turbulent dissipation) should be correlated with low Richardson number, which is not observed. (Haack et al., 2014)

Physical models predict that a low buoyancy/shear ratio (Richardson number) implies turbulence, and that high values of turbulent dissipation should be correlated with low Richardson number (Figure 8). However, recent balloon born measurements during the LITOS campaign did not agree with this, with numerous instances of high values of turbulent dissipation occurring at high Richardson numbers (Haack et al., 2014). As detailed above, both the impact of turbulence on mixing and the associated dissipation of energy are important for general stratospheric science. The point at which viscous fluid forces dominate atmospheric motion is the point where atmospheric motions become purely statistical and is called the dissipation scale. At this scale, models no longer require computationally expensive deterministic modeling. Furthermore, these viscous forces are also responsible for the dissipation of turbulent kinetic energy. Therefore, measurements which resolve the winds at the dissipation scale will allow numerical models to realistically close the atmospheric kinetic energy budget, an important metric of model fidelity.

4.1.2. Importance of Small-Scale Mixing for SAI and SCoPEx

From an SAI and SCoPEx perspective, plume-scale turbulence influences the frequency of collisions of monomer particles within the SCoPEx plume, which determines the rate of formation of fractal, larger aggregates. While Van der Waals forces finally determine whether particles that collide stick together and remain as a fractal aggregate (Sukhodolov et al., 2018), the collision rate is a critical quantity in determining total coagulation rate. Therefore, it is essential to know the frequency of collisions. This frequency is controlled by the wind variability at small spatial scales, i.e., the power spectrum. Intuitively, inertial forcing of particles by wind is much stronger than thermal forcing (e.g. Boltzmann distribution of velocity for ~1 µm particles at ~220 K). Fractal aggregates have a shorter lifetime in the stratosphere and are less effective at scattering light on a per mass basis (Weisenstein et al., 2015), so being able to model the formation

rate of fractal aggregates is an important aspect of SAI, especially with alternate SAI materials.

Improved knowledge of collision rates from wind measurements will allow for the selection of the appropriate mathematical representation of particle coagulation, the coagulation kernel. An accurate kernel is essential for numerical models to correctly simulate aerosol microphysical processes that determine the size distribution and residence time of solid aerosol particles. Adding wind and turbulence measurements to the SCoPEx payload will therefore address the major sources of uncertainty in aerosol microphysics under real atmospheric conditions, which include small-scale fluid flow, particle composition, and humidity.

4.1.3. Experimental Methods to Measure Turbulence in the Stratosphere

Multiple technologies are possible to achieve wind measurements with the necessary spatial resolution under stratospheric conditions. Current state of the art options include pitot tubes (with high sensitivity micro-pirani pressure sensors), hot wire anemometers, and acoustic anemometers. An existing stratospheric program has utilized hot wire anemometers to make measurements that are a close analog to what is necessary for SCoPEx. The program developed LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere), an instrument which made measurements of stratospheric turbulence up to 29 km (Gerding et al., 2009; Theuerkauf et al., 2011). The LITOS instrument has undergone significant calibration and has been compared against radiosondes (Schneider et al., 2015). One drawback of its deployment on a balloon has been the contamination of its wind measurements due to the influence of the balloon's wake. In contrast, SCoPEx is engineered so that the wind environment of the instrument payload is well separated from the balloon wake when SCoPEx is traveling horizontally. For this reason, SCoPEx could provide significantly more data per flight at a chosen float altitude. In this way, SCoPEx and LITOS would be very complementary. The horizontal flight path of SCoPEx, combined with measurements of the wind power spectrum, would provide an excellent complement to the LITOS observations, which are only obtained along a vertical profile. These power spectra obtained by SCoPEx would contribute to improved micrometeorology understanding relevant both to stratospheric aerosol injection and to fundamental atmospheric science.

Additionally, air flow through the turbulence instrument will be simulated using CFD tools. The CFD runs will provide a means to identify key flow characteristics that drive sensor performance (sensitivity and accuracy) and detailed sensor design. This application of the SCoPEx platform would therefore constitute a nonperturbative means to obtain necessary turbulence measurements that have, to date, eluded the scientific community. This information is important for understanding stratospheric dynamics, including the response to climate change or stratospheric heating from SAI. As no injection of particles is needed, these could be among the first scientific measurements to be conducted.

4.2. Goal 2: Evaluation of Aerosol Microphysics of AM-Sulfate and Alternative SAI Materials

One of the goals for which there are insufficient observational analogues is the near-field evolution of particles injected from a point source in the stratosphere. Specifically, observations of the temporal and spatial evolution of the aerosol size distribution (number and volume) of solid, alternate SAI materials or AM-H_2SO_4 injected form a point source can

only be compared with plume model predictions via a perturbative experiment such as SCoPEx. In the following we describe a plume model by Golja et al. (2020) specifically designed for SCoPEx. We also explain the results from the model and the SCoPEx experimental approach for comparing observations with model results.

4.2.1. Plume Model

Golja et al. (2020) incorporated the SCoPEx design features in their model to study the injection of a solid aerosol and vapor-phase sulfuric acid from a balloon payload. To provide observations relevant to SAI, SCoPEx needs to produce downstream aerosols with radii within the range of roughly 0.2 to 1.0 μm. For calcium carbonate, the objective is to maintain a high fraction of the aerosol in monomer form, while for sulfate an ideal distribution would have a peak diameter of 0.6 μm (Dykema et al., 2016). The generation of largely smaller than ideal particles, while imperfect for assessing radiative efficiency relevant to SAI, does not serve to increase particle sedimentation rates within the plume. Such smaller sizes may, however, result in a larger surface to volume ratio, which can strongly influence stratospheric composition as heterogeneous chemistry is directly related to surface area. Distributions centered on small particle sizes in the near field may, however, continue to evolve beyond the domain of the study.

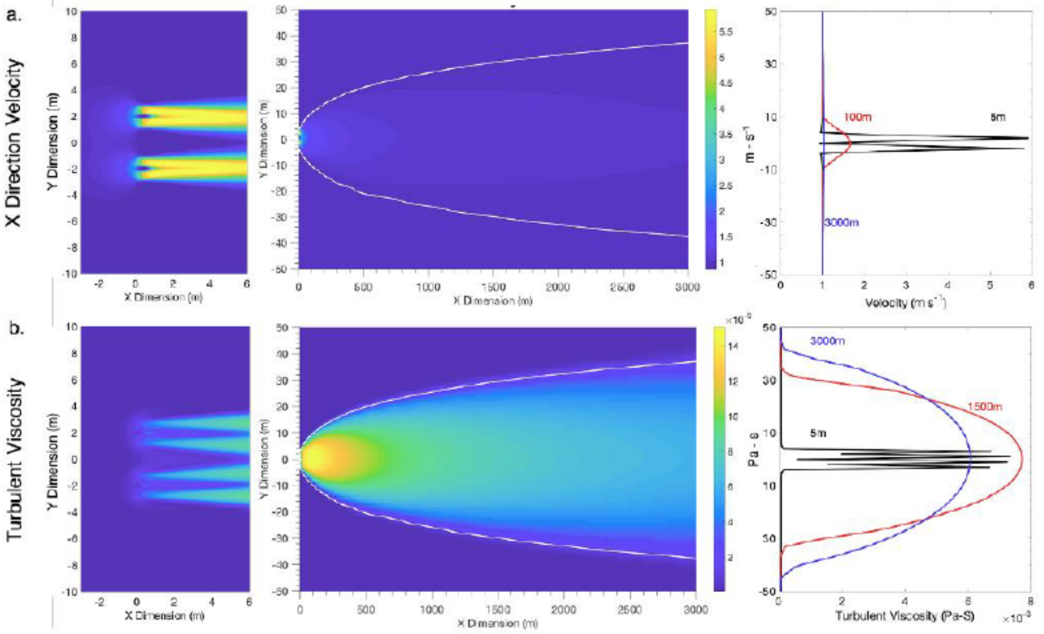

Figure 9 : ANSYS Fluent Velocity and Turbulence Fields. Shown above are the steady state x-direction velocity, u, and turbulent viscosity fields generated by ANSYS Fluent. Left panels show the genesis of disruptions to background X direction flow of 1 ms^{-1}, where propeller features are imposed at locations of 0,2) and (0,-2) meters. The center panel shows the entire domain, from 0 to 3 km, where the imposed red line contours 1 ms^{-1} in plot A, and contours 10% of the absolute maximum turbulent viscosity in plot B. Note Y direction scaling differs between the center and left panels. The right panel shows cross sections of velocity (A) and turbulent viscosity (B) through the Y plane at varying X locations. (Golja et al. 2020)

The velocity and turbulent viscosity fields from Fluent are shown in Figure 9. These fields form the basis of the simulation environment and are instructive in achieving an understanding of SCoPEx and the perturbation it achieves. Peaks in the x-direction velocity, u, are found directly downstream from the modeled propeller centers with an absolute maximum value of 6.3 ms^{-1}. By 1500 m downstream from the inlet locations, the velocity is reduced to the imposed background flow of 1 ms^{-1}. Turbulent viscosity, used as a measure

of particle mixing with background air, exhibits a narrow distribution of peak values ~10 m downstream from simulated propellers. With increasing distance downstream, the turbulent velocity spatial distribution widens, attaining a full width half maximum (FWHM) of 60 m by 1500 m downstream. The wake of the balloon itself is not visible, as it is sufficiently far from the payload to avoid wake crossing/interaction. Additionally, this simulation assumes a laminar stratospheric background flow, neglecting the potential impacts of breaking gravity waves.

For SCoPEx, precipitated calcium carbonate powder with roughly monodisperse size distribution centered at ~0.5 mm diameter will be aerosolized using the expansion of powder suspended in high pressure CO_2 through a 1-2 mm nozzle (see description in Section 3). The model injects aerosol as a 3D gaussian distribution of mass flux into the model grid, where the size of that distribution represents the scale of which the high velocity jet from the nozzle mixes with ambient air. The model considered two injection scenarios: scenario 1 (S1), a single point injection between the propellers; and scenario 2 (S2), injection from the center of each propeller. The model plume diameter at 3 km is, however, insensitive to the injection scenario for injection of both AM-H_2SO_4 and calcium carbonate. This suggests that injection at or between the propellers does not significantly alter the characteristics of the particles' experienced velocity field, and scenario S1 is the one selected for testing the model of plume evolution on SCoPEx. This is also important for the SCoPEx experiment as it necessitates only one sprayer that can be more easily placed in the equipment gondola.

4.2.2. Modelled Mass Injection Rate Dependence of Aerosol Size Distribution

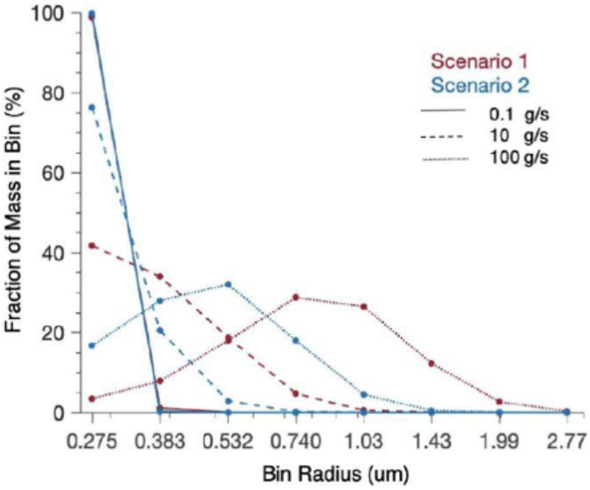

Figure 10: Calcium carbonate aerosol size distributions. Fraction of total mass in each sectional bin where the x-axis markers represent the central radius of each sectional size bin. These distributions represent the percent of total aerosol mass in the final 100 m of the plume across the full domain. Results are shown for three injection rates, 0.1 g s^{-1}, 10 gs^{-1}, and 100 gs^{-1}, for injection scenario 1 (red) and 2 (blue). (Golja et al. 2020)

Mass injection rates of 0.1, 10, and 100 g s^{-1} (0.36, 36, and 360 kg hr^{-1}) were used to test the influence of initial particle number density on the final plume aerosol size distribution. Although some of these are high, their use in the model is instructive as it can answer how different a short burst of high injection rate (much less than an hour) is from a slower but longer injection for the same total mass. Increasing calcium carbonate injection rates from 0.1 to 100 g s^{-1} reduces the share of monomer particles and increases undesired multi-monomer fractal aggregates. Figure 10 shows calcium carbonate's size distribution in the final 100 m of the modeled plume, i.e., the percent in each bin for the three different

injection rates of 0.275 μm radius particles. The low calcium carbonate injection rate of 0.1 g s^{-1} is the most desirable, maintaining 99% of the total mass in the final 100 m of the plume in monomer form. Increasing mass injection rate to 10 g s^{-1} and 100 g s^{-1}, with an S1 injection, shifts peak mass loading to favor particles of radii 0.5 and 0.75 um, respectively, corresponding to fractal "dimers" and "trimers".

Golja et al. (2020) also evaluated whether, in addition to the very sensitive in-situ optical particle counting aerosol size distribution instrument which originally was designed to measure background stratospheric aerosol size distributions (Murphy et al., 2016), the plumes could also be detected optically via scattered light. It should be emphasized that this does not refer to measurements from the ground but rather from close to the plume, e.g., when the equipment gondola is in close vicinity to the plume. Measuring the scattering from one view angle gives the product of the scattering phase at that angle and the scattering efficiency. This is closely related to the radiative forcing, but it does not uniquely determine the radiative forcing. By measuring at multiple angles, we could obtain enough information to quantify the radiative forcing. For example, we could measure from the side and below to obtain the forward scatter fraction, then calculate backscatter by flux conservation.

In the model, the extinction optical depth was calculated using Mie scattering theory and vertically integrating down columns in the y-z plane. Figure 11 shows the relative optical thickness of a sulphate and calcite aerosol plume formed via scenario 1 with an injection rate of 0.1 g s^{-1}. Calcite exhibits greater optical thickness by an order of magnitude at 550 nm, with an average value of 8.6×10^{-4} and maximum of 0.014 across the domain, as compared to sulphate, with an average of 9.4×10^{-5} and maximum 0.001. From these values, Golja et al. calculated that we expect adequate SNR to confidently detect the plume with a fast-scanning radiometer via the solar radiation it scatters. This calculation assumed an altitude of 21 km, solar elevation angle of 60°, an observing instrument situated on the payload gondola, and the gondola 200 m away from the edge of the plume and 1 km downstream of the termination of a scenario 1 type injection of calcite aerosol. Details of this calculation can be found in Golja et al. (2020).

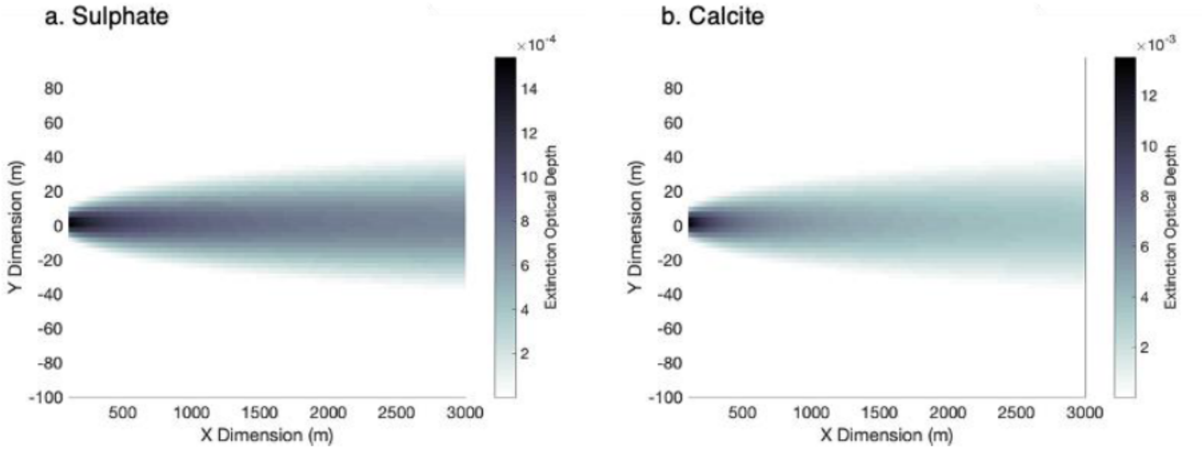

Figure 11: Extinction optical depth integrated vertically through all columns in the plume from 100-3000 m. Plots a and b show results for 0.1 gs^{-1} injections of condensable H_2SO_4 and calcite, respectively. The resulting number density of calcite aerosol is 490 cm^{-3} on the centerline at a downstream distance of 1000 m, predominantly as monomers. Aerosol optical depths were derived from Mie scattering theory at 550 nm, using refractive indices for sulphate and calcite stated in Dykema et al. (2016). (Golja et al. 2020)

4.2.3. SCoPEx Experimental Design and Analysis of Plume Evolution

For this goal, SCoPEx will follow the standard concept of operations, first spraying calcium carbonate at an injection rate suggested by the model analysis. It is desirable to maximize the contrast with the background stratosphere, both with respect to the aerosol concentration and the potential resulting chemical changes, while also maintaining calcium carbonate as monodisperse aerosol. To this end, additional models will be run at injection rates between 0.1 and 10 gs^{-1}. Based on these results, an injection rate will be chosen for the actual SCoPEx experiment. In addition to the basic components of the SCoPEx platform (gondola, ascender, propulsion, power, flight computer, communication, and wind), the calcium carbonate sprayer as well as the LIDAR and POPS instrument are critical for this science goal; without these components, there would not be a way to make and find the plume or measure the aerosol size distribution. While the turbulence measurement from goal 1 is desirable, it is, at least initially, not necessary. Similar studies of AM-H_2SO_4 injection would also be extremely useful. Our current plan is to conduct these after the calcium carbonate injection studies, as initially calcium carbonate is easier to handle than sulfuric acid and its precursors (see next section for motivation of calcium carbonate).

The aerosol size distribution measurements will be compared with the model predictions. In combination with turbulence measurements, discrepancies between the observed and modeled aerosol size distributions can be used to identify issues within the aerosol microphysical scheme or highlight misrepresentations of the velocity and turbulence field of the payload. The results of these studies will provide critical observational constraints on the aerosol microphysics and plume evolution of an injection with solid particles. It will be unique data that is ideal for testing the model of plume evolution as SCoPEx does not have to address problems resulting from the much more violent injection regime associated with injection from airplanes. Clearly, such studies are also needed, but SCoPEx represents a feasible and compelling first step in a sequence of new studies that more comprehensively investigate the aerosol microphysics of point source injections.

4.3. Goal 3: Evaluation of Process Level Chemical Models of Stratospheric Chemistry of Sulfate and Alternative SAI Materials

4.3.1. Need for Alternative SAI Materials

As previously discussed, the two largest first-order stratospheric risks of SAI with sulfate aerosol are ozone depletion and stratospheric heating. For sulfate aerosol the relative magnitude of these two risks can be adjusted if the size distribution can be controlled, e.g., via the AM-H_2SO_4 approach. It is worth noting that the impact on stratospheric ozone may be greatly reduced in the future if reactive halogen concentrations are lower. In contrast, the impact of stratospheric heating will not change. This represents a risk with a poorer understanding of its consequences, which makes it highly desirable to minimize stratospheric heating and resulting dynamic response. Therefore, it is important to investigate alternative SAI materials.

The properties of the “ideal” SAI material is (i) no absorption of radiation, i.e., purely scattering aerosol both fresh and aged, (ii) chemically inert, i.e., no direct impact of this material on stratospheric composition, and (iii) minimal down-stream effects, i.e., no impact on cirrus or other clouds, no environmental impact on deposition on the ground, etc. In reality, it is unlikely that a material with no impacts exists and rather the question is which materials can minimize these impacts. There have been a number of studies investigating

SAI materials in this context. High refractive index materials have been suggested as they reduce the mass of material that have to be lofted (Ferraro et al., 2015; Ferraro et al., 2011; Pope et al., 2012; Keith et al., 2016; Dai et al., 2020; Weisenstein et al., 2015). This largely cost-driven perspective is not a motivation for our work. In contrast, one of the goals of SCoPEx is to decrease the uncertainty in SRM models that use calcium carbonate SAI. The rationale for the choice of calcium carbonate as well as the approach to evaluate some of these risks is described in the following sections.

4.3.2. Unreactive Alternative SAI Materials

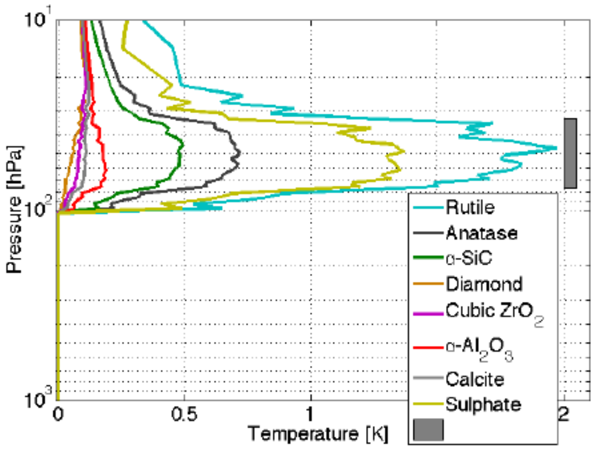

Figure 12: Comparison of stratospheric heating for different materials. Diamond has the lowest impact, although cubic zirconia and calcite are very similar. Sulfate and rutile result in much larger heating. (Dykema et al., 2016)

Diamond is probably the material with the best properties for SAI from a purely stratospheric perspective. Diamond has no absorption features in the solar or terrestrial spectrum and thus triggers the minimal possible dynamical response Figure 12. In addition, diamond should have ideal chemical properties. Hydrogen-terminated diamond surfaces are extremely inert and hydrophobic, precluding the ozone destroying chemistry initiated on sulfuric acid surfaces. The surface itself is also resistant to concentrated sulfuric acid. Exposure to OH radicals would probably slowly make the surface more hydrophilic. From a purely stratospheric perspective the only first-order risk of diamond would be increased ozone loss from the increased sulfuric acid surface area resulting from coagulation with background sulfate aerosol.

4.3.3. Reactive Alternative SAI Materials: The Case for Calcium Carbonate

Although the impact on cloud properties and the risk to Earth's surface from deposition of SAI diamond is likely very low, it could be preferable to have a material that dissolved easily in water, hence not persisting for long times outside of the stratosphere. It would also be preferable to have a material that is naturally abundant at Earth's surface. In addition, it would be ideal to overcome increased ozone loss due to coagulation by using a reactive aerosol. We therefore propose calcium carbonate as a prototype alternate SAI material for the following reasons: First, its optical properties are nearly equal to diamond and stratospheric heating and resulting dynamic response should be negligible compared to sulfate (Figure 12). Second, carbonates are typically quite reactive with acids, especially with concentrated sulfuric acid (Figure 13). Hence, calcium carbonate will neutralize upon

coagulation with sulfate aerosol eliminating the acidic surfaces resulting from coagulation of diamond and sulfate aerosol. Of course, the reactivity of calcium carbonate also makes model predictions with calcium carbonate more complex. The evolution of chemical and optical aerosol properties has to be modeled over its stratospheric lifetimes. One of the key research questions that SCoPEx will help address is whether the reactivity of calcium carbonate and the evolution of its chemical and optical properties and those of the surrounding gas-phase correspond to the detailed hypothesis laid out below. To this end, SCoPEx will compare observations of the chemical evolution of calcium carbonate, as well as the gas-phase, with those of a model based on known properties of calcium carbonate and recent laboratory experiments (Dai et al., 2020). This will provide a real-world evaluation of kinetic parameters, such as heterogeneous uptake coefficients derived from the laboratory studies, that will enable GCMs to include reliable parameterizations of the stratospheric impacts of calcium carbonate SAI.

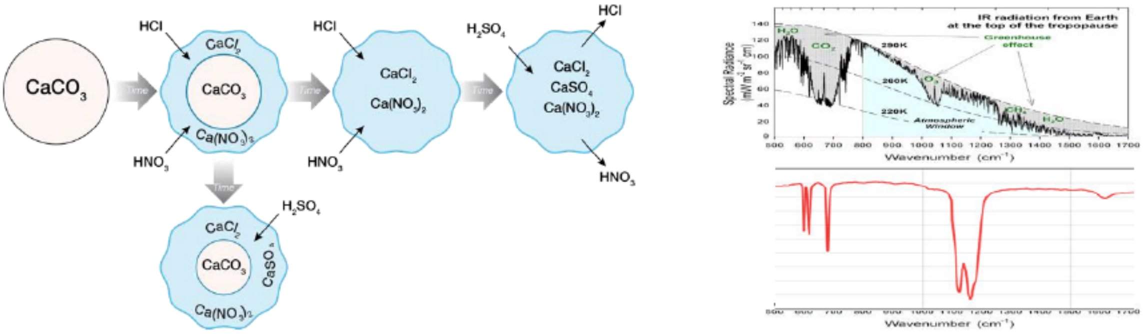

Figure 13: The left panel shows schematic of potential chemical reactivity of calcium carbonate in the stratosphere. The right panel shows the atmospheric windows in the terrestrial infrared (top) as well as the infrared absorption spectrum of calcium sulfate (bottom). The position of the 1150 cm^{-1} sulfate in part explains the stratospheric heating effect of sulfuric acid.

4.3.3.1. Optical Properties

Based on well-established chemistry, the reaction of sulfuric acid aerosol with calcium carbonate can be assumed to go to completion, i.e., be reagent limited. The optical properties of calcium sulfate in the terrestrial infrared are similar to those of sulfuric acid with only slight differences in relative band intensities and wavelengths (Figure 13 right hand inset). This is important as it implies that there will be no large first-order changes in stratospheric heating from changing background sulfuric acid to calcium sulfate. There are higher order impacts due to slight differences in the absorption of sulfuric acid, which has some liquid water compared to calcium sulfate. There are also numerous forms of calcium sulfate (anhydrite, bassanite, gypsum, etc.). However, the resulting differences are much smaller than introducing an absorbing material via SAI.

4.3.3.2. Chemical Properties

Predicting the evolution of the chemical properties of calcium carbonate under stratospheric conditions is more challenging. It is certain that calcium carbonate does not have the same heterogeneous reactions that activate ozone destroying substances as sulfuric acid. Figure 13 shows a schematic of the expected reactivity. Calcium carbonate is expected to react with acidic substances neutralizing them, forming salts and carbon dioxide. These acid neutralizing reactions can deplete gas-phase HNO_3, HCl, etc. There are a large number of ozone destroying catalytic cycles involving NOx, chlorine and other

halogens, which are altitude (and latitude) dependent. NOx can be produced via HNO_3 photolysis and lost via heterogeneous reaction of N_2O_5. It participates both in ozone destroying catalytic cycles and is important for deactivation of ozone destroying halogen radicals. Thus, knowledge of the heterogeneous reaction rates of numerous substances with calcium carbonate are required to predict the impact it will have on stratospheric composition.

However, until the recent study by Dai et al. in our laboratory, no heterogeneous chemistry studies of calcium carbonate under stratospheric conditions had been conducted, to our knowledge, although there exists a rich data set under tropospheric conditions (Dai et al., 2020). This work, as well as the work of Dai et al., highlights that reactive solid aerosols are indeed more complex than liquid sulfuric acid: The authors observed moderate initial uptake of the gas-phase acids HCl and HNO_3 on fresh calcium carbonate, as the dry stratospheric conditions already make uptake coefficients lower than under typical tropospheric conditions. An additional large difference to liquid aerosol is that the surface of the solid calcium carbonate passivates, drastically reducing the uptake coefficients of HCl and HNO_3. Hence, based on the Dai et al. laboratory study, calcium carbonate rapidly becomes effectively unreactive with respect to uptake of these gas-phase acids, an important finding that confirms calcium carbonate as a good candidate as alternate SAI material. In addition, calcium carbonate particles are abundant at Earth's surface due to windblown mineral dust. And the small calcium carbonate SAI particles should dissolve rapidly in water. This does not exclude risks associated with the deposition of calcium carbonate SAI particles or impacts on clouds (Cziczo et al., 2019). However, due to its abundance at the Earth's surface, there already exists a large knowledge base for its environmental impacts in contrast to, e.g., diamond. Further laboratory work is required to study especially the $ClONO_2$ + HCl and N_2O_5 hydrolysis reactions on fresh and aged calcium carbonate. However, the existing results prepare the stage for studying them in the real stratospheric environment as outlined below. Figure 14 shows results of the AER 2-D chemistry-transport-aerosol model for annual average ozone column changes of calcium carbonate SAI compared to a control for 2040. Ignoring the passivation of calcium carbonate (thk-ind) results in increases in ozone columns from calcium carbonate SAI whereas the inclusion of passivation can either result in very little ozone column change or losses in the Southern Hemisphere, depending how the $ClONO_2$+HCl is parameterized. Either of the two, more realistic, passivation scenarios result in significantly lower ozone loss than the equivalent amount of sulfate SAI, consistent with the hypothesis.

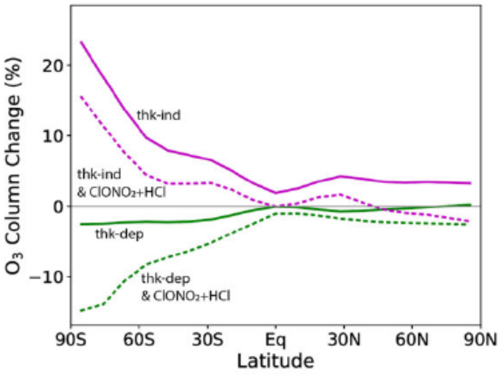

Figure 14: Shows the role of passivation and the heterogeneous $ClONO_2$+HCl reaction on ozone column change using the AER 2-D model taken from Dai et al. 2020. Inclusion of this reaction with the same rate as measured for Al_2O_3 results in a substantial reduction in ozone for scenarios including, thk-ind, or excluding passivation, thk-dep.

4.3.4. Need for SCoPEx Calcium Carbonate Plume Studies

One of the challenges for alternate SAI aerosol is the lack of materials such as calcium carbonate in the stratosphere. The only way to then study these materials in the actual stratosphere is via deliberate stratospheric injection of a small amount of these materials. In environmental studies, including stratospheric studies, it is not possible to rely purely on laboratory studies. For example, flights on the NASA ER-2 into the polar vortex over Antarctica provided the ability to test whether laboratory-derived reaction mechanisms were able to capture real-world ozone destruction chemistry. Without these flights, the level of confidence in the model predictions would have been much lower, and for good reason. It is not clear that a given experimental setup in the laboratory can faithfully capture the entire complexity of the real stratosphere; only field observations are able to provide this. For a number of natural stratospheric processes, remote observations can provide important information in addition to in situ aircraft or balloon. However, these are only possible when large-scale phenomena are at work.

Since there are no natural calcium carbonate plumes in the stratosphere that would even allow for in situ observations, intentional injection is necessary to perform these studies. Calcium carbonate injections will allow SCoPEx to provide invaluable observations as it will quantitively test the mechanisms determined in the laboratory. As stated above, there is a need for more laboratory studies, however, there is good reason to proceed with the planning of SCoPEx calcium carbonate experiments. First, by the time of the first injection experiments, additional studies should have been conducted. In addition, N_2O_5 uptake coefficients used in the model are likely a very good estimation as similar values have been found for different solid materials, e.g., Al_2O_3 and SiO_2 (Molina et al., 1997). In addition, even with these additional lab determined mechanisms, the same type of experiments as proposed here will still have to be conducted, as we expect these reactions to not make a significant difference. In other words, they will not be a deciding factor about the viability of calcium carbonate as an alternate SAI material. Only field experiments will help shed insight into these questions. In summary, there is a critical need for evaluating not just the aerosol microphysics (goal 2) but also the stratospheric chemistry of calcium carbonate due to the promise it holds as a lower risk SAI material.

4.3.5. SCoPEx Experimental Design and Analysis of Chemical Calcium Carbonate Plume Evolution

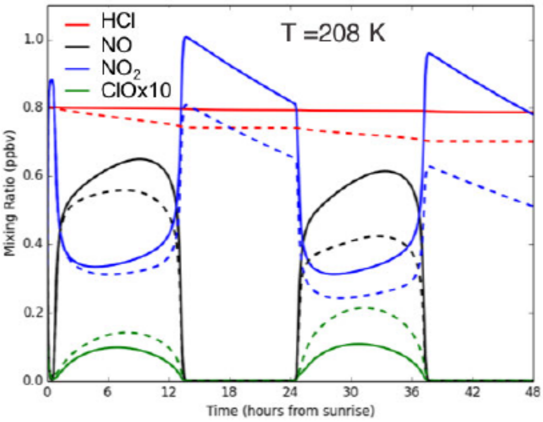

Figure 15: Solid lines: background $2\mu m^2\ cm^{-3}$ sulfate $5ppm_v$ H_2O. Dashed lines: plume $15\mu m^2\ cm^{-3}$ sulfate 10 ppm_v H_2O.

The experiments will again follow the standard concept of operations as under goal 2. In order to determine optimal injection rates, we will include chemical reactions in the plume model, updated with the newest mechanisms available at that time. Figure 15 shows the evolution of an air mass perturbed by a sulfate aerosol injection over multiple days, i.e., significantly longer than the initial SCoPEx experiments. Significant changes in HCl and NOx can be observed already over short time periods and these are easily detectable with existing instrumentation. For this science goal, it is desirable to measure aerosol composition and size distribution as well as key gas-phase chemical species, especially HCl, NOx and water. Therefore, this science goal requires a much larger set of instruments. In addition, the equivalent model to Figure 15 for calcium carbonate is informed by the results of science goal 2. The work of Dai et al. provides kinetic parameters needed for this model, and reactions for which there are no laboratory data to date are parameterized using close analogues and conditions, e.g., $ClONO_2$ + HCl are parameterized using the results for alumina (and silica) from Molina et al. (1997). One key question is whether the changes in HCl and NOx will indeed be smaller for calcium carbonate than those for sulfate shown in the figure above, which would confirm the hypothesis for calcium carbonate as a potential alternate SAI material.

In summary, SCoPEx experiments using calcium carbonate injections will provide a unique evaluation as to whether calcium carbonate indeed is an alternate SAI material that could substantially reduce risk from SAI compared to sulfate. Follow-up studies will be needed. For example, improved chemical and aerosol microphysics models will provide improved models of the chemical and physical evolution of calcium carbonate, which likely will motivate specific laboratory investigations. These will provide information for SCoPEx studies using "stratospherically aged" calcium carbonate as precursor for injection that can then be used to compare whether the laboratory mechanisms of this aged calcium carbonate agree with that found in the real stratospheric environment.

5. Data Management Plan and Dissemination of Results

Products of the research. The data generated during this project consists of meteorological, navigational, telemetry, and a variety of instrumentation data, in particular aerosol size distributions as well as chemical composition data during later science flights. In addition, there will be model data on plume chemical evolution.

Access to data, data sharing practices, and policies and dissemination of results. Data relevant for scientific analysis will be made public within 60 days of the end of flight. This taw data will be made public with appropriate warnings that it has not undergone QA/QC. The email address of users will be recorded so that they can be automatically notified when revised versions become available. Based on previous experiences with stratospheric airborne campaigns, this is typically 6-15 months after the flight depending on the type of data, e.g., the amount of calibration and data workup required. We have chosen to make raw data available rapidly—going far beyond what is typical for stratospheric science missions—because of the public scrutiny of SCoPEx and because of the broad commitment to Open Access data principles articulated by Harvard's Solar Geoengineering Research Program which is funding SCoPEx.

Principal Investigators (PI) and their groups have an excellent track record with presenting their work at major national and international conferences and workshops. All data that go into key analyses and figures in the group's publications will be made publicly available via the PI's group website. All publications resulting from this project will be posted on the PI's webpage (https://projects.iq.harvard.edu/keutschgroup/publications). Preprints of manuscripts submitted for publication as well as the underlying data will also be posted on Harvard's Dash manuscript repository. Publications will be made in open access formats.

Archiving of data. All data acquisition/storage computers in the PI's group are automatically backed up daily, both wirelessly to a server elsewhere on campus, and/or to a cloud server. Both of these processes ensure that data will not be lost and enable rapid access to the data. The file naming system used for all software (which includes the date of the experiment) ensures straightforward retrieval and use of archived data. Group laptops are also backed up daily, ensuring that analyzed data are archived as well.

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From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Fwd: Update
To: Frank Keutsch
Cc: Keith, David; Ronda Knott - NOAA Federal
Sent: October 27, 2020 10:25 PM (UTC-04:00)
Attached: Untitled attachment

Frank,

I hope this finds you doing well with the family in Germany.

DavidK and I invited you to a Friday v-meeting to catch up on CI matters. He will give me a brief download of his CDR ideas/perspective at the beginning at my request. So you could join late to miss that.

Let us know.
THanks
Dave

David W. Fahey, PhD
Director of the Earth System Research Laboratories (ESRL)
Director of the ESRL Chemical Sciences Laboratory
NOAA Earth System Research Laboratories
325 Broadway R/CSD
Boulder, CO 80305 USA
303-497-5277 -5822 fax
david.w.fahey@noaa.gov

Ronda Knott, Admin. Assistant
ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

Begin forwarded message:

From: Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
Subject: Re: Update
Date: October 26, 2020 at 7:51:29 PM MDT
To: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Cc: "Keith, David" (b) (6) >

Hi Dave and David,

The meeting has been set for this Friday, October 30th at 7am MT and included Frank Kuetsch.
The connection details are:

Meeting ID
meet.google.com/zgb-gfnu-gdr
Phone Numbers
(US) +1 561-408-9337
PIN: 857 507 300#

Thank you,
Ronda

Ronda Knott
Executive Administrative Assistant to

Dr. David W. Fahey, Director

NOAA Chemical Sciences Laboratory
325 Broadway, R/CSL

Boulder CO 80305

I am currently teleworking, please call my cell: (b) (6)

303.497.4404 phone

303-497-5822 fax

ronda.knott@noaa.gov

On Mon, Oct 26, 2020 at 2:56 PM David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:

> David,
> 7Am Friday will work.
> Ronda can reach out to FrankK if you like. She will send a link to all.
> Thanks
> Dave
>
> > On Oct 25, 2020, at 9:17 PM, Keith, David (b) (6) > wrote:
> >
> > How about 8:30 AM MT on Friday the 30th? (I can do any time from 7:00 to 10:00) MT that AM. Suggest we choose a time, then I will see if Frank can join (he can miss the CDR part).
> >
> > D
> >
> > ---
> >
> > **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> > **Sent:** Saturday, October 24, 2020 6:29 PM
> > **To:** Keith, David (b) (6) >
> > **Cc:** Ronda Knott - NOAA Federal <ronda.knott@noaa.gov>
> > **Subject:** Re: Update

David,

Thanks for the reply. I appreciate the perspective on Pierrehumbert; a bit frustrating. We will launch a webpage for the Earth Radiation Budget program (ie the Congressional funding) soon (albeit a bit late) that will explain NOAA's role and intent and in effect pushback on Pierrehumbert and others.

Thanks for your offer of a CDR debrief and catching up on other matters. My CDR meeting is 4 Nov so best would be next week sometime. Let me know if that might work (w/ or w/o Frank) and a preferred day/time.

Regards
Dave
PS Canmore seems like a good faraway place to get fresh air devoid of C-19.

> On Oct 21, 2020, at 2:13 PM, Keith, David (b) (6) wrote:
>
> Dave
>
> Thanks. Yet, I'm particularly frustrating because Ray repeats the idea that doing it at all commits us to doing it for a thousand years, yet I think he knows that's not true. When he was at Harvard and from the public audience we challenged him on that pointing out that you could always taper off slowly even if you didn't have carbon removal and so the net result would be a reduction in the rate of change even if it didn't change the ultimate endpoint. He agreed. Yet he keeps coming back to this claim.
>
> I don't have an overview on CDR. I step back because of the conflict of interest after starting Carbon Engineering (the air capture company). In fact I think that CDR is a bit overhyped and I have been trying to figure out how to say that without frustrating people at Carbon Engineering too much. I have fragments of talks and some opinions. I could dump these on you in a short (15 minutes) conversation which might be helpful to me because I'm trying to polish the stuff.
>
> I think you catch up with you, me and Frank would make sense. I'm thinking early November at that point we will of got science plan out to the SCoPEx committee and have made the next step towards reality on a spring flight.
>
> It's beautiful and snowy up here in Canmore Alberta.
>
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>

Sent: Wednesday, October 21, 2020 1:23 PM
To: Keith, David <(b) (6)
Subject: Update

David,

Very good article in Globe. Pierrehumbert's article is frustrating since he attacks CI and calls out people like me yet at the end says there might be an appropriate role for CI, something he has done in other articles.

My management has asked me to inform them about CDR in an internal meeting. I am not very well prepared to do that and wondered if you had a presentation that you would be willing share to draw from for this purpose.

A call to catch up with Frank would be welcome.

Regards
Dave

David W. Fahey, PhD
Director of the Earth System Research Laboratories (ESRL)
Director of the ESRL Chemical Sciences Laboratory
NOAA Earth System Research Laboratories
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Boulder, CO 80305 USA
303-497-5277 -5822 fax
david.w.fahey@noaa.gov

Ronda Knott, Admin. Assistant
ronda.knott@noaa.gov, 303-497-4404
http://www.esrl.noaa.gov/csd/

From: Kelly Wanser (b) (6) >
Subject: Nice job on the NOVA episode!
To: David Fahey - NOAA Federal; Frank Keutsch
Cc: John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:13 PM (UTC-04:00)

You were excellent and the piece came out great.
We'll promote it as we are able.

Best,
k.

--
Kelly Wanser
Executive Director, SilverLining | http://www.silverlining.ngo
Board Director, Dendra Systems | http://www.dendra.io
Advisor, University of Washington Marine Cloud Brightening Project | http://www.mcbproject.org
President's Circle, National Academy of Sciences | http://nas-sites.org/PC/
Phone: (b) (6)

TEDTalk: *Emergency Medicine for Our Climate Fever*
Report: *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: Kelly Wanser (b) (6) >
Subject: Re: Nice job on the NOVA episode!
To: David Fahey - NOAA Federal; David Keith
Cc: Frank Keutsch; John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:22 PM (UTC-04:00)

Ha, thanks, Dave. Adding David here.
Terrific piece, David!

Sent from my iPhone

> On Oct 29, 2020, at 1:19 PM, David Fahey - NOAA Federal <david.w.fahey@noaa.gov> wrote:
>
> Kelly,
> I think you want to praise David K instead of me. I too thought they all did a great job.
> Dave
>
>> On Oct 29, 2020, at 1:12 PM, Kelly Wanser <(b) (6) > wrote:
>>
>> You were excellent and the piece came out great.
>> We'll promote it as we are able.
>>
>> Best,
>> k.
>>
>> --
>> Kelly Wanser
>> Executive Director, SilverLining | http://www.silverlining.ngo
>> Board Director, Dendra Systems | http://www.dendra.io
>> Advisor, University of Washington Marine Cloud Brightening Project | http://www.mcbproject.org
>> President's Circle, National Academy of Sciences | http://nas-sites.org/PC/
>> Phone: (b) (6)
>>
>> **TEDTalk:** *Emergency Medicine for Our Climate Fever*
>> **Report:** *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: Douglas MacMartin (b) (6) [redacted]>
Subject: RE: 2022 GRC program
To: Karen Rosenlof - NOAA Federal; Trude Storelvmo
Sent: July 19, 2021 10:15 AM (UTC-04:00)

Excellent! We should have a great conference ☺. (More later… probably not for a while.)

doug

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Sent: Thursday, July 15, 2021 5:04 PM
To: Douglas MacMartin (b) (6) [redacted] Trude Storelvmo (b) (6) [redacted]
Subject: Re: 2022 GRC program

Doug and Trude,

I should be available during that time frame, and would like to attend the test GRC. I'd be happy to adjust topics as you feel is needed.

Take care,

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
Boulder, CO 80305
office: 3A-121, DSRC
e-mail: Karen.H.Rosenlof@noaa.gov
phone: 303 497-7761
fax: 303 497-5373
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while safer at home remains in effect, email is the most reliable contact

> On Jul 15, 2021, at 9:06 AM, Douglas MacMartin (b) (6) [redacted]> wrote:
>
> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
>
> As a start to our planning, could you let us know whether you would be interested in talking at the 2022 meeting? We would of course still love to hear from you, but schedules may not permit and research interests change (and, indeed, for some or many of you that may mean that the topic we were originally thinking you would talk about would no longer be what you are currently most excited by – the GRC is supposed to be cutting-edge current research, of course – so if you let us know we can start revising sessions and think about what gaps we'd like to fill). There are also some new people who are doing some great research too that we would like to hear from, so it's conceivable that – given the now 5 year gap since the last GRC – we might choose to slightly increase the number of talks and reduce the time available per talk.

Thanks,
Doug & Trude

From: Douglas MacMartin
Sent: Wednesday, February 19, 2020 10:27 AM
To: (b) (6) ; (b) (6) ; Alan Robock
<(b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine
Ricke (b) (6) >; (b) (6) ; Robert Wood
<(b) (6) ; (b) (6) | (b) (6) <(b) (6) ;
Daniele Visioni <(b) (6) >; (b) (6) ; Peter Irvine <(b) (6) >; Jonathan
Proctor (b) (6) ; (b) (6) ; Keith, David (b) (6) >;
Kravitz, Ben (b) (6) >; Wake Smith <(b) (6) >; Izidine Pinto
(b) (6) ; Gabriel Chiodo (b) (6) >; Keutsch, Frank N
<(b) (6) >
Cc: Lawrence, Mark <(b) (6) >; valentina Aquila (b) (6) ; Ulrike
Niemeier (b) (6) >; Leisner, Thomas (IMK) (b) (6) >; Olivier
Boucher <(b) (6) >; Schrag, Daniel P. <(b) (6) >; TAYLOR,Michael
<(b) (6) >; (b) (6) Trude Storelvmo <(b) (6) >;
'Simone Tilmes' (b) (6) >; (b) (6) Jim Hurrell
(b) (6)
Subject: RE: 2020 GRC program

Hi all,

Just a reminder that if you haven't sent me a title yet, to do so (otherwise I'll have to make something up; GRC needs us to upload our "final" program by the end of this month) I have titles for about half of you (though some of those are draft titles you sent quite some time ago, e.g. for Pete, Isla, Danny).

And, if you haven't responded yet regarding need for travel support, let me know (about half of you have). For those of you who haven't been to a GRC before, there's a bus from Boston airport, and from Portland Maine airport.

If you've already both sent me a title and responded regarding travel, then you can ignore this email.

Also, regarding format, this year we're explicitly including 10-15 minutes for the discussion leader to make some remarks to help frame each session (taking 5 minutes from each speaker's time), and rather than having a lengthy discussion after each talk, we'll have a shorter 10-minute discussion after each talk and a 20-minute general session discussion at the end (that's as long as GRC will allow) with everyone from a given session.

Thanks, and see you in June!
doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) ; (b) (6) 'Jadwiga (Yaga) Richter'
(b) (6) >; Alan Robock (b) (6) >; Karen Rosenlof - NOAA Federal
<karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >; (b) (6) ; Robert
Wood
(b) (6) >; (b) (6) ; (b) (6) <(b) (6) >;
Daniele Visioni <(b) (6) >; (b) (6) Peter Irvine <(b) (6) >; Jonathan

Proctor <(b) (6) >; Govindasamy Bala <(b) (6) >; (b) (6)
Keith, David (b) (6) >; Kravitz, Ben <bkravitz@iu.edu>; Wake Smith
<(b) (6) ; Chris Field (b) (6)
Cc: Lawrence, Mark (b) (6) >; valentina Aquila <(b) (6) Ulrike
Niemeier <(b) (6) >; Leisner, Thomas (IMK) <(b) (6) Olivier
Boucher (b) (6) >; Schrag, Daniel P. (b) (6) ; TAYLOR,Michael
(b) (6) ;(b) (6) ; Lynn Russell (b) (6) Trude Storelvmo
<(b) (6) 'Simone Tilmes' (b) (6) >; (b) (6)
Subject: 2020 GRC program

Hi all,

Happy New Year!

The full program for GRC is due on February 28; if you haven't sent us a title for your talk (or if you did and want to revise it), please do so before the end of February so I have time to enter everything into the conference management system online.

The cc-line has discussion leaders for each session.

Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin
Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and
Faculty Fellow, Atkinson Center for a Sustainable Future
Cornell University
(b) (6)
https://climate-engineering.mae.cornell.edu/

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Nice job on the NOVA episode!
To: Kelly Wanser
Cc: Frank Keutsch; John Dykema; Burns, Elizabeth; Alex Wong
Sent: October 29, 2020 3:19 PM (UTC-04:00)
Attached: Untitled attachment

Kelly,
I think you want to praise David K instead of me. I too thought they all did a great job.
Dave

> On Oct 29, 2020, at 1:12 PM, Kelly Wanser (b) (6) wrote:
>
> You were excellent and the piece came out great.
> We'll promote it as we are able.
>
> Best,
> k.
>
> --
> Kelly Wanser
> Executive Director, SilverLining | http://www.silverlining.ngo
> Board Director, Dendra Systems | http://www.dendra.io
> Advisor, University of Washington Marine Cloud Brightening Project | http://www.mcbproject.org
> President's Circle, National Academy of Sciences | http://nas-sites.org/PC/
> Phone: (b) (6)
>
> **TEDTalk:** *Emergency Medicine for Our Climate Fever*
> **Report:** *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction*

From: Smith, Wake (b) (6) [redacted]
Subject: RE: CCIS webinar Wednesday Sept 22nd
To: Karen Rosenlof - NOAA Federal
Sent: September 18, 2021 7:59 AM (UTC-04:00)

Will do.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6) [redacted]

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Sent: Friday, September 17, 2021 4:44 PM
To: Andrea Smith (b) (6) [redacted]
Cc: Simone Tilmes (b) (6) [redacted]; Keutsch, Frank N (b) (6) [redacted]>; Smith, Wake <(b) (6) [redacted]; Graham Feingold - NOAA Federal <Graham.Feingold@noaa.gov>; Brian Medeiros (b) (6) [redacted]
Subject: Re: CCIS webinar Wednesday Sept 22nd

And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.

Thanks!

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
Boulder, CO 80305
office: 3A-121, DSRC
e-mail: Karen.H.Rosenlof@noaa.gov
phone: 303 497-7761
fax: 303 497-5373
----
while safer at home remains in effect, email is the most reliable contact

> On Sep 17, 2021, at 11:06 AM, Andrea Smith (b) (6) [redacted]> wrote:
>
> Hello Frank, Wake and Graham,
>
> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>
> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
> Meeting ID: 816 4261 9898
> Passcode: 148321

Please join 10 mins early to test tech and troubleshoot if needed.

2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) [redacted] (preferably by Tuesday night):

3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.

After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.

Let me know if you have questions on any of the above.

Thanks again, and see you next Wednesday.

Andrea

On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) [redacted] > wrote:

> Hi Frank, Wake and Graham,
> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>
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>
> Cheers, Simone

> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6)

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.
<CCISspeaker_consent_form.pdf>

From: Graham Feingold - NOAA Federal <graham.feingold@noaa.gov>
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Andrea Smith; Simone Tilmes; Keutsch, Frank N; Smith, Wake; Karen Rosenlof - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:47 AM (UTC-04:00)

zoom link not working for me. is there something else i need to do?

On 9/17/21 11:06 AM, Andrea Smith wrote:

> Hello Frank, Wake and Graham,
>
> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>
> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
> Meeting ID: 816 4261 9898
> Passcode: 148321
>
> Please join 10 mins early to test tech and troubleshoot if needed.
>
> 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) [redacted] (preferably by Tuesday night):
>
> 3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.
>
> After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.
>
> Let me know if you have questions on any of the above.
>
> Thanks again, and see you next Wednesday.
>
> Andrea
>
> On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) [redacted]> wrote:
>
>> Hi Frank, Wake and Graham,
>> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
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> (b) (6) [redacted]

--
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(b) (6) [redacted] (cell)

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--
Graham Feingold
NOAA Earth System Research Laboratories
Chemical Sciences Laboratory (R/CSL9)
325 Broadway
Boulder, Colorado 80305, USA
Tel: (303) 497-3098
Fax: (303) 497-5318

From: Andrea Smith (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Karen Rosenlof - NOAA Federal
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Graham Feingold - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:36 AM (UTC-04:00)

Good morning everyone,

If you haven't already done so, please reply here with slide decks or drop them in (b) (6) if large file size.

See you in 10-15 mins!

Cheers,

Andrea

On Fri, Sep 17, 2021 at 2:43 PM Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov> wrote:

> And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
> So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.
>
> Thanks!
>
> Karen
>
> \---
> Karen Rosenlof
> NOAA Chemical Sciences Laboratory
> Mail Stop R/CSL8
> 325 Broadway
> Boulder, CO 80305
> office: 3A-121, DSRC
> e-mail: Karen.H.Rosenlof@noaa.gov
> phone: 303 497-7761
> fax: 303 497-5373
> \---
> while safer at home remains in effect, email is the most reliable contact
>
>> On Sep 17, 2021, at 11:06 AM, Andrea Smith (b) (6) > wrote:
>>
>> Hello Frank, Wake and Graham,
>>
>> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>>
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3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.

After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.

Let me know if you have questions on any of the above.

Thanks again, and see you next Wednesday.

Andrea

On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) [redacted] wrote:

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> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
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My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Newsletter from Harvard's Solar Geoengineering Research Program
To: Keith, David
Cc: Frank Keutsch; Ronda Knott - NOAA Federal
Sent: December 28, 2020 11:44 AM (UTC-05:00)
Attached: Untitled attachment

David,
Good, yes let's talk on the 6th.
Ronda can arrange a time and link.
Happy New Year.
Dave

> On Dec 28, 2020, at 9:30 AM, Keith, David <(b) (6) [redacted]> wrote:
>
> Dave
>
> Yes, we expect to fly POPS.
>
> Also, interesting developments on turbulence.
>
> Now that this mission seems to be (finally) coming together it would be good how about the three of us to touch base again about this and about the meeting to discuss future flight missions?
>
> How about Wednesday the 6th?
>
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Saturday, December 26, 2020 5:51 PM
> **To:** Keith, David (b) (6) [redacted]
> **Subject:** Re: Newsletter from Harvard's Solar Geoengineering Research Program
>
> David,
>
> Thanks for the newsletter. I am impressed with your productivity.
>
> Good progress with Esrange launch plans and committee approval. Do you plan to fly POPS? It would be of value to get a high lat profile and adds to your flight data return. No communication with the device is needed since it records onboard. Let us know if you want assistance.
>
> We have prepared a POPS unit and backup to fly on the World View Stratollite in 2021 when they are able to resume launches.
>
> I hope you and yours are doing well enough this Holiday Season. We are OK.
> Regards
> Dave

On Dec 16, 2020, at 9:18 AM, David Keith (b) (6) wrote:

Dear Readers,

As this strange year comes to a close, we wanted to share updates from Harvard's Solar Geoengineering Research Program (SGRP), which supports research at Harvard on the science, technology, and governance of solar geoengineering.

We hope everyone and their families are safe and well. We wish you a healthy new year.

Yours,
David Keith and Lizzie Burns
Faculty Director and Managing Director
Harvard's Solar Geoengineering Research Program

SCoPEx

SCoPEx Update

Led by Frank Keutsch, the Stratospheric Controlled Perturbation Experiment (SCoPEx) is a scientific experiment to advance understanding of stratospheric aerosols that could be relevant to solar geoengineering. It aims to reduce the uncertainty around specific science questions by making quantitative measurements of some of the aerosol microphysics and atmospheric chemistry required for estimating the risks and benefits of solar geoengineering in large atmospheric models.

The SCoPEx research team has asked the independent SCoPEx Advisory Committee to review our plans for a proposed platform test in Sweden in June 2021. This test would notbe the experiment itself, but rather a test of the SCoPEx platform without the release of any particles. Specifically, we would like to test the gondola's horizontal and vertical control using the winch system and propellers as well as the power, data, navigation, and communication systems. We would not release any aerosols, nor fly an aerosol injection/release system. Still, we will not proceed with this flight without a formal recommendation authorizing the flight from the Advisory Committee to Harvard management. We have asked the Advisory Committee if they can complete their review and reach a decision—be it positive or negative—about this platform test by February 15, 2021. You can learn more about this platform test here.

SCoPEx Advisory Committee

Recognizing the complex societal and governance issues surrounding solar geoengineering, Harvard has ensured the SCoPEx project has the guidance of an independent Advisory Committee, as noted above. The Advisory Committee has already begun to carry out a significant amount of work, including a financial review, legal review, and scientific and technical review, and they have proposed a draft process for a societal engagement review. You can learn more by visiting their website. We are grateful for the time the Committee members are volunteering and look forward to the work ahead.

Opportunities

SGRP Fellowship

SGRP is now accepting applications to its 2021 Fellowship Program, which offers short-term and long-term opportunities. Applications are due January 29, 2021. We are seeking applications from scholars in a range of disciplines, including the natural sciences, economics, law, government, public policy, public health, medicine, design, and the humanities. We also are looking for applicants who are new to the field of solar geoengineering and/or have critical views, and we strongly encourage applications from

women and minority candidates. More information can be found here.

We would also like to congratulate our current and future fellows who were accepted during our previous fellowship application process.

- Cody Floerchinger, (August 2019-July 2021) advised by Frank Keutsch, is using datasets from upcoming measurements campaigns to provide a comprehensive analysis of the state of our ability to model stratospheric plume dynamics and highlight areas where the community should focus its efforts when attempting to improve these model products (science).
- Yuanchao Fan, (October 2019-October 2021) advised by Kaighin McColl, is quantifying the impact of solar geoengineering on terrestrial ecosystems, including forests and agriculture, and their biophysical and biogeochemical feedbacks to climate. He is also collaborating with David Keith on a paper about geoengineering and food supply (science).
- Irina Bakalova (February 2021-April 2021) will be advised by Professor Rob Stavins, working closely to study the effectiveness and stability of potential international agreements on solar geoengineering (economics).
- Britta Clark (February 2021-June 2021) will be advised by Lucas Stanczyk and will analyze the intergenerational justice impacts of solar geoengineering as a mitigative strategy to address climate change (philosophy).
- Ermanno Napolitano (August 2021-July 2022) will be advised by Lucas Stanczyk and will catalogue and explore all of the existing international legal principles that are likely to have some bearing on the deployment of solar geoengineering (law).

Online Community for Junior Researchers

A group of junior scientists are organizing a diverse online community of young researchers new to the solar geoengineering field, designed to engage researchers with new perspectives. This group will provide young researchers the chance to informally present on their research, share ideas, receive feedback, and create a space for open and non-judgmental discussion on the topic. The first few sessions took place in November and December and were held live on Zoom. Graduate students and recent postdocs from across the globe, including from developing countries, discussed various publications containing alternate viewpoints on solar geoengineering. Future sessions scheduled include presentations by a former SGRP DECIMALS resident and other participants as well as discussion forums and networking opportunities on Slack. Undergraduate students, graduate students, and postdoctoral fellows within five years of completing their degree are welcome to join the group. If you are interested in participating, please email Selena Wallace: swallace@seas.harvard.edu.

Events

Due to COVID-19, we had to cancel in-person events beginning in March. Since that time, we have held countless Zoom conversations (like so many others). For example, in November we hosted a public health workshop at Harvard to try to broaden the diversity of researchers studying solar geoengineering on campus. We are also now in the process of building an exciting opportunity that will allow us to reach a broader audience outside of Harvard that will include experts, practitioners new to solar geoengineering, and the general public. We invite you to join us.

Public Health Roundtable

In November 2020, we held a virtual event with the Harvard Chan School of Public Health Center for Climate, Health, and the Global Environment where experts from both the geoengineering and the public health communities had the opportunity to discuss the potential public health challenges posed by solar geoengineering. Few studies to date have considered the public health implications of geoengineering, and those that have have been limited to mortality due to ambient air pollution and UV-induced malignant melanoma. This event discussion addressed questions of the risk factors that these studies might be omitting, the vast array of other public health issues that may arise, as well as the environmental justice implications of human interventions to the climate system such as geoengineering. The organizers of the event may publish a paper that summarizes the key points and questions to hopefully inspire other experts in the public health field to begin research on solar geoengineering. Overall, this event was significant because it not only signaled new interest from various public health experts who, years prior, had not yet engaged, but also because it will hopefully unlock even more new interest from a critical community that has yet to fully participate in solar geoengineering research.

Public Seminar Series

In the spring of 2020, we will launch a virtual seminars series to promote understanding and discussion of solar geoengineering and to enable audiences to learn from a broader set of perspectives in the area of solar geoengineering research and public policy. These seminars will contain a combination of practitioners and experts from around the world and will have a variety of formats including single speakers, moderated debate, and moderated panels. Previously, SGRP seminar attendance was limited to the Harvard community, but we are now able to extend the reach of this series to a global, public audience. We invite you to participate in these seminars. We will email this listserv when seminars are scheduled.

Publications, Video, and Audio Clips

The following written publications were funded all or in part by SGRP.

Recent Peer Reviewed Publications

Zhen Dai, Debra K. Weisenstein, Frank N. Keutsch, and David W. Keith. (2020). "Experimental reaction rates constrain estimates of ozone response to calcium carbonate geoengineering." Communications Earth and Environment 1, 63.

Jacob T. Seeley, Nicholas J. Lutsko, and David W. Keith. "Designing a radiative antidote to CO2." Geophysical Research Letters (Submitted).

Joshua B. Horton and Barbara Koromenos. (2020). "Steering and Influence in Transnational Climate Governance: Nonstate Engagement in Solar Geoengineering Research." Global Environmental Politics 20, 3: 93-111.

Nicholas J. Lutsko, Jacob T. Seeley, and David W. Keith. (2020). "Estimating Impacts and Trade-offs in Solar Geoengineering Scenarios With a Moist Energy Balance Model." Geophysical Research Letters 47, 9.

Joshua B. Horton, Penehuro Lefale, David Keith. (2020). "Parametric Insurance for Solar Geoengineering: Insights from the Pacific Catastrophe Risk Assessment and Financing Initiative." Global Policy, Special Issue.

David Keith and Peter Irvine. (2020). "Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards." Environmental Research Letters 15, 4.

Jesse Reynolds and Joshua Horton. (2020) "An earth system governance perspective on solar geoengineering." Earth System Governance, 3.

Other Publications

David W. Keith and John Deutch (2020) "Climate Policy Enters Four Dimensions." In *Securing our Economic Future,* edited by Amy Ganz and Melissa Kearney, Aspen Institute Press.

Cody Floerchinger, John Dykema, David Keith, and Frank Keutsch (2020) "A Need for In Situ Observations to Inform Nearfield Plume Transport and Aerosol Dynamics as well as Chemistry of Alternate Geoengineering Materials in the Stratosphere." Letter to the National Academy for Science.

David Keith, Frank Keutsch, and Cody Floerchinger (February 15, 2020) "Empirical methods to reduce uncertainty about solar geoengineering," public input to the National Academy Committee on *Climate Intervention Strategies that Reflect Sunlight to Cool Earth*.

Recent Video and Audio Recordings

AGU TV (December 2, 2020). "SCoPEx, Harvard University – New Frontiers in Climate Change Research." WebsEdge Science.

Anthony Padilla (October 23, 2020) "I spent a day with climate change scientists" *Youtube*.

PBS Nova (October 16, 2020). "Can We Cool the Planet?" *WGBH*.

Harvard Magazine (October 16, 2020). "Daniel Schrag and David Keith: Can Solar Geoengineering Help Fight Climate Change?"

All Things Considered (July 22, 2020) "Harvard Scientists Plan First-Ever Field Experiment Related To Solar Geoengineering." *WBUR*. (This aired again on Here & Now on December 4, 2020 as "Experiment To Help Researchers Understand Risk, Efficacy of Solar Geoengineering.")

Harvard Museum of Natural History (December 12, 2019) "The Peril and Promise of Solar Geoengineering" *Youtube*.

From: Keith, David (b) (6) >
Subject: RE: Experimental research platform requirements
To: David Fahey - NOAA Federal
Cc: Smith, Wake; Keutsch, Frank N
Sent: February 3, 2021 9:59 AM (UTC-05:00)

Dave

Thanks. I think we see this about the same way.

From my perspective I came into this field working for Jim with all the excitement about Aurora's aircraft which ended up amounting to nothing. It took some years of my life. And yes, Global Hawk has been a big disappointment. So I definitely get the basis for skepticism.

On the other hand, there does seem to be a commercial-driven shakeup in the ability to develop low altitude aircraft. That's true from the new entrants into general aviation market through to the startups building off drone technology. So I'd like to understand whether this could apply to higher altitude light aircraft. I don't know, but if Wake spurs some interest I am open to find out more.

Have you had any conversations with these folks: Sceye | A new generation of HAPS | High Altitude Platform Stations? The head guy just reached out to me again and I will talk with.

David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Saturday, January 30, 2021 6:38 PM
To: Keith, David (b) (6) >
Cc: Smith, Wake (b) (6) >; Keutsch, Frank N (b) (6) >
Subject: Re: Experimental research platform requirements

David,

Yes, I think if one has funding, then existing a/c become available. Certainly for the UT/LS, the WB-57s have been underutilized for years now and hence availability hasn't been an issue. Indeed a trip back to the boneyard was perhaps a growing threat.

I note that no one has ever built an aircraft for atmospheric chemistry, leaving the field to exploit as best they can existing a/c, which we have done very well. Thus, if there were runway a/c available that could do 30kg, 8hr, 79kft, the community would no doubt rush to use it. So the answer to your question is yes.

My problem with new-platforms-will-be-cheap is the issue of having truly operational a/c rather than experimental a/c. If one is trying to fly an experiment on an experimental a/c it reduces the probability of success by a large measure. Making an experimental a/c operational requires larger upfront and sustained investment by entities other than the science communities, creating the underwater part of the iceberg. This is why we don't have new operational a/c. And one can look to the Global Hawk and see that even starting at a high level (a mature platform) it failed to become operational because no one wants to pay the price, in this case neither NASA or NOAA. Now deeper pockets (DoD) have taken it over.

And to your final point about what payloads, yes, the new generation of lightweight instruments make 30kg interesting and valuable, and, yes, comprehensive chemistry payloads still want to be on heavy lift long-range a/c.

In reply to Wake's question about perturbation/monitoring a/c, hmmm, it depends. In the early days, perhaps they could be the same. Eventually the perturbations sought would be as large as possible per flight and not every flight would need diagnostics, so I think eventually they are different a/c. And monitoring a/c could be below the perturbation a/c altitudes and diagnose with lidar.

Interest above 70kft: in general because we would be deeper into the ozone layer. And perhaps the injection altitude would be there once we understand things better.

Regards
Dave

> On Jan 30, 2021, at 9:29 AM, Keith, David <(b) (6)> wrote:
>
> Dave
>
> Interesting back-and-forth.
>
> I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.
>
> I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30 kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.
>
> I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.
>
> I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.
>
> Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.
>
> Interesting conversation. No simple answers.
>
> Cheers,
> David
>
> ---
>
> **From:** David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
> **Sent:** Thursday, January 28, 2021 11:49 AM
> **To:** Smith, Wake (b) (6) >

Cc: Keith, David <(b) (6) [redacted]>; Keutsch, Frank N (b) (6) [redacted]
Subject: Re: Experimental research platform requirements

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi-flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" <(b) (6) [redacted]>
Cc: Frank Keutsch (b) (6) [redacted]

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can't control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake <(b) (6) [redacted]> wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6) [redacted]

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Keith, David
Cc: Smith, Wake; Frank Keutsch
Sent: January 30, 2021 6:38 PM (UTC-05:00)
Attached: Untitled attachment

David,

Yes, I think if one has funding, then existing a/c become available. Certainly for the UT/LS, the WB-57s have been underutilized for years now and hence availability hasn't been an issue. Indeed a trip back to the boneyard was perhaps a growing threat.

I note that no one has ever built an aircraft for atmospheric chemistry, leaving the field to exploit as best they can existing a/c, which we have done very well. Thus, if there were runway a/c available that could do 30kg, 8hr, 79kft, the community would no doubt rush to use it. So the answer to your question is yes.

My problem with new-platforms-will-be-cheap is the issue of having truly operational a/c rather than experimental a/c. If one is trying to fly an experiment on an experimental a/c it reduces the probability of success by a large measure. Making an experimental a/c operational requires larger upfront and sustained investment by entities other than the science communities, creating the underwater part of the iceberg. This is why we don't have new operational a/c. And one can look to the Global Hawk and see that even starting at a high level (a mature platform) it failed to become operational because no one wants to pay the price, in this case neither NASA or NOAA. Now deeper pockets (DoD) have taken it over.

And to your final point about what payloads, yes, the new generation of lightweight instruments make 30kg interesting and valuable, and, yes, comprehensive chemistry payloads still want to be on heavy lift long-range a/c.

In reply to Wake's question about perturbation/monitoring a/c, hmmm, it depends. In the early days, perhaps they could be the same. Eventually the perturbations sought would be as large as possible per flight and not every flight would need diagnostics, so I think eventually they are different a/c. And monitoring a/c could be below the perturbation a/c altitudes and diagnose with lidar.

Interest above 70kft: in general because we would be deeper into the ozone layer. And perhaps the injection altitude would be there once we understand things better.

Regards
Dave

> On Jan 30, 2021, at 9:29 AM, Keith, David (b) (6) [redacted]> wrote:
>
> Dave
>
> Interesting back-and-forth.
>
> I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.
>
> I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30

kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.

I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.

I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.

Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.

Interesting conversation. No simple answers.

Cheers,
David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Thursday, January 28, 2021 11:49 AM
To: Smith, Wake (b) (6) [redacted] >
Cc: Keith, David <(b) (6) [redacted] >; Keutsch, Frank N (b) (6) [redacted]
Subject: Re: Experimental research platform requirements

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi-flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" (b) (6) >
Cc: Frank Keutsch <(b) (6)

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can't control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake (b) (6) > wrote:

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understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6)

From: Alan Robock ☮ (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin;(b) (6) ;(b) (6) ; Karen Rosenlof - NOAA Federal; Katharine Ricke; (b) (6) Robert Wood; (b) (6) ; (b) (6) Daniele Visioni; Isla Simpson; Peter Irvine; Jonathan Proctor; (b) (6) ; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N
Cc: Trude Storelvmo; 'Simone Tilmes'; (b) (6)
Sent: July 15, 2021 5:37 PM (UTC-04:00)

Dear Doug and Trude,

I would like to give a talk. Thanks.

Alan

On 7/15/2021 11:06 AM, Douglas MacMartin wrote:

> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
>
> As a start to our planning, could you let us know whether you would be interested in talking at the 2022 meeting? We would of course still love to hear from you, but schedules may not permit and research interests change (and, indeed, for some or many of you that may mean that the topic we were originally thinking you would talk about would no longer be what you are currently most excited by – the GRC is supposed to be cutting-edge current research, of course – so if you let us know we can start revising sessions and think about what gaps we'd like to fill). There are also some new people who are doing some great research too that we would like to hear from, so it's conceivable that – given the now 5 year gap since the last GRC – we might choose to slightly increase the number of talks and reduce the time available per talk.
>
> Thanks,
> Doug & Trude
>
> ---
>
> **From:** Douglas MacMartin
> **Sent:** Wednesday, February 19, 2020 10:27 AM
> **To:**(b) (6) ;(b) (6) ; Alan Robock (b) (6) ; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke(b) (6) ;(b) (6) ; Robert Wood(b) (6) (b) (6) ;(b) (6) (b) (6) ; Daniele Visioni (b) (6) ;(b) (6) ; Peter Irvine(b) (6) ; Jonathan Proctor (b) (6) ;(b) (6) Keith, David(b) (6) Kravitz, Ben (b) (6) Wake Smith(b) (6) ; Izidine Pinto(b) (6) Gabriel Chiodo(b) (6) ; Keutsch, Frank N(b) (6) >
> **Cc:** Lawrence, Mark(b) (6) ; valentina Aquila(b) (6) >; Ulrike Niemeier(b) (6) >; Leisner, Thomas (IMK)(b) (6) Olivier Boucher(b) (6) Schrag, Daniel P.(b) (6) TAYLOR,Michael (b) (6) (b) (6) Trude Storelvmo(b) (6) ;

'Simone Tilmes' (b) (6) ; (b) (6) Jim Hurrell
(b) (6)
Subject: RE: 2020 GRC program

Hi all,

Just a reminder that if you haven't sent me a title yet, to do so (otherwise I'll have to make something up; GRC needs us to upload our "final" program by the end of this month) I have titles for about half of you (though some of those are draft titles you sent quite some time ago, e.g. for Pete, Isla, Danny).

And, if you haven't responded yet regarding need for travel support, let me know (about half of you have). For those of you who haven't been to a GRC before, there's a bus from Boston airport, and from Portland Maine airport.

If you've already both sent me a title and responded regarding travel, then you can ignore this email.

Also, regarding format, this year we're explicitly including 10-15 minutes for the discussion leader to make some remarks to help frame each session (taking 5 minutes from each speaker's time), and rather than having a lengthy discussion after each talk, we'll have a shorter 10-minute discussion after each talk and a 20-minute general session discussion at the end (that's as long as GRC will allow) with everyone from a given session.

Thanks, and see you in June!
doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) ; (b) (6) 'Jadwiga (Yaga) Richter'
(b) (6) >; Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal
<karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >; (b) (6) ; Robert
Wood (b) (6) >; (b) (6) ; (b) (6)
(b) (6) >; Daniele Visioni (b) (6) >; (b) (6) ; Peter Irvine
(b) (6) ; Jonathan Proctor (b) (6) ; Govindasamy Bala
(b) (6) >; (b) (6) Keith, David <(b) (6) ; Kravitz, Ben
(b) (6) ; Wake Smith <(b) (6) >; Chris Field (b) (6)
Cc: Lawrence, Mark (b) (6) >; valentina Aquila (b) (6) >; Ulrike
Niemeier (b) (6) ; Leisner, Thomas (IMK) (b) (6) ; Olivier
Boucher (b) (6) ; Schrag, Daniel P. (b) (6) ; TAYLOR,Michael
(b) (6) >; (b) (6) ; Lynn Russell (b) (6) >; Trude Storelvmo
(b) (6) >; 'Simone Tilmes' (b) (6) >; (b) (6)
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The cc-line has discussion leaders for each session.

Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin
Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and
Faculty Fellow, Atkinson Center for a Sustainable Future
Cornell University
(b) (6) [redacted]
https://climate-engineering.mae.cornell.edu/

From: Peter Irvine (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin
Cc: Piers Forster; (b) (6) Alan Robock; Karen Rosenlof - NOAA Federal; Katharine Ricke; Seneviratne Sonia Isabelle; Robert Wood; Helene Muri; (b) (6) Daniele Visioni; Isla Simpson; Jonathan Proctor; Ines Camilloni; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N; Trude Storelvmo; Simone Tilmes; Lohmann Ulrike
Sent: July 18, 2021 4:53 PM (UTC-04:00)

Hi Doug, Trude,

It's be happy to present in 2022, with the same title for now.

Cheers,

Pete

On Thu, Jul 15, 2021, 16:06 Douglas MacMartin (b) (6) > wrote:

> Hi all,
>
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<(b) (6) >; Keutsch, Frank N (b) (6)
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<(b) (6) >;(b) (6) Trude Storelvmo (b) (6) >; 'Simone
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From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) ;(b) (6) ; 'Jadwiga (Yaga) Richter' <(b) (6) >;
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<(b) (6) >

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doug

Douglas MacMartin

Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and

Faculty Fellow, Atkinson Center for a Sustainable Future

Cornell University

(b) (6)

[redacted]

https://climate-engineering.mae.cornell.edu/

From: Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Andrea Smith
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Graham Feingold - NOAA Federal; Brian Medeiros
Sent: September 17, 2021 4:44 PM (UTC-04:00)
Attached: Untitled attachment

And logging in 10 minutes early, so we can make sure everything is working would be most helpful.
So at 8:50 AM Mountain, 10:50AM Eastern next Wednesday.

Thanks!

Karen

Karen Rosenlof
NOAA Chemical Sciences Laboratory
Mail Stop R/CSL8
325 Broadway
Boulder, CO 80305
office: 3A-121, DSRC
e-mail: Karen.H.Rosenlof@noaa.gov
phone: 303 497-7761
fax: 303 497-5373
----
while safer at home remains in effect, email is the most reliable contact

> On Sep 17, 2021, at 11:06 AM, Andrea Smith (b) (6) > wrote:
>
> Hello Frank, Wake and Graham,
>
> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>
> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
> Meeting ID: 816 4261 9898
> Passcode: 148321
>
> Please join 10 mins early to test tech and troubleshoot if needed.
>
> 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) (preferably by Tuesday night):
>
> 3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.

After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.

Let me know if you have questions on any of the above.

Thanks again, and see you next Wednesday.

Andrea

On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) wrote:

> Hi Frank, Wake and Graham,
> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>
> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?
>
> 1. Frank Keutsch: ...
> 2. Wake Smith:...
> 3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening
>
> Here is Andreas rundown for logistics:
>
> -please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
> -send slide decks to Andrea by Tuesday (9/21) evening for backup purposes
> -arrive ~10 mins early so we can do quick test of screenshares
> -15 min talk length, w/ immediate clarifying question(s) and then ~30 mins broad discussion and questions at end
> -moderator will collect questions in chat window throughout and ask most pertinent ones for discussion
> -panelists and question askers encouraged to unmute & turn on camera
> -session will be recorded and posted later - we'll send a release form for them to complete
>
> Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,
>
> Cheers, Simone
>
> --
> *Simone Tilmes,*
> *Atmospheric Chemistry, Observations & Modeling Lab*
> *National Center for Atmospheric Research*
> *PO Box 3000*
> *Boulder, Colorado 80307-3000*
> *303-497-1445*
> *303-497-1400 (fax)*
> (b) (6)

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.

Boulder, CO 80301
303-497-8320 (office)
(b) (6)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.
<CCISspeaker_consent_form.pdf>

The Stratospheric Controlled Perturbation Experiment (SCoPEx)

Version 1.0

Executive Summary

Climate model studies of stratospheric solar radiation modification (SRM) depend, perhaps implicitly, on processes that take place in the near field of an injection plume. This is because materials delivered to the stratosphere by aircraft will form persistent, high aspect-ratio plumes with strong gradients before becoming well mixed, and processes within the plume will alter the large-scale, well-mixed aerosol and chemical properties that are simulated in global atmospheric models. All models ultimately depend on observations, yet we lack experimental data to assess some of the critical transport, microphysical, and chemical processes that directly control aerosol dynamics in the near-field that are important for understanding stratospheric SRM.

The scientific goal of the Stratospheric Controlled Perturbation Experiment (SCoPEx) is to improve process models that will, in turn, reduce uncertainties in global-scale models, thus reducing uncertainty in predictions of important SRM risks and benefits.

SCoPEx addresses questions in stratospheric aerosol injection (SAI) research that observations of existing analogues are incapable of addressing. For example, existing observational data do not include chemistry of alternate geoengineering materials specific to SAI, near-field particle microphysics of injection plumes, and relevant scales of atmospheric transport in the near-field. Yet these are needed to assess processes that control aerosol dynamics in the near field of an injection plume and that allow for the evaluation of alternate SAI materials, i.e., materials other than the naturally existing sulfate aerosol.

We first review why existing observations do not address the questions that SCoPEx will answer. We then give a description of the basic design of the platform and the concept of operations of SCoPEx. Finally, we describe the three specific science goals of SCoPEx, explain how they represent critical knowledge gaps in SAI research, and specify what measurements are needed to enable SCoPEx to provide quantitative answers to these questions. The three specific science goals are improving understanding of (i) turbulent mixing scales, (ii) aerosol microphysics with a focus on alternative SAI materials in the near-field of an injection, and (iii) process level chemical interactions of alternative SAI materials in the stratosphere.

We do not provide a detailed engineering document of the SCoPEx platform or its scientific instrumentation, nor do we provide a justification for the need for research on SRM via SAI in general. Rather, we focus specifically on the merits of SCoPEx itself.

1. Introduction

In this document we focus on the motivation and scientific merit of SCoPEx. We do not provide detailed engineering documentation of the SCoPEx platform or its scientific instrumentation. We also do not provide general justification for the need for research on solar radiation modification (SRM) via stratospheric aerosol injection (SAI), which can be found in many prior documents such as the 1992 NAS report that recommended the US government "Undertake research and development projects to improve our understanding of both the potential of geoengineering options to offset global warming and their possible side effects. This is not a recommendation that geoengineering options be undertaken at this time, but rather that we learn more about their likely advantages and disadvantages" (National Academy of Sciences et al., 1992) or the recent 2015 NAS report (National Research Council, 2015). Rather, we focus specifically on the need for small-scale field experiments such as SCoPEx, and the specific, critical SAI research needs that will be addressed by SCoPEx.

1.1. Role of and Need for Small-Scale Field Experiments

There is a vast array of science and engineering questions that have to be answered to achieve a better understanding of the risks, benefits and feasibility of SAI. The tools and topics that are needed to address these questions range from General Circulation Models (GCMs) all the way to detailed design of instrumentation to monitor or disperse aerosol. SCoPEx addresses a subset of questions that require small-scale field experiments for ground-truthing and that are aimed at improving the ability of models to predict the consequences of SAI.

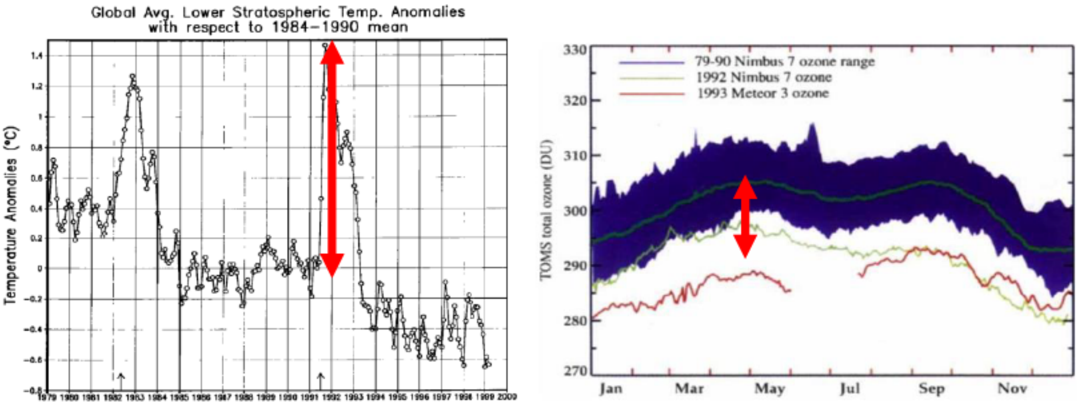

Figure 1: The two most important first-order stratospheric risks from sulfate SAI. The left panel shows stratospheric temperature anomalies from the El Chichon and Mount Pinatubo eruptions on top of background temperatures that are decreasing due to greenhouse gas emissions (Robock, 2000). The dynamical response of the stratosphere from such a short heating pulse likely is different than from sustained heating from longer-term SAI. The right panel shows that in the two years following the Mount Pinatubo reaction total ozone columns were lower than in the 1979-90 average as a result of increase sulfate aerosol surface area. Smaller eruptions also contributed to this. (McCormick et al., 1995)

There are numerous known risks associated with SAI, and SCoPEx focuses primarily on improving understanding of the first-order impacts in the stratosphere, i.e., risks and risk reduction associated with impacts of SAI within the stratosphere. There are many downstream / higher-order risks, e.g., impact on cloud formation as SAI particles leave the stratosphere (Cziczo et al., 2019), impacts on ecosystems via changes in the hydrological cycle (Bala et al., 2008; Russell et al., 2012; Tilmes et al., 2013), or the amount of direct

versus diffuse radiation (Gu et al., 2002; Farquhar & Roderick, 2003; Gu et al., 2003). Despite their importance, these impacts are not the direct target of this proposal although many of these are also influenced by stratospheric processes and properties of SAI aerosol. Two first-order risks are at the focus of this work: stratospheric ozone loss and the dynamic response resulting from stratospheric heating as a result of SAI.

Whereas stratospheric ozone chemistry is fairly well understood (World Meteorological Organization, 2019), there are still substantial uncertainties in the understanding and ability to model stratospheric dynamics (Figure 1). For example, models have only recently been able to reproduce the quasi-biennial oscillation without having it imposed (see Butchart et al., 2018 for a discussion of challenges). One approach taken in this work is to evaluate whether there are types of aerosols or methods of aerosol injection that can reduce first-order risks for a given amount of radiative forcing. It stands to reason that a reduction in the first-order stratospheric impacts will reduce downstream and higher-order risks. A case in point is the growing body of work that has been investigating the impacts of stratospheric heating on stratospheric water vapor and the dynamic response on regional climate (Simpson et al., 2019; Ferraro et al., 2015; Richter et al., 2018; Ji et al., 2018). It is important to note that the amount of stratospheric heating for a given material will be primarily driven by the total mass of aerosol, ozone destruction will be driven by the total surface area of aerosol, and the desired radiative forcing will be determined by the amount and size distribution of aerosol. Critically, both the aerosol mass required for a given desired radiative forcing *and* the resulting surface area are tied to this size distribution. Therefore, accurate models of the evolution of the size distribution of injected aerosol are critically needed. In addition, alternate materials with reduced stratospheric heating have to be investigated, as do injection methods for sulfate that minimize stratospheric heating and ozone loss for a given radiative forcing, as this will reduce risks associated with the dynamic response to this first-order perturbation.

2. Observational SAI Research Needs

Most of the rapidly growing body of literature on SAI rests on General Circulation Models (GCMs). We acknowledge the importance of GCM studies, but in the following we focus on research needs that require experiments and observations, and especially questions that can only be answered by conducting perturbative field experiments such as SCoPEx (see supplemental manuscripts Keith et al., 2020 and Floerchinger et al., 2020). In fact, SCoPEx will in the end inform GCMs by providing improved process level information that will be integrated in parameterizations used in GCMs. Below we review existing observational data sets and describe their utility for different SAI approaches, highlighting where they are unable to shed light on critical issues thus motivating studies like SCoPEx.

2.1. Field Experimental Needs for Sulfate SAI

Most studies that have sought to research SAI have assumed the addition of aerosol would take place by means of an injection of gas-phase SO_2, which is ultimately converted to H_2SO_4 and then to sulfate aerosol in the stratosphere on a timescale of approximately one month. The aerosol size distribution from this injection of gas phase precursor must be accurately predicted as it will control the shortwave (SW) scattering properties, the stratospheric lifetime of the aerosol, and ultimately be the driver for the radiative forcing (RF) efficiency per mass of injected sulfate. Some studies, such as Niemeier & Timmreck (2015), have suggested that with higher injection rates of SO_2, the resulting sulfate aerosol would be forced into a larger, coarse-mode size distribution and functionally reach a point of diminishing return. In this diminishing return scenario, the added amount of SW RF achieved per added mass of sulfate decreases exponentially.

Recent work by Pierce et al. (2010), Benduhn et al. (2016), and Vattioni et al. (2019) has highlighted the potential benefits of injecting H_2SO_4 aerosol directly into the accumulation mode (AM), i.e., aerosols with a radius of 0.1–1.0 µm, potentially by emitting H_2SO_4 vapor into an aircraft plume. This work has suggested better control of the resulting aerosol size distribution and thus the radiative forcing per unit mass sulfur injection, which would allow for the design of a system that maximizes the radiative forcing per mass of sulfate in a way that would not have the diminishing returns at high SO_2 injection rates. This would thus minimize the increase in the stratospheric sulfate burden and hence the risk of stratospheric heating which is driven by total mass whereas ozone loss is driven by surface area. While injecting AM–H_2SO_4 may represent the best possible approach for SAI with stratospheric sulfate, there is currently no proven way to introduce vapor phase AM–H_2SO_4 into the stratosphere. As AM–H_2SO_4 has not been studied, perturbative experiments are required to provide observational constraints on the aerosol size distributions predicted by models.

2.2. Field Experimental Needs for Alternate Aerosol Material SAI

Though sulfate aerosol does exist in the background stratosphere and there are some natural analogs of broad stratospheric sulfate injections (volcanic eruptions), it likely is not the optimal candidate for SAI. Alternative aerosol may be most appropriate in order to mitigate SAI risks (Teller et al., 1996; Crutzen, 2006; Ferraro et al., 2011; Ferraro et al., 2015; Weisenstein et al., 2015; Keith et al., 2016; Dykema et al., 2016; Weisenstein et al., 2015). These alternate aerosols could reduce the previously noted two major first-order stratospheric impacts, i.e., changes in ozone and stratospheric heating. Due to the uncertainties in the impacts of stratospheric heating, the study of materials with optical

properties that negate stratospheric heating is especially important. Materials such as calcium carbonate ($CaCO_3$), alumina (Al_2O_3), diamond (carbon), and several others, have been proposed as a way to minimize the inherent risks from SAI (Keith et al., 2016; Dykema et al., 2016; Weisenstein et al., 2015; Ferraro et al., 2015; Ferraro et al., 2011; Crutzen, 2006). Although model results of these aerosol species suggest that some of them possess optical properties that make them well suited to be used in a SRM scenario ($CaCO_3$, Al_2O_3, and diamond) (Dykema et al., 2016; Ferraro et al., 2011), the stratospheric aerosol microphysics of these compounds (especially coagulation) is poorly understood. As with AM–H_2SO_4 injections, there is a profound lack of in situ data to assess the ability to model the microphysics of alternative aerosols and the stratospheric chemistry of these materials. This is especially pertinent with respect to changes in ozone, and is exacerbated by the fact that these aerosols have no naturally existing analog in the stratosphere that could be studied. Because early studies suggest that these aerosols show much promise with respect to deploying SAI while mitigating the inherent risks of the deployment, it is imperative to design and execute in situ experiments in order to test our current understanding of the aerosol microphysics and observe the effects of alternative aerosol on the chemical composition and dynamics of the stratosphere.

2.3. Limitations in Existing Analogues

In this section we will review previous in situ studies of stratospheric plume processes, show how those datasets have contributed to our current understanding, and demonstrate the need for experiments such as SCoPEx to inform small-scale models of aerosol microphysics (nucleation and coagulation), plume transport and physical morphology, and chemical properties of new aerosol species that have thus far not been observed in the stratosphere. Because the nature of the injection scenarios (AM–H_2SO_4 or solid aerosols) are so complex compared to natural analogs, new experiments must be designed and implemented to provide observational constraints on our current nearfield modeling framework. Experimental data from carefully targeted small-scale studies would contribute to the development of nearfield-scale models that represent currently uncertain processes in detail.

We note that sub-grid scale processes do not represent the only unknowns in GCMs that are relevant to high-fidelity simulations of SRM scenarios, and that there are many large scale model phenomena which should be further assessed with observational evidence. However, here we focus on the need for in situ data to constrain sub-grid scale processes that can be addressed by SCoPEx and highlight the need for reducing the uncertainty in transport and aerosol dynamics and chemistry at this scale.

2.3.1. Limitations of Solid Rocket Motor Plume Observations

From 1996 to 2000 a number of rocket plumes were observed by high-altitude research aircraft. Generally, these missions involved a research team coordinating stratospheric sampling flights on either the NASA ER-2 or on the NASA WB-57 with coincident rocket launch events from either Cape Canaveral or Vandenberg Airforce Base. These studies sampled plumes from a host of rocket types including Titan IV, Space Shuttle (STS106, STS83, STS85), Delta II, Athena II, and Atlas IIAS.

Plumes were intercepted by the sampling aircraft between 5 and 125 minutes after emission from the rocket motor at stratospheric altitudes ranging from 11 to 19.8km (Voigt et al., 2013). The main science objective of these missions was to assess the stratospheric

ozone depletion potential of space exploration by understanding the halogen chemistry occurring as a result of the high-altitude rocket burn. However, in studying the effects on the ozone layer, this era of stratospheric sampling provided a unique set of plume measurements to study nearfield processes of chemical injections into the stratosphere.

While measuring the plumes from the Titan IV rocket (as a part of the United States Airforce Rocket Impacts on Stratospheric Ozone (RISO) Campaign) and attempting to develop a plume chemistry model to solve for the Cl_2 concentration in a rocket plume as it evolves shortly after its emission, Ross et al. (1997) noted the many assumptions that had to be made about the plume morphology in order to simulate the mixing and diffusion that the rocket plume had with the surrounding stratosphere. Their model solved for the Cl_2 concentration of a circular nighttime plume as it expanded in diameter along an isentropic surface. Subsequent aircraft measurements showed that plumes contained more than twice the predicted concentration of Cl_2 despite the plume being intercepted during the day time (when the Cl_2 reservoir should be somewhat depleted by the photolysis reaction $Cl_2 + h\nu \rightarrow 2Cl$), suggesting that there may be an error in the assumption of a circular plume morphology on the short transport time scales observed in this study ($\sim 28min$).

Ross went on to publish a second study as a part of the RISO project in 1999, this time looking to quantify the size distribution of alumina aerosols emitted from the rocket engines which contained particulate alumina (Al_2O_3) (Ross et al.,1999). They compared measured aerosol size distributions from the WB-57F plume interceptions to results from an aerosol coagulation model and highlighted a massive discrepancy. The model predicted a much smaller aerosol size distribution with 1-10% of the aerosol mass being in the smallest (0.005µm) mode and the aircraft observed only fractions (<0.05%) of the model estimate in that same small mode. At the same time, over 99% of the aerosol mass sampled by the aircraft was found in the coarsest mode (2 µm), which the model was unable to predict. It is most likely that the model used in Ross et al. (1999) did not well account for the effects of ion mediated nucleation as described by Yu & Turco (1997). However, the data from Ross et al. (1999) was some of the first in situ data to highlight the uncertainty in stratospheric aerosol coagulation models. Alumina aerosol, as well as other solid aerosols, in contrast to liquid sulfate aerosol, have since been investigated as a candidate for use in SAI (Weisenstein et al., 2015). Therefore, it is imperative that we understand the chemical, coagulation, and accumulation properties of these and other solid aerosols in a stratospheric environment.

2.3.2. Limitations of Previous Stratospheric Aircraft Wake Crossing Observations

We can look to the few times high-altitude aircraft wake plumes have been sampled in situ for another example of stratospheric plume measurements. In the early 1990s the popularity and capability of the Concorde spurred discussions of a large fleet of High Speed Civil Transport (HSCT) aircraft that would operate in the lower stratosphere between 16 and 23 km. Scientists became concerned with the effects of high-altitude aircraft and high-altitude supersonic aircraft on stratospheric ozone destruction via the creation of a large NOx source in the lower stratosphere. NASA then launched several field campaigns using the ER-2 to study the exhaust profiles of high-altitude aircraft. In 1992 NASA commissioned the Stratospheric Photochemistry Aerosols and Dynamics Expedition (SPADE) to look at the effects of HSCTs. As a part of SPADE the ER2 sampled its own plume on several occasions by making a hairpin turn and heading into its original path, therefore measuring its own wake

(Figure 2). SPADE resulted in at least 11 published studies and some of these can inform us about the mixing and aerosol dynamics that may be relevant to an SAI scenario (Stolarski & Wesoky, 1993).

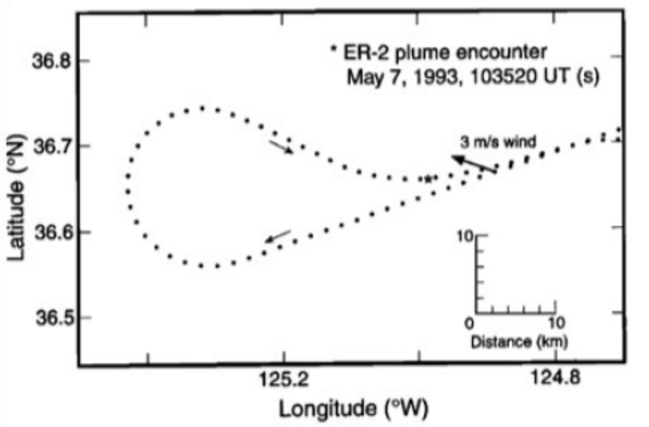

Figure 2: Shows the ER-2 flight track on a typical wake crossing trajectory (adapted from Fahey et al. 1995).

Fahey et al. (1995a) described measurements made of condensation nuclei (CN) present in the ER-2's exhaust plume from the emission of aerosol carbon and of sulfur compounds during one of its SPADE wake crossing events. Because the main focus of this study was to quantify the emission indices (EIs) of various compounds measured by the ER-2 that may have ozone depletion implications, they focused mainly on gas phase compounds. However, for the three wake crossings that the study focused on, they observed large variability in their EI measurements for CN. They noted that this is likely due to differences in mixing history of the encountered air parcels and noted that a full explanation of CN coagulation required more in-depth study and further measurements (Fahey et al, 1995b).

In another study published by Fahey et al. (1995b), they used a similar wake crossing technique to measure the exhaust of the Concorde aircraft and developed an aerosol coagulation model to predict particle formation and size as a function of the time since emission from the aircraft. The coagulation model was initialized at the observed conditions from the one-hour old Concord transect. The results from this model estimated that from 0 to 10 hr since emission from the engine, the mean particle diameter remained fairly constant at 0.06 µm before growing exponentially to a factor of 3 times its initial value over the next 1,000hr. The model predicted exponential mean particle diameter growth continuing right until the of the simulation at 1,000 hr (Fahey et al., 1995a).

Yu & Turco (1997) attempted to model the observed aerosol plume during the Concorde wake crossings with the goal of determining the driving factor for the large aerosol size distributions observed by the ER-2 in the exhaust which had not yet been explained by models. Yu proposed that aerosol formation was being aided by ion-mediated nucleation (IMN), that is, charged particles formed by chemi-ionization processes within the aircraft engines provide charged centers (H_2SO_4 [S(VI)]) around which molecular clusters rapidly coalesce. "The resulting charged micro-particles exhibit enhanced growth due to condensation and coagulation aided by electrostatic effects" (Yu & Turco, 1997). It is likely that IMN is the reason previous particle coagulation modeling of solid rocket motor plumes had overestimated the amount of aerosol in the small size ranges when compared to the in situ data, though this has not since been tested. Because of these effects, and the fact that specific size distributions of aerosol are desired to obtain the optimal radiative

forcing effects for SAI (nominally smaller than observed in rocket or aircraft plumes), we must understand the aerosol nucleation and coagulation dynamics in an unperturbed stratosphere.

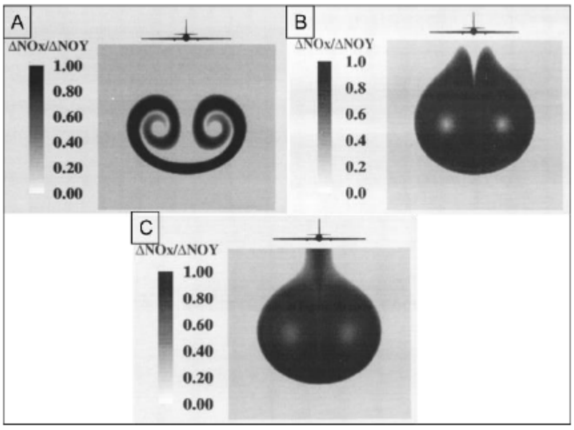

Figure 3: Shows the chemical and morphological evolution of an ER-2 plume during SPADE at 1.7 km (A), 4.8 km (B), and 7.9 km (C). (adapted from Anderson et al. (1996))

As a part of the SPADE project, Anderson et al. (1996) computed the flow field and chemical kinetics of the ER-2 aircraft exhaust using the Aerodyne Research Inc. UNIWAKE model. Their calculations address the effects of complex plume morphology on in-plume chemistry as a function of dilution time since emission from the aircraft engine. They showed that the plume morphology is highly variable out to about 5 km post emission Figure 3 and estimated that the stability of the wing vortex pair begins to break up at roughly 20 km post emission. Although this study was completed in the mid 1990s, it is still one of the only studies that attempts to compute nearfield chemistry within a dynamic stratospheric plume. However, particles were not considered as part of this study.

2.3.3. Limitations of Stratospheric Wake Crossings

Previous stratospheric plume studies of solid rocket motors and aircraft wake crossings have laid the foundation for our understanding of stratospheric plume chemical, aerosol, and mixing dynamics on transport scales of 0→100 km. These studies highlight the types of processes we must be aware of when considering the logistics of SAI. However, the violent initial conditions of engine exhaust plumes (such as temperatures of 700K, IMN) make it difficult to relate these observations to other systems. Because the engines drive the mixing and transport in the nearfield, and the ionic injection conditions of the plume create electrostatic forces that introduce complex nucleation affinities (IMN), understanding individual parameters can become analogous to finding a needle in a haystack. Moreover, because the radiative properties of any stratospheric aerosol that may be used for SRM depend on the diameter of the particle, we must understand the coagulation of that aerosol in the nearfield after the injection, which means that we must also understand the plume morphology that dictates the concentrations of that aerosol. Currently there have been no in situ data gathered that help us understand nearfield aerosol nucleation and plume dynamics in the absence of a very disruptive source. These conditions are necessary to understand as SAI may require that we mitigate the effect of IMN in order to obtain an aerosol size distribution that is small enough to provide the desired radiative properties.

2.3.4. Limitations of Naturally Occurring Analogs

Another source of useful in situ data on plume dynamics in the stratosphere can be found in literature addressing the fate and transport of convective overshooting events that often occur at the top of a Mesoscale Convective Complex (MCC). These events drive brief airmass exchange with the troposphere and often end up resulting in a plume-like parcel of tropospheric air being injected into the stratosphere.

Measurements of convective systems and upper troposphere-lower stratosphere exchange, as a means to interrogate stratospheric plume transport, have provided valuable in situ datasets that help us understand mid-field (10 to >1000 km) plume dynamics in the lower stratosphere. Similar to convective overshooting events, volcanic eruptions have provided an immense amount of in situ data that has informed us about regional and even global transport of stratospheric injections (Robock, 2000). Although their data are applicable in some sense to the transport of an SAI plume after its initial injection, the turbulent nature of a convective storm makes it difficult to measure these events at points near their injection source. Additionally, the storm conditions themselves dramatically complicate the system in the lower stratosphere such that is difficult to see through the effects of the induced turbulence in the nearfield. Indeed, an important limitation of these type of natural analogs is the spatial extent of their perturbation, which does not allow for near-field observations analogous to that of a point source. This also arises from the violent nature of these events which does not allow airborne platforms, such as the ER-2, to sample the initial conditions of the injection. We also note that volcanic eruptions are limited in their utility to evaluate dynamic response to stratospheric heating from sulfate aerosol, as they represent a perturbative pulse rather than the long-term heating one would expect from SAI.

In addition, these natural analogues provide extremely limited ability to study alternate materials, although organic and mineral dust aerosol injections into the lowermost stratosphere have been documented from convective overshoots. However, the complexity of the massive perturbations of both gas- and particle-phase preclude a study focusing on the impact on stratospheric composition and aerosol evolution that would result from SAI of a single material.

3. SCoPEx Short Overview

This section provides a brief overview of the engineering and operational aspects of SCoPEx. We first describe the platform, the instruments, and the concept of operations before describing the rationale for the overall SCoPEx design choices.

3.1. SCoPEx Platform

The SCoPEx gondola (Figure 4) is a balloon-born new research platform being developed at Harvard by the engineering and science staff within the Anderson/Keith/Keutsch laboratory group. The development builds on four decades of stratospheric research on aircraft, balloon, and rocket platforms that has focused on understanding the environmental chemistry of the ozone layer. The SCoPEx experiment was first described by Dykema et al. (2014). While many details of the design have changed, that paper still succinctly describes the advantages of choosing a balloon born platform over an aircraft, particularly for studying perturbations like solar geoengineering, and several of the limits of laboratory experiments that that could be addressed in a perturbative experiment like SCoPEx.

The gondola has three primary features: the frame, the ascender, and the propellers. The aluminum and carbon fiber frame contains two decks and a ballast hopper for coarse altitude control. One deck is primarily dedicated to platform support (power and flight control) and one deck is primarily dedicated to instruments. At the top of the gondola is an ascender and rope which allows the distance between the bottom of the balloon train and the gondola to vary from 0 to 150 m, which provides fine altitude control of the gondola. The ascender has been developed and tested by Atlas (Chelmsford, MA) building on their previous hardware in collaboration with the Harvard engineering team. The propellers serve two purposes: to create a well-mixed volume of air where observations of the aerosols and perturbed gas-phase can be made, and to reposition the gondola within the evolving aerosol plume. While the trajectory of the balloon and gondola system will be dictated by the balloon, the propellers allow for repositioning relative to the prevailing winds.

The ascender makes it impossible to have cables and other physical connections between the flight operations equipment and the gondola. Thus, the platform will handle its own communications and power. The SCoPEx platform will be powered using 28 V and 100 V DC power supplies which will power all operations on the platform including the propellers, ascender, and instruments. Elements of the flight platform are listed in Table 1. The gondola flight, flight safety, recovery parachute, and recovery operations will be managed by the balloon operator (in contrast to the SCoPEx team itself). Because the absolute velocity and distance capability of the gondola are so small compared to balloon drift, the trajectory will be determined by the balloon operator as if it was a passive nonpowered payload. During operations, the detailed float altitude will be jointly managed by the balloon operator via control of the balloon vents and the Harvard team via control of the ballast and ascender.

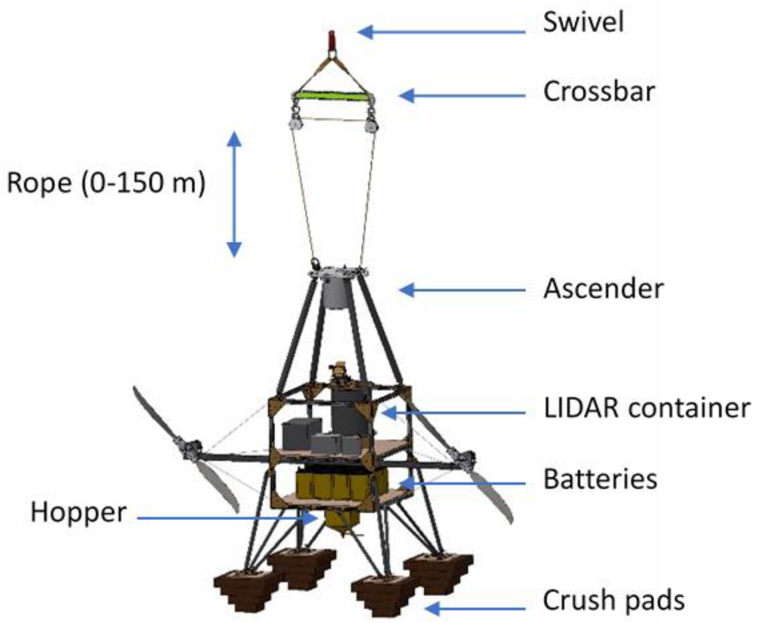

Figure 4: A representation of the SCoPEx flight platform. The final configuration may have subsystems packaged differently.

Parameter	Description
Total mass (Frame, all subsystems, hopper with ballast)	600 kg
Interface to balloon	Crosby 5-S-2 jaw & jaw swivel
Ascender	13 mm diameter rope Range of motion: 0-150 m Max speed: 10 m/min
Gondola propulsion	Twin propellers, 1.88 m diameter 32 N thrust each Max airspeed: 3 m/s
Power	28 V and 100 V DC power supplies with 24 MJ and 10 MJ total energy when fully charged
Communications	Satellite phone for communication between ground equipment and payload
Maximum termination shock	10 g

Table 1: Elements of the SCoPEx flight platform.

3.2. Instruments for First Science Flights (Science Goals 1 and 2)

The proposed instruments for the first science flight, addressing science Goals 1 and 2, are listed in Table 2. The corresponding science goals that motivate their inclusion are detailed in Section 4.

Measurement	Instruments	Rationale	Corresponding Science Goal
Wind speed measurement	Wind pendulum	Gondola and plume movement relative to balloon	Platform operation
Meteorology	Commercial off-the-shelf instrument	Temperature and pressure measurement throughout the flight	1, 2, 3
Wind turbulence	Constant temperature anemometer	Stratospheric mixing and modeling evolution of aerosol size distribution	1, 2
Particle dispersal	Solid Aerosolizer	Injects monodispersed particles for measurement and study	2, 3
Plume tracking	LIDAR	Tracking plume and navigation back into plume	2, 3
Particle sizer	POPS	Aerosol size distribution measurement for comparison with microphysics models of near-field evolution	2, 3
Light Scattering	Radiometer	Comparison of aerosol scattering with model prediction	2

Table 2: Instruments for first SCoPEx science flight.

Wind Pendulum: Understanding differential wind speed measurements between the balloon and payload will be important for plume evolution relative to the balloon trajectory and navigating the payload back into the plume. Commercial equipment to measure wind speed is typically not designed for the low densities found in the stratosphere. SCoPEx will therefore use a pendulum-based instrument and model to extract wind speed measurements. A camera will track a pendulum bob with high surface area and low mass, light enough to be perturbed by low winds in the stratosphere. Using the location and tilt data from the payload and a 3-dimentail kinetic model, the wind speed will be extracted from photos of the pendulum bob.

Commercial Meteorology Instrument: Commercial off-the-shelf instruments will be used for meteorological measurements on SCoPEx. They will record pressures and temperatures of the ambient stratosphere.

Constant Temperature Anemometer: A constant temperature anemometer (CTA) uses convective cooling caused by air flowing across a heated thin wire to measure flow velocity. LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere) (Gerding et al., 2009; Theuerkauf et al., 2010) used such a measurement to study stratospheric turbulence up to 29 km. LITOS consisted of a 5 μm diameter and 1.25 mm long tungsten wire CTA and a 16 bit ADC with 2000 samples per second to collect measurements with a vertical resolution of 2.5 mm at 5 m/s ascent speed. The anemometer data was analyzed by performing a spectral

analysis on the voltage signal to retrieve the spectral slope of the observed variation. A similar instrument will be used on SCoPEx to measure stratospheric turbulence. Air flow around the device will be simulated using CFD tools. The CFD runs will provide a means to identify key flow characteristics that drive sensor performance (sensitivity and accuracy), and to drive detailed sensor design.

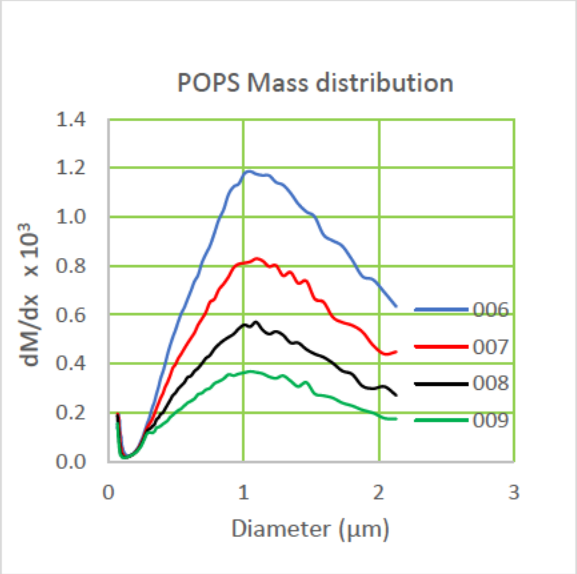

Figure 5: Successive measurements of sprayed $CaCO_3$ using an optical particle spectrometer. 006-009 indicate numbered time intervals spaced 4 minutes apart with 006 being the earliest measurement. $CaCO_3$ was sprayed using a 200 µm nozzle. In this laboratory experiment there was no significant variation in the shape of the distribution over time. (personal communication A Neukermans and team)

Solid Aerosolizer: The solid particle aerosolizer has been developed by a team lead by Armand Neukermans. For SCoPEx, the goal is to spray roughly monodisperse ~0.5 µm diameter precipitated calcium carbonate powder, the first candidate for solid SAI, through a 1-2 mm nozzle using the expansion of powder suspended in high pressure liquid CO_2. The aerosolizer would use a 1:4 weight ratio of $CaCO_3$ to CO_2. For 1 kg of $CaCO_3$ this would require a 5-7 L pressurized container. This concept has already been demonstrated in the lab. Figure 5 shows successive measurements of sprayed $CaCO_3$ with a size distribution centered at 1 µm diameter. Measurements were taken every 4 minutes using POPS (see below). In this case, total particle count decreased over time but there was no significant variation in the shape of the size distribution.

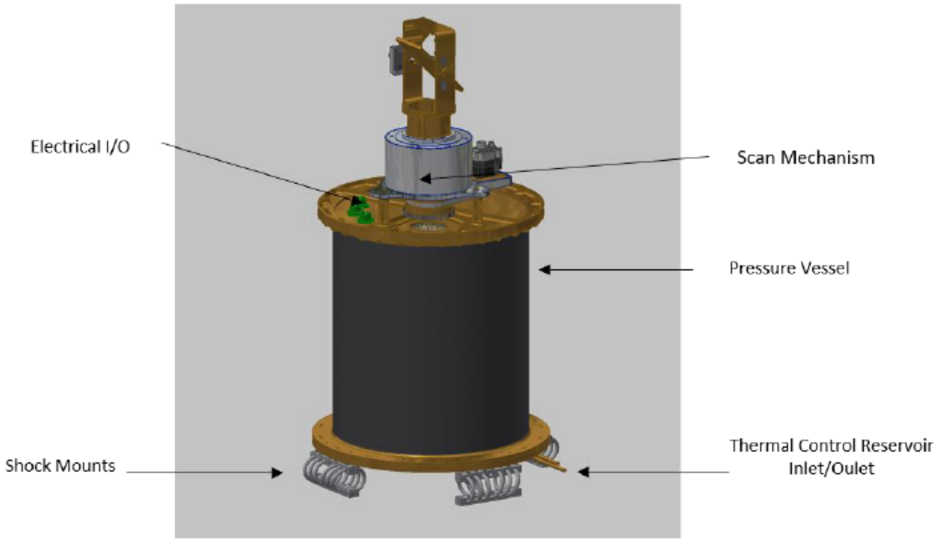

Figure 6: LIDAR pressure vessel provides safe storage and operating environment and support equipment.

LIDAR: The LIDAR is used to track the plume and allow navigation back into it. The core of the LIDAR system is an off-the-shelf eye-safe visible LIDAR, purchased from Sigma Space (now owned and operated by Droplet Measurement Technologies). This LIDAR produces 4 µJ pulses of 532 nm light at a repetition rate of 532 nm. The light that is backscattered by molecules and aerosols is collected by an 80 mm telescope and detected with a high-speed, high-sensitivity photodiode.

We have integrated this LIDAR in a pressure vessel (Figure 6) to provide a near-1 atm pressure environment with adequate temperature stability to ensure safe operation of the LIDAR at float altitude and safe storage on launch, ascent, descent, and recovery. This pressure vessel includes equipment for electrical and mechanical support, including command, data handling, and shock mounting. The LIDAR requires a scan capability to search the nearby atmosphere for the extent and geometry of the plume. The tilt and pan functions of the scan capability allows the LIDAR to be scanned over a set of angles that define the plausible location of the plume.

Portable Optical Particle Spectrometer (POPS): The POPS instrument will provide the aerosol size distribution measurements for studying aerosol formation and agglomeration. POPS is a light-weight instrument that directly samples the aerosol. It was built by and provided to SCoPEx through a collaboration with NOAA. The particles are illuminated with a 405 nm diode laser and the scattered light is collected onto a photomultiplier tube. The particle size is determined by the intensity of the scattered light. It has both the detection limit and size range (0.13 – 3 µm) to measure background stratospheric aerosol, which is more than sufficient for SCoPEx needs (Gao et al., 2016).

The Keutsch Group has already developed and extensively characterized a POPS instrument in preparation for the NASA-EVS3 Dynamics and Chemistry of the Summer Stratosphere field campaign on board the NASA-ER2, for which Keutsch is the deputy-PI. The POPS instrument tests include extensive thermal vacuum chamber characterizations to ensure operation under harsh stratospheric conditions. Compared to the ER-2, operation for SCoPEx will be simpler due to the insignificant air speed of the balloon and a much simpler operational pressure regime (on the ER-2 there is a large range of external pressures for both sampling and exhaust).

Radiometer: The aerosol plume can also be detected using a narrowband, narrow field of view radiometer with azimuthal/zenith pointing capability. The relationship between measurements of scattered solar radiation and the physical characteristics of atmospheric aerosols has been studied for more than two decades. Sky scanning measurements at multiple wavelengths between 300 nm and 1200 nm have been obtained using robotically pointed ground-based spectral radiometers deployed worldwide (Holben et al., 1998). The theory of these measurements has been refined and validated as a function of viewing geometry to provide a strong basis for inferring aerosol microphysics from radiometer data (Torres et al., 2014). The success of these approaches has motivated the development of compact sky scanning radiometers suitable for deployment on unsteady platforms like unmanned aerial vehicles (UAVs) and SCoPEx. One such design, reported by NOAA (Murphy et al., 2016), measures at 4 wavelengths (460 nm, 550 nm , 670 nm, and 860 nm) with a field of view of 0.006 sr (equivalent to 2.5° half-angle) and a circular limiting aperture of 1.1 mm diameter. A radiometer like this one deployed on SCoPEx would be capable of observing a SCoPEx plume, based on Golja et al. (2020), formed by a 0.1 g s^{-1} injection of calcite from a distance of 200 m with an approximate signal-to-noise ratio of 6000 for a 1 ms signal accumulation.

3.3. Instruments for Future Science Flights (Science Goal 3)

The additional instruments listed in Table 3 are candidates for future SCoPEx flights beyond the initial science flight, i.e., addressing science goal 3. They have not yet been adapted to fly on the SCoPEx platform. Instrument choices will be refined based on experiences in the first science flights. The corresponding science goals that motivate their inclusion are detailed in Section 4.

Measurement	**Candidate Instrument**	**Rationale**	**Corresponding science goal**
Aerosol composition	Drum Sampler	Collecting aerosols for offline analysis	3
Water Vapor	IR Absorption or Frost Point	H_2O outgassing of platform, Influence on coagulation and heterogenous chemistry	2, 3
Atmospheric trace gas concentrations (ex: HCl, NOx)	Spectroscopic trace gas instruments	For measuring concentrations of various atmospheric trace gases before and after addition of solid ASI material	3

Table 3: Potential instrument for future SCoPEx science flights.

Aerosol Composition: Aerosol composition can be analyzed via the collection of aerosol with a drum sampler followed by offline analysis in the laboratory using standard offline methods. Aerosol sampling has been done numerous times aboard stratospheric platforms.

Water Vapor: Gas-phase water vapor measurements are important as relative humidity likely has a large impact on the heterogeneous reactivity of solid SAI material. The balloon and gondola can outgas significant amounts of water and thus an initial experiment will characterize how long, if at all, this outgassing perturbs the SCoPEx plume. As mentioned previously, the goal of SCoPEx is to ideally minimize the perturbation to only the introduction of calcium carbonate. Water vapor measurements are common on many stratospheric platforms.

Hydrogen Chloride: HCl can be measured via infrared absorption spectroscopy. The Anderson group at Harvard, which shares a laboratory with the Keutsch group, has developed a stratospheric HCl instrument and thus has extensive experience with the design of stratospheric HCl instrumentation. In addition, the Keutsch group has designed multiple spectroscopic trace gas measurements. The much lower air speeds of the balloon compared to aircraft favor the design of an open path system, which eliminates the notorious wall effects that can make HCl measurements challenging.

NOx: For NOx there exist a number of good instrumentation options. Recently, a compact NO-LIF instrument has been designed that has spectacular detection limits in the low ppt range, more than sufficient for the needs of SCoPEx. The instrument is a close analogue of the fiber-laser based formaldehyde LIF instrument that the Keutsch Group developed, so there is a high degree of expertise available for such an instrument. There are also sensitive cavity enhanced techniques available usually in the visible range of the spectrum.

3.4. SCoPEx Concept of Operations

Flights will proceed in the following manner. The payload would be launched with the ascender retracted such that there is minimal distance between the crossbar and platform. Once the balloon reaches the float altitude, the rope will be let out through the ascender such that there is 100 m between the crossbar and platform. The platform will then be ready to perform experiments and execute maneuvers. Figure 7 illustrates a proposed flight maneuver. The platform will initially travel in a straight line laying out a plume, after which it will maneuver back through the plume to make measurements. During these maneuvers the ascender can be used to fine tune the altitude of the platform and instruments. Several series of such maneuvers can be performed within each flight. At the conclusion of the experiments the ascender retracts the rope before the descent.

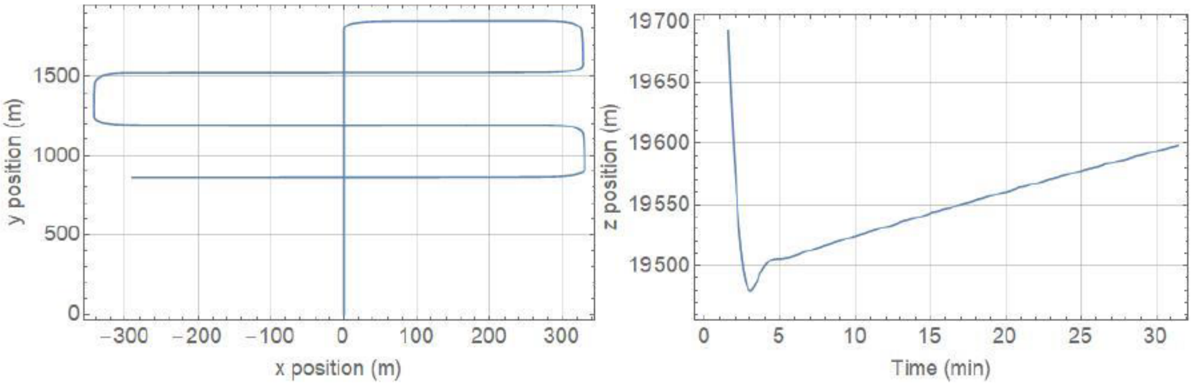

Figure 7: (left) A top down view of the proposed flight maneuvers over a 35-minute window. x and y are in the horizontal plane. The platform begins at (0,0). (right) The vertical position expected without any ascender or hopper vertical trimming over the same 35-minute platform maneuver.

4. SCoPEx Goals

In this section we describe the three long-term SCoPEx science goals. For each goal we describe the scientific problem, the need for SCoPEx, and the measurements required. The first phase of science flights targets the first two science goals. The design of the flights for the third goal will be informed by an understanding of the evolution of particle size distribution in the plume and the plume size. Thus, if later stage science flights move forward, they will be refined based on the results of the first science flights and the most up-to-date knowledge within the solar geoengineering and stratospheric science research communities.

4.1. Goal 1: Measurements of Turbulence for Small-Scale Mixing

4.1.1. The Importance of Plume-Scale Turbulence

Stratospheric turbulence influences the evolution of aerosol distribution from plume to regional to global scale. The mixing of air masses (of differing composition) in the stratosphere is a combination of two processes (Nakamura, 1996; Schoeberl & Bacmeister, 1993). The first process is strain, the distortion of streamline flow that brings air masses of differing composition adjacent to one another (Prather& Jaffe, 1990). Sometimes this is also referred to as “stirring” (Haynes, 2005). The second process occurs when air masses of differing composition are transported across the streamlines. This second process is the true “mixing” process.

In the stratosphere, mixing ultimately occurs because of molecular diffusion. This happens at the length scale of molecular viscosity. It is accelerated by turbulence, which can dramatically enhance the rate at which differing air masses are deformed to small enough spatial scales for molecular diffusion to mix them efficiently. Stratospheric turbulence is, however, highly intermittent (Vanneste, 2004). Understanding the mechanisms of stratospheric turbulence production is essential to understanding the spatial inhomogeneity and effective rate of mixing on spatial scales of 10-500 m (Schneider et al., 2017).

An understanding of this role of turbulence is of interest to stratospheric science because studies suggest that more accurate representations of mixing influence tracer distributions (Hoppe et al., 2014). Measurements of long-lived tracers are the strongest observational constraint on the stratospheric age of air, a key measure of the stratospheric large-scale circulation. Turbulence also modifies the character of kinetic energy fluxes. The magnitude and variability of these energy fluxes determine the rate of frictional dissipation in the atmosphere. This dissipation is represented in global models by a damping parameter and is the primary determinant of the mesoscale atmospheric kinetic energy spectrum. The uncertainty in kinetic spectrum is important to the understanding of the large-scale circulation of the middle atmosphere (Jablonowski & Williamson, 2011).

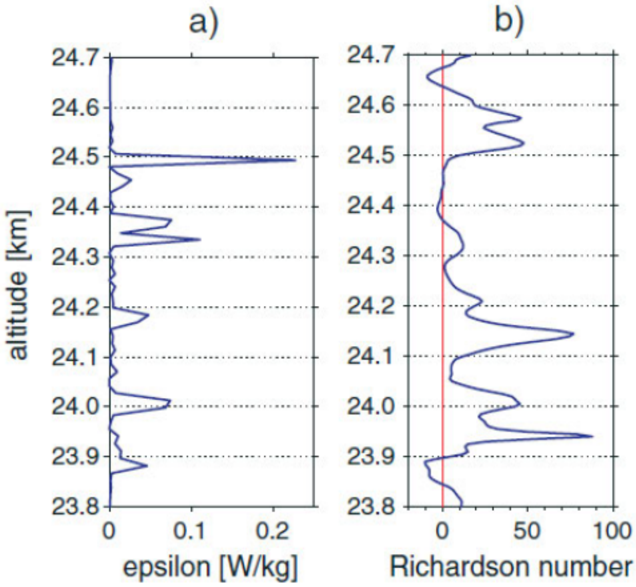

Figure 8: LITOS balloon-borne high-speed anemometer measurements reveal that models of atmospheric turbulence do not explain observed stratospheric turbulence. Physical models predict that a low Richardson number (buoyancy/shear ratio) implies turbulence, but high values of epsilon (turbulent dissipation) should be correlated with low Richardson number, which is not observed. (Haack et al., 2014)

Physical models predict that a low buoyancy/shear ratio (Richardson number) implies turbulence, and that high values of turbulent dissipation should be correlated with low Richardson number (Figure 8). However, recent balloon born measurements during the LITOS campaign did not agree with this, with numerous instances of high values of turbulent dissipation occurring at high Richardson numbers (Haack et al., 2014). As detailed above, both the impact of turbulence on mixing and the associated dissipation of energy are important for general stratospheric science. The point at which viscous fluid forces dominate atmospheric motion is the point where atmospheric motions become purely statistical and is called the dissipation scale. At this scale, models no longer require computationally expensive deterministic modeling. Furthermore, these viscous forces are also responsible for the dissipation of turbulent kinetic energy. Therefore, measurements which resolve the winds at the dissipation scale will allow numerical models to realistically close the atmospheric kinetic energy budget, an important metric of model fidelity.

4.1.2. Importance of Small-Scale Mixing for SAI and SCoPEx

From an SAI and SCoPEx perspective, plume-scale turbulence influences the frequency of collisions of monomer particles within the SCoPEx plume, which determines the rate of formation of fractal, larger aggregates. While Van der Waals forces finally determine whether particles that collide stick together and remain as a fractal aggregate (Sukhodolov et al., 2018), the collision rate is a critical quantity in determining total coagulation rate. Therefore, it is essential to know the frequency of collisions. This frequency is controlled by the wind variability at small spatial scales, i.e., the power spectrum. Intuitively, inertial forcing of particles by wind is much stronger than thermal forcing (e.g. Boltzmann distribution of velocity for ~1 µm particles at ~220 K). Fractal aggregates have a shorter lifetime in the stratosphere and are less effective at scattering light on a per mass basis (Weisenstein et al., 2015), so being able to model the formation

rate of fractal aggregates is an important aspect of SAI, especially with alternate SAI materials.

Improved knowledge of collision rates from wind measurements will allow for the selection of the appropriate mathematical representation of particle coagulation, the coagulation kernel. An accurate kernel is essential for numerical models to correctly simulate aerosol microphysical processes that determine the size distribution and residence time of solid aerosol particles. Adding wind and turbulence measurements to the SCoPEx payload will therefore address the major sources of uncertainty in aerosol microphysics under real atmospheric conditions, which include small-scale fluid flow, particle composition, and humidity.

4.1.3. Experimental Methods to Measure Turbulence in the Stratosphere

Multiple technologies are possible to achieve wind measurements with the necessary spatial resolution under stratospheric conditions. Current state of the art options include pitot tubes (with high sensitivity micro-pirani pressure sensors), hot wire anemometers, and acoustic anemometers. An existing stratospheric program has utilized hot wire anemometers to make measurements that are a close analog to what is necessary for SCoPEx. The program developed LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere), an instrument which made measurements of stratospheric turbulence up to 29 km (Gerding et al., 2009; Theuerkauf et al., 2011). The LITOS instrument has undergone significant calibration and has been compared against radiosondes (Schneider et al., 2015). One drawback of its deployment on a balloon has been the contamination of its wind measurements due to the influence of the balloon's wake. In contrast, SCoPEx is engineered so that the wind environment of the instrument payload is well separated from the balloon wake when SCoPEx is traveling horizontally. For this reason, SCoPEx could provide significantly more data per flight at a chosen float altitude. In this way, SCoPEx and LITOS would be very complementary. The horizontal flight path of SCoPEx, combined with measurements of the wind power spectrum, would provide an excellent complement to the LITOS observations, which are only obtained along a vertical profile. These power spectra obtained by SCoPEx would contribute to improved micrometeorology understanding relevant both to stratospheric aerosol injection and to fundamental atmospheric science.

Additionally, air flow through the turbulence instrument will be simulated using CFD tools. The CFD runs will provide a means to identify key flow characteristics that drive sensor performance (sensitivity and accuracy) and detailed sensor design. This application of the SCoPEx platform would therefore constitute a nonperturbative means to obtain necessary turbulence measurements that have, to date, eluded the scientific community. This information is important for understanding stratospheric dynamics, including the response to climate change or stratospheric heating from SAI. As no injection of particles is needed, these could be among the first scientific measurements to be conducted.

4.2. Goal 2: Evaluation of Aerosol Microphysics of AM-Sulfate and Alternative SAI Materials

One of the goals for which there are insufficient observational analogues is the near-field evolution of particles injected from a point source in the stratosphere. Specifically, observations of the temporal and spatial evolution of the aerosol size distribution (number and volume) of solid, alternate SAI materials or AM-H_2SO_4 injected form a point source can

only be compared with plume model predictions via a perturbative experiment such as SCoPEx. In the following we describe a plume model by Golja et al. (2020) specifically designed for SCoPEx. We also explain the results from the model and the SCoPEx experimental approach for comparing observations with model results.

4.2.1. Plume Model

Golja et al. (2020) incorporated the SCoPEx design features in their model to study the injection of a solid aerosol and vapor-phase sulfuric acid from a balloon payload. To provide observations relevant to SAI, SCoPEx needs to produce downstream aerosols with radii within the range of roughly 0.2 to 1.0 µm. For calcium carbonate, the objective is to maintain a high fraction of the aerosol in monomer form, while for sulfate an ideal distribution would have a peak diameter of 0.6 µm (Dykema et al., 2016). The generation of largely smaller than ideal particles, while imperfect for assessing radiative efficiency relevant to SAI, does not serve to increase particle sedimentation rates within the plume. Such smaller sizes may, however, result in a larger surface to volume ratio, which can strongly influence stratospheric composition as heterogeneous chemistry is directly related to surface area. Distributions centered on small particle sizes in the near field may, however, continue to evolve beyond the domain of the study.

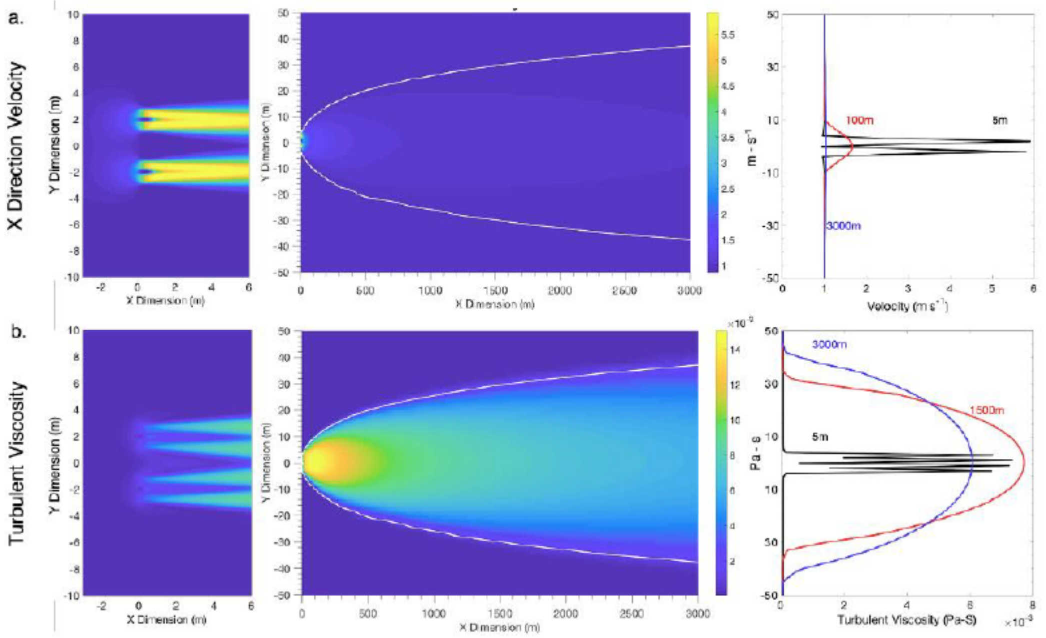

Figure 9 : ANSYS Fluent Velocity and Turbulence Fields. Shown above are the steady state x-direction velocity, u, and turbulent viscosity fields generated by ANSYS Fluent. Left panels show the genesis of disruptions to background X direction flow of 1 ms^{-1}, where propeller features are imposed at locations of 0,2) and (0,-2) meters. The center panel shows the entire domain, from 0 to 3 km, where the imposed red line contours 1 ms^{-1} in plot A, and contours 10% of the absolute maximum turbulent viscosity in plot B. Note Y direction scaling differs between the center and left panels. The right panel shows cross sections of velocity (A) and turbulent viscosity (B) through the Y plane at varying X locations. (Golja et al. 2020)

The velocity and turbulent viscosity fields from Fluent are shown in Figure 9. These fields form the basis of the simulation environment and are instructive in achieving an understanding of SCoPEx and the perturbation it achieves. Peaks in the x-direction velocity, u, are found directly downstream from the modeled propeller centers with an absolute maximum value of 6.3 ms^{-1}. By 1500 m downstream from the inlet locations, the velocity is reduced to the imposed background flow of 1 ms^{-1}. Turbulent viscosity, used as a measure

of particle mixing with background air, exhibits a narrow distribution of peak values ~10 m downstream from simulated propellers. With increasing distance downstream, the turbulent velocity spatial distribution widens, attaining a full width half maximum (FWHM) of 60 m by 1500 m downstream. The wake of the balloon itself is not visible, as it is sufficiently far from the payload to avoid wake crossing/interaction. Additionally, this simulation assumes a laminar stratospheric background flow, neglecting the potential impacts of breaking gravity waves.

For SCoPEx, precipitated calcium carbonate powder with roughly monodisperse size distribution centered at ~0.5 mm diameter will be aerosolized using the expansion of powder suspended in high pressure CO_2 through a 1-2 mm nozzle (see description in Section 3). The model injects aerosol as a 3D gaussian distribution of mass flux into the model grid, where the size of that distribution represents the scale of which the high velocity jet from the nozzle mixes with ambient air. The model considered two injection scenarios: scenario 1 (S1), a single point injection between the propellers; and scenario 2 (S2), injection from the center of each propeller. The model plume diameter at 3 km is, however, insensitive to the injection scenario for injection of both AM-H_2SO_4 and calcium carbonate. This suggests that injection at or between the propellers does not significantly alter the characteristics of the particles' experienced velocity field, and scenario S1 is the one selected for testing the model of plume evolution on SCoPEx. This is also important for the SCoPEx experiment as it necessitates only one sprayer that can be more easily placed in the equipment gondola.

4.2.2. Modelled Mass Injection Rate Dependence of Aerosol Size Distribution

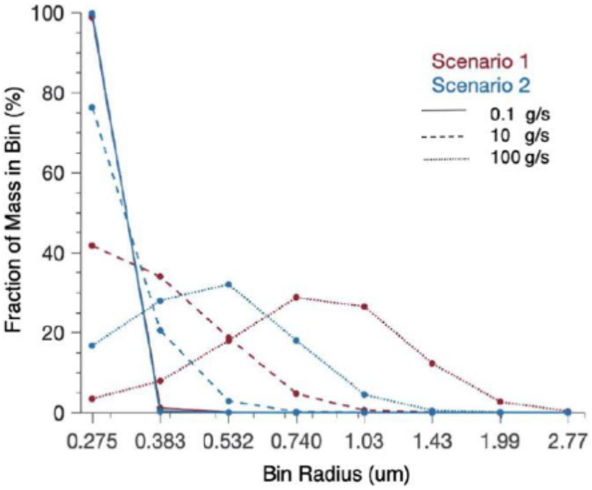

Figure 10: Calcium carbonate aerosol size distributions. Fraction of total mass in each sectional bin where the x-axis markers represent the central radius of each sectional size bin. These distributions represent the percent of total aerosol mass in the final 100 m of the plume across the full domain. Results are shown for three injection rates, 0.1 g s^{-1}, 10 gs^{-1}, and 100 gs^{-1}, for injection scenario 1 (red) and 2 (blue). (Golja et al. 2020)

Mass injection rates of 0.1, 10, and 100 g s^{-1} (0.36, 36, and 360 kg hr^{-1}) were used to test the influence of initial particle number density on the final plume aerosol size distribution. Although some of these are high, their use in the model is instructive as it can answer how different a short burst of high injection rate (much less than an hour) is from a slower but longer injection for the same total mass. Increasing calcium carbonate injection rates from 0.1 to 100 g s^{-1} reduces the share of monomer particles and increases undesired multi-monomer fractal aggregates. Figure 10 shows calcium carbonate's size distribution in the final 100 m of the modeled plume, i.e., the percent in each bin for the three different

injection rates of 0.275 μm radius particles. The low calcium carbonate injection rate of 0.1 g s^{-1} is the most desirable, maintaining 99% of the total mass in the final 100 m of the plume in monomer form. Increasing mass injection rate to 10 g s^{-1} and 100 g s^{-1}, with an S1 injection, shifts peak mass loading to favor particles of radii 0.5 and 0.75 um, respectively, corresponding to fractal "dimers" and "trimers".

Golja et al. (2020) also evaluated whether, in addition to the very sensitive in-situ optical particle counting aerosol size distribution instrument which originally was designed to measure background stratospheric aerosol size distributions (Murphy et al., 2016), the plumes could also be detected optically via scattered light. It should be emphasized that this does not refer to measurements from the ground but rather from close to the plume, e.g., when the equipment gondola is in close vicinity to the plume. Measuring the scattering from one view angle gives the product of the scattering phase at that angle and the scattering efficiency. This is closely related to the radiative forcing, but it does not uniquely determine the radiative forcing. By measuring at multiple angles, we could obtain enough information to quantify the radiative forcing. For example, we could measure from the side and below to obtain the forward scatter fraction, then calculate backscatter by flux conservation.

In the model, the extinction optical depth was calculated using Mie scattering theory and vertically integrating down columns in the y-z plane. Figure 11 shows the relative optical thickness of a sulphate and calcite aerosol plume formed via scenario 1 with an injection rate of 0.1 g s^{-1}. Calcite exhibits greater optical thickness by an order of magnitude at 550 nm, with an average value of 8.6×10^{-4} and maximum of 0.014 across the domain, as compared to sulphate, with an average of 9.4×10^{-5} and maximum 0.001. From these values, Golja et al. calculated that we expect adequate SNR to confidently detect the plume with a fast-scanning radiometer via the solar radiation it scatters. This calculation assumed an altitude of 21 km, solar elevation angle of 60°, an observing instrument situated on the payload gondola, and the gondola 200 m away from the edge of the plume and 1 km downstream of the termination of a scenario 1 type injection of calcite aerosol. Details of this calculation can be found in Golja et al. (2020).

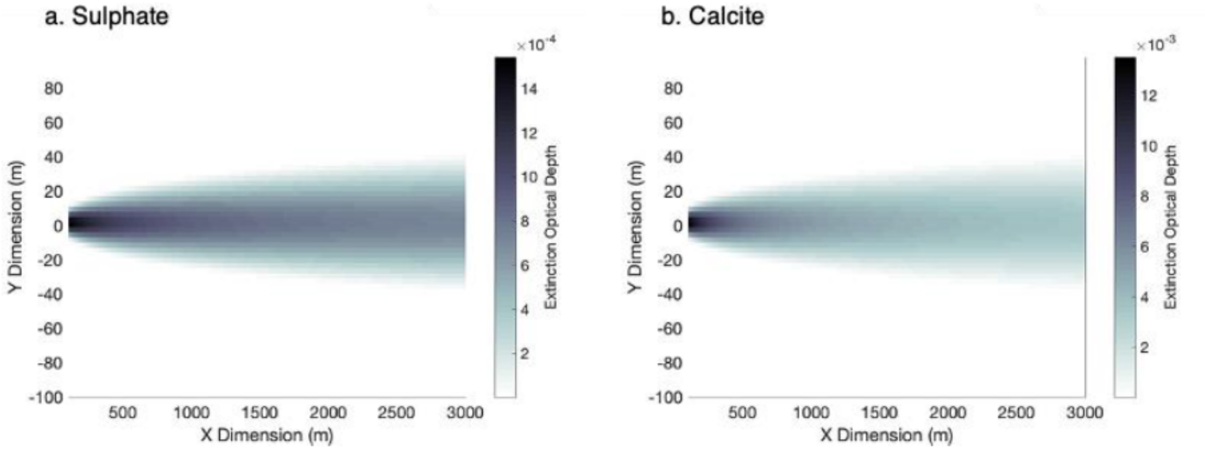

Figure 11: Extinction optical depth integrated vertically through all columns in the plume from 100-3000 m. Plots a and b show results for 0.1 gs^{-1} injections of condensable H_2SO_4 and calcite, respectively. The resulting number density of calcite aerosol is 490 cm^{-3} on the centerline at a downstream distance of 1000 m, predominantly as monomers. Aerosol optical depths were derived from Mie scattering theory at 550 nm, using refractive indices for sulphate and calcite stated in Dykema et al. (2016). (Golja et al. 2020)

4.2.3. SCoPEx Experimental Design and Analysis of Plume Evolution

For this goal, SCoPEx will follow the standard concept of operations, first spraying calcium carbonate at an injection rate suggested by the model analysis. It is desirable to maximize the contrast with the background stratosphere, both with respect to the aerosol concentration and the potential resulting chemical changes, while also maintaining calcium carbonate as monodisperse aerosol. To this end, additional models will be run at injection rates between 0.1 and 10 gs^{-1}. Based on these results, an injection rate will be chosen for the actual SCoPEx experiment. In addition to the basic components of the SCoPEx platform (gondola, ascender, propulsion, power, flight computer, communication, and wind), the calcium carbonate sprayer as well as the LIDAR and POPS instrument are critical for this science goal; without these components, there would not be a way to make and find the plume or measure the aerosol size distribution. While the turbulence measurement from goal 1 is desirable, it is, at least initially, not necessary. Similar studies of AM-H_2SO_4 injection would also be extremely useful. Our current plan is to conduct these after the calcium carbonate injection studies, as initially calcium carbonate is easier to handle than sulfuric acid and its precursors (see next section for motivation of calcium carbonate).

The aerosol size distribution measurements will be compared with the model predictions. In combination with turbulence measurements, discrepancies between the observed and modeled aerosol size distributions can be used to identify issues within the aerosol microphysical scheme or highlight misrepresentations of the velocity and turbulence field of the payload. The results of these studies will provide critical observational constraints on the aerosol microphysics and plume evolution of an injection with solid particles. It will be unique data that is ideal for testing the model of plume evolution as SCoPEx does not have to address problems resulting from the much more violent injection regime associated with injection from airplanes. Clearly, such studies are also needed, but SCoPEx represents a feasible and compelling first step in a sequence of new studies that more comprehensively investigate the aerosol microphysics of point source injections.

4.3. Goal 3: Evaluation of Process Level Chemical Models of Stratospheric Chemistry of Sulfate and Alternative SAI Materials

4.3.1. Need for Alternative SAI Materials

As previously discussed, the two largest first-order stratospheric risks of SAI with sulfate aerosol are ozone depletion and stratospheric heating. For sulfate aerosol the relative magnitude of these two risks can be adjusted if the size distribution can be controlled, e.g., via the AM-H_2SO_4 approach. It is worth noting that the impact on stratospheric ozone may be greatly reduced in the future if reactive halogen concentrations are lower. In contrast, the impact of stratospheric heating will not change. This represents a risk with a poorer understanding of its consequences, which makes it highly desirable to minimize stratospheric heating and resulting dynamic response. Therefore, it is important to investigate alternative SAI materials.

The properties of the “ideal” SAI material is (i) no absorption of radiation, i.e., purely scattering aerosol both fresh and aged, (ii) chemically inert, i.e., no direct impact of this material on stratospheric composition, and (iii) minimal down-stream effects, i.e., no impact on cirrus or other clouds, no environmental impact on deposition on the ground, etc. In reality, it is unlikely that a material with no impacts exists and rather the question is which materials can minimize these impacts. There have been a number of studies investigating

SAI materials in this context. High refractive index materials have been suggested as they reduce the mass of material that have to be lofted (Ferraro et al., 2015; Ferraro et al., 2011; Pope et al., 2012; Keith et al., 2016; Dai et al., 2020; Weisenstein et al., 2015). This largely cost-driven perspective is not a motivation for our work. In contrast, one of the goals of SCoPEx is to decrease the uncertainty in SRM models that use calcium carbonate SAI. The rationale for the choice of calcium carbonate as well as the approach to evaluate some of these risks is described in the following sections.

4.3.2. Unreactive Alternative SAI Materials

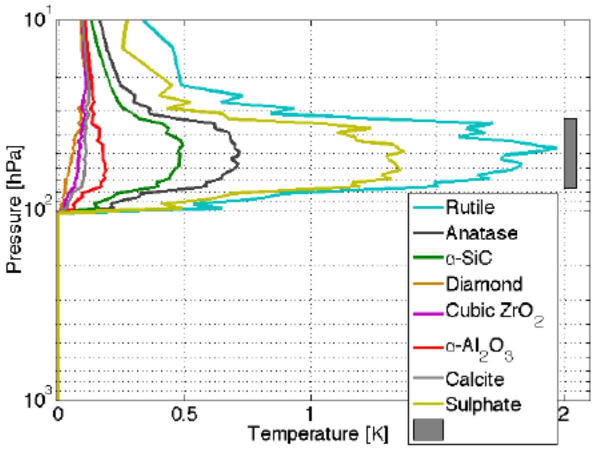

Figure 12: Comparison of stratospheric heating for different materials. Diamond has the lowest impact, although cubic zirconia and calcite are very similar. Sulfate and rutile result in much larger heating. (Dykema et al., 2016)

Diamond is probably the material with the best properties for SAI from a purely stratospheric perspective. Diamond has no absorption features in the solar or terrestrial spectrum and thus triggers the minimal possible dynamical response Figure 12. In addition, diamond should have ideal chemical properties. Hydrogen-terminated diamond surfaces are extremely inert and hydrophobic, precluding the ozone destroying chemistry initiated on sulfuric acid surfaces. The surface itself is also resistant to concentrated sulfuric acid. Exposure to OH radicals would probably slowly make the surface more hydrophilic. From a purely stratospheric perspective the only first-order risk of diamond would be increased ozone loss from the increased sulfuric acid surface area resulting from coagulation with background sulfate aerosol.

4.3.3. Reactive Alternative SAI Materials: The Case for Calcium Carbonate

Although the impact on cloud properties and the risk to Earth's surface from deposition of SAI diamond is likely very low, it could be preferable to have a material that dissolved easily in water, hence not persisting for long times outside of the stratosphere. It would also be preferable to have a material that is naturally abundant at Earth's surface. In addition, it would be ideal to overcome increased ozone loss due to coagulation by using a reactive aerosol. We therefore propose calcium carbonate as a prototype alternate SAI material for the following reasons: First, its optical properties are nearly equal to diamond and stratospheric heating and resulting dynamic response should be negligible compared to sulfate (Figure 12). Second, carbonates are typically quite reactive with acids, especially with concentrated sulfuric acid (Figure 13). Hence, calcium carbonate will neutralize upon

coagulation with sulfate aerosol eliminating the acidic surfaces resulting from coagulation of diamond and sulfate aerosol. Of course, the reactivity of calcium carbonate also makes model predictions with calcium carbonate more complex. The evolution of chemical and optical aerosol properties has to be modeled over its stratospheric lifetimes. One of the key research questions that SCoPEx will help address is whether the reactivity of calcium carbonate and the evolution of its chemical and optical properties and those of the surrounding gas-phase correspond to the detailed hypothesis laid out below. To this end, SCoPEx will compare observations of the chemical evolution of calcium carbonate, as well as the gas-phase, with those of a model based on known properties of calcium carbonate and recent laboratory experiments (Dai et al., 2020). This will provide a real-world evaluation of kinetic parameters, such as heterogeneous uptake coefficients derived from the laboratory studies, that will enable GCMs to include reliable parameterizations of the stratospheric impacts of calcium carbonate SAI.

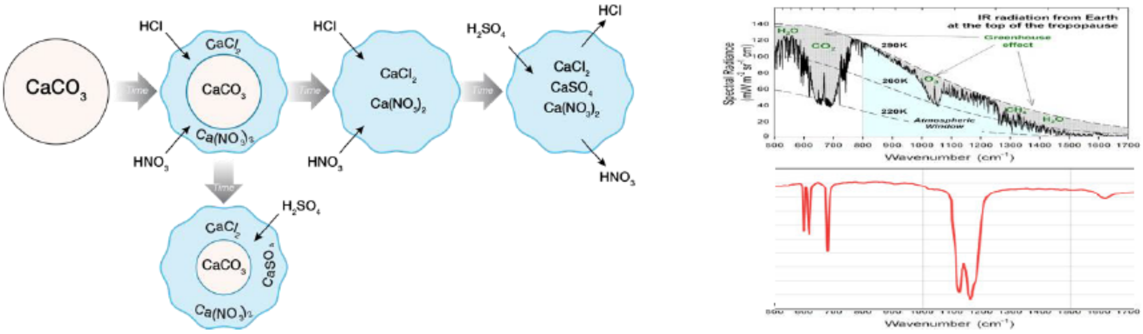

Figure 13: The left panel shows schematic of potential chemical reactivity of calcium carbonate in the stratosphere. The right panel shows the atmospheric windows in the terrestrial infrared (top) as well as the infrared absorption spectrum of calcium sulfate (bottom). The position of the 1150 cm^{-1} sulfate in part explains the stratospheric heating effect of sulfuric acid.

4.3.3.1. Optical Properties

Based on well-established chemistry, the reaction of sulfuric acid aerosol with calcium carbonate can be assumed to go to completion, i.e., be reagent limited. The optical properties of calcium sulfate in the terrestrial infrared are similar to those of sulfuric acid with only slight differences in relative band intensities and wavelengths (Figure 13 right hand inset). This is important as it implies that there will be no large first-order changes in stratospheric heating from changing background sulfuric acid to calcium sulfate. There are higher order impacts due to slight differences in the absorption of sulfuric acid, which has some liquid water compared to calcium sulfate. There are also numerous forms of calcium sulfate (anhydrite, bassanite, gypsum, etc.). However, the resulting differences are much smaller than introducing an absorbing material via SAI.

4.3.3.2. Chemical Properties

Predicting the evolution of the chemical properties of calcium carbonate under stratospheric conditions is more challenging. It is certain that calcium carbonate does not have the same heterogeneous reactions that activate ozone destroying substances as sulfuric acid. Figure 13 shows a schematic of the expected reactivity. Calcium carbonate is expected to react with acidic substances neutralizing them, forming salts and carbon dioxide. These acid neutralizing reactions can deplete gas-phase HNO_3, HCl, etc. There are a large number of ozone destroying catalytic cycles involving NOx, chlorine and other

halogens, which are altitude (and latitude) dependent. NOx can be produced via HNO_3 photolysis and lost via heterogeneous reaction of N_2O_5. It participates both in ozone destroying catalytic cycles and is important for deactivation of ozone destroying halogen radicals. Thus, knowledge of the heterogeneous reaction rates of numerous substances with calcium carbonate are required to predict the impact it will have on stratospheric composition.

However, until the recent study by Dai et al. in our laboratory, no heterogeneous chemistry studies of calcium carbonate under stratospheric conditions had been conducted, to our knowledge, although there exists a rich data set under tropospheric conditions (Dai et al., 2020). This work, as well as the work of Dai et al., highlights that reactive solid aerosols are indeed more complex than liquid sulfuric acid: The authors observed moderate initial uptake of the gas-phase acids HCl and HNO_3 on fresh calcium carbonate, as the dry stratospheric conditions already make uptake coefficients lower than under typical tropospheric conditions. An additional large difference to liquid aerosol is that the surface of the solid calcium carbonate passivates, drastically reducing the uptake coefficients of HCl and HNO_3. Hence, based on the Dai et al. laboratory study, calcium carbonate rapidly becomes effectively unreactive with respect to uptake of these gas-phase acids, an important finding that confirms calcium carbonate as a good candidate as alternate SAI material. In addition, calcium carbonate particles are abundant at Earth's surface due to windblown mineral dust. And the small calcium carbonate SAI particles should dissolve rapidly in water. This does not exclude risks associated with the deposition of calcium carbonate SAI particles or impacts on clouds (Cziczo et al., 2019). However, due to its abundance at the Earth's surface, there already exists a large knowledge base for its environmental impacts in contrast to, e.g., diamond. Further laboratory work is required to study especially the $ClONO_2$ + HCl and N_2O_5 hydrolysis reactions on fresh and aged calcium carbonate. However, the existing results prepare the stage for studying them in the real stratospheric environment as outlined below. Figure 14 shows results of the AER 2-D chemistry-transport-aerosol model for annual average ozone column changes of calcium carbonate SAI compared to a control for 2040. Ignoring the passivation of calcium carbonate (thk-ind) results in increases in ozone columns from calcium carbonate SAI whereas the inclusion of passivation can either result in very little ozone column change or losses in the Southern Hemisphere, depending how the $ClONO_2$+HCl is parameterized. Either of the two, more realistic, passivation scenarios result in significantly lower ozone loss than the equivalent amount of sulfate SAI, consistent with the hypothesis.

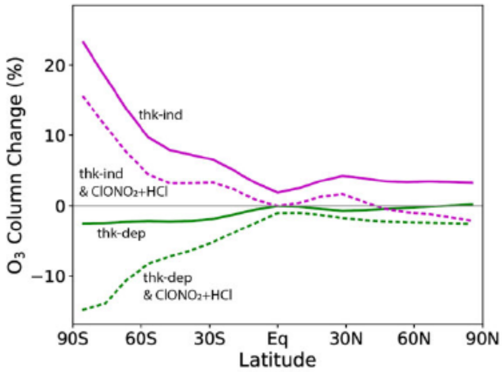

Figure 14: Shows the role of passivation and the heterogeneous $ClONO_2$+HCl reaction on ozone column change using the AER 2-D model taken from Dai et al. 2020. Inclusion of this reaction with the same rate as measured for Al_2O_3 results in a substantial reduction in ozone for scenarios including, thk-ind, or excluding passivation, thk-dep.

4.3.4. Need for SCoPEx Calcium Carbonate Plume Studies

One of the challenges for alternate SAI aerosol is the lack of materials such as calcium carbonate in the stratosphere. The only way to then study these materials in the actual stratosphere is via deliberate stratospheric injection of a small amount of these materials. In environmental studies, including stratospheric studies, it is not possible to rely purely on laboratory studies. For example, flights on the NASA ER-2 into the polar vortex over Antarctica provided the ability to test whether laboratory-derived reaction mechanisms were able to capture real-world ozone destruction chemistry. Without these flights, the level of confidence in the model predictions would have been much lower, and for good reason. It is not clear that a given experimental setup in the laboratory can faithfully capture the entire complexity of the real stratosphere; only field observations are able to provide this. For a number of natural stratospheric processes, remote observations can provide important information in addition to in situ aircraft or balloon. However, these are only possible when large-scale phenomena are at work.

Since there are no natural calcium carbonate plumes in the stratosphere that would even allow for in situ observations, intentional injection is necessary to perform these studies. Calcium carbonate injections will allow SCoPEx to provide invaluable observations as it will quantitively test the mechanisms determined in the laboratory. As stated above, there is a need for more laboratory studies, however, there is good reason to proceed with the planning of SCoPEx calcium carbonate experiments. First, by the time of the first injection experiments, additional studies should have been conducted. In addition, N_2O_5 uptake coefficients used in the model are likely a very good estimation as similar values have been found for different solid materials, e.g., Al_2O_3 and SiO_2 (Molina et al., 1997). In addition, even with these additional lab determined mechanisms, the same type of experiments as proposed here will still have to be conducted, as we expect these reactions to not make a significant difference. In other words, they will not be a deciding factor about the viability of calcium carbonate as an alternate SAI material. Only field experiments will help shed insight into these questions. In summary, there is a critical need for evaluating not just the aerosol microphysics (goal 2) but also the stratospheric chemistry of calcium carbonate due to the promise it holds as a lower risk SAI material.

4.3.5. SCoPEx Experimental Design and Analysis of Chemical Calcium Carbonate Plume Evolution

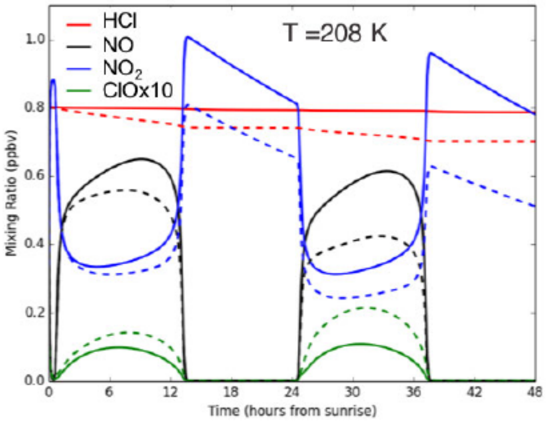

Figure 15: Solid lines: background 2μm^2 cm^{-3} sulfate 5ppm$_v$ H_2O. Dashed lines: plume 15μm^2 cm^{-3} sulfate 10 ppm$_v$ H_2O.

The experiments will again follow the standard concept of operations as under goal 2. In order to determine optimal injection rates, we will include chemical reactions in the plume model, updated with the newest mechanisms available at that time. Figure 15 shows the evolution of an air mass perturbed by a sulfate aerosol injection over multiple days, i.e., significantly longer than the initial SCoPEx experiments. Significant changes in HCl and NOx can be observed already over short time periods and these are easily detectable with existing instrumentation. For this science goal, it is desirable to measure aerosol composition and size distribution as well as key gas-phase chemical species, especially HCl, NOx and water. Therefore, this science goal requires a much larger set of instruments. In addition, the equivalent model to Figure 15 for calcium carbonate is informed by the results of science goal 2. The work of Dai et al. provides kinetic parameters needed for this model, and reactions for which there are no laboratory data to date are parameterized using close analogues and conditions, e.g., $ClONO_2$ + HCl are parameterized using the results for alumina (and silica) from Molina et al. (1997). One key question is whether the changes in HCl and NOx will indeed be smaller for calcium carbonate than those for sulfate shown in the figure above, which would confirm the hypothesis for calcium carbonate as a potential alternate SAI material.

In summary, SCoPEx experiments using calcium carbonate injections will provide a unique evaluation as to whether calcium carbonate indeed is an alternate SAI material that could substantially reduce risk from SAI compared to sulfate. Follow-up studies will be needed. For example, improved chemical and aerosol microphysics models will provide improved models of the chemical and physical evolution of calcium carbonate, which likely will motivate specific laboratory investigations. These will provide information for SCoPEx studies using "stratospherically aged" calcium carbonate as precursor for injection that can then be used to compare whether the laboratory mechanisms of this aged calcium carbonate agree with that found in the real stratospheric environment.

5. Data Management Plan and Dissemination of Results

Products of the research. The data generated during this project consists of meteorological, navigational, telemetry, and a variety of instrumentation data, in particular aerosol size distributions as well as chemical composition data during later science flights. In addition, there will be model data on plume chemical evolution.

Access to data, data sharing practices, and policies and dissemination of results. Data relevant for scientific analysis will be made public within 60 days of the end of flight. This taw data will be made public with appropriate warnings that it has not undergone QA/QC. The email address of users will be recorded so that they can be automatically notified when revised versions become available. Based on previous experiences with stratospheric airborne campaigns, this is typically 6-15 months after the flight depending on the type of data, e.g., the amount of calibration and data workup required. We have chosen to make raw data available rapidly—going far beyond what is typical for stratospheric science missions—because of the public scrutiny of SCoPEx and because of the broad commitment to Open Access data principles articulated by Harvard's Solar Geoengineering Research Program which is funding SCoPEx.

Principal Investigators (PI) and their groups have an excellent track record with presenting their work at major national and international conferences and workshops. All data that go into key analyses and figures in the group's publications will be made publicly available via the PI's group website. All publications resulting from this project will be posted on the PI's webpage (https://projects.iq.harvard.edu/keutschgroup/publications). Preprints of manuscripts submitted for publication as well as the underlying data will also be posted on Harvard's Dash manuscript repository. Publications will be made in open access formats.

Archiving of data. All data acquisition/storage computers in the PI's group are automatically backed up daily, both wirelessly to a server elsewhere on campus, and/or to a cloud server. Both of these processes ensure that data will not be lost and enable rapid access to the data. The file naming system used for all software (which includes the date of the experiment) ensures straightforward retrieval and use of archived data. Group laptops are also backed up daily, ensuring that analyzed data are archived as well.

6. SCoPEx Research Team Biographies

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World Meteorological Organization, United States, National Oceanic and Atmospheric Administration, United States, National Aeronautics and Space Administration, United Nations Environment Programme, & European Commission. (2019). *Scientific assessment of ozone depletion: 2018.*

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From: Andrea Smith (b) (6)
Subject: Re: CCIS webinar Wednesday Sept 22nd
To: Graham Feingold - NOAA Federal
Cc: Simone Tilmes; Keutsch, Frank N; Smith, Wake; Karen Rosenlof - NOAA Federal; Brian Medeiros
Sent: September 22, 2021 10:49 AM (UTC-04:00)

https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09

Do you need to use the web client? NOAA or other government users can use Zoom’s government-approved web client

Try that, let me know how it goes.

A

On Wed, Sep 22, 2021 at 8:47 AM Graham Feingold - NOAA Federal <graham.feingold@noaa.gov> wrote:

> zoom link not working for me. is there something else i need to do?
>
> On 9/17/21 11:06 AM, Andrea Smith wrote:
>
>> Hello Frank, Wake and Graham,
>>
>> Thanks again for finding time for introductions and webinar planning last week. Here are the logistical details and links Simone mentioned during the chat:
>>
>> 1) Zoom info to join the 9am MDT Wednesday morning session (also coming to you in a calendar invite):
>> https://us02web.zoom.us/j/81642619898?pwd=b013aFFtMzZ4QW93aWxSOW0rak9jUT09
>> Meeting ID: 816 4261 9898
>> Passcode: 148321
>>
>> Please join 10 mins early to test tech and troubleshoot if needed.
>>
>> 2) Whenever your slide decks are ready, please attach in a reply or upload (b) (6) (preferably by Tuesday night):
>>
>> 3) Finally, I've attached UCAR/NCAR's "speaker consent form", which just needs a few details for your acknowledgement that we can share the recording and .pdf of slides on our website - I'll try to collect these from everyone after the webinar. Digital entry and signatures work just fine. Let me know if you have any questions.
>>
>> After the webinar, if you have interest in chatting via our forums, you can sign up at top right of the forums page for a free account.
>>
>> Let me know if you have questions on any of the above.
>>
>> Thanks again, and see you next Wednesday.
>>
>> Andrea
>>
>> On Mon, Sep 13, 2021 at 10:39 AM Simone Tilmes (b) (6) > wrote:
>>
>>> Hi Frank, Wake and Graham,
>>> thanks for joining our meeting on Friday, and here is a little summary and a todo list:
>>>
>>> First, I think we are very happy with the discussed content of the talks. This is the order of the presentations (see

below). I do have the title from Graham, but not sure if I have it also from Frank and Wake. Therefore, Frank and Wake, could you send us your title again?

1. Frank Keutsch: ...
2. Wake Smith:...
3. Graham Feingold: Physical Science Challenges associated with Marine Cloud Brightening

Here is Andreas rundown for logistics:

-please share talk titles, bio and headshot by Wednesday (9/15) (mostly done)
-send slide decks to Andrea by Tuesday (9/21) evening for backup purposes
-arrive ~10 mins early so we can do quick test of screenshares
-15 min talk length, w/ immediate clarifying question(s) and then ~30 mins broad discussion and questions at end
-moderator will collect questions in chat window throughout and ask most pertinent ones for discussion
-panelists and question askers encouraged to unmute & turn on camera
-session will be recorded and posted later - we'll send a release form for them to complete

Please let us know if you have further questions. I think, Andrea will send you a zoom link and meeting invite,

Cheers, Simone

--
Simone Tilmes,
Atmospheric Chemistry, Observations & Modeling Lab
National Center for Atmospheric Research
PO Box 3000
Boulder, Colorado 80307-3000
303-497-1445
303-497-1400 (fax)
(b) (6) [redacted]

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) [redacted] (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

--
Graham Feingold
NOAA Earth System Research Laboratories
Chemical Sciences Laboratory (R/CSL9)
325 Broadway
Boulder, Colorado 80305, USA

> `Tel: (303) 497-3098`
> `Fax: (303) 497-5318`

--
Andrea Smith
Associate Scientist & Program Manager
The COMET® Program
University Corporation for Atmospheric Research
3085 Center Green Dr.
Boulder, CO 80301
303-497-8320 (office)
(b) (6) (cell)

My working hours may differ from your own. Please do not feel obligated to reply outside of your normal working hours.

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Experimental research platform requirements
To: Keith, David
Cc: Smith, Wake; Frank Keutsch
Sent: February 3, 2021 6:41 PM (UTC-05:00)
Attached: Untitled attachment

David,

Yes, the Perseus a/c was a big distraction that I was only on the edge of fortunately.

I will remain skeptical about the likelihood of new non-military a/c but want to be first in line to use them. We were first in line and funded to use the new Boeing/Aurora a/c, Odysseus, when the plug was pulled.

Yes we have had conversations with the Sceye folks and would like to have a chance to use when the day comes.

BTW, the CU group here apparently demonstrated a 1.5km reel down from a balloon quite recently. No other details.

Regards
Dave

On Feb 3, 2021, at 7:59 AM, Keith, David (b) (6) > wrote:

Dave

Thanks. I think we see this about the same way.

From my perspective I came into this field working for Jim with all the excitement about Aurora's aircraft which ended up amounting to nothing. It took some years of my life. And yes, Global Hawk has been a big disappointment. So I definitely get the basis for skepticism.

On the other hand, there does seem to be a commercial-driven shakeup in the ability to develop low altitude aircraft. That's true from the new entrants into general aviation market through to the startups building off drone technology. So I'd like to understand whether this could apply to higher altitude light aircraft. I don't know, but if Wake spurs some interest I am open to find out more.

Have you had any conversations with these folks: Sceye | A new generation of HAPS | High Altitude Platform Stations? The head guy just reached out to me again and I will talk with.

David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Saturday, January 30, 2021 6:38 PM
To: Keith, David (b) (6) >
Cc: Smith, Wake (b) (6) ; Keutsch, Frank N (b) (6)

Subject: Re: Experimental research platform requirements

David,

Yes, I think if one has funding, then existing a/c become available. Certainly for the UT/LS, the WB-57s have been underutilized for years now and hence availability hasn't been an issue. Indeed a trip back to the boneyard was perhaps a growing threat.

I note that no one has ever built an aircraft for atmospheric chemistry, leaving the field to exploit as best they can existing a/c, which we have done very well. Thus, if there were runway a/c available that could do 30kg, 8hr, 79kft, the community would no doubt rush to use it. So the answer to your question is yes.

My problem with new-platforms-will-be-cheap is the issue of having truly operational a/c rather than experimental a/c. If one is trying to fly an experiment on an experimental a/c it reduces the probability of success by a large measure. Making an experimental a/c operational requires larger upfront and sustained investment by entities other than the science communities, creating the underwater part of the iceberg. This is why we don't have new operational a/c. And one can look to the Global Hawk and see that even starting at a high level (a mature platform) it failed to become operational because no one wants to pay the price, in this case neither NASA or NOAA. Now deeper pockets (DoD) have taken it over.

And to your final point about what payloads, yes, the new generation of lightweight instruments make 30kg interesting and valuable, and, yes, comprehensive chemistry payloads still want to be on heavy lift long-range a/c.

In reply to Wake's question about perturbation/monitoring a/c, hmmm, it depends. In the early days, perhaps they could be the same. Eventually the perturbations sought would be as large as possible per flight and not every flight would need diagnostics, so I think eventually they are different a/c. And monitoring a/c could be below the perturbation a/c altitudes and diagnose with lidar.

Interest above 70kft: in general because we would be deeper into the ozone layer. And perhaps the injection altitude would be there once we understand things better.

Regards
Dave

> On Jan 30, 2021, at 9:29 AM, Keith, David (b) (6) [redacted]> wrote:
>
> Dave
>
> Interesting back-and-forth.
>
> I think part of the differences were hearing relate to different assumptions about ready availability of the existing NASA platforms. As I read it, you are effectively assuming you can get them when you want them so no benefit to additional aircraft to do this.
>
> I'm thinking that there might be significant research interest ***if*** a runway based smaller aircraft (e.g. 30 kg payload, 8hr duration, 70 kft max alt) was much more cheaply and flexibly available.

I'm conscious that I may be falling into the kind of new-platforms-will be-cheap-and-great advocacy that brought me into this field as a postdoc for Jim Anderson in the late 90s. I think it all depends on whether there is a performance window where platforms could be developed that are reasonably low risk and cheap.

I guess the bottom line is I see the runway limitation as less important than the cost and ease of access limitations.

Dave and Frank: do you agree that there is a set of optical measurements (IR or visible spectrometers, particle measurements, and instruments that collect samples such as air core or drum sample) that can reasonably fit into payloads of well under 100 kg whereas the photochemistry suite is fundamentally harder and "wants" to be on a large aircraft.

Interesting conversation. No simple answers.

Cheers,
David

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Sent: Thursday, January 28, 2021 11:49 AM
To: Smith, Wake <(b) (6)
Cc: Keith, David (b) (6) Keutsch, Frank N
(b) (6)
Subject: Re: Experimental research platform requirements

Wake,

Thanks for the follow up. I appreciate that you are investing in new platform ideas for CI and other applications. I assume David has shared my original reply to him (see below).

You are correct that runways are plentiful. However, if I am using a runway then I could use existing hi- flyers to carry small payloads to 70kft. So we are already there.

The no-runway option would allow remote site launches and presumably lower technical/logistic overhead. We are currently investing in small balloon launches from the Lauder NZ station to profile stratospheric aerosol to 25-30kft. Of course we risk losing the payload by default and have no substantial trajectory control during flight. An unpiloted a/c that could meet the payload and altitude specs while offering some inflight control and safe landing and recovery and not needing a runway would be transformative to this stratospheric sampling. I realize this is perhaps fanciful thinking and unlikely leads to a credible proposal given the current laws of physics and energy storage.

I am happy to discuss further.

Regards
Dave

Begin forwarded message:

From: David Fahey - NOAA Federal <david.w.fahey@noaa.gov>
Subject: Re: Small stratospheric aircraft
Date: January 22, 2021 at 8:56:59 AM MST
To: "Keith, David" <(b) (6) [redacted]>
Cc: Frank Keutsch <(b) (6) [redacted]>

David,
Hmmm. Interesting/good to know that WakeS continues to think about aircraft needs. Certainly if we were to ever implement strat CI there would be more demand for reconnaissance of composition and radiation fields, and new a/c could help meet that demand.

That said, I am not sure that 70kft, 10kg, and 3hrs is of sufficient interest unless I can launch/recover from non-runway locations without great expense. For comparison, an ER-2 can meet and exceed those specs today but requires a runway and $6-10K/hr which is still reasonable. With far less cost, a small balloon could also meet and exceed those specs but needs permission and can't control flight path well.

In general, the alt/payload/duration puzzle is frustrating because we can't have it all. To really create interest, the duration would need to be 2-3 times longer at least; otherwise it is too much like a balloon. Second, the altitude would need to be more than 70kft to distinguish from ER-2 and GH, realizing that this may simply not be possible. And the payload must be more than 10kg to be interesting given today's technology (and to distinguish from balloon), so perhaps 100kg.

I am not sure that this is very helpful. I go back to my early statement: launch/recover from non-runway locations without great expense. If that were met, this platform would be used and could be disproportionately valueable.

Thanks for the SCoPEx document. Well done. I would like to share it with ERB folks in CSL. Is this acceptable?

Regards
Dave

On Jan 26, 2021, at 9:11 AM, Smith, Wake <(b) (6) [redacted]> wrote:

Dave – I trust you are well in this odd COVID season. I am in dialogue with David Keith about the prospect of new lightweight high-altitude platforms for geoengineering research and perhaps climate research more generally. Once I

understand the requirements, I will endeavor to clarify what the options and costs might be.

In addition to basic range/payload/altitude requirements, David has mentioned that you see utility in a vehicle that could launch and recover from non-runway locations. Given that runways are plentiful and such a vehicle would not require a long one, I would love to understand what gives rise to this parameter and how highly to prioritize it.

Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6)

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Cc: Keith, David; Frank Keutsch
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Wake Smith
Senior Fellow; Mossavar_Rahmani Center for Business & Government; Harvard Kennedy School &
Lecturer in Yale College
(b) (6) [redacted]

From: Robert Wood (b) (6)
Subject: Re: 2022 GRC program
To: Douglas MacMartin
Cc: (b) (6) ; (b) (6) ; Alan Robock; Karen Rosenlof - NOAA Federal; Katharine Ricke; (b) (6) (b) (6) ; (b) (6) Daniele Visioni; Isla Simpson; Peter Irvine; Jonathan Proctor; (b) (6) ; Keith, David; Kravitz, Ben; Wake Smith; Izidine Pinto; Gabriel Chiodo; Keutsch, Frank N; Trude Storelvmo; Simone Tilmes; (b) (6)
Sent: July 15, 2021 3:52 PM (UTC-04:00)

Hi Doug and Trude,

Thank you for the offer to present at next year's GRC. I am still interested.

Regards

Rob

Robert Wood
Professor, Atmospheric Sciences
Department of Atmospheric Sciences,
718 ATG Building
University of Washington, Seattle
WA 98195-1640

Tel: 206-267-8343 (cell); 206-543-1203 (office)
Web: atmos.washington.edu/~robwood
Email: (b) (6)

On Thu, Jul 15, 2021 at 8:11 AM Douglas MacMartin <(b) (6) > wrote:

> Hi all,
>
> Trude and I, together with co-chairs Simone and Ulrike, are beginning to plan the 2022 Gordon Research Conference, https://www.grc.org/climate-engineering-conference/2022/, June 26 - July 1 2022 in Maine – so a little less than a year away. All of you were invited speakers in the 2020 meeting that, of course, never occurred.
>
> As a start to our planning, could you let us know whether you would be interested in talking at the 2022 meeting? We would of course still love to hear from you, but schedules may not permit and research interests change (and, indeed, for some or many of you that may mean that the topic we were originally thinking you would talk about would no longer be what you are currently most excited by – the GRC is supposed to be cutting-edge current research, of course – so if you let us know we can start revising sessions and think about what gaps we'd like to fill). There are also some new people who are doing some great research too that we would like to hear from, so it's conceivable that – given the now 5 year gap since the last GRC – we might choose to slightly increase the number of talks and reduce the time available per talk.
>
> Thanks,

Doug & Trude

From: Douglas MacMartin
Sent: Wednesday, February 19, 2020 10:27 AM
To: (b) (6) ; (b) (6) ; Alan Robock (b) (6) >;
Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >;
(b) (6) ; Robert Wood (b) (6) >; (b) (6)
(b) (6) <(b) (6) >; Daniele Visioni (b) (6) >;
(b) (6) ; Peter Irvine (b) (6) >; Jonathan Proctor (b) (6) >;
(b) (6) ; Keith, David <(b) (6) >; Kravitz, Ben <(b) (6) >; Wake Smith
(b) (6) >; Izidine Pinto (b) (6) >; Gabriel Chiodo
<(b) (6) ; Keutsch, Frank N (b) (6) >
Cc: Lawrence, Mark <(b) (6) >; valentina Aquila (b) (6) >; Ulrike
Niemeier <(b) (6) >; Leisner, Thomas (IMK) (b) (6) >; Olivier Boucher
<(b) (6) >; Schrag, Daniel P. (b) (6) >; TAYLOR,Michael
(b) (6) >; (b) (6) Trude Storelvmo <(b) (6) ; 'Simone
Tilmes' (b) (6) ; (b) (6) Jim Hurrell (b) (6) >
Subject: RE: 2020 GRC program

Hi all,

Just a reminder that if you haven't sent me a title yet, to do so (otherwise I'll have to make something up; GRC needs us to upload our "final" program by the end of this month) I have titles for about half of you (though some of those are draft titles you sent quite some time ago, e.g. for Pete, Isla, Danny).

And, if you haven't responded yet regarding need for travel support, let me know (about half of you have). For those of you who haven't been to a GRC before, there's a bus from Boston airport, and from Portland Maine airport.

If you've already both sent me a title and responded regarding travel, then you can ignore this email.

Also, regarding format, this year we're explicitly including 10-15 minutes for the discussion leader to make some remarks to help frame each session (taking 5 minutes from each speaker's time), and rather than having a lengthy discussion after each talk, we'll have a shorter 10-minute discussion after each talk and a 20-minute general session discussion at the end (that's as long as GRC will allow) with everyone from a given session.

Thanks, and see you in June!

doug

From: Douglas MacMartin
Sent: Wednesday, January 8, 2020 3:41 PM
To: (b) (6) (b) (6) ; 'Jadwiga (Yaga) Richter' <(b) (6) >; Alan Robock <(b) (6) >; Karen Rosenlof - NOAA Federal <karen.h.rosenlof@noaa.gov>; Katharine Ricke <(b) (6) >;(b) (6) ; Robert Wood <(b) (6) >; (b) (6) ;(b) (6) <(b) (6) >; Daniele Visioni <(b) (6) >;(b) (6) ; Peter Irvine <(b) (6) >; Jonathan Proctor <(b) (6) >; Govindasamy Bala <(b) (6) >;(b) (6) ; Keith, David <(b) (6) >; Kravitz, Ben <(b) (6) >; Wake Smith <(b) (6) >; Chris Field <(b) (6) >
Cc: Lawrence, Mark <(b) (6) >; valentina Aquila <(b) (6) >; Ulrike Niemeier <(b) (6) >; Leisner, Thomas (IMK) <(b) (6) >; Olivier Boucher (b) (6) >; Schrag, Daniel P. <(b) (6) >; TAYLOR,Michael (b) (6) >;(b) (6) ; Lynn Russell (b) (6) >; Trude Storelvmo <(b) (6) >; 'Simone Tilmes' (b) (6) >;(b) (6)
Subject: 2020 GRC program

Hi all,

Happy New Year!

The full program for GRC is due on February 28; if you haven't sent us a title for your talk (or if you did and want to revise it), please do so before the end of February so I have time to enter everything into the conference management system online.

The cc-line has discussion leaders for each session.

Thanks, and looking forward to seeing you in June! (Or some of you before that.)

doug

Douglas MacMartin

Senior Research Associate and Senior Lecturer, Mechanical and Aerospace Engineering, and

Faculty Fellow, Atkinson Center for a Sustainable Future

Cornell University

(b) (6)

> (b) (6)
>
> https://climate-engineering.mae.cornell.edu/