Leonard, Rachael L.

From: Holdren, John P.
Sent: Friday, May 15, 2009 1:26 PM
To: Leonard, Rachael L.
Subject: Geo-engineering

JOHN P. HOLDREN
Assistant to the President for Science and Technology
and Director, Office of Science and Technology Policy
Executive Office of the President of the United States
jholdren@ostp.eop.gov, 202-456-7116
Executive Assistant Pat McLaughlin
pmclaughlin@ostp.eop.gov, 202-456-6045

From: Holdren, John P.
Sent: Wednesday, April 08, 2009 12:52 PM
To: Moran, Ellen L.
Cc: Weiss, Richard S.
Subject: RE: wow -- here's the AP stub

Ellen -- Good grief. In a half-hour interview, I got asked about geoengineering and talked about it for maybe three minutes, making clear that approaches that have been surfaced so far are problematic in terms of both efficacy and side effects, but we have to look at it and understand it because it if we get desperate enough people will want to consider it. I also made clear that this was my personal view, not Administration policy. So this is what AP's Seth Borenstein runs with for his whole story. [redacted] Happy to talk (I guess). Am in meetings (not more press) until 2. Cheers anyway, John

Exemption 5 - deliberative

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[redacted]

WHO record
Referred to WHO

[redacted]

[redacted]

WHO record
Referred to WHO

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

WHO record
Referred to WHO

Leonard, Rachael L.

From: Holdren, John P.
Sent: Friday, May 15, 2009 1:26 PM
To: Leonard, Rachael L.
Subject: FW: AP story about geo-engineering and the White House

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From: Holdren, John P.
Sent: Wednesday, April 08, 2009 5:22 PM
To: 'SChu@hq.doe.gov'; 'Lubchenco, Jane'; Harold Varmus; 'Eric Lander'
Subject: AP story about geo-engineering and the White House

Steve, Jane, Harold, Eric --

In case the account of an interview with me that went out on the AP wire today comes to your notice, please know -- as you probably will suspect -- that the AP account gives a serious misimpression about what I actually said. In the course of a wide-ranging half-hour interview on my new job, high-tech innovation for economic growth, energy, national security, and climate change, I got asked about whether we need to think about geo-engineering as a response to the climate problem and I spent about three minutes on it. I said that the approaches that have been surfaced so far seem problematic in terms of both efficacy and side effects, but we have to look at the possibilities and understand them -- including their shortcomings -- because if other approaches to mitigation fall short the geo-engineering approach will end up being considered. I also made clear that this was my personal view, not Administration policy. Asked whether I had mentioned geo-engineering in any White House discussions, though, I said that I had. This is of course NOT the same thing as saying the White House is giving serious consideration to geo-engineering -- which it isn't at this point -- and I am dismayed that the headline and the text of the article suggest otherwise, as well as dismayed that the entire AP story focused on this minor point in the interview.

Cheers anyway,
John

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From: Holdren, John P.
Sent: Wednesday, April 08, 2009 5:32 PM
To: 'whrcspam@whrc.org'
Subject: AP story about geo-engineering and the White House

Colleagues:

In case the account of an interview with me that went out on the AP wire today comes to your notice, please know -- as you probably will suspect -- that the AP account gives a serious misimpression about what I actually said. In the course of a wide-ranging half-hour interview on my new job, high-tech innovation for economic growth, energy, national security, and climate change, I got asked about whether we need to think about geo-engineering as a response to the climate problem and I spent about three minutes on it. I said that the approaches that have been surfaced so far seem problematic in terms of both efficacy and side effects, but we have to look at the possibilities and understand them -- including their shortcomings -- because if other approaches to mitigation fall short the geo-engineering approach will end up being considered. I also made clear that this was my personal view, not Administration policy. Asked whether I had mentioned geo-engineering in any White House discussions, though, I said that I had. This is of course NOT the same thing as saying the White House is giving serious consideration to geo-engineering – which it isn't at this point -- and I am dismayed that the headline and the text of the article suggest otherwise, as well as dismayed that the entire AP story focused on this minor point in the interview.

Cheers anyway,
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Leonard, Rachael L.

From: Holdren, John P.
Sent: Friday, May 15, 2009 1:25 PM
To: Leonard, Rachael L.
Subject: FW: AP story about geo-engineering and the White House

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From: Holdren, John P.
Sent: Wednesday, April 08, 2009 5:36 PM
To: Kohlenberger, Jim C.; Kalil, Thomas A.
Subject: FW: AP story about geo-engineering and the White House

FYI

From: Holdren, John P.
Sent: Wednesday, April 08, 2009 5:05 PM
To: Moran, Ellen L.
Cc: Recos; Sutphen, Mona K.; Axelrod, David M.; Messina, James A.; Browner, Carol M.; Weiss, Richard S.
Subject: AP story about geo-engineering and the White House

Ellen -- I have sent the note below to a few of my scientific colleagues outside the government who are likely to be asked about my views in the wake of the AP story this morning. I am copying a few of our colleagues on the Senior Staff who were doubtless as surprised as I was to read the AP's account. If you think I should [redacted], please let me know. Cheers anyway, John

└ Exemption 5, deliberative

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From: Holdren, John P.
Sent: Wednesday, April 08, 2009 7:24 PM
To: 'rbierbau@hotmail.com'; 'SternTD@state.gov'; 'DSandalow@brookings.edu'
Subject: AP story about geo-engineering and the White House

Todd, David, Rosina --

In case the account of an interview with me that went out on the AP wire today comes to your notice, please know -- as you probably will suspect -- that the AP account gives a serious misimpression about what I actually said. In the course of a wide-ranging half-hour interview on my new job, high-tech innovation for economic growth, energy, national security, and climate change, I got asked about whether we need to think about geo-engineering as a response to the climate problem and I spent about three minutes on it. I said that the approaches that have been surfaced so far seem problematic in terms of both efficacy and side effects, but we have to look at the possibilities and understand them -- including their shortcomings -- because if other approaches to mitigation fall short the geo-engineering approach will end up being considered. I also made clear that this was my personal view, not Administration policy. Asked whether I had mentioned geo-engineering in any White House discussions, though, I said that I had. This is of course NOT the same thing as saying the White House is giving serious consideration to geo-engineering – which it isn't at this point -- and I am dismayed that the headline and the text of the article suggest otherwise, as well as dismayed that the entire AP story focused on this minor point in the interview.

Cheers anyway,
John

PS: The Washington Post on-line article about their interview with me is also something of a mess. The headline, which I hope we can get changed in the print edition, confuses not starting with a 100% auction with not starting cap-and-trade at all. The first sentence is better but still hardly a model of clarity. I may never talk to the press again.

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Leonard, Rachael L.

From: Holdren, John P.
Sent: Friday, May 15, 2009 1:25 PM
To: Leonard, Rachael L.
Subject: FW: AP story about geo-engineering and the White House

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From: Holdren, John P.
Sent: Thursday, April 09, 2009 8:04 AM
To: 'Michael Schlesinger'
Subject: RE: AP story about geo-engineering and the White House

Thanks for the paper. We are in discussion here about the best way to deal with the AP distortion of what I said.
Best, John

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From: Michael Schlesinger [mailto:schlesin@illinois.edu]
Sent: Thursday, April 09, 2009 3:11 AM
To: Holdren, John P.
Cc: schlesin@atmos.uiuc.edu
Subject: Re: AP story about geo-engineering and the White House

John:

I think that what you have requested me to do about the AP piece below is not wise.

"Michael --
I'm dismayed by the account of an interview with me that went out on the AP wire today, and I hope that if you distribute it to your list you will consider adding a clarification from me. In the course of a half-hour interview, I got asked about whether we need to think about geo-engineering and I spent about three minutes on it. I said that the approaches that have been surfaced

so far seem problematic in terms of both efficacy and side effects, but we have to look at the possibilities and understand them because it if we get desperate enough it will be considered. I also made clear that this was my personal view, not Administration policy. Asked whether I had mentioned geo-engineering in any White House discussions, though, I said that I had. This is NOT the same thing as saying the White House is giving serious consideration to geo-engineering – which it isn't -- and I am disappointed that the headline and the text of the article suggest otherwise.
Best,
John"

Rather, I think that your Office of Science Advisor to President Obama should issue your statement above about Geo-engineering.

Michael

P.S. I am both a scientist and an engineer (and a bit older than you). Accordingly I think that Geo-engineering our way out of global warming is not a viable solution, as it is as impossible for us to foresee the ramifications of our so doing as it was for us to foresee the ramifications of our use of fossil fuels during the past 150 years. This situation of not knowing is what I and my engineering colleagues 45 years ago called: "Don't Know Squared". This means that are some things you know, and some things that you know you don't know. But it is the things that you don't know you don't know that can really 'kill you'.

A way of hedging against this uncertainly is described in the attached paper.

Leonard, Rachael L.

From: Holdren, John P.
Sent: Friday, May 15, 2009 1:24 PM
To: Leonard, Rachael L.
Subject: FW: Geoengineering and ocean acidification

JOHN P. HOLDREN
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and Director, Office of Science and Technology Policy
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Executive Assistant Pat McLaughlin
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From: Holdren, John P.
Sent: Thursday, April 09, 2009 9:42 AM
To: 'Granger Morgan'
Subject: RE: Geoengineering and ocean acidification

And, yes, I did tell him about acidification, prominently.

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pmclaughlin@ostp.eop.gov, 202-456-6045

From: Granger Morgan [mailto:granger.morgan@andrew.cmu.edu]
Sent: Thursday, April 09, 2009 9:23 AM
To: SBorenstein@ap.org
Subject: Geoengineering and ocean acidification

Seth,

Nice piece.

However, the potentially most worrying externality did not really get mentioned. That is the continued acidification of the world's oceans that will occur if one lowers the temperature by increasing albedo but does not stop the build-up of CO_2. Already the oceans are 30% more acidic than in preindustrial times. By late this century we could loose most coral reefs (a disaster in itself but even more important because of all the services they provide – breeding grounds for many species, etc.) See the dramatic reef pictures on page 1741 in the attached paper from Science. We could also loose a number of zooplankton that fish like salmon live on because in more acidic water they could no longer make their very tiny shells.

In the event you are not up to speed on this I suggest you talk with Scott Doney at Woods Hole and Richard Feely at NOAA. They and others have produced some very nice recent reviews of what we know (and the great deal we do NOT know). As interest in geoengineering grows, this is a topic that deserves MUCH more attention.

Granger

Leonard, Rachael L.

From: Holdren, John P.
Sent: Friday, May 15, 2009 1:24 PM
To: Leonard, Rachael L.
Subject: FW: AP story about geo-engineering and the White House

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From: Holdren, John P.
Sent: Thursday, April 09, 2009 9:45 AM
To: 'Camille Romano'; WHRC Staff
Subject: RE: AP story about geo-engineering and the White House

Love it that my picture is on the obituary page; although I am feeling thoroughly beaten up, I am not yet dead.

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Executive Assistant Pat McLaughlin
pmclaughlin@ostp.eop.gov, 202-456-6045

From: Camille Romano [mailto:cromano@whrc.org]
Sent: Thursday, April 09, 2009 8:31 AM
To: Holdren, John P.; WHRC Staff
Subject: RE: AP story about geo-engineering and the White House

and if you are looking for the AP story in today's print edition of the Cape Cod Times, it is found on the Obituary page, complete with a picture of John.

Somewhat disturbing to see before your morning coffee...

> -----Original Message-----
> **From:** Holdren, John P. [mailto:John_P._Holdren@ostp.eop.gov]
> **Sent:** Wednesday, April 08, 2009 5:32 PM
> **To:** whrcspam@whrc.org
> **Subject:** AP story about geo-engineering and the White House
>
> Colleagues:

In case the account of an interview with me that went out on the AP wire today comes to your notice, please know -- as you probably will suspect -- that the AP account gives a serious misimpression about what I actually said. In the course of a wide-ranging half-hour interview on my new job, high-tech innovation for economic growth, energy, national security, and climate change, I got asked about whether we need to think about geo-engineering as a response to the climate problem and I spent about three minutes on it. I said that the approaches that have been surfaced so far seem problematic in terms of both efficacy and side effects, but we have to look at the possibilities and understand them -- including their shortcomings -- because if other approaches to mitigation fall short the geo-engineering approach will end up being considered. I also made clear that this was my personal view, not Administration policy. Asked whether I had mentioned geo-engineering in any White House discussions, though, I said that I had. This is of course NOT the same thing as saying the White House is giving serious consideration to geo-engineering – which it isn't at this point -- and I am dismayed that the headline and the text of the article suggest otherwise, as well as dismayed that the entire AP story focused on this minor point in the interview.

Cheers anyway,
John

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Leonard, Rachael L.

From: Holdren, John P.
Sent: Friday, May 15, 2009 1:23 PM
To: Leonard, Rachael L.
Subject: FW: Geoengineering and stuff

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Assistant to the President for Science and Technology and Director, Office of Science and Technology Policy Executive Office of the President of the United States
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pmclaughlin@ostp.eop.gov, 202-456-6045

-----Original Message-----
From: Holdren, John P.
Sent: Thursday, April 09, 2009 9:57 AM
To: 'Joe Romm'
Subject: RE: Geoengineering and stuff

I said exactly that to Seth Borenstein. He did an absolutely terrible job reporting on the 3 minutes we spent on his question about geo-engineering in a 30-minute interview about science and technology policy broadly, not least by making that minor side point the entire focus of his article.

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-----Original Message-----
From: Joe Romm [mailto:jromm@americanprogress.org]
Sent: Thursday, April 09, 2009 9:57 AM
To: Holdren, John P.
Subject: Geoengineering and stuff

John:

Congrats on new job. I'd love an interview/chat sometime for ClimateProgress.org, the most widely read climate blog in the country.

One question -- I don't have a problem with anything you've said on geo-engineering but would since I have quoted your 2006 "Innovations" article -- http://belfercenter.ksg.harvard.edu/publication/765/energy_innovation_imperative.html -- repeatedly on my blog, I'd just like to be able to tell my readers you still agree with what you wrote 3 years ago:

"The 'geo-engineering' approaches considered so far appear to be afflicted with some combination of high costs, low leverage, and a high likelihood of serious side effects."

Joseph Romm
Senior Fellow
Center for American Progress
Editor, ClimateProgress.org

Leonard, Rachael L.

From: Holdren, John P.
Sent: Friday, May 15, 2009 1:23 PM
To: Leonard, Rachael L.
Subject: FW: AP story about geo-engineering and the White House

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From: Holdren, John P.
Sent: Thursday, April 09, 2009 10:42 AM
To: Fetter, Steven A.
Subject: FW: AP story about geo-engineering and the White House

Realized I failed to send you any version of this, [redacted]

L Exemption 5 - deliberative

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From: Holdren, John P.
Sent: Wednesday, April 08, 2009 7:24 PM
To: 'rbierbau@hotmail.com'; 'SternTD@state.gov'; 'DSandalow@brookings.edu'
Subject: AP story about geo-engineering and the White House

Todd, David, Rosina --

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Cheers anyway,
John

PS: The Washington Post on-line article about their interview with me is also something of a mess. The headline, which I hope we can get changed in the print edition, confuses not starting with a 100% auction with not starting cap-and-trade at all. The first sentence is better but still hardly a model of clarity. I may never talk to the press again.

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From: Holdren, John P.
Sent: Thursday, April 09, 2009 10:46 AM
To: Fetter, Steven A.
Subject: RE: AP story about geo-engineering and the White House

You can send it to Joe. I sent it last night to Carol.

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From: Fetter, Steven A.
Sent: Thursday, April 09, 2009 10:44 AM
To: Holdren, John P.
Subject: RE: AP story about geo-engineering and the White House

Thanks, John. Can I also forward your explanation to Joe Aldy, who asked to talk to me about this? Or would you prefer that I simply convey the jist to him in person?

From: Holdren, John P.
Sent: Thursday, April 09, 2009 10:42 AM
To: Fetter, Steven A.
Subject: FW: AP story about geo-engineering and the White House

Realized I failed to send you any version of this, [redacted]

L exemption 5 - deliberative

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Leonard, Rachael L.

From: Holdren, John P.
Sent: Friday, May 15, 2009 1:22 PM
To: Leonard, Rachael L.
Subject: FW: Holdren e-mail on AP story about geo-engineering and the White House

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Executive Assistant Pat McLaughlin
pmclaughlin@ostp.eop.gov, 202-456-6045

From: Holdren, John P.
Sent: Thursday, April 09, 2009 2:56 PM
To: Weiss, Richard S.
Subject: Holdren e-mail on AP story about geo-engineering and the White House

Rick -- I sent out a couple of versions of the e-mail explaining the problems with the AP story. The one below, which says "about three minutes", is fine *with me* to send to AP. (If they put a stopwatch to me and discover it was five minutes in a half hour interview and not three, nobody is going to give them a pass on what they did.) But Ellen said this morning that I should *not* [redacted] and this could be seen as the equivalent of that -- or could become so [redacted]
Cheers, John

Exemptions 5, deliberative

JOHN P. HOLDREN
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and Director, Office of Science and Technology Policy
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jholdren@ostp.eop.gov, 202-456-7116
Executive Assistant Pat McLaughlin
pmclaughlin@ostp.eop.gov, 202-456-6045

From: Holdren, John P.
Sent: Wednesday, April 08, 2009 7:24 PM
To:
Subject: AP story about geo-engineering and the White House

Colleagues --

In case the account of an interview with me that went out on the AP wire today comes to your notice, please know -- as you probably will suspect -- that the AP account gives a serious misimpression about what I actually said. In the course of a wide-ranging half-hour interview on my new job, high-tech innovation for economic growth, energy, national security, and climate change, I got asked about whether we need to think about geo-engineering as a response to the climate problem and I spent about three minutes on it. I said that the approaches that have been surfaced so far seem problematic in terms of both efficacy and side effects, but we have to look at the possibilities and understand them -- including their shortcomings -- because if other approaches to mitigation fall short the geo-engineering approach will end up being considered. I also made clear that this was my personal view, not Administration policy. Asked whether I had mentioned geo-engineering in any White House discussions, though, I said that I had. This is of course NOT the same thing as saying the White House is giving serious consideration to geo-engineering – which it isn't at this point -- and I am dismayed that the headline and the text of the article suggest otherwise, as well as dismayed that the entire AP story focused on this minor point in the interview.

Cheers anyway,
John

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Leonard, Rachael L.

From: Holdren, John P.
Sent: Friday, May 15, 2009 1:22 PM
To: Leonard, Rachael L.
Subject: FW: Holdren on Geoengineering Solutions to Climate Change

JOHN P. HOLDREN
Assistant to the President for Science and Technology
and Director, Office of Science and Technology Policy
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Executive Assistant Pat McLaughlin
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From: Holdren, John P.
Sent: Thursday, April 09, 2009 5:05 PM
To: 'Richard Caputo'
Subject: RE: Holdren on Geoengineering Solutions to Climate Change

Rich -- I was hideously misrepresented. Note below is what I sent to colleagues here and there. White House Press Office judgment was not to send it as a letter to the editor, I think because they believe that just keeps the story alive. Cheers anyway, John

> In case the account of an interview with me that went out on the AP wire today comes to your notice, please know -- as you probably will suspect -- that the AP account gives a serious misimpression about what I actually said. In the course of a wide-ranging half-hour interview on my new job, high-tech innovation for economic growth, energy, national security, and climate change, I got asked about whether we need to think about geo-engineering as a response to the climate problem and I spent about three minutes on it. I said that the approaches that have been surfaced so far seem problematic in terms of both efficacy and side effects, but we have to look at the possibilities and understand them -- including their shortcomings -- because if other approaches to mitigation fall short the geo-engineering approach will end up being considered. I also made clear that this was my personal view, not Administration policy. Asked whether I had mentioned geo-engineering in any White House discussions, though, I said that I had. This is of course NOT the same thing as saying the White House is giving serious consideration to geo-engineering – which it isn't at this point -- and I am dismayed that the headline and the text of the article suggest otherwise, as well as dismayed that the entire AP story focused on this minor point in the interview.

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From: Richard Caputo [mailto:richardcaputo@sbcglobal.net]
Sent: Thursday, April 09, 2009 4:44 PM
To: Holdren, John P.
Subject: Re: Holdren on Geoengineering Solutions to Climate Change

John,

I know this sort of statement is news, but do read *Hitting the Wall*.

Rich

Rich Caputo
American Solar Energy Society
760-765-3157
P.O. Box 1660
Julian, CA 92036

From: Toshio Fujita <Toshio.Fujita@jpl.nasa.gov>
To: manvi_ram@yahoo.com; rmanvi@calstatela.edu; "Manvi, Ram" <Ram.Manvi@canyons.edu>; Henry <engineer@hawayahealing.com>; Philip I Moynihan <pimoynihan@earthlink.net>; Bill J Nesmith <Bill.J.Nesmith@jpl.nasa.gov>; Jeffrey M Schredder <Jeffrey.M.Schredder@jpl.nasa.gov>; jeff@alumni.caltech.edu; Richard Caputo <richardcaputo@sbcglobal.net>; Gajanana C Birur <Gajanana.C.Birur@jpl.nasa.gov>; Chris England <cengland@theplanetelectric.com>; Nabil Elgabalawi <Nabil.Elgabalawi@aero.org>; nabil elgabalawi <nabil.elgabalawi@gmail.com>; Bill Dean <wldeanpe@sbcglobal.net>; Long.K.Pham@sce.com; nfries1111@aol.com; Edmund C Baroth <Edmund.C.Baroth@jpl.nasa.gov>; Hung Q Pham <Hung.Q.Pham@jpl.nasa.gov>; Richard E Wirz <Richard.E.Wirz@jpl.nasa.gov>; Daniel B Klein <Daniel.B.Klein@jpl.nasa.gov>; Mauro Prina <Mauro.Prina@gmail.com>; Robert Phen <rphen@earthlink.net>; Wesley Menard <wesleymenard@msn.com>; Kudret Selcuk <mkudret@yahoo.com>; Gani B Ganapathi <Gani.B.Ganapathi@jpl.nasa.gov>; Steven J Hendricks <stevenjhendrix@yahoo.com>; William R Revere <William.R.Revere@jpl.nasa.gov>; Alan Marriott <almarriott@msn.com>; Bob Beale <rjbeale@vcweb.org>; Z.Sibel Ozdogan <sozdogan@eng.marmara.edu.tr>; Isil I Gulsac <isil.gulsac@mam.gov.tr>; Tommaso P Rivellini <Tommaso.P.Rivellini@jpl.nasa.gov>; oguz turkyilmaz <oguz.turkyilmaz@mmo.org.tr>; ronoglevie@aol.com; owinn@att.net; gvoecks@gmail.com; ygogus@metu.edu.tr
Sent: Thursday, April 9, 2009 10:21:40 AM
Subject: Holdren on Geoengineering Solutions to Climate Change

FYI--Tosh

AP Newsbreak: Obama looks at climate engineering
Apr 8 10:55 AM US/Eastern
By SETH BORENSTEIN
AP Science Writer
Comments (630)

Bookmark and Share

Obama Looking Into "Radical Technologies to Cool Earth's Air'

WASHINGTON (AP) - The president's new science adviser said Wednesday that global warming is so dire, the Obama administration is discussing radical technologies to cool Earth's air.

John Holdren told The Associated Press in his first interview since being confirmed last month that the idea of geoengineering the climate is being discussed. One such extreme option includes shooting pollution particles into the upper atmosphere to reflect the sun's rays. Holdren said such an experimental measure would only be used as a last resort.

"It's got to be looked at," he said. "We don't have the luxury of taking any approach off the table."

Holdren outlined several "tipping points" involving global warming that could be fast approaching. Once such milestones are reached, such as complete loss of summer sea ice in the Arctic, it increases chances of "really intolerable consequences," he said.

Twice in a half-hour interview, Holdren compared global warming to being "in a car with bad brakes driving toward a cliff in the fog."

At first, Holdren characterized the potential need to technologically tinker with the climate as just his personal view. However, he went on to say he has raised it in administration discussions.

Holdren, a 65-year-old physicist, is far from alone in taking geoengineering more seriously. The National Academy of Science is making climate tinkering the subject of its first workshop in its new multidiscipline climate challenges program. The British parliament has also discussed the idea.

The American Meteorological Society is crafting a policy statement on geoengineering that says "it is prudent to consider geoengineering's potential, to understand its limits and to avoid rash deployment."

Last week, Princeton scientist Robert Socolow told the National Academy that geoengineering should be an available option in case climate worsens dramatically.

But Holdren noted that shooting particles into the air-making an artificial volcano as one Nobel laureate has suggested-could have grave side effects and would not completely solve all the problems from soaring greenhouse gas emissions. So such actions could not be taken lightly, he said.

Still, "we might get desperate enough to want to use it," he added.

Another geoengineering option he mentioned was the use of so-called artificial trees to suck carbon dioxide-the chief human-caused greenhouse gas-out of the air and store it. At first that seemed prohibitively expensive, but a re-examination of the approach shows it might be less costly, he said.

Leonard, Rachael L.

From: Holdren, John P.
Sent: Friday, May 15, 2009 1:21 PM
To: Leonard, Rachael L.
Subject: Geo-engineering

JOHN P. HOLDREN
Assistant to the President for Science and Technology and Director, Office of Science and Technology Policy Executive Office of the President of the United States
jholdren@ostp.eop.gov, 202-456-7116 Executive Assistant Pat McLaughlin
pmclaughlin@ostp.eop.gov, 202-456-6045

-----Original Message-----
From: Holdren, John P.
Sent: Friday, April 10, 2009 6:58 AM
To: 'jholdren@whrc.org'
Subject: RE: Climate change

Douglas --

Thanks for this note. My views on geo-engineering were garbled by the AP story. In the course of a wide-ranging half-hour interview on my new job, high-tech innovation for economic growth, energy, national security, and climate change, I got asked about whether we need to think about geo-engineering as a response to the climate problem and I spent about three minutes on it. I said that the approaches that have been surfaced so far seem problematic in terms of both efficacy and side effects, but we have to look at the possibilities and understand them -- including their shortcomings -- because if other approaches to mitigation fall short the geo-engineering approach will end up being considered. I also made clear that this was my personal view, not Administration policy. Asked whether I had mentioned geo-engineering in any White House discussions, though, I said that I had. This is of course NOT the same thing as saying the White House is giving serious consideration to geo-engineering – which it isn't at this point -- and I am dismayed that the headline and the text of the article suggest otherwise, as well as dismayed that the entire AP story focused on this minor point in the interview.

Best,
John

JOHN P. HOLDREN
Assistant to the President for Science and Technology and Director, Office of Science and Technology Policy Executive Office of the President of the United States
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pmclaughlin@ostp.eop.gov, 202-456-6045

-----Original Message-----
From: jholdren@whrc.org [mailto:jholdren@whrc.org]
Sent: Friday, April 10, 2009 6:28 AM
To: Holdren, John P.
Subject: Fw: Climate change

------Original Message------
From: Douglas R Shanklin
To: jholdren@whrc.org
Sent: Apr 9, 2009 9:02 PM
Subject: Climate change

This is on the theory you still get some email through WHRC. Noted the Woods Hole Compact recently agreed to between WHRC, MBL, and WHOI. I view this as a good development. Hadn't heard from you since

confirmation referent Cosmos Club but figured you likely have a very full plate right now. You made the paper Washington Examiner for today, April 9th, page 16, with a piece about geoengineering and climate change. Like your metaphor for the pending cliff fall but would note that the really public grabbing metaphor has yet to be designed. Particles in the air reminds one of Krakatoa in 1883 and the effects on sunsets, crops, and global temperatures, not to mention the evidence for a possible earlier eruption in 535 C.E. My publisher, Charles C Thomas, wants a third edition of my book "Maternal nutrition and child health, (2nd ed. 2000)"
- - they just contacted me this week - - this is very timely because the effects of global warming and climate change on crops and other food stocks will underlie international success or failure to provide both sufficient food and good diet for all, especially pregnant women, and this topic has to appear in the revised book. I plan to refresh my knowledge of the situation in The Gambia, one of the "canaries in the coal mine" parts of the world with dramatically different results in pregnancy between the dry and wet seasons. There have been many aspects of newer knowledge on gross nutrition and the cell biology behind nutrition since I rewrote the book for the 2000 second edition. The first edition came out in 1979 in time for the then congressionally mandated evaluation of the WIC food supplement program under USDA. I was the chair of the evaluation team, partially by default I think, because I was the only member of the panel with a lot of obstetrical experience beyond medical school (US Navy - 18 months). Best wishes. D. R. Shanklin, M.D., FRSM

Leonard, Rachael L.

From: Holdren, John P.
Sent: Friday, May 15, 2009 1:21 PM
To: Leonard, Rachael L.
Subject: FW: AP story on geo-engineering and the White House

JOHN P. HOLDREN
Assistant to the President for Science and Technology
and Director, Office of Science and Technology Policy
Executive Office of the President of the United States
jholdren@ostp.eop.gov, 202-456-7116
Executive Assistant Pat McLaughlin
pmclaughlin@ostp.eop.gov, 202-456-6045

From: Holdren, John P.
Sent: Friday, April 10, 2009 7:24 AM
To: 'pgleick@pipeline.com'; 'dlashof@nrdc.org'; 'dhawkins@nrdc.org'; 'jhansen@giss.nasa.gov'; 'omichael@princeton.edu'; 'schrag@eps.harvard.edu'; 'rlg2@us.ibm.com'; 'william_clark@harvard.edu'; 'jharte@berkeley.edu'; 'kammen@berkeley.edu'; 'hkelly@fas.org'; 'Ann.Kinzig@asu.edu'; 'roger@rkennedy.net'; 'jgkoomey@stanford.edu'; 'neal@rice.edu'; 'amory@rmi.org'; 'mmaccrac@comcast.net'; 'edmarkey@edmarkey.org'; 'jmathews@ceip.org'; 'jmelillo@mbl.edu'; 'gborisy@mbl.edu'; 'savery@whoi.edu'; 'mnorthrop@rbf.org'; 'schipper@wri.org'; 'nick@sundt.org'; 'diana@nrel.colostate.edu'; 'twirth@unfoundation.org'; 'mirth@unfoundation.org'; 'lovejoy@heinzctr.org'; 'aimee@christensenglobal.com'; 'stc@loe.org'
Subject: AP story on geo-engineering and the White House

Colleagues --

The stance of the White House on geoengineering was garbled in the AP story about an interview with me that went out earlier this week. In the course of a wide-ranging half-hour interview on my new job, high-tech innovation for economic growth, energy, national security, and climate change, I got asked about whether we need to think about geo-engineering as a response to the climate problem and I spent a few minutes on it. I said that the approaches that have been surfaced so far seem problematic in terms of both efficacy and side effects, but we have to look at the possibilities and understand them -- including their shortcomings -- because if other approaches to mitigation fall short the geo-engineering approach will end up being considered. I also made clear that this was my personal view, not Administration policy. I was asked to describe some examples of geo-engineering approaches and mentioned orbiting reflecting particles and sulfates injected into the stratosphere, explaining their shortcomings and making clear that I was not endorsing them. Asked whether I had mentioned geo-engineering in any White House discussions, though, I said that I had. This is of course NOT the same thing as saying the White House is giving serious consideration to geo-engineering – which it isn't at this point -- and I am dismayed that the headline and the text of the article suggest otherwise, as well as dismayed that the entire AP story focused on this minor point in the interview.

Cheers anyway,
John

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jholdren@ostp.eop.gov, 202-456-7116
Executive Assistant Pat McLaughlin
pmclaughlin@ostp.eop.gov, 202-456-6045

Leonard, Rachael L.

From: Holdren, John P.
Sent: Friday, May 15, 2009 1:20 PM
To: Leonard, Rachael L.
Subject: FW: AP story on geo-engineering and the White House

JOHN P. HOLDREN
Assistant to the President for Science and Technology
and Director, Office of Science and Technology Policy
Executive Office of the President of the United States
jholdren@ostp.eop.gov, 202-456-7116
Executive Assistant Pat McLaughlin
pmclaughlin@ostp.eop.gov, 202-456-6045

From: Holdren, John P.
Sent: Friday, April 10, 2009 7:33 AM
To: 'hcullen@climatecentral.org'; 'bmoore@climatecentral.org'
Subject: AP story on geo-engineering and the White House

Dear Heidi and Berrien --

Wanted you to know, as you probably suspected, that the stance of the White House on geoengineering was garbled in the AP story about an interview with me that went out earlier this week. In the course of a wide-ranging half-hour interview on my new job, high-tech innovation for economic growth, energy, national security, and climate change, I got asked about whether we need to think about geo-engineering as a response to the climate problem and I spent a few minutes on it. I said that the approaches that have been surfaced so far seem problematic in terms of both efficacy and side effects, but we have to look at the possibilities and understand them -- including their shortcomings -- because if other approaches to mitigation fall short the geo-engineering approach will end up being considered. I also made clear that this was my personal view, not Administration policy. I was asked to describe some examples of geo-engineering approaches and mentioned orbiting reflecting particles and sulfates injected into the stratosphere, explaining their shortcomings and making clear that I was not endorsing them. Asked whether I had mentioned geo-engineering in any White House discussions, though, I said that I had. This is of course NOT the same thing as saying the White House is giving serious consideration to geo-engineering – which it isn't at this point -- and I am dismayed that the headline and the text of the article suggest otherwise, as well as dismayed that the entire AP story focused on this minor point in the interview.

Cheers anyway,
John

PS: Feel free to share this with ClimateCentral staff and board.

JOHN P. HOLDREN
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Climate-Change Science and Technology

What Do We Know? What Could We Do?

John P. Holdren

Assistant to the President for Science and Technology
and Director, Office of Science and Technology Policy
Executive Office of the President of the United States

Presentation for the
Energy Bar Association Annual Meeting
Washington, DC ▪ 23 April 2009

Prologue

- The intersection of energy, economy, and environment poses diverse challenges. Among the most important are…
  - providing reliable & affordable energy services to meet the basic needs of our poorest citizens;
  - providing the larger quantities of affordable energy that our economy needs to grow;
  - reducing our costly & dangerous dependence on foreign oil;
  - upgrading our aging & vulnerable transmission infrastructure;
  - and ameliorating the wide-ranging impacts of energy supply on the environmental underpinnings of our well-being.

Prologue (continued)

- Taking nothing away from the importance of all of these, I focus here on the part of the challenge that I think is the most demanding in what it will require of us, but also the most promising in the potential of the solutions to drive innovation, new businesses, and new jobs:

  The challenge of providing the energy that will be needed to create and sustain economic prosperity everywhere without wrecking the global climate with the emissions of carbon dioxide from the kinds of fossil-fuel technologies that provide most of world energy use today.

Coverage of these remarks

- The essence of the challenge
- Current insights from climate-change science
- The choices: mitigation, adaptation, suffering
- How much mitigation should we want?
- What technologies could provide it, and what would they cost?
- The option space for policy

The energy-economy-climate challenge is central to the human condition because...

- Without energy there is no economy
- Without climate there is no environment
- Without economy & environment there is no material well-being, no civil society, no security

Alas, the world is getting most of the energy its economies need in ways that are wrecking the climate its environment needs.

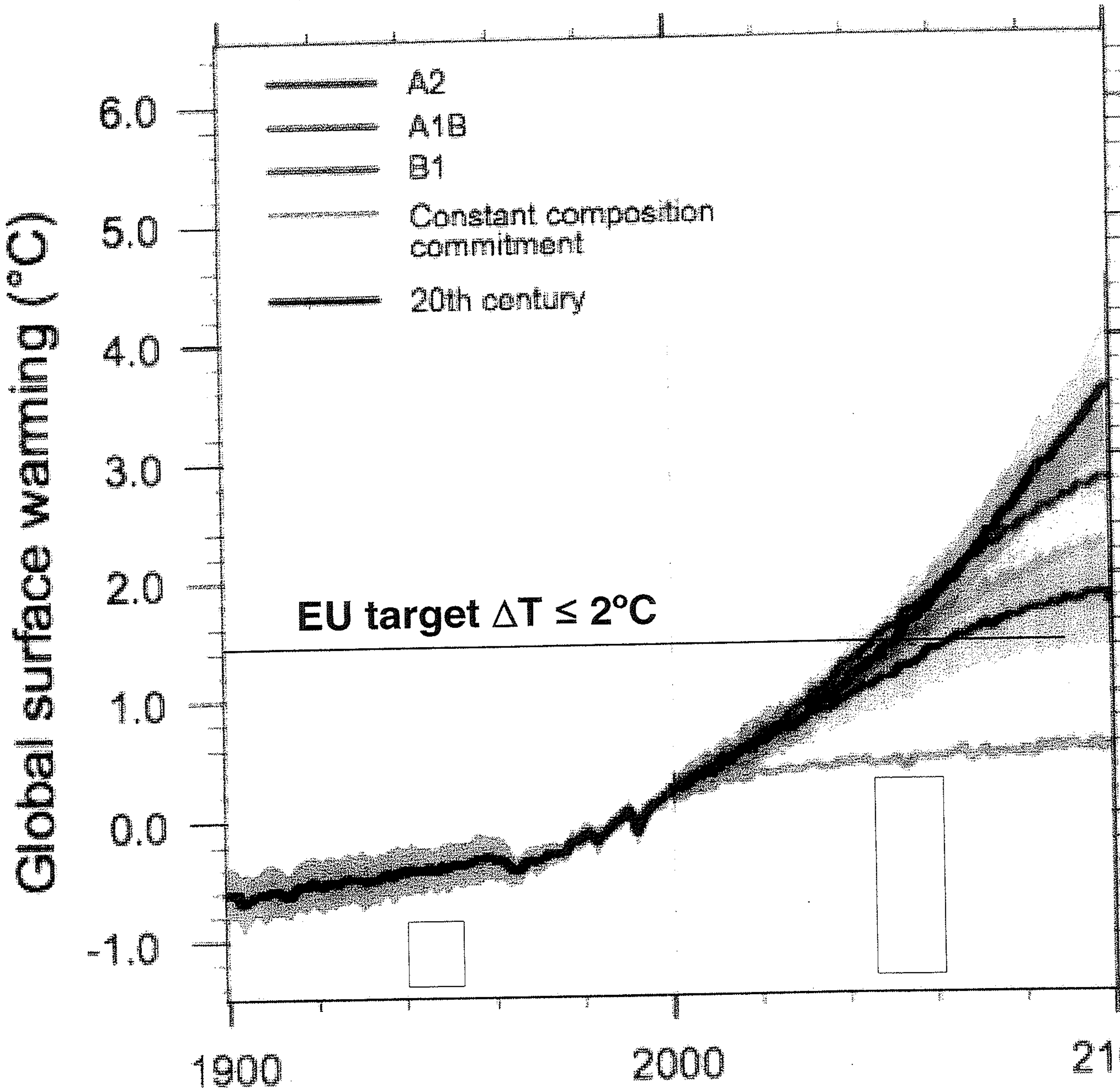
Current insights from climate science

- Climate change is happening faster than previously predicted
  - emissions, concentrations, temperatures (regional & global), & sea level all rising at rates at or above those of earlier IPCC “high” scenarios
- Significant harm to human well-being is already occurring
  - avoiding “dangerous” human interference is no longer possible: we’re experiencing “dangerous” now
- Evidence is emerging that “tipping points” into ecologically & societally unmanageable changes could occur sooner rather than later

Climate-change impacts already happening

- monsoon changes → agriculture impacts
- extreme precipitation → more floods
- ΔT + reduced precipitation in some regions & more loss to storm runoff in others → increased drought & soil drying
- ΔT & soil drying → increased wildfires
- ΔT → more heat stress and worse air pollution
- ΔT → pest population explosions → big timber losses (Alaska, CO, CA...)
- tropical ocean ΔT is affecting corals (bleaching)
- increased integrated power of tropical storms is <u>likely</u> linked to ocean ΔT

Bigger disruption is coming: IPCC 2007 scenarios



Last time T was 2°C above 1900 level was 130,000 yr BP, with sea level 4-6 m higher than today.

Last time T was 3°C above 1900 level was ~30 million yr BP, with sea level 20-30 m higher than today.

Note: Shaded bands denote 1 standard deviation from mean in ensembles of model runs

IPCC 2007

Tipping points aren't necessarily far off

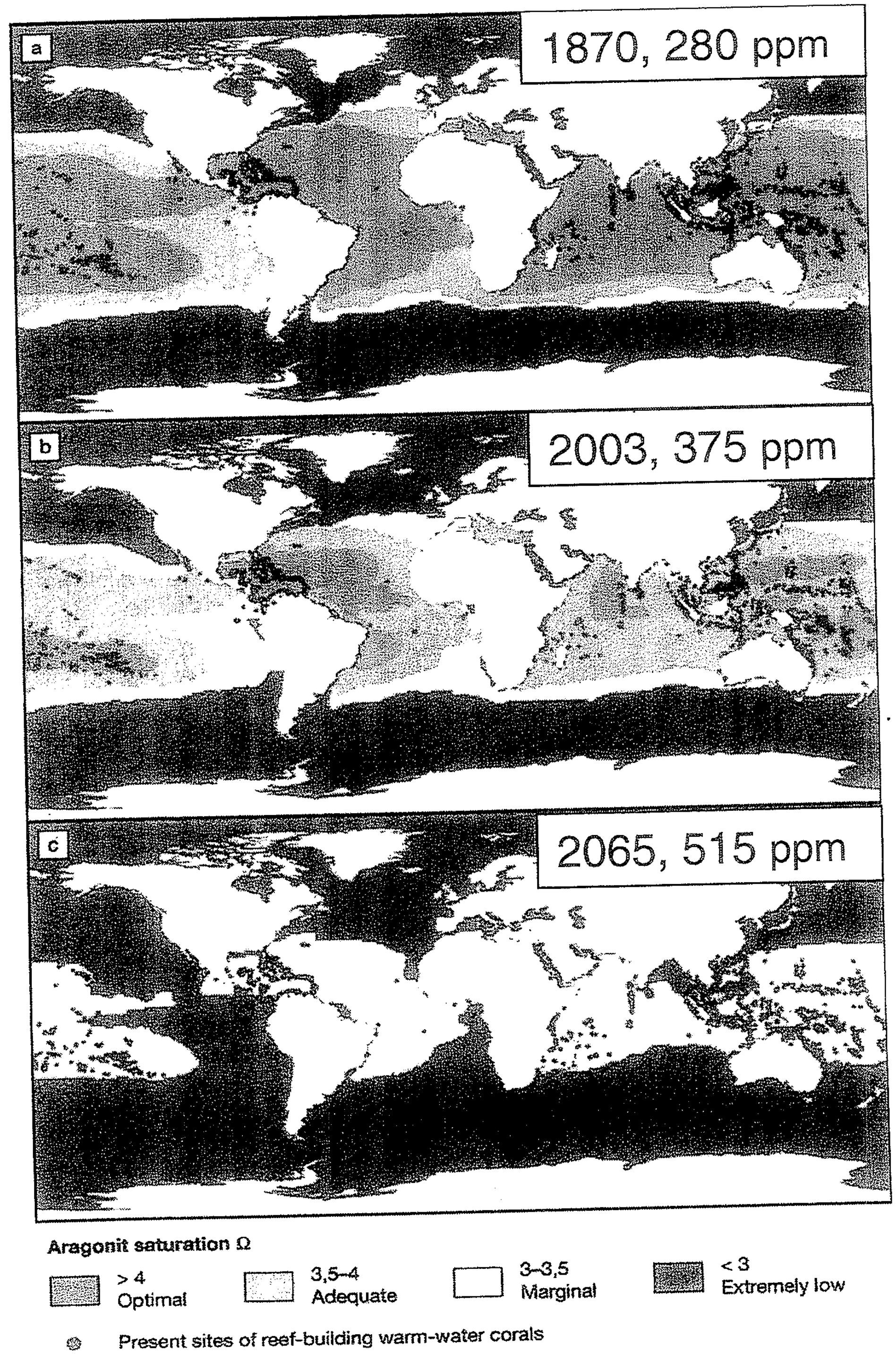
- Arctic sea ice is shrinking much faster than expected; if it disappears and doesn't re-form, climate of N hemisphere would change drastically.
- Rapid ice-sheet disintegration (1-2 m per century sea-level rise) possible for $\Delta T_{avg} \geq 1.5°C$.
- Tundra & permafrost are warming & thawing, with potential for CO_2 and methane outpouring that would accelerate climate disruption overall.
- Ocean acidification by dissolution of part of excess atmospheric CO_2 further stresses corals as well as other ocean creatures that make $CaCO_3$ shells or skeletons.

Pickling the oceans: a tipping point?

About 1/3 of CO_2 added to atmosphere is quickly taken up by the surface layer of the oceans (top 80 meters).

This lowers pH as dissolution of CO_2 forms weak carbonic acid ($H_2O + CO_2 \rightarrow H_2CO_3$).

Increased acidity lowers the availability of $CaCO_3$ to organisms that use it for forming their shells & skeletons, including corals.



Steffen et al., 2004

What can be done?

There are 3 options:

- <u>Mitigation</u>, meaning measures to reduce the pace & magnitude of the changes in global climate being caused by human activities.
- <u>Adaptation</u>, meaning measures to reduce the adverse impacts on human well-being resulting from the changes in climate that do occur.
- <u>Suffering</u> the adverse impacts that are not avoided by either mitigation or adaptation.

Mitigation possibilities

CERTAINLY

- Reduce emissions of greenhouse gases & soot from the energy sector
- Reduce deforestation; increase reforestation & afforestation
- Modify agricultural practices to reduce emissions of greenhouse gases & build up soil carbon

CONCEIVABLY

- "Geo-engineering" to create cooling effects offsetting greenhouse heating
- "Scrub" greenhouse gases from the atmosphere technologically

Adaptation possibilities include…

- Changing cropping patterns
- Developing heat-, drought-, and salt-resistant crop varieties
- Strengthening public-health & environmental-engineering defenses against tropical diseases
- Building new water projects for flood control & drought management
- Building dikes and storm-surge barriers against sea-level rise
- Avoiding further development on flood plains & near sea level

Some are "win-win": They'd make sense in any case.

Mitigation & adaptation are both essential

- No feasible amount of mitigation can stop climate change in its tracks.
- Adaptation efforts are already taking place and must be expanded.
- But adaptation becomes costlier & less effective as the magnitude of climate changes grows.
- The more mitigation can be achieved at affordable cost, the smaller the burdens placed on adaptation and the smaller the suffering.

Emissions implications of "prudence"

- 550 ppmv CO_2-e (50% chance of $\Delta T_{avg} < 3^oC$) looks unlikely to avoid unmanageable change
- 450 ppmv CO_2-e (50% chance of $\Delta T_{avg} < 2^oC$) would be more prudent (but still no guarantee)
- Achieving 450 ppmv requires global emissions to level off by ~2020 and decline thereafter to ~50% below 2000 emissions by 2050.
- For this to occur, emissions in USA & other industrial countries probably need to level off by 2015 and decline thereafter to ~80% below 2000 emissions by 2050.

Realities of reducing CO_2 emissions

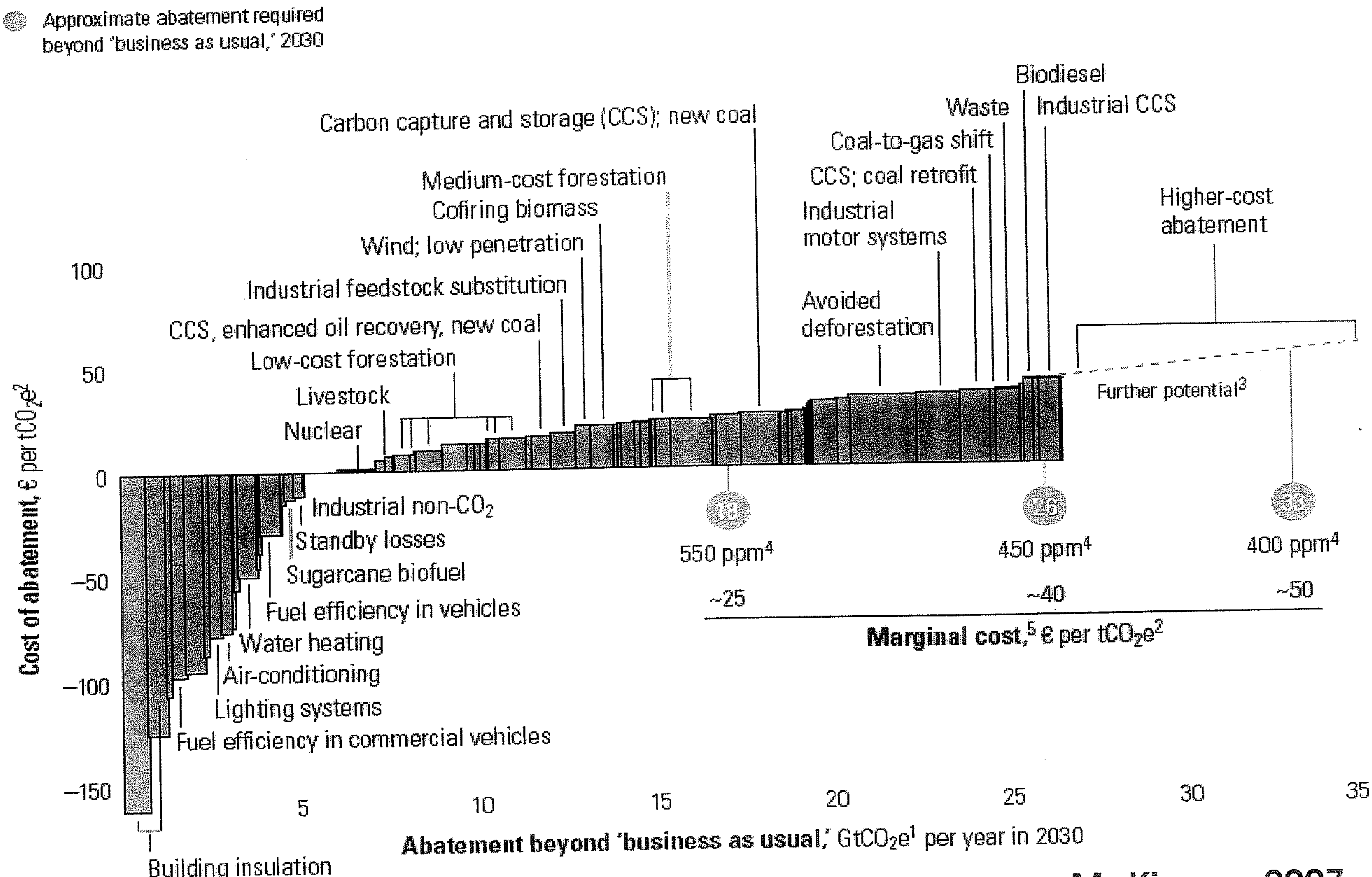
- Stabilizing at 450 ppmv CO_2-e means 2050 global CO_2 emissions must be ~7-9 GtC/yr below BAU.
- To understand the size of this challenge, consider some examples of how much it takes to avoid <u>one</u> GtC/yr in 2050:

- energy use in all the world's buildings cut ~25% below BAU in 2050, <u>or</u>
- fuel economy of 2 billion cars is ~60 mpg instead of 30, <u>or</u>
- 800 1-GWe coal-burning power plants capture & sequester their CO_2 rather than emitting it, <u>or</u>
-1 million 2-MWe wind turbines replace coal power plants <u>or</u>
- 2,000 1-GWe(peak) photovoltaic power plants replace coal power plants <u>or</u>
- tropical deforestation rate is cut in half worldwide from 2005

Socolow & Pacala, 2004

Supply curve for mitigation in 2030

Global cost curve for greenhouse gas abatement measures beyond 'business as usual'; greenhouse gases measured in $GtCO_2e$[1]



McKinsey, 2007

Possible focuses for policy: the option space

- Remove barriers to harvesting the low-hanging fruit (and the fruit lying on the ground)

  options include: consumer education; labeling; remedies for perverse incentives /disincentives

- Provide incentives for reaching higher into the tree

  options include: elimination of subsidies for high-emitting energy sources; provision of subsidies for low-emitting ones; charges on emissions; regulation

- Support and promote RD&D to lower the highest-hanging fruit

  options include: gov't funding; tax credits for private –sector RD&D; price guarantees for new sources

I leave to the next speaker, Dr. Sue Tierney, the task of discussing the pros, cons, and prospects of different combinations of these approaches in the current U.S. political context.

DeCola, Philip L.

From: Decola, Philip L. (HQ-DK000) [pdecola@nasa.gov]
Sent: Tuesday, May 05, 2009 7:57 AM
To: DeCola, Philip L.
Subject: FW: [geo] Re: John Holdren puts geoengineering on the table
Attachments: Erice-Geoengineering-040509.doc

------ Forwarded Message
From: MacCracken_Mike <mmaccrac@comcast.net>
Date: Thu, 9 Apr 2009 15:27:22 -0500
To: Phil DeCola <pdecola@hq.nasa.gov>
Subject: FW: [geo] Re: John Holdren puts geoengineering on the table

Hi Phil—You might clear John up on all of this (see below)—the idea is not particles in orbit (they would get knocked out quickly), but in the stratosphere like a volcano.

It is a bit long but here is report I just did for an Erice conference (based on my paper for the World Bank) that provides a whole range of ideas and review on the topic. Make sure to get John H up to date.

Best, Mike

------ Forwarded Message
From: Alvia Gaskill <agaskill@nc.rr.com>
Reply-To: Alvia Gaskill <agaskill@nc.rr.com>
Date: Thu, 9 Apr 2009 04:46:56 -0400
To: David Keith <keith@ucalgary.ca>, <dwschnare@gmail.com>
Cc: <kelly.wanser@gmail.com>, Geoengineering <Geoengineering@googlegroups.com>
Subject: [geo] Re: John Holdren puts geoengineering on the table

http://cosmos.bcst.yahoo.com/up/ynews;_ylt=AgWN.Ual3bpVBdthMQx.sxJdRJ54;_ylu=X3oDMTE2YnQ ch=4226722&cl=12882507&lang=en

Here is part of the actual video of the interview with Holdren by Seth Borenstein. In it, he refers to injecting reflective particles into low Earth orbit as one of the most discussed geoengineering ideas. It is not. He does seem to be aware of some of the generic arguments for and against SRM. He says SRM would be too expensive and would interfere with spacecraft. The other article I posted indicates he has a crude and possibly inaccurate understanding of aerosol formation and effectiveness. I don't expect all people at the senior policy level to be conversant with all aspects of these technologies, but his mixing up and confusion of these ideas concerns me, especially given the low level of understanding of journalists, leading to a "blind-leading-the-blind" scenario when the time comes to explain this to the public.

----- Original Message -----

From: David Keith <mailto:keith@ucalgary.ca>

To: dwschnare@gmail.com ; agaskill@nc.rr.com

Cc: kelly.wanser@gmail.com ; geoengineering <mailto:geoengineering@googlegroups.com>

Sent: Wednesday, April 08, 2009 11:22 PM

Subject: [geo] Re: John Holdren puts geoengineering on the table

I think this comment is (a) factually incorrect and (b) unhelpful. Holdren has know about this and paid attention for some time, certainly since before we held the 2007 Harvard meeting. I talked with him in the fall on this topic. I don't think it's fair to say that he was "backed into a corner". Further, I can think of several senior folks in DC who take geoengineering seriously. (Heck, I am there twice in the next few weeks on the topic…) I think over-statements like this do more harm than good.

-David

From: geoengineering@googlegroups.com [mailto:geoengineering@googlegroups.com] **On Behalf Of** David Schnare
Sent: April 8, 2009 8:37 PM
To: agaskill@nc.rr.com
Cc: kelly.wanser@gmail.com; geoengineering
Subject: [geo] Re: John Holdren puts geoengineering on the table

Holdren, unlike folks in the environmental advocacy community, can be backed into a corner. Holdren is not stupid and he is not an advocate, so he has to answer the question asked, rather than spin any response into the "on message" screed. Thus, he said the least that he could get away with.

Holdren actually understands the moral dilemma of rejecting AGW or admitting it is too late to "fix" the problem through carbon emissions reductions policies alone.

I don't find any more support from Holdren than we have seen from Hawkins.

I repeat what I have written to this group before. You have no friends in Washington, D.C. (i.e., the government).

David Schnare

On Wed, Apr 8, 2009 at 1:10 PM, Alvia Gaskill <agaskill@nc.rr.com> wrote:

Not much different than what he said in the Hot Planet documentary. Joe Romm misrepresented Holdren's views on this in an article he write late last year by selectively truncating a quote Holdren made about the use of geoengineering. What he actually said was the same as in these articles. We can't take any option off the table. The problems with air capture extend beyond just cost also. It continues to amaze me how journalists still don't grasp the concept of aerosol precursors. I guess it's like teaching a dog to make a phone call. It can be done with great difficulty, but you still can't have an intelligent conversation.

http://www.huffingtonpost.com/2009/04/08/obama-global-warming-plan_n_184657.html

Obama Global Warming Plan Involves Cooling Air
digg Huffpost - Obama Global Warming Plan Involves Cooling Air stumble reddit del.ico.us <http://del.ico.us/> ShareThisSETH BORENSTEIN | April 8, 2009 11:55

AM EST |

WASHINGTON - The president's new science adviser said Wednesday that global warming is so dire, the Obama administration is discussing radical technologies to cool Earth's air.

John Holdren told The Associated Press in his first interview since being confirmed last month that the idea of geoengineering the climate is being discussed. One such extreme option includes shooting pollution particles into the upper atmosphere to reflect the sun's rays. Holdren said such an experimental measure would only be used as a last resort.

"It's got to be looked at," he said. "We don't have the luxury of taking any approach off the table."

Holdren outlined several "tipping points" involving global warming that could be fast approaching. Once such milestones are reached, such as complete loss of summer sea ice in the Arctic, it increases chances of "really intolerable consequences," he said.

Twice in a half-hour interview, Holdren compared global warming to being "in a car with bad brakes driving toward a cliff in the fog."

At first, Holdren characterized the potential need to technologically tinker with the climate as just his personal view. However, he went on to say he has raised it in administration discussions.

Holdren, a 65-year-old physicist, is far from alone in taking geoengineering more seriously. The National Academy of Science is making climate tinkering the subject of its first workshop in its new multidiscipline climate challenges program. The British parliament has also discussed the idea.

The American Meteorological Society is crafting a policy statement on geoengineering that says "it is prudent to consider geoengineering's potential, to understand its limits and to avoid rash deployment."

Last week, Princeton scientist Robert Socolow told the National Academy that geoengineering should be an available option in case climate worsens dramatically.

But Holdren noted that shooting particles into the air _ making an artificial volcano as one Nobel laureate has suggested _ could have grave side effects and would not completely solve all the problems from soaring greenhouse gas emissions. So such actions could not be taken lightly, he said.

Still, "we might get desperate enough to want to use it," he added.

Another geoengineering option he mentioned was the use of so-called artificial trees to suck carbon dioxide _ the chief human-caused greenhouse gas _ out of the air and store it. At first that seemed prohibitively expensive, but a re-examination of the approach shows it might be less costly, he said.

----- Original Message -----
From: "Kelly Wanser" <kelly.wanser@gmail.com>
To: "geoengineering" <geoengineering@googlegroups.com>
Sent: Wednesday, April 08, 2009 11:52 AM
Subject: [geo] John Holdren puts geoengineering on the table

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\> http://www.startribune.com/nation/42671837.html
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\> Obama science adviser: Global warming so dire, we may need to tinker
\> with Earth's atmosphere
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\> Associated Press
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\> WASHINGTON - The president's new science adviser said that global
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\> taking any approach off the table."
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\> Kelly Wanser
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Geoengineering: Getting a Start on a Possible Insurance Policy

Michael C. MacCracken
Chief Scientist for Climate Change Programs
Climate Institute
Washington DC 20036

Abstract

While rapidly reducing emissions of greenhouse gases is the most obvious approach to reducing the deleterious consequences of the accelerating pace and nature of global climate change, doing so will require a near total shift away from carbon-emitting fuels by the mid- to late-21st century. At the present pace of international actions aimed at limiting emissions, there seems little likelihood that atmospheric composition can be stabilized at a level that will avoid "dangerous anthropogenic interference" with the climate system, as called for in the UN Framework Convention on Climate Change. Complicating the situation, as greenhouse gas emissions are reduced, reductions in the offsetting cooling influence of sulfate aerosols from the associated sulfur dioxide emissions will create an additional warming influence that could raise global average temperature by about 0.5°C, over and above a similar commitment that will materialize as oceans warm.

That climate change can be inadvertently induced by human activities has led to consideration of whether advertent steps could be taken to counterbalance the warming influence of greenhouse gases, thus allowing continued benefits from the use of fossil fuels while limiting or avoiding the dangerous and damaging consequences. The approaches that have been proposed include: (1) accelerating removal of greenhouse gases from the atmosphere; (2) limiting incoming solar radiation or increasing the amount of solar radiation reflected by the atmosphere-surface system back to space; and (3) taking actions to limit one or more of the most severe impacts. To date, none of the proposed approaches is capable of counterbalancing all of the most important impacts of fossil fuel use, although a few, while inducing some side effects, appear capable of limiting some of the most adverse consequences if implemented in the near future and continued for many decades into the future.

Before the relative costs, benefits and risks of intentionally intervening can be evaluated in terms of their potential to complement mitigation and proactive adaptation, substantial research is needed. As a first phase in evaluating potential global-scale actions, it would seem most practical and acceptable to initiate research and testing on the effectiveness and complications of four possible interventions that would limit particularly serious impacts: (1) limiting ocean acidification by increasing the removal of carbon dioxide from the atmosphere and upper ocean; (2) limiting the increasing intensity of tropical cyclones; (3) limiting the warming of the Arctic and slowing consequent sea level rise from the melting of glaciers and ice sheets; and (4) sustaining or enhancing the existing sulfate cooling influence that presently offsets about 0.5°C of global warming. To complement the physical and ecological research, in depth consideration is needed of the potential governance structure for an international geoengineering decision-making framework in the event that geoengineering of the global climate system over the long-term becomes essential.

Introduction

In its Fourth Assessment Report, Working Group I of the Intergovernmental Panel on Climate Change (IPCC, 2007a) made clear that warming of the climate system over the 20th century is "unequivocal" and that "[m]ost of the observed increase in global average temperatures since the mid-20th century is *very likely* [meaning greater than 90% likelihood] due to the observed increase in anthropogenic greenhouse gas concentrations." IPCC goes on to project with high confidence that continued reliance on coal, petroleum, and natural gas to generate most of the world's energy, as described in several plausible emission scenarios for the 21st century (IPCC, 2000b), will lead to additional warming of roughly 1 to 6°C and additional sea level rise of at least 0.18 to 0.59 m by 2100,[1] and likely significant further increases during the 22nd century and beyond. The impacts of such changes in climate, particularly changes in the hydrologic cycle, in ocean acidity, in sea level (as a result of melting of the Greenland and West Antarctic ice shelves), and in the intensity and frequency of extreme events, are likely to cause widespread, even catastrophic, damage to the many societies and the environments that will be put at risk.

As a first step, taken well before the changes had become so significant and convincingly established, the nations of the world in 1992 negotiated and agreed to the UN Framework Convention on Climate Change, which set as its objective to achieve "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." The trials and tribulations of nations seeking to meet the Kyoto Protocol, negotiated in 1997 and coming into force in 2005 for most, but not all of the industrialized nations, have indicated the level of inertia and difficulty in reducing emissions. Negotiations over a successor agreement are also indicating only slow progress.

At the same time that it is appearing difficult to reduce emissions, the rate of change of the climate is suggesting that the level to achieve stabilization and avoid 'dangerous anthropogenic interference' is lower than had been projected. Early estimates were that the impacts associated with a carbon dioxide (CO_2) concentration as high as 550 ppmv, which would be about twice its preindustrial level, would be acceptable, and would have allowed a measured transition to non-fossil energy technologies over the 21st century. With important impacts already evident at the present CO_2 concentration of 385 ppmv, the lowest concentration at which economic analyses suggested that stabilization seemed even remotely possible was 450 ppmv. By default, this level has seemed to become the lowest level negotiators are considering, even though Meinshausen (2006) indicates that such a level would lead to a 50% probability that the global average temperature increase since preindustrial will exceed 2°C. The Commission of European Communities (2007) has, based on Schellnhuber et al. (2006), concluded that staying below a 2°C warming would avoid 'dangerous' impacts. However, some in the scientific community are

[1] IPCC's (2007a) numerical estimates for sea level rise during the 21st century did not include the potential contributions from dynamic movement of the Greenland and Antarctic ice sheets. Studies since the IPCC assessment suggest that global sea level rise during the 21st century could be from 1 to 2 meters (e.g., Rahmstorf, 2007; Pfeffer et al., 2008).

suggesting that avoiding impacts such as the loss of Arctic sea ice (with commensurate impacts on biodiversity and megafauna), the deterioration of Greenland causing the rate of sea level rise to increase to 1-2 m (or more) per century, significant increases in storm intensity, and large changes in the regional occurrence of drought and flooding and more will require setting the non-dangerous level at 350 ppmv (Hansen et al., 2008) or even below if sea level rise is to be stopped (Wigley, 2005).

If such low levels are really what must be achieved, either emissions need to be cut to zero essentially immediately, or, in that this would be both difficult to achieve and very expensive (Hoffert et al., 2002), the world is going to experience increasingly severe impacts, particularly for particular regions as emissions are more slowly and cost effectively reduced. While proactive adaptation can help to moderate some of the impacts, it very much appears as if the world community is going to have to suffer through quite severe impacts for a century or more until future atmospheric concentrations are brought back to mid- to late-20th century values.

Increasing Interest in Geoengineering

The importance of fossil fuel-derived energy for the world and the difficulties this would create for those negotiating agreements to limit emissions have long been recognized. Budyko (1974) and Marchetti (1975), for example, gave early attention to the potential for geoengineering to limit the amount of warming. The first comprehensive analysis was carried out by the National Academy of Sciences in the early 1990s as part of a study of mitigation, adaptation, and geoengineering options (NAS, 1992). Despite that study, and perhaps because of its finding that firing artillery shells loaded with sulfur would be a cost-effective offset for continued greenhouse gas concentrations, geoengineering remained peripheral until recently because of a hope and desire that mitigation would be sufficient, and because of the technical, political, and moral challenges that taking control of the climate would seemingly bring.

With the pace of climate change and associated impacts accelerating (IPCC, 2007a, 2007b) and the Kyoto Protocol proving insufficient to slow the rate of growth in global emissions (IPCC, 2007c), there has been renewed interest in the potential for geoengineering to, at the very least, help provide additional time for policy actions to take effect. In 2001, the US Department of Energy held a workshop to prepare a proposal for a research program on geoengineering as part of the National Climate Change Technology Initiative (Ehsan Khan, unpublished); while a number of approaches were considered, the plan never came to fruition, largely because of the recognition that pursuing geoengineering might well weaken even the limited push toward mitigation being made at the federal level in the US.

With little action early this decade and scientists finding that the climate was changing faster than their best projections, Nobel Laureate Paul Crutzen (2006) stepped forward, arguing that it might be time to think much more seriously about geoengineering the Earth's climate. In addition to undertaking geoengineering to avoid "dangerous anthropogenic interference with the climate system," Crutzen proposed to do so to offset the warming influence that would result from the decrease in tropospheric sulfate aerosol loading that would occur as fossil fuel (particularly coal) emissions were reduced. Crutzen's paper was accompanied by five commentaries that raised additional ideas, questions, and issues (Bengtsson, 2006; Cicerone, 2006; Kiehl, 2006; Lawrence, 2006; MacCracken, 2006). Crutzen's call has since been echoed by others, including Wigley (2006), Barker and Bashmakov (2007), and a major scientific workshop reported on by Kintisch (2007).

The following sections provide an overview of the most feasible approaches that have been proposed, describe the most important scientific, legal, ethical, and societal issues that would be associated with any serious effort to move forward, and suggest that initiating a research and demonstration program that focuses on intervening to limit four especially serious and imminent impacts might prove to be a useful and practical first step. With each of the actions being limited and reversible, such a step would allow exploration, development and testing of critical technologies for moving to limit global climate change, if that proves to be necessary and is internationally supported, while at the same time establishing the basis for intervening to limit important impacts.

On the Range of Geoengineering Possibilities

There are three fundamental approaches to geoengineering the climate: (1) actions aimed at reducing the concentrations of greenhouse gases in the atmosphere; (2) actions taken to reduce the amount of solar radiation incident on or absorbed by the Earth system; and (3) actions directed toward reducing the most serious consequences of human-induced climate change. Within each of these general categories there are many specific proposals for how to achieve the desired effect, only the most plausible of which will be considered in this article.

In seeking to reduce the concentrations of greenhouse gases in the atmosphere, the most obvious step is to reduce the emissions of greenhouse gases (including reducing demand for energy through gains in efficiency and conservation, switching to sources of energy that do not generate greenhouse gases, etc.); this general area is the focus of national and international *mitigation* policies, as called for in the UN Framework Convention on Climate Change and Kyoto Protocol. In addition, there are technologies for capturing the greenhouse gases before they are emitted and to sequester them beneath the oceans or land surface (e.g., carbon capture and storage); these approaches are also generally included as a component of mitigation (IPCC, 2007c). In addition to reducing fossil fuel emissions, the land use contribution to CO_2 emissions can also be reduced by maintaining and restoring forests and other land cover (IPCC, 2000a).

Geoengineering approaches to accelerate the removal of greenhouse gases from the atmosphere have also been proposed. In addition to afforestation (i.e., foresting new areas), a number of additional, sunlight-driven processes are also receiving attention, including fertilization of the ocean with micro- or macro-nutrients to promote biological transfer of carbon to the deep ocean, and chemically scrubbing greenhouse gases from the atmosphere (e.g., using a CO_2 absorbing solution to scavenge CO_2 and then sequestering it underground or in or below the deep ocean); or stirring the ocean to try to encourage downward carbon transport. These approaches, preferably solar driven, would, if successful and cost-effective, not only possibly allow additional emissions from fossil fuel combustion, but, more importantly, likely also be critical if ocean acidification is to be limited.

Approaches for reducing the incidence and/or absorption of solar radiation have been reviewed by MacCracken (1991), NAS (1992), Leemans et al. (1995), Flannery et al. (1997), Keith (2000), Schneider (2001), and, most recently by Lane et al. (2006) and Schneider (2008). Starting furthest from the surface of the Earth, these include: placing a solar deflector in an orbit synchronous with the orbit of the Earth around the Sun; placing mirrors in near-Earth orbit; injecting aerosols into the stratosphere to reduce the amount of solar radiation that reaches the lower atmosphere and the Earth's surface (reviewed recently by Rasch et al., 2008b); brightening the clouds in the troposphere so less solar radiation is absorbed by the surface-troposphere system; and increasing surface reflectivity or otherwise altering the surface to counteract the global warming influence.

Less consideration has been given to trying to disrupt and counter the influences of a warming atmosphere on the environment and society. There are, however, a number of proposals to accomplish this that are distinct from adaptation, which is taken to include making society and the environment more robust to change and adjusting what is done to account for or to offset the consequences of climate change (IPCC, 2007b). Examples of this approach to geoengineering include, for example, efforts to diminish the intensity of hurricanes, limit the amount of glacial melting, redirect ocean currents, and the like.

As indicated above, proposals to geoengineer the climate go back to at least the 1960s, and only slightly less ambitious ideas go back even further (Fleming, 2004). Over this period, reviews and preliminary examinations have thinned the ranks, eliminating approaches that seem least viable. The following sections review a number of approaches that have withstood early examination; see Boyd (2008) and Lenton and Vaughan (2009) for early efforts to intercompare the effectiveness of at least some of these approaches.

Lowering the Atmospheric Concentrations of Greenhouse Gases

The present atmospheric loading of carbon is roughly 770 PgC (1 PgC equals 1 petagram of carbon, or a billion metric tons of carbon). Human-caused emissions of carbon in 2007 totaled ~10 PgC, of which ~8.5 PgC (equivalent to roughly 31,000 $MMTCO_2e$ in the units used in the energy policy community) were from combustion of fossil fuel and the rest were from changes in land cover (Canadell et al., 2007). Interestingly, assuming that the amplitude of the seasonal cycle in the CO_2 concentration at Mauna Loa is representative of conditions in the Northern Hemisphere, the seasonal cycle of net biospheric uptake (i.e., growth minus decay from spring until fall) and release (decay minus growth from fall to spring) totals about 8 PgC, so annual fossil fuel emissions are now exceeding the seasonal greening of the Northern Hemisphere biosphere.

The annual increment in the atmospheric concentration is now over 2 ppmv per year. This rise is equivalent to an increase in the atmospheric burden of over 4 PgC/yr, indicating that about half of the annual fossil fuel emissions are persisting in the atmosphere for an extended period, with the rest being taken up by the terrestrial biosphere and the ocean. Even with some types of non-fossil energy technologies becoming cost competitive, it will take intensive efforts and substantial investments over many decades to construct the facilities needed to displace fossil fuels (Hoffert et al., 2002; IPCC, 2007c). As a result, for at least several decades, greenhouse gas emissions are likely to remain far above the 80-90% cutback from current emission levels that will be needed to stabilize atmospheric composition. In addition, for far longer, emissions levels are likely to be above the near 100% cutback needed to eventually return atmospheric greenhouse gas concentrations to present levels or lower, as will be required in order to return warming to less than the level that the CEC has deemed "dangerous" (Meehl and Stocker, 2007; Matthews and Caldeira, 2008; Ramanathan and Feng, 2008).

Proposals to limit the increase in the CO_2 concentration by geoengineering seek to increase terrestrial and/or marine uptake or to scrub CO_2 from the atmosphere (e.g., Kauppi and Sedjo, 2001; Martin and Kubic, 2007; Keith, 2008a) and sequester it underground or in the depths of the ocean or in ocean sediments (e.g., IPCC, 2005; Caldeira et al., 2005; Goldberg et al., 2008). An alternative set of approaches being proposed is, in effect, to accelerate the weathering of rock (Kelemen and Matter, 2008; Rau et al., 2008), which would have the effect of increasing the capacity of the ocean to take up CO_2 without increasing ocean acidification.

The terrestrial biosphere includes about 500 PgC in above ground biomass and about three times that amount in the soils (Prentice, 2001). The annual net primary productivity is about 10% of the aboveground biomass (giving an average lifetime for living biomass of just under 10 years). About 20% of the soil carbon (the detritus component) has a lifetime of less than 10 years but ~10% has a lifetime of over 1000 years. If fossil fuel emissions continue at their present rate through the century, storing all of the carbon emitted during the 21st century in the terrestrial biosphere reservoir would require storing an amount of carbon roughly equal to all of the carbon now present in the world's aboveground biomass and short-lived detritus, or roughly doubling the 30% of the Earth's land area covered by forests (Fischlin and Midgley, 2007). As a result, early ideas about planting more trees along highways or other limited corridors would not accomplish much. Indeed, given the demand for land for food and fiber products and for communities, fully offsetting CO_2 emissions by expanding terrestrial carbon uptake is just not possible. While every effort should be made to increase land storage of carbon (IPCC, 2000a; Lovejoy et al., 2008), it is likely to be a challenge just to keep the net amount of terrestrial carbon constant.

Given the difficulty of accumulating and storing sufficient carbon in the terrestrial biosphere, consideration is being given to limiting emissions by capturing the CO_2 at power plants and then transporting it to the deep ocean by pipeline. While this is generally categorized as mitigation, gathering the carbon after it has been emitted into the atmosphere and dispersed, and then sequestering it in the ocean is generally categorized as geoengineering. An early approach proposed for capturing dispersed carbon involved growing trees on land, harvesting them, and then sinking them to the bottom of the ocean (Marchetti, 1975). To counterbalance fossil fuel emissions, this would require harvesting and sinking roughly 1% of the existing vegetation per year to the ocean bottom as well as replanting and likely having to fertilize those areas to encourage regrowth of the trees. Assuming the average time to maturity of a tree is 50 years, this approach would require including about 50% of the world's forested area in a sequential process of harvesting trees, sinking them in the ocean, and then regrowing trees on the cleared land. This level of sequestration seems far more than would be possible, and, in addition, it would be a terrible waste of the solar energy that has been captured in the wood as the trees grow. If indeed the economic costs of climate change impacts justified a harvest/sink/regrow process of this magnitude, it would seem to make far more sense, and likely be far more economical, to be transforming the biomass to biofuels and not mining and combusting the fossil fuels at all. Indeed, pursuing a combined biomass-fossil fuel process that generates energy while also sequestering carbon underground appears to be a quite promising mitigation technology (Kreutz et al., 2008).

At the present rate of CO_2 emissions, the net uptake of CO_2 by the oceans is ~2.3 PgC/yr, split between the extra net amount carried down to the deep ocean by the overturning circulation (actually a reduction in the net upward transport) and by the sinking of biomass (fecal pellets, skeletons, etc.) as a result of biological activity. Warming of the ocean is projected to reduce the overturning component, and, assuming a constant atmospheric CO_2 concentration, warmer ocean waters (like carbonated beverages) hold less CO_2, so climate change is likely to affect the natural carbon cycle in a way that reduces ocean uptake rather than increases it. However, because there are some indications that biological activity could be increased in some regions of the ocean by the addition of apparently missing micro- or macro-nutrients, there is considerable interest in determining if fertilizing the ocean could be used to increase ocean uptake and downward transport of carbon. Basically, powered by solar energy, the notion would be to make an investment of nutrients to drive additional uptake of carbon by the marine biosphere while perhaps also increasing fish stocks to help feed the world.

A number of small-scale tests of ocean fertilization have been conducted and more have been proposed (Barker and Bashmakov, 2007; Lampitt et al., 2009). A number of the experiments have been funded by venture capitalists hoping that success might provide carbon credits that could be sold to those needing to offset emissions in the international cap-and-trade system that may be negotiated. Results to date are not nearly definitive, and the scientific community has raised a number of concerns about the effectiveness and safety of iron fertilization (e.g., see http://www.scor-int.org/SCOR-GESAMP.pdf). Questions meriting investigation include: whether adding micronutrients in one location to utilize apparently unused macronutrients is just displacing growth of marine life that would have occurred further along the path of the water mass; whether the carbon that sinks is really kept away from the atmosphere for centuries or is only dissolved a bit deeper in the ocean and so would be released back to the atmosphere within a few decades; and how all of the accounting is being done, because drawing CO_2 into the ocean in one location will just lead, by adjustment of the chemical equilibrium between the atmosphere and upper ocean, to out-gassing elsewhere of at least a fraction of the CO_2 that is being taken up? In addition, the long-term problems with this approach are that: (a) the higher the ocean carbon content, the more acidic the ocean waters become, thereby adversely affecting the ability of many marine organisms to form carbonate shells; and (b) the warmer the ocean gets, the less the ocean overturns, and so the less nutrient-rich waters are brought to the surface, diminishing the level of natural ocean biological activity and the pumping of carbon to the deep ocean.

There have also been proposals to basically farm the ocean for biomass. Such proposals are at the interface of mitigation and geoengineering in that they are, basically, biologically harvesting the solar energy that falls on the ocean surface. The American Methanol Institute a number of years ago proposed growing algae out in the equatorial Pacific, and augmenting the available ocean nutrients by using a fraction of the resulting biofuel (in their case, methanol) to bring up deeper, nutrient-rich waters. The rest of the resulting methanol was to be used to displace use of fossil fuels, so this ocean-based approach was intended mainly as a way to mitigate fossil fuel emissions. Although not now so focused on sequestration, the present range of activities in this area is quite broad (e.g., see http://www.algaebiofuelsummit.com/), and might well be combined with efforts to enhance fish production, so helping to increase global food stocks.

While most attention has gone to removal of atmospheric CO_2, removing other greenhouse gases, especially those that have a high global warming potential (GWP) as compared to CO_2, also merits consideration as a geoengineering approach. During the early implementation process for the Montreal Protocol, one proposal to limit depletion of stratospheric ozone was to use lasers to dissociate, and thus destroy, chlorofluorocarbons (CFCs) before they could contribute to ozone depletion. To make up for the low concentration of CFCs, the notion was to bounce a laser signal many times between mirrors on nearby mountaintops such that the pathlength was extended and an energetic photon was more likely to actually strike a halocarbon molecule. Such an approach may merit further consideration as a means of limiting the long-acting warming influence of many of the long-lived halocarbons and perfluorocarbons (Bala et al., 2005; Montenegro et al., 2007). Finding a way to destroy methane (CH_4) in this manner would also be particularly useful, given that its 20-year GWP is ~3 times its 100-year value (Forster and Ramaswamy, 2007), meaning that reducing the concentration of methane to well below its present concentration, whether by mitigation or geoengineering, would have an early and significant limiting effect on the warming influence of greenhouse gases [Scientific Expert Group (SEG), 2007; Levy et al., 2008; Moore and MacCracken, 2009].

With nearly 100 PgC tied up in arctic soils (Ping et al., 2008), much of it likely as CH_4, another class of productive geoengineering actions could well involve finding ways to keep the ground frozen and/or, because of its high GWP, converting the CH_4 to CO_2 before release (e.g., by using the emitted CH_4 to displace use of natural gas from underground reservoirs). With observations indicating that the CH_4 concentration is again starting to rise, possibly as a result of increased natural emissions from thawing permafrost and/or from the ocean floor, successful research could have a very large payoff.

Reducing the Incidence and Absorption of Solar Radiation

Geoengineering the climate via solar radiation management refers to efforts to reduce the amount of solar radiation absorbed by the Earth system by the amount required to offset the increased trapping of infrared (IR) radiation by the rising concentrations of greenhouse gases. Considerations of the Earth's energy balance indicate that fully offsetting the equivalent of a CO_2 doubling, which is often calculated to lead to an increase in net downward IR at the tropopause of between 3.5 and 4.1 W/m^2 (Ramaswamy, 2001), would require reducing the amount of incident solar radiation by ~1.8%.[2] Although the latitudinal and seasonal patterns of the changes in IR and solar radiative forcings are quite different, model simulations indicate that the latitude-season temperature responses to the two forcings are nearly equal and opposite (Manabe and

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[2] Based on a solar irradiance of about 1368 W/m^2, the global average incident flux of solar radiation at the top of the atmosphere is about 342 W/m^2. About 30% is reflected away, primarily by clouds but also by the Earth's surface, so 1.8% of the absorbed radiation is ~4.3 W/m^2. This is necessarily larger than the often cited figure for the radiative forcing from a CO_2 doubling because that figure has been reduced as a result of the rapid thermal adjustment of the stratosphere to the CO_2 doubling.

Wetherald, 1980; Hansen et al., 1984; Govindasamy and Caldeira, 2000). The results of these modeling studies seem to confirm the IPCC presumption that the global average temperature response is largely independent of the spatial and seasonal variability of the forcing (i.e., that the climate sensitivity is essentially independent of the type and spatial distribution of the forcing).

While these results appear to ease the challenge of geoengineering, such a conclusion is also somewhat surprising, given that changes in the Earth's orbital elements,[3] which simply redistribute solar energy by latitude and season while causing virtually no change in global annual forcing, are the recognized driver of ice age cycling. What is apparently happening is that the oceans are providing an important buffering effect to the seasonal variation of solar radiation. Considerably more research is needed, however, to understand the potential long-term consequences of solar radiation management, especially because the offsetting effect of geoengineering is not nearly as strong for the seasonal and latitudinal distribution of precipitation as it is for temperature.

For purposes of comparison of suggested approaches in the following discussion, the actions required to reduce solar radiation by 1% are described. Such an effort would be roughly enough to offset half (in a logarithmic sense) of a doubling of the CO_2 concentration. Based on current emissions scenarios, this would be about the level of effort required to offset the radiative forcing for the emissions projected for the 21st century, assuming one of the moderate IPCC SRES scenarios (IPCC, 2000b). The proposed geoengineering approaches are considered starting from highest above the surface of the Earth.

Geostationary orbit: Early (1989) proposed placing a solar deflector at the first Sun-Earth Lagrange point (~1.5 million kilometers toward the Sun, referred to as the L1 point), where the gravitational pull of the Sun and Earth would be about equal and opposite so that maintaining the deflector in place would require minimal energy. To reduce solar radiation by ~1%, a disk having a diameter of ~1400 km would be required. Viewed from Earth, the deflector would appear to be smaller than the Sun (so would not be visible without special telescopes) and its effect would be to reduce the intensity of the solar beam by about 1%, which is likely too small to have significant ecological or other detrimental consequences. However, Early suggested that constructing the proposed solar shield in the most cost-effective manner would require setting up a manufacturing plant on the Moon; as a result, the cost of construction would be in the trillions of dollars. While the rate of onset of the effect could be controlled by angling the deflector and easily stopped if unforeseen, but adverse, environmental consequences arose, the resources for this approach would need to be essentially fully expended up front before there could be any diminution of solar radiation. Because these costs would likely be greater than the diminishing difference in costs between fossil fuel and renewable or other energy sources, and, in that the

[3] Three aspects of the Earth's orbit around the Sun vary in time, leading to cyclic variations in the seasonal and latitudinal distributions of solar energy. The three elements are: (1) the ellipticity of the Earth's orbit, which varies between near circularity and slight ellipticity with a frequency of ~100,000 years; (2) the tilt of the Earth's axis, which varies between about 22 and 25 degrees with a period of ~41,000 years; and (3) the precession of the Earth's orbit, which cycles the time of year of closest approach to the Sun through the seasons with a period of almost 26,000 years. When the major and minor contributions of these cycles, which are a result of the time-varying pull of the Sun and planets, are combined, the periodicities that emerge, particularly for the amount of solar radiation reaching high latitudes where glaciers and ice sheets form, match well with the periodicities for glacial cycling determined from variations in isotopic ratios and other variables observed in ice cores.

shift away from CO_2 emitting energy technologies would be needed in any case to limit ocean acidification, augmenting funding for renewable energy technologies from the start might well be a less expensive and risky path and would not require sustaining the offsetting effort for many generations.

To overcome the large initial costs for building a manufacturing plant on the Moon, Angel (2006) proposed creating a sunshade at the L1 point by lofting a very large number of small deflectors directly from the Earth's surface. When fully deployed, Angel's proposed sunshade (or parasol) would consist of roughly 10 trillion autonomous flyers, each being very thin, having a diameter of 0.5 to 1 meter, and including an onboard control mechanism that would use the solar wind to "sail" the flyer in a way that would maintain orientation and separation. Angel proposed that the flyers be launched from the Earth's surface to the L1 point using an electronic launcher that would be fired 20 million times over coming decades, each launch carrying 800,000 flyers in a stack weighing 1000 kg. While the overall cost would be substantial, the offsetting effect could be incrementally increased to the level needed and there are likely few adverse side effects (other than associated with the launching process). Further analysis of this approach is underway, with the most important issues relating to engineering and technological aspects.

Near-Earth orbit: Solar shielding could also be lofted into near-Earth orbit, although the effects of rocket exhaust on the stratospheric ozone layer might well become problematic with the large number of rocket launches that would likely be required. NAS (1992) calculated that offsetting roughly 1% of the incoming solar radiation would require about 55,000 orbiting solar mirrors (e.g., spread out Mylar sheets), each roughly 10 km by 10 km in size. While this approach could be undertaken incrementally, the control problem would be overwhelming, not to mention that in passing between the Sun and Earth's surface, each of the orbiting mirrors would eclipse the Sun, causing sunlight at the surface to flicker. Kahle and Deirmendjian (1973), expanding on an idea appearing in Hoyle (1957), had much earlier proposed creation of an orbiting cloud of particles. Due to the pressure of the solar wind, such a cloud would be difficult to maintain. Given the relatively significant problems of tackling global warming from near-Earth orbit, such approaches have received little attention and are not discussed further in this article.

Stratosphere and mesosphere: Enhancing the global loading of sulfate aerosol particles in the stratosphere is receiving considerable attention by researchers. An important advantage is that the reduction in solar radiation would be roughly equivalent to the influence of an annual to biennial series of major volcanic eruptions, so similar to what has been experienced in the past, although the aerosol loading would need to be sustained indefinitely by an ongoing injection program. In addition to having a natural demonstration of stratospheric injection, the lifetime of stratospheric sulfate particles is typically a few years as opposed to a week or so for the tropospheric sulfate aerosols that presently offset about 0.5°C of warming (e.g., see Wigley, 2005). Another advantage of the sulfate-injection approach is that it can be tried in an incremental manner and, in the event of adverse consequences or a major volcanic eruption, relatively quickly halted.

Although enhancing stratospheric aerosol loading would lead to very colorful sunrises and sunsets, an important disadvantage of sulfate aerosol particles is that they forward scatter roughly five to ten times as much radiation as they reflect, whitening the skies and seriously diminishing the direct solar beam (e.g., Izrael, 2008). Such scattering would reduce the effectiveness of the technologies that generate energy using the direct component of the solar beam, such as the solar power tower.[4] In addition, the biosphere would be affected; for example, following the Pinatubo eruption, Gu et al. (2003) found that the greater amount of diffuse radiation was able to better penetrate the vegetation canopy, enhancing primary productivity and carbon uptake.

Because the aerosols reduce the amount of solar radiation reaching the surface, they also tend to reduce the amount of energy available to drive the hydrologic cycle. Model simulations by Bala et al. (2008) indicate that, for similar changes in the net change in the energy balance at the tropopause, stratospheric aerosols and greenhouse gases have similar effects on surface temperature, but that the aerosols result in a larger proportional reduction in the hydrologic cycle than would a decrease in the greenhouse gas concentration.

Rasch et al. (2008a) summarize the results of the newest model calculations that have been carried out to evaluate the use of sulfate aerosols for solar radiation management. They find that there are many details that will need to be investigated, ranging from considerations of the effects on particle size distribution of injecting the particles using a million 4-hour aircraft flights per year to issues of the seasonal effects of the aerosols and their lifetimes and distribution in the stratosphere. Calculations by Robock et al. (2008) also indicate that, while the temperature change from the rising concentrations of greenhouse gases can largely be offset, this may not be the case for precipitation.

While much more analysis is needed to clarify these issues, investigation is also needed of potential advantages and disadvantages of alternative injection patterns that might limit adverse and/or enhance beneficial outcomes. For example, would there be a benefit in having particular latitudinal, longitudinal, or seasonal patterns of aerosol loading and how would the findings be affected by opting for greater or lesser offsets than the changing radiative forcing from greenhouse gases. In addition, analysis of the impacts of aerosol injections need to look at more than the average responses of temperature and precipitation, looking, in particular, at changes in the higher moments of atmospheric behavior (i.e., the weather and its variability) and how humans and ecosystems might be affected (Kravitz et al., 2008; Robock, 2008a).

While model simulations are likely the best approach to evaluating potential scenarios of sulfate loading, an experimental program is likely to be needed to explore how best to create the desired loading. Among the proposed approaches for injection are aircraft, artillery, hoses, and upward mixing and then stratospheric oxidation of tropospherically inert carbonyl sulfide (COS). Each of these approaches introduces scientific and technological aspects meriting research, development, and even demonstration.

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[4] Following the El Chichón eruption in 1982, engineers from the Sandia National Laboratory in Livermore CA asked atmospheric scientist at the nearby Lawrence Livermore National Laboratory how their observations at the Barstow, California prototype solar power tower installation, which was roughly in the same latitudinal band as the early volcanic cloud, could be showing that total solar radiation dropped ~2% whereas power production had dropped ~25%. They were encouraged to upgrade their instrumentation to measure the reduction in the direct beam radiation, and found that it had, like their power production, dropped about 25%. Once the volcanic aerosol loading decreased, the system worked as designed.

There have been several suggestions for how best to overcome the negative impacts on stratospheric ozone (Tilmes et al., 2008) and sky color. For example, Crutzen (2006), presumably recalling the "nuclear winter" studies of the 1980s (Pittock et al., 1986), suggested injecting soot instead of sulfates, which not only would reduce scattering but would warm the stratosphere and help to offset CO_2-induced stratospheric cooling and the consequent reduction in ozone. Chang and Shih (1991) not only proposed the use of "Welsbach materials and other oxides of metals which have high emissivity (and thus low reflectivities) in the visible and 8-12 micron infrared wavelength regions," but also patented the idea.

Canavan and Teller (1991) and Teller et al. (1997) proposed injecting microscopic particles that were actually small corner reflectors.[5] Such reflectors could be sized to efficiently bounce selected wavelengths of the solar radiation back toward the Sun without scattering significant radiation. As another alternative in its analysis, NAS (1992) considered an approach involving lofting millions to trillions of reflective, high-altitude balloons. Maintaining enough aloft would likely make this approach costly due to the need to provide lift and to limit deterioration of the balloon material resulting from exposure to high-energy UV radiation. Such balloons could relatively easily be configured like corner reflectors or especially coated on their upper side to increase reflectivity. Whether so many balloons might interfere with communications would need to be considered, however.

The most recent proposal (Keith, 2008b) is to inject small particles into the mesosphere. By clever design and choice of materials, the injected particles could be self-levitating, taking advantage of the electrostatic and magnetic fields present at high altitudes. While the particles would age and be damaged in the harsh high-altitude stream of solar radiation, these particles could have a lifetime of several years or more, thereby balancing the greater cost for their production and injection. Theoretically, at least, the particles could also be designed to primarily reflect wavelengths that are not in the visible part of the spectrum (so, for example, being in the near-infrared range), thus reducing adverse ecological effects (except perhaps for species making use of a wider spectral band than humans).

While modifying the upper atmosphere in order to limit incoming solar radiation appears to be technically possible and potentially cost-effective (e.g., Barrett, 2008), identifying the optimal approach, developing and testing its implementation, and evaluating the importance of side effects remains to be done.

Troposphere: The present global tropospheric sulfate loading, which results primarily from sulfur dioxide (SO_2) emissions from elevated stacks of coal-fired power plants,[6] creates the whitish haze that extends over and often far downwind from major industrialized areas. Because there are both direct and indirect (i.e., cloud-brightening) components of the global cooling influence, the strength of the cooling influence is only roughly known. IPCC's best estimate is that aerosol cooling offsets ~40% of the overall warming influence of the human-induced

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[5] Corner reflectors are created by three intersecting, orthogonal planes, just as are the corners in a room. Assuming each of the planes are coated with a reflective material, light incident on a corner reflector strikes the three planes in succession and comes out in exactly the opposite direction, much like a handball hit into a corner.

[6] Surface-level emissions of SO_2 have an atmospheric lifetime of only a day or two before being removed by dry or wet deposition, so only a small fraction of the emitted SO_2 is typically converted to sulfate.

increase in the concentrations of greenhouse gases, an amount equivalent to the warming influences of the increases in concentration of all of the non-CO_2 greenhouse gases (Forster and Ramaswamy, 2007).[7] Because the SO_2 emissions are primarily in the Northern Hemisphere, the cooling influence is also, and it was likely the increase in SO_2 emissions from elevated sources in the mid-20th century that led to a sharp increase in the Northern Hemisphere's sulfate loading that counter-balanced the warming influence of the rising greenhouse gas concentrations until the collective greenhouse gas influences began to prevail in the early 1970s.

While the health, visibility, and ecological impacts of sulfates have led to extensive efforts in the developed world to reduce SO_2 emissions, the emission levels in China, India, and other nations where coal combustion is increasing are very likely increasing. That most of the emissions in Asia are likely occurring near the surface is one factor contributing to the visibility impairment in these regions. Primarily low-level emission is also suggested by satellite observations of optical depth, which do not show the emissions creating long plumes extending far downwind (see Figures 2.11 and 2.12 in Forster and Ramaswamy, 2007). If developing nations follow the path of the developed nations in cleaning up their air pollution, their initial step will be to build tall stacks that loft the SO_2 emissions, thereby reducing near-surface deposition and visibility impairment, but allowing more sulfate formation and creating whitish haze layers that extend far downwind. The more time that the sulfate plumes are over the dark ocean surface, the greater will be the cooling influence. It is not inconceivable that if this path is followed, the Northern Hemisphere could experience another pause in global warming as it did during the mid-20th century.

Given the cooling effects of tropospheric sulfates, augmenting (or geoengineering) the tropospheric loading may thus be an alternative to augmenting the stratospheric sulfate loading. There are, however, several potentially important adverse consequences. First, because the lifetime of sulfates in the troposphere is roughly a week, the emission of SO_2 into the troposphere would seem to need to be ~100 times larger than the emissions that would be required for stratospheric injections, where particle lifetimes average ~2 years. As a result, to generate global coverage and to minimize the disturbance of the atmospheric circulation that would result from sharp spatial inhomogeneities, augmenting tropospheric sulfate loading would seem to require a worldwide array of source locations that included existing power plants and possibly special towers constructed to burn and inject sulfur previously removed from power plant exhaust streams elsewhere. The increased sulfate loading could also have adverse health consequences, reduce visibility, and increase acidic deposition ("acid rain") that would need to be considered in comparison to the benefits from the warming that is averted.

The advantage of choosing to augment the tropospheric sulfate loading, of course, is that injecting SO_2 into the troposphere is straightforward and the effects are reasonably well understood in that coal-fired power plants presently emit large amounts of SO_2. One way of optimizing the beneficial outcomes of such an effort would be to limit emission of SO_2 to times when trajectory forecasts indicated a relatively long atmospheric lifetime and a low likelihood of

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[7] An inadvertent consequence of this near-perfect offsetting has been to limit many of the discussions of policy actions to CO_2, thereby sometimes hiding the important and cost-effective opportunities that exist for control of the non-CO_2 greenhouse gases (Moore and MacCracken, 2009) That the offset is so close is purely fortuitous and is very unlikely to persist as emissions and control measures change.

deposition on sensitive regions, thus reducing the amount of sulfur emitted and the subsequent deposition and damage that would occur. Assuming that high sulfur coal continues to be burned in at least some regions, it would likely be relatively straightforward to bypass the sulfur removal step and thus to intentionally increase the tropospheric sulfate loading. This would have the effect of reflecting some of the incoming solar radiation and also brightening clouds. To the extent that emissions could be timed so that the sulfate remains over the oceans and is scavenged there, the associated environmental consequences would likely to be quite low; on the other hand, if the sulfate is removed by precipitation in localized areas (e.g., in precipitation onto the mountainous areas of Japan and California), there could be important ecological effects. While there are a number of investigators modeling the global tropospheric aerosol budget, there has not been, to my knowledge, any analysis of optimal designs for a tropospheric release strategy. To conduct such a study, research is needed on the implications of emissions being from limited areas, the consequences for weather and the environment, the consequences for health, and the long-term consequences of persisting in the effort for perhaps many decades or longer.

Bower et al. (2006) and Salter and Latham (2007) have proposed an alternative approach for increasing tropospheric reflection of solar radiation. Rather than create a sulfate haze, they propose to brighten existing marine stratus cloud decks by decreasing the size and increasing the number of droplets in the clouds. This approach is intended to mimic and expand upon the observation that the exhaust plumes from ships sailing under marine stratus clouds appear to create bright contrail-like streaks that have been clearly visible from satellites. Because the persistence of the cloud brightening is only a few days, a growing fleet of vessels would be needed over time to keep up with the warming influence resulting from the rising concentrations of greenhouse gases. The authors suggest that indefinitely deploying on order of a few dozen uniquely designed, wind-propelled vessels roughly the size of a clipper-ship could offset each year's emissions by spraying a mist of seawater out the top of their masts (Salter et al., 2008); alternatively, although their routing is more limited, the contribution of the existing commercial fleet of vessels might be equipped with a shipping container containing the required spraying devices for a given voyage. The mist would then be carried aloft into the low-level clouds by naturally generated convective motions, providing additional cloud condensation nuclei that would lead to brightening of the clouds. Latham et al. (2008b) have analyzed the potential effects of full implementation of this approach in a climate model, finding that it would lead to a noticeable increase in the global albedo, thereby creating a cooling influence that would offset at least some of the radiative forcing contributed by higher greenhouse gas concentrations over coming decades.

Disadvantages of this approach are that it would only work in regions having the right set of atmospheric conditions, and that regional implementation might well perturb regional weather patterns. On the other hand, this approach might be particularly suitable for counterbalancing local to regional-scale impacts, such as reducing the warming of ocean waters in regions where hurricanes and typhoons form and intensify, where bleaching of corals is expected, or where melting of Arctic sea ice is occurring. Given the likelihood that cloud brightening would have a net positive impact, the next step beyond the ongoing modeling is to proceed to a field test, which, in comparison to many of the other approaches, should be doable with an annual budget a few tens of millions of dollars.

Sea, Gulf of Mexico, Bay of Bengal, Philippine Sea, etc.). There are even proposals more akin to weather modification for modifying the atmosphere in order to promote development of the large-scale weather patterns such that they tend, a few days hence, to push advancing tropical storms out to sea (e.g., see Fleming, 2007). Although research on such ideas is in its very earliest stages, the newest models are becoming capable of analyzing the potential effectiveness of such proposals, something that was not possible when hurricane modification was first attempted.

Preserving the ocean's meridional overturning circulation: Johnson (1997) argues that, to reduce the likelihood of a reduction in the Meridional Overturning Circulation and consequent cooling of the North Atlantic, damming the Strait of Gibraltar might be useful. Taking this action would tend to keep Europe and the North Atlantic region warm by cutting off the cooling influence of the high salinity waters that form in the Mediterranean. Other, less developed, ideas have also been proposed. The very high-resolution ocean models that are becoming available provide a useful tool for evaluating such ideas.

Preserving Arctic sea ice: Although there was interest during the anomalously cold 1960s in the possibility of taking actions to melt Arctic sea ice (e.g., see Weart, 2004), recent attention has focused on ways to preserve it. Several authors have suggested that damming the Bering Strait or Siberian rivers flowing into the Arctic, which could be done to alter the salinity, stabilization, and or heat transport, might be useful in controlling what happens in the Arctic Ocean. Ocean circulation models are finally becoming adequate to undertake such investigations.

Rather than altering ocean currents, sharply reducing incoming solar radiation over the Arctic[8] seems likely to offer a number of the benefits of stratospheric aerosol injection while avoiding the global consequences of sharply modifying the ratio of diffuse and direct solar radiation. Reductions in the radiation could, theoretically, be accomplished by lofting of sulfate aerosols or other reflectors (e.g., corner reflecting balloons or particles) in large amounts over the high latitudes where natural ecosystems are used to dealing with low light levels. The injection altitude could be chosen to ensure that the aerosols would stay aloft only during the sunlit months, thereby limiting their contribution to intensification of springtime ozone depletion. The diminution in solar radiation would be made sufficient to promote earlier and more extensive formation of Arctic sea ice. Augmenting the sea ice cover, with its high albedo, would in turn reduce absorption of solar radiation and induce further cooling. The longer duration of a cold sea-ice surface would extend the time during which the overlying air that later spreads to mid-latitudes would be cooled, thus tending to restore traditional weather patterns.

Calculations by Caldeira and Wood (2008) indicate that sufficiently reducing solar radiation in the Arctic could indeed offset greenhouse-gas-induced warming in that region and that moderation of temperature increases would extend southward through the northern mid-latitudes. While a substantial aerosol loading or lofting of balloons would be needed to fully counteract a CO_2 doubling (e.g., enough to reduce radiation north of about 60°N by about 10% or north of 70°N by 25%, or about half this amount for 50% of this effect), it might be possible that, rather than darkening the skies every year, a heavier injection every few years might promote sufficient

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[8] Proposed initially by the author of this article at the Department of Energy's 2001 workshop (E. Khan, unpublished manuscript).

Arctic cooling that the additional sea ice with its high albedo would persist for several years and so self-sustain the cooling.

An interesting insight gained from the model simulations is that, while the Arctic's temperature and sea ice cover could theoretically be returned to preindustrial conditions, the increase in precipitation caused by global warming would persist. This would result because most global evaporation occurs over the mid- and lower-latitude oceans, and cooling the Arctic would not substantially reduce that warming, and, so, the evaporation, in those regions. Because the existing and additional precipitation would occur mainly as snow, the loss of mass by mountain glaciers and the Greenland Ice Sheet might well be reversed, thereby benefiting nations around the world by slowing the rate of sea level rise (and perhaps also helping to sustain the Meridional Overturning Circulation). An additional benefit would be that the colder Arctic would likely lead to recovery of the region's unique ecosystems and species (e.g., polar bears, seals, etc.).

Sustaining mountain glaciers and ice sheets: Another significant adverse impact of global warming is the melting back of mountain glaciers and other large masses of ice in mid- and low-latitudes. Not only would slowing their melting limit sea level rise, but the annual release of meltwater is also an important source of water for rivers and communities. In that deposition of dark particles on the surface of ice sheets significantly enhances glacial melting, the most straightforward approach would be to sharply reduce their emission. Because that will take time, in part because there are so many distributed sources (e.g., from cooking stoves, inefficient vehicles, etc.), attempts are beginning over very limited areas to determine if reflective insulation could cover and protect the glaciers through the period of summer warmth, thus reducing the solar load and keeping air warmer than freezing from direct contact with the glacier's surface. Expanding such efforts to the large-scale is likely to be problematic because the insulating material that would limit melting during the warm part of the year would need to be removed in winter in order to allow essential cooling during the cold part of the year.

Limiting sea level rise: The rate of sea level rise over the past decade has increased to about double the average rate observed over the 20th century, and is now much larger than the average rate experienced over the past few thousand years when many major cities came to be located in vulnerable coastal areas. Sea level rise results mainly from the melting of glaciers and ice sheets and from thermal expansion of warming ocean waters, although other terms, including depletion of groundwater and slowing down in the global Meridional Overturning Circulation could be contributing. Increasing the storage of water in reservoirs, groundwater, and reforested areas would help to limit sea level rise, although this will likely prove to be difficult as rain systems shift and warmer temperatures increase the rate of evaporation from reservoirs. Actively spraying seawater atop the East Antarctic Ice Sheet would be helpful, but the energy would need to be derived from local renewable sources (e.g., temperature gradients) and the engineering of the large system that would be needed would be difficult, particularly in the very cold climate of Antarctica.

Limiting ocean acidification: The rising concentration of CO_2, while beneficial to many land plants up to a somewhat higher CO_2 concentration than at present assuming water and nutrients are not limiting, causes acidification of ocean waters. Acidification could be reduced by limiting emissions of CO_2, by increasing CO_2 removal from the atmosphere through augmentation of natural removal processes, or by altering oceanic chemistry to limit acidification. A range of proposals has been put forward. For example, Rau and Caldeira (2002), House et al. (2007), and Rau et al. (2007) have proposed approaches to, in effect, accelerate the long-term natural buffering process that occurs as a result of the weathering of rocks. Such an enhancement of natural weathering processes—equivalent to giving a bromide to the ocean—would likely pose a very large logistical challenge as the mass of material required for buffering is typically several times as large as the mass of CO_2 to be sequestered.

Creating a Decision Process for Geoengineering

Research on the scientific aspects of geoengineering, including the cost of actually carrying it out, is one aspect of determining whether such approaches merit consideration as a policy option that could be considered along with mitigation, adaptation, and suffering through the impacts of climate change. A traditional approach for evaluating the merits of a course of action is comparison of costs and benefits of such efforts. Comparing the direct costs of the geoengineering itself relative to the costs of reducing emissions by an equivalent amount is the most straightforward (e.g., see NAS, 1992), but this leaves out the potential benefits of the avoided impacts of climate change, which seem likely to be important.

As made clear in analyses by Stern (2007) and Nordhaus (2007), evaluating the benefits of limiting the pace of future climate change can lead to quite different results because of differing assumptions about the appropriate manner with which to weigh the present importance of future impacts. In addition, reductions in impacts are necessarily estimated based on the results of extended term simulations of very complex climatic, ecological and socioeconomic models, which leads to outcomes that are at least as uncertain as the projections of climatic impacts without mitigation or geoengineering. For example, in evaluating approaches for solar radiation management, in addition to all the climate-related impacts, an analysis would have to weigh the direct effects of the further rise in the CO_2 concentration, including the negative consequences of allowing ongoing acidification of the ocean and the positive effects of enhanced water use efficiency and productivity of some crops. That many analyses (e.g., IPCC, 2007b) comparing fossil versus renewable sources of energy are so limited in their analysis of the consequences of changes in the CO_2 concentration and climate makes clear that considerably more research and analysis will be needed, including considering the results in both cost-benefit and risk-based frameworks.

One important complication of any such analysis involves the time dimension, because, assuming that one or more viable and cost-effective approaches to geoengineering can be found (e.g., injection of aerosols into the stratosphere), the commitment to the approach must match the lifetime of the CO_2 increment that is supposedly being offset (Archer, 2005: Bala et al., 2005; Montenegro et al., 2007). To first order, this means that continued emission of CO_2 would need to be offset by roughly a 200-year commitment to the stratospheric injection because, were the geoengineering effort to be halted for any reason, the radiative forcing of the remaining CO_2 would no longer be offset and the atmospheric temperatures would likely jump up toward a higher equilibrium temperature relatively rapidly (Brovkin et al., 2008; Robock et al., 2008). In that each of the approaches requires some maintenance or renewal (e.g., additional launching of mirrors, lofting of particles or reflecting balloons, or augmenting the number of mist-dispersing ships), the commitment to the offset will, without the approval of future generations, impose unavoidable responsibilities and costs on them.

Coming to an understanding of what creating a multi-generational commitment might mean is likely to be very difficult. Certainly there have been national, and even international commitments to creating infrastructure (e.g., road, rail, and air transportation) over multiple generations, but most of these commitments have been related to increasing some tangible or visible benefit—and, indeed, profit has likely been the most powerful motivating force. By contrast, there are only a few examples of multi-century commitments to protective efforts (e.g., the Great Wall of China and the dikes constructed by The Netherlands), and these were generally constructed in response to actual calamities or visible threats. For geoengineering, the prospective benefit is avoiding a projected, but not experienced, calamity, and the effort would require that, at the very least, a significant coalition of nations persist in the effort for a century or more. In addition, because a number of the impacts are likely irreversible, taking action before the most adverse consequences are actually apparent is important; indeed, because waiting to invoke geoengineering until after the emergence of such damaging changes as the loss of critical biodiversity or the initiation of the melting of much of the Greenland Ice Sheet would forego most of the potential benefits. Quite clearly, better understanding of governance issues is required.

That implementation of some of the geoengineering approaches might not require an international effort has introduced a new twist to the issue. Indeed, solar radiation management using stratospheric aerosols might well be within the capabilities of one nation, with insertion of aerosols doable over the land area of that nation and from over the open ocean. Wanting to sustain its use of fossil fuel derived energy to raise the living standards of its people, for example, might China act unilaterally if it became convinced that global warming was leading to sharp disruption of the life-sustaining monsoons on which it depends? If the US became convinced that global warming was leading to more and more powerful hurricanes that were devastating its Southeast, might it choose to act unilaterally? Scott Barrett (2007) has begun to examine such issues, and there are many additional questions (not further elaborated here) that will need to be addressed if geoengineering is going to be seriously considered.

In addition to the political, ethical, and economic issues that such a long-term commitment would raise, there is also a potential legal hurdle. In reaction to US attempts at weather modification during the Vietnam War, the nations of the world agreed in 1978 to the *UN Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques*[9] (Fleming, 2004), which essentially prohibits weather modification that any nation experiencing the impacts would consider hostile or environmentally damaging. In that "climate" is really a mathematical construct created by averaging over the weather, it would not be far-fetched to argue that this treaty might well not permit geoengineering schemes to be used for the purpose of climate change, or for counterbalancing it (indeed, changing climate patterns is specifically mentioned as being covered in one of the understandings of the treaty). The notion of one or a few countries proceeding to undertake some geoengineering action without the permission of all countries would almost certainly be considered hostile by some nation. While

[9] The text of the treaty can be downloaded from http://www1.umn.edu/humanrts/peace/docs/conenvironmodification.html

there is an exception in the Convention relating to peaceful purposes, a treaty modification might need to be negotiated to move forward regarding how much change would be undertaken and who would decide the conditions to be aimed for.

While geoengineering might well be able to slow the pace of climate change, a powerful argument against proceeding geoengineering emerged during the course of the DOE analysis (Ehsan Khan, personal communication). The central question became whether, if a viable and low cost geoengineering approach to limiting global climate change became available, would this reduce the pressure for reducing greenhouse gas emissions? Were this the case (and it would seem plausible), geoengineering would really be, in essence, an enabler for ongoing addiction to fossil fuels. Indeed, if finding and implementing an effective approach to geoengineering were to weaken the resolve for reducing emissions, then the benefit of limiting climate change would come at the cost of imposing an even longer and greater responsibility for future generations to continue the geoengineering offset, especially because the consequences of failure would be increased due to the extra emissions that would be allowed. Recognition of this unintended response chain led to a change in the argument that DOE staff planned to use to justify research on geoengineering, namely to viewing geoengineering only as a backstop strategy or insurance policy, to be called upon only in the event of unexpectedly rapid or extremely damaging impacts (Ehsan Khan, personal communication).

Crutzen (2006), however, argues that climate change has nearly or already reached the point where dangerous consequences seem likely to result, and Hansen et al. (2008) point out that important tipping points are near or have already been passed, so the qualification is becoming moot. Indeed, Crutzen (2006) argues that societal addiction to fossil fuels is so severe that society needs to move ahead with research and even testing of viable approaches, especially in that the costs of research are likely to be small compared to the costs of energy research, much less conversion to non-CO_2 emitting energy technologies.

Quite clearly, wider discussion and exploration of views are needed (Wigley, 2006; Ragaini, 2008; Robock, 2008a, 2008b; Robock and discussants, 2008), both at international scientific and intergovernmental levels.

Impact Intervention as a First, Learning Step

With so many possibilities and so much scientific research needed, all while there is also significant controversy about the moral, ethical, and environmental aspects of considering *global* geoengineering, it seems appropriate to identify some initial steps that would seek to determine if, as a first step, focusing geoengineering on impact intervention could be used to moderate some of the worst and most inevitable climate change impacts. In addition to determining how best to moderate these impacts, meaningful research on the following four approaches would also start to build the knowledge base needed to consider the much more significant step of planning and undertaking global-scale geoengineering.

1. Geoengineering to Limit Ocean Acidification and Carbon Dioxide Build-up in the Atmosphere

While dramatically cutting CO_2 emissions from fossil-fuel combustion must be the primary action to moderate ocean acidification and its impacts on marine life and coral atolls and islands,[10] finding effective ways to increase the sequestration of carbon in ocean sediments and in the very deep ocean could play a significant role in limiting both acidification and climate change. Iron fertilization of nutrient rich, but biologically depleted waters is the most widely touted possibility, although there are serious questions about how much of the carbon taken up in new growth really makes it to the deep ocean. Given the time it takes for the micronutrient addition to promote growth, larger and longer-lasting field experiments are needed to evaluate potential effectiveness. An alternative fertilization approach would be to add urea to increase the macronutrient loading. Considerable research is needed to determine the amount of carbon sequestration and to determine potential impacts on ocean ecosystems. For example, in that both of these fertilization approaches change ocean color, the vertical profile of ocean heat uptake would be altered; research would be needed to determine if such changes could then affect the intensity of storms drawing heat from the ocean.

A more aggressive and geographically expandable approach would be to bring cool, nutrient rich waters to the surface. Such a change could be used not only to stimulate regional marine life over areas presently having virtually no fish life, but also to cool ocean areas where the warmth is causing adverse impacts (e.g., hurricane intensification regions or coral reefs). Harvesting the increased marine life could provide fish-protein and biomass for food and to create biofuels (thus reducing the need for fossil fuels). The skeletons and fecal matter of the marine life that are not harvested would add to the downward flux of carbon to the sediments and the skeletons of the fish that are harvested might also add to carbon sequestration. In that this approach would not be using nutrients already being used by existing marine life, the ecological effects of such efforts are likely to be less than would result from iron fertilization. Initial research on aspects of a wave-powered pump suggests that the approach might work (see http://www.atmocean.com/), but much more investigation is needed. Even if not implementable on a large enough scale to significantly limit climate change and ocean acidification, success would likely be beneficial because of the potential increase in harvestable marine biomass and the consequent reduction in utilization (and release) of carbon by terrestrial biomass.

2. Geoengineering to Limit Ocean Warming in Critical Areas

The accumulation of heat in the ocean due to the higher greenhouse gas concentrations both increases evaporation and warms surface waters, both of which contribute to the intensification of tropical cyclones and other storms. Already, there are indications that a larger percentage of nascent tropical cyclones are developing into more powerful hurricanes and typhoons, increasing the damage and inundation occurring along coasts and inland. In addition, warmer than typical ocean temperatures have been increasing the frequency of coral bleaching episodes. Reducing, or at least limiting the rise, in the temperatures of waters in tropical-cyclone formation and intensification regions could be very beneficial.

[10] That the threat is real and imminent is clear from the observed shoaling (shallowing) of the saturation horizon—the depth at which the calcium carbonate that makes up fish skeletons and coral atolls is made (Bindoff and Willebrand, 2007).

Approaches for doing this include, at least, the Latham et al. (2008) suggestion for increasing cloud albedo, wave-powered ocean pumps that could be used to cool specific ocean areas, and an emerging approach to increasing ocean surface albedo by injecting small bubbles. While these approaches have the potential for exerting a global influence if widely deployed, demonstration of a much more limited deployment in specific areas could be very beneficial and would allow testing of the global concept. Even were the climate not changing, exploring the potential for these approaches to limit storm intensification and coral bleaching could be beneficial, especially considering the situations being faced by the increasing numbers of people living in coastal regions and on vulnerable islands.

3. Geoengineering to Limit High-Latitude Warming and its Contribution to Sea Level Rise

The Arctic is already experiencing adverse impacts from the amplified onset of global warming that occurs in high latitudes—and then spreads its meteorological effects to lower latitudes. Sea ice retreat is threatening both key species and coastal communities, while melting of glaciers and ice sheets is contributing to sea level rise. These changes have been caused by a relatively small increase in the warming influence in the region, suggesting that a relatively modest reduction in solar radiation absorbed in the region might well have beneficial consequences. If enhancing the tropospheric or lower stratospheric aerosol loading in the region could be used to exert a cooling influence, the change would also benefit mid-latitudes because the Arctic serves, in effect, as the "air conditioner" for the Northern Hemisphere, creating the cold air that is necessary to sustain mid-latitude weather patterns. Indeed, initial model studies indicate that reduced solar radiation into the region would limit regional and Northern Hemisphere warming while also promoting increased snowfall and building up glaciers and ice sheets, thereby helping to limit sea level rise.

Both tropospheric and stratospheric aerosol injection merit investigation, as does cloud-albedo modification, and perhaps even surface albedo enhancement. Ships sailing the Arctic to increase cloud albedo is a possibility, but this would likely be difficult because cruises would need to be done when at least partial ice cover is present. By releasing SO_2 from existing power plant stacks in Europe and North America only when meteorological conditions are forecast to carry the air mass into the stable summertime Arctic, increasing the tropospheric aerosol loading should be possible without causing significant damage due to acid deposition. Because the stratosphere is at comparatively low altitude in the region and the aerosols only need to be present during the Arctic summer, injection by aircraft should be relatively inexpensive. That tropospheric aerosols would have a shorter lifetime than stratospheric aerosols might also be beneficial in limiting the spread of the injected aerosols to lower latitudes.

In that the Arctic Ocean's biological activity is dependent on cold temperatures and the presence of sea ice, returning the Arctic to conditions more like those during the early 20th century would likely be beneficial to existing species while the reduction in solar radiation seems unlikely to have significant side effects. Evaluating the region's response to previous volcanic eruptions would provide one way of evaluating potential impacts, and, in any case, given that the aerosols would naturally be removed from the atmosphere each year, it would be unlikely that pursuing this approach would cause any long-term ecological harm. However, much more detailed modeling experiments are needed to investigate the issue and to design the optimal protocol for an initial experiment. While sulfate aerosols can be used, and research is needed on the best and most practical injection techniques, investigation could also begin on alternative materials that might lead to less scattering of the incoming solar beam so that the stratospheric aerosol approach might be considered over more of the Earth if warming indeed accelerates.

4. Geoengineering to Sustain the Global Aerosol Offset

At present, the emission of SO_2 from coal combustion is leading to a global sulfate burden that is offsetting about 0.5°C of global warming. Were the world to be able to cut its CO_2 emissions to zero, human-induced SO_2 emissions would also approach zero. Because the atmospheric lifetime of sulfate aerosols is roughly a week whereas the greenhouse gas lifetimes tend to be centuries (or more) for all key gases except methane, the sulfate offset would be lost relatively quickly, leading to a strong warming influence despite a reduction in greenhouse gas emissions. While one of the most frequently suggested geoengineering steps is SO_2 injection into the global stratosphere, that would likely require a very significant effort and lead to a significant worldwide reduction in the direct solar beam that is needed by solar thermal and other energy technologies that use mirrors to concentrate the energy or depend on the intensity of the solar beam.

In addition to the possible use of the Salter-Latham cloud albedo increase approach, a viable and perhaps more acceptable alternative to stratospheric injection might well be to manage the emission of SO_2 to the troposphere from existing and planned coal-fired power plants, seeking to maintain or even increase the overall cooling influence of these aerosols, especially by building up their concentrations in remote regions (such as over the ocean) where problems of acidification of precipitation and scattering of the direct beam would not cause serious impacts. While the developed nations have been reducing their SO_2 emissions in order to reduce acid precipitation onto sensitive regions (generally in the upper mid-latitudes), with China and India building coal-fired power plants, there is likely to be an increase in lower latitude sulfate loading, especially over ocean areas. Just as the developed nations built tall stacks 50-80 years ago in order to disperse the emitted pollutants more broadly, economic and health concerns would make it logical for the developing countries to follow a similar course of action. Were this to lead to an increase in sulfate aerosol loading primarily over the ocean, the cooling influence would be amplified because ocean albedo is low and solar intensity is high.

A focused modeling and enhanced observation program could evaluate the potential for cloud albedo enhancement as well as seeking to manage the global sulfate burden in ways that would provide the maximum offset to greenhouse gas accumulation, helping to limit peak warming and, if carried on intentionally as overall greenhouse concentrations decline, helping to sustain the present cooling offset of sulfate aerosols. Associated with this research effort should also be an evaluation of the effects of all types of aerosols on precipitation and precipitation systems in the lower latitudes, especially in terms of effects on the monsoons, for which there is some evidence that current aerosol emissions and changes in land cover may be having a detrimental effect (Levin and Cotton, 2009).

Concluding Thoughts

The rate of increase of climate change, along with the continuing increase in emissions of greenhouse gases, has created a very serious predicament for the world. Drastically reducing the world's use of fossil fuels will take time, even after the effort gets seriously started. As a result, global warming is likely to press up against or even exceed the level that the Commission of European Communities, for example, has concluded is likely to lead to dangerous and unacceptable consequences. For this reason, it seems prudent for the nations of the world to initiate an effort in geoengineering, with the first, ten-year phase devoted to: (a) addressing whether global engineering can be used to moderate some of the most severe impacts that are emerging, and (b) exploring what next steps might be possible if reducing global emissions and adapting to the consequent impacts of climate change prove especially difficult.

A comprehensive socioeconomic and political governance research effort needs to be undertaken in coordination with the research activities on the physical, chemical, and biological aspects and complications of various of geoengineering approaches. Although it may be possible for geoengineering to be undertaken by one nation, every nation would be affected by any action that is taken. For this reason, it is essential that discussions begin on governance issues relating to geoengineering. Already, investor-funded experiments in support of iron fertilization have raised questions over what international entity or institution has jurisdiction. Questions about using geoengineering to limit the intensity of tropical cyclones or Arctic warming would be much more complicated, and questions about even further efforts to limit overall global warming would be even more complex. Thus, in addition to scientific research on possible approaches and their impacts, social, ethical, legal, and economic research should be supported to explore what geoengineering is and is not within bounds of international acceptance.

What is most clear from review of the various global-scale geoengineering options is that returning the climate to its undisturbed state is not likely to be possible. Therefore, especially in light of the increasing seriousness and imminence of potentially catastrophic impacts, sharply reducing the increasing emissions of greenhouse gases merits strong near-term action, even if geoengineering approaches might offer some help in moderating the most adverse outcomes over coming decades.

Nonetheless, in that some moderation of impacts likely can be achieved, research into geoengineering that has the potential of benefiting the world community of nations would seem to be a prudent step to take in order to expand the set of policy choices available for meeting the objective of the UNFCCC to avoid "dangerous anthropogenic interference" with the climate system. An optimal outcome would seem to be that mitigation can be accomplished relatively rapidly, such that geoengineering might need to be implemented for only a few decades in order to shave off the peak change in climate, thereby increasing the likelihood that the most adverse environmental and societal impacts would not be as severe as projected.

Continued delay in sharply cutting emissions, however, will not only lead to more adverse impacts, but would be likely to create the need for implementing global-scale geoengineering that would need to be carried on for centuries. Because the benefit to the typical citizen over this time would be based on avoiding projected disasters rather than responding to actual ones, the need for sustaining geoengineering for centuries would be equivalent to sustaining a nuclear deterrent over many centuries, unless additional efforts were taken to scrub the atmosphere of the excess concentration of greenhouse gases. Indeed, the risks and the necessary multi-generational commitment involved in geoengineering appear to favor making an even stronger case for recognizing the seriousness of the climate change issue and encouraging a much more aggressive energy research and emissions control effort by all nations.

From this perspective, over the next few decades, geoengineering is less a complement to mitigation that would allow a slower pace for emissions reductions than a complement to adaptation and the building of resilience. Over the longer term, if warming really takes off in spite of strong mitigation efforts and an geoengineering approach can be found to limit solar radiation without inducing significant side effects, global geoengineering can be viewed as an insurance policy against the very worst impacts, but at the cost of imposing its implementation on many future generations. For such a two-phased approach to become viable, a broad-based research and assessment program needs to be initiated in the near-term.

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DeCola, Philip L.

From: Mike MacCracken [mmaccrac@comcast.net]
Sent: Tuesday, April 28, 2009 11:08 PM
To: DeCola, Philip L.
Subject: Re: In your spare time....

Hi Phil-Well, I have looked at both of the papers:

1. On reforesting the Sahara and Australian deserts is interesting scientifically—though cultural issues seem likely to me to be quite a challenge. Given the potential threat from from ocean acidification, this type of approach might well be needed very soon to protect marine life, etc.
2. On the harvesting of fallen trees, I think that is just not practical or sufficient—he should come to the family homestead we have with other families in Connecticut and climb over the rocks, etc. And one would have to do all sorts of patrolling to find these fallen trees. I also do not think that all carbon production is in tree trunks—plus the forests need the nutrients and there is lots of life in the fallen trees. I just think this idea is not at all practical or a good idea.

Best, Mike

On 4/28/09 11:59 AM, "DeCola, Philip L." <Philip_L._DeCola@ostp.eop.gov> wrote:

Mike,

Thought you would find these two articles of interest. Would love to hear your take on these, given your interest in geoengineering.

Talk soon?

Phil

From: Mike MacCracken [mailto:mmaccrac@comcast.net]
Sent: Thursday, April 23, 2009 12:13 PM
To: DeCola, Philip L.
Subject: Re: In your spare time....

Hi Phil—The best and most authoritative effort at this was, not surprisingly, by Jim Hansen. I have attached his paper that argues 350 ppm is the right target—and I agree (he continues on into policy implications—but that is something else). Then there is the Wigley paper saying that to halt sea level rise would require to going far below that. Clearly, the consequences of going higher are, at least ultimately given the time constants, very severe.

I really can't do any better (and a bit tied up with various things)—these papers would be best to extract from—and since you know just what you need, I'll not try to do better (but will keep thinking of any other possible papers).

DeCola, Philip L.

From: Mike MacCracken [mmaccrac@comcast.net]
Sent: Tuesday, April 28, 2009 11:22 PM
To: DeCola, Philip L.
Subject: Re: In your spare time....

BUT---I should add, of course, that growing eucalyptus is really inviting fierce fires, given the terpenes they generate. Eucalyptus were the reasons the burning of the Oakland Hills occurred a decade or two ago, burning something like 2000 homes. And what was so shocking about that was that the Berkeley hills had burned in the 1920s and they had made many recommendations that were forgotten. I just don't think the firebreaks the first article mentions will be adequate—I would think they might be able to find some other type of vegetation, and something that might be readily convertible to biofuels.

Best, Mike

On 4/28/09 11:59 AM, "DeCola, Philip L." <Philip_L._DeCola@ostp.eop.gov> wrote:

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> Thought you would find these two articles of interest. Would love to hear your take on these, given your interest in geoengineering.
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>
> Best, Mike

Climatic Change

Irrigated Afforestation of the Sahara and Australian Outback to End Global Warming

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Abstract Each year, irrigated Saharan- and Australian-desert forests could sequester amounts of atmospheric CO_2 at least equal to that from burning fossil fuels.

Without any rain, to capture CO_2 produced from gasoline requires adding about

$1 to the per-gallon pump-price to cover irrigation costs, using reverse osmosis (RO), desalinated, sea water. Such mature technology is economically competitive with the currently favored, untested, power-plant Carbon Capture (and deep underground, or under-ocean) Sequestration (CCS). Afforestation sequesters CO_2, mostly as easily stored wood, both from distributed sources (automotive, aviation, etc., that CCS can not address) and from power plants.

Climatological feasibility and sustainability of such irrigated forests, and their potential global impacts are explored using a general circulation model (GCM). Biogeophysical feedback is shown to stimulate considerable rainfall over these forests, reducing desalination and irrigation costs; economic value of marketed, renewable, forest biomass, further reduces costs; and separately, energy conservation also reduces the size of the required forests and therefore their total capital and operating costs. The few negative climate impacts outside of the forests are discussed, with caveats.

If confirmed with other GCMs, such irrigated, subtropical afforestation probably provides the best, near-term route to complete control of green-house-gas-induced, global warming.

1 Introduction

About 7.2 ± 0.3 Gigatonnes[1] (Gt) of carbon (C) from fossil fuel (estimated for 2000-2005), and an additional increment of about 1.6 ± 0.9 GtC/yr (estimated for the 1990's) consumed by burning and/or biodegradation following deforestation and 'land use', have been introduced annually into the atmosphere as CO_2 (Alley et al. 2007). About 58% of this (5.3 GtC/yr $\approx$ 19 Gt CO_2/yr $\approx$ 2 ppm CO_2/yr) presently remains airborne (Hansen and Sato 2004). The rest of the anthropogenic CO_2 is absorbed from the atmosphere by the oceans and biosphere (Battle et al. 2000). This increasing atmospheric concentration of CO_2, is the major cause of global warming (Hansen et al 1981). Although gradual in its effects, unabated, it may pose the greatest environmental challenge to humanity since the development of modern civilization.

Afforestation of temperate regions seems to have been rejected as a practical solution to warming because the additional net warming, from albedo decrease, almost cancels the cooling effects produced by the sequestration of CO_2 by the trees (Bala et al. 2007).

But afforestation of subtropical regions, with broad-leaf evergreen trees with the potential for 12-month growing-seasons, is entirely another matter. The Sahara and the Australian Outback are two Hadley-Cell deserts; vast, subtropical, continental areas, where human occupation, agricultural food and fiber resources and competing natural biomes are minimal (only the Antarctic land mass is comparably vast and barren). Were either, or both, planted with irrigated forests, very large CO_2 sinks would be generated.

In addition to proposing this 'cure', this report will provide a preliminary examination of other possible climatological impacts of such projects, and their potential for sustainability.

2 The Model

If we define the Sahara as a swath, about 16° Latitude x 50° Longitude, (sum of the yellow and orange areas in Figure 1a) this encompasses about 9.8×10^8 ha. At such latitudes, 5 to 8 year-old Eucalyptus plantations of about 1,000 trees/ha can sequester aboveground, net, primary productivity (ANPP), from about 1 to 2 $\times 10^7$ g dry mass/ha/yr ($\approx$ 0.5 to 1 $\times 10^7$ gC/ha/yr). This is achieved with about 1,000 mm/yr precipitation; the variation was attributed largely to differing soil fertility (Stape et al. 2004). Underground carbon adds about another 20% to give the total NPP. High-efficiency irrigation (Howell 2001), can be at least twice as efficient as rainfall in delivering water to trees. Such irrigation is scheduled to just replace moisture consumed, so that virtually no losses occur due to runoff at the surface, to the soil below the root zone or to evaporation from wet foliage. This is managed by estimating local evapotranspiration, using either observations derived from satellites, local pan-evaporation or soil-moisture sensors in the root-zone[2]. Therefore, irrigated with about 500 mm/yr, the Sahara might sequester from about 6 to 12 GtC/yr in wood, bark, leaves and roots. Such a forest (of ≈100 m-tall trees; e.g., ***Eucalyptus grandis***) can accumulate carbon at such a rate for about a century, reaching a steady-state, when photosynthetic CO_2 in = respiratory CO_2 out. However, within a few decades of planting, a growing portion of such a forest could be harvested (and replanted), ramping up to a yield of about 7.2 GtC/yr, providing a 'forever' renewable carbon source, for marketing at less than the taxed prices of coal, oil and gas. Used for direct burning, conversion to liquid fuel (as a substitute for non-renewable, fossil fuels), conversion to synthetic feed-stock, construction use and/or storage, as credits against the burning of unrenewed biofuels or of fossil fuels, it could solve both the warming problem and the depletion of non-renewable fuels and organic feed-stocks. Ash and other inorganic residues would be recycled to the forest floor.

Such calculations combine a number of measurements with large error bars. The proposed model assumes that 'truth' falls within the approximations of these calculations.

The case for Australia is similar, but the comparable 'desert' has an area about 60% of that of the Sahara.

The Sahara and Australian Outback present tremendous infrastructural challenges. Installation of roads and aqueducts, in some areas might be prohibitive. But to "end" global warming, only sequestration of something like 7.2 GtC/yr is 'required', if deforestation and land abuse end; otherwise about 8.8 GtC/yr. Therefore, a more selective, culturally-compatible, restricted planting of the forests within the deserts may be possible, avoiding mountains and saline, toxic or other particularly infertile or inaccessible areas. Sufficient area might still remain for even further drawdown of atmospheric CO_2, if desired.

But from where will the 500 mm/yr irrigation water come, ($\approx 4.9 \times 10^{12}$ m^3/yr for the Sahara, as defined)? What will it cost? Over and above the global control of atmospheric CO_2 buildup and global warming, what will be the climatological consequences of such extensive terraforming: for example, on rainfall within the Sahara; on rainfall in the rest of the world; on Atlantic hurricanes; on the loss of the 'Sahara dust fertilization' of the Atlantic, Amazon and Caribbean; on Atlantic upwellings and the fisheries they support; and on the climate of surrounding countries?

Support for answers to these questions will be sought with simple calculations, with modeling of global climate with such irrigated forests 'installed' (Figure 1a), using the GISS ModelE GCM (Schmidt et al. 2006; Friend and Kiang 2005) and with speculations about other testable models.

2.1 Water and its Cost

Fresh water resources are rare in deserts. Precipitation over much of the Sahara ranges from 0 to only 40 mm per year; and 50 to 300 mm per year over much of the driest part of the Australian Outback.

AFFORESTATION AREAS

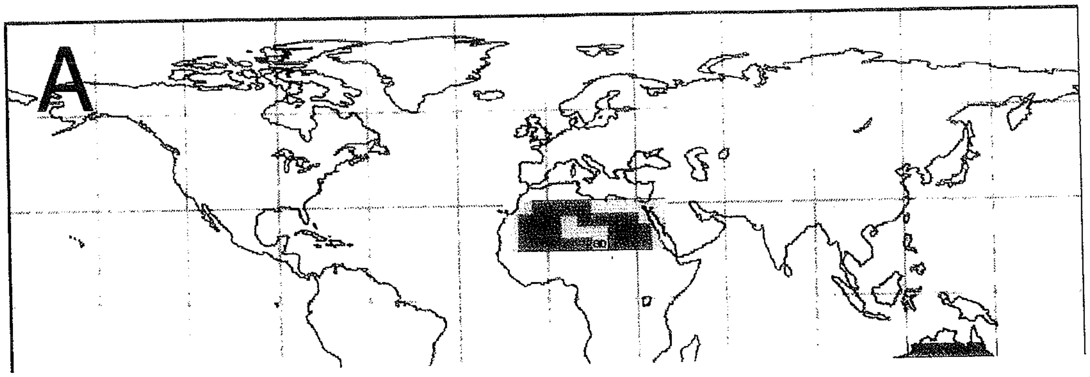

Fig. 1 (a) Illustrates which 4° x 5° cells were modified with irrigation and Rain Forest (RF) for GCM runs: Yellow plus orange represent Sahara-Forest only runs [SRF fixed ocean (FO) and SRF dynamic coupled ocean (DCO)]. Red plus magenta represent Australian-Forest only runs [AuRF (FO) and AuRF (DCO)]. Orange plus magenta represent combined Sahara- and Australian-Forest runs [SRF/AuRF (FO) and SRF/AuRF (DCO)]. (b) The difference (anomaly) between the 10-year averages of August sea surface

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