Stratospheric Sulfur Geoengineering - Benefits and Risks

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Reviews of Geophysics http://www.agu.org/journals/rg/

Reviews of Geophysics distills and places in perspective previous scientific work in currently active subject areas of geophysics. Contributions evaluate overall progress in the field and cover all disciplines embraced by AGU.

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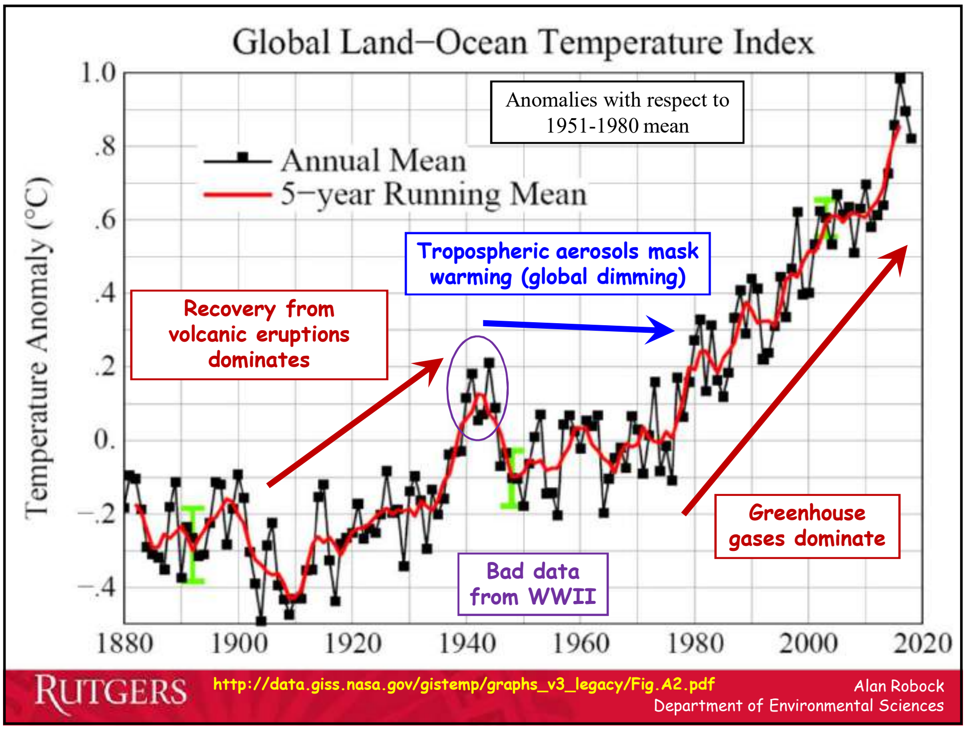
Global Land−Ocean Temperature Index
Anomalies with respect to 1951-1980 mean
Annual Mean
5−year Running Mean
Tropospheric aerosols mask warming (global dimming)
Recovery from volcanic eruptions dominates
Greenhouse gases dominate
Bad data from WWII
Temperature Anomaly (°C)
1.0
.8
.6
.4
.2
0.
−.2
−.4
1880
1900
1920
1940
1960
1980
2000
2020
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http://data.giss.nasa.gov/gistemp/graphs_v3_legacy/Fig.A2.pdf
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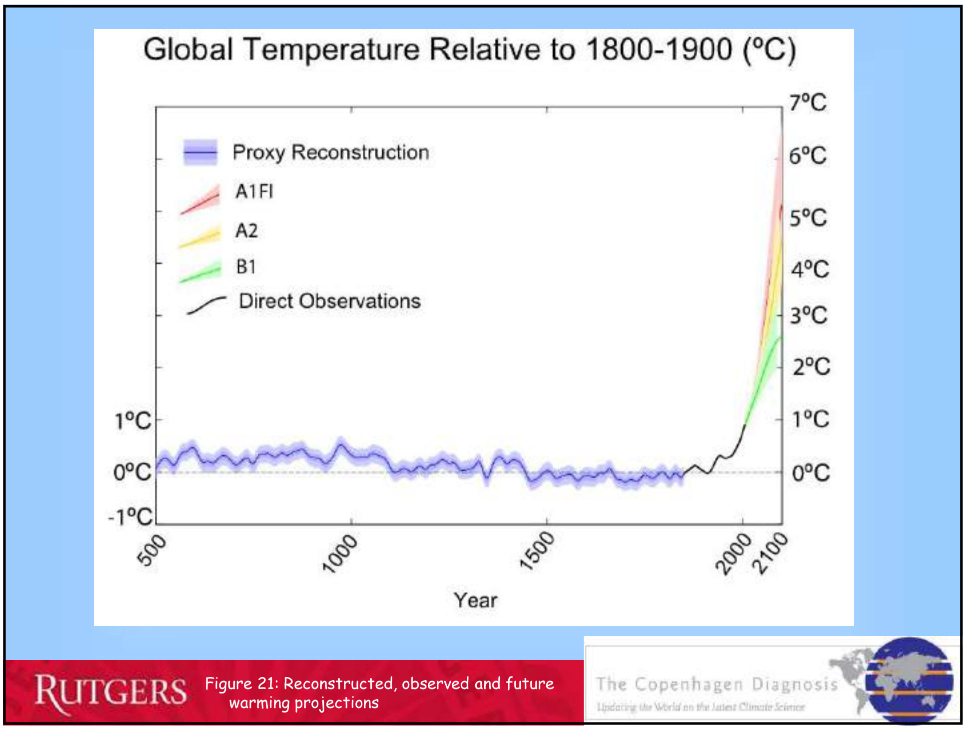
Global Temperature Relative to 1800-1900 (°C)
Proxy Reconstruction
A1FI
A2
B1
Direct Observations
7°C
6°C
5°C
4°C
3°C
2°C
1°C
0°C
-1°C
500
1000
1500
2000
2100
Year
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Figure 21: Reconstructed, observed and future warming projections
The Copenhagen Diagnosis

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Global Warming in 10 Words

It's real.
It's us.
It's bad.
We're sure.
There's hope.

RUTGERS Anthony Leiserowitz, Yale University

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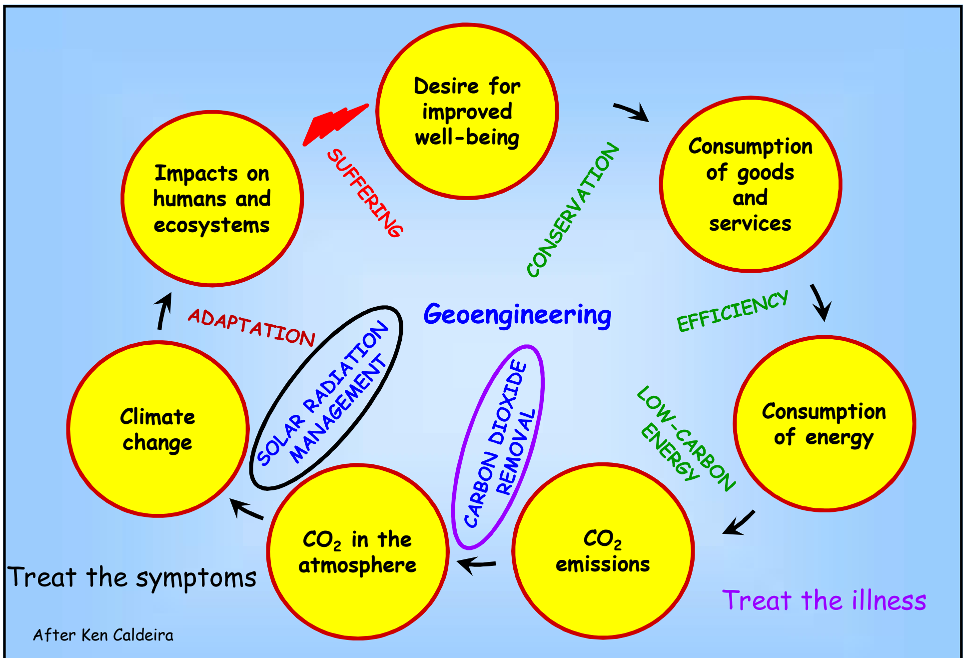

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Geoengineering is defined as

"deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change."

Shepherd, J. G. S. et al., 2009: *Geoengineering the climate: Science, governance and uncertainty*, RS Policy Document 10/09, (London: The Royal Society).

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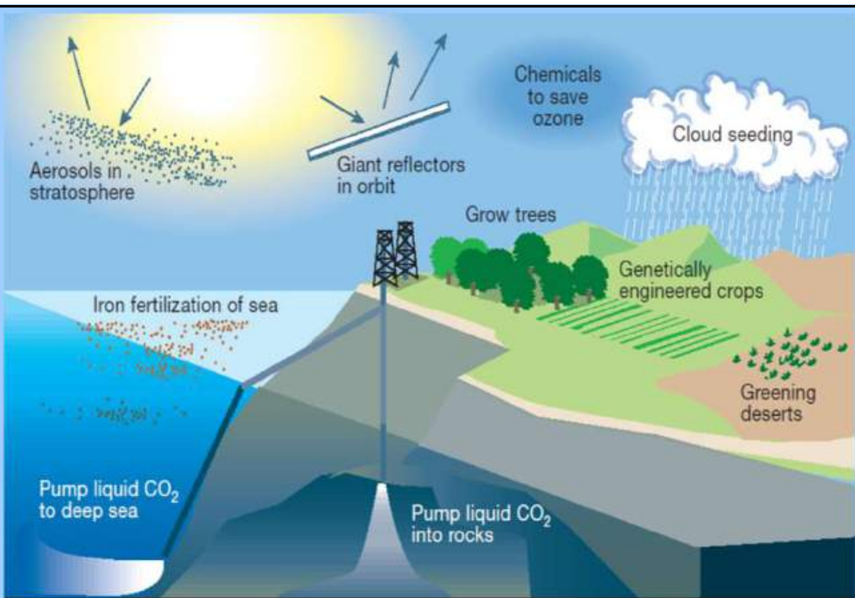

Schematic representation of various climate-engineering proposals (courtesy B. Matthews).

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Keith, David, 2001: Geoengineering, *Nature*, **409**, 420.

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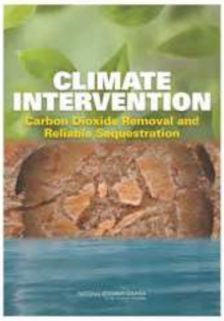
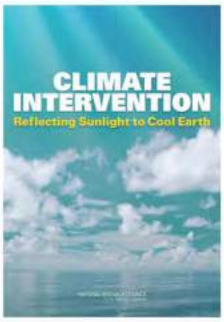
CLIMATE INTERVENTION

Carbon Dioxide Removal (CDR)





Solar Radiation Management (SRM)

Released February 14, 2015

BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Sponsors: U.S. National Academy of Sciences, U.S. intelligence community, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, and U.S. Department of Energy

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WHY "CLIMATE INTERVENTION"?

There are several meanings to the term "geoengineering"

In general, the term "engineering" implies a more precisely tailored and controllable process than might be the case for climate interventions

Intervention is an action intended to improve a situation

BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

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Some Proposed Geoengineering Schemes:

A. Space
Modifier of solar radiation at L1 point
B. Stratospheric
Stratospheric aerosols (sulfate, soot, dust)
Stratospheric balloons or mirrors
C. Tropospheric
Modifying total reflection from marine clouds
D. Surface
Making deserts more reflective
Modifying ocean albedo

Solar Radiation Management (SRM)

Reforestation (CO_2 and evapotranspiration effects, but albedo effect causes warming)
Direct absorption of CO_2
Ocean fertilization

Carbon Dioxide Reduction (CDR)

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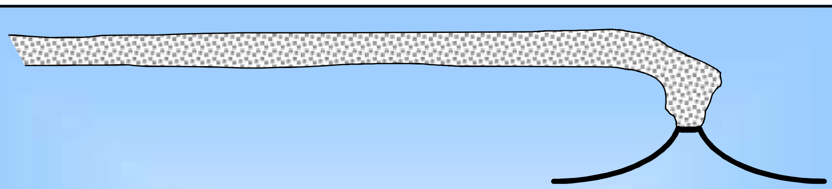

This talk focuses on injecting sulfate aerosol precursors into the stratosphere to reduce insolation to counter global warming, which brings up the question:

Are volcanic eruptions an innocuous example that can be used to demonstrate the safety of geoengineering? **No.**

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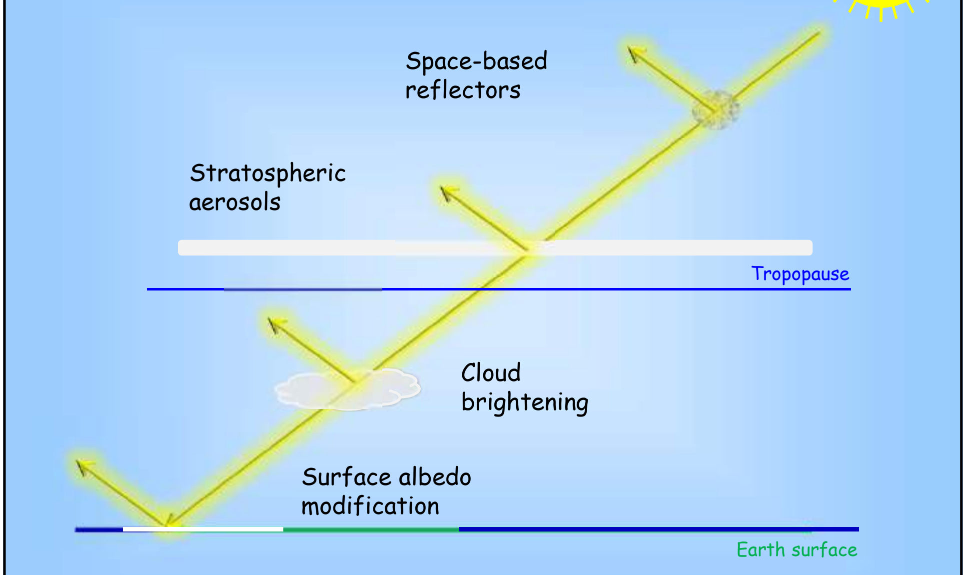
Solar Radiation Management



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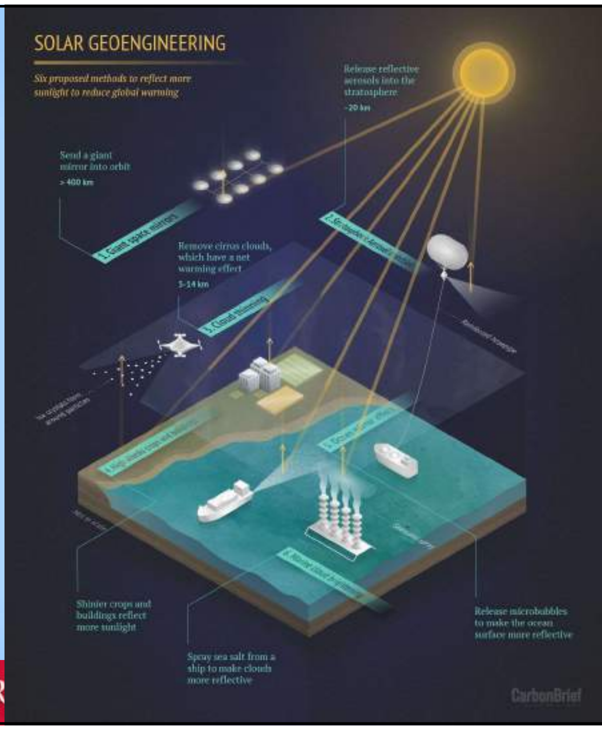

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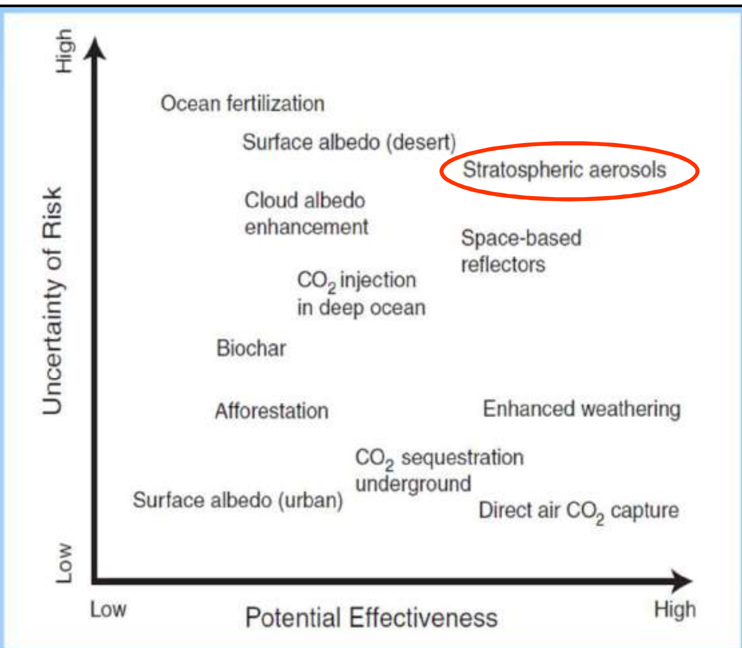

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Matthews, H. Damon and Sarah E. Turner, 2009: Of mongooses and mitigation: ecological analogues to geoengineering. *Environ. Res. Lett.*, **4**, doi: 10.1088/1748-9326/4/4/045105.

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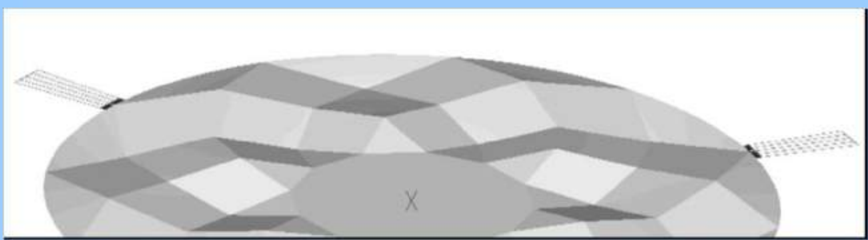

Flyer concept. The 0.6 m diameter, 5 μm thick refracting disc is faceted to improve stiffness. The three 100 μm thick tabs have 2% of the disc area, and contain the MEMS solar sails, tracker cameras, control electronics and solar cells.

He envisions over a 10-yr period, vertical 2-km magnetic launchers with 800,000 flyers each, every 5 min from 20 sites simultaneously to put 20 Mt of flyers into orbit.

Angel, Roger, 2006: Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proc. Nat. Acad. Sci.*, **103**, 17,184-17,189.

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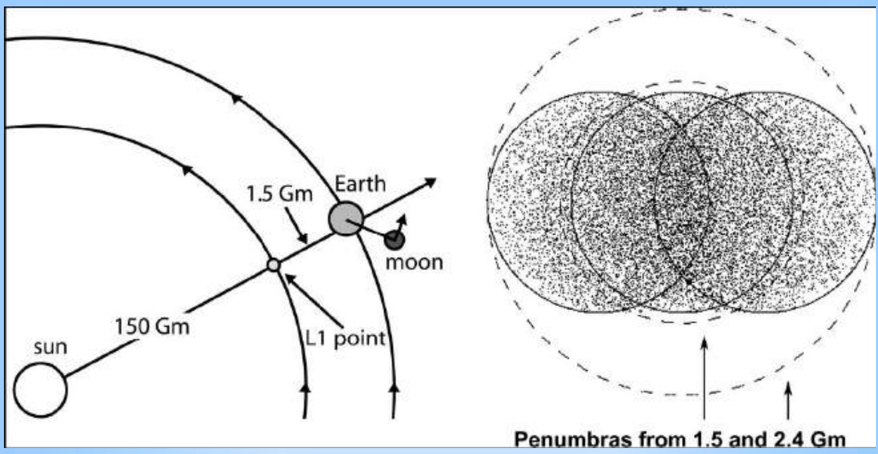

Angel, Roger, 2006: Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proc. Nat. Acad. Sci.*, **103**, 17,184-17,189.

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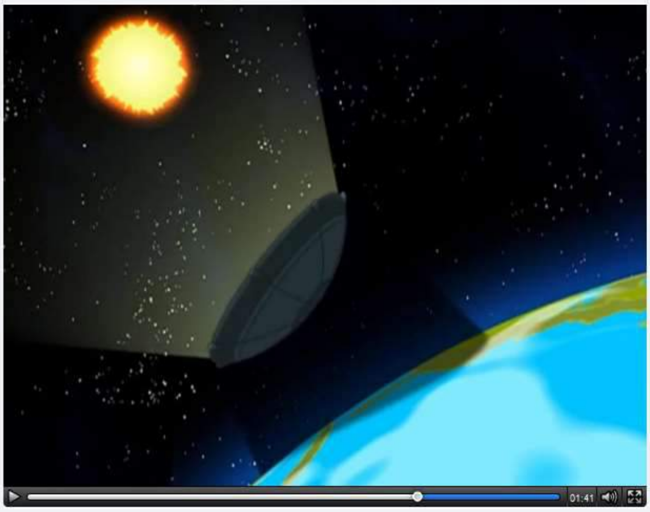
And then on *Futurama*...

VLC



http://io9.com/5665736/blotting-out-the-sun-to-slow-down-global-warming-could-be-outlawed

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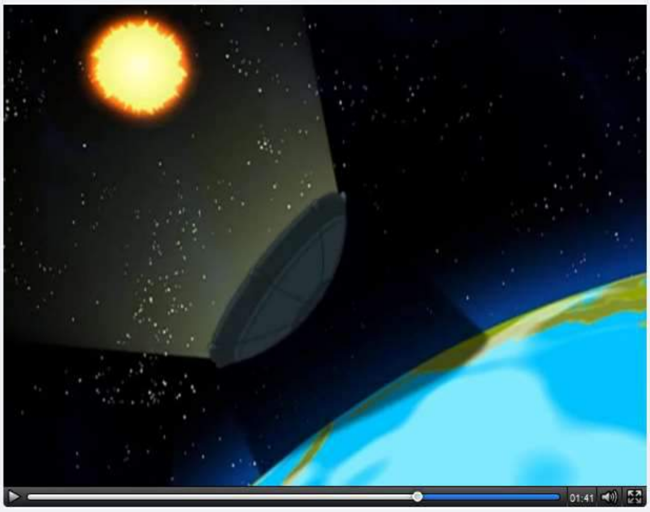
And then on *Futurama*...

From Web



http://io9.com/5665736/blotting-out-the-sun-to-slow-down-global-warming-could-be-outlawed

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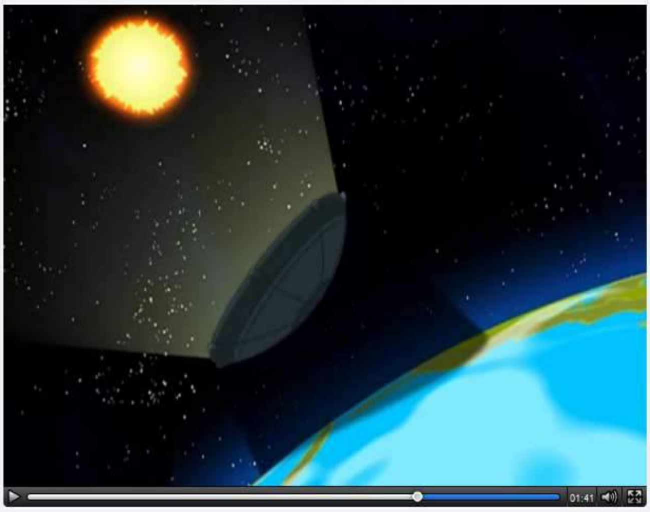
And then on *Futurama*...

Media Player



http://io9.com/5665736/blotting-out-the-sun-to-slow-down-global-warming-could-be-outlawed

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This image of ship tracks was taken by the Moderate Resolution Imaging Spectro-radiometer (MODIS) on NASA's Terra satellite on May 11, 2005.

RUTGERS http://eobglossary.gsfc.nasa.gov/Newsroom/NewImages/Images/ShipTracks_TMO_2005131_lrg.jpg

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Scheme by John Latham (University of Manchester, NCAR) and Steve Salter (University of Edinburgh) to increasing cloud albedo with by injecting more sea salt cloud condensation nuclei into marine stratus clouds.

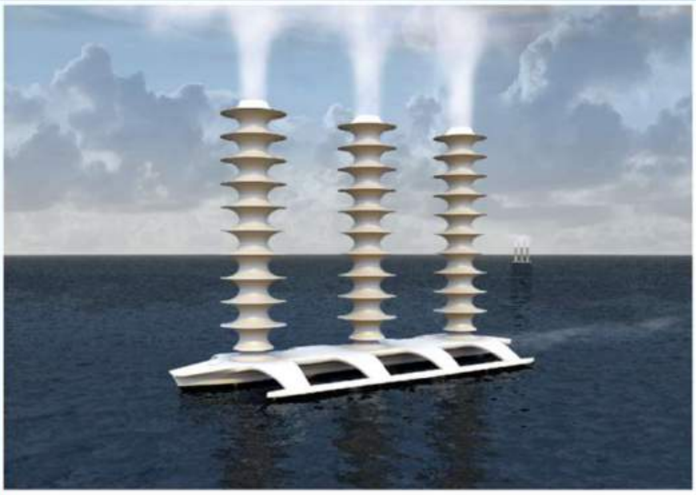

Figure 4. Albedo spray vessels. They would sail back and forth square to the local prevailing wind. Flettner rotors with Thom fences can give lift coefficients up to 20 and lift drag ratios of 35, much higher than cloth sails. Artwork by John MacNeill.

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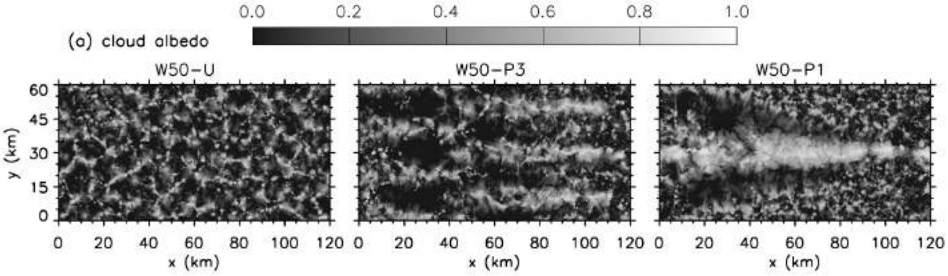
Marine cloud brightening issues

Would evaporating ocean water droplets cool and sink, and never make it to the clouds?

Cloud seeding can produce opposite effects.



Wang, H.. P. J. Rasch, and G. Feingold, 2011: Manipulating marine stratocumulus cloud amount and albedo: A process-modelling study of aerosol-cloud-precipitation interactions in response to injection of cloud condensation nuclei. *Atmos. Chem. Phys.*, **11**, 4237–4249.

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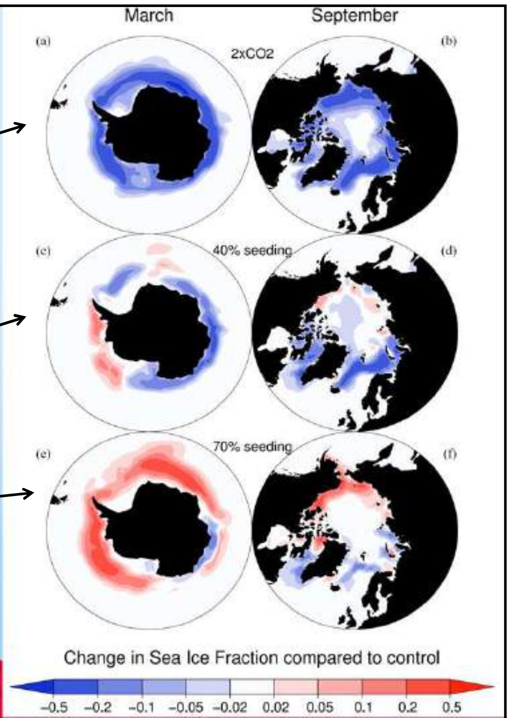
Sea ice is affected by global warming and geoengineering

Summer sea ice goes away with a doubling of CO_2

Ice returns with geoengineering

It is possible to overdo the effect

Rasch et al. (2009)



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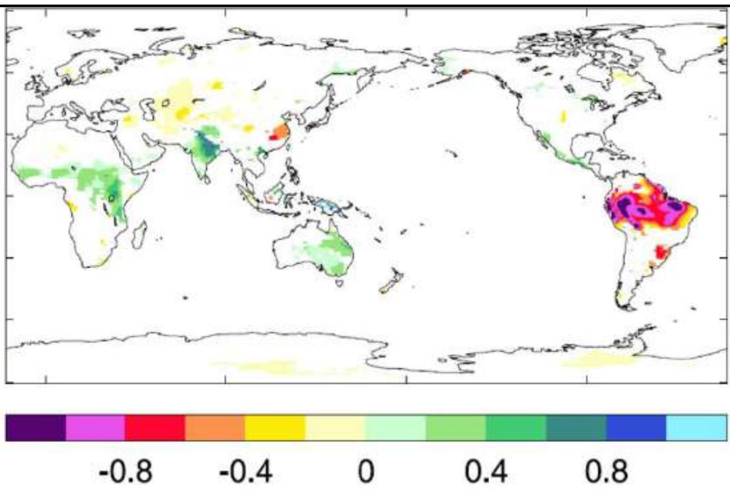

Figure 4. Mean 2030–2059 land precipitation (mm day^{-1}): ALL – A1B. Land areas in Figure 4b where the change is not statistically significant at the 5% level are in white.

Precipitation change for geoengineering with brighter marine stratocumulus clouds.

Damage to Amazon would not be reversible.

(Jones et al., 2009)

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Jones, Andy, Jim Haywood, and Olivier Boucher (2009), Climate impacts of geoengineering marine stratocumulus clouds, *J. Geophys. Res.*, **114**, D10106, doi:10.1029/2008JD011450.

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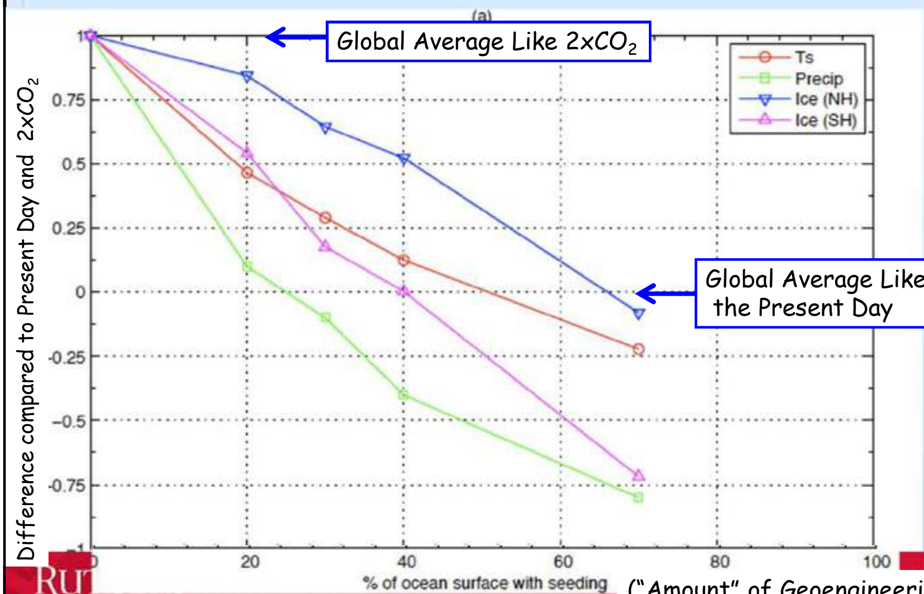
SRM will not operate "uniformly" (even for global averages) (Rasch et al., 2009)



("Amount" of Geoengineering)

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Making the surface brighter?

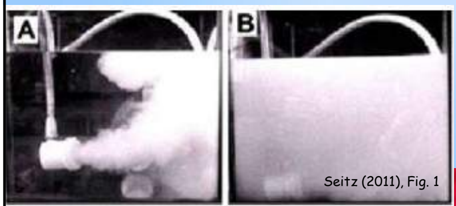
http://www.treehugger.com/white-roof.jpg

Oleson et al. (2010) found minimal global impacts of urban white roofs.

Oleson, K., G. Bonan, and J. Feddema, 2010: Effects of white roofs on urban temperature in a global climate model, *Geophys. Res. Lett.*, **37**, L03701, doi:10.1029/2009GL042194.

Doughty et al. (2011) found leaf brightening would have minimal effect.

Doughty, C. E., C.B. Field, and A. M. S. McMillan, 2011: Can crop albedo be increased through the modification of leaf trichomes, and could this cool regional climate? *Climatic Change*, **104**, 379–387, doi:10.1007/s10584-010-9936-0



Seitz (2011), Fig. 1

Seitz (2011) proposed bubbles to brighten the ocean, but Robock (2011) found many issues with proposal.

Seitz, R., 2011: Bright water: hydrosols, water conservation and climate change. *Climatic Change*, **105**, 365-381, doi:10.1007/s10584-010-9965-8.
Robock, Alan, 2011: Bubble, bubble, toil and trouble. An editorial comment. *Climatic Change*, **105**, 383-385, doi:10.1007/s10584-010-0017-1.

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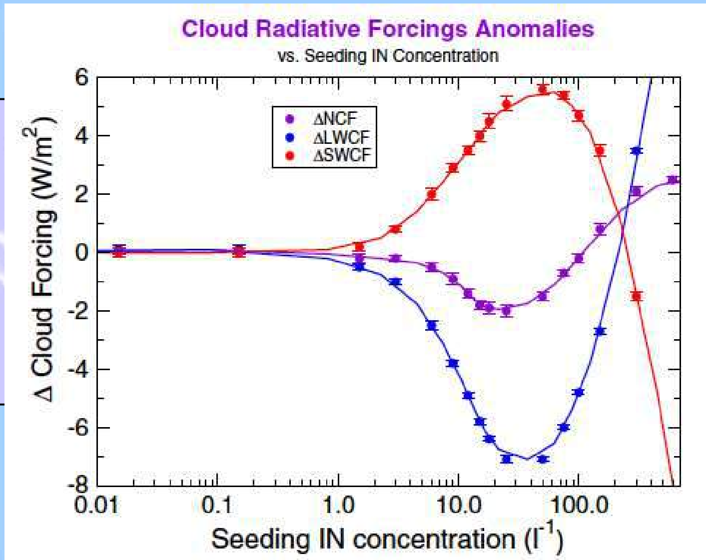
Reducing cirrus clouds to let more longwave escape



Storelvmo T., J. E. Kristjansson, H. Muri, M. Pfeffer, D. Barahona and A. Nenes (2013), Cirrus cloud seeding has potential to cool climate, *Geophys. Res. Lett.*, *40*, 178–182, doi:10.1029/2012GL054201.

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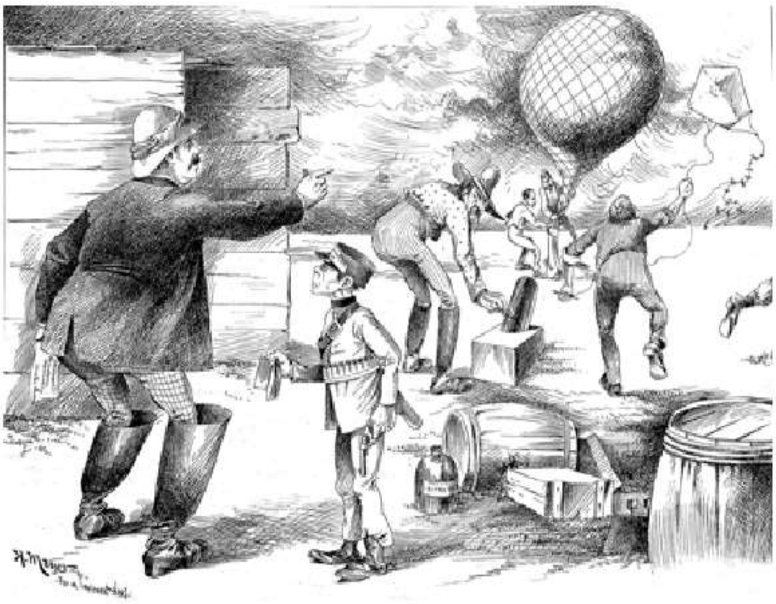
The Climate Engineers



Robert St. George Dyrenforth claimed success after his federally funded rainmaking mission to Texas in 1891, but in this cartoon from a local magazine he is shown ordering his assistants to speed up: "Here's a telegram announcing a storm. If we don't hurry, it will be on before we raise our racket."

Ru

n Robock
Sciences

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The Climate Engineers

Experiments with cloud seeding during the Cold War inspired fantastic predictions about America's ability to control the weather, as in this 1954 article, and use it as a weapon against its communist adversaries.

Ridicule greeted a 1992 proposal to combat global warming by shooting reflective particles into the atmosphere. The response could be different today.

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RESTORING THE QUALITY

OF

OUR ENVIRONMENT

APPENDIX Y4

Atmospheric Carbon Dioxide

ROGER REVELLE, *Chairman*

WALLACE BROECKER   C. D. KEELING
HARMON CRAIG   J. SMAGORINSKY

The climatic changes that may be produced by the increased CO_2 content could be deleterious from the point of view of human beings. The possibilities of deliberately bringing about countervailing climatic changes therefore need to be thoroughly explored. A change in the radiation balance in the opposite direction to that which might result from the increase of atmospheric CO_2 could be produced by raising the albedo, or reflectivity, of the earth. Such a change in albedo could be brought about, for example by spreading very small reflecting particles over large oceanic areas.

An early development of the needed technology might have other uses, for example in inhibiting the formation of hurricanes in tropical oceanic areas.

THE WHITE HOUSE

NOVEMBER 1965

Alan Robock
Department of Environmental Sciences

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Budyko (1974)

Head, Division for Physical Climatology
Main Geophysical Observatory
Leningrad, USSR

CONTROVERSIAL ISSUES

CLIMATE MODIFICATION TECHNIQUES

[Article by Member-Correspondent AN USSR, M. I. Budyko; Moscow, Meteorologiya i Gidrologiya, Russian, No 2, 1974, submitted 11 December 1972, pp 91-97]

A method of changing the influx of short wave radiation in the troposphere by influencing the aerosol layer of the lower stratosphere is examined. It is noted that the use of comparatively small quantities of reagents can appreciably reduce the summary radiation and reduce the surface air temperature, and also have an effect on the amount of precipitation that falls in intracontinental regions.

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Broecker (1984)

Professor, Columbia University

SO_2; A BACKSTOP AGAINST A BAD CO_2 TRIP?

Wallace S. Broecker
Lamont-Doherty Geological Observatory of Columbia University

WRITTEN IN 1984
NEVER PUBLISHED

34

Bolin (1989)

As chairman of the Intergovernmental Panel on Climatic Change I am very anxious now to see the overall assessment be pursued quickly and in depth. Three working groups have been formed:

1) scientific basis for projections of a climatic change

2) impacts of a climatic change

3) policies and strategies to prevent or mitigate a climatic change.

In the light of these activities I am not going to engage myself in any other work with anyone other body in this context. I am a little hesitant to see work proceed on the kind of aspects of the problem that you outline in your letter at this time, but I am sure that sooner or later this will certainly be on our agenda. It is important in this context, however, to note that it is not very likely that any reliable prediction about the regional distribution of climatic change will be available until the models have been verified reasonably well with the aid of data that clearly show that the climatic change is on the way, and that it is caused by human activities.

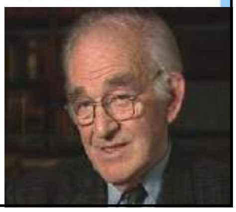
With best personal regards.

Sincerely yours,

Bert Bolin

Bert Bolin

Professor
University of Stockholm
Chair of IPCC



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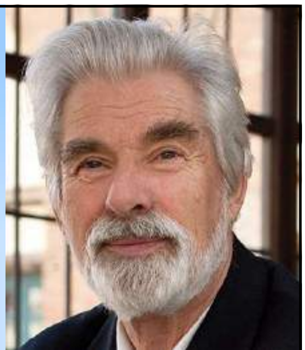
Hasselmann (1989)

Professor, Max Planck Institute for Meteorology, Hamburg, Germany



My personal view is that the only way that man will survive on this planet is to learn to live within the natural limitations of the planet and not to tinker around with it until he has really understood what he is doing.

Maybe in a 100 years we will be wise enough to embark on speculations of the kind your propose. But at present I think a public hearing of ideas of this kind can only be detrimental. I am of course in full favour of trying to understand how the planet earth works. But lets not give the impression we are ready to play around with it.

Cheers, Klaus

(Professor Dr. Klaus Hasselmann)

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Mahlman (1989)

I am also concerned about a possibly inappropriate emphasis upon mitigation at this time. I worry that establishing a psychology that a "fix is possible" might be counterproductive. Why change our ways if a cure is just around the corner? This is a non-scientific opinion.

Scientifically, I am concerned that the only possible "fixes" are those that try to repair a given simple quantity, such as global average surface temperature. Such a focussed approach almost by definition exposes a whole new set of hazards. I think that Budyko's SO_2 solution falls into that category.

In summary, my first reactive response is to worry that the whole exercise has a significant danger of being misguided and counterproductive. Perhaps further enlightenment will dissipate my fears.

Best regards,

J. D. Mahlman
Director

75 Years Stimulating America's Progress ★ 1913-1988

Director
Geophysical Fluid Dynamics Laboratory

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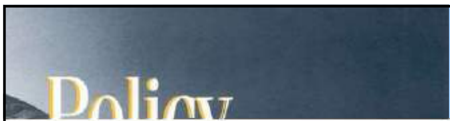

National Academy of Engineering, 1992
https://doi.org/10.17226/1605.

SCREENING OUT SOME SUNLIGHT

Another option for mitigating a global warming would be to try to control the global radiation balance by limiting the amount of incoming radiation from the sun. This could be done by increasing the reflectivity of the earth, i.e., the albedo. Proposals for increasing the whiteness of roofs and surface features would have some effect, but only a fraction of incident solar radiation reaches the earth's surface and a purposeful change in albedo would have more impact if done high in the atmosphere. According to Ramanathan (1988), an increase in planetary albedo of just 0.5 percent is sufficient to halve the effect of a CO_2 doubling. Placing a screen in the atmosphere or low earth orbit could take several forms: it could involve changing the quantity or character of cloud cover, it could take the form of a continuous sheet, or it could be divided into many "mirrors" or a cloud of dust. Preliminary characterizations of some of the possibilities that might be considered are provided below.

Appendix Q

Geoengineering Options

This appendix is divided into four sections: (1) naval rifle system, (2)-balloon system, (3) multiple balloon system, (4) changing cloud abundance. Each section either describes the system or indicates how the costs were computed.

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Department of Environmental Sciences

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Several journal articles and reports:

Leemans et al., 1996
Dickinson, 1996
Schneider, 1996, 2001
Flannery et al., 1997
Teller et al., 1997, 1999, 2002
Keith, 2000, 2001
Boyd et al., 2000
Khan et al., 2001
Bower et al., 2006

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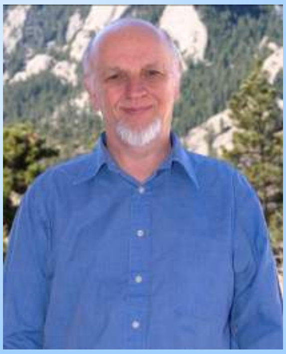
Despairing of prompt political response to global warming, in August and September 2006, Paul Crutzen (Nobel Prize in Chemistry) and Tom Wigley (NCAR) suggested that we consider temporary geoengineering as an emergency response.



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Can Dr. Evil Save The World?

Forget about a future filled with wind farms and hydrogen cars. The Pentagon's top weaponeer says he has a radical solution that would stop global warming now -- no matter how much oil we burn.

Jeff Goodell
Rolling Stone
November 3, 2006

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Reasons geoengineering may be a bad idea

Climate system response

1. Regional climate change, including temperature and precipitation
2. Rapid warming when it stops
3. How rapidly could effects be stopped?
4. Continued ocean acidification
5. Ozone depletion
6. Enhanced acid precipitation
7. Whitening of the sky (but nice sunsets)
8. Less solar radiation for solar power, especially for those requiring direct radiation
9. Effects on plants of changing the amount of solar radiation and partitioning between direct and diffuse
10. Effects on cirrus clouds as aerosols fall into the troposphere
11. Environmental impacts of aerosol injection, including producing and delivering aerosols

Robock, Alan, 2008: 20 reasons why geoengineering may be a bad idea. *Bull. Atomic Scientists*, **64**, No. 2, 14-18, 59, doi:10.2968/064002006.

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Stratospheric Geoengineering

Benefits

1. Reduce surface air temperatures, which could reduce or reverse negative impacts of global warming, including floods, droughts, stronger storms, sea ice melting, land-based ice sheet melting, and sea level rise
2. Increase plant productivity
3. Increase terrestrial CO_2 sink
4. Beautiful red and yellow sunsets
5. Unexpected benefits

Each of these needs to be quantified so that society can make informed decisions.

Robock, Alan, 2008: 20 reasons why geoengineering may be a bad idea. *Bull. Atomic Scientists*, **64**, No. 2, 14-18, 59, doi:10.2968/064002006.

Robock, Alan, Allison B. Marquardt, Ben Kravitz, and Georgiy Stenchikov, 2009: The benefits, risks, and costs of stratospheric geoengineering. *Geophys. Res. Lett.*, **36**, L19703, doi:10.1029/2009GL039209.

Robock, Alan, 2014: Stratospheric aerosol geoengineering. *Issues Env. Sci. Tech.* (Special issue "Geoengineering of the Climate System"), **38**, 162-185.

Risks

1. Drought in Africa and Asia
2. Perturb ecology with more diffuse radiation
3. Ozone depletion
4. Continued ocean acidification
5. Will not stop ice sheets from melting
6. Impacts on tropospheric chemistry
7. Whiter skies
8. Less solar electricity generation
9. Degrade passive solar heating
10. Rapid warming if stopped
11. Cannot stop effects quickly
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19. Effects on airplanes flying in stratosphere
20. Effects on electrical properties of atmosphere
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25. More sunburn
26. Moral hazard – the prospect of it working would reduce drive for mitigation
27. Moral authority – do we have the right to do this?

43

Stratospheric Geoengineering

Benefits

1. Reduce surface air temperatures, which could reduce or reverse negative impacts of global warming, including floods, droughts, stronger storms, sea ice melting, and sea level rise
2. Increase plant productivity
3. Increase terrestrial CO_2 sink
4. Beautiful red and yellow sunsets
5. Unexpected benefits
6. Prospect of implementation could increase drive for mitigation

Each of these needs to be quantified so that society can make informed decisions.

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Risks or Concerns

Physical and biological climate system

1. Drought in Africa and Asia
2. Perturb ecology with more diffuse radiation
3. Ozone depletion
4. Continued ocean acidification
5. Additional acid rain and snow
6. May not stop ice sheets from melting
7. Impacts on tropospheric chemistry
8. Rapid warming if stopped

Human impacts

9. Less solar electricity generation
10. Degrade passive solar heating
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17. Whiter skies
18. Affect stargazing

Unknowns

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Proposals for "solar radiation management" using injection of stratospheric aerosols

1. Inject them into the tropical stratosphere, where winds will spread them around the world and produce global cooling, like tropical volcanic eruptions have.
2. Inject them at high latitudes in the Arctic, where they will keep sea ice from melting, while any negative effects would not affect many people.

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Arctic geoengineering

(In response to New York Times Op-Ed "How to Cool the Globe" by Ken Caldeira, October 24, 2007)

Screwing (with) the Planet

James Fleming
Colby College, Waterville, ME

We would all like to see the polar bears flourish, but Ken Caldiera's suggestion to "seed" the Earth's stratosphere with acidic particles using military technology is not the way to do this.

Naval artillery, rockets, and aircraft exhaust are all "manly" ways to declare "war" on global warming. "A fire hose suspended from a series of balloons" alludes to the proposal by Edward Teller's protégé Lowell Wood to attach a 25-mile long phallus to a futuristic military High Altitude Airship. If the geoengineers can't keep it up, imagine a "snake" filled with more than a ton of acid ripping loose, writhing wildly, and falling out of the sky!

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Arctic geoengineering: continued

(In response to New York Times Op-Ed "How to Cool the Globe" by Ken Caldeira, October 24, 2007)

Screwing (with) the Planet

James Fleming
Colby College, Waterville, ME

The pair of overheated polar bears in the cartoon alludes to such nonsense. And whose warships are those in the distance? Better check with Vladimir Putin before we screw (with) the Arctic.

The geoengineers have been playing such games with the planet since computerized general circulation models were developed back in the late 1950s. While this kind research will undoubtedly continue, it should remain indoors between consenting adults. What needs to be aired out are the underlying assumptions.

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We conducted the following geoengineering simulations with the NASA GISS ModelE atmosphere-ocean general circulation model run at 4°x 5° horizontal resolution with 23 vertical levels up to 80 km, coupled to a 4°x 5° dynamic ocean with 13 vertical levels and an online chemistry and transport module:

- 80-yr control run
- 40-yr anthropogenic forcing, IPCC A1B scenario: greenhouse gases (CO_2, CH_4, N_2O, O_3) and tropospheric aerosols (sulfate, biogenic, and soot), 3-member ensemble
- 40-yr IPCC A1B + Arctic lower stratospheric injection of 3 Mt SO_2/yr, 3-member ensemble
- 40-yr IPCC A1B + Tropical lower stratospheric injection of 5 Mt SO_2/yr, 3-member ensemble
- 40-yr IPCC A1B + Tropical lower stratospheric injection of 10 Mt SO_2/yr

Robock, Alan, Luke Oman, and Georgiy Stenchikov, 2008: Regional climate responses to geoengineering with tropical and Arctic SO_2 injections. *J. Geophys. Res.*, **113**, D16101, doi:10.1029/2008JD010050

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Aerosol properties

We define the dry aerosol effective radius as 0.25 μm compared to 0.35 μm for our Pinatubo simulations. This creates hydrated sulfate aerosols approx 0.30-0.35 μm for our geoengineering runs and 0.47-0.52 μm for our Pinatubo simulations.

It is difficult to say the size at which the aerosols will end up without a microphysical model that has coagulation but by injecting daily vs. one eruption per year, coagulation would be reduced since concentrations are lower and more globally distributed. On the other hand, particles might grow larger than those typical of a volcanic eruption if existing particles grow rather than having new particles form.

The smaller size aerosols have a slightly longer lifetime so this would reduce the rate of injection needed to maintain a specific loading.

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Heckendorn et al. (2009) showed particles would grow, requiring much larger injections for the same forcing.

Environ. Res. Lett. 4 (2009) 045108 P Heckendorn *et al*

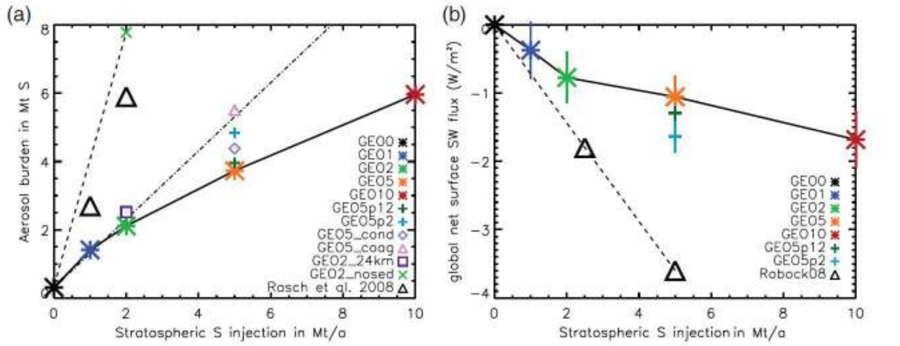

Figure 4. (a) Total aerosol burden as function of sulfur injected annually into the stratosphere (0, 1, 2, 5 and 10 Mt/a S) calculated by the AER model. Dash–dotted line: aerosol burden, if the aerosol residence time were 1 year irrespective of injection strength. Dashed line: aerosol burden when aerosol sedimentation is suppressed in the stratosphere. All results for injections at 20 km, except black square for 24 km emissions. (b) Change in global annual mean net SW flux change at the surface due to geoengineering in comparison with GEO0 calculated by SOCOL for all-sky conditions. Vertical bars: standard deviation of monthly values. Triangles: SW downward flux changes due to geoengineering as proposed by Robock *et al* (2008). All lines in both panels are meant to guide the eye.

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Pierce et al. (GRL, 2010) claimed that emitting sulfuric acid directly will produce larger particles, helping solve the problem of aerosol growth.

L18805 PIERCE ET AL.: AEROSOL FROM CONDENSIBLE VAPOR L18805

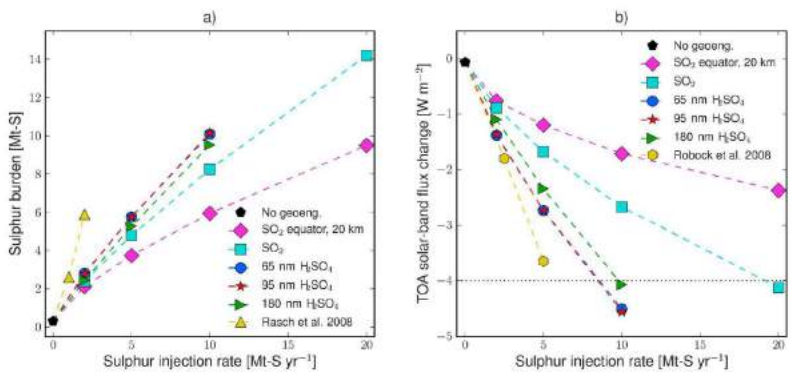

Figure 4. Steady-state (a) stratospheric sulfur burden and (b) top-of-atmospheric solar-band (shortwave) radiative flux change from the stratospheric aerosols as a function of sulfur injection rate. All simulations have emissions evenly distributed between 30°S–30°N and 20–25 km, except results for SO_2 emitted only above the equator (5°S–5°N) at 20 km (19.5–20.5 km). Also included for comparison are the stratospheric sulfur burdens computed by *Rasch et al.* [2008a] (with fixed effective radius of 0.43 μm) and the solar flux changes by *Robock et al.* [2008], both without aerosol microphysics. Black horizontal dotted line in Figure 4b represents the approximate cooling necessary to offset a doubling of CO_2 in the global-mean energy budget.

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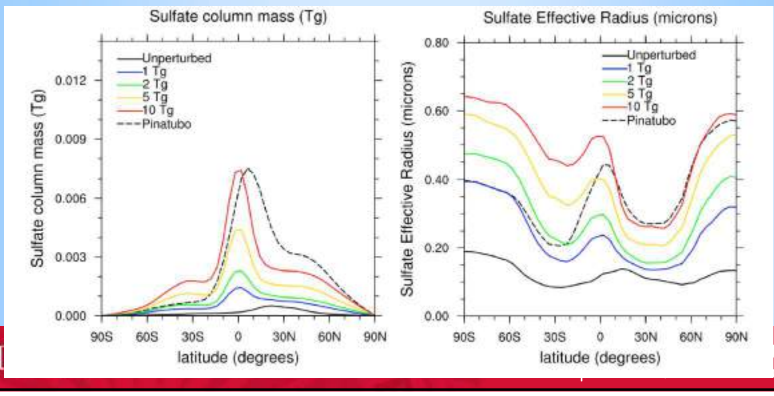
But English et al. (ACP, 2012) found that

"increasing injection rates of SO_2 in a narrow band around the equator to have limited efficacy while broadening the injecting zone as well as injecting particles instead of SO_2 gas increases the sulfate burden for a given injection rate, in agreement with previous work. We find that injecting H_2SO_4 gas instead of SO_2 does not discernibly alter sulfate size or mass, in contrast with a previous study using a plume model with a microphysical model."



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Aerosol properties

By using a smaller aerosol size (about 30% less than Pinatubo), there is about half the heating of the lower tropical stratosphere as compared to the equivalent loading using a Pinatubo size aerosol.

We injected it at about the same altitude as Pinatubo but if the sulfate was closer to the tropopause and larger in size it would warm the tropopause cold point and let a lot more water vapor into the stratosphere, and this could cause additional problems that would have to be considered.

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Latitudes and Altitudes

Tropical: We put SO_2 into the lower stratosphere (16-22 km) over the Equator at a daily rate equal to
5 Mt/yr (1 Pinatubo every 4 years) or
10 Mt/yr (1 Pinatubo every 2 years) for 20 years,
and then continue to run for another 20 years to see how fast the system warms afterwards.

Arctic: We put SO_2 into the lower stratosphere (10-15 km) at 68° N at a daily rate equal to 3 Mt/yr for 20 years, and then continue to run for another 20 years to see how fast the system warms afterwards.

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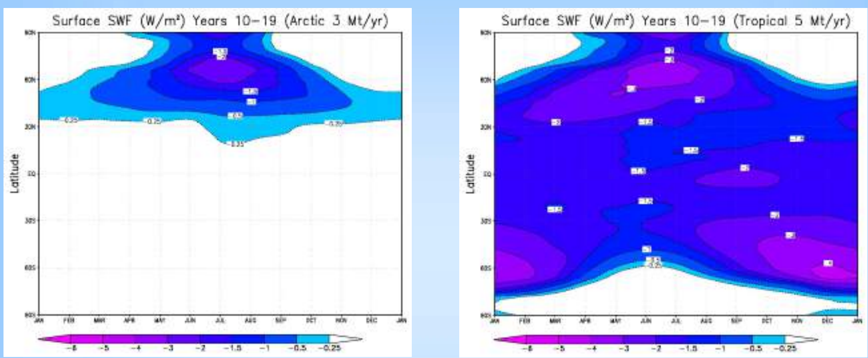
Change in downward solar radiation at Earth's surface



Arctic emission at 68° N leaks into the subtropics

Tropical emission spreads to cover the planet

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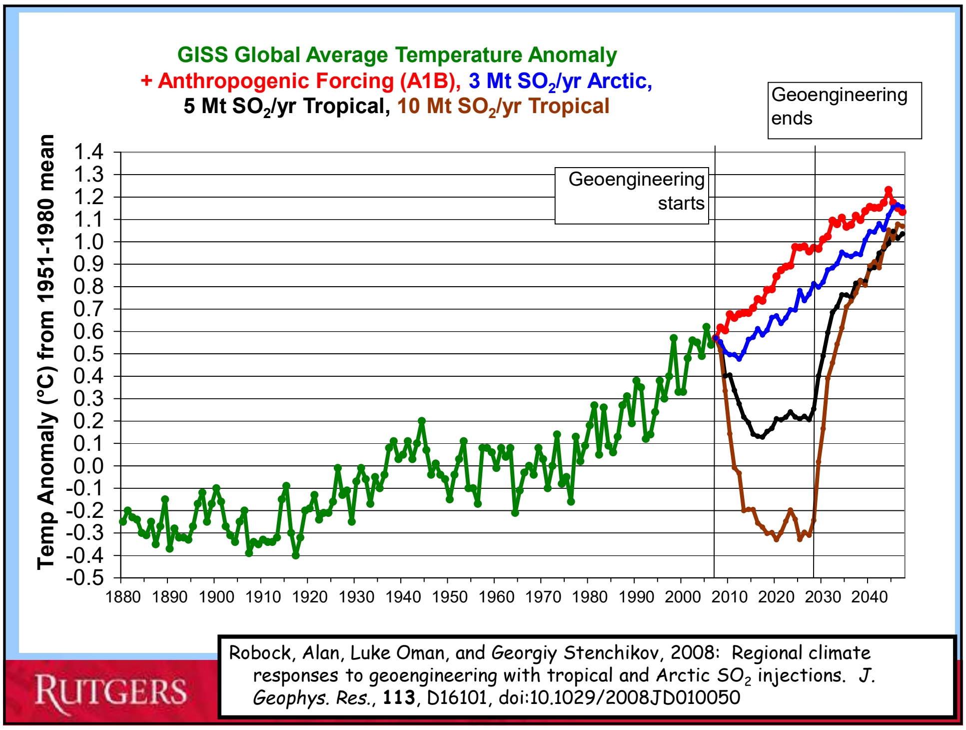

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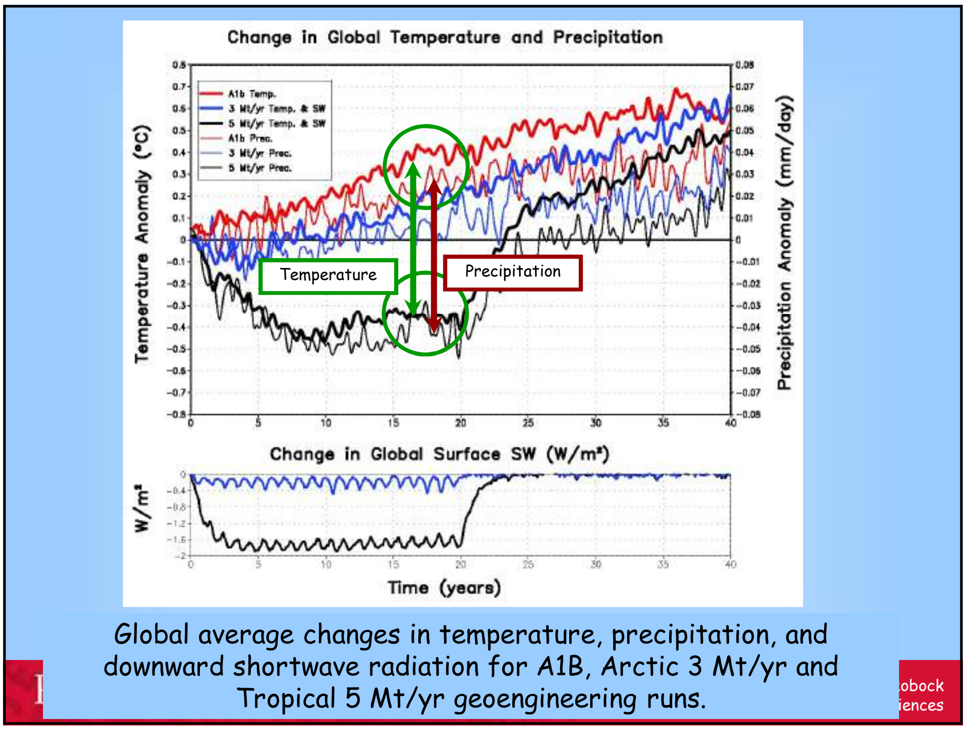

Global average changes in temperature, precipitation, and downward shortwave radiation for A1B, Arctic 3 Mt/yr and Tropical 5 Mt/yr geoengineering runs.

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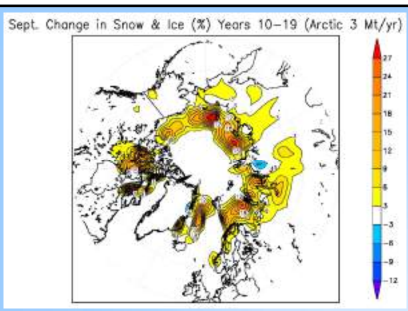

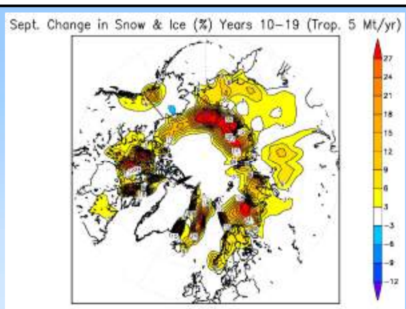

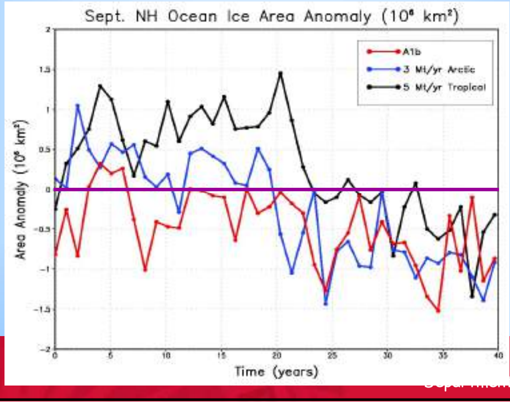

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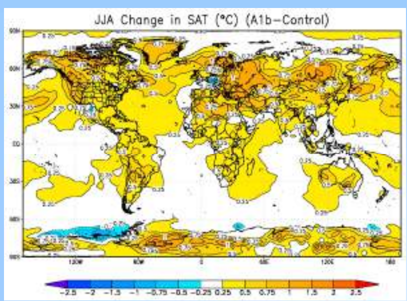
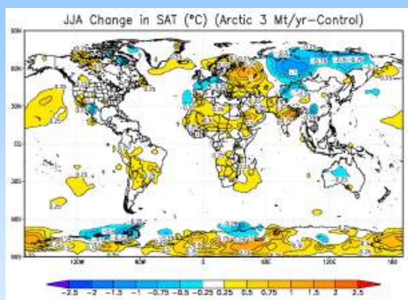
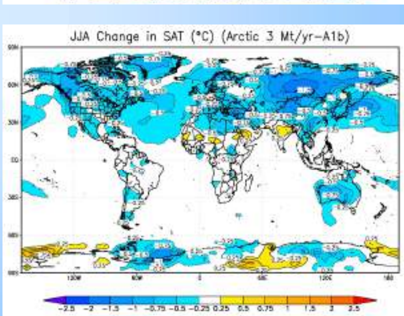




Mean response for second decade of aerosol injection for IPCC A1B + Arctic 3 Mt/yr case for NH summer surface air temperature



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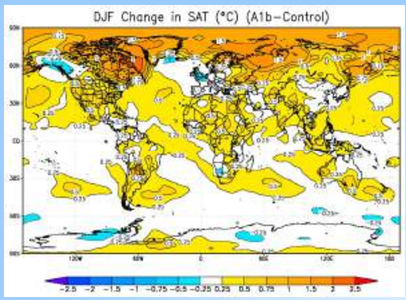

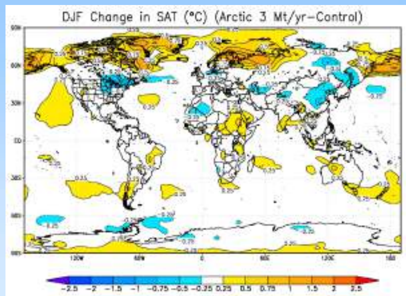

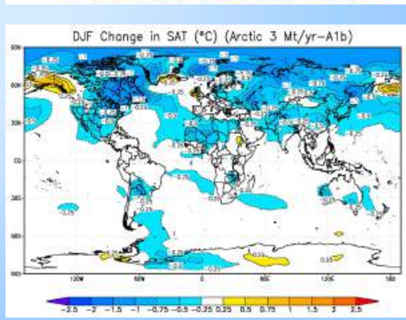

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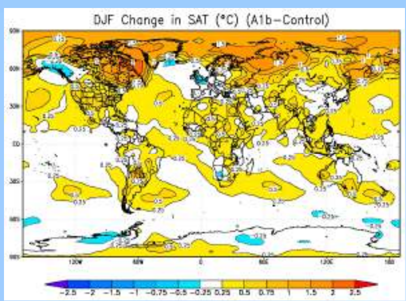

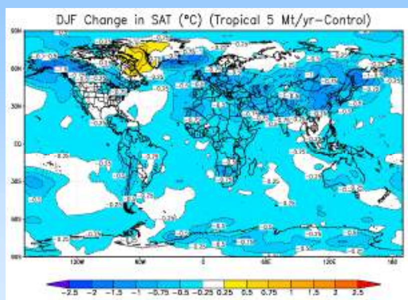

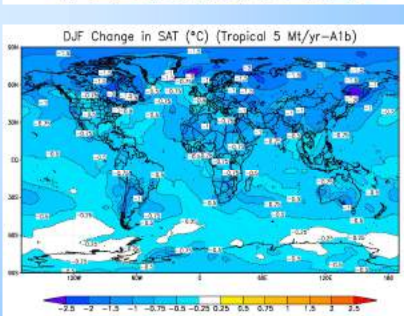

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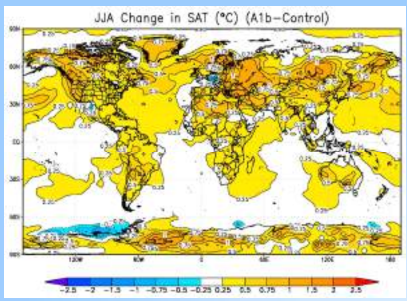

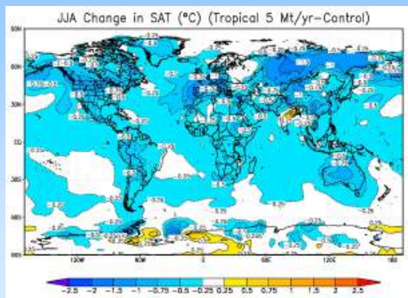

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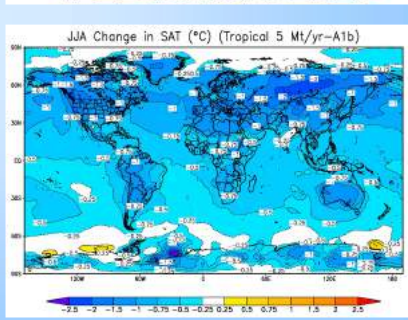

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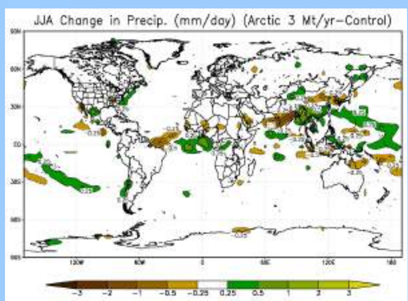
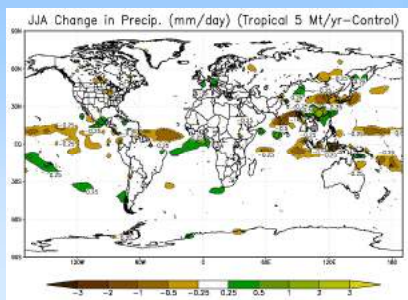
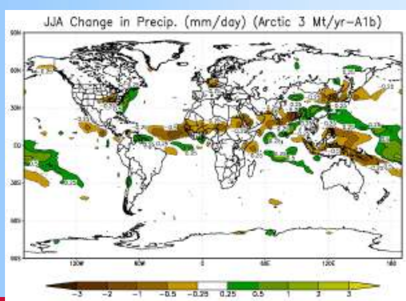
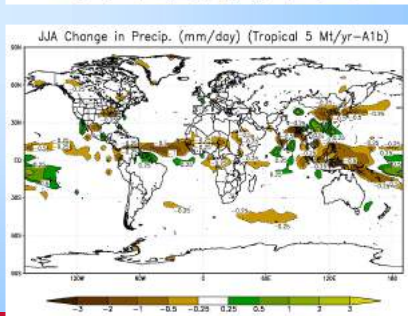
Arctic 3 Mt/yr NH summer precipitation Tropical 5 Mt/yr









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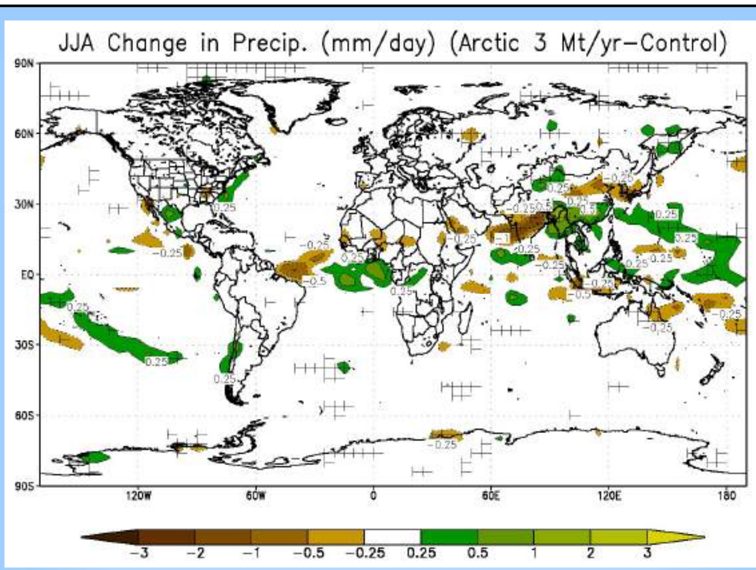

= significant at the 95% level

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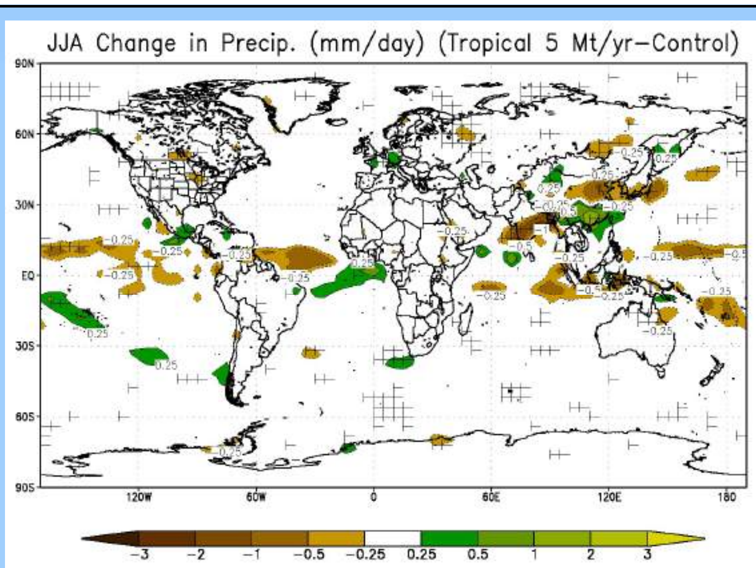

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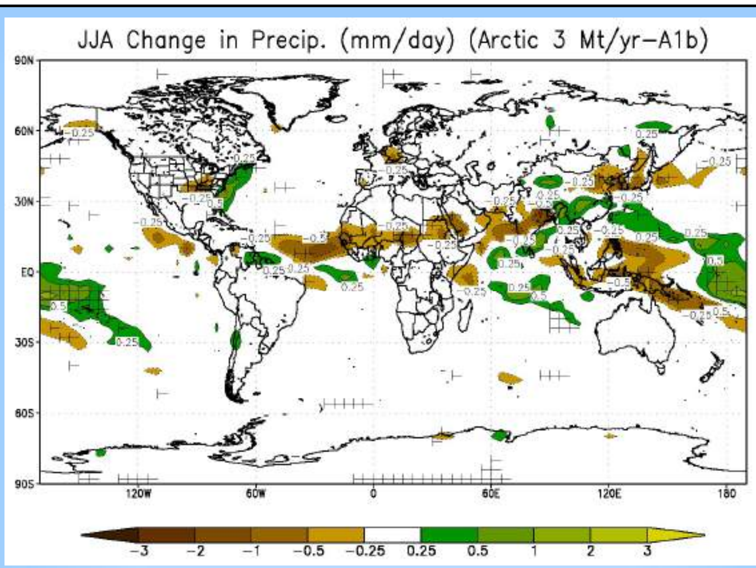

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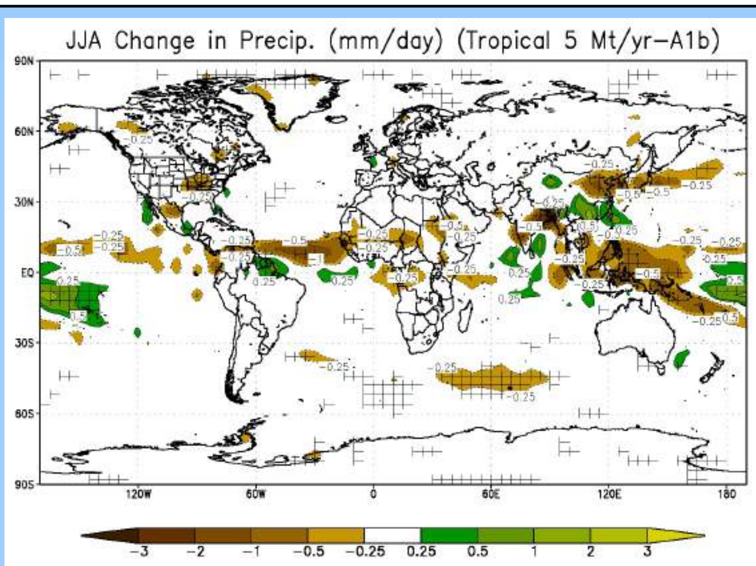

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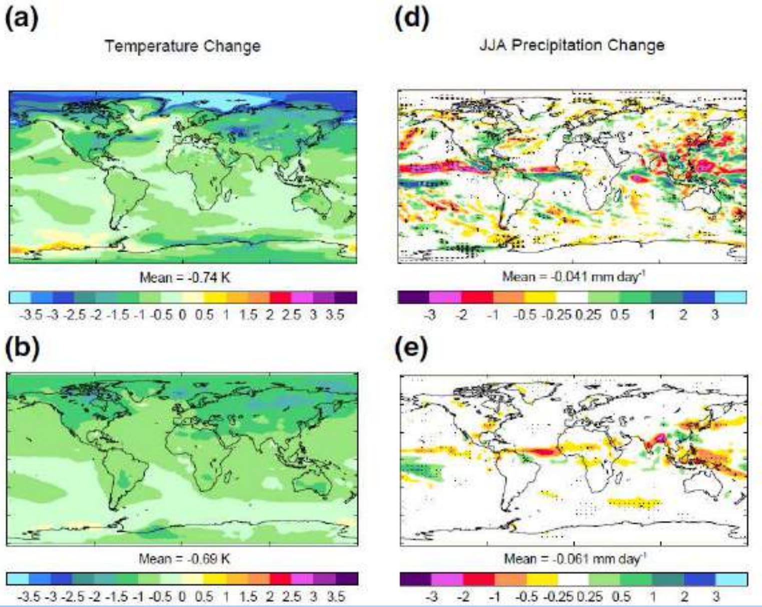

Met Office, Hadley Centre

5Mt/yr – A1b

ModelE

5Mt/yr – A1b

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Jones, Andy, Jim Haywood, Olivier Boucher, Ben Kravitz, and Alan Robock, 2010: Geoengineering by stratospheric SO_2 injection: Results from the Met Office HadGEM2 climate model and comparison with the Goddard Institute for Space Studies ModelE. *Atmos. Chem. Phys.*, **10**, 5999-6006.

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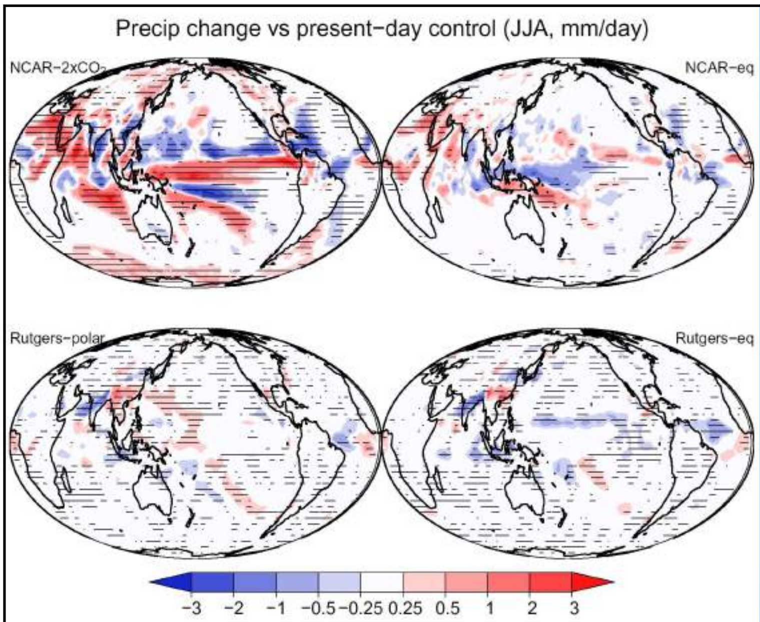

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Rasch, Philip J., Simone Tilmes, Richard P. Turco, Alan Robock, Luke Oman, Chih-Chieh (Jack) Chen, Georgiy L. Stenchikov, and Rolando R. Garcia, 2008: An overview of geoengineering of climate using stratospheric sulphate aerosols. *Phil. Trans. Royal Soc. A.*, **366**, 4007-4037, doi:10.1098/rsta.2008.0131.

72

Conclusions

1. If there were a way to continuously inject SO_2 into the lower stratosphere, it would produce global cooling.
2. Tropical SO_2 injection would produce sustained cooling over most of the world, with more cooling over continents.
3. Arctic SO_2 injection would not just cool the Arctic.
4. Solar radiation reduction produces larger precipitation response than temperature, as compared to greenhouse gases.
5. Both tropical and Arctic SO_2 injection might disrupt the Asian and African summer monsoons, reducing precipitation to the food supply for billions of people.

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Geoengineering Model Intercomparison Project (GeoMIP)

We have carried out standard experiments with the GCMs run as part of CMIP5 using identical global warming and geoengineering scenarios, to see whether our results are robust.

For example, how will the hydrological cycle respond to stratospheric geoengineering? Will there be a significant reduction of Asian monsoon precipitation? How will ozone and UV change?

Kravitz, Ben, Alan Robock, Olivier Boucher, Hauke Schmidt, Karl Taylor, Georgiy Stenchikov, and Michael Schulz, 2011: The Geoengineering Model Intercomparison Project (GeoMIP). *Atmospheric Science Letters*, **12**, 162-167, doi:10.1002/asl.316.

So far, 83 peer-reviewed GeoMIP publications, many of which are in the special sections of *Journal of Geophysical Research – Atmospheres* and *Atmospheric Chemistry and Physics / Geoscientific Model Development*.

GeoMIP is a CMIP Coordinated Experiment, as part of the Coupled Model Intercomparison Projects 5 and 6 (CMIP5, CMIP6).

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http://climate.envsci.rutgers.edu/GeoMIP/publications.html

74

First GeoMIP Workshop, Rutgers University, February 10-12, 2011

http://climate.envsci.rutgers.edu/GeoMIP/events/rutgersfeb2011.html

Workshop was sponsored by the United Kingdom embassy in the United States.

Robock, Alan, Ben Kravitz, and Olivier Boucher, 2011: Standardizing Experiments in Geoengineering; GeoMIP Stratospheric Aerosol Geoengineering Workshop; New Brunswick, New Jersey, 10-12 February 2011, *EOS*, **92**, 197, doi:10.1029/ 2011ES003424.

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75

Second GeoMIP Workshop, University of Exeter, March 30-31, 2012

http://climate.envsci.rutgers.edu/GeoMIP/events/exetermarch2012.html

Workshop was sponsored by the Integrated Assessment of Geoengineering Proposals project.

Kravitz, Ben, Alan Robock, and James Haywood, 2012: Progress in climate model simulations of geoengineering: 2nd GeoMIP Stratospheric Aerosol Geoengineering Workshop; Exeter, UK, 30-31 March 2012, *EOS*, **93**, 340, doi:10.1029/2012ES003871.

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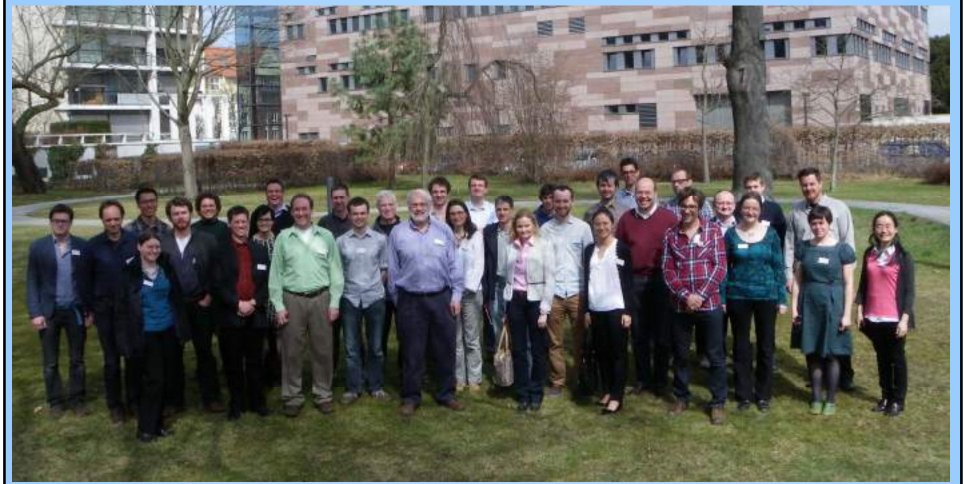
76

Third GeoMIP Workshop, Institute for Advanced Sustainability Studies, Potsdam, Germany, April 15-16, 2013

http://climate.envsci.rutgers.edu/GeoMIP/events/potsdamapril2013.html



Workshop was sponsored by IASS and NSF.

Kravitz, Ben, Alan Robock, and Peter Irvine, 2013: Robust results from climate model simulations of geoengineering: GeoMIP 2013; Potsdam, Germany, 15–16 April 2013. *Eos*, **94**, 292, doi:10.1002/2013EO330005.

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77

Fourth GeoMIP Workshop, Paris, France, April 24-25, 2014

http://climate.envsci.rutgers.edu/GeoMIP/events/parisapril2014.html

Workshop was sponsored by the Laboratoire de Météorologie Dynamique and US National Science Foundation.

Kravitz, Ben, Alan Robock, and Olivier Boucher, 2014: Future directions in simulating solar geoengineering; Fourth GeoMIP Workshop; Paris, France, 24–25 April 2014. *Eos*, **95** (31), 280, doi:10.1002/ 2014EO310010.

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78

Fifth GeoMIP Workshop, National Center for Atmospheric Research, Boulder, Colorado, July 22-23, 2015

http://www.asp.ucar.edu/ecsa/geoengineering-workshop.php

Workshop sponsored by the University Corporation for Atmospheric Research and the US National Science Foundation.

Kravitz, Ben, Alan Robock, and Simone Tilmes, 2016: New Paths in Geoengineering; National Center for Atmospheric Research Fifth Annual Geoengineering Model Intercomparison Workshop and Early Career Summer School; Boulder, Colorado, 20–24 July 2015. *Eos*, **97**, doi:10.1029/2016EO045915.

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Sixth GeoMIP Workshop, University of Oslo, Norway, June 21-22, 2016

http://www.asp.ucar.edu/ecsa/geoengineering-workshop.php

Workshop sponsored by the Research Council of Norway and the US National Science Foundation.

Kravitz, Ben, Alan Robock, and Jón Egill Kristjánsson, 2017: Understanding How Climate Engineering Can Offset Climate Change; Sixth Meeting of the Geoengineering Model Intercomparison Project (GeoMIP); Oslo, Norway, 21–22 June 2016. *Eos*, **98**, No. 4, p. 11, doi:10.1029/2016EO005279.

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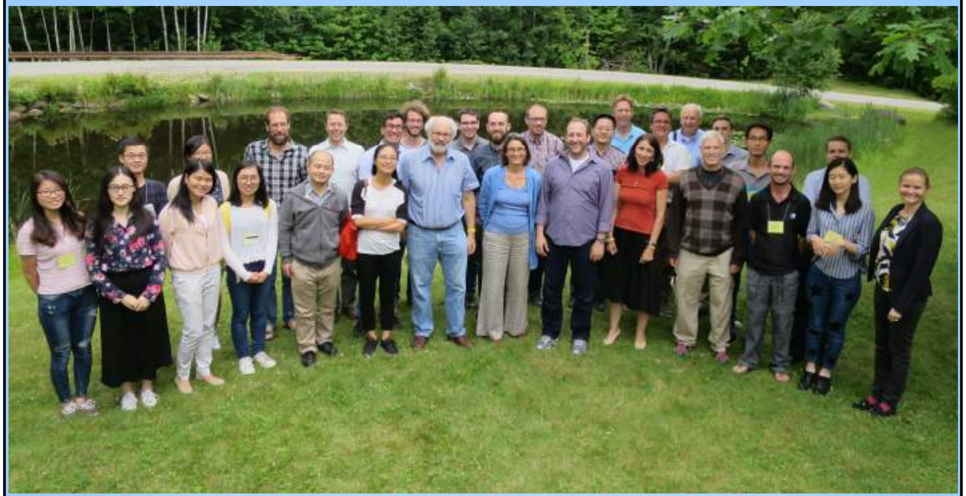
Seventh GeoMIP Workshop, Sunday River, Newry, Maine, USA, July 27, 2017



Workshop sponsored by the US National Science Foundation.

Kravitz, Ben, and Alan Robock, 2017: Vetting new models of climate responses to geoengineering: The Seventh Meeting of the Geoengineering Model Intercomparison Project; Newry, Maine, 26 July 2017, *Eos*, **98**, doi:10.1029/2017EO089383.

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81

Eighth GeoMIP Workshop, ETH Zürich, Switzerland April 16-17, 2018

Workshop sponsored by the US National Science Foundation.

Kravitz, Ben, Alan Robock, and Ulrike Lohman, 2018: Modeling the impacts of geoengineering: Report on the Eighth Annual GeoMIP Meeting, 16-17 April 2018, Zürich, Switzerland, *Eos*, **99**, doi:10.1029/2018EO103333.

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Ninth GeoMIP Workshop
Beijing Normal University, Beijing, China
August 15-16, 2019

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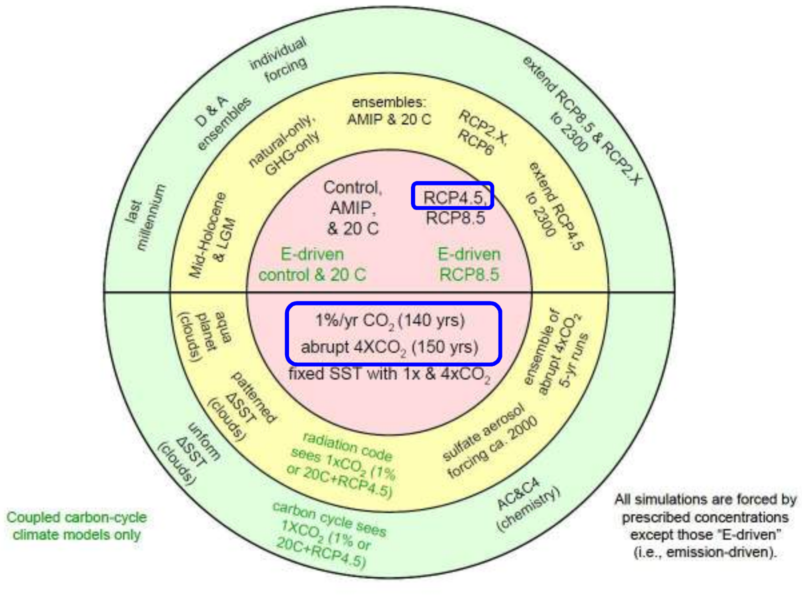

Figure 3: Schematic summary of CMIP5 long-term experiments.

RUTGERS Taylor et al. (*BAMS*, 2012)

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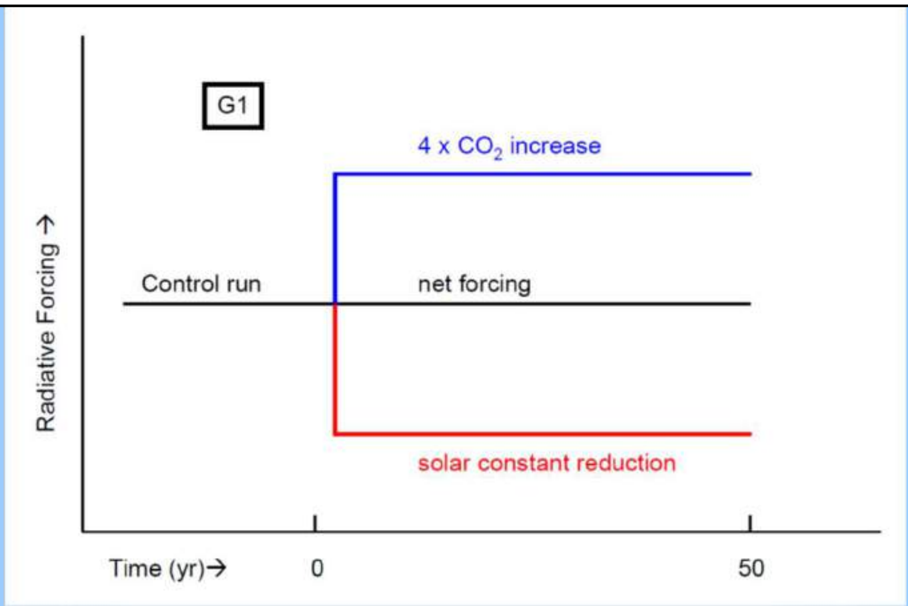
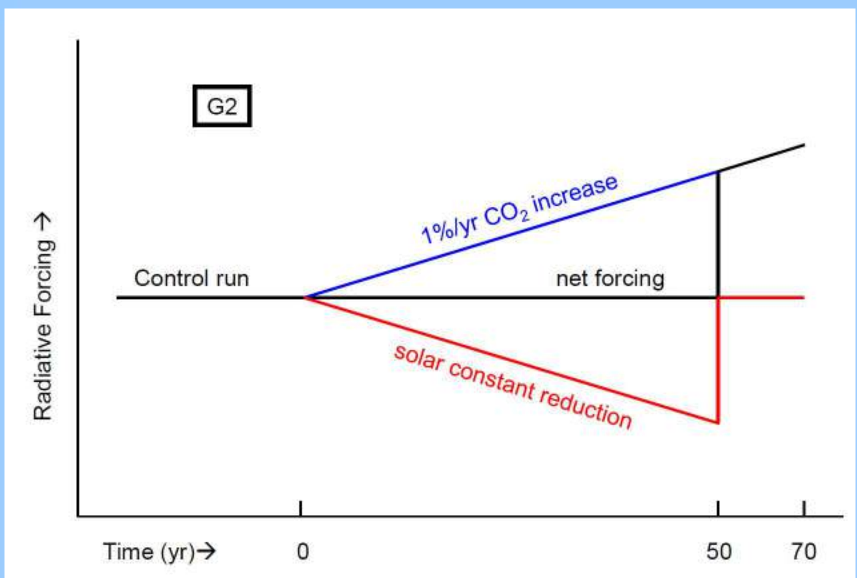


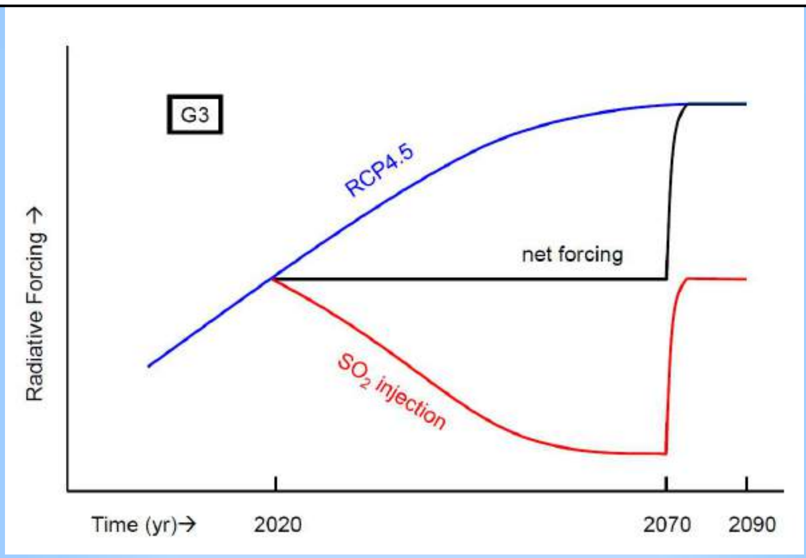
G1: Instantaneously quadruple CO_2 concentrations (as measured from preindustrial levels) while simultaneously reducing the solar constant to counteract this forcing.

85



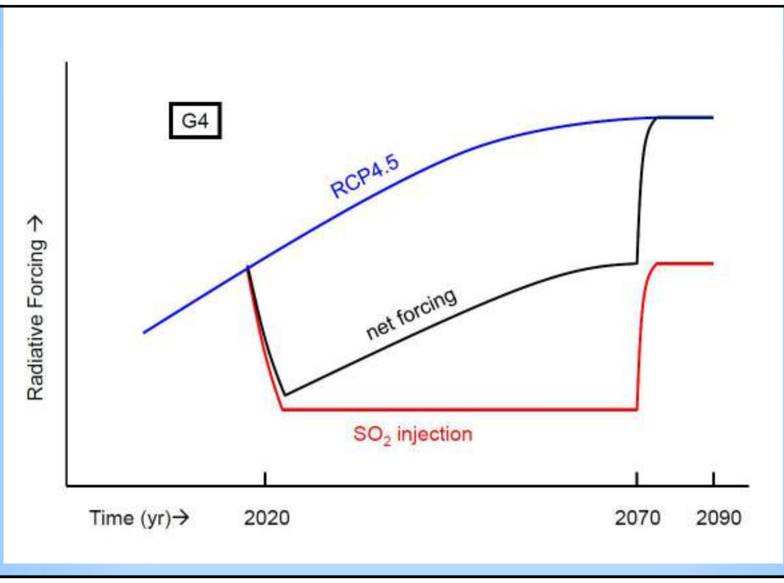
G2: In combination with 1% CO_2 increase per year, gradually reduce the solar constant to balance the changing radiative forcing.

86



G3: In combination with RCP4.5 forcing, starting in 2020, gradual ramp-up the amount of SO_2 or sulfate aerosol injected, with the purpose of keeping global average temperature nearly constant. Injection will be done at one point on the Equator or uniformly globally.

87



G4: In combination with RCP4.5 forcing, starting in 2020, daily injections of a constant amount of SO_2 at a rate of 5 Tg SO_2 per year at one point on the Equator through the lower stratosphere (approximately 16-25 km in altitude).

88

Results from G1 experiments by 12 climate models.

This is a very artificial experiment, with large forcing so as to get large response.

Shown are averages from years 11-50 of the simulations, balancing 4xCO_2 with solar radiation reduction to achieve global average radiation balance.

Kravitz, Ben, et al., 2013: Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP). *J. Geophys. Res. Atmos.*, **118**, 8320-8332, doi:10.1002/jgrd.50646.

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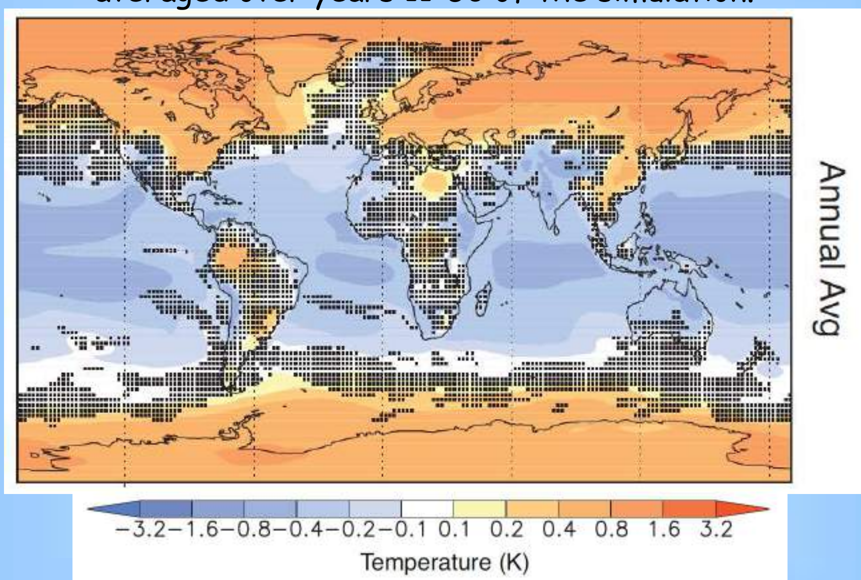
Surface air temperature differences (*G1–piControl*), averaged over years 11-50 of the simulation.



No stippling denotes agreement on the sign of the response in at least 75% of models.

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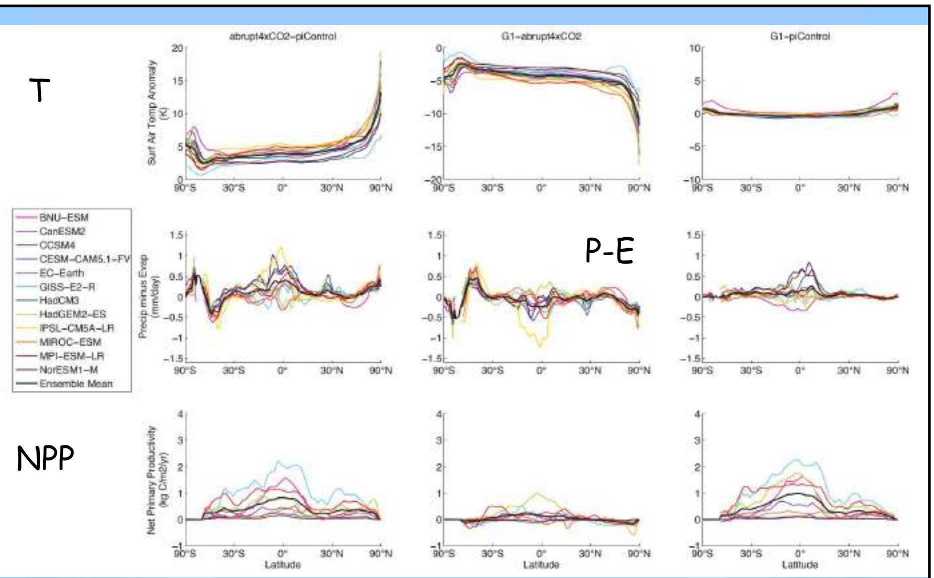

Zonal average over years 11-50 of simulation

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Results from G1 experiments by 12 climate models

This is a very artificial experiment, with large forcing so as to get large response.

Shown are averages from years 11-50 of the simulations, balancing $4xCO_2$ with solar radiation reduction to achieve global average radiation balance.

Tilmes, Simone, et al., 2013: The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP). *J. Geophys. Res. Atmos.*, **118**, 11,036-11,058, doi:10.1002/jgrd.50868.

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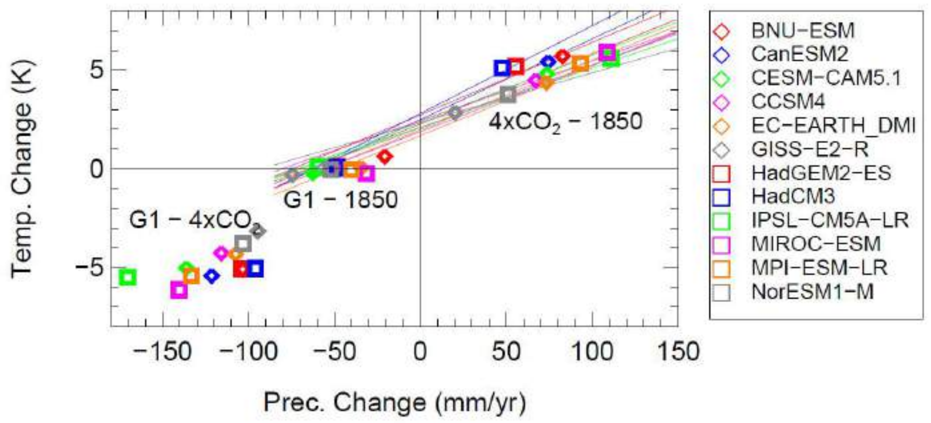
Global average results for all years for G1 and for years 11-50 of simulation for $4xCO_2$



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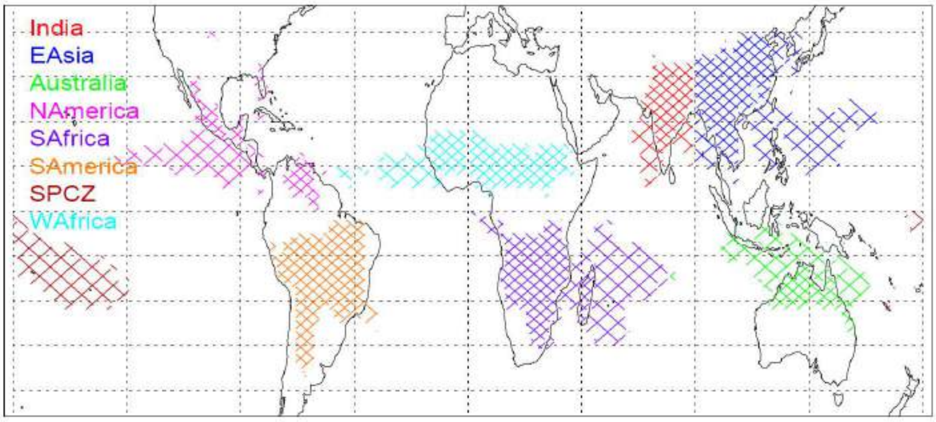
Monsoon regions



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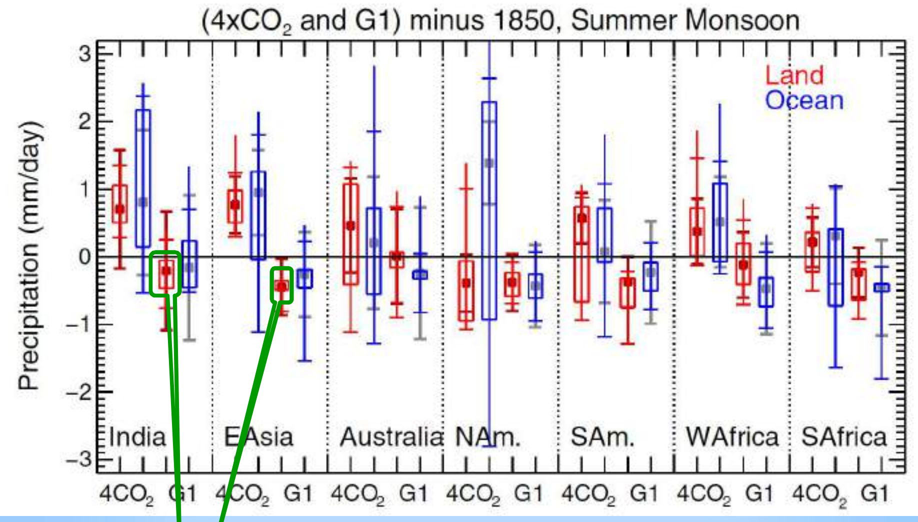

Summer monsoon precipitation reduction

Years 11-50

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Results from G2 experiments by 11 climate models.

This is a 1%/year increase of CO_2 balanced by a reduction of insolation.

Jones, Andy, et al., 2013: The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP). *J. Geophys. Res. Atmos.*, **118**, 9743-9752, doi:10.1002/jgrd.50762.

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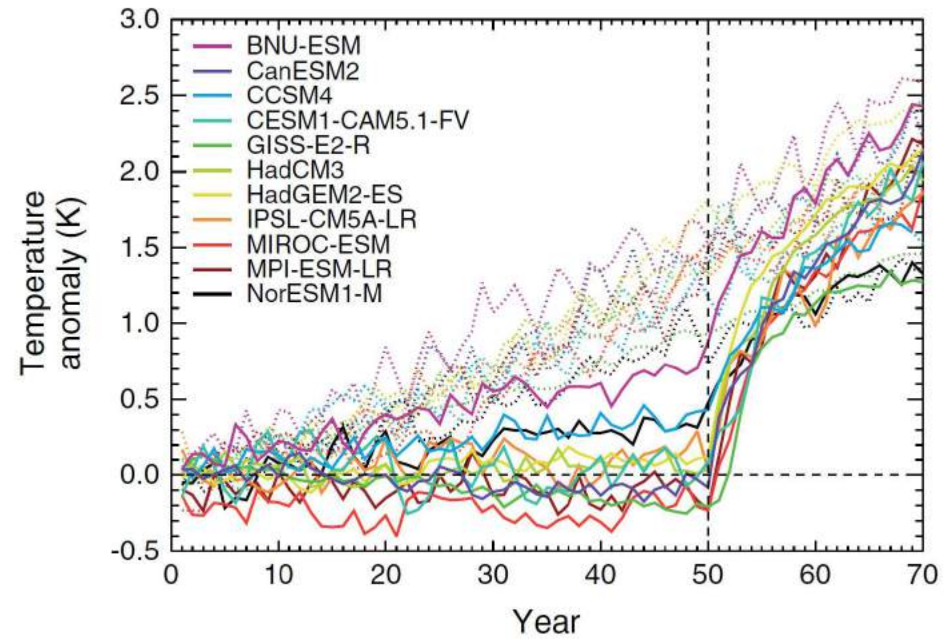
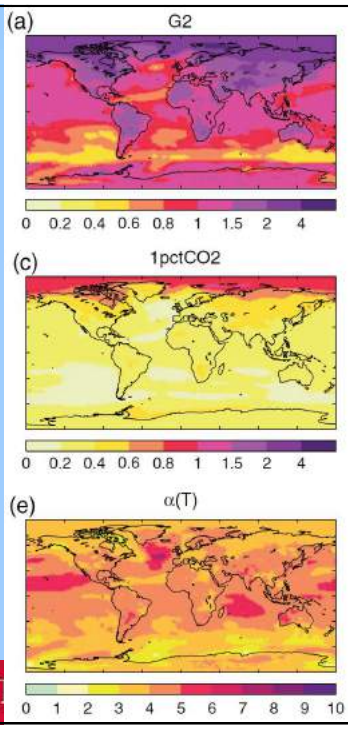


dotted lines are +1%/yr CO_2 solid lines are G2

97



Rate of change of temperature in first 10 years of G2 (K/decade)

Rate of change of temperature in 70 years of +1%/yr CO_2 (K/decade)

Ratio of G2 to +1%/yr CO_2

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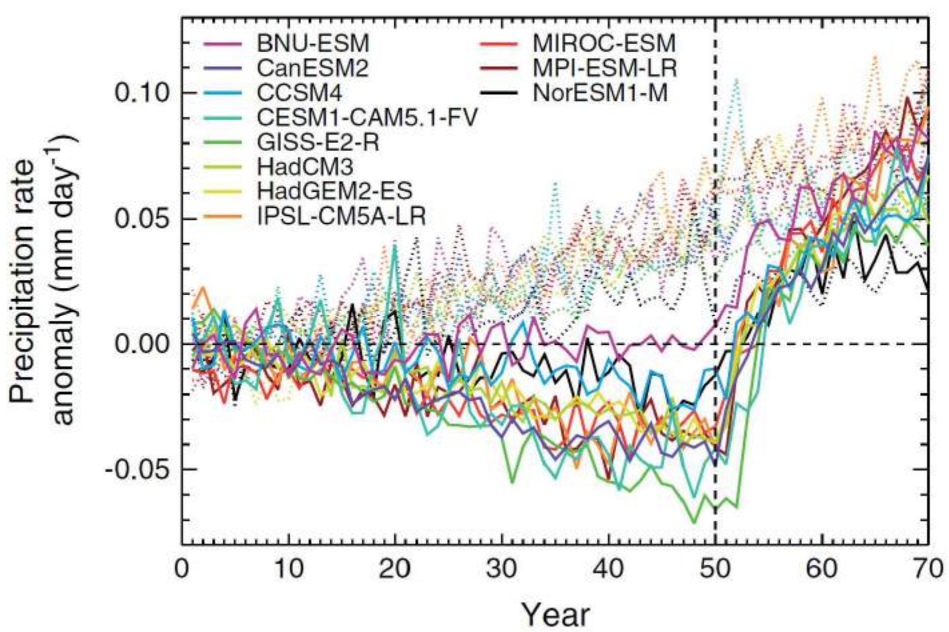
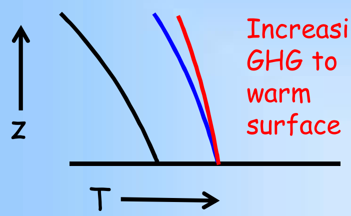


dotted lines are +1%/yr CO_2 solid lines are G2

99

Reducing solar radiation to keep temperature constant **reduces precipitation**

Increasing short wave to warm surface



Increasing GHG to warm surface

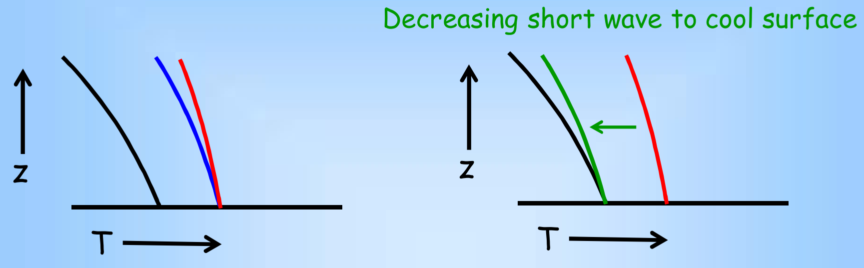
If we compensate for the increased downward longwave radiation from greenhouse gases by reducing solar radiation by the same amount, we can produce a net radiation balance at the surface so temperature will not change.

However, this will result in a reduction of precipitation, since changing solar radiation has a larger impact on precipitation than changing longwave radiation.

This will produce warming from drier surfaces requiring even more solar reduction and more drying.

100

Reducing solar radiation to keep temperature constant **reduces precipitation**

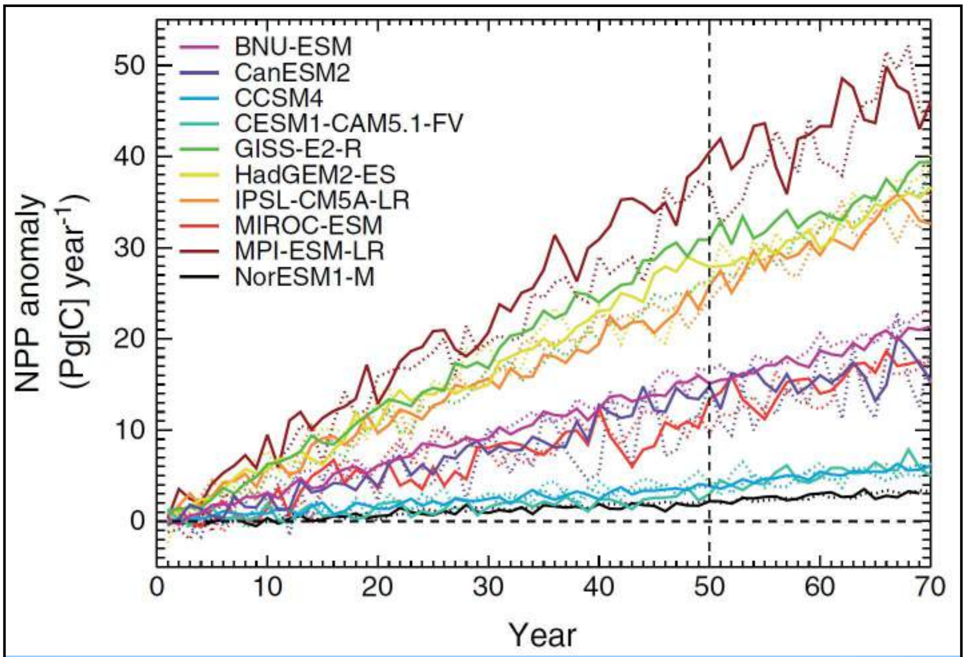


If we compensate for the increased downward longwave radiation from greenhouse gases by reducing solar radiation by the same amount, we can produce a net radiation balance at the surface so temperature will not change.

However, this will result in a reduction of precipitation, since changing solar radiation has a larger impact on precipitation than changing longwave radiation.

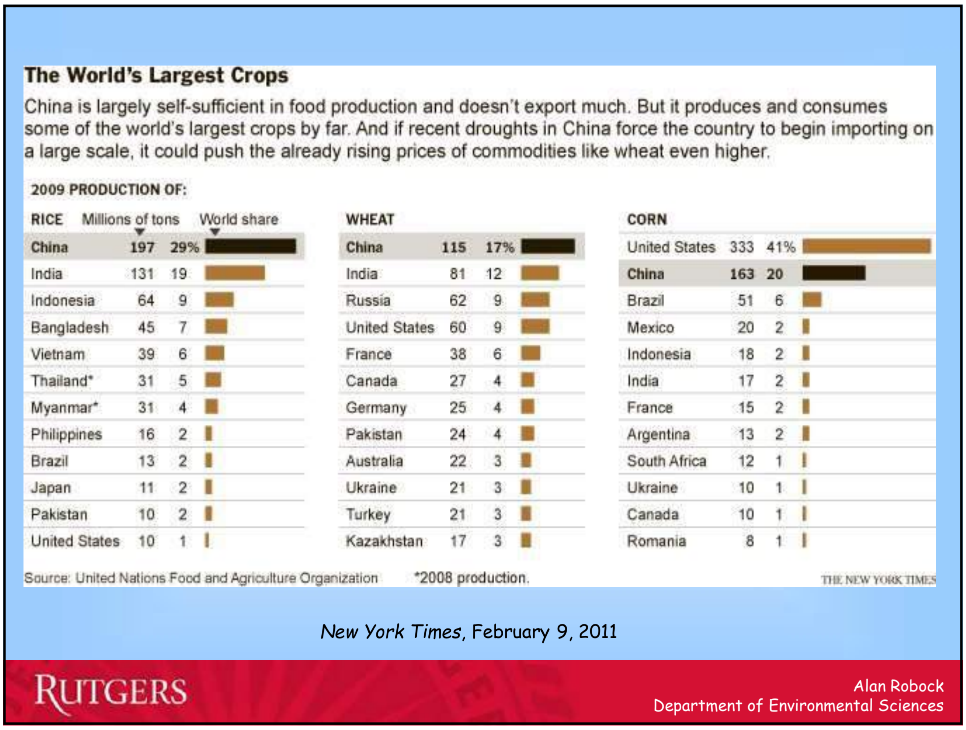
This will produce warming from drier surfaces requiring even more solar reduction and more drying.

101



dotted lines are +1%/yr CO_2 solid lines are G2

102



The World's Largest Crops

China is largely self-sufficient in food production and doesn't export much. But it produces and consumes some of the world's largest crops by far. And if recent droughts in China force the country to begin importing on a large scale, it could push the already rising prices of commodities like wheat even higher.

2009 PRODUCTION OF:

RICE	Millions of tons	World share	WHEAT			CORN		
China	197	29%	China	115	17%	United States	333	41%
India	131	19	India	81	12	China	163	20
Indonesia	64	9	Russia	62	9	Brazil	51	6
Bangladesh	45	7	United States	60	9	Mexico	20	2
Vietnam	39	6	France	38	6	Indonesia	18	2
Thailand*	31	5	Canada	27	4	India	17	2
Myanmar*	31	4	Germany	25	4	France	15	2
Philippines	16	2	Pakistan	24	4	Argentina	13	2
Brazil	13	2	Australia	22	3	South Africa	12	1
Japan	11	2	Ukraine	21	3	Ukraine	10	1
Pakistan	10	2	Turkey	21	3	Canada	10	1
United States	10	1	Kazakhstan	17	3	Romania	8	1

Source: United Nations Food and Agriculture Organization *2008 production. THE NEW YORK TIMES

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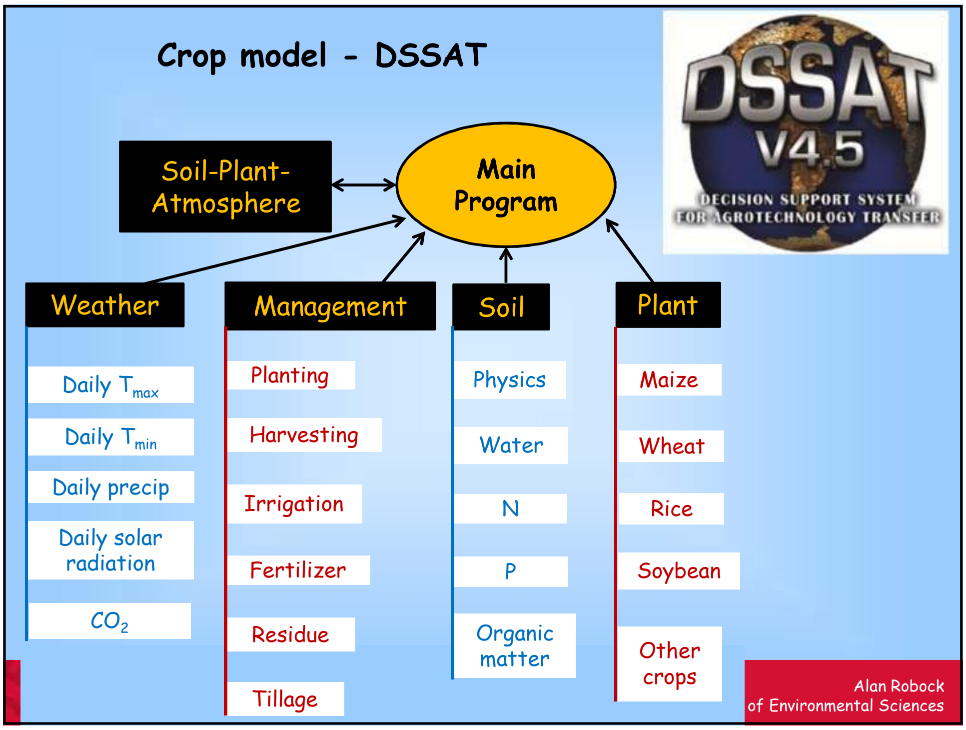

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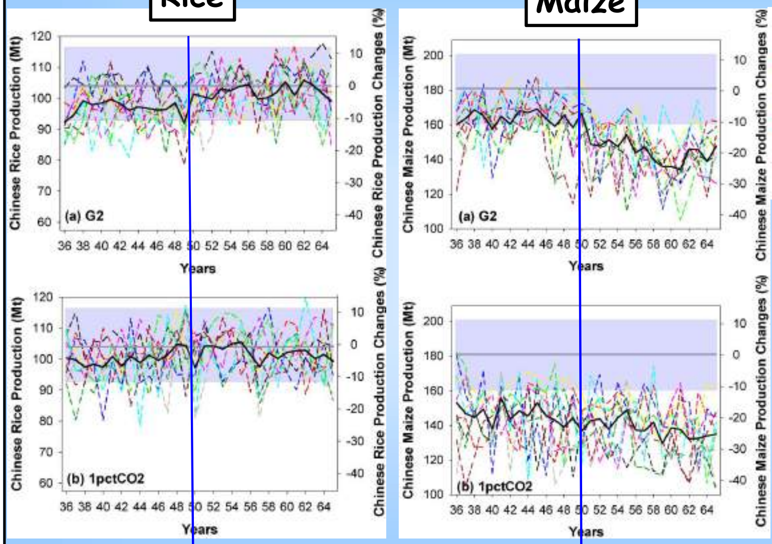
Crop Simulations - Geoengineering – G2



Xia et al., 2014: Solar radiation management impacts on agriculture in China: A case study in the Geoengineering Model Intercomparison Project (GeoMIP). *J. Geophys. Res. Atmos.*, **119**, doi:10.1002/2013JD020630.

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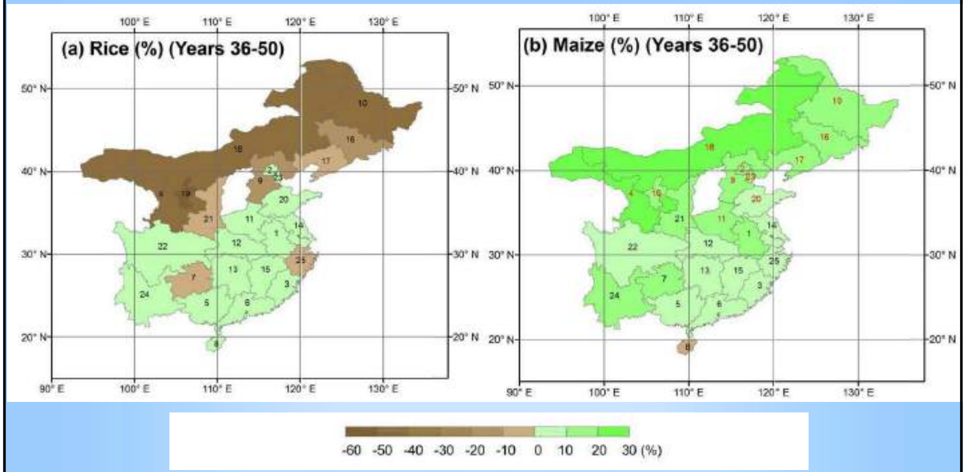
Crop Simulations - Geoengineering – G2



Crop yield changes under simulated G2 geoengineering **(Years 36-50)** compared with the same period of 1pctCO2.

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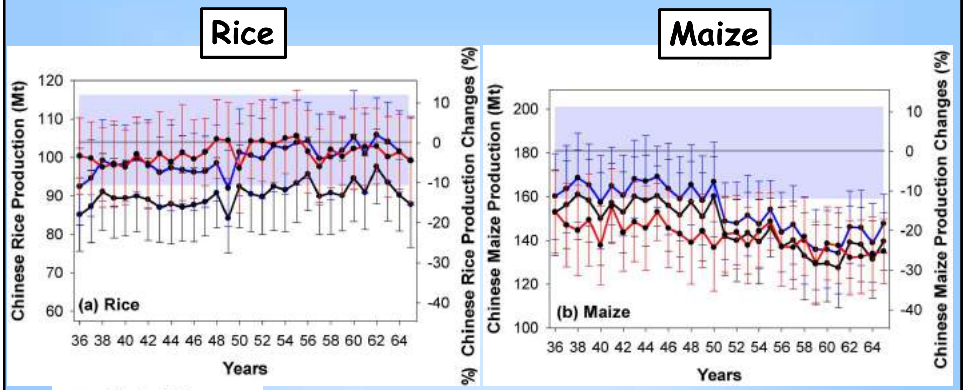
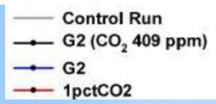
Crop Simulations - Geoengineering – G2

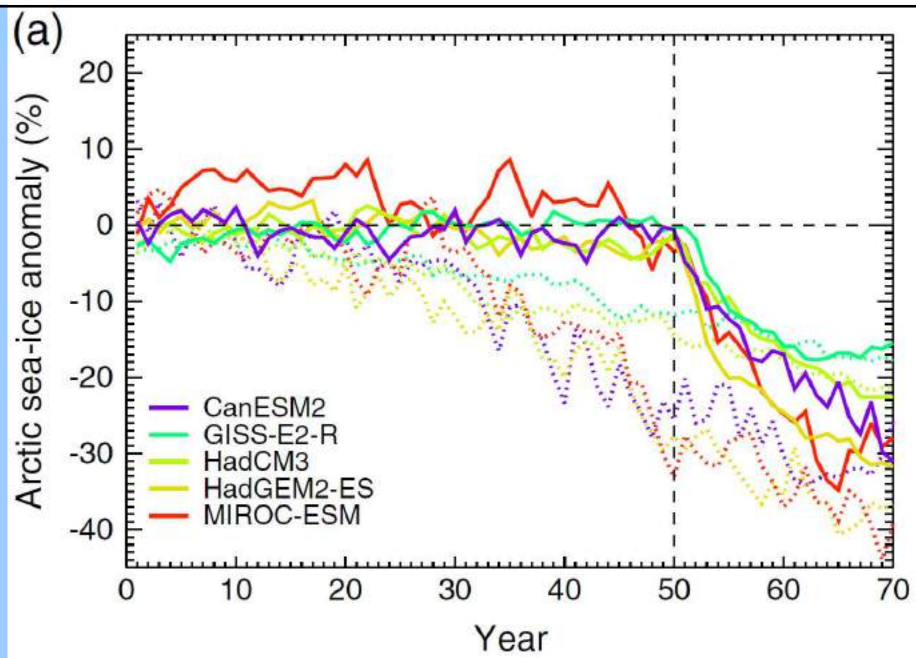




CO_2 fertilization effect:

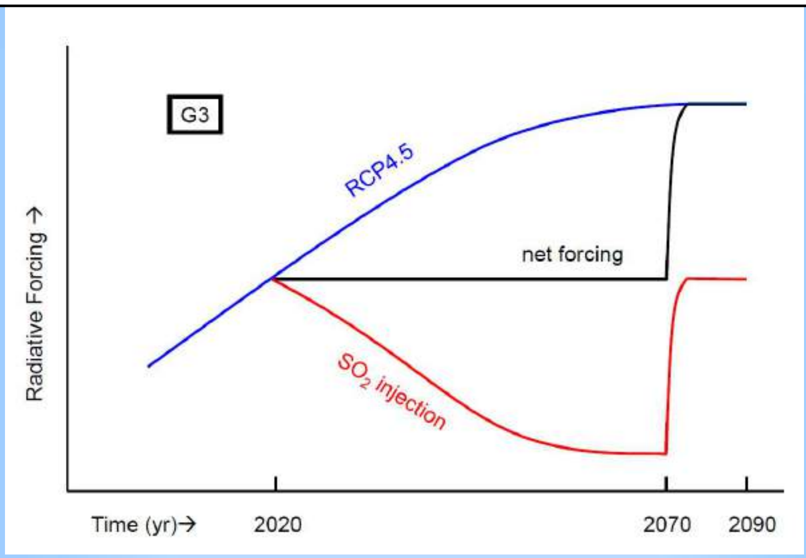
- raises rice production by 8.6 Mt and compensates the negative impacts from other climate changes due to G2 on rice.
- contributes 42.4% of the maize production increase compared with 1pctCO2

107



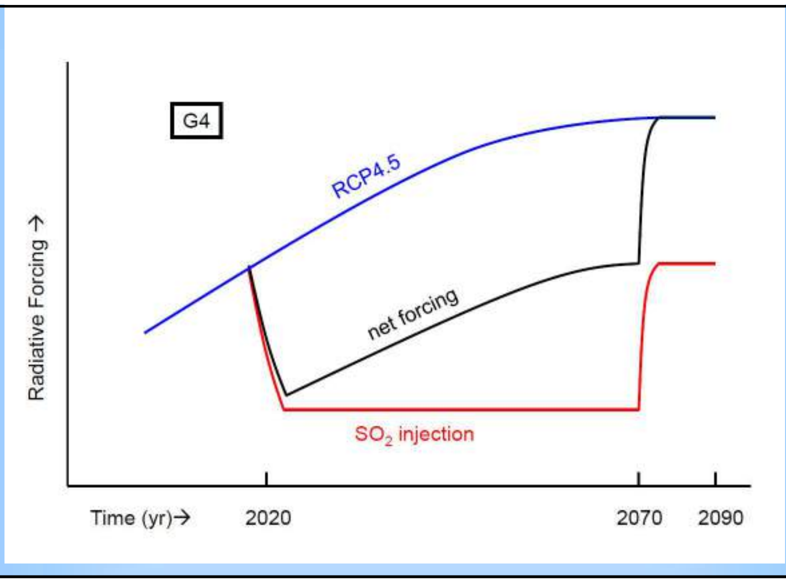
dotted lines are +1%/yr CO_2 solid lines are G2

108



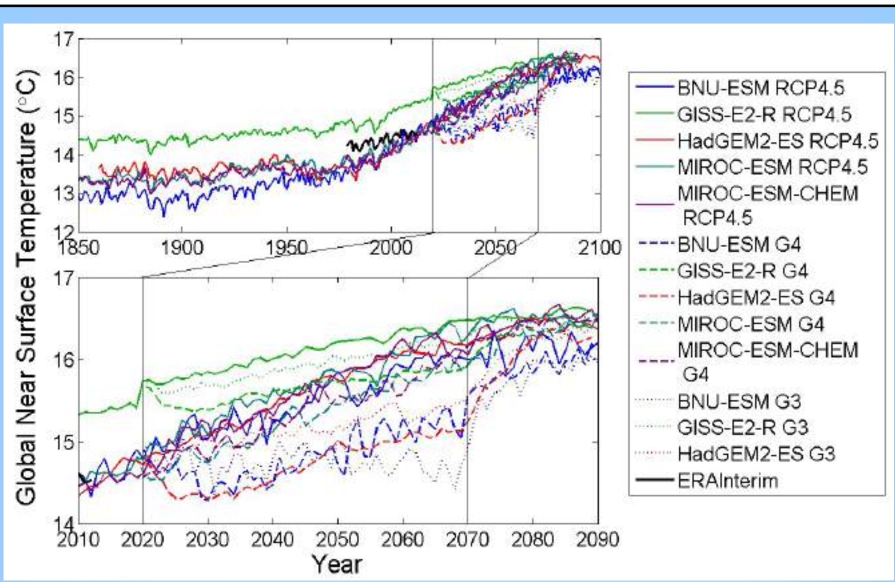
G3: In combination with RCP4.5 forcing, starting in 2020, gradual ramp-up the amount of SO_2 or sulfate aerosol injected, with the purpose of keeping global average temperature nearly constant. Injection will be done at one point on the Equator or uniformly globally.

109



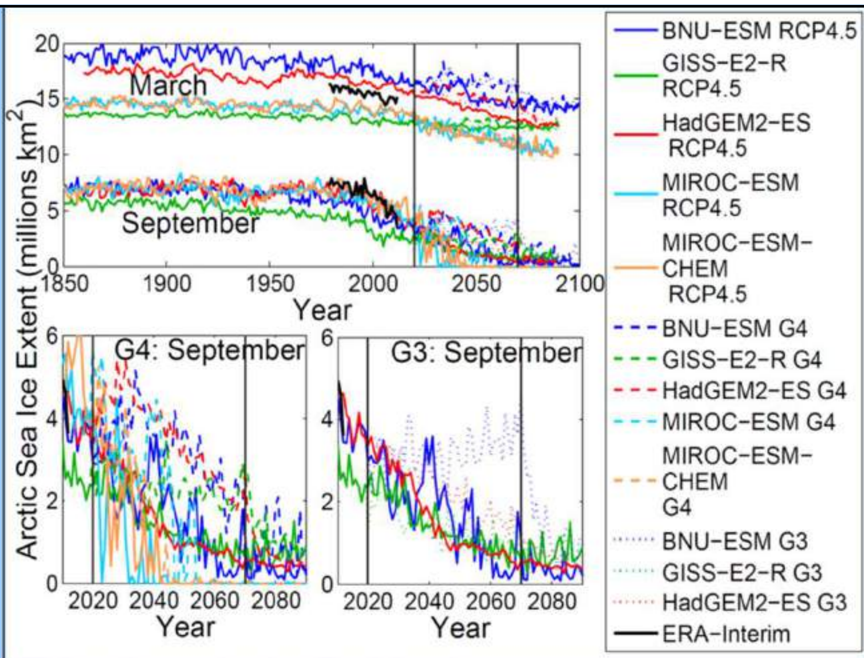
G4: In combination with RCP4.5 forcing, starting in 2020, daily injections of a constant amount of SO_2 at a rate of 5 Tg SO_2 per year at one point on the Equator through the lower stratosphere (approximately 16-25 km in altitude).

110



Berdahl, Mira, Alan Robock, Duoying Ji, Andy Jones, Ben Kravitz, John C. Moore, and Shingo Watanabe, 2014: Arctic cryosphere response in the Geoengineering Model Intercomparison Project (GeoMIP) G3 and G4 scenarios. *J. Geophys. Res. Atmos.*, **119**, 1308–1321, doi:10.1002/2013JD020627.

111



RUTGERS Berdahl, Mira, et al., 2014: Arctic cryosphere response in the Geoengineering Model Intercomparison Project (GeoMIP) G3 and G4 scenarios. *J. Geophys. Res. Atmos.*, **119**, 1308–1321.

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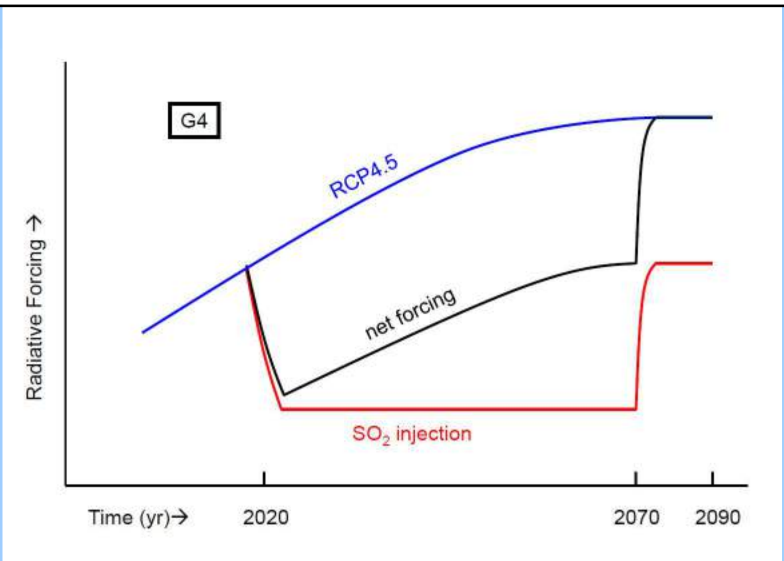

G4: In combination with RCP4.5 forcing, starting in 2020, daily injections of a constant amount of SO_2 at a rate of 5 Tg SO_2 per year at one point on the Equator through the lower stratosphere (approximately 16-25 km in altitude).

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Trisos, Christopher H., Giuseppe Amatulli, Jessica Gurevitch, Alan Robock, Lili Xia, and Brian Zambri, 2018: Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination. *Nature Ecology and Evolution*, **2**, 475-482, doi:10.1038/s41559-017-0431-0.

We used four climate models that have run both the RCP4.5 and G4 scenarios for our calculations, with multi-model averages across the four climate models.

Models	Institution
CanESM2	Canadian Centre for Climate Modeling and Analysis, Environment Canada
CSIRO-Mk3L-1-2	Commonwealth Scientific and Industrial Research Organisation, Australia
GISS-E2-R	NASA Goddard Institute for Space Studies, USA
HadGEM2-ES	Met Office Hadley Centre, UK

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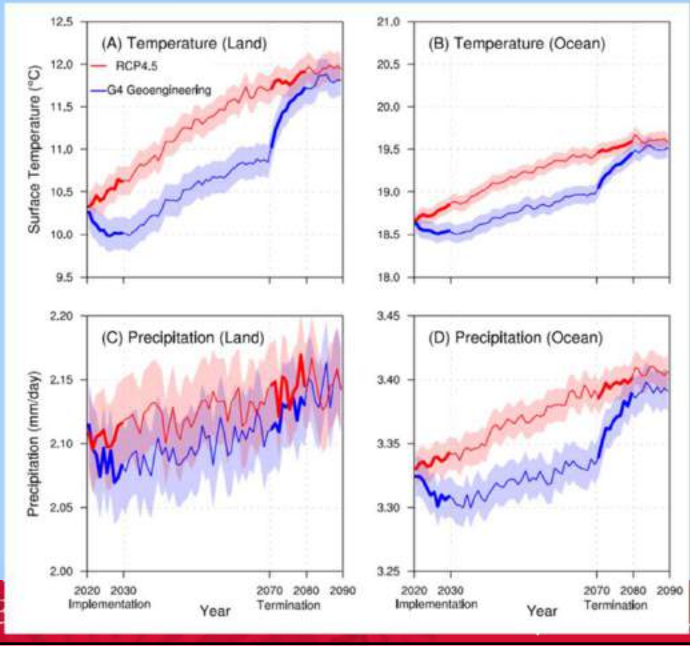
Air Temperature and Precipitation with RCP4.5 and G4



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Climate Velocity

"Now, here, you see, it takes all the running you can do, to keep in the same place." – the Red Queen to Alice in *Through the Looking Glass*

How fast does a population or system have to move to keep in the same climate space?

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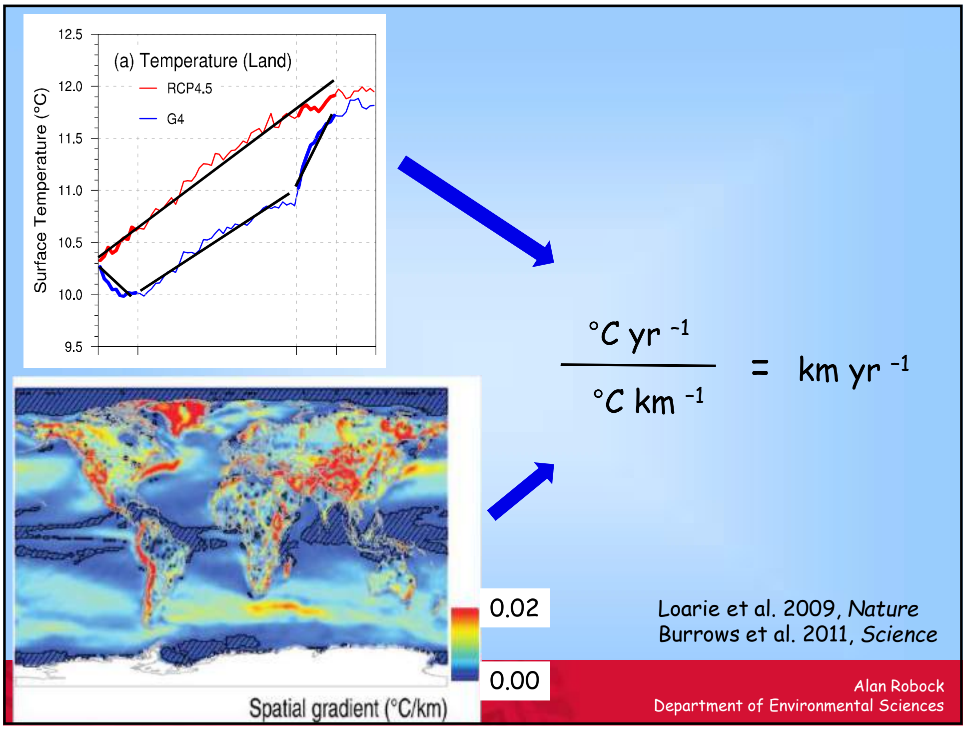
(a) Temperature (Land)
RCP4.5
G4
Surface Temperature (°C)
12.5
12.0
11.5
11.0
10.5
10.0
9.5
0.02
0.00
Spatial gradient (°C/km)
°C yr -1 / °C km -1 = km yr -1
Loarie et al. 2009, *Nature*
Burrows et al. 2011, *Science*
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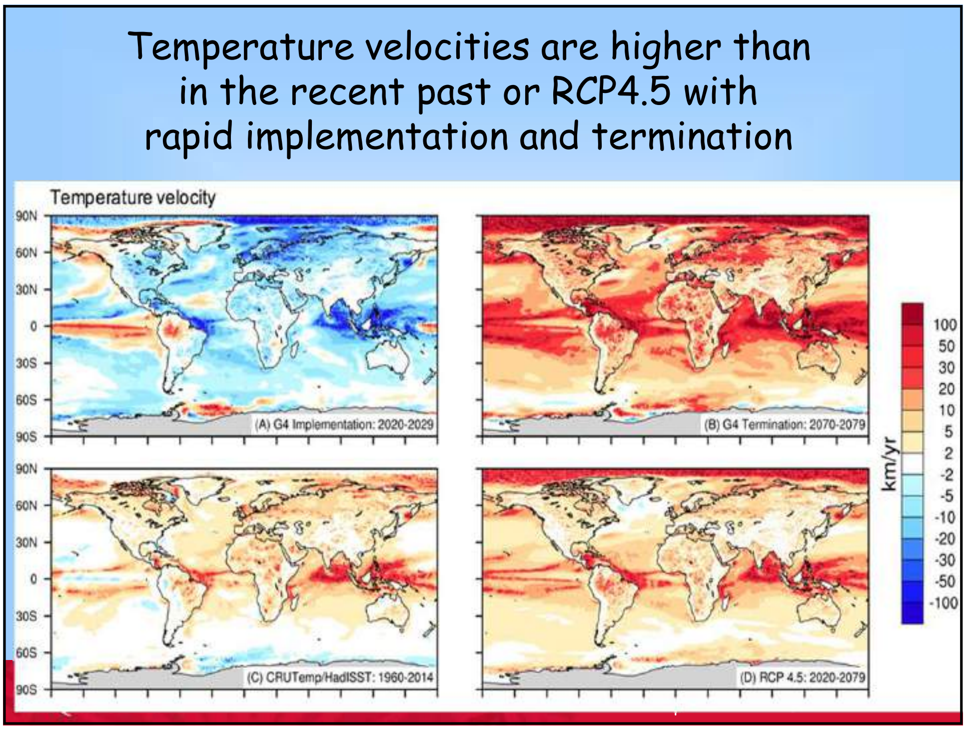
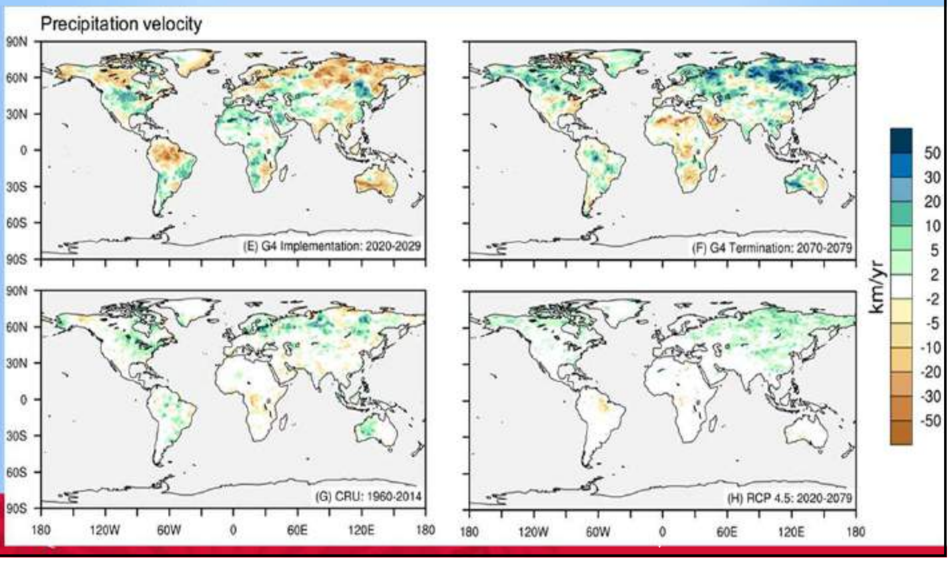

Temperature velocities are higher than in the recent past or RCP4.5 with rapid implementation and termination
Temperature velocity
(A) G4 Implementation: 2020-2029
(B) G4 Termination: 2070-2079
(C) CRUTemp/HadISST: 1960-2014
(D) RCP 4.5: 2020-2079
90N
60N
30N
0
30S
60S
90S
km/yr
100
50
30
20
10
5
2
-2
-5
-10
-20
-30
-50
-100

118

Precipitation velocities are complex, but are higher than in the past or RCP4.5 with rapid implementation and termination

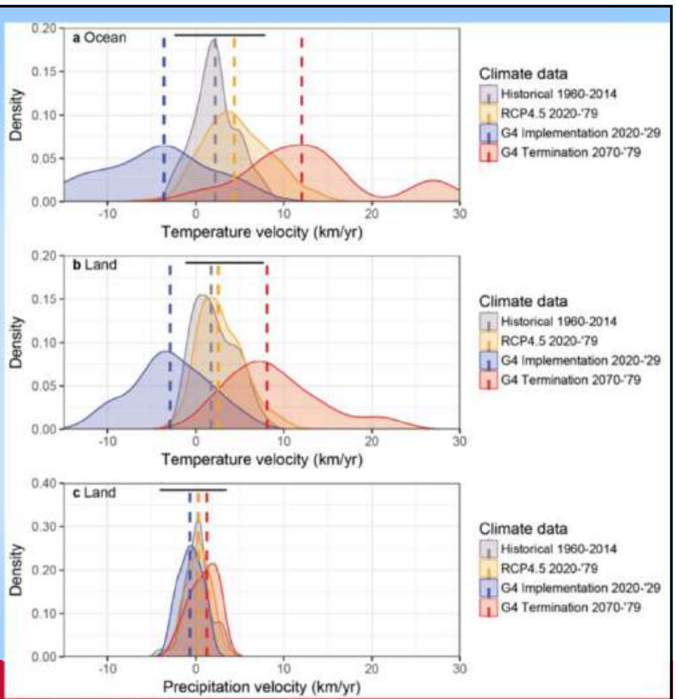


119

Distributions of climate velocities

Ocean and land air temperatures different from Historical and RCP4.5 during Implementation and Termination

Precipitation not much different



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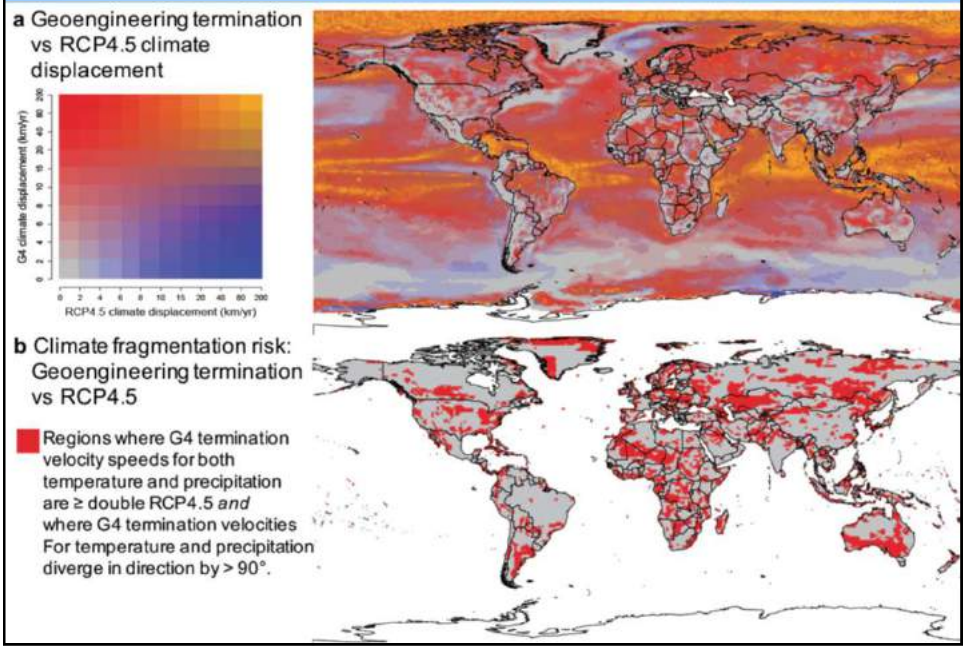
a. Red: G4 termination has much higher temperature velocities than RCP4.5
b. Red: Temperature and precip diverge strongly with high velocities at G4 termination



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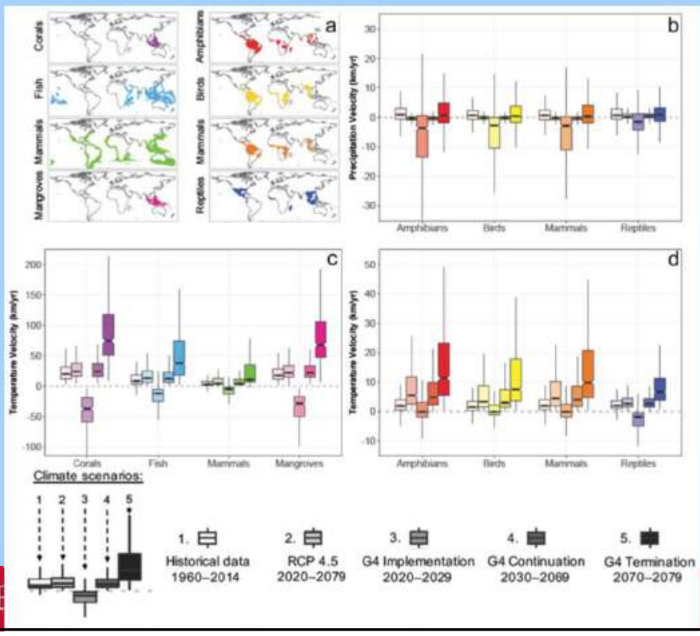
High velocities for precip and temp for implementation, continuation and termination in many **biodiversity hotspots**



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Conclusions

1. Geoengineering implementation and rapid termination can produce very large increases in both temperature and precipitation velocities compared to RCP4.5.
2. Termination poses the risk of rapid fragmentation of climate niches due to divergence between the direction of temperature and precipitation changes.
3. Many biodiversity hotspots have high exposure to extreme velocities (drying) at implementation and extreme temperature velocities at termination.
4. Ecological and conservation implications of albedo modification must be taken into account by climate scientists; ecologists should pay more attention to geoengineering scenarios and proposals.

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Proposed GeoMIP Cloud Brightening Experiments

to be run for 50 years with solar geoengineering followed by 20 years in which geoengineering is ceased

Experiment	*Description*
G1ocean-albedo	Instantaneously quadruple the preindustrial CO_2 concentration while simultaneously increasing ocean albedo to counteract this forcing.
G4cdnc	In combination with RCP4.5 forcing, starting in 2020, increase cloud droplet number concentration by 50% over the ocean.
G4sea-salt	In combination with RCP4.5 forcing, starting in 2020, increase sea salt emissions in the marine boundary layer between 30°S and 30°N by a uniform amount, with an additional total flux of sea salt of 100 Tg a^{-1}.

Kravitz, Ben, et al., 2013: Sea spray geoengineering experiments in the Geoengineering Model Intercomparison Project (GeoMIP): Experimental design and preliminary results. *J. Geophys. Res. Atmos.*, **118**, 11,175–11,186, doi:10.1002/jgrd.50856.

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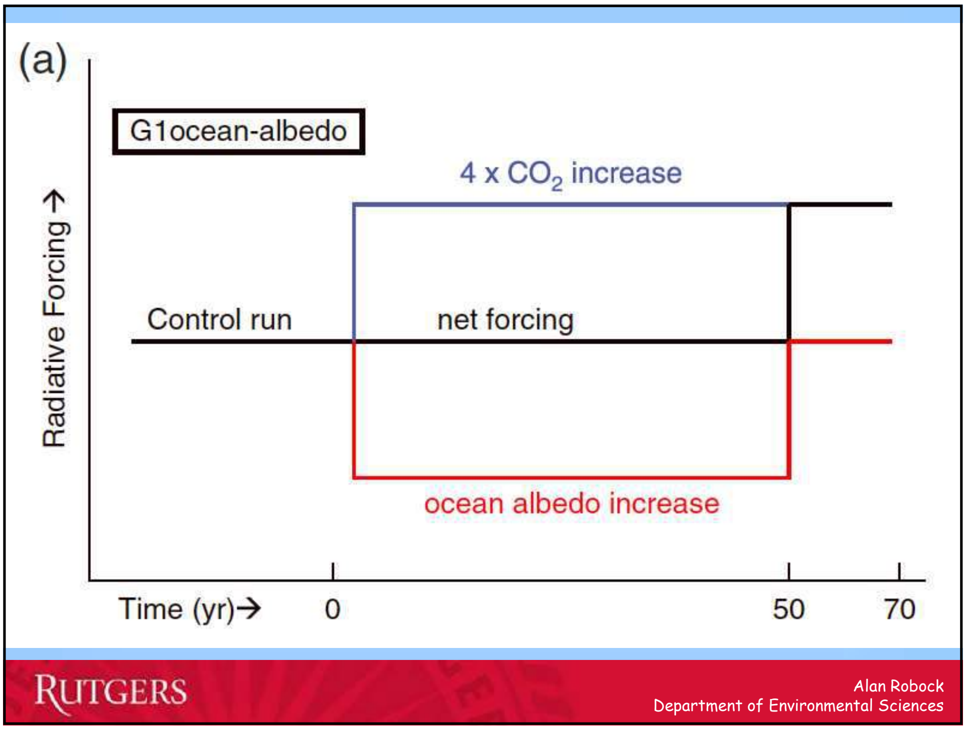
(a)
G1ocean-albedo
4 x CO_2 increase
Control run
net forcing
ocean albedo increase
Radiative Forcing →
Time (yr)→
0
50
70
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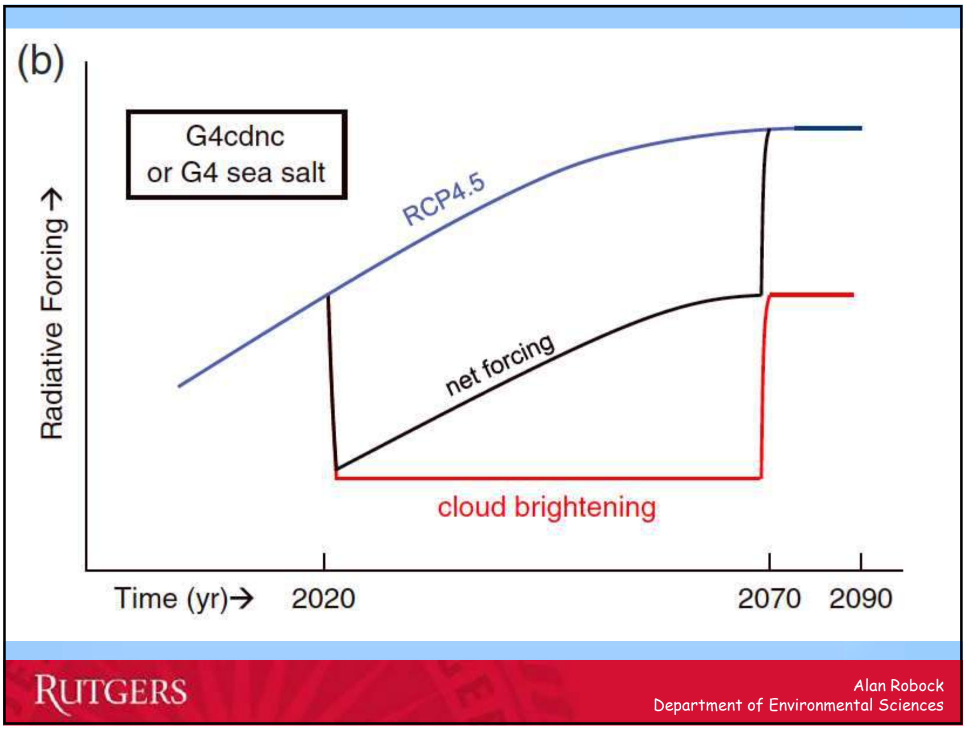
(b)
G4cdnc
or G4 sea salt
RCP4.5
net forcing
cloud brightening
Radiative Forcing →
Time (yr)→
2020
2070
2090
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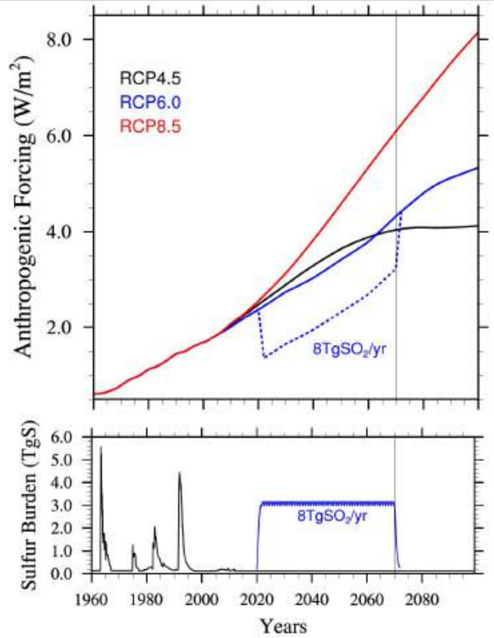
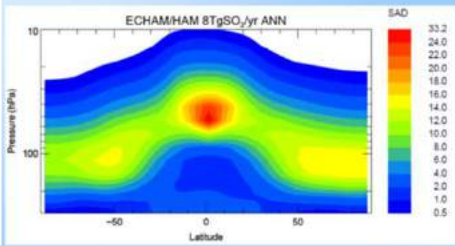


G4SSA Forcing:

Steady-state prescribed aerosol distribution, based on an 8 Tg SO_2 year^{-1} emission scenario using the ECHAM5-HAM model, combined with RCP6.0



Tilmes, S., M. J. Mills, U. Niemeier, H. Schmidt, A. Robock, B. Kravitz, J.-F. Lamarque, G. Pitari, and J. M. English, 2015: *A new Geoengineering Model Intercomparison Project (GeoMIP) experiment designed for climate and chemistry models.* *Geosci. Model Dev.*, **8**, 43-49, doi:10.5194/gmd-8-43-2015.

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Scientific questions:

- How will stratospheric chemistry and dynamics respond to stratospheric aerosols?
- How will the resulting increase in downward diffuse radiation affect the carbon cycle?
- How will the troposphere respond to changed radiation, stratosphere-troposphere exchange of ozone, volatile organic carbon (VOC) emissions from vegetation, and increased downward ultraviolet radiation?
- What will be the impacts on crops?

Xia, Lili, Alan Robock, Simone Tilmes, and Ryan R. Neely III, 2016: Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate. *Atmos. Chem. Phys.*, **16**, 1479-1489, doi:10.5194/acp-16-1479-2016.

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Simulations with:

NCAR Community Earth System Model Community Atmospheric Model 4 (CESM CAM4-chem)

- horizontal resolution of 0.9° x 1.25° lat-lon
- 26 levels from the surface to about 40 km (3.5 mb)
- coupled with Community Land Model (CLM) version 4.0 with prescribed satellite phenology (CLM4SP)
  - no interactive carbon-nitrogen cycle, but nitrogen limitation is implicit because nitrogen availability limits the leaf area index in the satellite measurements used in CLM4SP
- 3 ensemble members of RCP6.0
- 3 ensemble members of G4SSA
- 3 ensemble members of G4SSA-S (solar)

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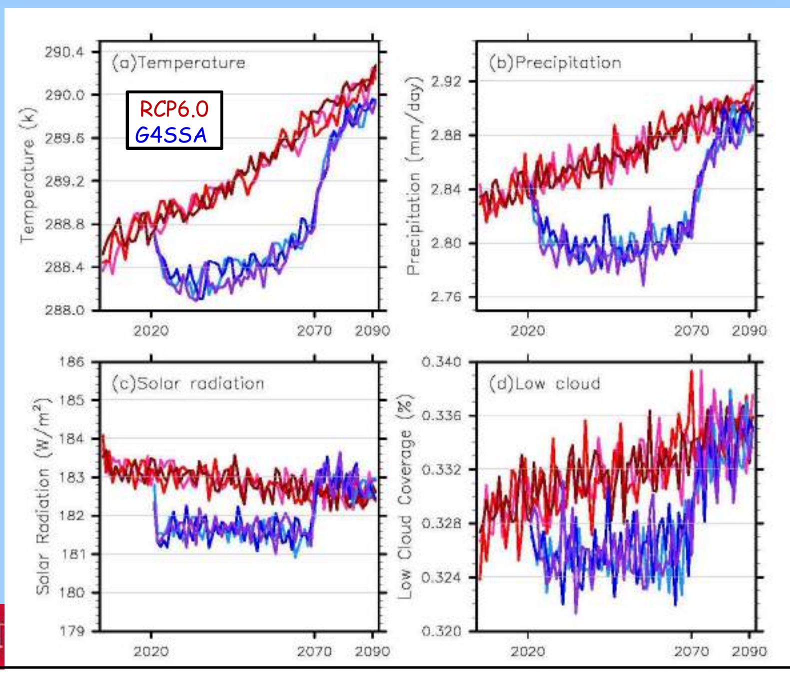
Global, annual averages



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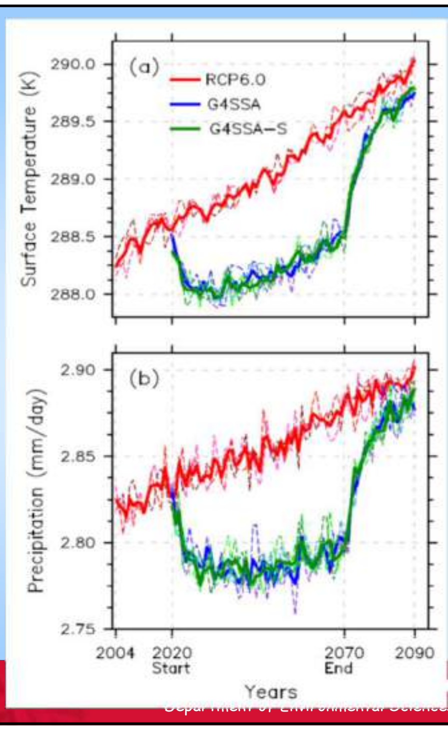
Global, annual averages



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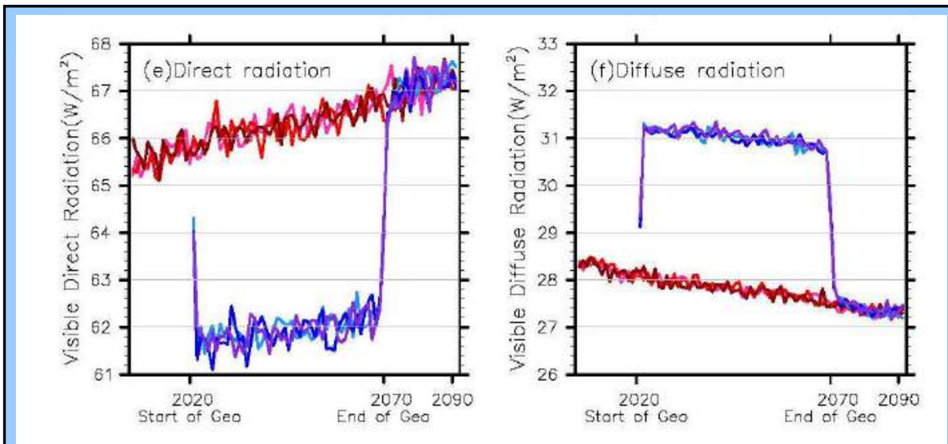

Land Average of:

Direct Radiation

↓ 4.2 W/m²

Diffuse Radiation

↑ 3.0 W/m²

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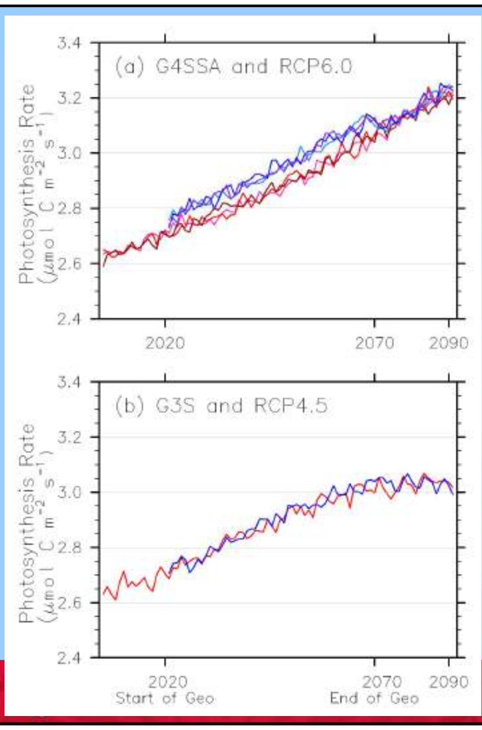

Photosynthesis

↑ **0.07 ± 0.02 μmol C m^{-2} s^{-1}**

Produces an additional
3.8 ± 1.1 Gt C yr^{-1}
global gross primary
productivity

No change for
solar reduction forcing in
related experiment

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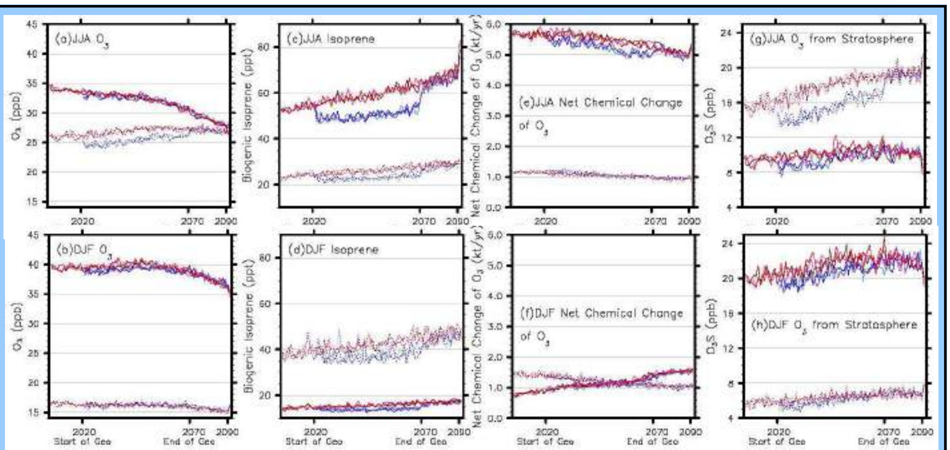

Average of Northern Hemisphere (solid lines) and Southern Hemisphere (dashed lines) surface O_3, biogenic isoprene, net chemical change of O_3, and surface O_3 transported from the stratosphere under G4SSA (blue lines) and RCP6.0 (red lines) in JJA and DJF

- changes in JJA (winter in SH) show strongest differences, due to changes in stratosphere –troposphere exchange.
- chemistry is changed mainly due to differences in isoprene (and other VOC) emissions

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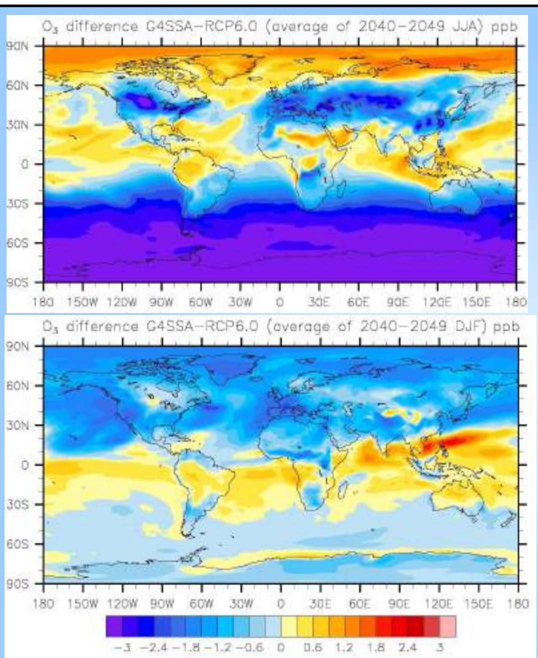

Ten-year seasonal averaged surface O_3 concentration difference (ppb) between G4SSA and RCP6.0 (2040-2049)

Tropospheric ozone reduction in high latitudes impacted by changes in stratospheric circulation and chemical changes in the stratosphere.

Reduction in summer (JJA) in polluted areas due to chemical processes

Xia, L., Nowack, P. J., Tilmes, S., and Robock, A. (2017), Impacts of stratospheric sulfate geoengineering on tropospheric ozone, *Atmos. Chem. Phys.*, *17*, 11,913-11,928, doi:10.5194/acp-17-11913-2017.

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Crop model used for global agriculture simulation

Model: Off-line post4.5CLM-crop, coupled with the most recent O_3 impact module [*Lombardozzi et al.*, 2015]

Resolution: 2° latitude and longitude

Crops: Maize, Rice, Soybean, Cotton, Sugarcane

Methodology:

Collaboration with Danica Lombardozzi and Peter Lawrence

Simulations with no O_3 impact

- Fixed CO_2 (392 ppm), fertilizer (year 2000), irrigation (year 2000)
- CLM-crop control run: AgMERRA reanalysis data 1978-2012
- Climate model control run: RCP6.0 2004-2019
- RCP6.0 monthly anomalies and G4SSA monthly anomalies (2060-2069)
- Perturb 35 years AgMERRA with each year of RCP6.0/G4SSA climate anomalies

In total: 35 + 35*10 + 35*10 = 735 years of simulation

control | G4SSA | RCP6.0

Simulations with O_3 impact

- Two reference runs (G4SSA and RCP6.0) with no O_3 module, two runs with O_3 module from 2040 to 2049
- Use raw climate output from GCM

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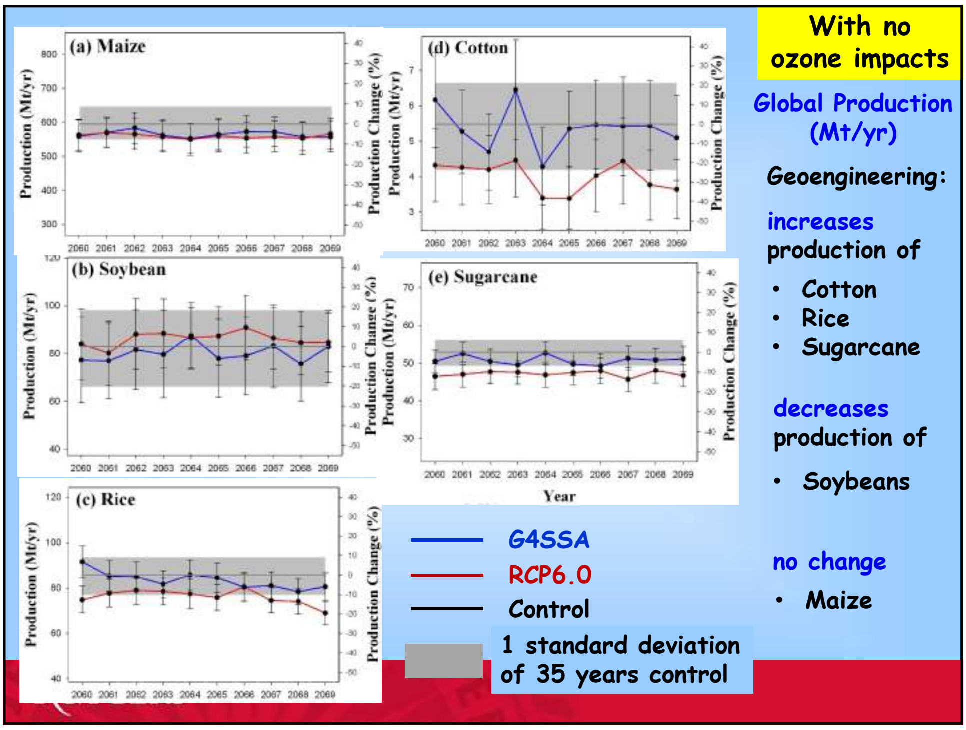

(a) Maize
(b) Soybean
(c) Rice
(d) Cotton
(e) Sugarcane
Production (Mt/yr)
Production Change (%)
Year
With no ozone impacts
Global Production (Mt/yr)
Geoengineering:
increases production of
• Cotton
• Rice
• Sugarcane
decreases production of
• Soybeans
no change
• Maize
G4SSA
RCP6.0
Control
1 standard deviation of 35 years control

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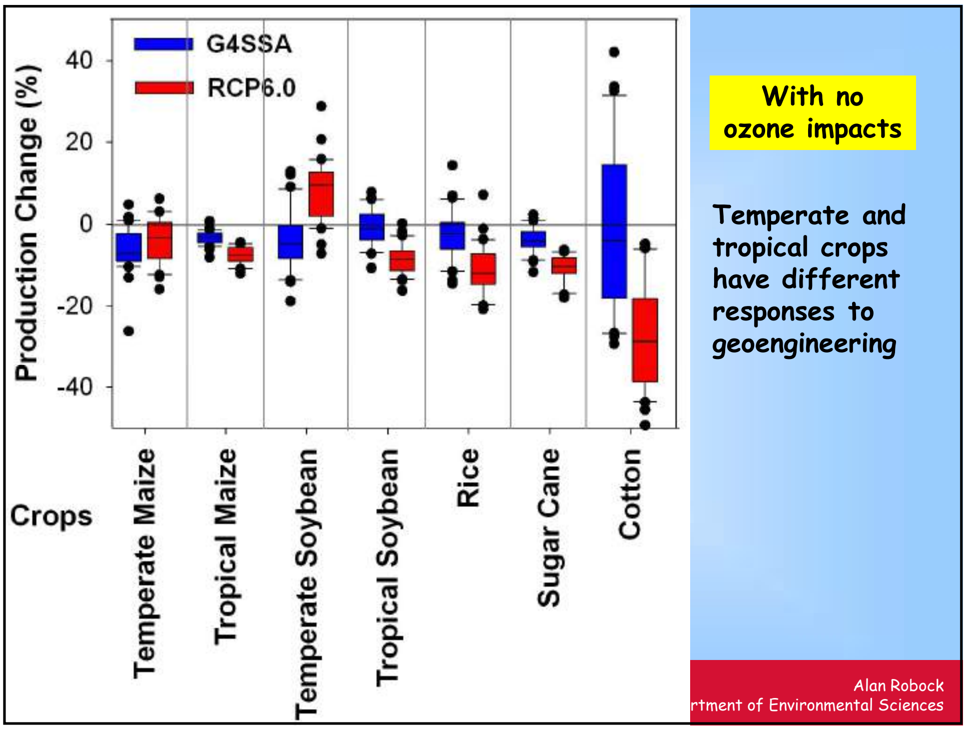

G4SSA
RCP6.0
Production Change (%)
Crops
Temperate Maize
Tropical Maize
Temperate Soybean
Tropical Soybean
Rice
Sugar Cane
Cotton
With no ozone impacts
Temperate and tropical crops have different responses to geoengineering
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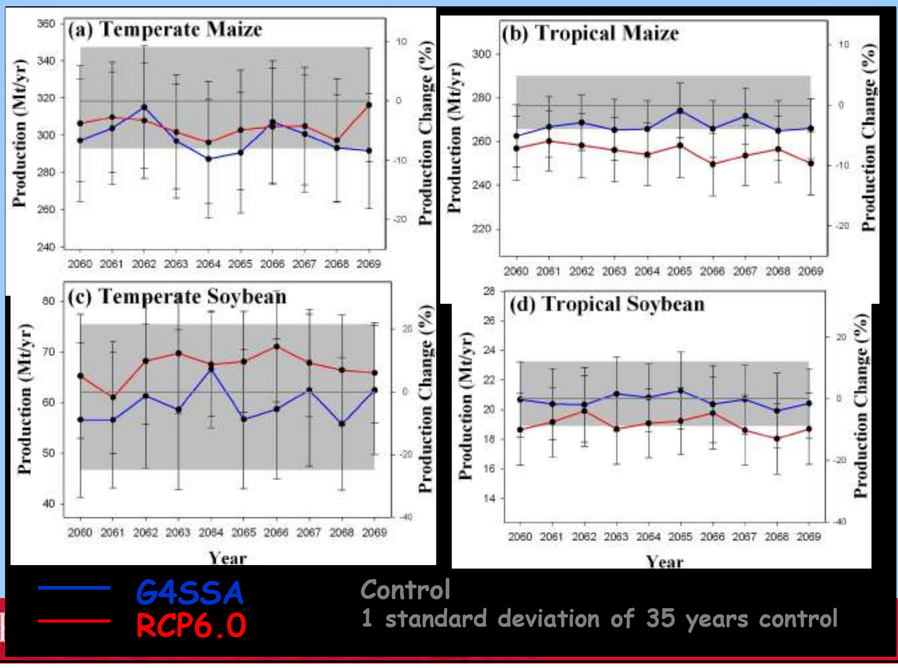
Temperate and tropical crops have different responses to geoengineering



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National production change (%) (G4SSA minus RCP6.0) (average of 2060-2069)

	Rice	Maize	Soy	Cotton	Sugarcane
U.S.		-1%	-14%	23%	
China	-20%	5%		30%	5%
India	7%			20%	17%
Indonesia	5%				7%
Brazil		3%	13%		
Argentina			-17%		

Countries listed are the top 3 crop production nations for each crop.

With no ozone impacts

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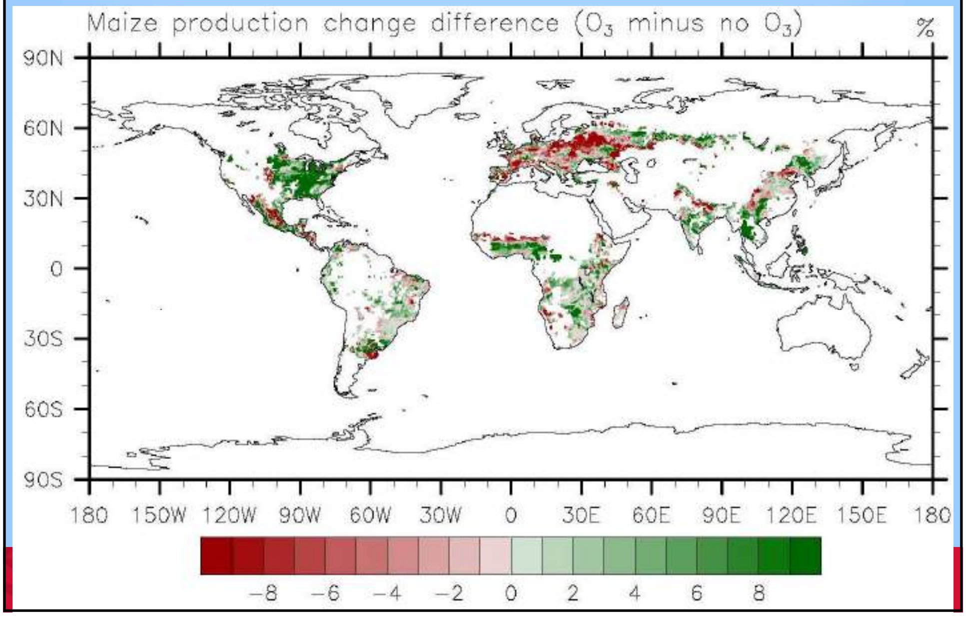
Ten-year average maize production change difference (%) with O_3 impacts from G4SSA as compared to RCP6.0



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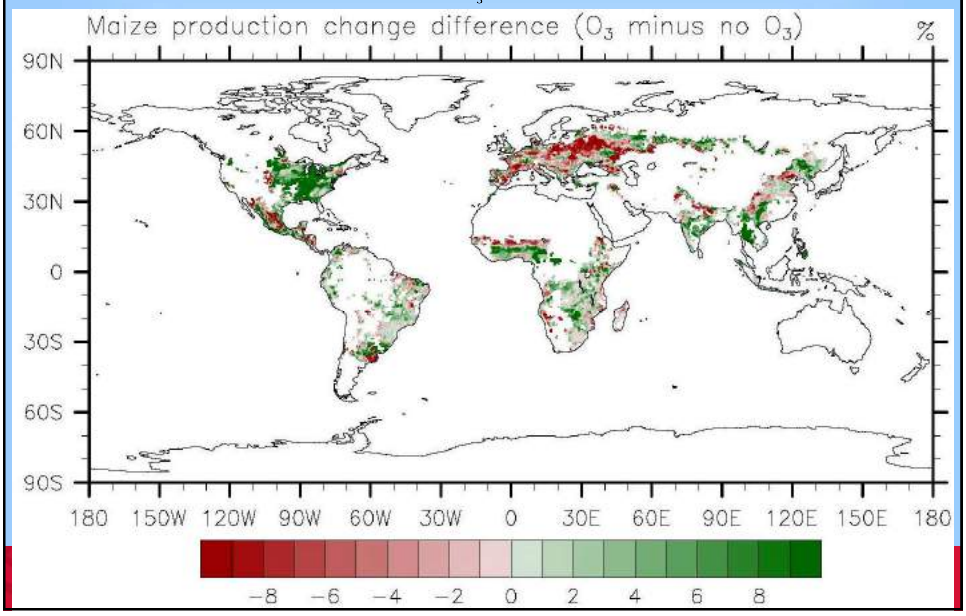
Ten year averaged maize production change difference (%)

$$100 * \left(\frac{P_{G4SSA\ \ _3} - P_{RCP6.0O_3}}{P_{RCP6.0O_3}} - \frac{P_{G4SSA} - P_{RCP6.0}}{P_{RCP6.0}}\right)$$



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Conclusions: For one sulfate geoengineering scenario and one global vegetation and crop model, compared with RCP6.0, under the G4SSA scenario:

- **Sulfate geoengineering increases diffuse radiation by 11%, which increases global photosynthesis by 1%, with large increases in the Amazon.**
- **Compared with a global warming scenario, the cooling effect from G4SSA benefits tropical crop production, while it decreases temperate crop production for maize and soybeans. For cotton, geoengineering has large positive impacts.**
- **Less surface O_3 concentration in agricultural regions would reduce the negative impact and enhance the positive impact on agriculture in most regions.**

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We need to improve the following aspects of our study:

- Robust climate change signal
  - Geoengineering Model Intercomparison Project
  - Chemistry-Climate Model Initiative
- Accurate climate input
  - Comparing different downscaling methods including methods for O_3 downscaling
- Sufficient agricultural practice data
  - Gathering agriculture practice information, such as seeds used
- Improved crop model
  - Add responses to diffuse radiation and UV
- Robust agricultural response
  - Agricultural Model Intercomparison and Improvement Project
  - Global Gridded Crop Model Intercomparison

AgMIP The Agricultural Model Intercomparison and Improvement Project

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Impact of Solar and Sulfate Geoengineering on Surface Ozone

Lili Xia[1], Peer J. Nowack[2], Simone Tilmes[3] and Alan Robock[1]

[1]Department of Environmental Sciences, Rutgers University, New Brunswick, NJ, USA

[2]Faculty of Natural Sciences, Imperial College, London, UK

[3]Atmospheric Chemistry Observations and Modeling Laboratory, National Center for Atmospheric Research, Boulder, CO, USA

Xia, L., Nowack, P. J., Tilmes, S., and Robock, A. (2017), Impacts of stratospheric sulfate geoengineering on tropospheric ozone, *Atmos. Chem. Phys., 17*, 11,913-11,928, doi:10.5194/acp-17-11913-2017.

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NCAR UCAR | CESM COMMUNITY EARTH SYSTEM MODEL

Simulating two SRM scenarios: Sulfate injection and solar irradiance reduction

- Full tropospheric and stratospheric chemistry version of CESM CAM4-Chem (Community Atmospheric Model version 4 - Chemistry)
- Fully coupled to ocean, land and ice models
- 1 degree resolution in latitude and longitude

G4 specified stratospheric aerosols

- Three ensemble members of RCP6.0 (2004-2089)
- Three ensemble members of G4SSA (2020-2089)
- Three ensemble members of G4SSA-S (2020-2089)

Solar irradiance reduction with the same forcing as in G4SSA at the top of the atmosphere

Tilmes, S., et al. (2015), A new Geoengineering Model Intercomparison Project (GeoMIP) experiment designed for climate and chemistry models, *Geosci. Model Dev., 8*, 43-49, doi:10.5194/gmd-8-43-2015.

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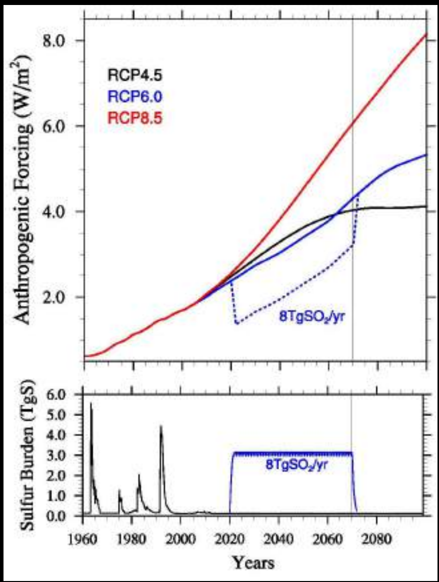
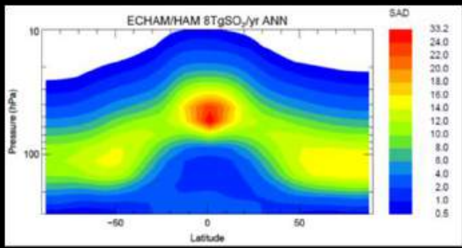
G4SSA Forcing:



Steady-state prescribed aerosol distribution, based on an 8 Tg SO_2 year^{-1} emission scenario using the ECHAM5-HAM model, combined with RCP6.0



Tilmes, S., et al. (2015), A new Geoengineering Model Intercomparison Project (GeoMIP) experiment designed for climate and chemistry models, *Geosci. Model Dev.*, *8*, 43-49, doi:10.5194/gmd-8-43-2015.

Niemeier, U., et al. (2013), Solar irradiance reduction via climate engineering: Impact of different techniques on the energy balance and the hydrological cycle, *J. Geophys. Res.-Atmos.*, *118*, 11,905–11,917, doi:10.1002/2013JD020445.

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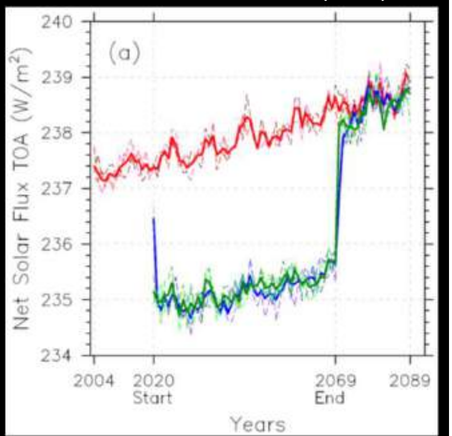
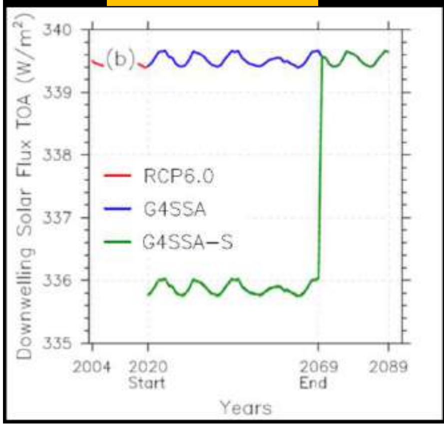
G4SSA-S Forcing:

Keep the net solar radiation at top of atmosphere (TOA) the same as in G4SSA, which is 2.5 W/m^2 less than RCP6.0.

Net Solar Flux (TOA)



Insolation (TOA)



Total insolation reduction at top of atmosphere is ~1%

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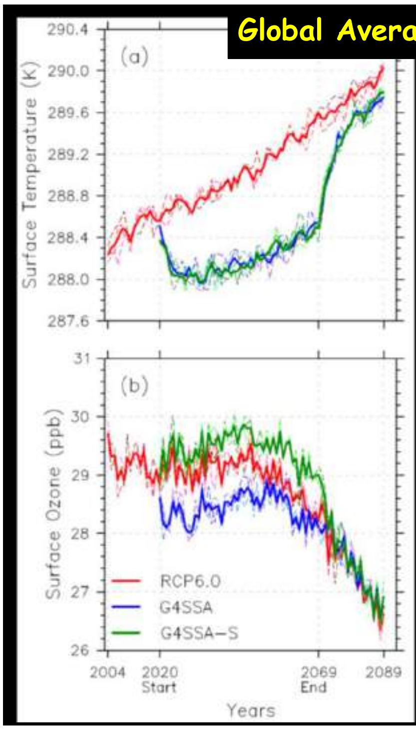
Global Averaged Surface Temperature and Ozone



- Compared with RCP6.0, global (land/ocean) averaged annual surface temperature reductions of G4SSA and G4SSA-S are very similar.
- G4SSA shows less surface O_3 when compared with RCP6.0 as a global average, while G4SSA-S shows an opposite change – surface O_3 concentration increases relative to RCP6.0.

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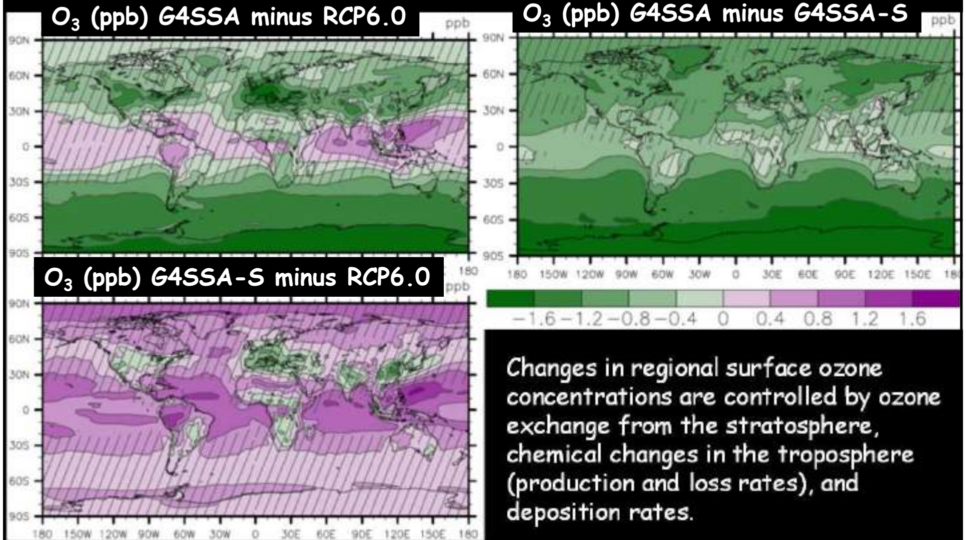
Surface Ozone Concentration Difference (ppb)
(average of three ensembles, average of 2030-2069)



Changes in regional surface ozone concentrations are controlled by ozone exchange from the stratosphere, chemical changes in the troposphere (production and loss rates), and deposition rates.

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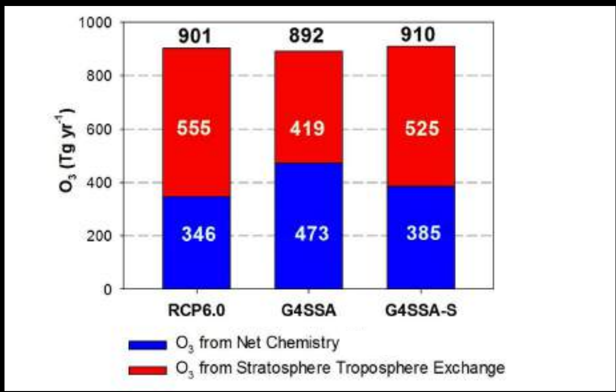
Tropospheric O_3 Flux = O_3 from Net Chemistry + O_3 from STE

Net Chemistry = Chemistry Production – Chemistry Loss



- Compared with RCP6.0, tropospheric O_3 decreases in G4SSA and increases in G4SSA-S, which is consistent with the changes on surface ozone.
- Both G4SSA and G4SSA-S show increase of net chemistry and reduction of ozone from the stratosphere related to RCP6.0.
- Changes in G4SSA are stronger than changes in G4SSA-S.

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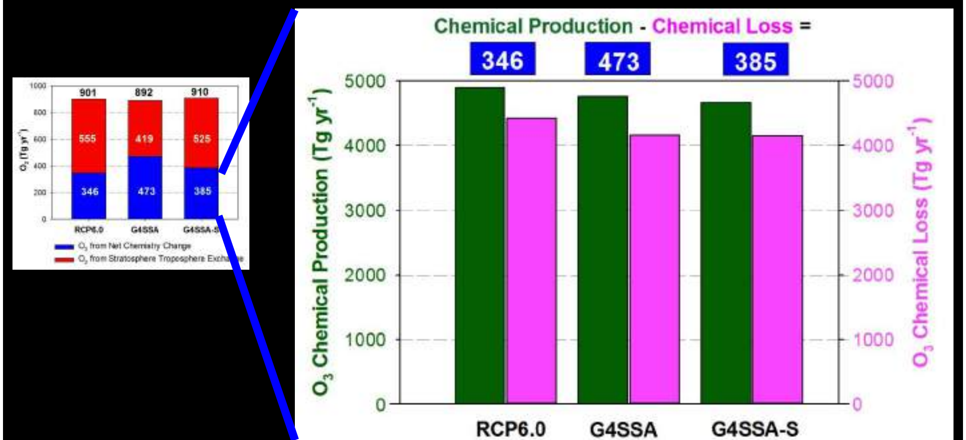
Tropospheric O_3 Net Chemistry =
O_3 Chemical Production – O_3 Chemical Loss



- G4SSA has stronger increase of ozone net chemical change than G4SSA-S;
- Reduction of ozone chemical loss in both G4SSA and G4SSA-S is due to less water vapor in the troposphere;
- Less reduction of ozone chemical production in G4SSA related to G4SSA-S is caused by more ultraviolet radiation in the troposphere under G4SSA.

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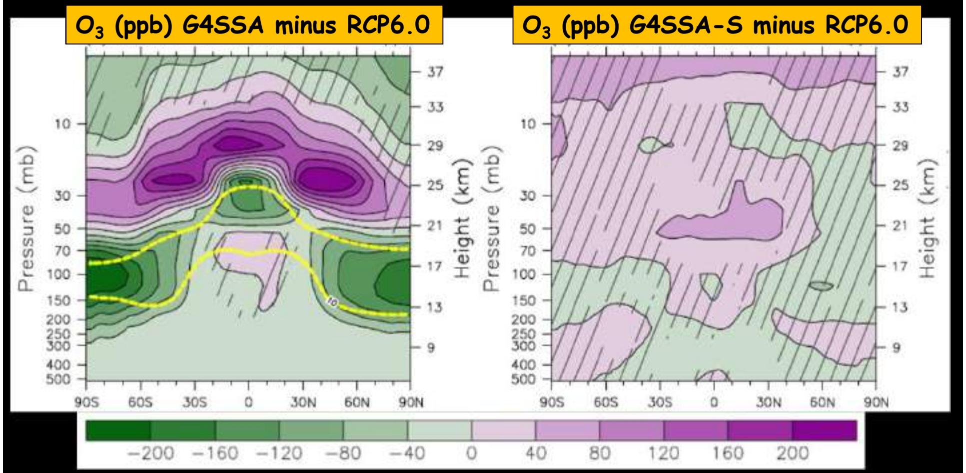
Stratospheric ozone depletion under G4SSA



Annual zonal mean O_3 concentration change (ppb)
(average of 2030-2069, average of three ensembles)

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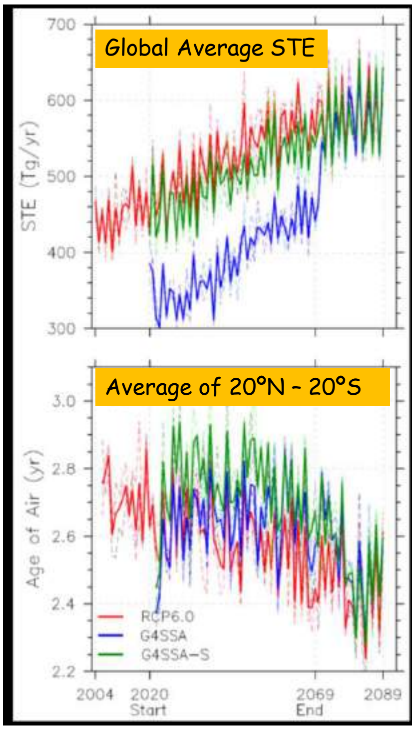

Ozone from the Stratosphere Troposphere Exchange (STE)

- Strong reduction of O_3 – STE in G4SSA is mainly due to stratospheric ozone depletion;
- Mild reduction of O_3 – STE in G4SSA-S is due to the slow down of the Brewer-Dobson Circulation, which is supported by the Age of Air.

Age of Air (at 10 mb) calculation is based on a point on a zonal mean map (1° N, 139 mb)

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Conclusions

- Surface ozone concentration is a balance between ozone transported from the stratosphere and net chemical change in the troposphere.
- With stratospheric sulfate injection, stratospheric ozone depletion is the main cause of surface ozone reduction.
- When we decrease insolation, the increase of tropospheric ozone net chemistry is the major cause of increased surface ozone concentration.
- **Stratospheric sulfate geoengineering may reduce surface ozone pollution, but decisions about implementation must weigh all possible benefits and risks. For example, the negative impacts of stratospheric ozone depletion would far outweigh any improvements in tropospheric air quality.**

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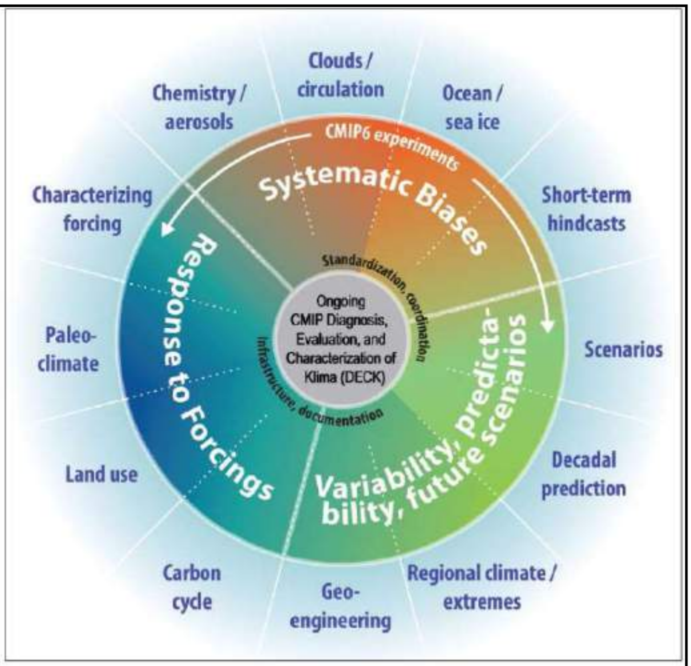
Climate Model Intercomparison Project 6 (CMIP6) design proposal



Meehl, G. A., R. Moss, K. E. Taylor, V. Eyring, R. J. Stouffer, S. Bony and B. Stevens, 2014: Climate model intercomparisons: Preparing for the next phase, *Eos*, **95**, 77-78, doi:10.1002/2014EO090001.

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Initial CMIP6 Proposal: A Distributed Organization under the oversight of the CMIP Panel

CMIP would be comprised of two elements:

1. **Ongoing CMIP Diagnostic, Evaluation and Characterization of Klima (DECK) experiments:** a small set of standardized experiments that would be performed whenever a new model is developed.

The DECK experiments are chosen to provide **continuity across past and future phases of CMIP**, to evolve only slowly with time, and to take advantage of what is already **common practice in many modeling centers**:

i. an AMIP simulation (~1979-2010);
ii. a multi-hundred year pre-industrial control simulation;
iii. a 1%/yr CO_2 increase simulation to quadrupling to derive the transient climate response;
iv. an instantaneous 4xCO_2 run to derive the equilibrium climate sensitivity;
v. a simulation starting in the 19th century and running through the 21st century using an existing scenario (RCP8.5).

2. **Standardization, coordination, infrastructure, and documentation functions** that make the simulations and their main characteristics performed under CMIP available to the broader community.

Meehl, G. A., R. Moss, K. E. Taylor, V. Eyring, R. J. Stouffer, S. Bony and B. Stevens, 2014: Climate model intercomparisons: Preparing for the next phase, *Eos*, **95**, 77-78, doi:10.1002/2014EO090001.

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Initial CMIP6 Proposal: A Distributed Organization under the oversight of the CMIP Panel

CMIP Phase 6 (CMIP6):

- **CMIP6-Endorsed MIPs** would propose additional experiments, and modeling groups could choose a subset of these to run according to their interest, computing and/or human resources and funding constraints.
- The MIPs would also likely have additional experiments that would not be part of CMIP6 but would be of interest and relevant to their respective communities.

Participation

- The ongoing nature of the proposed CMIP/CMIP6 structure means that anyone at any time could download model data for analysis.
- A scientist or group of scientists could send a 'Request for a **CMIP6-Endorsed MIP'** at any time to the CMIP Panel Chair (see template on CMIP webpage).

Meehl, G. A., R. Moss, K. E. Taylor, V. Eyring, R. J. Stouffer, S. Bony and B. Stevens, 2014: Climate model intercomparisons: Preparing for the next phase, *Eos*, **95**, 77-78, doi:10.1002/2014EO090001.

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CMIP6-Endorsed MIPs

- Request for **CMIP6-Endorsed MIPs** should be sent to the CMIP Panel Chair.
- **CMIP6-Endorsed MIPs**
  - can make full use of the ESGF infrastructure.
  - They can propose that part or all of their experiments be included in CMIP6.

The main criteria for MIPs to be endorsed for CMIP6 are

- The MIP addresses at least one of the key science questions of CMIP6;
- The MIP follows CMIP standards in terms of experimental design, data format and documentation;
- A sufficient number of modeling groups have agreed to participate in the MIP;
- The MIP builds on the shared CMIP DECK experiments;
- A commitment to contribute to the creation of the CMIP6 data request.

Meehl, G. A., R. Moss, K. E. Taylor, V. Eyring, R. J. Stouffer, S. Bony and B. Stevens, 2014: Climate model intercomparisons: Preparing for the next phase, *Eos*, **95**, 77-78, doi:10.1002/2014EO090001.

ck
es

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Additional Considerations

- The proposed experiments should address new scientific questions, and not just repeat past runs, which are still available for all models to do.
- Marine cloud brightening experiments are currently underway, so there is no need yet to repeat them. And they are also recommended for new models.
- The termination problem is now well-understood, and there is no need for more experiments. It would be more useful to use the computer time to extend the experiments to produce better statistics.

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Experiment name	Description	Reference
G1	Balance $4xCO_2$ via solar irradiance reduction	Kravitz et al. [2011]
G1ext	Same as G1 but extended an extra 50 years	Kravitz et al. [2015]
G1ocean-albedo	Balance $4xCO_2$ via global ocean albedo increase	Kravitz et al. [2013b]
G2	Balance 1% CO_2 increase per year via solar irradiance reduction	Kravitz et al. [2011]
G3	Keep top of atmosphere radiative flux at 2020 levels against RCP4.5 via stratospheric sulfate aerosols	Kravitz et al. [2011]
G4	Injection of 5 Tg SO_2 into lower stratosphere per year against a background of RCP4.5	Kravitz et al. [2011]
G4cdnc	Increase cloud droplet number concentration in marine low clouds by 50% against a background of RCP4.5	Kravitz et al. [2013b]
G4sea-salt	Inject sea salt aerosols into tropical marine boundary layer to achieve effective radiative forcing of −2.0 W m^{-2} against a background of RCP4.5	Kravitz et al. [2013b]
G4-SSA	Use Specified Stratospheric Aerosols from an annual 8 Tg SO_2 injection into the lower stratosphere against a background of RCP6.0	Tilmes et al. [2015]
G5	Identical setup as G3 but using sea salt injection into marine low clouds [IMPLICC experiment; named SALT in Niemeier et al., 2013]	Alterskjær et al. [2013], Niemeier et al. [2013]
G6sulfur	Reduce forcing from RCP8.5 to RCP4.5 with stratospheric sulfate aerosols	Kravitz et al. [2015]
G6solar	Reduce forcing from RCP8.5 to RCP4.5 with solar irradiance reduction	Kravitz et al. [2015]
G7cirrus	Reduce forcing by constant amount via increasing cirrus ice crystal fall speed	Kravitz et al. [2015]

GeoMIP

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CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) Project

Project Team: Simone Tilmes, Jadwiga H. Richter, Michael Mills, Ben Kravitz, and Douglas G. MacMartin

- 20-member ensemble of stratospheric sulfate aerosol geoengineering simulations between 2020-2099 and a 20-member ensemble of control simulations.
- The goal was to maintain not only global mean surface temperature, but also interhemispheric and equator-to-pole surface temperature gradients at 2020 values under a RCP8.5 greenhouse gas scenario.
- A feedback-control strategy was employed, optimizing annual injections at four different locations in the stratosphere, namely at 30°N, 30°S, 15°N and 15°S.

Tilmes, S., et al., 2018: CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) Project. *Bull. Amer. Meteor. Soc.*, **99**, 2361-2371, doi: 10.1175/BAMS-D-17-0267.1

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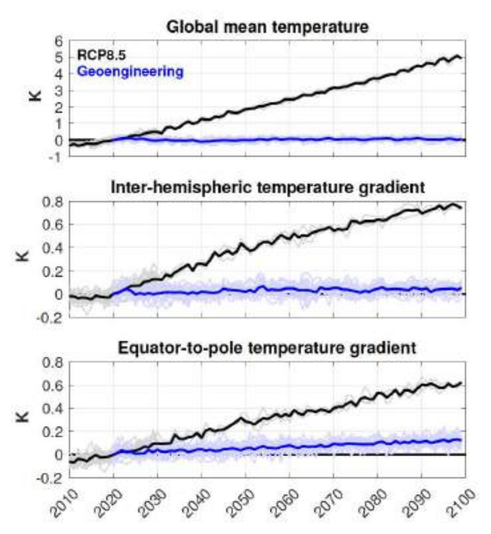
CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) Project



Tilmes, S., et al., 2018: CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) Project. *Bull. Amer. Meteor. Soc.*, **99**, 2361-2371, doi: 10.1175/BAMS-D-17-0267.1

163

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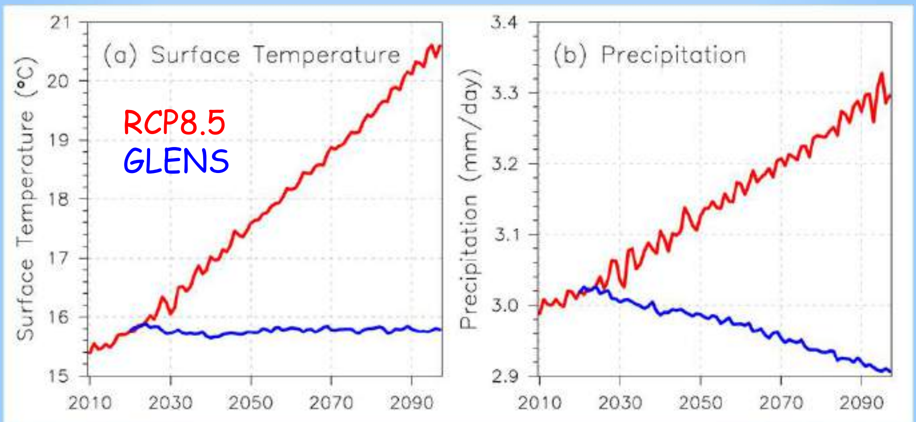

Global averages: Keeping temperature from increasing results in precipitation decreasing.

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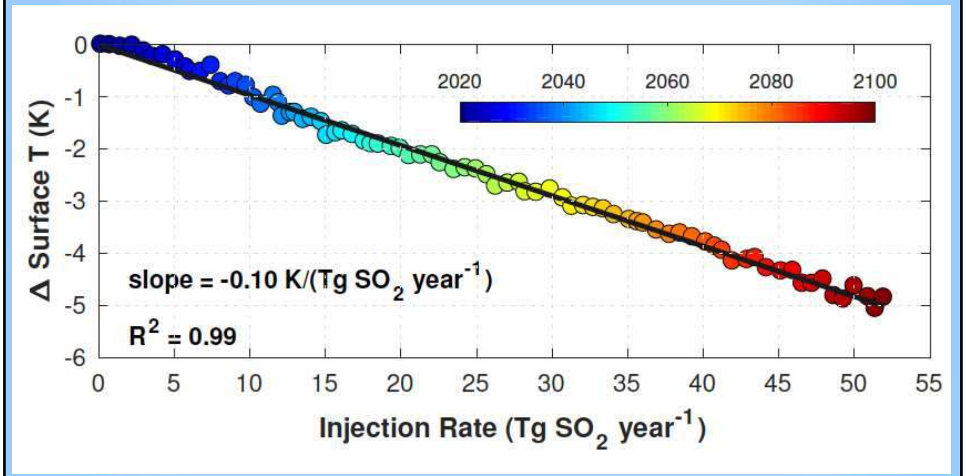
CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) Project



Tilmes, S., et al., 2018: CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) Project. *Bull. Amer. Meteor. Soc.*, **99**, 2361-2371, doi: 10.1175/BAMS-D-17-0267.1

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GeoMIP6 plans

(All experiments to be run for 100 years, with no termination; three ensemble members requested for each experiment)

G1ext [extended]: **G1**, but run for 100 years.

G6sulfur: With the RCP8.5 scenario as the control, stratospheric sulfate aerosols will be injected into the model with the goal of reducing top of atmosphere net radiative flux values to those of RCP4.5. This would be similar to the scenario proposed by David Keith in his book, to slow but not stop the temperature increase, to only partially compensate for CO_2 increase.

G6solar: Same as G6, but reduce insolation to achieve the reduction in radiative forcing from RCP8.5 down to RCP4.5.

G7: With the RCP8.5 scenario as the control, starting in 2020 increase the fall speed of ice crystals in high clouds in the extratropics (poleward of 45° latitude) to thin cirrus clouds and increase longwave cooling. Coordinate with Norwegian EXPECT project.

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G6solar: Same as G6, but reduce insolation to achieve the reduction in radiative forcing from RCP8.5 down to RCP4.5.

G8: Overshoot scenario, keeping global warming to +2°C over preindustrial with stratospheric aerosols.

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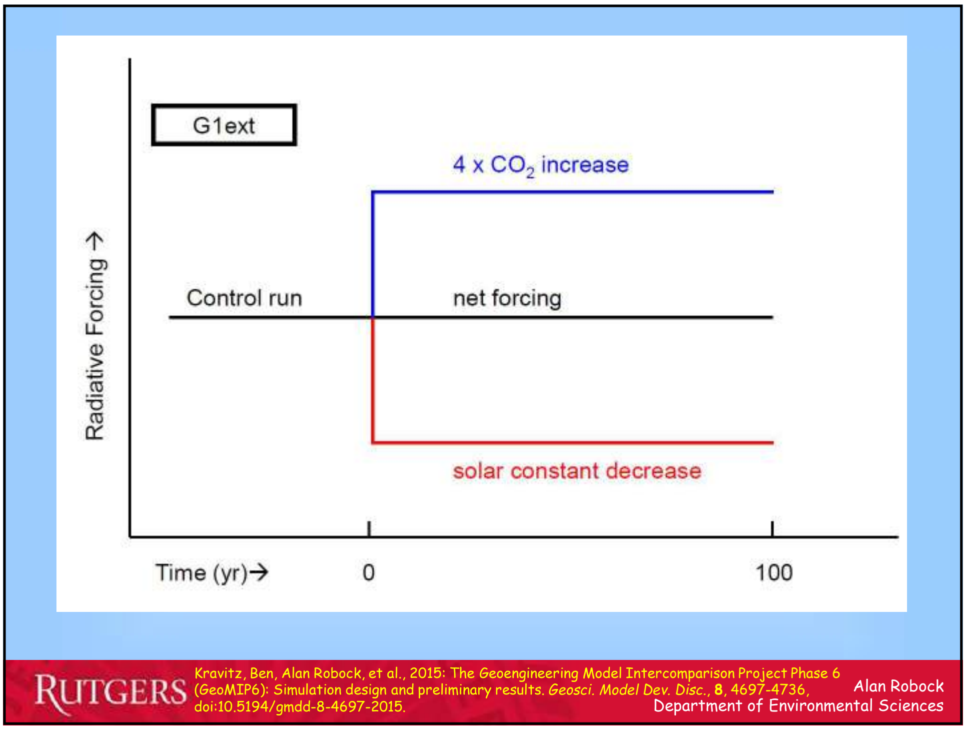
G1ext
4 x CO_2 increase
Radiative Forcing →
Control run
net forcing
solar constant decrease
Time (yr)→
0
100
RUTGERS
Kravitz, Ben, Alan Robock, et al., 2015: The Geoengineering Model Intercomparison Project Phase 6 (GeoMIP6): Simulation design and preliminary results. Geosci. Model Dev. Disc., 8, 4697-4736, doi:10.5194/gmdd-8-4697-2015.
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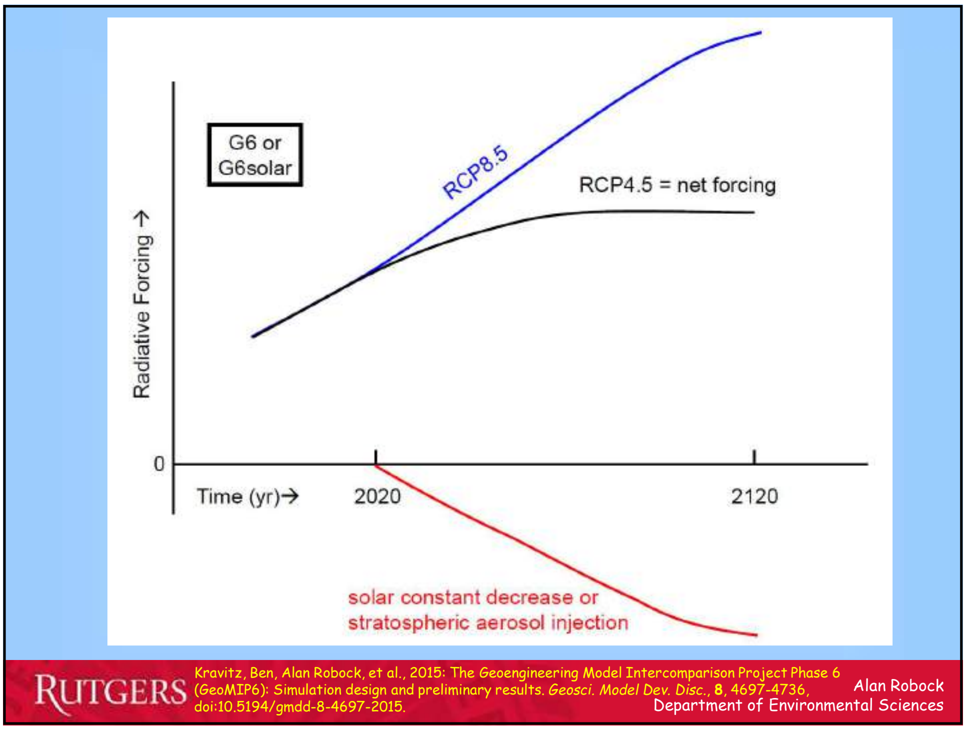
G6 or
G6solar
RCP8.5
RCP4.5 = net forcing
Radiative Forcing →
0
Time (yr)→
2020
2120
solar constant decrease or
stratospheric aerosol injection
RUTGERS
Kravitz, Ben, Alan Robock, et al., 2015: The Geoengineering Model Intercomparison Project Phase 6 (GeoMIP6): Simulation design and preliminary results. Geosci. Model Dev. Disc., 8, 4697-4736, doi:10.5194/gmdd-8-4697-2015.
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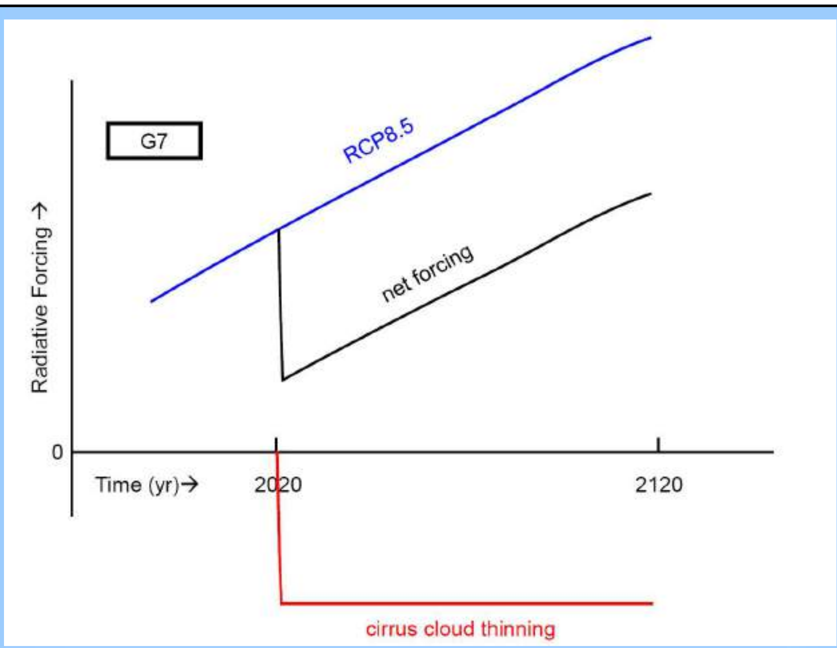

RUTGERS Kravitz, Ben, Alan Robock, et al., 2015: The Geoengineering Model Intercomparison Project Phase 6 (GeoMIP6): Simulation design and preliminary results. *Geosci. Model Dev. Disc.*, **8**, 4697-4736, doi:10.5194/gmdd-8-4697-2015.

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Successes

20 participating modeling groups (and we expect more)

Gaining confidence in model response to geoengineering

Issues

Limited resources (all time spent on GeoMIP is currently voluntary)

Some of the experiments (particularly G3) are difficult to carry out and analyze

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Reasons geoengineering may be a bad idea

Climate system response

✓1. Regional climate change, including temperature and precipitation
✓2. Rapid warming when it stops
✓3. How rapidly could effects be stopped?
✓4. Continued ocean acidification
5. **Ozone depletion**
6. Enhanced acid precipitation
7. Whitening of the sky (but nice sunsets)
8. Less solar radiation for solar power, especially for those requiring direct radiation
9. Effects on plants of changing the amount of solar radiation and partitioning between direct and diffuse
10. Effects on cirrus clouds as aerosols fall into the troposphere
11. Environmental impacts of aerosol injection, including producing and delivering aerosols

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Stratospheric Geoengineering

Benefits

1. Reduce surface air temperatures, which could reduce or reverse negative impacts of global warming, including floods, droughts, stronger storms, sea ice melting, land-based ice sheet melting, and sea level rise
2. Increase plant productivity
3. Increase terrestrial CO_2 sink
4. Beautiful red and yellow sunsets
5. Unexpected benefits

Volcanic analog

Robock, Alan, Douglas G. MacMartin, Riley Duren, and Matthew W. Christensen, 2013: Studying geoengineering with natural and anthropogenic analogs. *Climatic Change*, **121**, 445-458, doi:10.1007/s10584-013-0777-5.

Robock, Alan, Allison B. Marquardt, Ben Kravitz, and Georgiy Stenchikov, 2009: The benefits, risks, and costs of stratospheric geoengineering. *Geophys. Res. Lett.*, **36**, L19703, doi:10.1029/2009GL039209.

Robock, Alan, 2014: Stratospheric aerosol geoengineering. *Issues Env. Sci. Tech.* (Special issue "Geoengineering of the Climate System"), **38**, 162-185.

Risks

1. Drought in Africa and Asia
2. Perturb ecology with more diffuse radiation
3. Ozone depletion
4. Continued ocean acidification
5. Will not stop ice sheets from melting
6. Impacts on tropospheric chemistry
7. Whiter skies
8. Less solar electricity generation
9. Degrade passive solar heating
10. Rapid warming if stopped
11. Cannot stop effects quickly
12. Human error
13. Unexpected consequences
14. Commercial control
15. Military use of technology
16. Societal disruption, conflict between countries
17. Conflicts with current treaties
18. Whose hand on the thermostat?
19. Effects on airplanes flying in stratosphere
20. Effects on electrical properties of atmosphere
21. Environmental impact of implementation
22. Degrade terrestrial optical astronomy
23. Affect stargazing
24. Affect satellite remote sensing
25. More sunburn
26. Moral hazard – the prospect of it working would reduce drive for mitigation
27. Moral authority – do we have the right to do this?

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Robock, Alan, 2016: Albedo enhancement by stratospheric sulfur injection: More research needed. *Earth's Future*, **4**, 644-648, doi:10.1002/2016EF000407.

Risks or Concerns

Physical and biological climate system
1. Drought in Africa and Asia
2. Perturb ecology with more diffuse radiation
3. Ozone depletion
4. Continued ocean acidification
5. Additional acid rain and snow
6. May not stop ice sheets from melting
7. Impacts on tropospheric chemistry
8. Rapid warming if stopped

Human impacts
9. Less solar electricity generation
10. Degrade passive solar heating
11. Effects on airplanes flying in stratosphere
12. Effects on electrical properties of atmosphere
13. Affect satellite remote sensing
14. Degrade terrestrial optical astronomy
15. More sunburn
16. Environmental impact of implementation

Esthetics
17. Whiter skies
18. Affect stargazing

Unknowns
19. Human error during implementation
20. Unexpected consequences

Governance
21. Cannot stop effects quickly
22. Commercial control
23. Whose hand on the thermostat?
24. Societal disruption, conflict between countries
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26. Moral hazard – could reduce drive for mitigation

Ethics
27. Military use of technology
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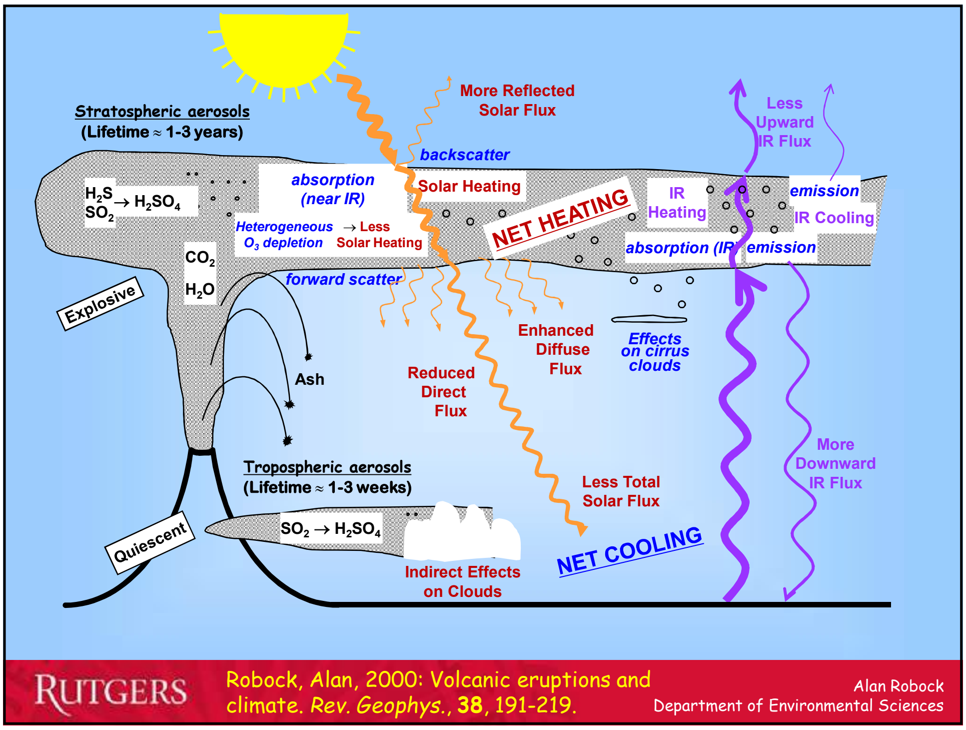
Stratospheric aerosols
(Lifetime ≈ 1-3 years)
H2S
SO2 → H2SO4
absorption
(near IR)
Heterogeneous → Less
O3 depletion Solar Heating
More Reflected
Solar Flux
backscatter
Solar Heating
NET HEATING
IR
Heating
emission
IR Cooling
absorption (IR) emission
Less
Upward
IR Flux
CO2
H2O
forward scatter
Explosive
Ash
Reduced
Direct
Flux
Enhanced
Diffuse
Flux
Effects
on cirrus
clouds
More
Downward
IR Flux
Tropospheric aerosols
(Lifetime ≈ 1-3 weeks)
SO2 → H2SO4
Less Total
Solar Flux
Quiescent
Indirect Effects
on Clouds
NET COOLING
RUTGERS
Robock, Alan, 2000: Volcanic eruptions and
climate. Rev. Geophys., 38, 191-219.
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1783-84, Lakagígar (Laki), Iceland

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1783-84 Laki Eruption in Iceland
(8 June 1783 – 7 February 1784)

Second largest flood lava eruption in historical time

Iceland's biggest natural disaster

Lava = 14.7 km^3
Tephra = 0.4 km^3

WVZ, EVZ, NVZ are Western, Eastern and Northern Volcanic Zones

RUTGERS Fig. 1 from Thordarson and Self (2003)

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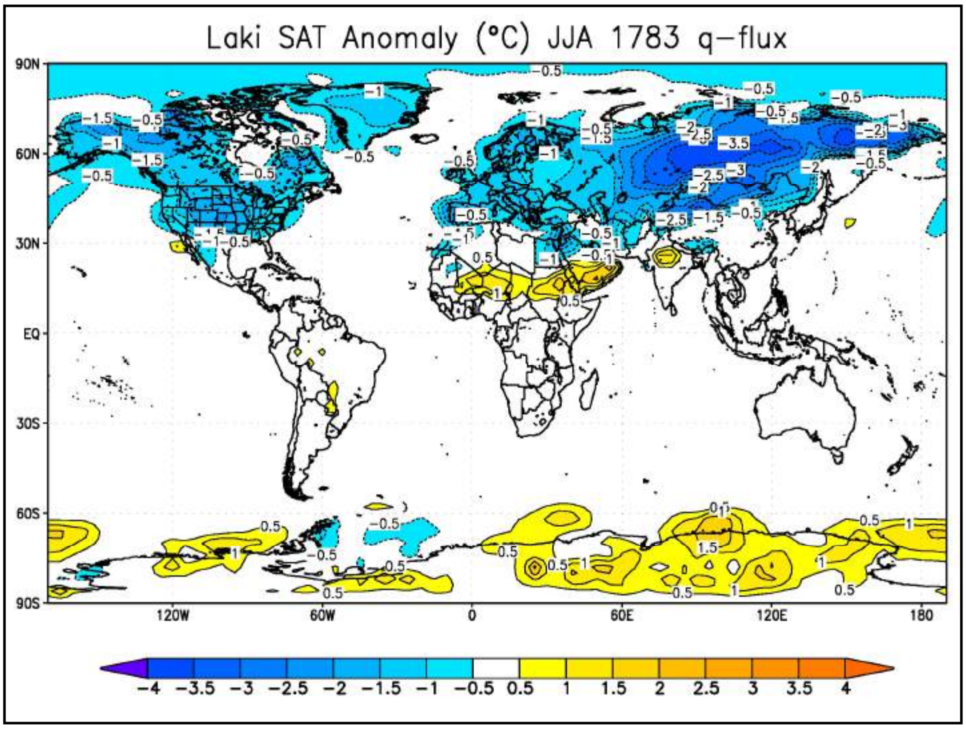
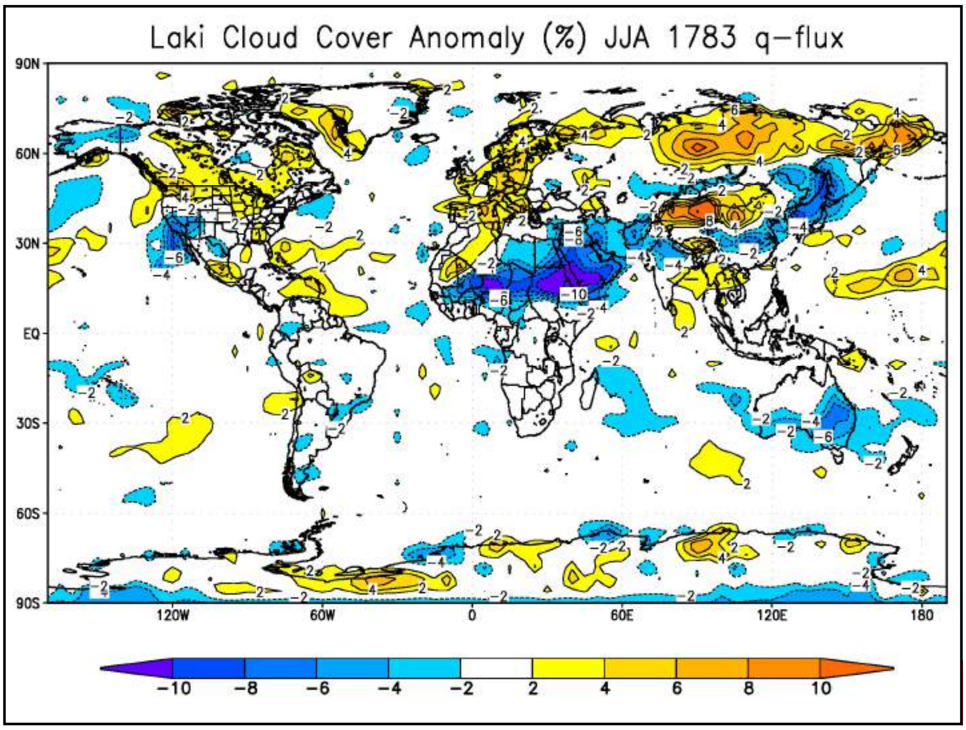
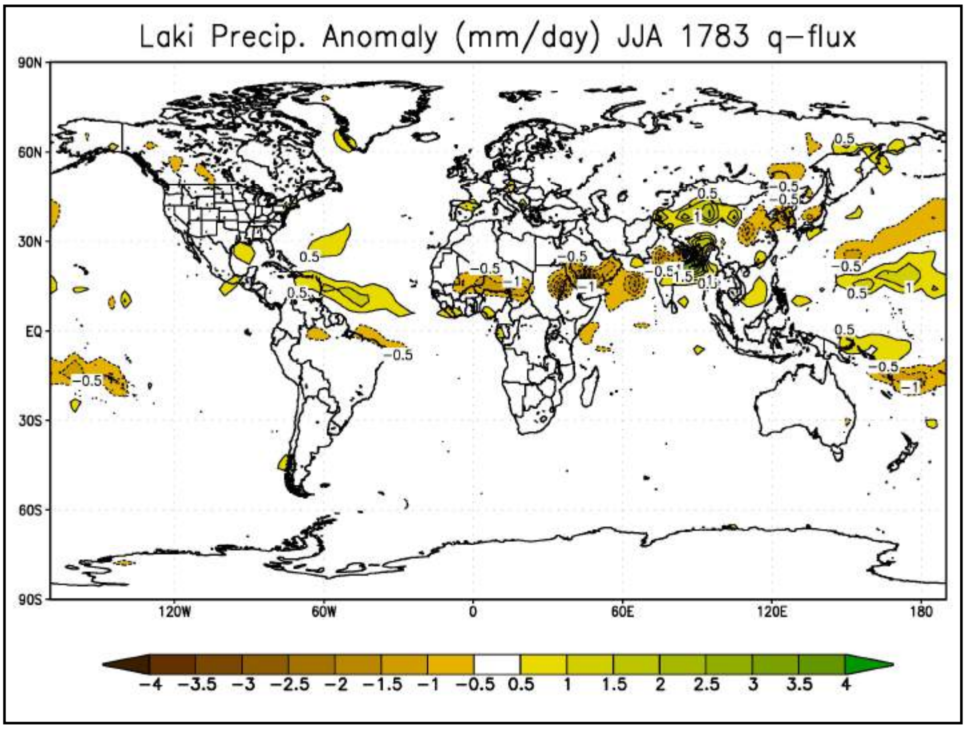

Laki SAT Anomaly (°C) JJA 1783 q−flux

181


Laki Cloud Cover Anomaly (%) JJA 1783 q−flux

182



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Constantin-François de Chasseboeuf,
Comte de Volney
Travels through Syria and Egypt, in the years 1783, 1784, and 1785, Vol. I
Dublin, 258 pp. (1788)

"The inundation of 1783 was not sufficient, great part of the lands therefore could not be sown for want of being watered, and another part was in the same predicament for want of seed. In 1784, the Nile again did not rise to the favorable height, and the dearth immediately became excessive. Soon after the end of November, the famine carried off, at Cairo, nearly as many as the plague; the streets, which before were full of beggars, now afforded not a single one: all had perished or deserted the city."

By January 1785, 1/6 of the population of Egypt had either died or left the country in the previous two years.

RUTGERS http://www.academie-francaise.fr/images/immortels/portraits/volney.jpg
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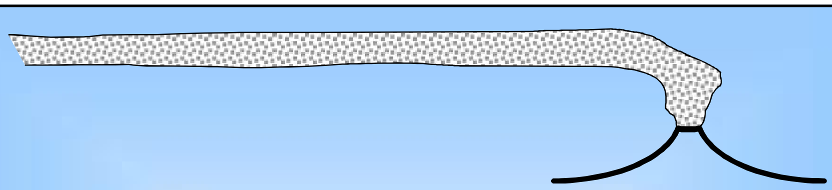

FAMINE IN INDIA AND CHINA IN 1783

The Chalisa Famine devastated India as the monsoon failed in the summer of 1783.

There was also the Great Tenmei Famine in Japan in 1783-1787, which was locally exacerbated by the Mount Asama eruption of 1783.

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What about other high latitude eruptions?

There have been three major high latitude eruptions in the past 2000 years:

939 Eldgjá, Iceland - Tropospheric and stratospheric

1783-84 Lakagígar (Laki), Iceland - Same as Eldgjá

1912 Novarupta (Katmai), Alaska - Stratospheric only

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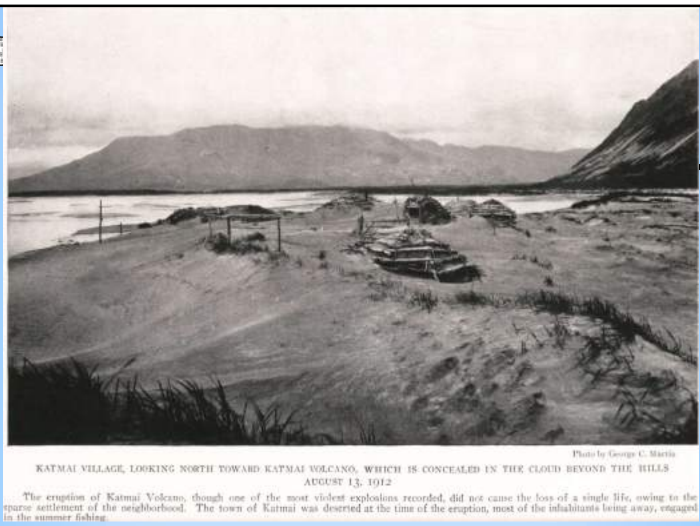

Katmai village, buried by ash from the June 6, 1912 eruption
Katmai volcano in background covered by cloud

Simulations showed same reduction in African summer precipitation.

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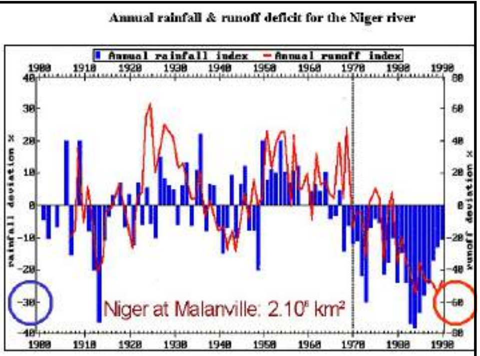
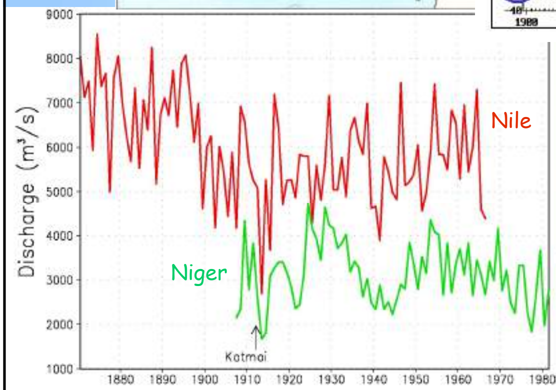
Niger Basin

http://www.festivalsegou.org





http://www.isiimm.agropolis.org

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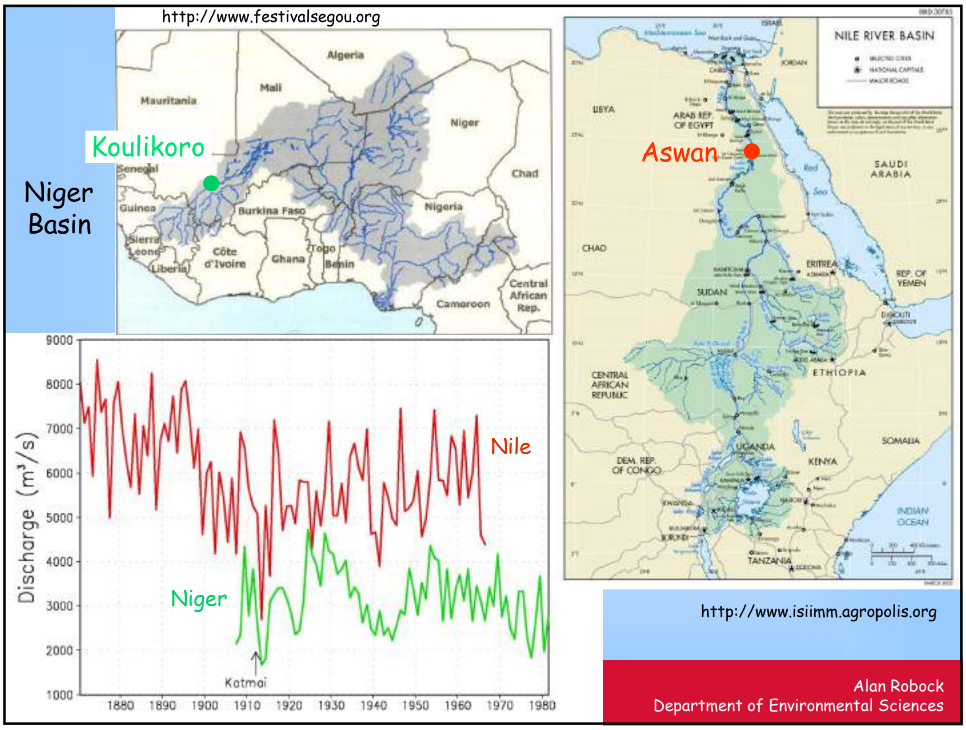

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High-latitude Eruptions and the Nile River Level

The exact dating of Eldgjá is not known but it is thought to have occurred between 933 and 941 A.D.

Several points suggest 939:

Astronomical observations in Irish Annals (McCarthy and Breen, 1997)

GISP2 ice core has peak acidity in 938 ±4 years (Zielinski, 1995)

Winter of 939-940 was very severe over Europe and similar to 1783-1784 after Laki.

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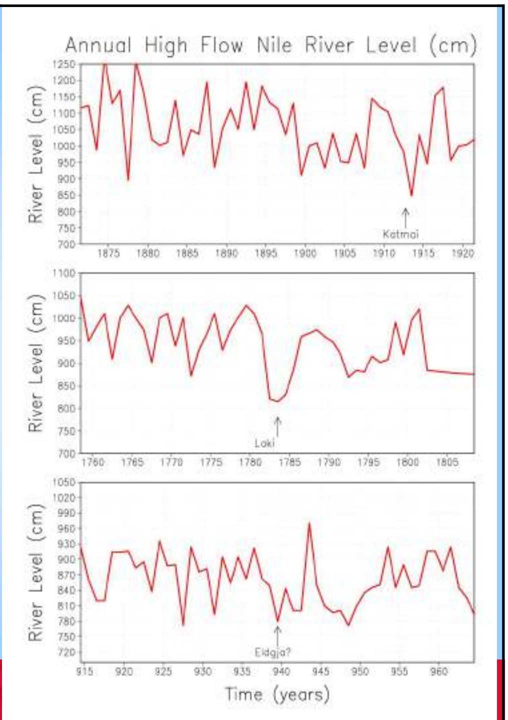
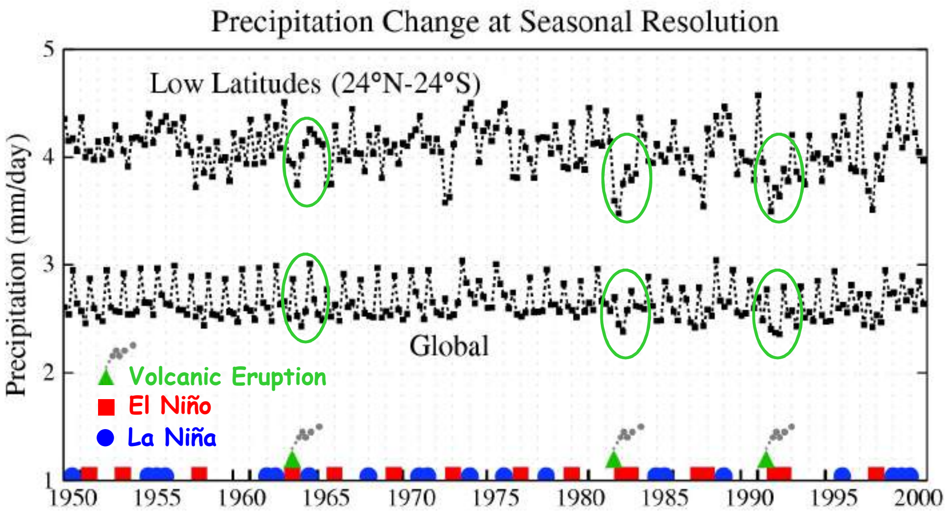


190



Drawn by Makiko Sato (NASA GISS)
using CRU TS 2.0 data

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Trenberth and Dai (2007)

Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering

Geophys. Res. Lett.

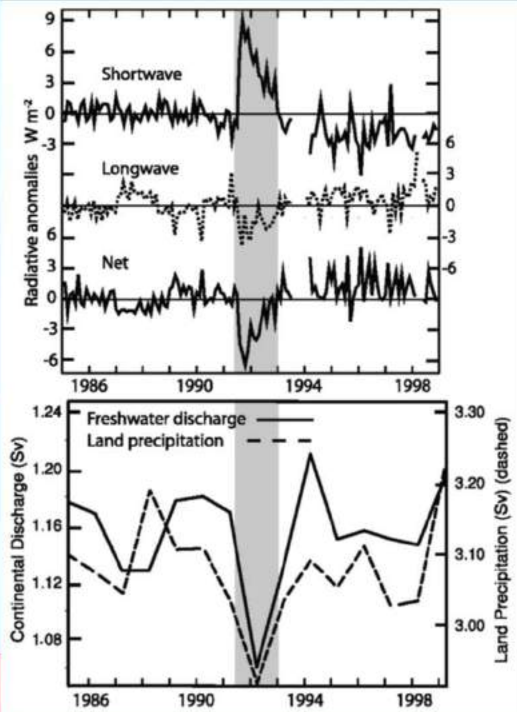

Figure 2. (top) Adapted time series of 20°N to 20°S ERBS non-scanner wide-field-of-view broadband shortwave, longwave, and net radiation anomalies from 1985 to 1999 [*Wielicki et al.*, 2002a, 2002b] where the anomalies are defined with respect to the 1985 to 1989 period with Edition 3_Rev 1 data [*Wong et al.*, 2006]. (bottom) Time series of the annual water year (Oct. to Sep.); note slight offset of points plotted vs. tick marks indicating January continental freshwater discharge and land precipitation (from Figure 1) for the 1985 to 1999 period. The period clearly influenced by the Mount Pinatubo eruption is indicated by grey shading.

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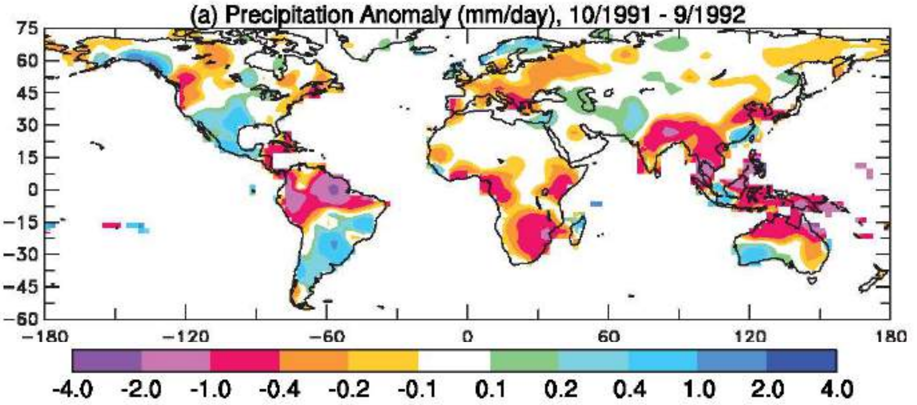
TRENBERTH AND DAI: PINATUBO AND THE HYDROLOGICAL CYCLE



Trenberth, K. E., and A. Dai, 2007: Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. *Geophys. Res. Lett.*, **34**, L15702, doi: 10.1029/2007GL030524.

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L15702 TRENBERTH AND DAI: PINATUBO AND THE HYDROLOGICAL CYCLE L15702

Trenberth and Dai (2007)

Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering

Geophys. Res. Lett.

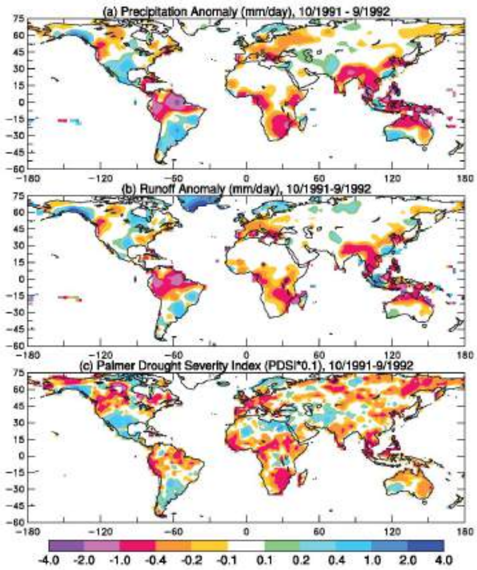

Figure 3. (a) Observed precipitation anomalies (relative to 1950–2004 mean) in mm/day during October 1991–September 1992 over land. Warm colors indicate below normal precipitation. (b) As for Figure 3a but for the simulated runoff [*Qian et al.*, 2006] using a comprehensive land surface model forced with observed precipitation and other atmospheric forcing in mm/day. (c) Palmer Drought Severity Index (PDSI, multiplied by 0.1) for October 1991–September 1992 [*Dai et al.*, 2004]. Warm colors indicate drying. Values less than −2 (0.2 on scale) indicate moderate drought, and those less than −3 indicate severe drought.

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Summer monsoon drought index pattern using tree rings for 750 years

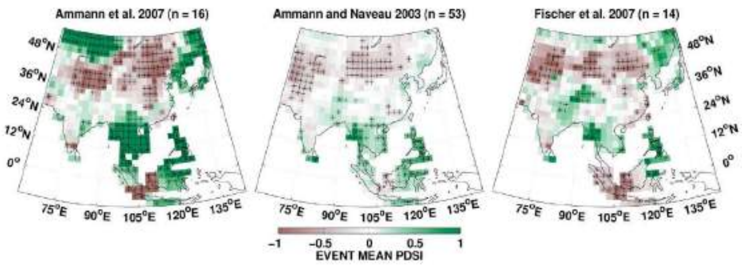

Figure 2. Superposed epoch analysis using the reconstructed PDSI values from the Monsoon Asia Drought Atlas (MADA) [*Cook et al.*, 2010] and the sets of events years shown in Table 1. Statistically significant (90% one-tailed) epochal anomalies based on Monte Carlo resampling (n = 10,000) are indicated by crosses.

Anchukaitis et al. (2010), Influence of volcanic eruptions on the climate of the Asian monsoon region. *Geophys. Res. Lett.*, *37*, L22703, doi:10.1029/2010GL044843

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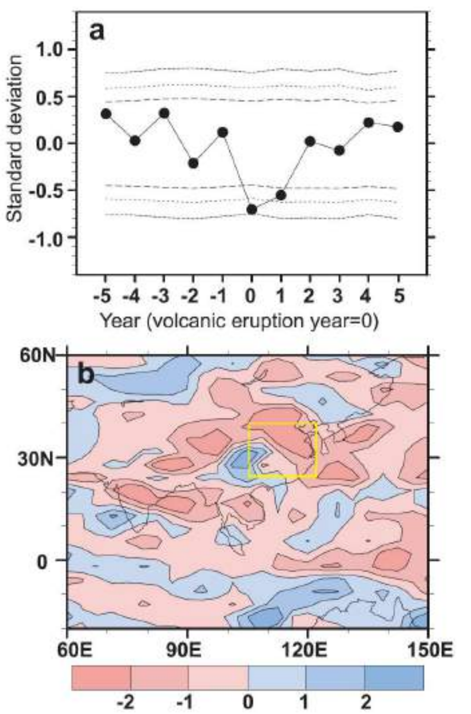

FIG. 1. (a) Results of superposed epoch analysis of modeled summer precipitation for 18 cases of large volcanic eruption showing the response of summer precipitation over eastern China. Bootstrapping procedures are used to assess the statistical significance of summer precipitation above and below the mean. The dashed and dotted lines represent confidence intervals of 90%, 95%, and 99% derived from 1000 Monte Carlo simulations. (b) Spatial pattern of composite anomalies of summer precipitation over East Asia and tropical oceans during the volcanic eruption year for 18 cases of large volcanic eruption; yellow box shows our study area.

NCAR CCSM 2.0.1 simulation for past 1000 years

Peng, Youbing, Caiming Shen, Wei-chyung Wang, and Ying Xu, 2010: Response of summer precipitation over Eastern China to large volcanic eruptions. *J. Climate*, **23**, 818-825.

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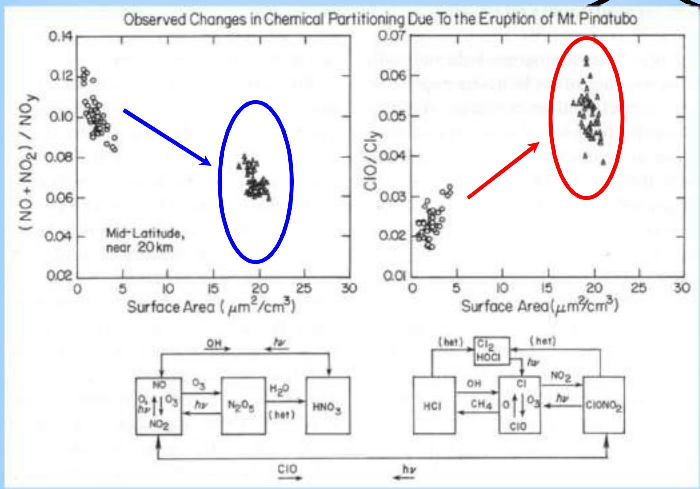
Volcanic aerosols produce more reactive chlorine



RUTGERS Solomon (1999) Department of Environmental Sciences

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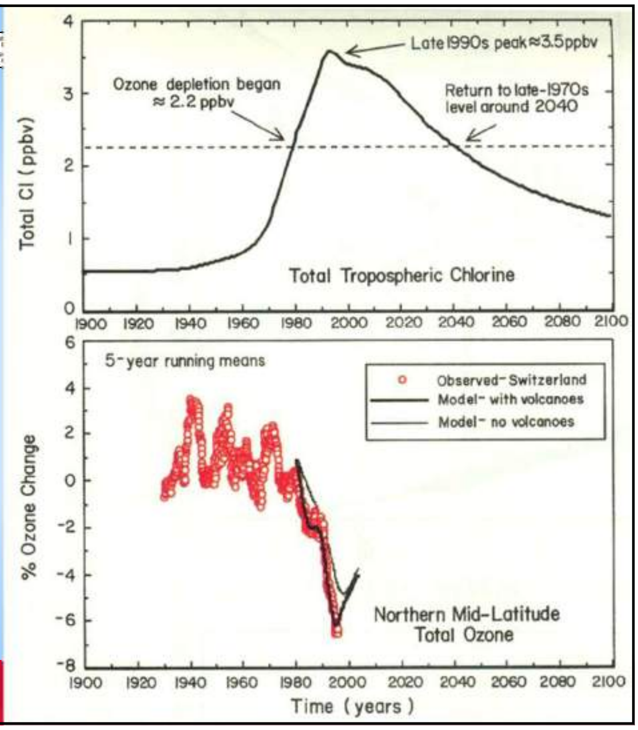
Tropospheric chlorine diffuses to stratosphere.

Volcanic aerosols make chlorine available to destroy ozone.

Solomon (1999)



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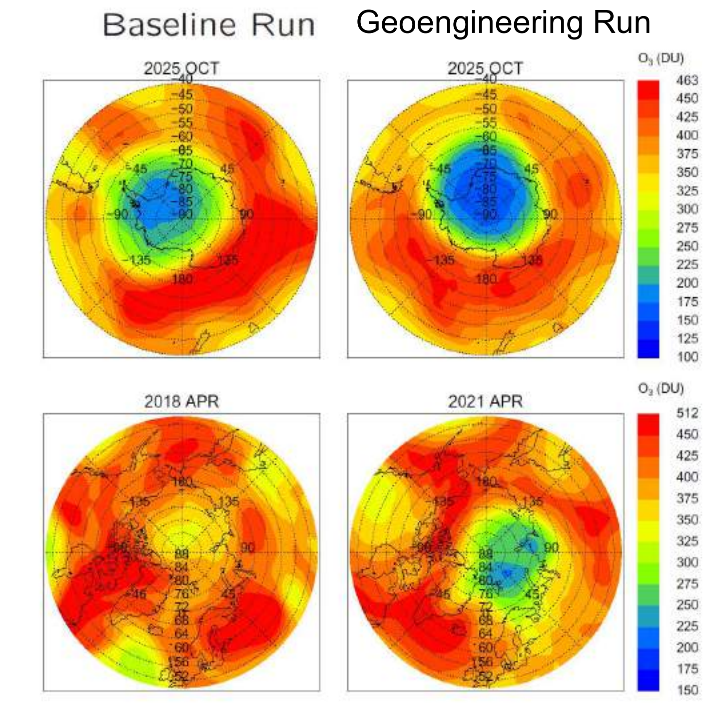
SH

Rasch et al. (2008)

Ozone concentration for coldest winters with and without geoengineering

WACCM3 model runs by Tilmes et al. (2008) with 2 Tg S/yr

NH



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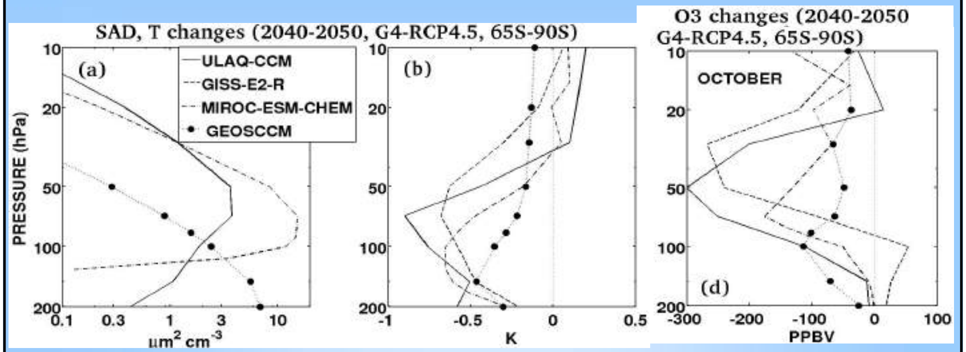
SRM using stratospheric aerosols would reduce ozone and enhance surface UV-B radiation, but the details depend on the size distribution of the aerosols, and the complex interaction between upwelling of ozone-poor air in the tropics, suppression of the NOx cycle, and increases of surface area density.

The net effect for a tropical injection rate of 5 Tg SO_2 per year is a **decrease in globally averaged ozone** by 1.1-2.1 DU in the years 2040-2050 for three models which include heterogeneous chemistry on the sulfate aerosol surfaces. GISS-E2-R, a fully coupled general circulation model, performed simulations with no heterogeneous chemistry and a smaller aerosol size; it showed a decrease in ozone by 9.7 DU.

Pitari, Giovanni, Valentina Aquila, Ben Kravitz, Alan Robock, Shingo Watanabe, Natalia De Luca, Glauco Di Genova, Eva Mancini, and Simone Tilmes, 2014: Stratospheric ozone response in experiments G3 and G4 of the Geoengineering Model Intercomparison Project (GeoMIP). *J. Geophys. Res. Atmos.*, doi:10.1029/2013JD020566, in press.

200



G4 minus RCP4.5 changes for 2040-2050
averaged over the South Polar region (65°S-90°S)

Pitari, Giovanni, Valentina Aquila, Ben Kravitz, Alan Robock, Shingo Watanabe, Natalia De Luca, Glauco Di Genova, Eva Mancini, and Simone Tilmes, 2014: Stratospheric ozone response in experiments G3 and G4 of the Geoengineering Model Intercomparison Project (GeoMIP). *J. Geophys. Res. Atmos.*, doi:10.1029/2013JD020566, in press.

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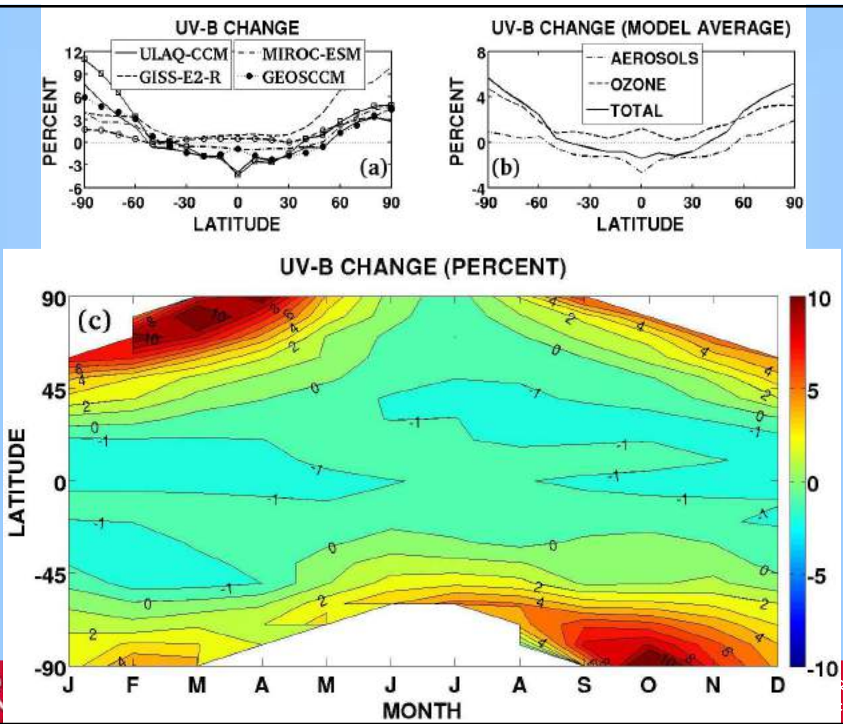

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Reasons geoengineering may be a bad idea

Climate system response

✓1. Regional climate change, including temperature and precipitation
✓2. Rapid warming when it stops
✓3. How rapidly could effects be stopped?
✓4. Continued ocean acidification
✓5. Ozone depletion
6. Enhanced acid precipitation
7. Whitening of the sky (but nice sunsets)
8. Less solar radiation for solar power, especially for those requiring direct radiation
9. Effects on plants of changing the amount of solar radiation and partitioning between direct and diffuse
10. Effects on cirrus clouds as aerosols fall into the troposphere
11. Environmental impacts of aerosol injection, including producing and delivering aerosols

Robock, Alan, 2008: Whither geoengineering? *Science*, **320**, 1166-1167.

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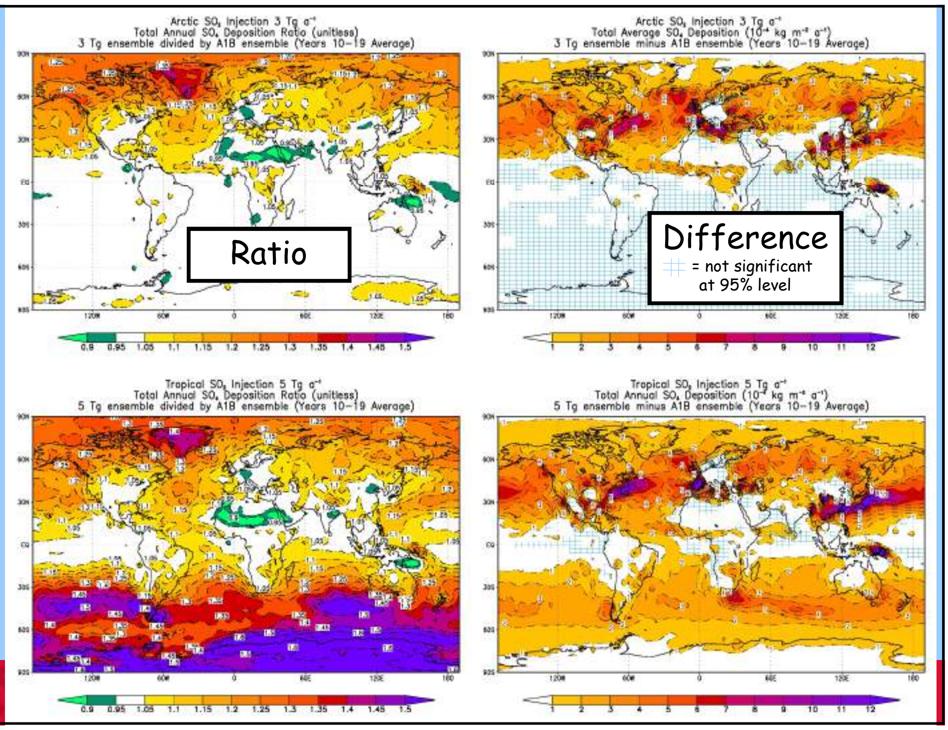

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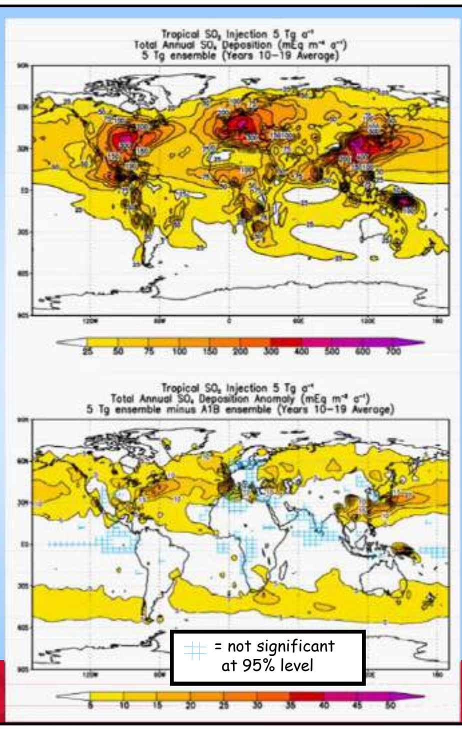
Ranges of critical loading of pollutant deposition (including sulfur) for various sites in Europe [*Skeffington*, 2006]

Region	**Critical Load ($mEq\ m^{-2}\ a^{-1}$)**
Coniferous forests in Southern Sweden	13-61
Deciduous forests in Southern Sweden	15-72
Varied sites in the UK	24-182
Aber in North Wales	32-134
Uhlirska in the Czech Republic	260-358
Fårahall in Sweden	29-134
Several varied sites in China (sulfur only)	63-880
Waterways in Sweden	1-44

While excess deposition will not cause significant acidification, sulfate can still damage human and ecosystem health.

Kravitz, Ben, Alan Robock, Luke Oman, Georgiy Stenchikov, and Allison B. Marquardt, 2009: Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols. *J. Geophys. Res.*, **114**, D14109, doi:10.1029/2009JD011918, corrected.



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Reasons geoengineering may be a bad idea

Climate system response

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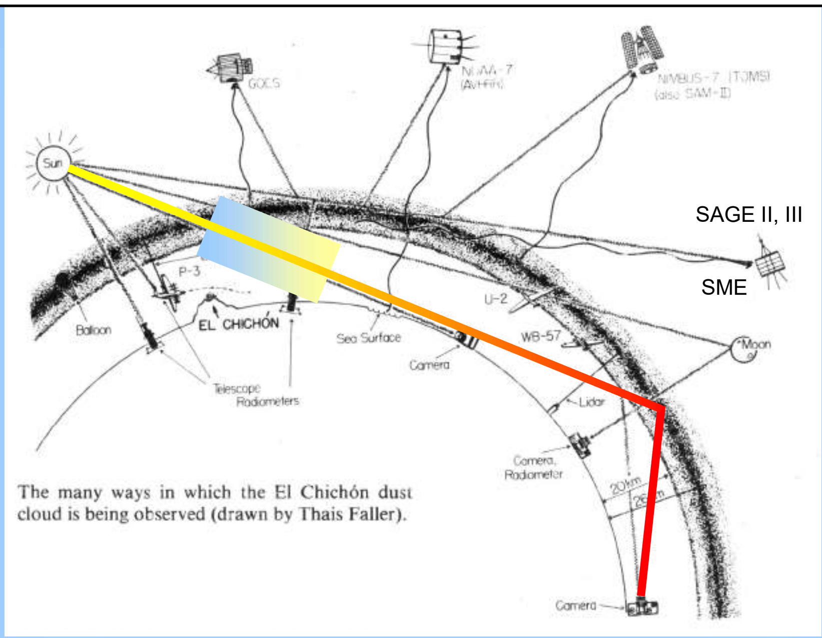

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Robock (1983)

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Krakatau, 1883
Watercolor by William Ascroft

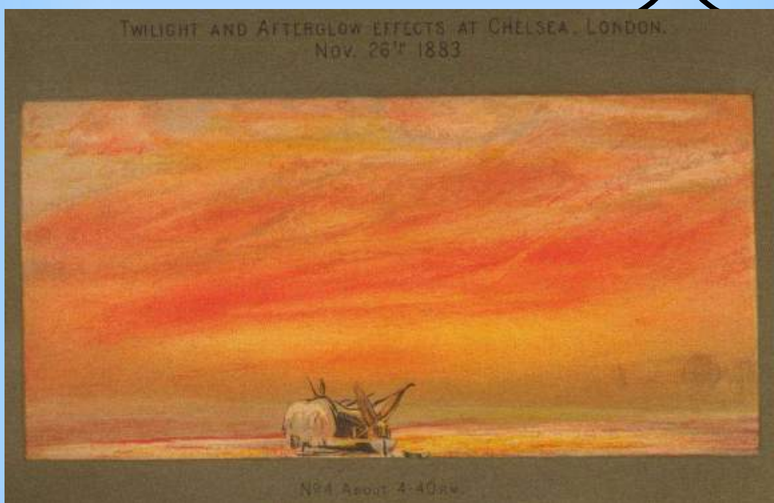

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Figure from Symons (1888)

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"The Scream"

Edvard Munch

Painted in 1893 based on Munch's memory of the brilliant sunsets following the 1883 Krakatau eruption.

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Sunset over Lake Mendota, July 1982

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Diffuse Radiation from Pinatubo Makes a Whiter Sky

Photographs by Alan Robock

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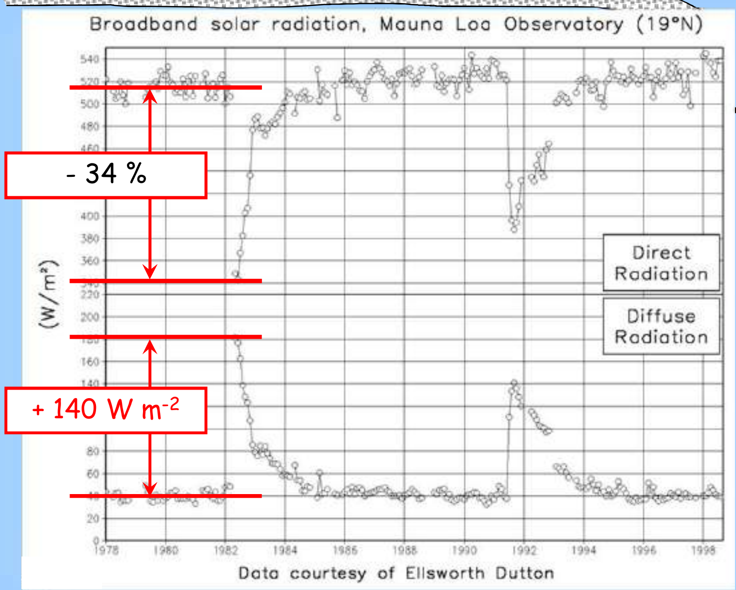

Robock (2000), Dutton and Bodhaine (2001)

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Geoengineering: Whiter skies?

Ben Kravitz,[1] Douglas G. MacMartin,[2] and Ken Caldeira[1]

Received 9 March 2012; revised 1 May 2012; accepted 2 May 2012; published 1 June 2012.

[1] One proposed side effect of geoengineering with stratospheric sulfate aerosols is sky whitening during the day and afterglows near sunset, as is seen after large volcanic eruptions. Sulfate aerosols in the stratosphere would increase diffuse light received at the surface, but with a non-uniform spectral distribution. We use a radiative transfer model to calculate spectral irradiance for idealized size distributions of sulfate aerosols. A 2% reduction in total irradiance, approximately enough to offset anthropogenic warming for a doubling of CO_2 concentrations, brightens the sky (increase in diffuse light) by 3 to 5 times, depending on the aerosol size distribution. The relative increase is less when optically thin cirrus clouds are included in our simulations. Particles with small radii have little influence on the shape of the spectra. Particles of radius ~0.5 μm preferentially increase diffuse irradiance in red wavelengths, whereas large particles (~0.9 μm) preferentially increase diffuse irradiance in blue wavelengths. Spectra show little change in dominant wavelength, indicating little change in sky hue, but all particle size distributions produce an increase in white light relative to clear sky conditions. Diffuse sky spectra in our simulations of geoengineering with stratospheric aerosols are similar to those of average conditions in urban areas today.

Citation: Kravitz, B., D. G. MacMartin, and K. Caldeira (2012), Geoengineering: Whiter skies?, *Geophys. Res. Lett.*, *39*, L11801, doi:10.1029/2012GL051652.

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Nevada Solar One
64 MW

Solar steam generators
requiring direct solar

Seville, Spain
Solar Tower
11 MW

http://www.electronichealing.co.uk/articles/solar_power_tower_spain.htm

http://judykitsune.wordpress.com/2007/09/12/solar-seville/

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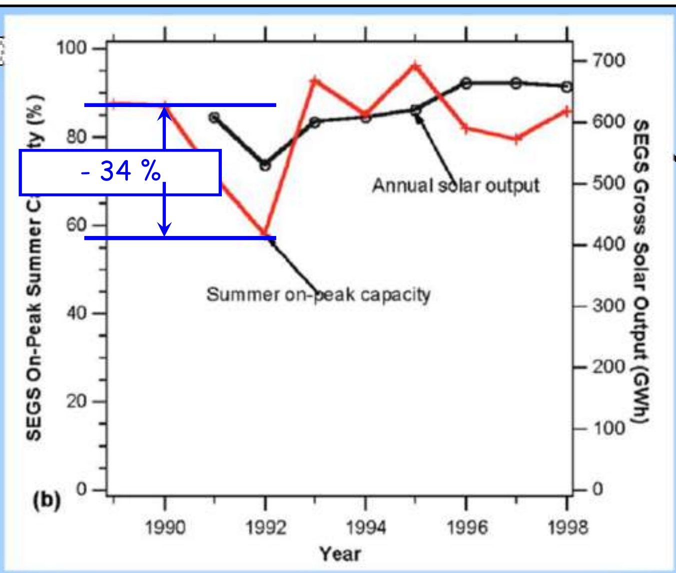

Output of solar electric generating systems (SEGS) solar thermal power plants in California (9 with a combined capacity of 354 peak MW). (Murphy, 2009, *ES&T*)

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Reasons geoengineering may be a bad idea

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X6. Enhanced acid precipitation
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9. Effects on plants of changing the amount of solar radiation and partitioning between direct and diffuse
10. Effects on cirrus clouds as aerosols fall into the troposphere
11. Environmental impacts of aerosol injection, including producing and delivering aerosols

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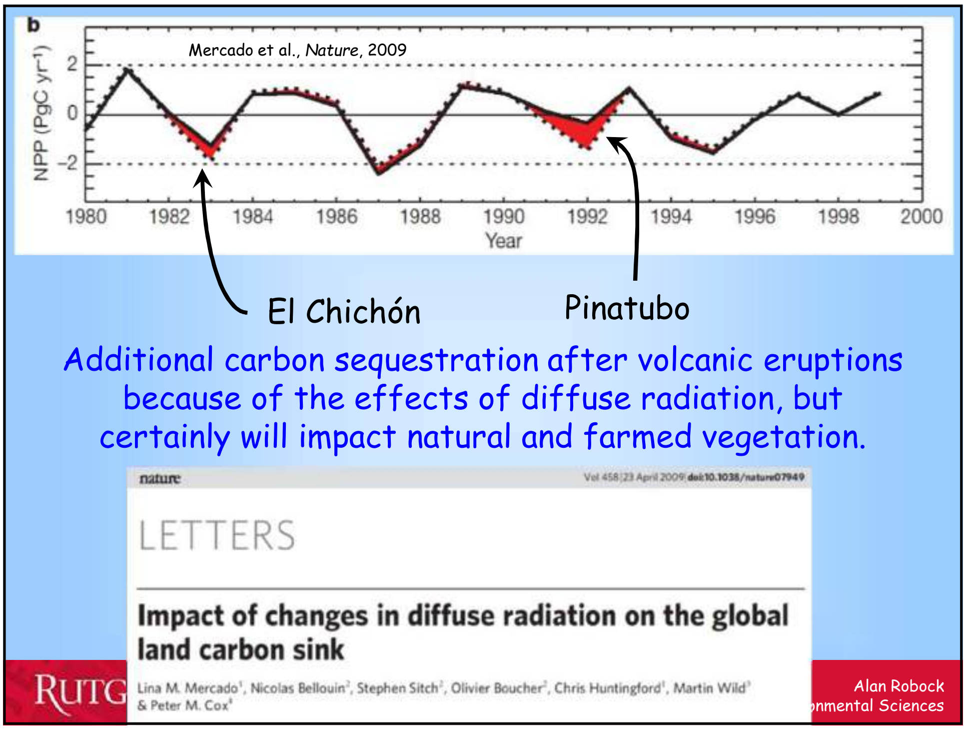
b
Mercado et al., Nature, 2009
NPP (PgC yr⁻¹)
2
0
−2
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
Year
El Chichón
Pinatubo
Additional carbon sequestration after volcanic eruptions because of the effects of diffuse radiation, but certainly will impact natural and farmed vegetation.
nature
LETTERS
Impact of changes in diffuse radiation on the global land carbon sink
Lina M. Mercado, Nicolas Bellouin, Stephen Sitch, Olivier Boucher, Chris Huntingford, Martin Wild & Peter M. Cox
Alan Robock
nmental Sciences

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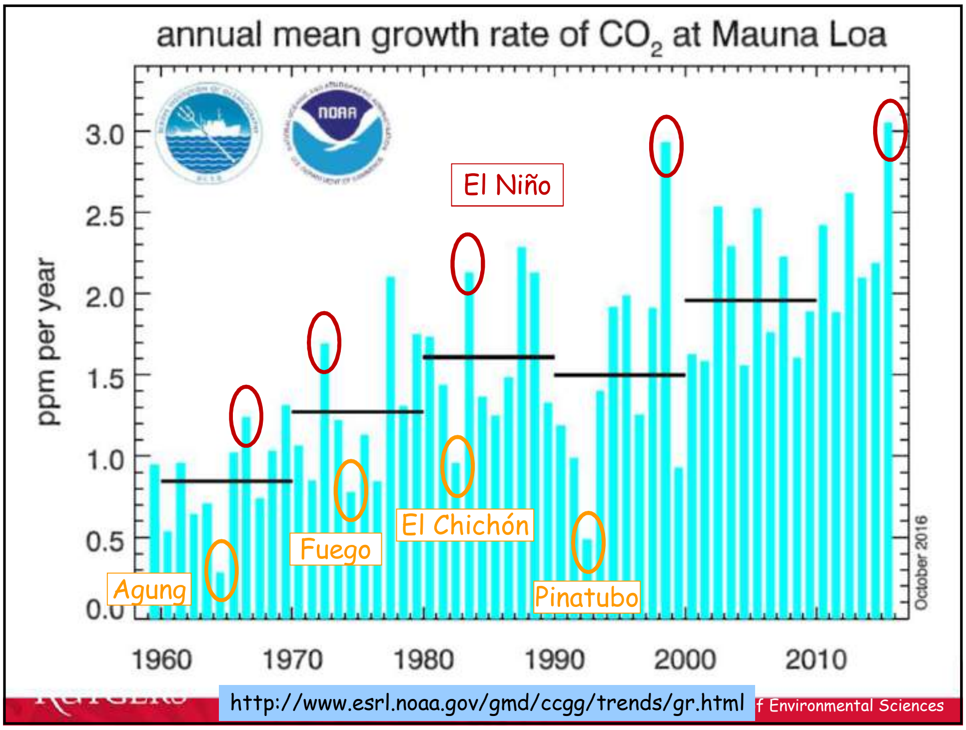
annual mean growth rate of CO2 at Mauna Loa
ppm per year
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1960
1970
1980
1990
2000
2010
El Niño
Agung
Fuego
El Chichón
Pinatubo
October 2016
http://www.esrl.noaa.gov/gmd/ccgg/trends/gr.html
f Environmental Sciences

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Reasons geoengineering may be a bad idea

Climate system response

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Reasons geoengineering may be a bad idea

Unknowns

✓12. Human error
✓13. Unexpected consequences (How well can we predict the expected effects of geoengineering? What about unforeseen effects?)

Political, ethical and moral issues

✓14. Schemes perceived to work will lessen the incentive to mitigate greenhouse gas emissions
✓15. Use of the technology for military purposes. Are we developing weapons?
✓16. Commercial control of technology
✓17. Violates UN Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques
18. Could be tremendously expensive
19. Even if it works, whose hand will be on the thermostat? How could the world agree on the optimal climate?
20. Who has the moral right to advertently modify the global climate?

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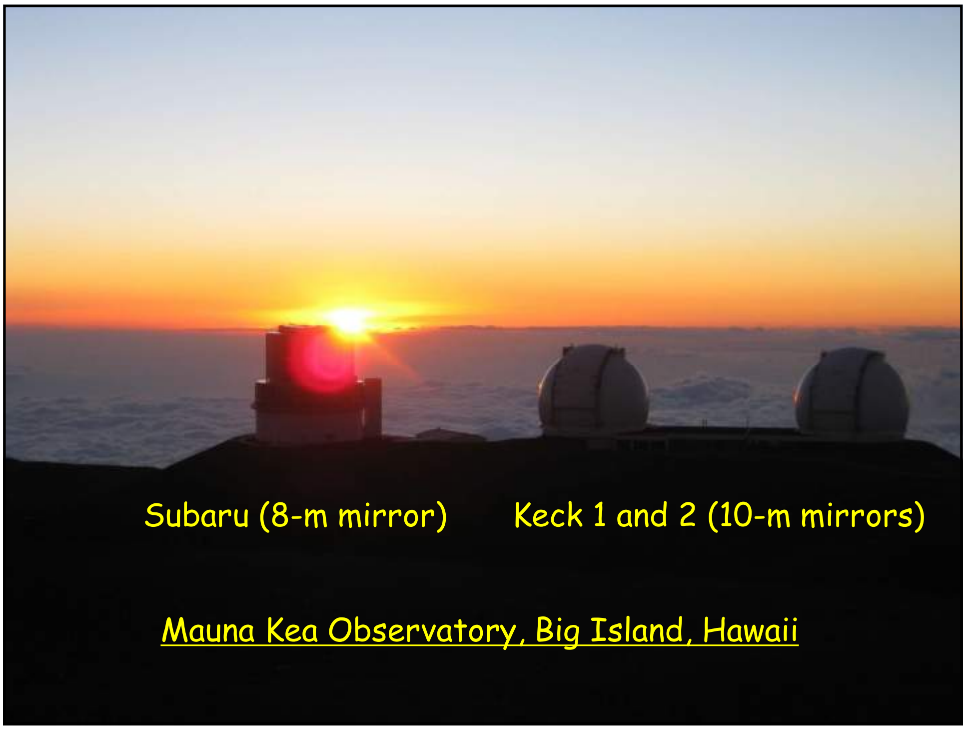
Subaru (8-m mirror)
Keck 1 and 2 (10-m mirrors)
Mauna Kea Observatory, Big Island, Hawaii

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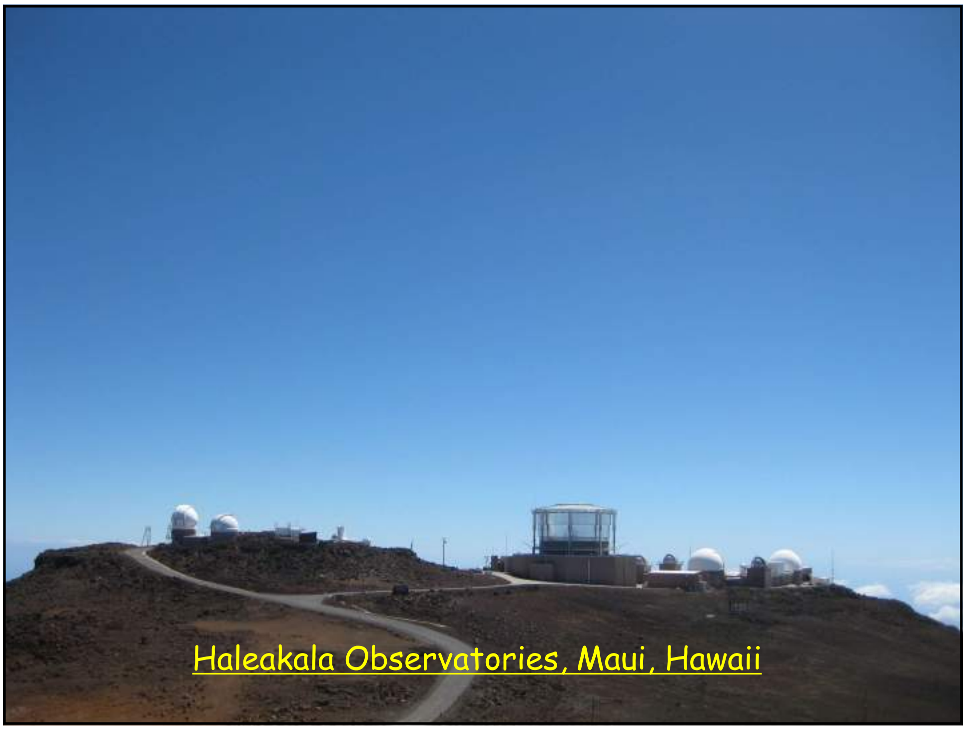
Haleakala Observatories, Maui, Hawaii

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Volcanic eruptions warn us that stratospheric geoengineering could:

- Cool the surface, reducing ice melt and sea level rise, produce pretty sunsets, and increase the CO_2 sink, ***but***
- Reduce summer monsoon precipitation,
- Destroy ozone, allowing more harmful UV at the surface,
- Produce rapid warming when stopped,
- Make the sky white,
- Reduce solar power,
- Perturb the ecology with more diffuse radiation,
- Damage airplanes flying in the stratosphere,
- Degrade astronomical observations,
- Affect remote sensing, and
- Affect stargazing

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The claim that stratospheric geoengineering is cheap and easy remains to be proven.

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How could we actually get the sulfate aerosols into the stratosphere?

Artillery?

Aircraft?

Balloons?

Tower?

Starting from a mountain top would make stratospheric injection easier, say from the Andes in the tropics, or from Greenland in the Arctic.

Robock, Alan, Allison B. Marquardt, Ben Kravitz, and Georgiy Stenchikov, 2009: The benefits, risks, and costs of stratospheric geoengineering. *Geophys. Res. Lett.*, **36**, L19703, doi:10.1029/2009GL039209.

RUTGERS Drawing by Brian West

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H_2S would be lightest and cheapest precursor to produce stratospheric aerosols.

While volcanic eruptions inject mostly SO_2 into the stratosphere, the relevant quantity is the amount of sulfur. If H_2S were injected instead, it would oxidize quickly to form SO_2, which would then react with water to form H_2SO_4 droplets. Because of the relative molecular weights, only 1 Tg of H_2S would be required to produce the same amount of sulfate aerosols as 2 Tg of SO_2. However, H_2S is toxic and flammable, so it may be preferable to use SO_2.

Here we evaluate the cost of lofting 1 Tg of H_2S into the stratosphere per year.

The total cost of geoengineering would depend on the total amount to be lofted and on the gas.

The National Academy of Sciences (1992) study estimated the price of SO_2 to be $50,000,000 per Tg, and H_2S would be much cheaper, so the price of the gases themselves is not an issue.

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How could we use airplanes to loft gas to the stratosphere?

- Put S back into the jet fuel.

  But, except for the Arctic, planes do not routinely fly that high.
- Have tanker aircraft carry it to the stratosphere.

  But they can only get into the stratosphere in the Arctic.
- Have fighter planes carry it to the stratosphere.

  But you would need many more planes.
- Have tanker aircraft carry it to the upper troposphere and have fighter jets carry it the rest of the way.
- Could you have a tanker tow a glider with a hose to loft the exit nozzle into the stratosphere?

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- There is currently no way to do geoengineering. No means exist to inject aerosol precursors (gases).
- Even if we could get the gases up there, we do not yet understand how to produce particles of the appropriate size.
- Here we investigate only the problem of lofting precursors to the lower stratosphere.

Henning Wagenbreth
Oct. 24, 2007

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F-15C Eagle

Ceiling: 20 km

Payload: 8 tons gas

Cost: $30,000,000
(1998 dollars)

http://www.af.mil/shared/media/photodb/photos/060614-F-8260H-310.JPG

http://www.fas.org/man/dod-101/sys/ac/f-15e-981230-F-6082P-004.jpg

With 3 flights/day,
operating 250 days/year

would need 167 planes
to deliver 1 Tg gas per year
to tropical stratosphere.

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KC-135 Stratotanker

Ceiling: 15 km

Payload: 91 tons gas

Cost: $39,600,000
(1998 dollars)

http://upload.wikimedia.org/wikipedia/commons/a/a8/Usaf.f15.f16.kc135.750pix.jpg

http://www.af.mil/shared/media/photodb/photos/021202-O-9999G-029.jpg

With 3 flights/day,
operating 250 days/year

would need 15 planes
to deliver 1 Tg gas per year
to Arctic stratosphere.

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KC-10 Extender

Ceiling: 12.73 km

Payload: 160 tons gas

Cost: $88,400,000
(1998 dollars)

http://www.af.mil/shared/media/factsheet/kc_10.jpg

http://www.af.mil/shared/media/photodb/photos/030317-F-7203T-013.jpg

With 3 flights/day,
operating 250 days/year

would need 9 planes
to deliver 1 Tg gas per year
to Arctic stratosphere.

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Costs of stratospheric aerosols (Aurora report, 2010)

(Robock et al., 2009)

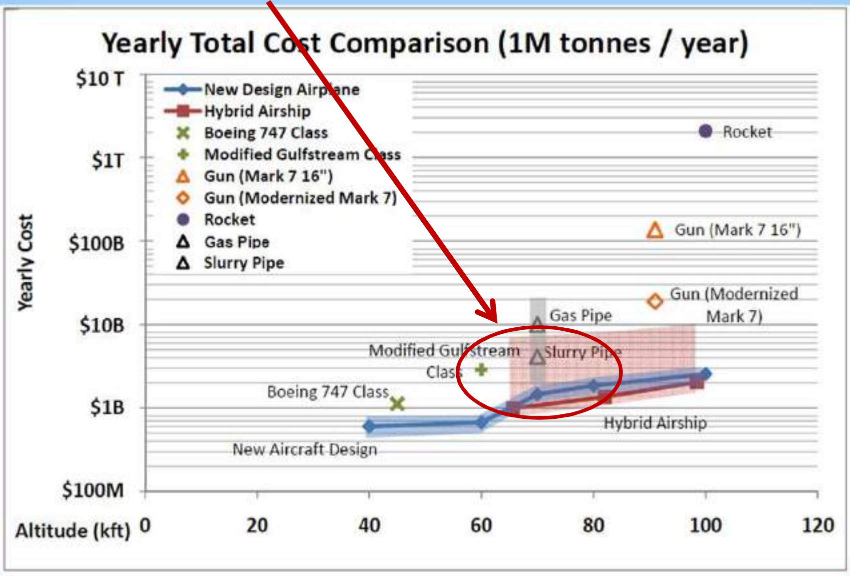

Figure 2: Yearly cost (including depreciation, interest, and operations costs) for 1M tonne per year geoengineering

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It may be possible to take H_2S gas, which would oxidize to SO_2, or SO_2 directly, to the lower stratosphere for a few billion dollars per year per Tg S, **but:**

Will spraying more SO_2 into the stratosphere produce new small particles or larger particles by condensation onto existing particles?

Theory tells us larger particles, which will reflect less sunlight per unit mass of S and fall out faster, greatly reducing their effectiveness.

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Robock, Alan, Martin Bunzl, Ben Kravitz, and Georgiy Stenchikov, 2010: *A test for geoengineering? Science*, **327**, 530-531, doi:10.1126/science.1186237.

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Costs of personnel, maintenance, and CO_2 emissions would depend on implementation strategy.

Each KC-135 costs $4,600,000 per year for total operations and support costs, including personnel, fuel, maintenance, and spare parts.*

* http://www.gao.gov/new.items/d03938t.pdf

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16" (41 cm) naval rifles (artillery) were evaluated by the National Academy of Sciences (1992).

The annual cost to inject 1 Tg (they used Al_2O_3 dust) into the stratosphere, including ammunition, gun barrels, stations, and personnel, was estimated to be $20,000,000,000.

"The rifles could be deployed at sea or in empty areas (e.g., military reservations) where the noise of the shots and the fallback of expended shells could be managed."

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Balloons could be used in several ways:

- To float in the stratosphere, suspending a hose to pump gas up there.
- Aluminized long-duration balloons floating as reflectors.
- To loft a payload under the balloon, in which case the additional mass of the balloon and its gas would be a weight penalty.
- To mix H_2 and H_2S inside a balloon. Maximize the ratio of H_2S to H_2, while still maintaining a buoyancy of 20%, standard for weather balloons. When the balloons burst the H_2S is released into the stratosphere.

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Large H_2 balloons lofting Al_2O_3 dust were also evaluated by the National Academy of Sciences (1992).

The annual cost to inject 1 Tg into the stratosphere, including balloons, dust, dust dispenser equipment, hydrogen, stations, and personnel, was also estimated to be $20,000,000,000. The cost of hot air balloon systems would be 4 to 10 times that of H_2 balloons.

"The fall of collapsed balloons might be an annoying form of trash rain."

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Plastic balloons (rather than rubber) would be required to get through the cold tropical tropopause or into the cold Arctic stratosphere without breaking. The largest standard weather balloon available is model number SF4-0.141-.3/0-T from Aerostar International, available in quantities of 10 or more for $1,711 each. I called, and there is currently no discount for very large numbers, but I am sure this could be negotiated. Each balloon has a mass of 11.4 kg. To fill it to the required buoyancy, would produce a mixture of 38.5% H_2, 61.5% H_2S, for a total mass of H_2S of 93.7 kg. The balloons would burst at 25 mb.

To put 1 Tg gas into stratosphere	**37,000**	**balloons per day**
	9,000,000	**balloons per year**
Total (balloons only)	**$16,000,000,000**	**per year**
	100,000,000	**kg (0.1 Tg) plastic per year**

According to NAS (1992), the additional costs for infrastructure, personnel, and H_2 would be $3,600,000,000 per year.

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To inject 1 Tg S (as H_2S) into the lower stratosphere per year

Method	Maximum Payload	Ceiling (km)	# of Units	Price per unit (2007 dollars)	Total Purchase Price (2008 dollars)	Annual Operation Costs
F-15C Eagle	8 tons	20	167 planes 3 flights/day	$38,100,000	**$6,362,700,000** but there are already 522	**$4,175,000,000***
KC-135 Strato-tanker	91 tons	15	15 planes 3 flights/day	$50,292,000	**$755,000,000** but there are already more than 481, and they will become surplus	**$375,000,000**
KC-10 Extender	160 tons	13	9 planes 3 flights/day	$112,000,000	**$1,000,000,000** but there are already 59	**$225,000,000***
~~Balloons~~	4 tons	30	37,000 per day	$1,711		~~$30,000,000,000~~
~~Naval Rifles~~	500 kg	20	8,000 shots per day			~~$30,000,000,000~~

Conclusions

1. Using airplanes for geoengineering would not be costly, especially with existing military planes, but there are still questions about whether desirable aerosols could be created.
2. There are still many reasons not to do geoengineering.

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Crude estimates show it would cost a few billion dollars to build a system, cost a few billion dollars per year to operate, and take less than a decade to implement.

Is this inexpensive?

Some say “yes” compared to other government expenditures or oil company profits.

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- There is currently no way to do geoengineering. No means exist to inject aerosol precursors (gases).
- Even if we could get the gases up there, we do not yet understand how to produce particles of the appropriate size.
- Putting sulfur gases into the lower stratosphere with existing military planes would cost a few billion dollars per year per Tg S.

© New York Times
Henning Wagenbreth
Oct. 24, 2007

Robock, Alan, Allison B. Marquardt, Ben Kravitz, and Georgiy Stenchikov, 2009: The benefits, risks, and costs of stratospheric geoengineering. *Geophys. Res. Lett.*, **36**, L19703, doi:10.1029/2009GL039209.

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LETTER

Stratospheric aerosol injection tactics and costs in the first 15 years of deployment

Wake Smith[1] and Gernot Wagner[2]

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Keywords: solar geoengineering, albedo modification, solar radiation management, high-altitude aircraft

Abstract

We review the capabilities and costs of various lofting methods intended to deliver sulfates into the lower stratosphere. We lay out a future solar geoengineering deployment scenario of halving the increase in anthropogenic radiative forcing beginning 15 years hence, by deploying material to altitudes as high as ~20 km. After surveying an exhaustive list of potential deployment techniques, we settle upon an aircraft-based delivery system. Unlike the one prior comprehensive study on the topic (McClellan *et al* 2012 *Environ. Res. Lett.* 7 034019), we conclude that no existing aircraft design—even with extensive modifications—can reasonably fulfill this mission. However, we also conclude that developing a new, purpose-built high-altitude tanker with substantial payload capabilities would neither be technologically difficult nor prohibitively expensive. We calculate early-year costs of ~\$1500 ton^{-1} of material deployed, resulting in average costs of ~\$2.25 billion yr^{-1} over the first 15 years of deployment.
increasing by ~4000
would unlikely be a secret, given the need for thousands of flights annually by airliner-sized aircraft operating from an international array of bases.

For only an average of 0.75 Tg S yr^{-1}

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Technical and Financial Feasibility of Geoengineering using Aircraft

I. de Vries, M. Janssens, S. Hulshoff, DSE16.2, DSE18.11

Faculty of Aerospace Engineering, Delft University of Technology

CCSS Symposium Geoengineering: Feasibility, Risks, Alternatives
Utrecht University, The Netherlands

Dec 4, 2018

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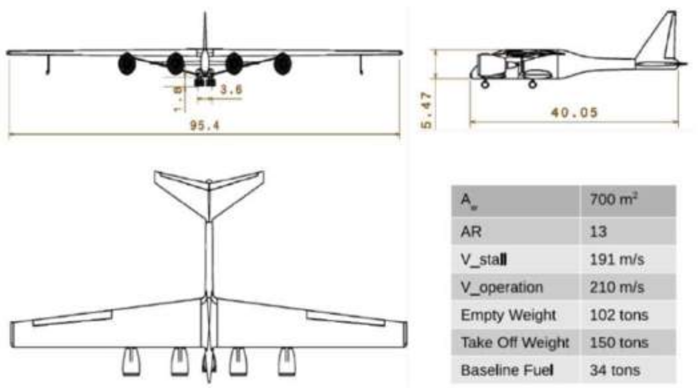
A feasible configuration



A_w	700 m^2
AR	13
V_stall	191 m/s
V_operation	210 m/s
Empty Weight	102 tons
Take Off Weight	150 tons
Baseline Fuel	34 tons

- Extreme design - high thrust, low payload/weight ratios
- Unmanned (avoids weight of complex pressurisation systems)
- New specialised high-altitude turbofan engines
  (Reduced fuel use/environmental impact relative to non-specialised designs)

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Injection Scenarios - H_2SO_4

- Delivery of 15 Mt-H_2SO_4 yr^{-1} (equivalent to 5 Mt-S yr^{-1} ~ -2.5W m^{-2})
- H_2SO_4 stored rather than its precursors *(conservative)*
- Injection into a single engine outflow to avoid undesirable interactions

Baseline: Core injection only, 10^2 m^2s^{-1} diffusivity (conservative)

Optimal: Bypass + core injection, 10^3 m^2s^{-1} diffusivity

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SO_2

- Delivery of 20 Mt-SO_2 yr^{-1} (equivalent to 10 Mt-S yr^{-1} ~ -2.5W m^{-2})
- Climb to 20km, delivery of payload as fast as possible (~ over 10km)
- Relies on natural convection/ H_2SO_4 /sulphate production

Impact Analysis - Summary

	H_2SO_4 Baseline	H_2SO_4 Optimised	SO_2
Delivery Altitudes	20-20.5 km	20-20.5 km	20 km
Delivery Radius	3400 km	53 km	10 km
Aerosol/Flight	6800 kg	29000 kg	29000 kg
Fleet Size	2400	233	286
Initial Cost	410 B	80 B	90 B
Operating Cost/yr	150 B	20 B	25 B
Initial CO_2eq	13 Mt	10 Mt	10 Mt
Operating CO_2eq/yr	370 Mt (0.74%)	25 Mt (0.05%)	30 Mt (0.06%)

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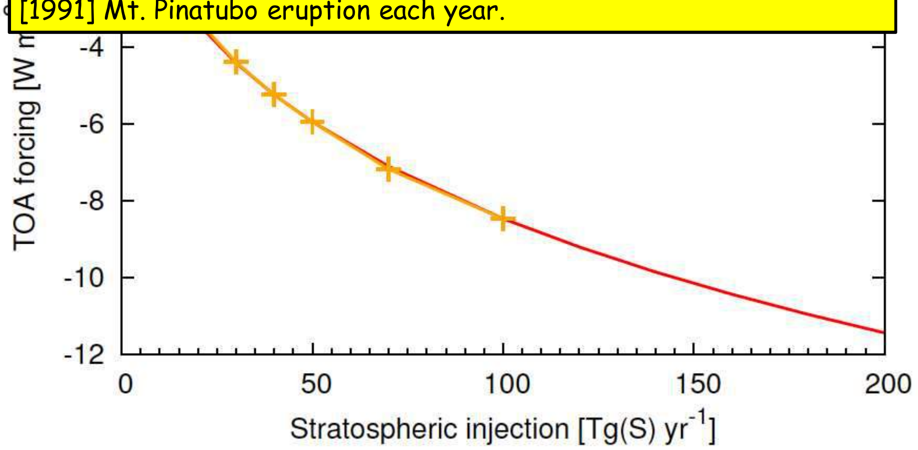
This result implies that the sulfate solar radiation management strategy required to keep temperatures constant at that anticipated for 2020, while maintaining business as usual conditions, would require atmospheric injections … equivalent to 5 to 7 times the [1991] Mt. Pinatubo eruption each year.



Niemeier, U. and C. Timmreck, 2015: What is the limit of climate engineering by stratospheric injection of SO_2?, *Atmos. Chem. Phys.*, **15**, 9129-9141, doi:10.5194/acp-15-9129-2015.

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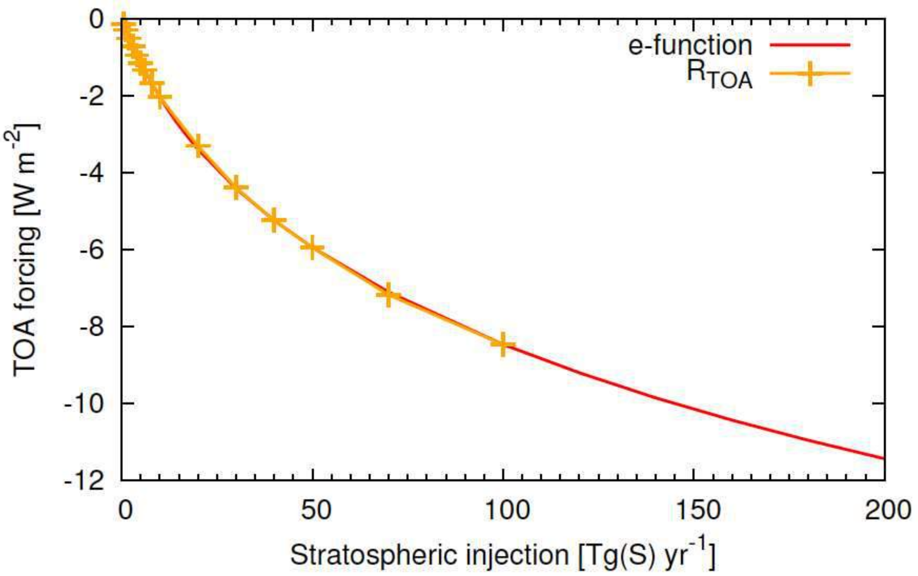

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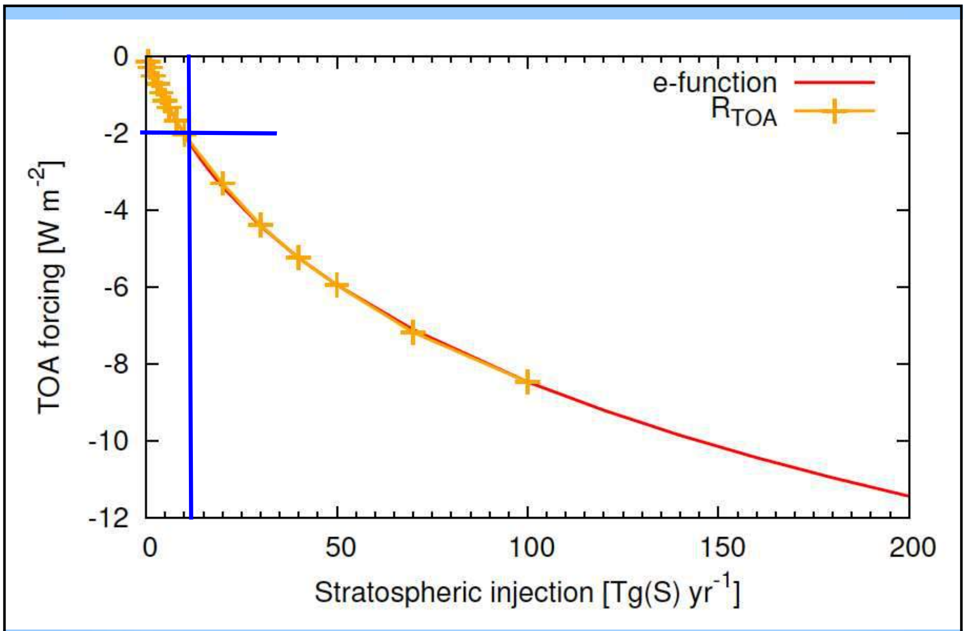

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To produce -2 W m^{-2} using sulfur would require 12 Tg (S) per year

H_2S (molecular weight 34 g/mole) gives 13 Tg (H_2S)

SO_2 (molecular weight 64 g/mole) gives 24 Tg (SO_2)

H_2SO_4 (molecular weight 98 g/mole) gives 37 Tg (H_2SO_4)

Cost per year in US $1,000,000,000 (billions of dollars)

	1 Tg/year	H_2S	SO_2	H_2SO_4
Robock et al. (2009)	4	**51**	**96**	**147**
McClellan et al. (2012)	1.5	**19**	**36**	**55**
Smith and Wagner (2018)	3	**38**	**72**	**110**
deVries et al. (2018)	6.4	**82**	**155**	**220**

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Reasons geoengineering may be a bad idea

Unknowns

✓12. Human error
✓13. Unexpected consequences (How well can we predict the expected effects of geoengineering? What about unforeseen effects?)

Political, ethical and moral issues

✓14. Schemes perceived to work will lessen the incentive to mitigate greenhouse gas emissions
✓15. Use of the technology for military purposes. Are we developing weapons?
✓16. Commercial control of technology
✓17. Violates UN Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques
X18. Could be tremendously expensive
✓19. Even if it works, whose hand will be on the thermostat? How could the world agree on the optimal climate?
✓20. Who has the moral right to advertently modify the global climate?

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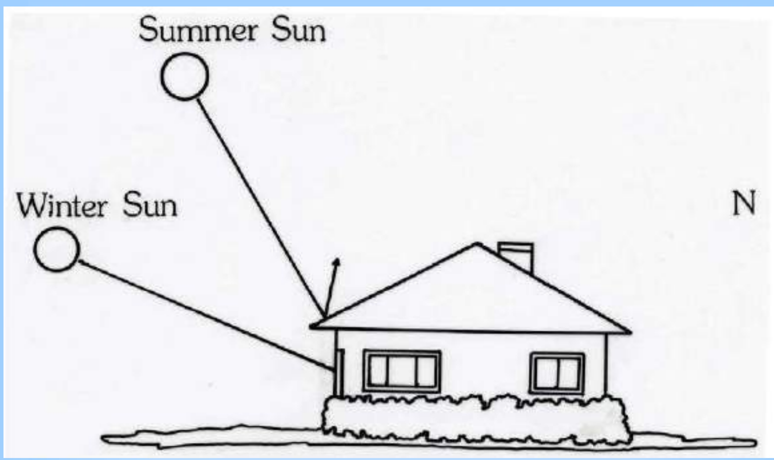
Passive solar homes require direct sunlight in winter.



ENERGY SMARTS: CHECKLIST TO DETERMINE ENERGY EFFICIENCY OF A HOME
Leona K. Hawks, Utah State University
http://www.builditsolar.com/Projects/SolarHomes/UtahExtFact_Sheet_3.pdf

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Conclusions

Of the 20 reasons why geoengineering may be a bad idea:

17 ✓ 2 X 1 ?

Since then I have added 9 more reasons:

✓It might mess up Earth-based optical astronomy.
✓It would affect nighttime stargazing.
✓It would mess up satellite remote sensing of Earth.
✓It would make passive solar heating work less well.
✓More sunburn from diffuse light and no sunscreen.
✓Effects on airplanes flying in stratosphere.
✓Effects on electrical properties of atmosphere.
✓Impacts on tropospheric chemistry.
✓Societal disruption, conflict between countries.

As of now, there are at least 26 reasons why geoengineering is a bad idea.

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Stratospheric Geoengineering

Benefits

1. Reduce surface air temperatures, which could reduce or reverse negative impacts of global warming, including floods, droughts, stronger storms, sea ice melting, land-based ice sheet melting, and sea level rise
2. Increase plant productivity
3. Increase terrestrial CO_2 sink
4. Beautiful red and yellow sunsets
5. Unexpected benefits

Each of these needs to be quantified so that society can make informed decisions.

Robock, Alan, 2008: 20 reasons why geoengineering may be a bad idea. *Bull. Atomic Scientists*, **64**, No. 2, 14-18, 59, doi:10.2968/064002006.

Robock, Alan, Allison B. Marquardt, Ben Kravitz, and Georgiy Stenchikov, 2009: The benefits, risks, and costs of stratospheric geoengineering. *Geophys. Res. Lett.*, **36**, L19703, doi:10.1029/2009GL039209.

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Risks

1. Drought in Africa and Asia
2. Perturb ecology with more diffuse radiation
3. Ozone depletion
4. Continued ocean acidification
5. Impacts on tropospheric chemistry
6. Whiter skies
7. Less solar electricity generation
8. Degrade passive solar heating
9. Rapid warming if stopped
10. Cannot stop effects quickly
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21. Degrade terrestrial optical astronomy
22. Affect stargazing
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24. More sunburn
25. Moral hazard – the prospect of it working would reduce drive for mitigation
26. Moral authority – do we have the right to do this?

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Being addressed by GeoMIP

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Volcanic analog

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26. Moral authority – do we have the right to do this?

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Stratospheric Geoengineering

Benefits

1. Cool planet
2. Reduce or reverse sea ice melting
3. Reduce or reverse ice sheet melting
4. Reduce or reverse sea level rise
5. Increase plant productivity
6. Increase terrestrial CO_2 sink
7. Beautiful red and yellow sunsets
8. Control of precipitation?
9. Unexpected benefits

Risks

1. Drought in Africa and Asia
2. Perturb ecology with more diffuse radiation
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IPCC
WG I
WG II
WG III

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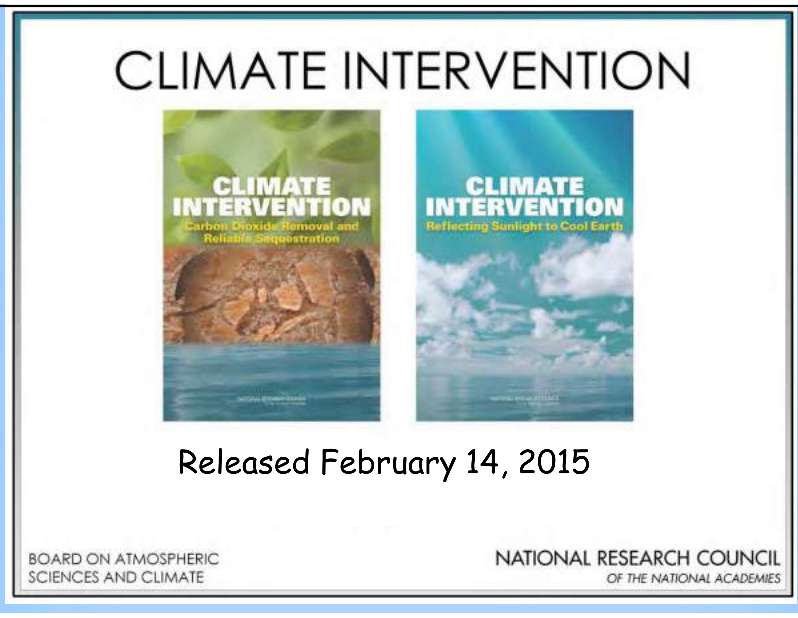

Sponsors: U.S. National Academy of Sciences, U.S. intelligence community, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, and U.S. Department of Energy

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THERE IS NO SUBSTITUTE FOR MITIGATION AND ADAPTATION

Recommendation 1:

Efforts to address climate change should continue to focus most heavily on
- **mitigating greenhouse gas emissions**
- **in combination with adapting to the impacts of climate change**

because these approaches
- **do not present poorly defined and poorly quantified risks and**
- **are at a greater state of technological readiness**

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WHY "CLIMATE INTERVENTION"?

There are several meanings to the term "geoengineering"

In general, the term "engineering" implies a more precisely tailored and controllable process than might be the case for climate interventions

Intervention is an action intended to improve a situation

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CARBON DIOXIDE REMOVAL READY FOR INCREASED RESEARCH AND DEVELOPMENT

Recommendation 2:

The Committee recommends research and development investment to

- **improve methods of carbon dioxide removal and disposal at scales that matter**

in particular to

- **minimize energy and materials consumption**
- **identify and quantify risks**
- **lower costs, and**
- **develop reliable sequestration and monitoring**

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ALBEDO MODIFICATION POSES SIGNIFICANT RISKS

Environmental risks – both known and poorly known

- Decreases in stratospheric ozone
- Changes in the amount and patterns of precipitation
- No reduction of root cause of climate change (greenhouse gases)
- Poorly understood regional variability
- Potential risk of millennial dependence

Significant potential for unanticipated, unmanageable, and regrettable consequences

- Including political, social, legal, economic, and ethical dimensions

Recommendation 3: Albedo modification at scales sufficient to alter climate should not be deployed at this time

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ALBEDO MODIFICATION RESEARCH

Research needed to determine if albedo modification could be viable climate response

- If there were a climate emergency
- Could it be key part of a portfolio of responses?

Better understanding of consequences needed if there were an action by a unilateral / uncoordinated actor

Recommendation 4:

The Committee recommends an albedo modification research program be developed and implemented that emphasizes multiple benefit research that furthers

- **basic understanding of the climate system**
- **and its human dimensions**

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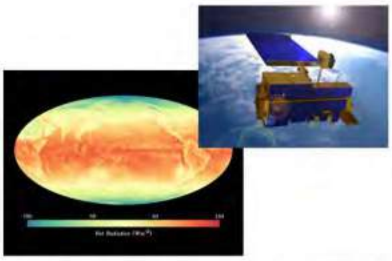
ALBEDO MODIFICATION RESEARCH

Current observational capabilities lack sufficient capacity to detect and monitor environmental effects of albedo modification deployment



Recommendation 5: The Committee recommends that the United States improve its capacity to detect and measure changes in radiative forcing and associated changes in climate

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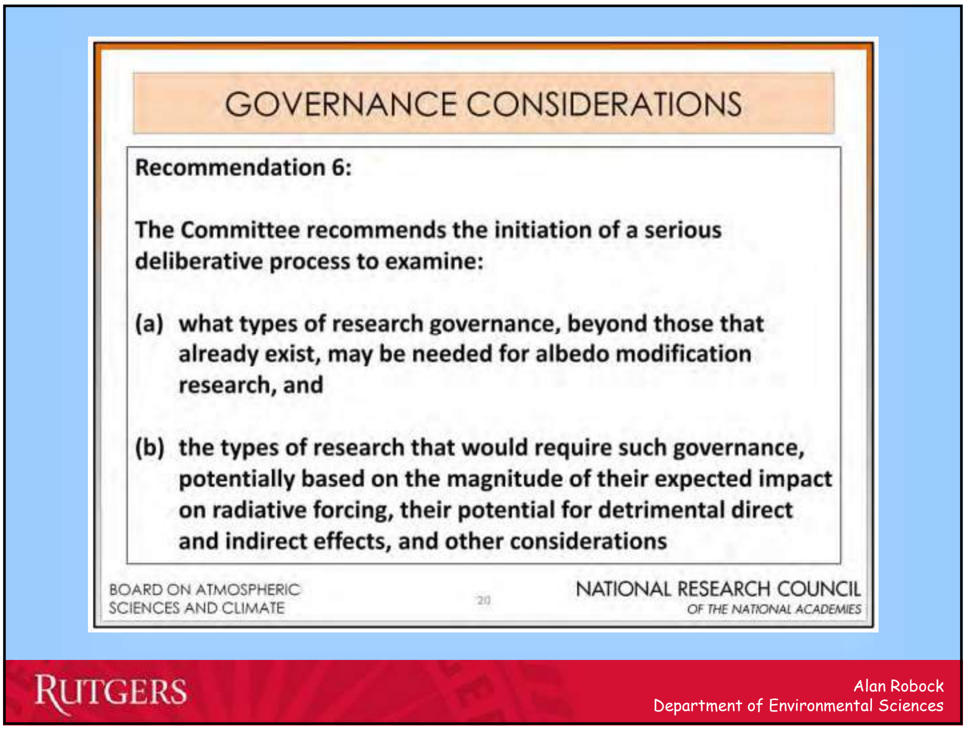
GOVERNANCE CONSIDERATIONS
Recommendation 6:
The Committee recommends the initiation of a serious deliberative process to examine:
(a) what types of research governance, beyond those that already exist, may be needed for albedo modification research, and
(b) the types of research that would require such governance, potentially based on the magnitude of their expected impact on radiative forcing, their potential for detrimental direct and indirect effects, and other considerations
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Good resource:
Solar Radiation Management Governance Initiative (2011), Solar Radiation Management: The Governance of Research.
http://www.srmgi.org/files/2016/02/SRMGI.pdf
Appendix 3: Analysis of existing international organisations and treaties potentially relevant to SRM research
http://www.srmgi.org/files/2016/02/Appendix-3-SRMGI-The-Governance-of-Research.pdf
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Not testable with modeling or the volcanic analog

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Risks

1. Drought in Africa and Asia
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3. Ozone depletion
4. Continued ocean acidification
5. Will not stop ice sheets from melting
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Robock, Alan, 2016: Albedo enhancement by stratospheric sulfur injection: More research needed. *Earth's Future*, **4**, 644-648, doi:10.1002/2016EF000407.

Risks or Concerns

Physical and biological climate system

1. Drought in Africa and Asia
2. Perturb ecology with more diffuse radiation
3. Ozone depletion
4. Continued ocean acidification
5. May not stop ice sheets from melting
6. Impacts on tropospheric chemistry
7. Rapid warming if stopped

Human impacts

8. Less solar electricity generation
9. Degrade passive solar heating
10. Effects on airplanes flying in stratosphere
11. Effects on electrical properties of atmosphere
12. Affect satellite remote sensing
13. Degrade terrestrial optical astronomy
14. More sunburn
15. Environmental impact of implementation

Esthetics

16. Whiter skies
17. Affect stargazing

Unknowns

18. Human error during implementation
19. Unexpected consequences

Governance

20. Cannot stop effects quickly
21. Commercial control
22. Whose hand on the thermostat?
23. Societal disruption, conflict between countries
24. Conflicts with current treaties
25. Moral hazard – the prospect of it working could reduce drive for mitigation

Ethics

26. Military use of technology
27. Moral authority – do we have the right to do this?

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Risks or Concerns

Physical and biological climate system

1. Drought in Africa and Asia
2. Perturb ecology with more diffuse radiation
3. Ozone depletion
4. Continued ocean acidification
5. Additional acid rain and snow
6. May not stop ice sheets from melting
7. Impacts on tropospheric chemistry
8. Rapid warming if stopped

Human impacts

9. Less solar electricity generation
10. Degrade passive solar heating
11. Effects on airplanes flying in stratosphere
12. Effects on electrical properties of atmosphere
13. Affect satellite remote sensing
14. Degrade terrestrial optical astronomy
15. More sunburn
16. Environmental impact of implementation

Esthetics

17. Whiter skies
18. Affect stargazing

Unknowns

19. Human error during implementation
20. Unexpected consequences

Governance

21. Cannot stop effects quickly
22. Commercial control
23. Whose hand on the thermostat?
24. Societal disruption, conflict between countries
25. Conflicts with current treaties
26. Moral hazard – could reduce drive for mitigation

Ethics

27. Military use of technology
28. Moral authority – do we have the right to do this?

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The ENMOD Treaty

UN Documents
Gathering a body of global agreements

Home | Sustainable Development | Education | Water | Culture of Peace | Human Rights | Keywords | Search

Adopted by *Resolution 31/72* of the United Nations General Assembly on 10 December 1976.

The Convention was opened for signature at Geneva on 18 May 1977.

Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques

"Each State Party to this Convention undertakes not to engage in military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage or injury to any other State Party."

RUTGERS http://www.un-documents.net/enmod.htm

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Confronting the Crisis of Global Governance

Report of the Commission on Global Security, Justice & Governance, June 2015

5.3.1.5 Establish a Climate Engineering Advisory Board and Experiments Registry

Climate engineering experiments should be subject to careful scrutiny, especially those involving solar radiation or albedo management techniques. All such experiments should be subject to review and approval by an expert advisory board attached to the new Climate Research Registry (see 5.3.1.4) and UN Member States should agree to treat its decisions as binding, in the common interest; an appeals board would also be desirable. All atmospheric research involving solar radiation management should be considered human subject experimentation insofar as its intent is to affect the living conditions of people and, even if conducted over uninhabited places, experimental effects could carry into populated areas. Approval should be conditioned on best available evidence and modeling indicating that expected transboundary effects are minimal. Experiments with purposeful transboundary impacts, where scientifically warranted, should also require the formal approval of the nations affected.

Carbon sequestration technologies could have a different threshold of action triggering oversight from the proposed advisory board because the effects of smaller experiments could be quite localized. Larger experiments, or those involving direct extraction of CO_2 from the atmosphere, should be presented to the advisory board.

All approved projects should be entered into a Climate Engineering Experiments Registry—a special track of the Climate Research Registry.

Commission on GLOBAL SECURITY JUSTICE & GOVERNANCE

http://www.stimson.org/images/uploads/research-pdfs/Commission_on_Global_Security_Justice%20_Governance.pdf

The Hague Institute for Global Justice

STIMSON

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American Meteorological Society and American Geophysical Union Policy Statement on Geoengineering

"The AMS and AGU recommend:

- "Enhanced research on the scientific and technological potential for geoengineering the climate system, including research on intended and unintended environmental responses.
- "Coordinated study of historical, ethical, legal, and social implications of geoengineering that integrates international, interdisciplinary, and intergenerational issues and perspectives and includes lessons from past efforts to modify weather and climate.
- "Development and analysis of policy options to promote transparency and international cooperation in exploring geoengineering options along with restrictions on reckless efforts to manipulate the climate system."

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A well-funded national or international research program, as part of the currently ongoing Intergovernmental Panel on Climate Change Fifth Scientific Assessment, would be able to look at several other aspects of geoengineering and provide valuable guidance to policymakers trying to decide how best to address the problems of global warming.

We currently lack the capability to monitor the evolution and distribution of stratospheric aerosol clouds. A robust space-based observing system would allow monitoring future volcanic eruptions or any geoengineering experiments.

Robock, Alan, 2008: Whither geoengineering? *Science*, **320**, 1166-1167.

Testing SRM in the stratosphere at less than full-scale will not allow the evaluation of cloud creation in the presence of a cloud nor of the climate response to the cloud.

Robock, Alan, Martin Bunzl, Ben Kravitz, and Georgiy Stenchikov, 2010: A test for geoengineering? *Science*, **327**, 530-531, doi:10.1126/science.1186237.

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Some advocate "small-scale" in situ cloud brightening or stratospheric injection experiments.

But what is "small-scale?" How large a region? For how long? How much material would be injected?

Until the governance issues are dealt with, the research needs to be limited to theoretical and laboratory work, with no in situ cloud brightening or stratospheric injection.

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If there will be a significant reduction of Asian monsoon precipitation, how will this affect food production?

Reduced precipitation will be countered by two factors which would increase plant growth: increased CO_2 and increased fraction of diffuse radiation.

This needs studies with agricultural experts and models, driven by climate change scenarios from the standardized runs.

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The World's Largest Crops

China is largely self-sufficient in food production and doesn't export much. But it produces and consumes some of the world's largest crops by far. And if recent droughts in China force the country to begin importing on a large scale, it could push the already rising prices of commodities like wheat even higher.

2009 PRODUCTION OF:

RICE	Millions of tons	World share
China	197	29%
India	131	19
Indonesia	64	9
Bangladesh	45	7
Vietnam	39	6
Thailand*	31	5
Myanmar*	31	4
Philippines	16	2
Brazil	13	2
Japan	11	2
Pakistan	10	2
United States	10	1

WHEAT		
China	115	17%
India	81	12
Russia	62	9
United States	60	9
France	38	6
Canada	27	4
Germany	25	4
Pakistan	24	4
Australia	22	3
Ukraine	21	3
Turkey	21	3
Kazakhstan	17	3

CORN		
United States	333	41%
China	163	20
Brazil	51	6
Mexico	20	2
Indonesia	18	2
India	17	2
France	15	2
Argentina	13	2
South Africa	12	1
Ukraine	10	1
Canada	10	1
Romania	8	1

Source: United Nations Food and Agriculture Organization *2008 production. THE NEW YORK TIMES

New York Times, February 9, 2011

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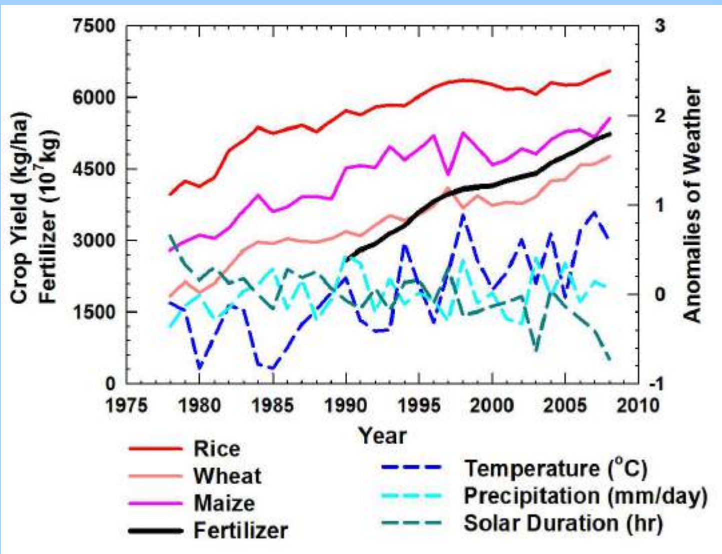
Yields of major crops and annual weather anomalies in mainland China



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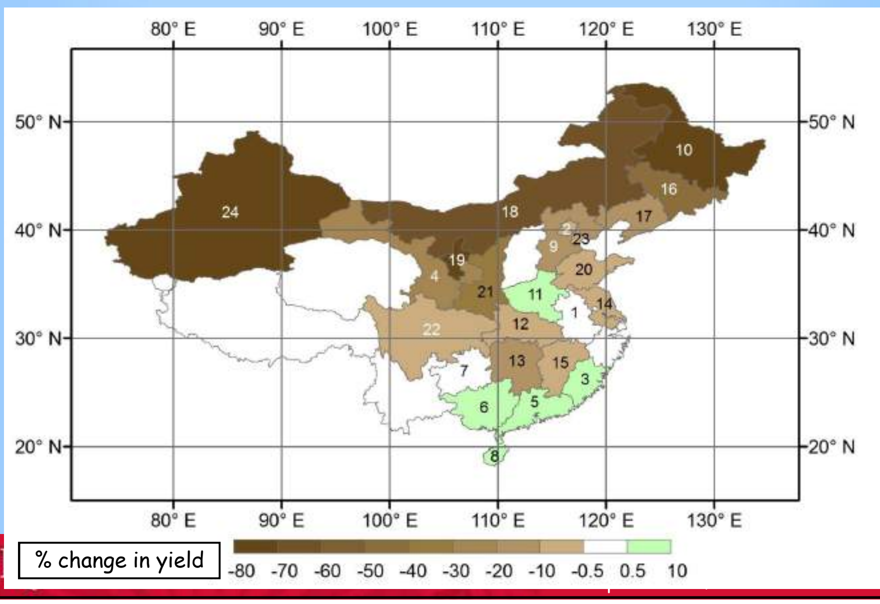
Using the DSSAT crop model, rice production in China would decrease 11±3% (13±4 Mt) in response to a 5 Tg SO_2 per year stratospheric injection, averaged over the second decade of geoengineering.



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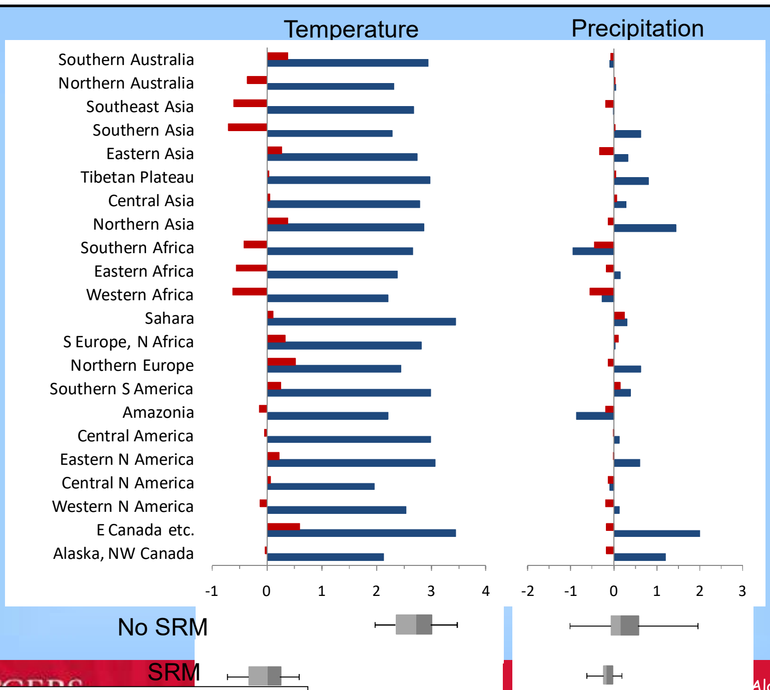

Moreno-Cruz, Ricke & Keith (2011)

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Conclusions

A well-funded national or international research program, as part of the currently ongoing Intergovernmental Panel on Climate Change Fifth Scientific Assessment, would be able to look at several other aspects of geoengineering and provide valuable guidance to policymakers trying to decide how best to address the problems of global warming.

Such research should include theoretical calculations as well as engineering studies. Small-scale experiments could examine nozzle properties and initial formation of aerosols, but they could not be used to test the climatic response of stratospheric aerosols.

We currently lack the capability to monitor the evolution and distribution of stratospheric aerosol clouds. A robust space-based observing system would allow monitoring future volcanic eruptions or any geoengineering experiments.

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Reasons mitigation is a good idea

Proponents of geoengineering say that mitigation is not possible, as they see no evidence of it yet. But it is clearly a political and not a technical problem.

Mitigation will not only reduce global warming but it will also

- reduce ocean acidification,
- reduce our dependence on foreign sources of energy,
- stop subsidizing terrorism with our gas dollars,
- reduce our military budget, freeing resources for other uses,
- clean up the air, and
- provide economic opportunities for a green economy, to provide solar, wind, cellulosic ethanol, energy efficiency, and other technologies we can sell around the world.

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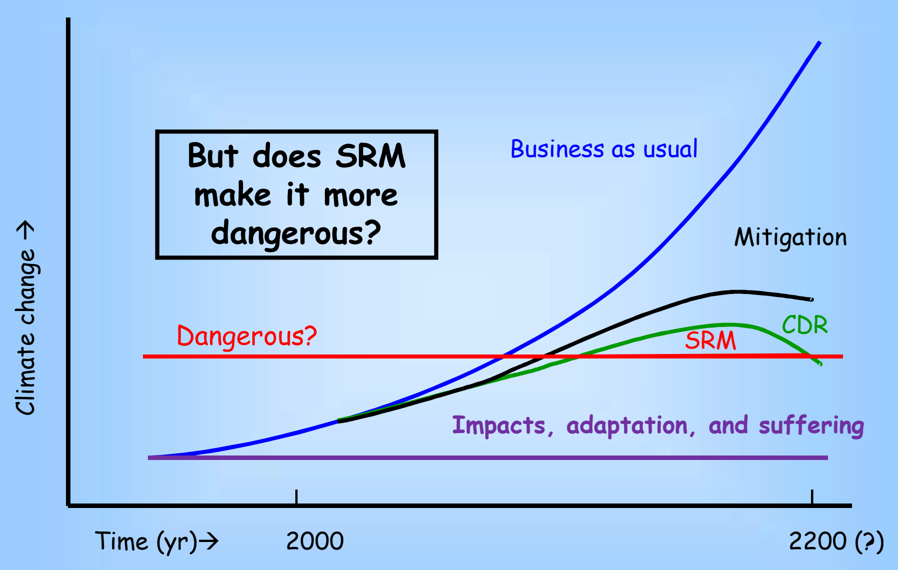

After John Shepherd's "napkin diagram"

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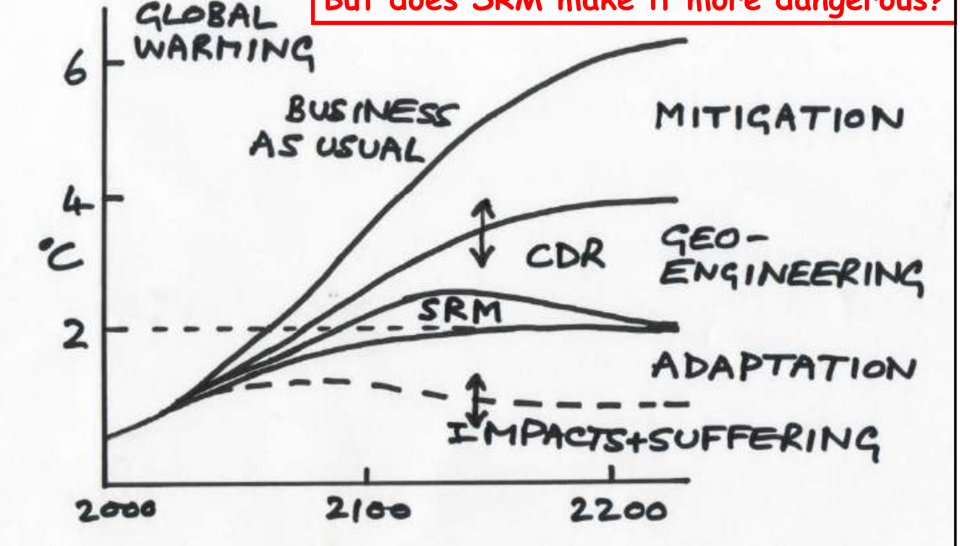
The Napkin Diagram

But does SRM make it more dangerous?



Long, Jane C. S., and John G. Shepherd, 2014: The Strategic Value of Geoengineering Research, Chapter 87 of *Global Environmental Change*, Bill Freedman (ed.), (Springer, Dordrecht), 757-770, doi:10.1007/978-94-007-5784-4_24.

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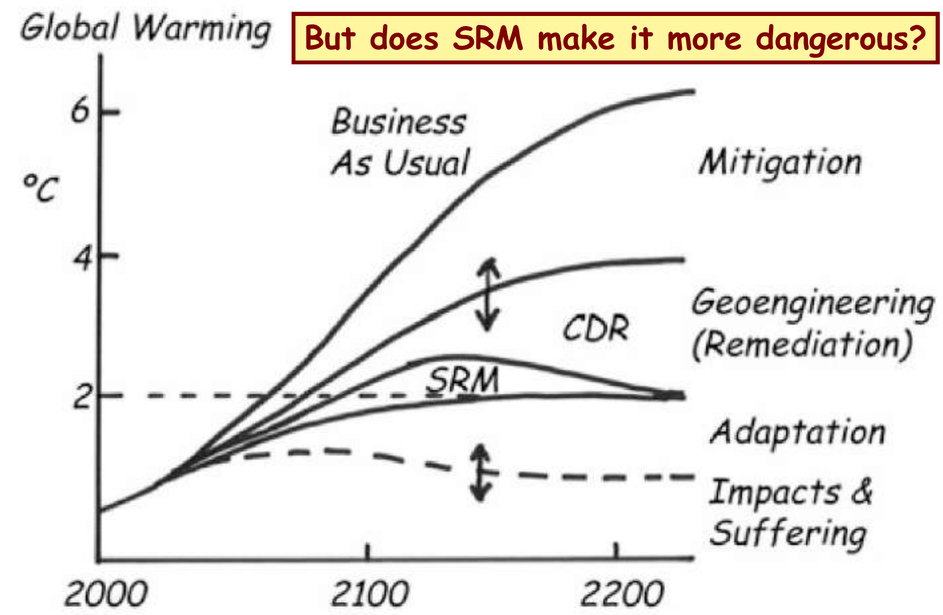
But does SRM make it more dangerous?



Long, Jane C. S., and John G. Shepherd, 2014: The Strategic Value of Geoengineering Research, Chapter 87 of *Global Environmental Change*, Bill Freedman (ed.), (Springer, Dordrecht), 757-770, doi:10.1007/978-94-007-5784-4_24.

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The United Nations Framework Convention On Climate Change, 1992

Signed by 197 countries. Came into force in 1994.

Signed and ratified in 1992 by the United States

The ultimate objective of this Convention ... is 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.

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The UN Framework Convention on Climate Change thought of "dangerous anthropogenic interference" as due to the inadvertent effects on climate from anthropogenic greenhouse gases .

We now must include geoengineering in our pledge to "prevent dangerous anthropogenic interference with the climate system."

© New York Times, Henning Wagenbreth, Oct. 24, 2007

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London Sunset After Krakatau
4:40 p.m., Nov. 26, 1883
Watercolor by William Ascroft
Figure from Symons (1888)

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"The Scream"

Edvard Munch

Painted in 1893 based on Munch's memory of the brilliant sunsets following the 1883 Krakatau eruption.

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