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The Many Problems with Geoengineering Using Stratospheric Aerosols

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This work is done in collaboration with

Luke Oman and Georgiy Stenchikov

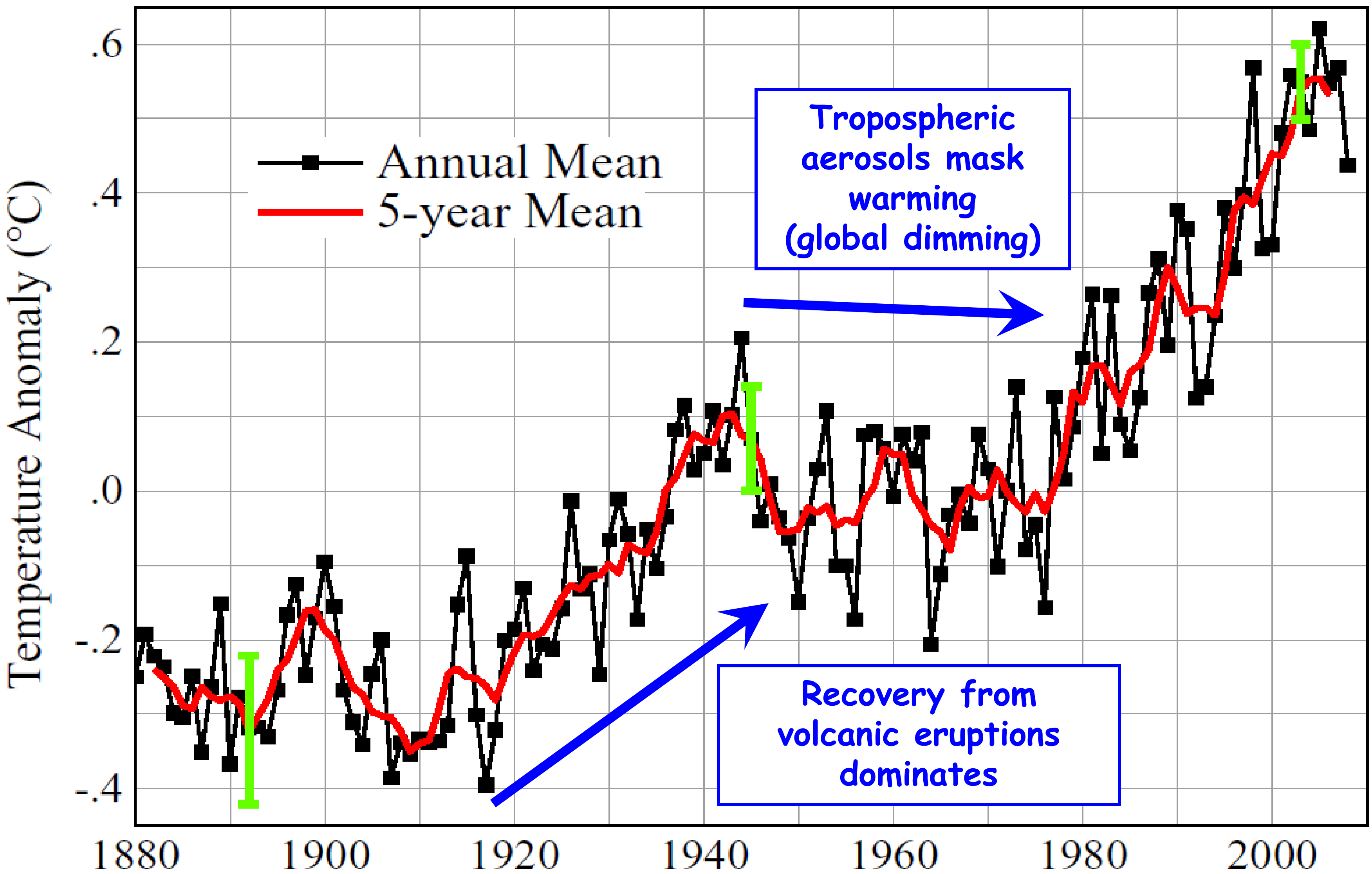
Johns Hopkins Rutgers University

Ben Kravitz and Allison Marquardt

Rutgers University

and supported by
NSF grant
ATM-0730452

Global Land-Ocean Temperature Index



http://data.giss.nasa.gov/gistemp/graphs/Fig.A2.pdf

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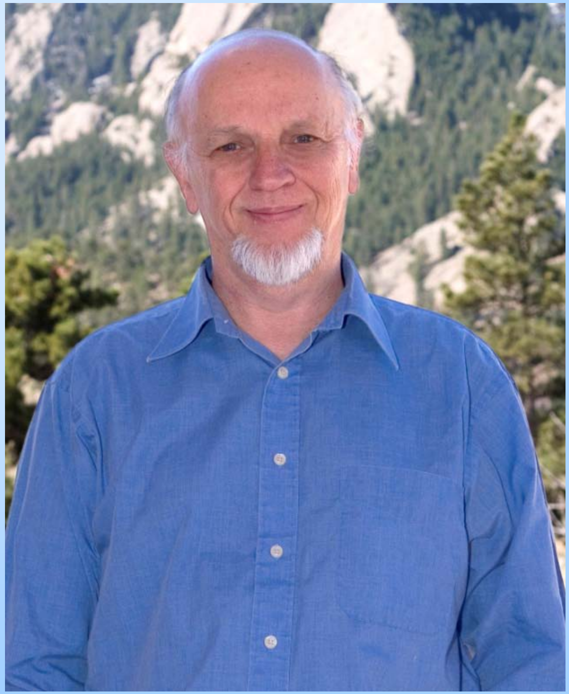
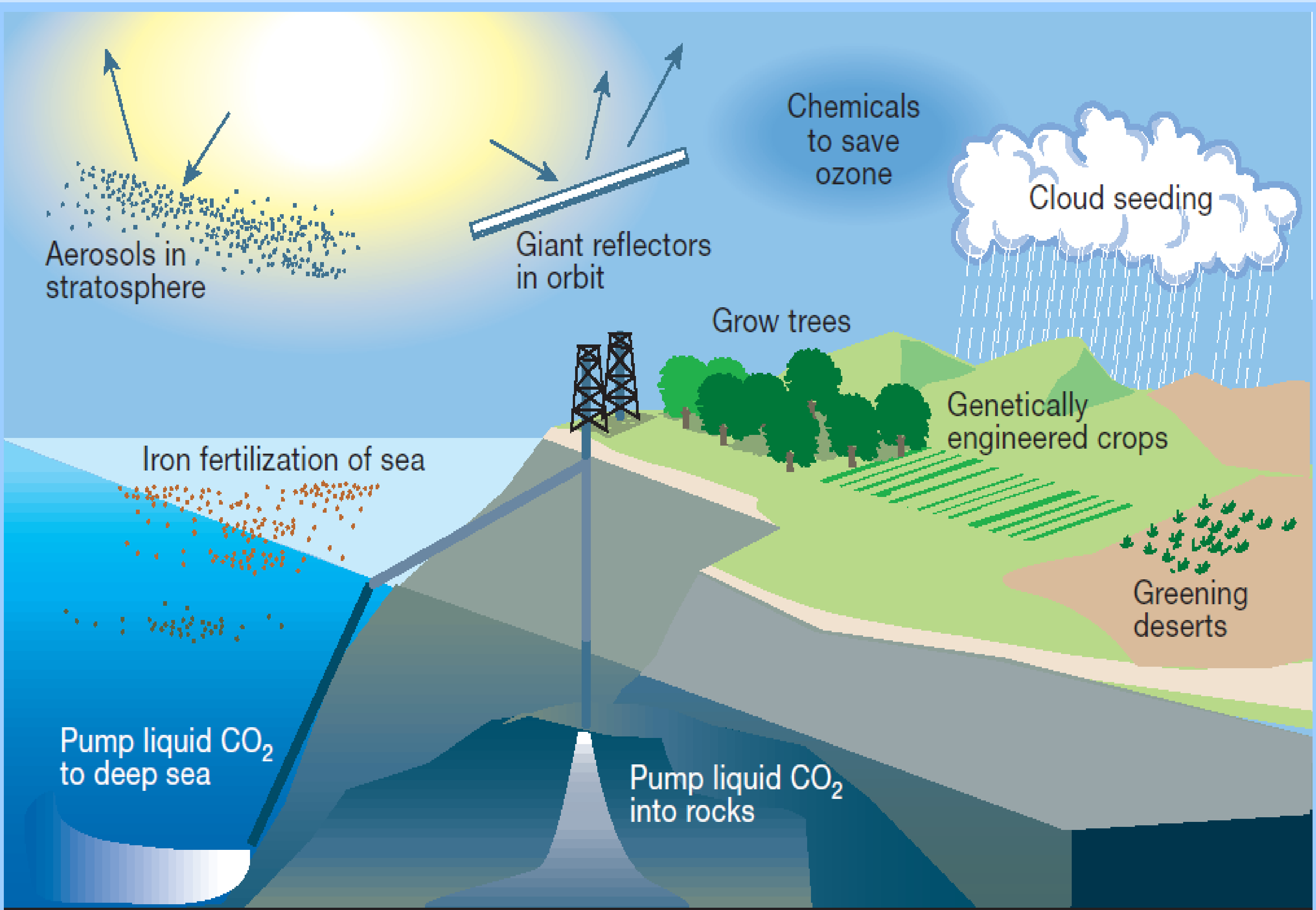
Despairing of prompt political response to global warming, in August and September 2006, **Paul Crutzen** (Nobel Prize in Chemistry) and **Tom Wigley** (NCAR) suggested that we consider temporary **geoengineering** as an emergency response.



Can Dr. Evil Save The World?

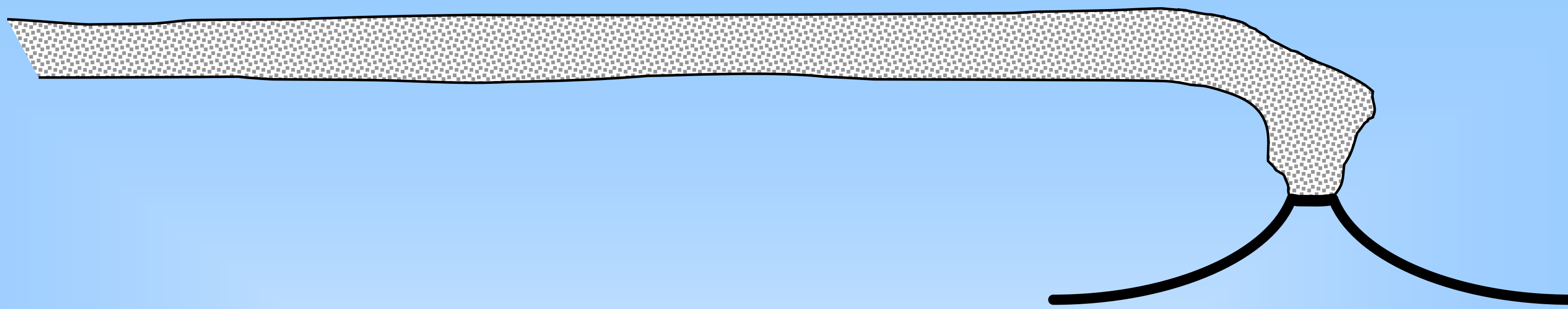
Forget about a future filled with wind farms and hydrogen cars. The Pentagon's top weaponeer says he has a radical solution that would stop global warming now -- no matter how much oil we burn.

Jeff Goodell
Rolling Stone
November 3, 2006



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

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



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

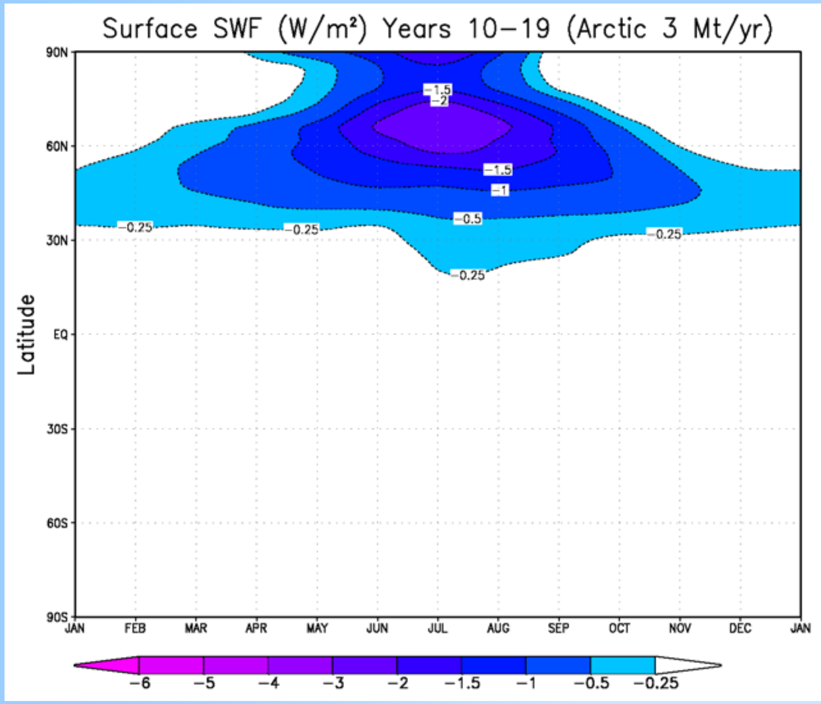
1. Inject them into the tropical stratosphere, where winds will spread them around the world and produce global cooling, like tropical volcanic eruptions have.
2. Inject them at high latitudes in the Arctic, where they will keep sea ice from melting, while any negative effects would not affect many people.

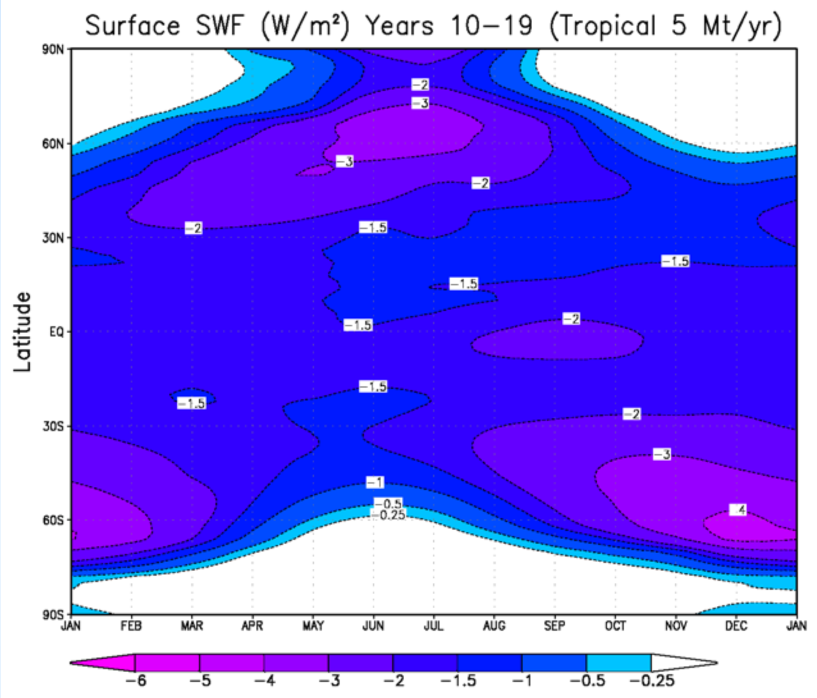
We conducted the following geoengineering simulations with the NASA GISS ModelE atmosphere-ocean general circulation model run at 4°x 5° horizontal resolution with 23 vertical levels up to 80 km, coupled to a 4°x 5° dynamic ocean with 13 vertical levels and an online chemistry and transport module:

- 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

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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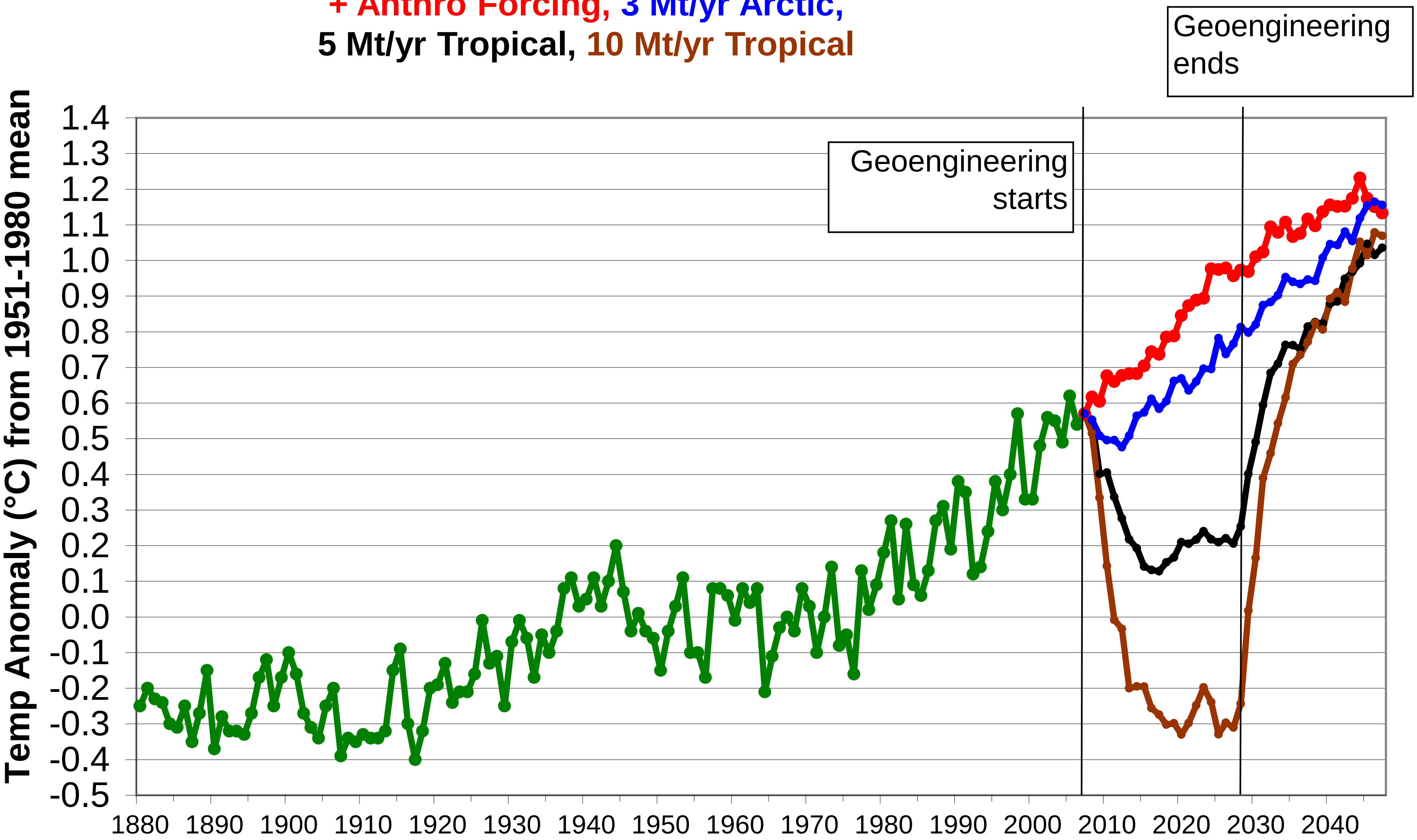
GISS Global Average Temperature Anomaly
+ Anthro Forcing, 3 Mt/yr Arctic,
5 Mt/yr Tropical, 10 Mt/yr Tropical



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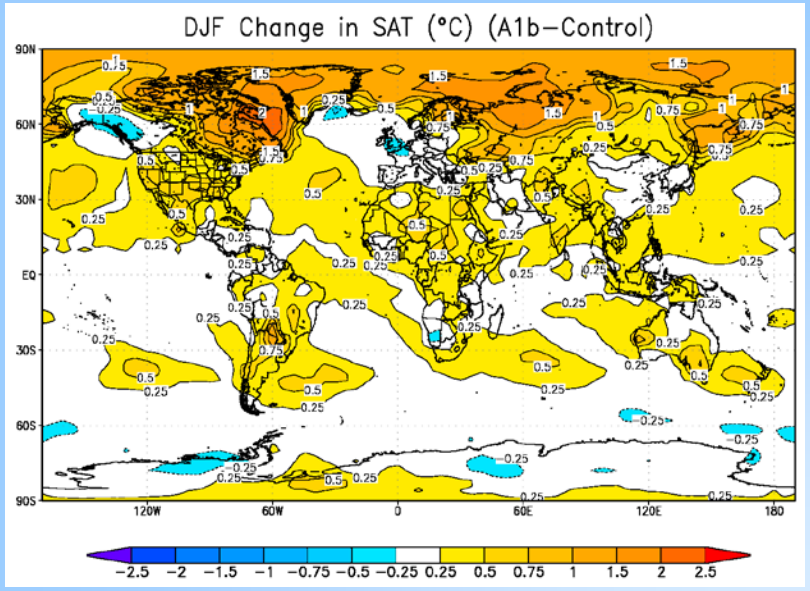
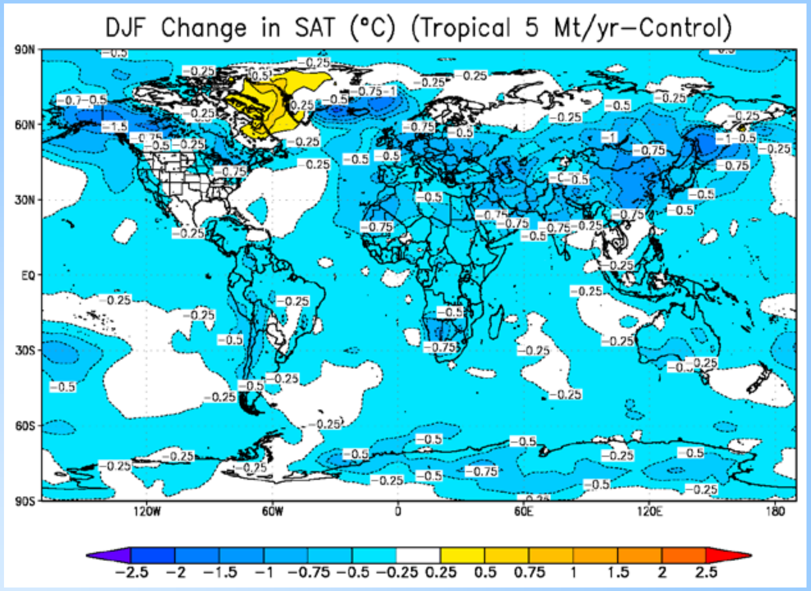
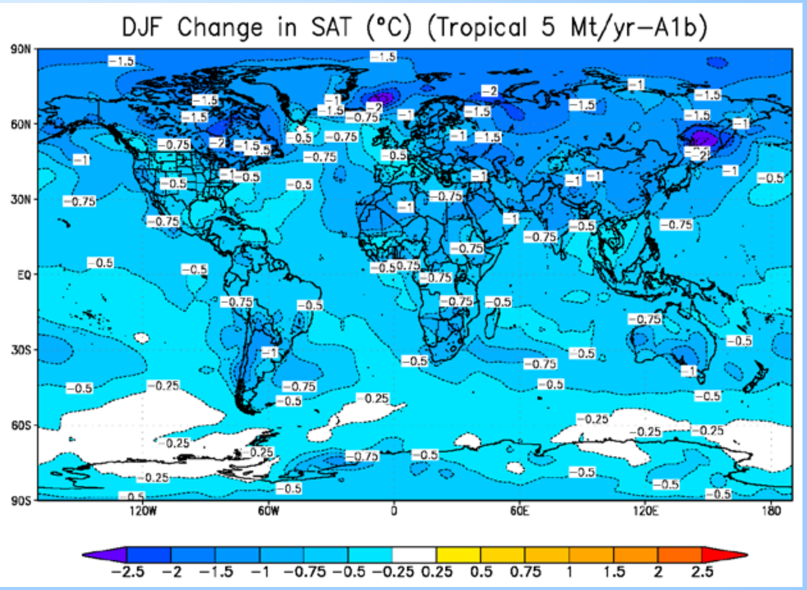
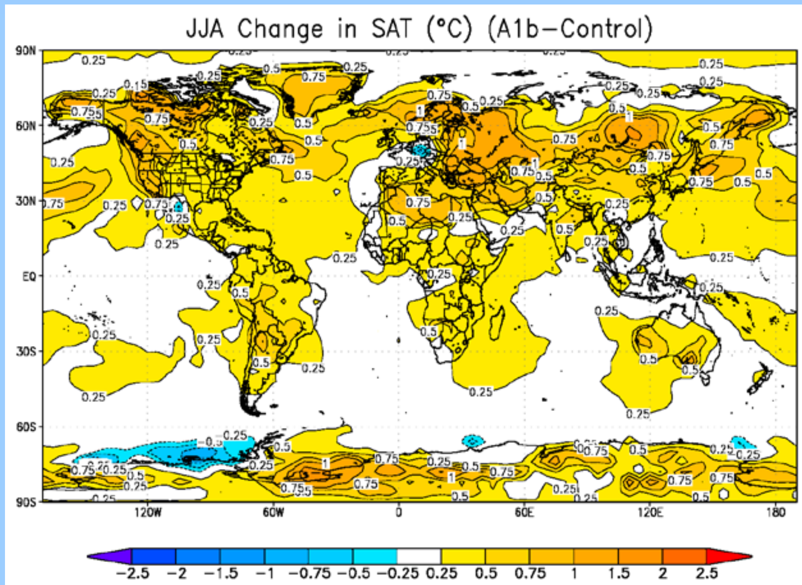
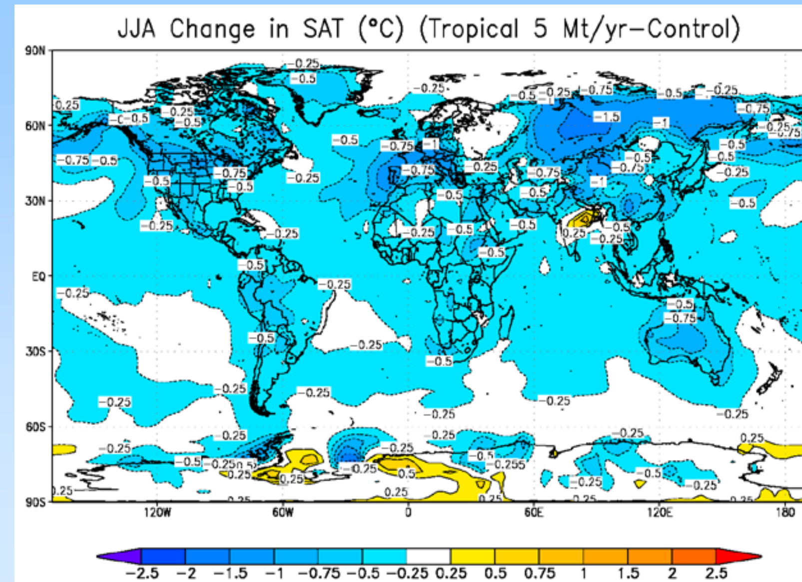




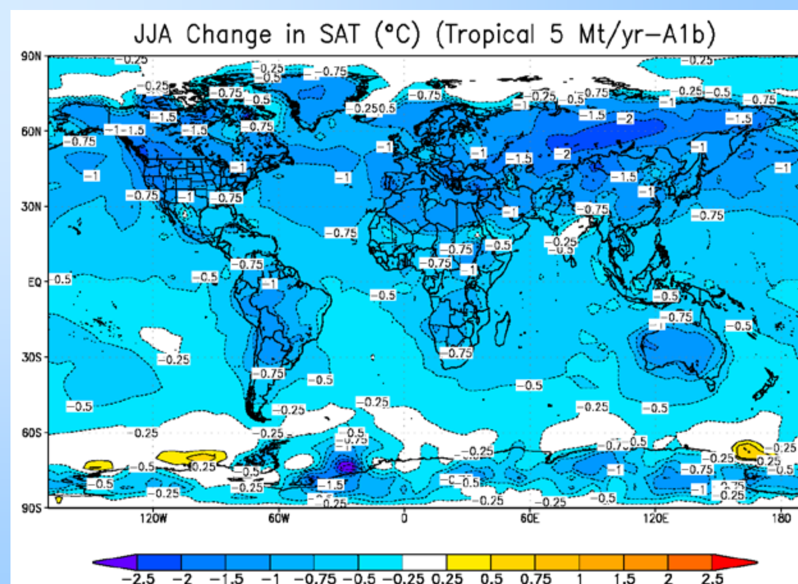
Mean response for second decade of aerosol injection for IPCC A1B + Tropical 5 Mt/yr case for NH winter surface air temperature







Mean response for second decade of aerosol injection for IPCC A1B + Tropical 5 Mt/yr case for NH summer surface air temperature



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Reducing solar radiation reduces precipitation

If we compensate for the increased downward longwave (heat) 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.

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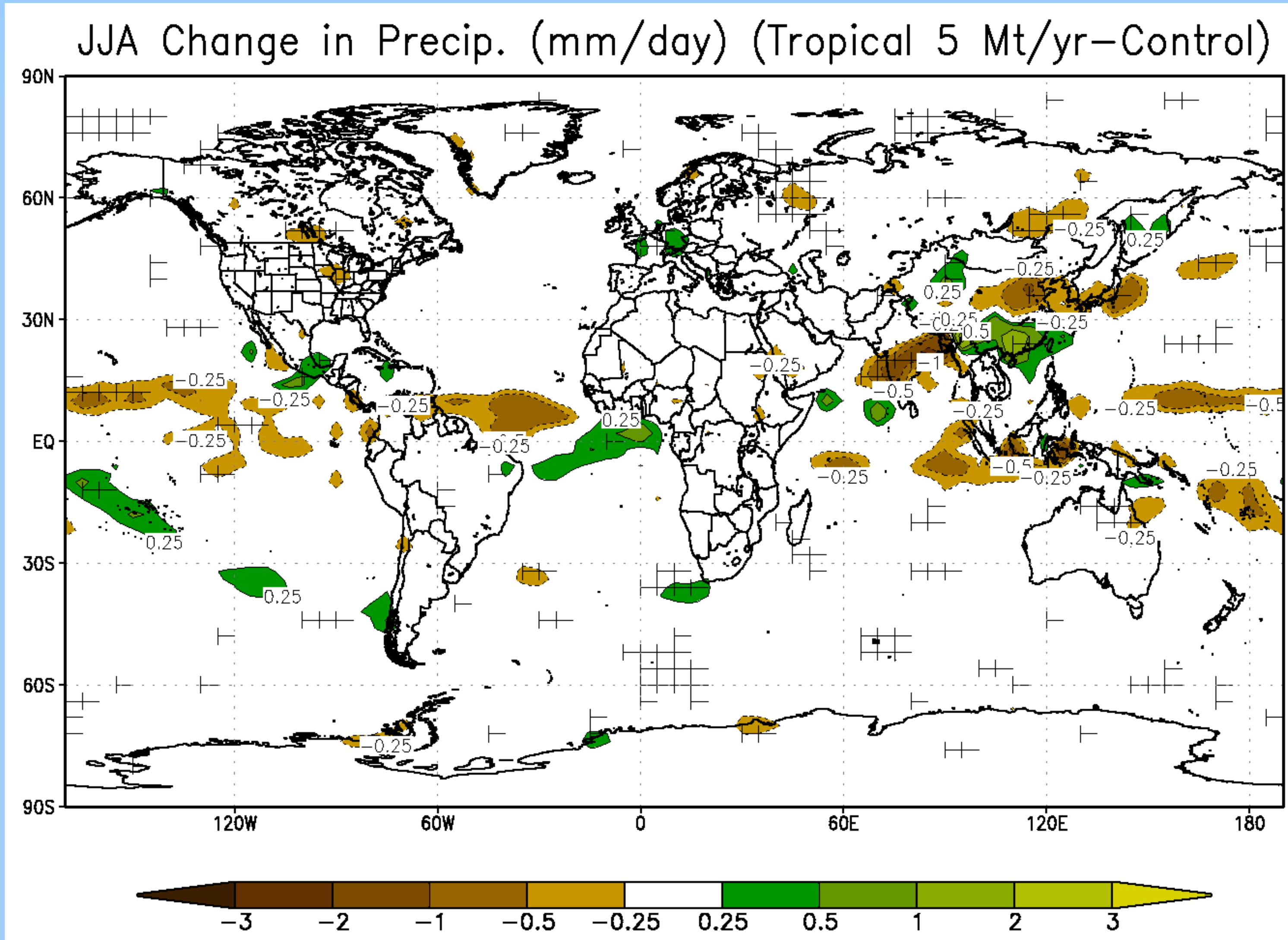

= significant at the 95% level

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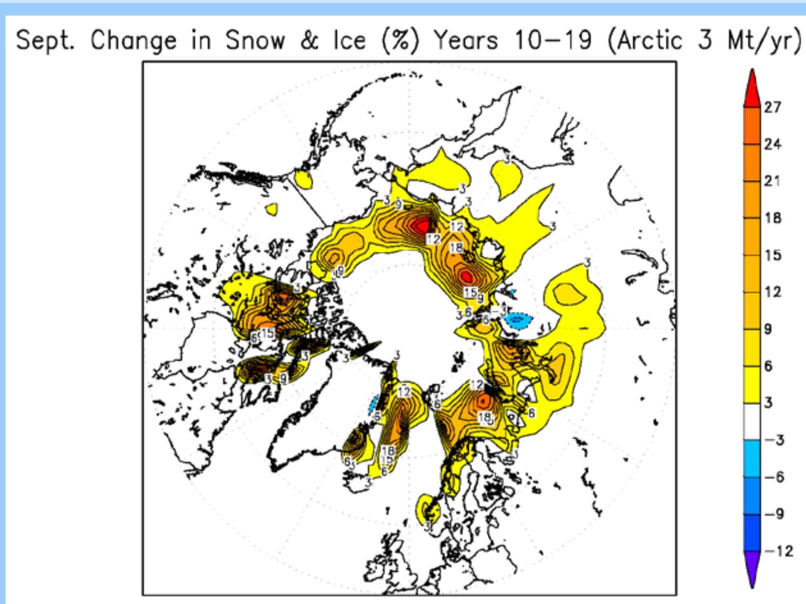

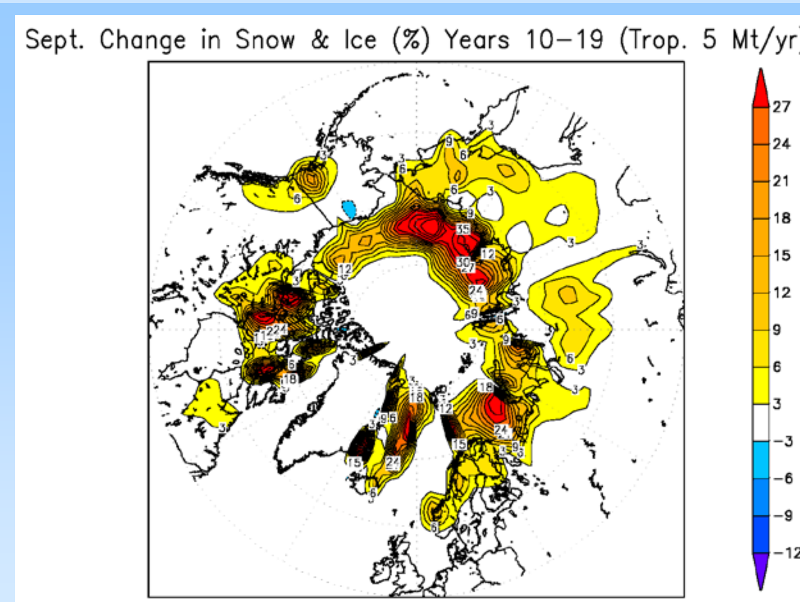

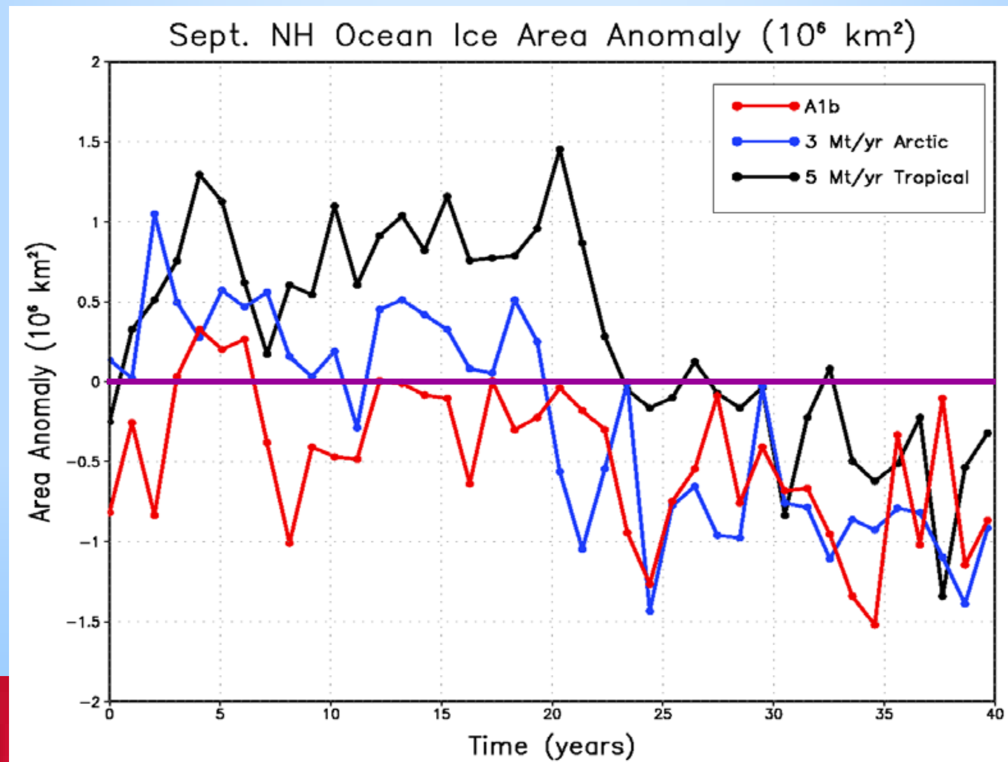

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Conclusions

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 would disrupt the Asian and African summer monsoons, reducing precipitation to the food supply for billions of people.

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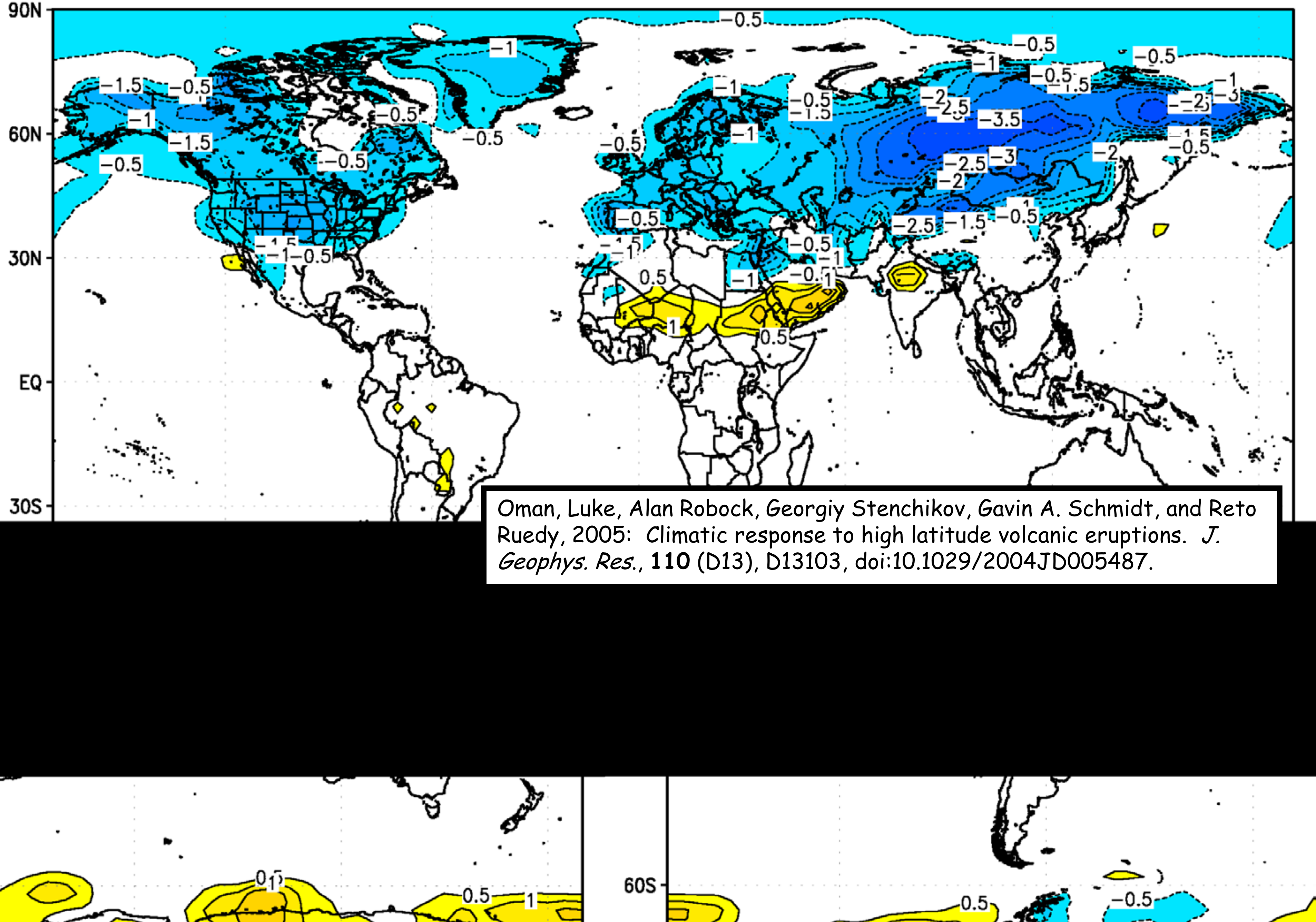
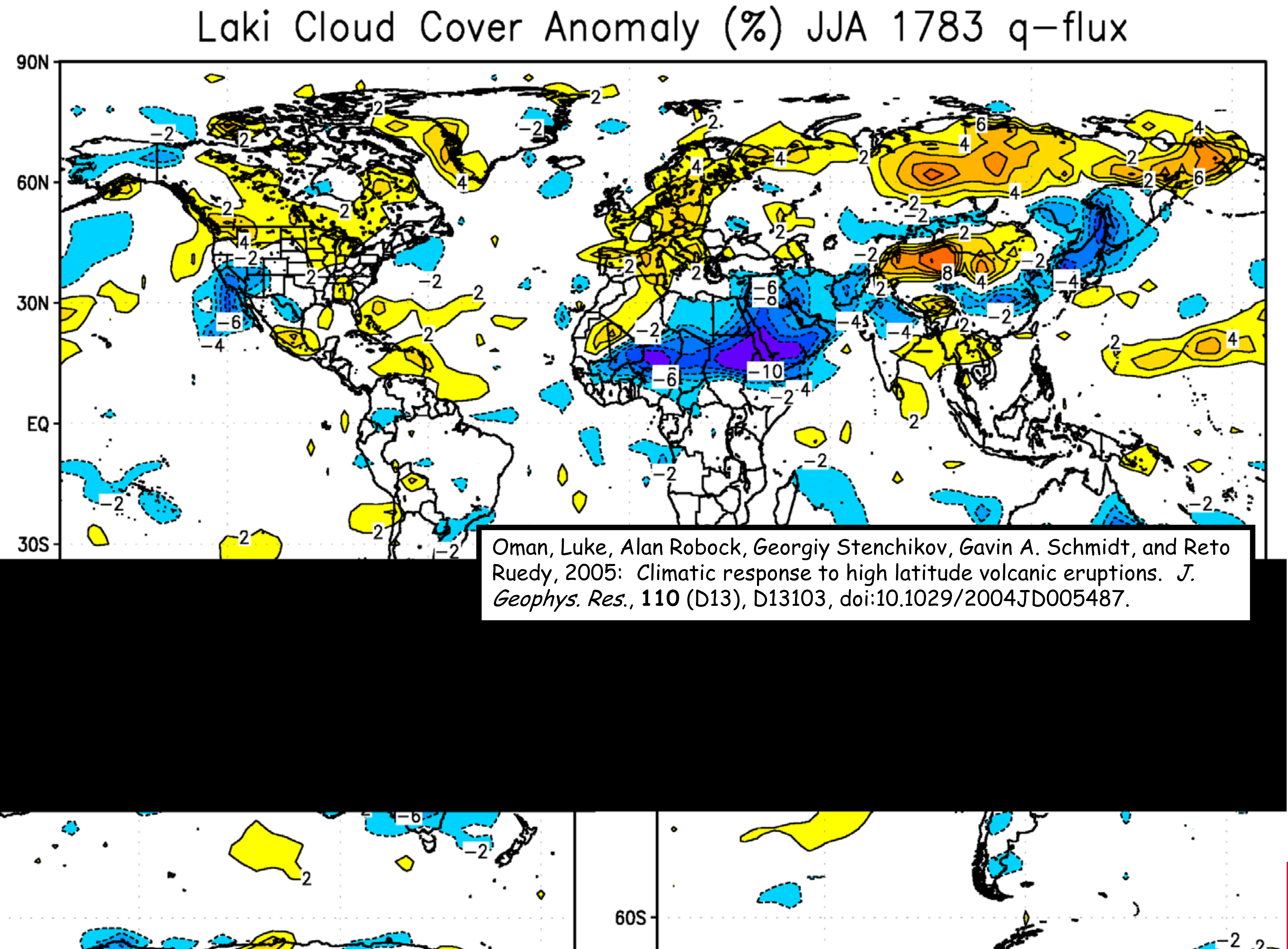
1783-84, Lakagígar (Laki), Iceland

Laki SAT Anomaly (°C) JJA 1783 q−flux



Oman, Luke, Alan Robock, Georgiy Stenchikov, Gavin A. Schmidt, and Reto Ruedy, 2005: Climatic response to high latitude volcanic eruptions. *J. Geophys. Res.*, **110** (D13), D13103, doi:10.1029/2004JD005487.



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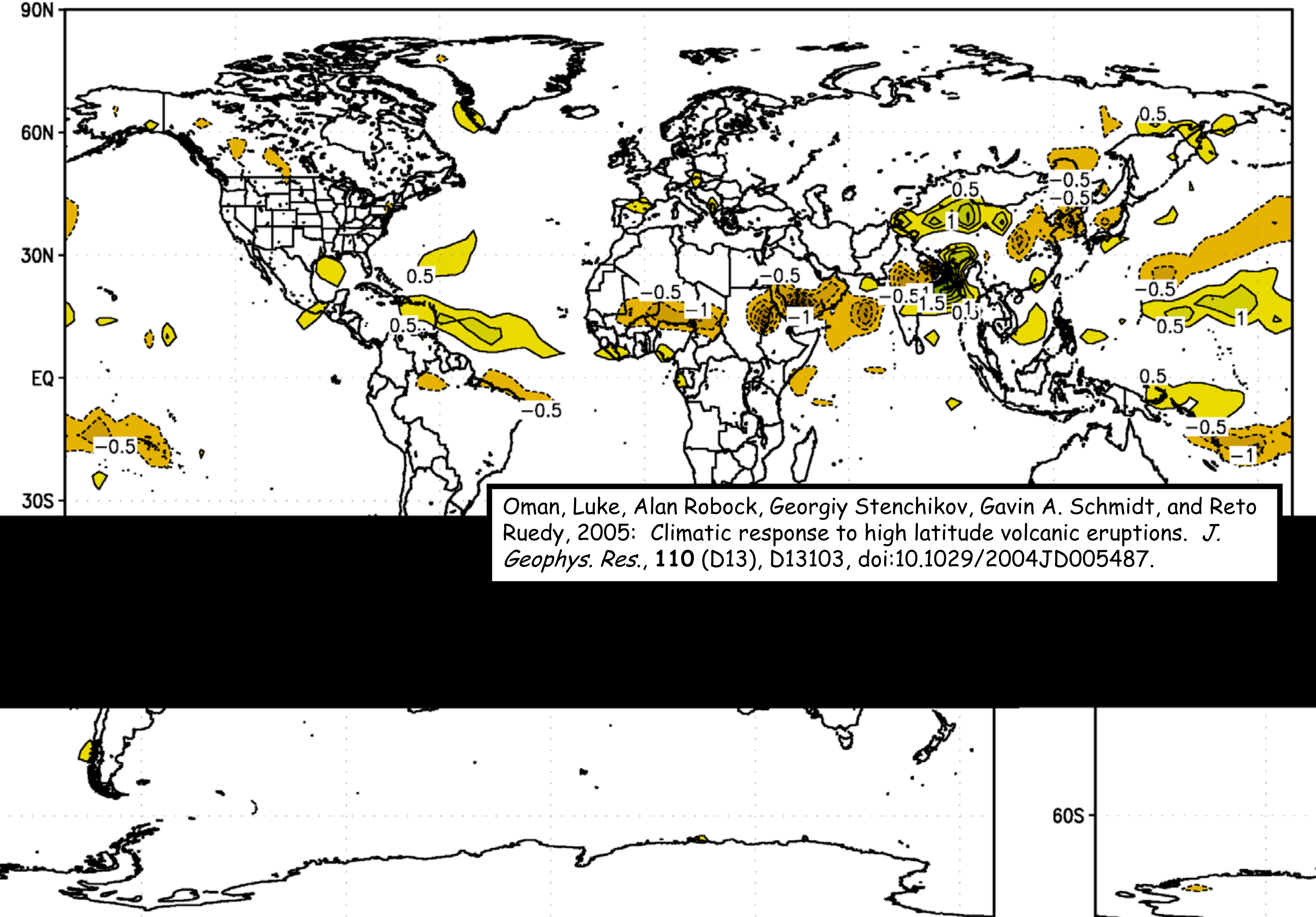
Laki Precip. Anomaly (mm/day) JJA 1783 q–flux



[redacted]

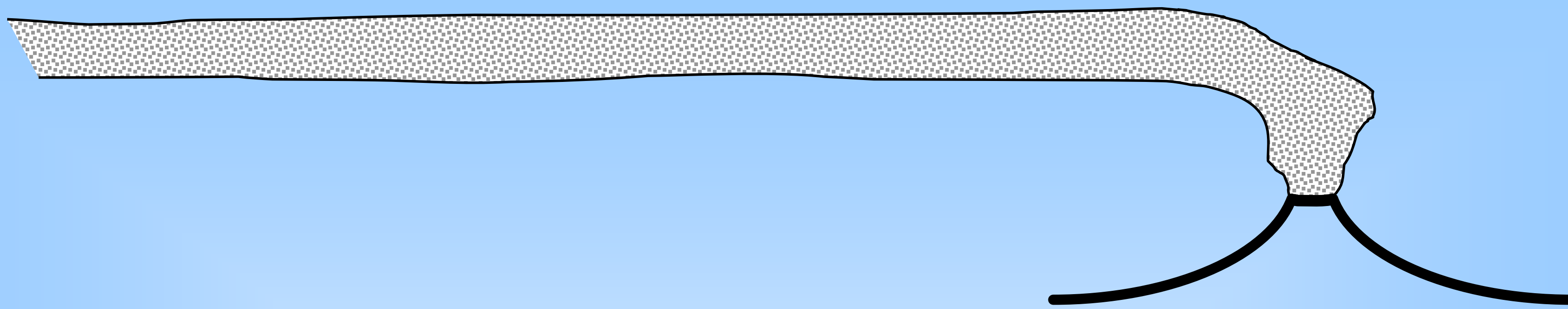
Oman, Luke, Alan Robock, Georgiy Stenchikov, Gavin A. Schmidt, and Reto Ruedy, 2005: Climatic response to high latitude volcanic eruptions. *J. Geophys. Res.*, **110** (D13), D13103, doi:10.1029/2004JD005487.

M. C-F. 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.

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



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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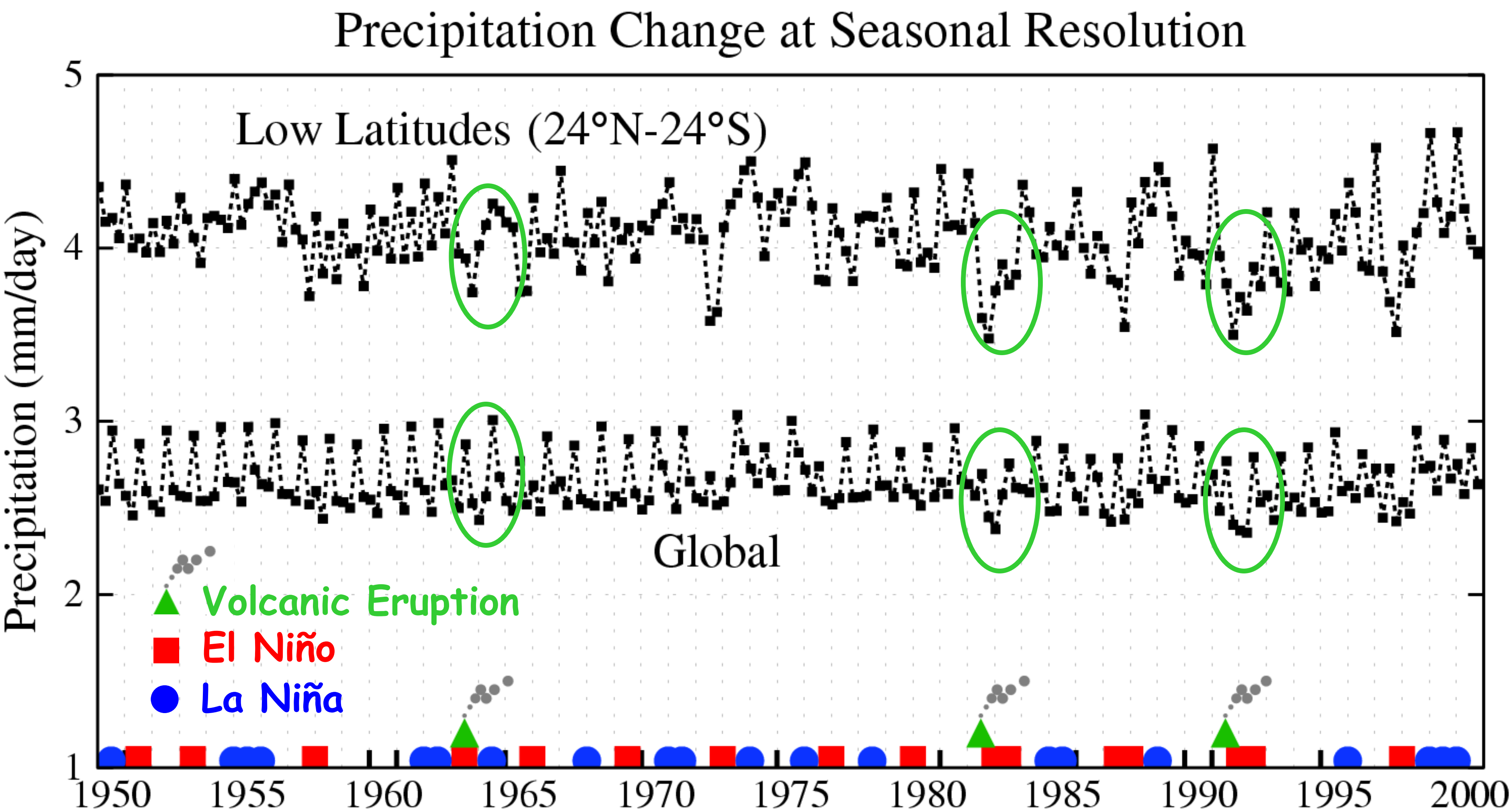

Drawn by Makiko Sato (NASA GISS)
using CRU TS 2.0 data

Trenberth and Dai (2007)

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

Geophys. Res. Lett.

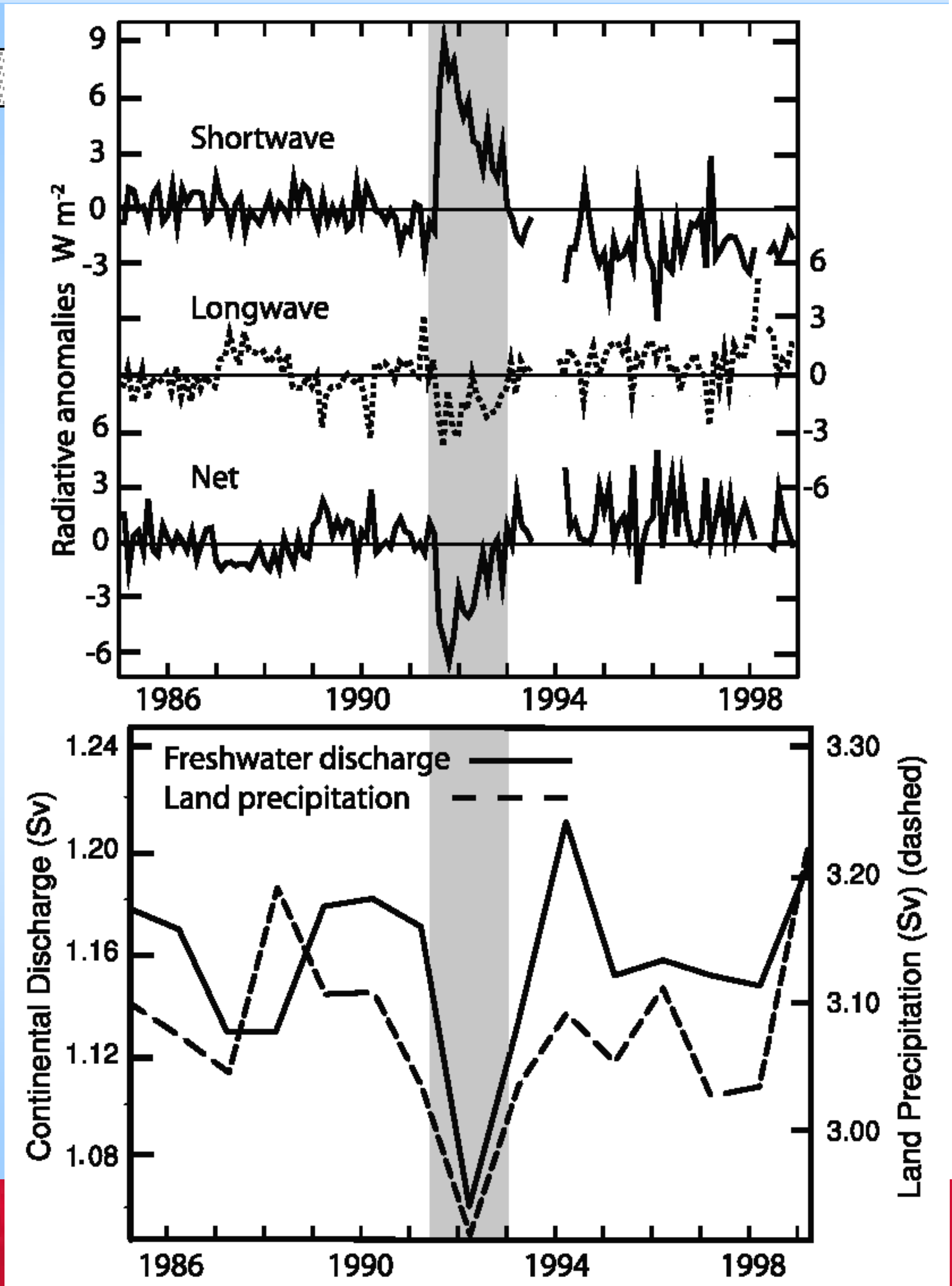

Figure 2. (top) Adapted time series of 20°N to 20°S ERBS non-scanner wide-field-of-view broadband shortwave, longwave, and net radiation anomalies from 1985 to 1999 [*Wielicki et al.*, 2002a, 2002b] where the anomalies are defined with respect to the 1985 to 1989 period with Edition 3_Rev 1 data [*Wong 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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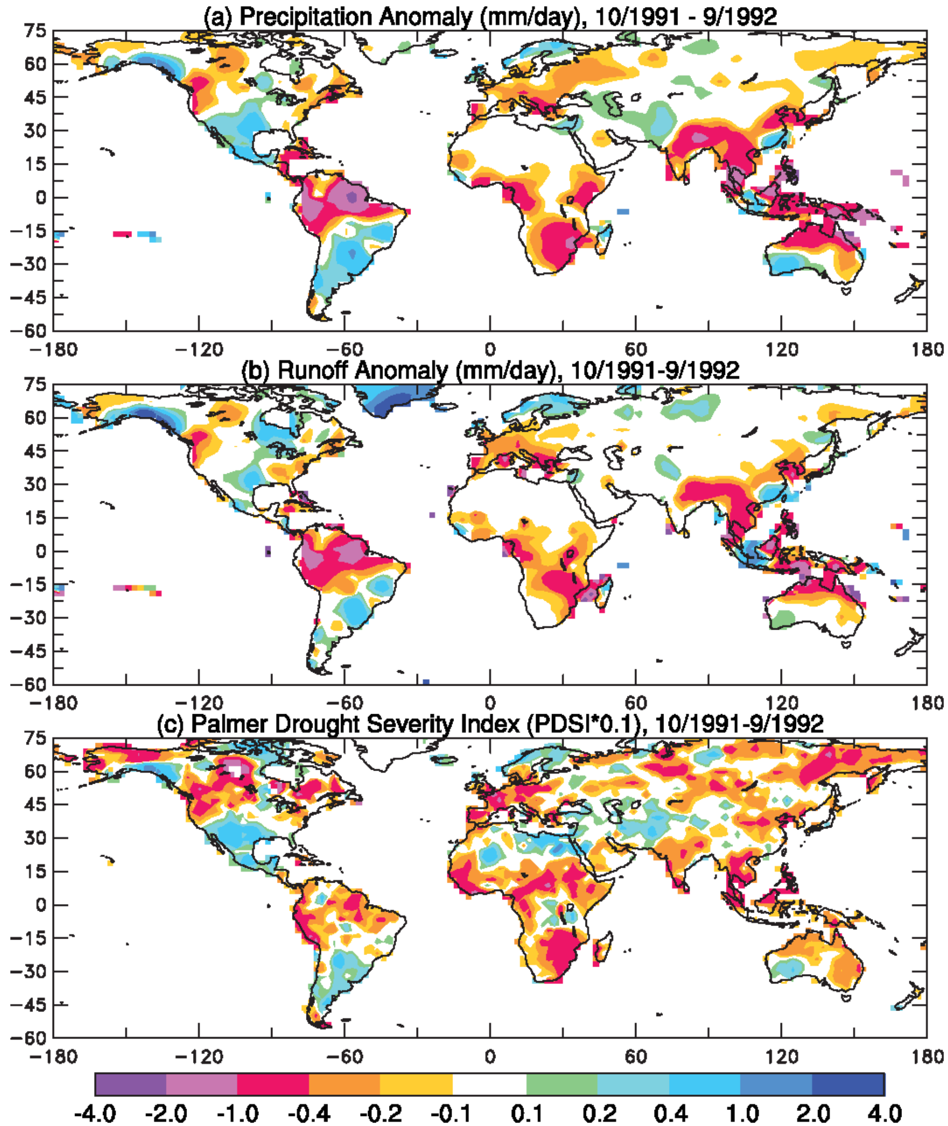

Figure 3. (a) Observed precipitation anomalies (relative to 1950–2004 mean) in mm/day during October 1991–September 1992 over land. Warm colors indicate below normal precipitation. (b) As for Figure 3a but for the simulated runoff [*Qian et al.*, 2006] using a comprehensive land surface model forced 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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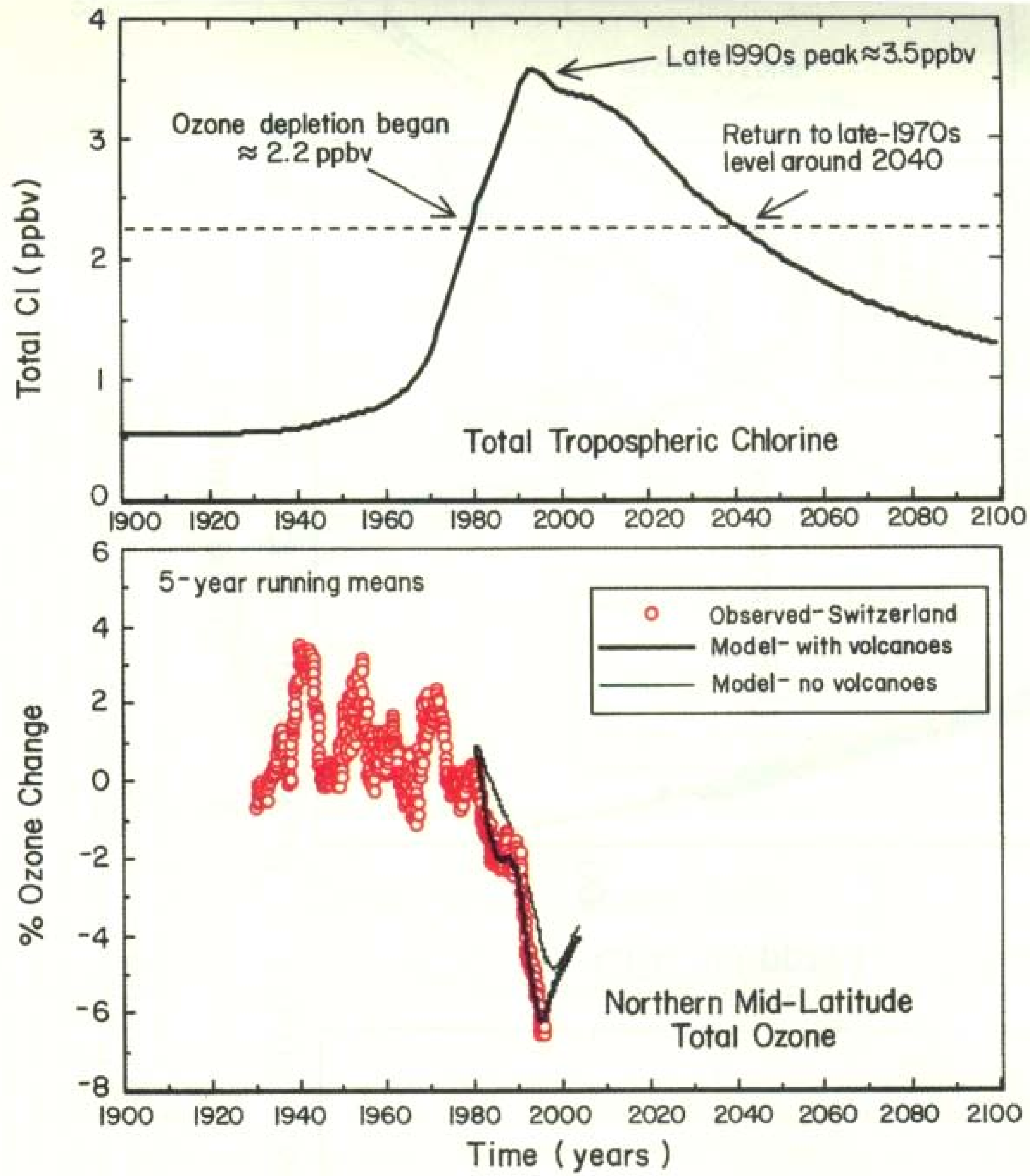
Tropospheric chlorine diffuses to stratosphere.

Volcanic aerosols make chlorine available to destroy ozone.

Solomon (1999)



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SH

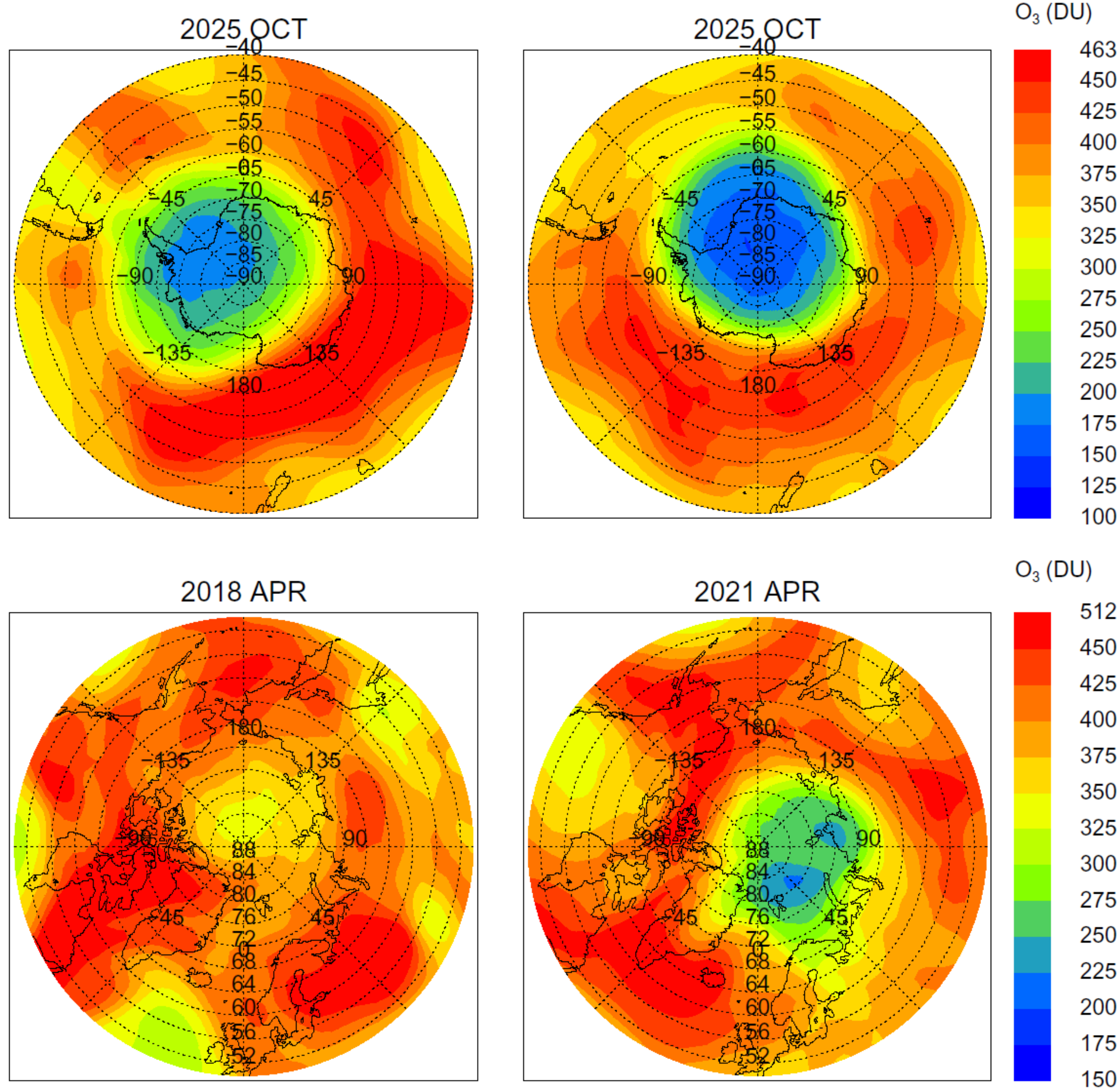
Rasch et al. (2008)

Ozone concentration for coldest winters with and without geoengineering

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

NH

Baseline Run Geoengineering Run



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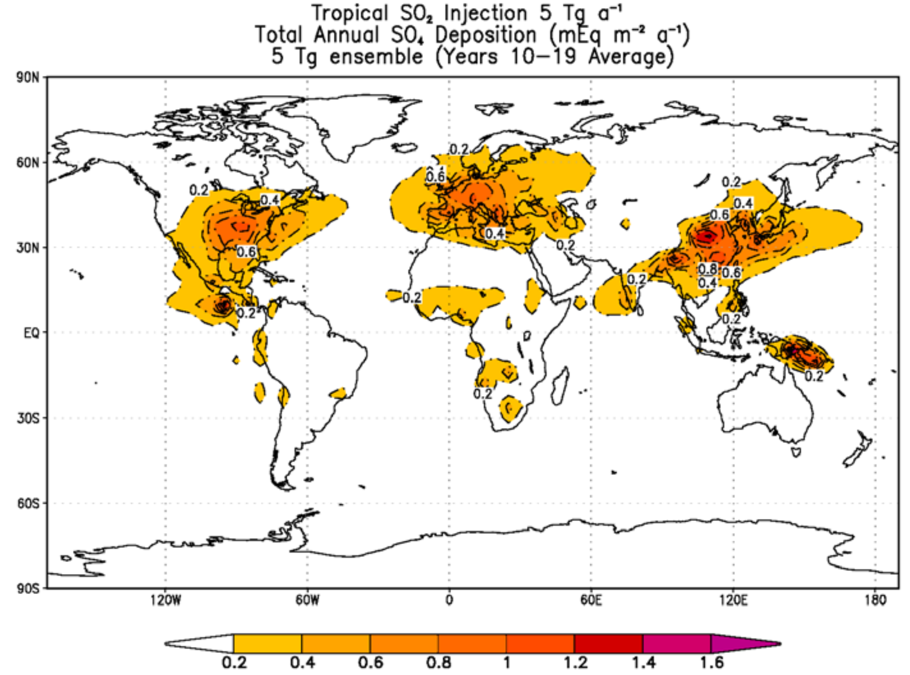
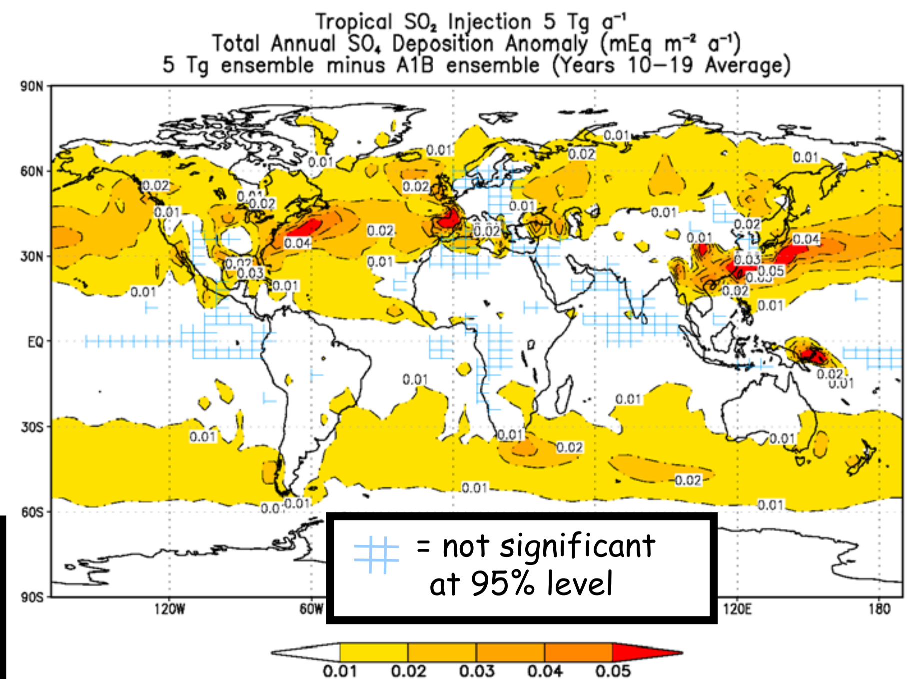
Robock, Alan, 2008: Whither geoengineering? *Science*, **320**, 1166-1167.

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

Excess deposition is orders of magnitude too small to be harmful.





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**, doi:10.1029/2009JD011918, in press.

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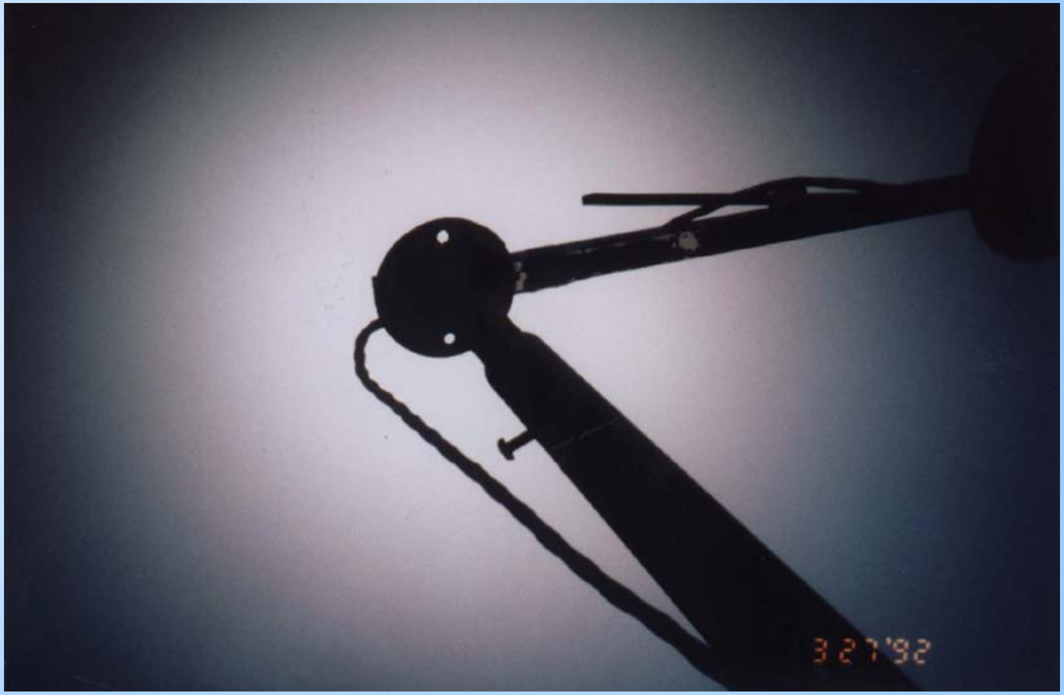
Diffuse Radiation from Pinatubo Makes a White Sky



Photographs by Alan Robock

Krakatau, 1883
Watercolor by William Ascroft

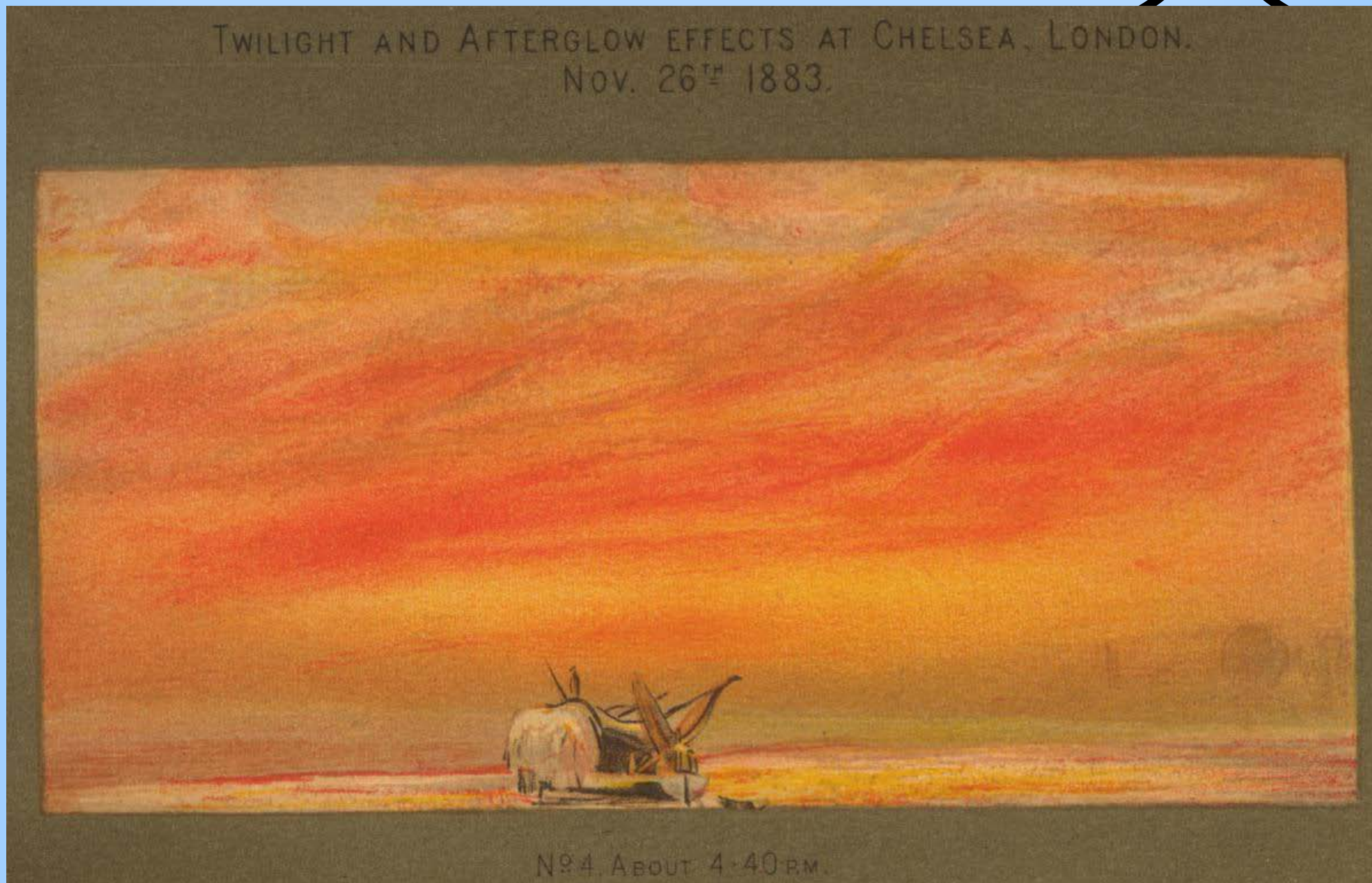


Figure from Symons (1888)

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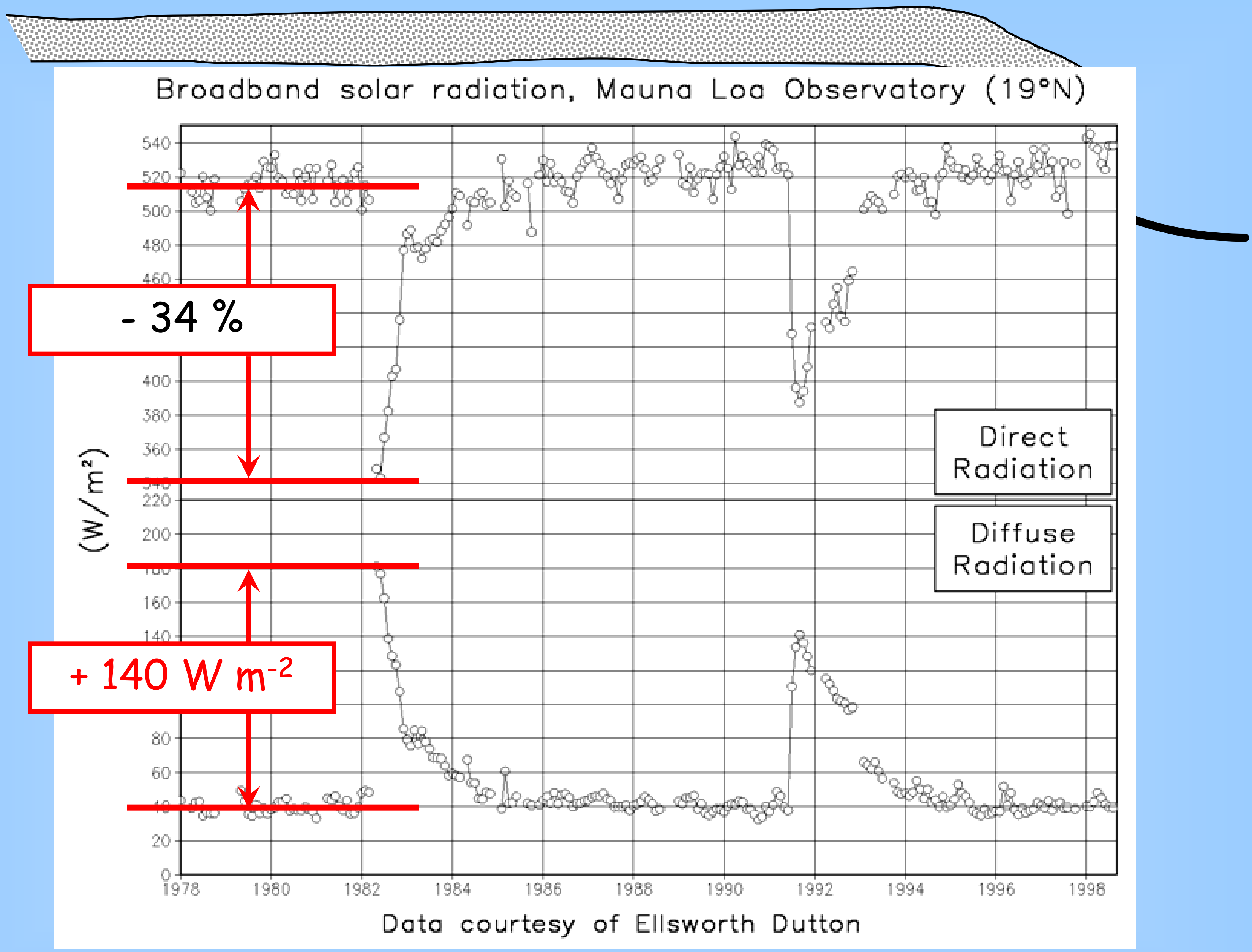
“The Scream”

Edvard Munch

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



Robock (2000), Dutton and Bodhaine (2001)

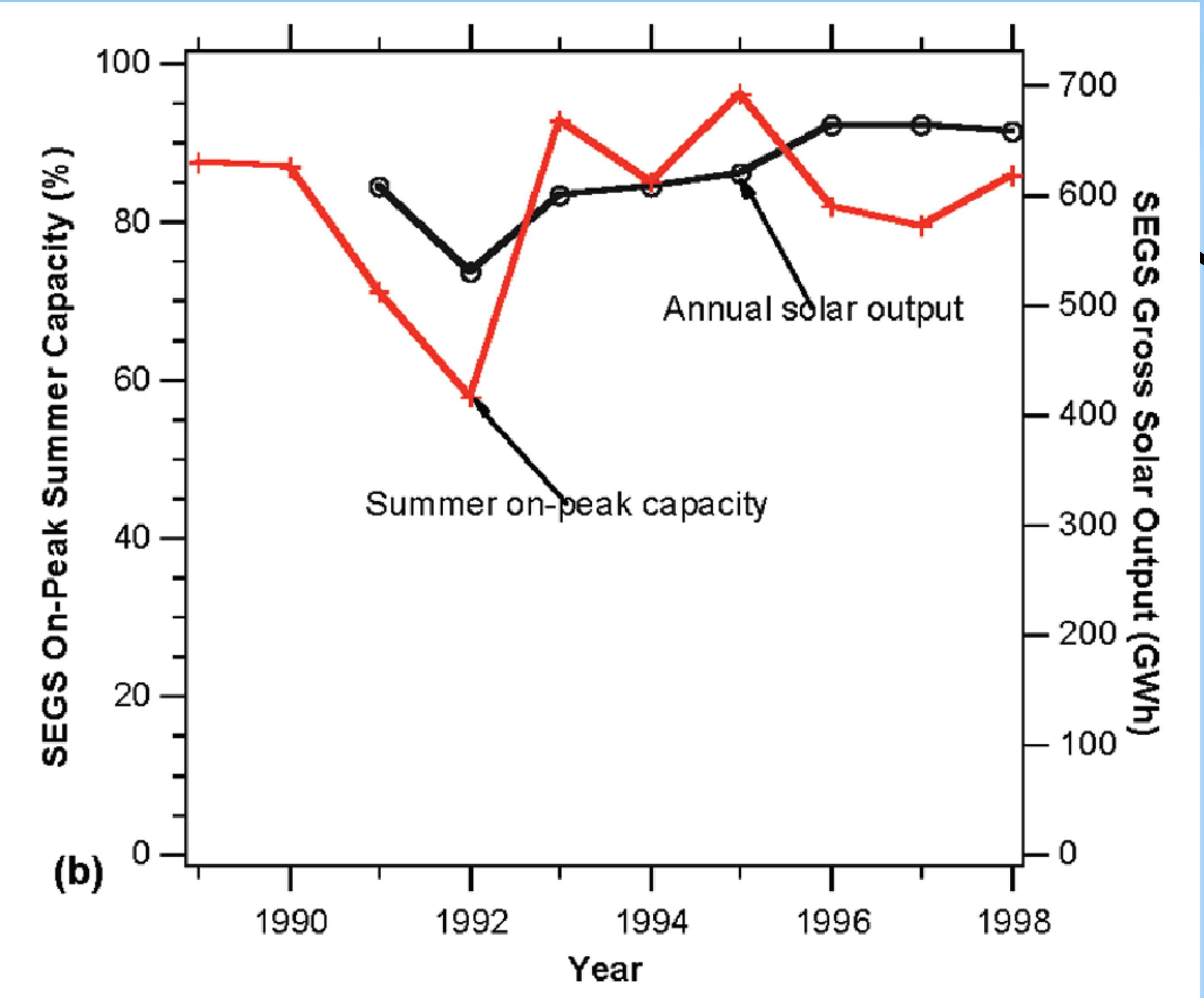
Nevada Solar One
64 MW

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/



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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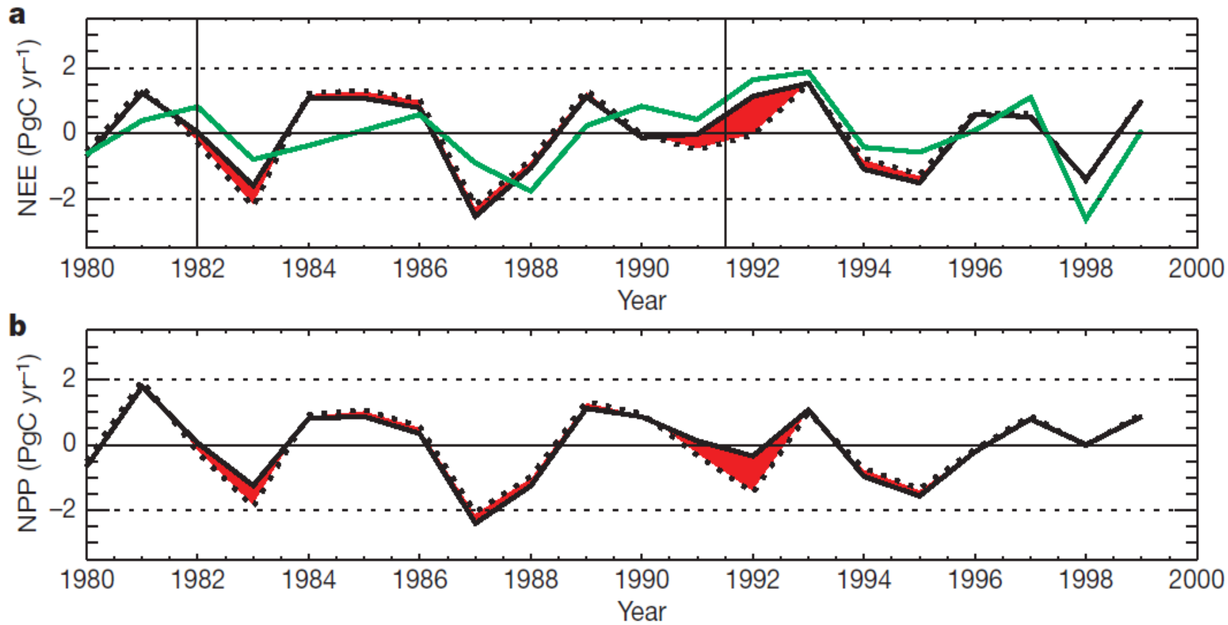

Figure 2 | Net ecosystem exchange (NEE) and net primary productivity (NPP). a, Inferred NEE values (derived from atmospheric CO_2 measurements[21] and simulated ocean flux[25]) are shown by the green line. Also presented are simulated global detrended flux anomalies of NEE (black) under varying (continuous line) and fixed (dashed line) diffuse fraction. The red shaded area corresponds to the contribution of the varying diffuse fraction to simulated NEE, calculated as the difference between the fluxes simulated under conditions of varying and fixed diffuse fraction. NEE is defined as the difference between net primary productivity (NPP) and heterotrophic respiration. Vertical lines correspond to the timing of the El Chichón (Mexico) and Pinatubo volcanic eruptions, respectively. **b**, Simulated NPP values for varying (continuous line) and fixed (dashed line) diffuse fraction, with the red shaded area again corresponding to the contribution of varying diffuse irradiance to simulated NPP.

nature Vol 458 | 23 April 2009 | **doi:10.1038/nature07949**

LETTERS

Impact of changes in diffuse radiation on the global land carbon sink

Lina M. Mercado[1], Nicolas Bellouin[2], Stephen Sitch[2], Olivier Boucher[2], Chris Huntingford[1], Martin Wild[3] & Peter M. Cox[4]

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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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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.

Drawing by Brian West

- 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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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.

How could we use <u>airplanes</u> 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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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 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.”

<u>Balloons</u> 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.

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 if existing military planes were used.
2. There are still many reasons not to do geoengineering.

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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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Conclusions

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

15 ✓

3 X

2 ?

Recently I added one more reason:

It would destroy Earth-based optical astronomy.

As of now, there are at least 16 reasons why geoengineering is a bad idea.

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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

Risks

1. Drought in Africa and Asia
2. Continued ocean acidification
3. Ozone depletion
4. No more blue skies
5. Less solar power
6. Environmental impact of implementation
7. Rapid warming if stopped
8. Cannot stop effects quickly
9. Human error
10. Unexpected consequences
11. Commercial control
12. Military use of technology
13. Conflicts with current treaties
14. Whose hand on the thermostat?
15. Ruin terrestrial optical astronomy
16. Moral hazard – the prospect of it working would reduce drive for mitigation
17. Moral authority – do we have the right to do this?

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

Robock, Alan, Allison B. Marquardt, Ben Kravitz, and Georgiy Stenchikov, 2009: The benefits, risks, and costs of stratospheric geoengineering. Submitted to *Geophys. Res. Lett.*

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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The United Nations Framework Convention On Climate Change 1992

Signed by 194 countries and ratified by 188 (as of February 26, 2004)

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.

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

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

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