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THE STATE UNIVERSITY
OF NEW JERSEY

Geoengineering

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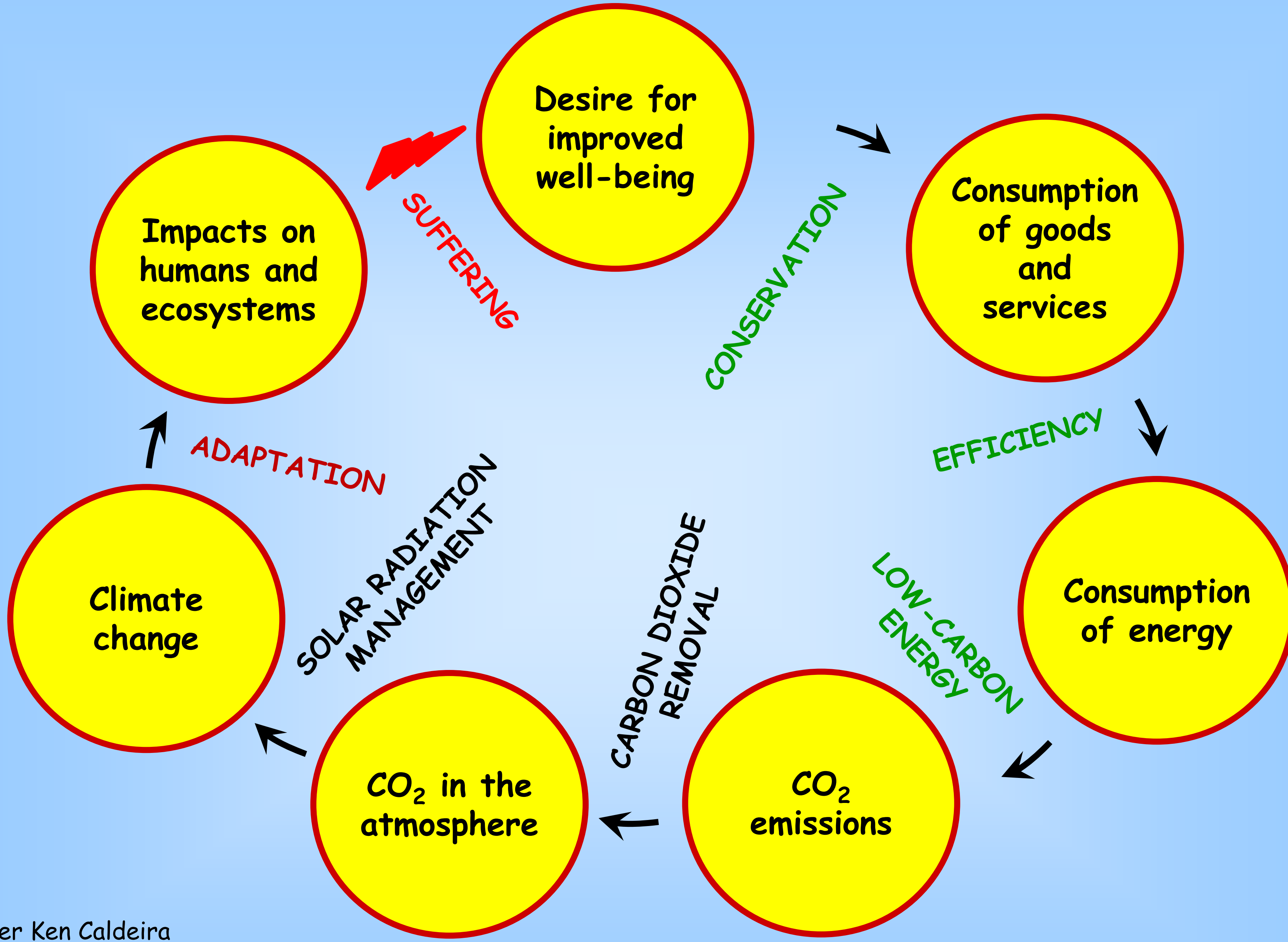

After Ken Caldeira

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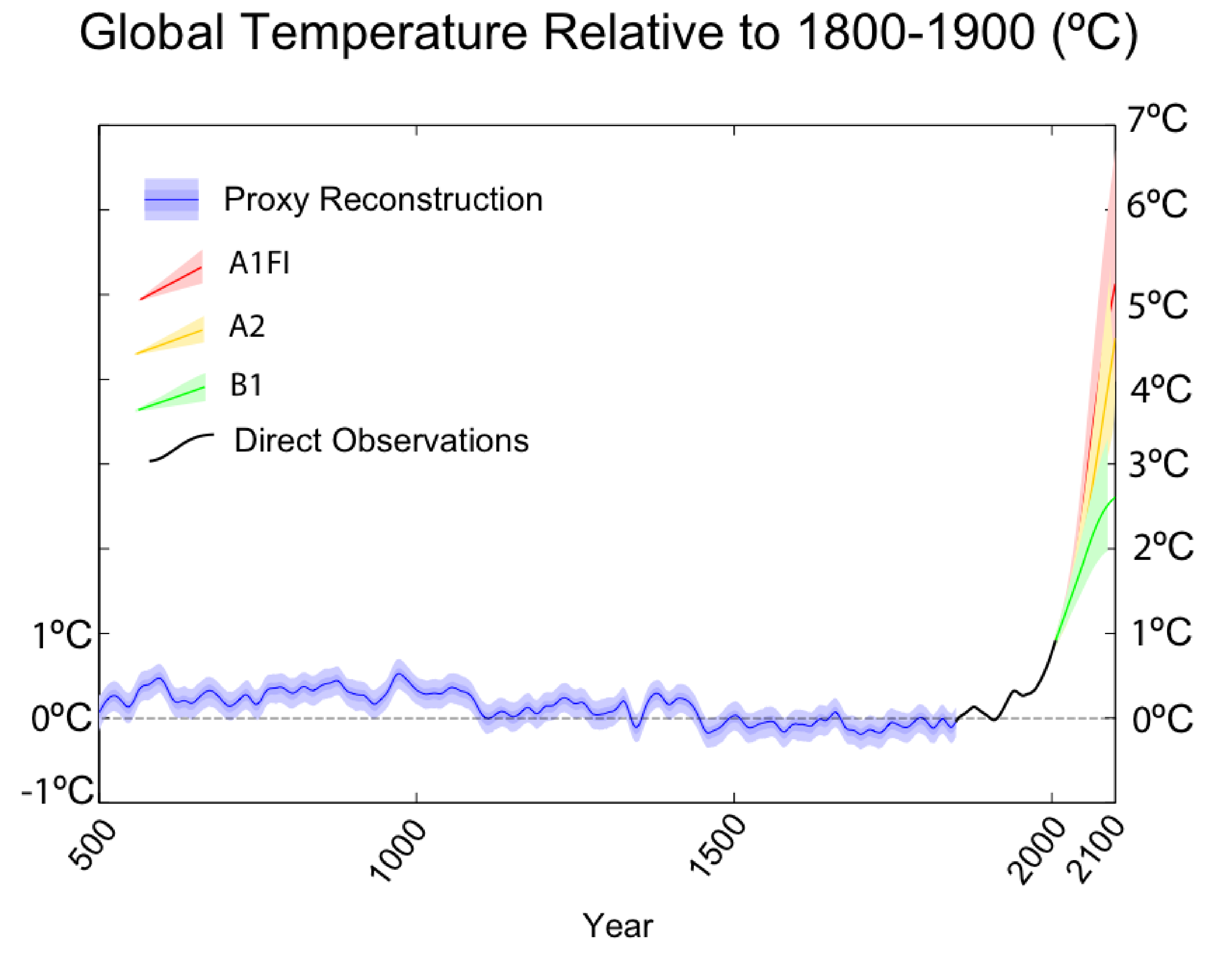
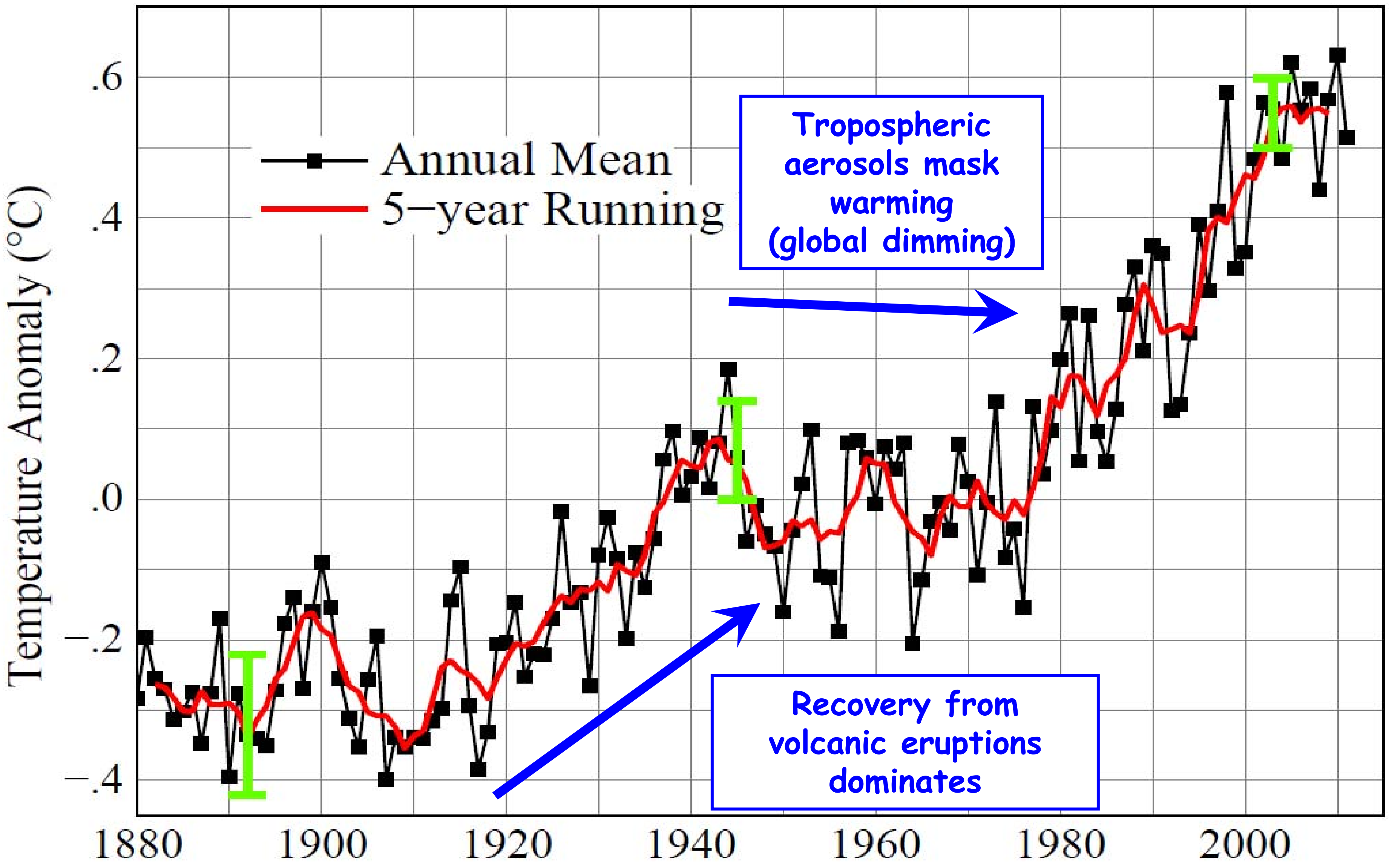


Figure 21: Reconstructed, observed and future warming projections

Global Land–Ocean Temperature Index



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

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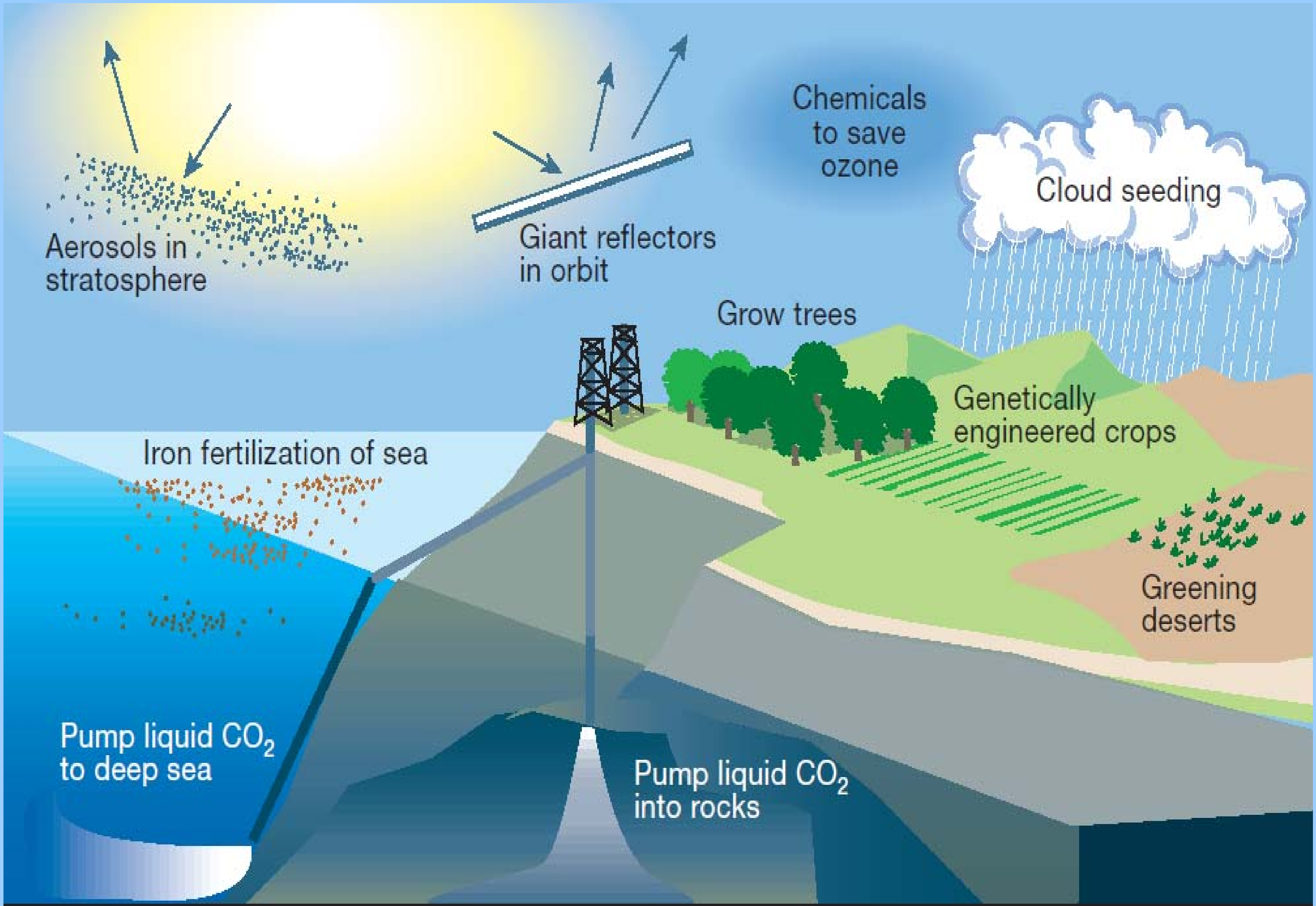

Schematic representation of various climate-engineering proposals (courtesy B. Matthews).

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

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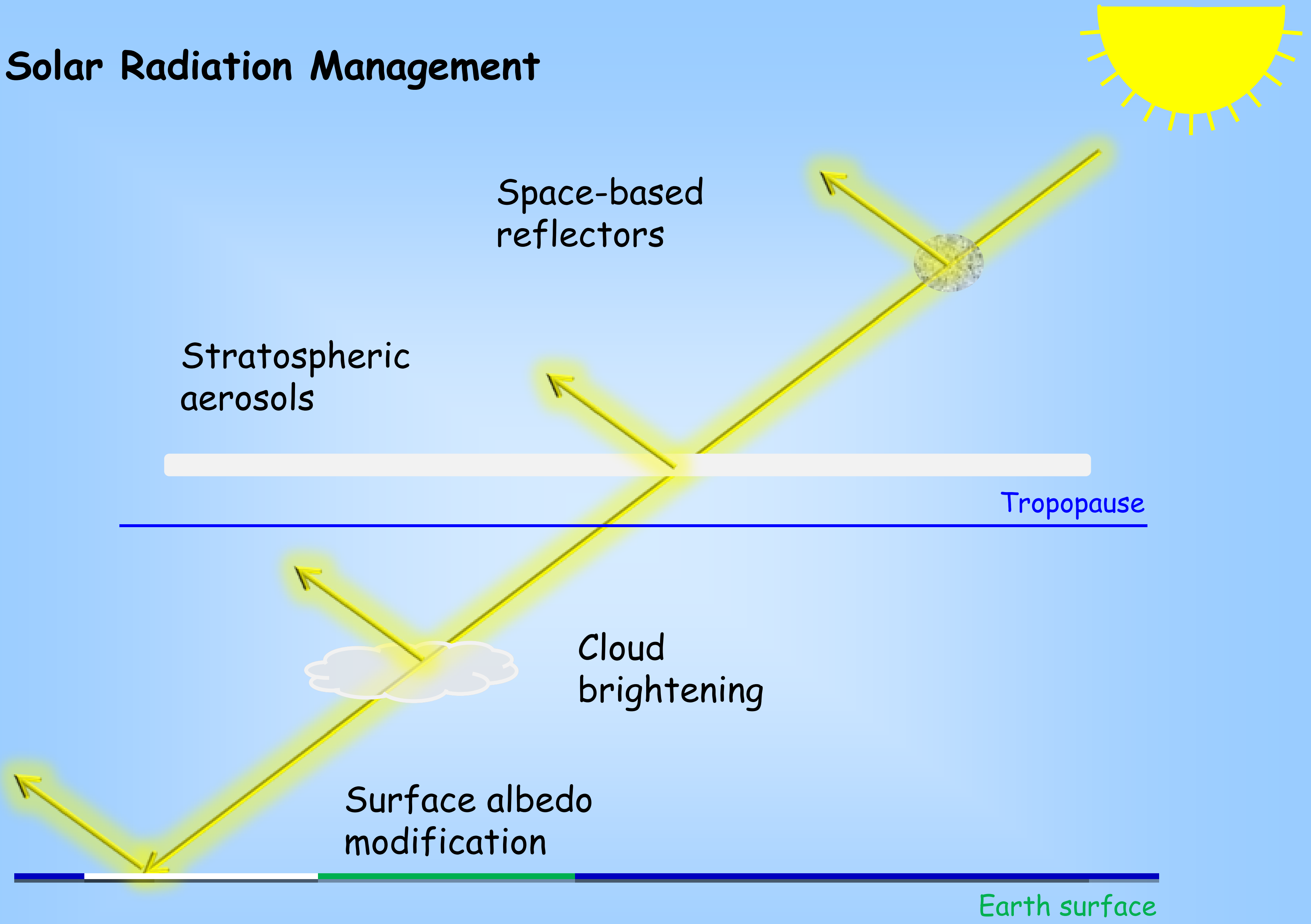
Solar Radiation Management



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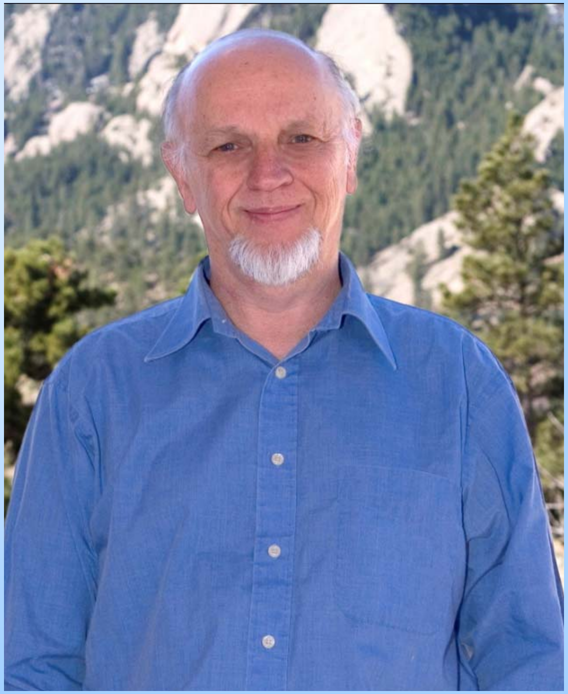
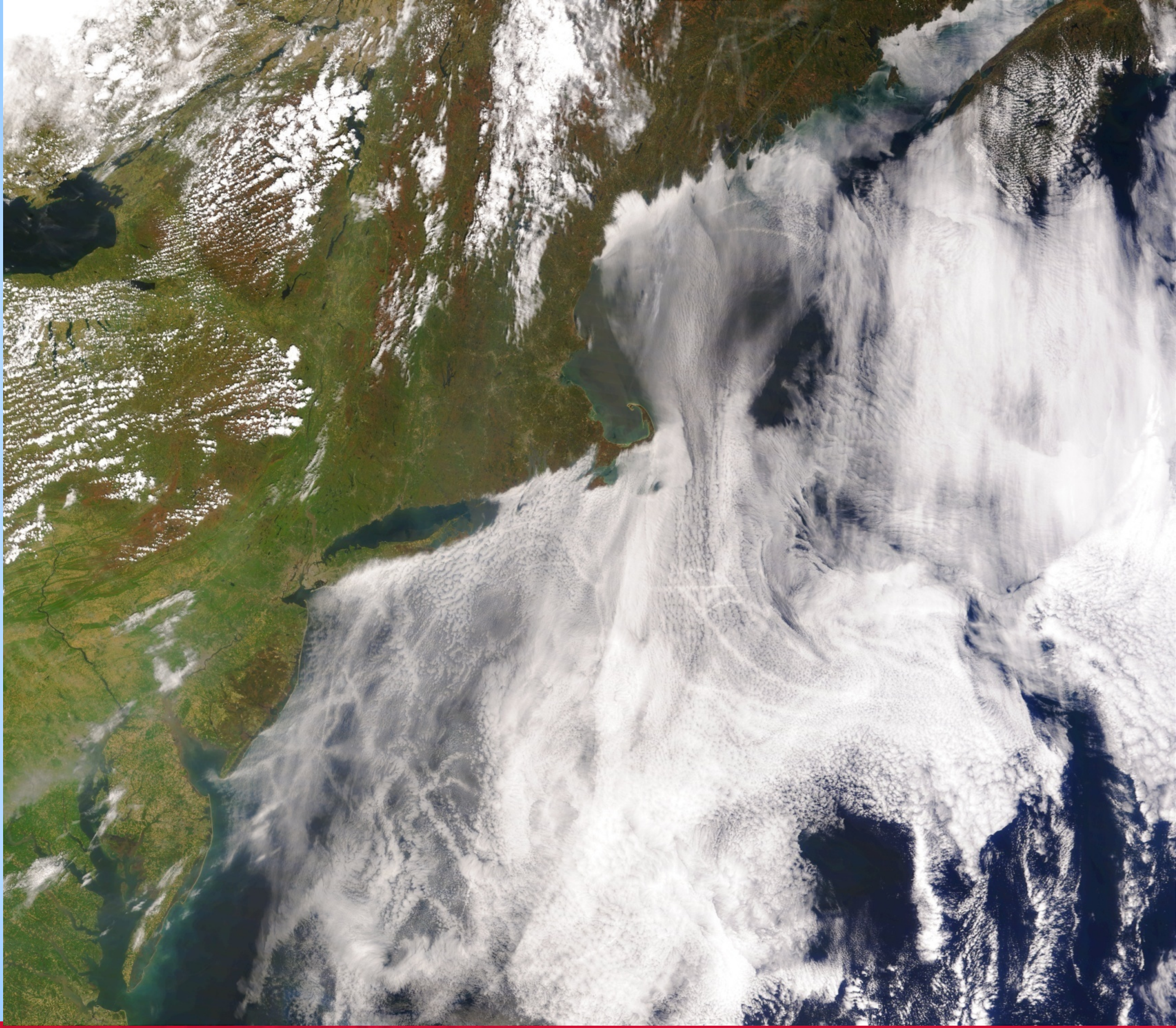
Despairing of prompt political response to global warming, in August and September 2006, **Paul Crutzen** (Nobel Prize in Chemistry) and **Tom Wigley** (NCAR) suggested that we consider temporary **geoengineering** as an emergency response.



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



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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.

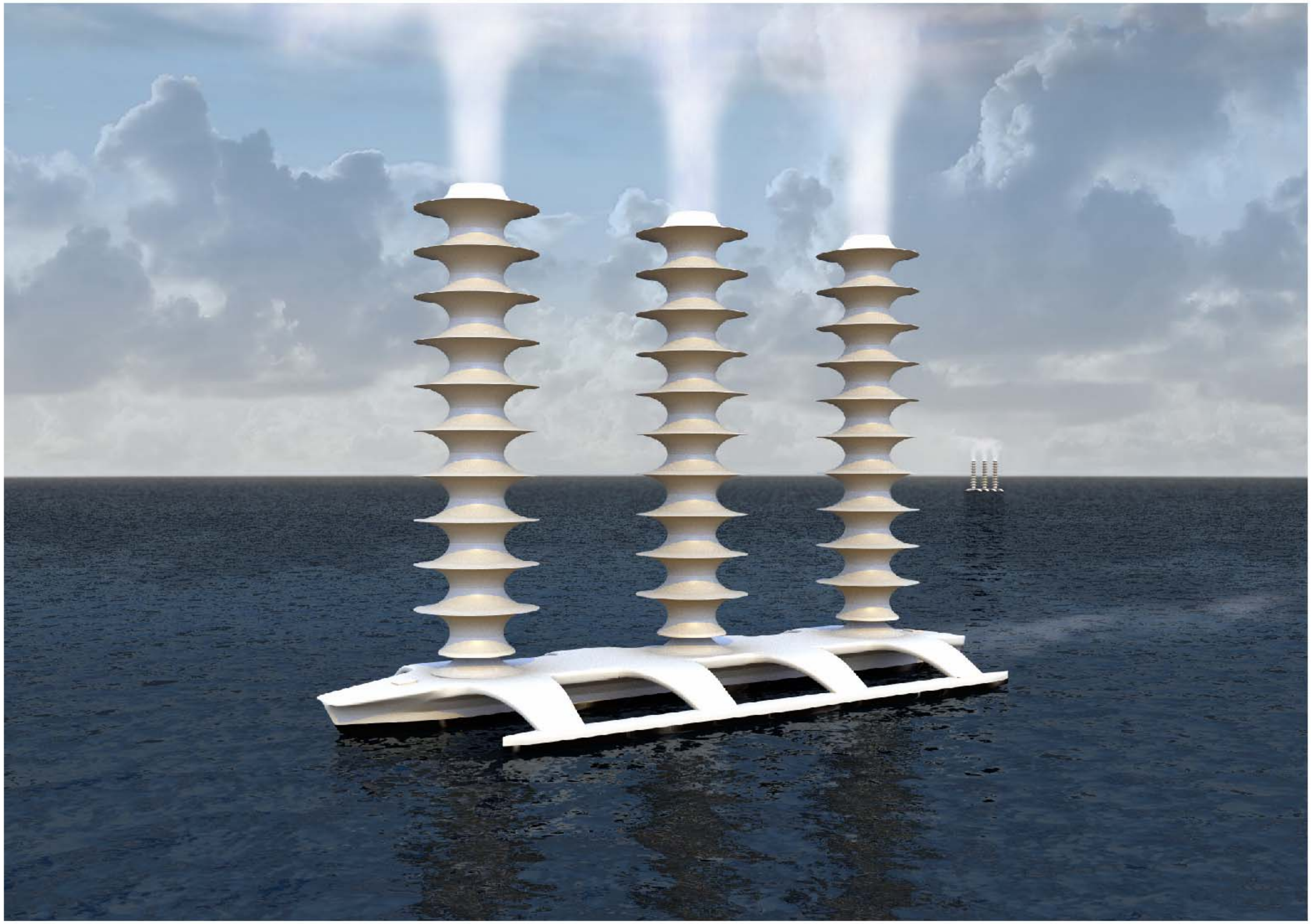

Figure 4. Albedo spray vessels. They would sail back and forth square to the local prevailing wind. Flettner rotors with Thom fences can give lift coefficients up to 20 and lift drag ratios of 35, much higher than cloth sails. Artwork by John MacNeill.

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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

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.

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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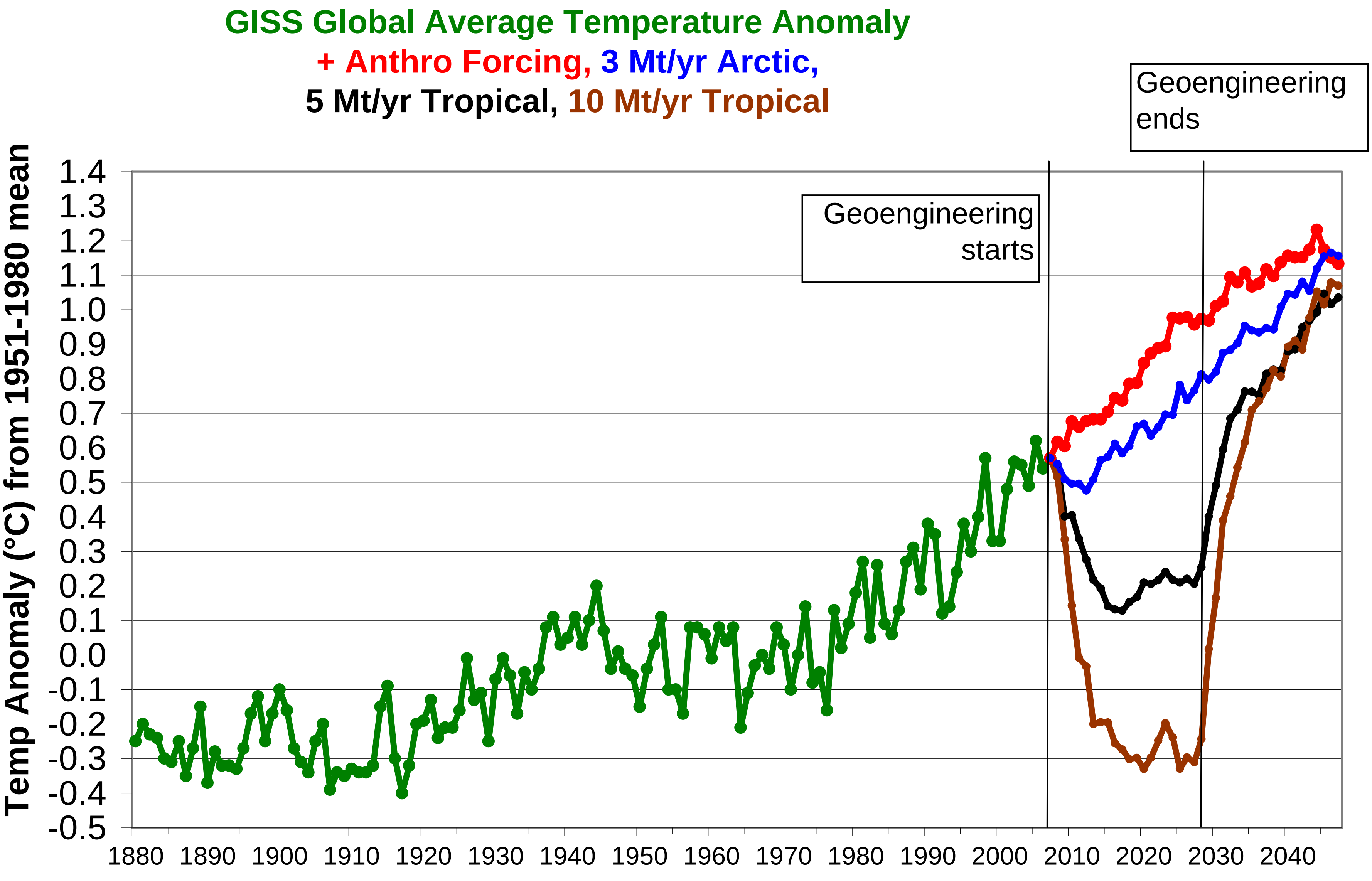

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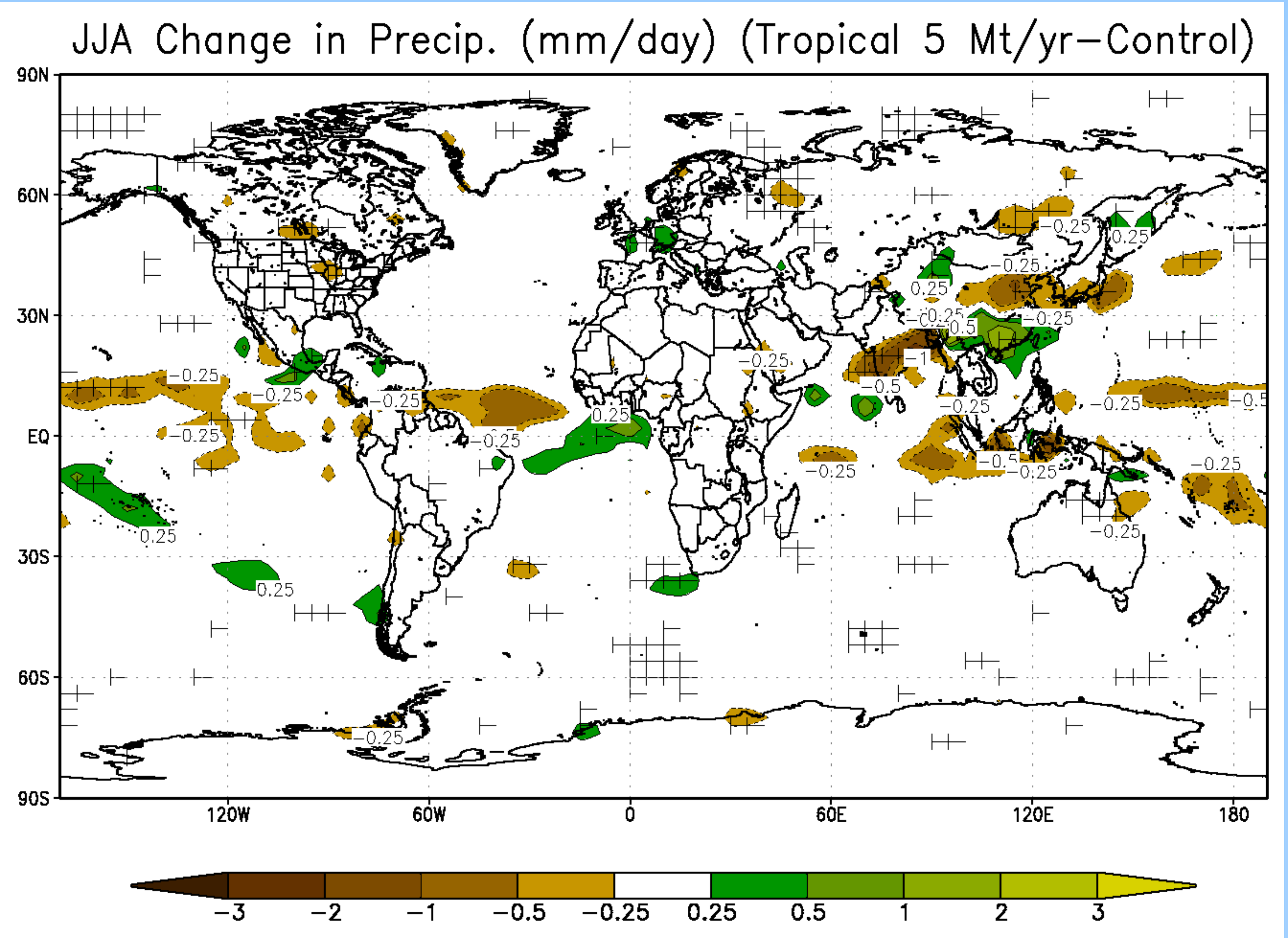
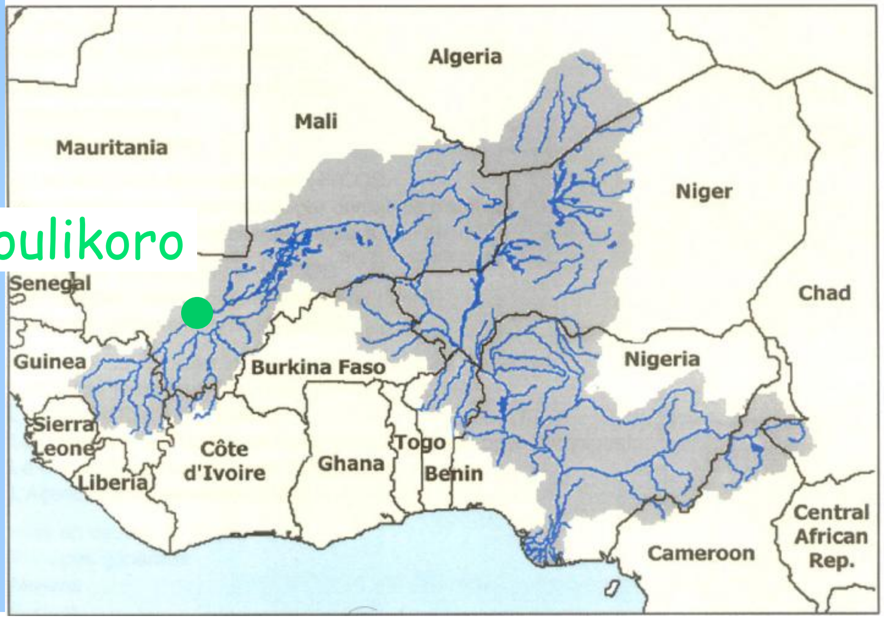
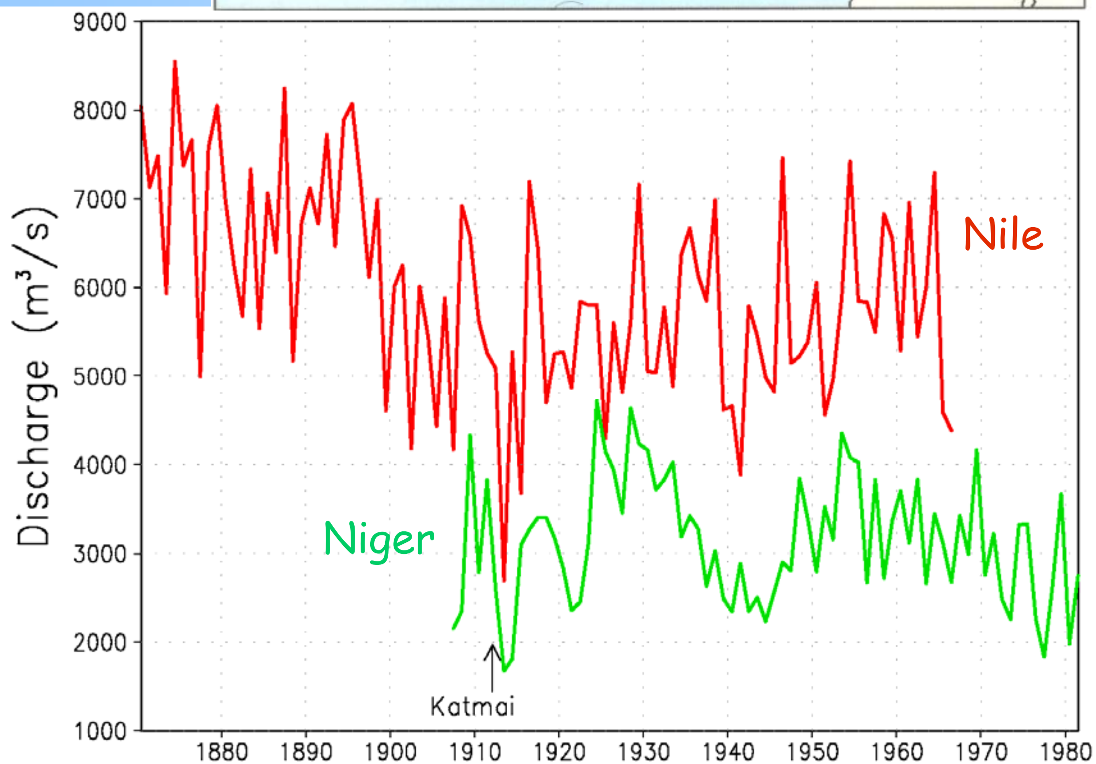


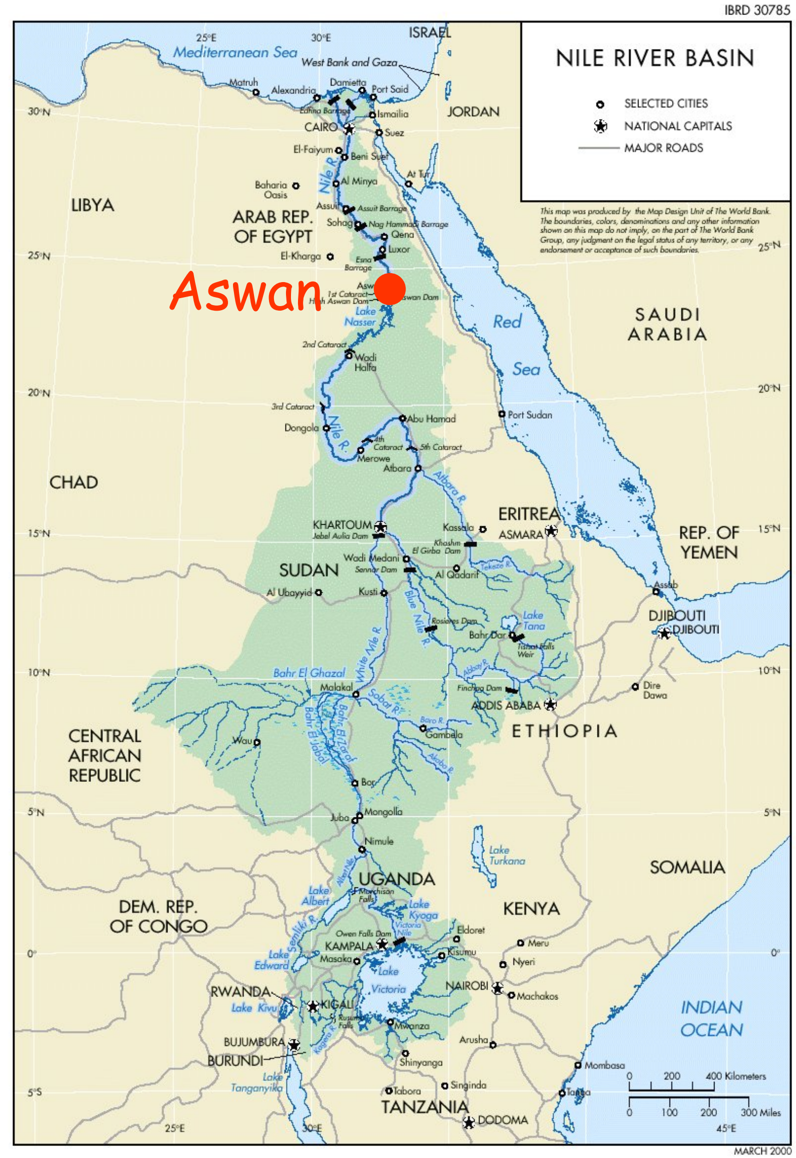
= significant at the 95% level

http://www.festivalsegou.org

Niger Basin







http://www.isiimm.agropolis.org

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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.

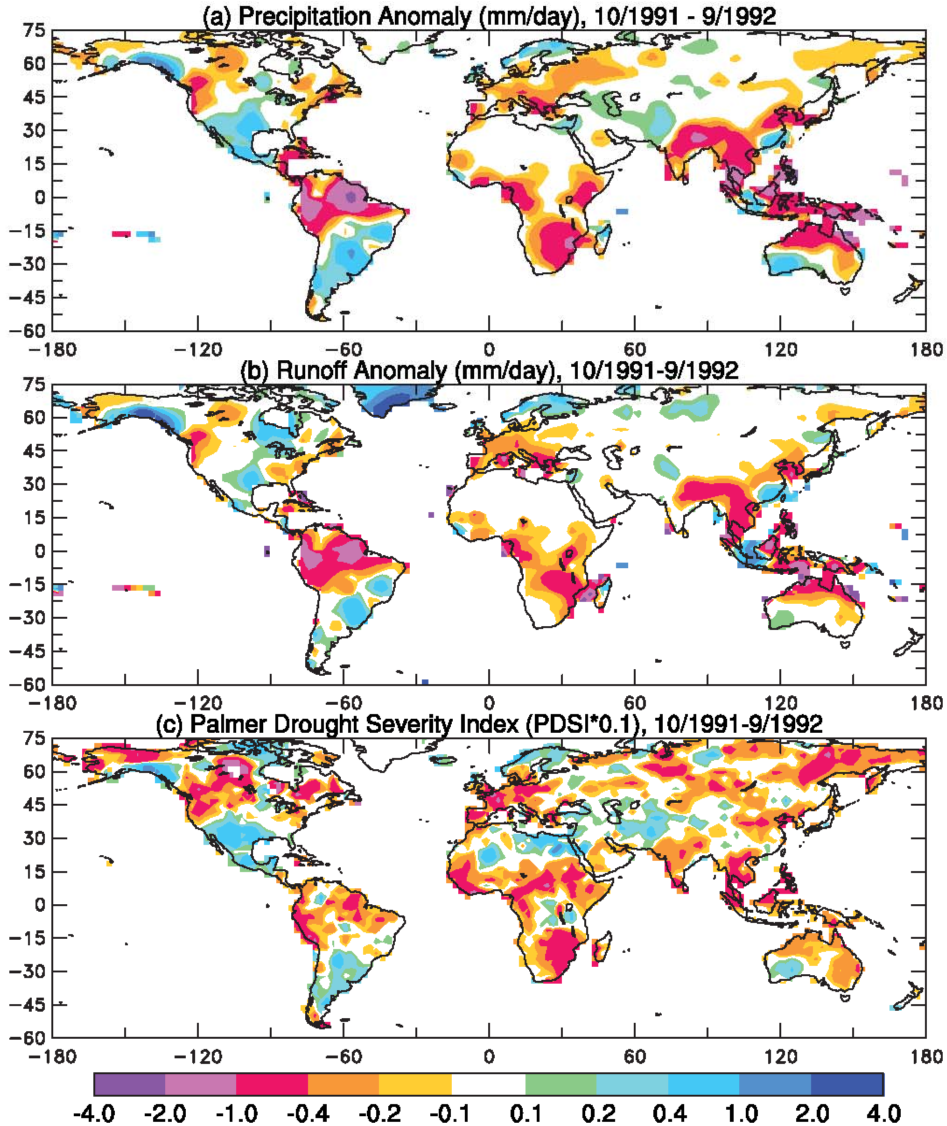

Figure 3. (a) Observed precipitation anomalies (relative to 1950–2004 mean) in mm/day during October 1991–September 1992 over land. Warm colors indicate below normal precipitation. (b) As for Figure 3a but for the simulated runoff [*Qian et al.*, 2006] using a comprehensive land surface model forced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

We are carrying out standard experiments with the new GCMs being 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.

GeoMIP is a CMIP Coordinated Experiment, as part of the Climate Model Intercomparison Project 5 (CMIP5).

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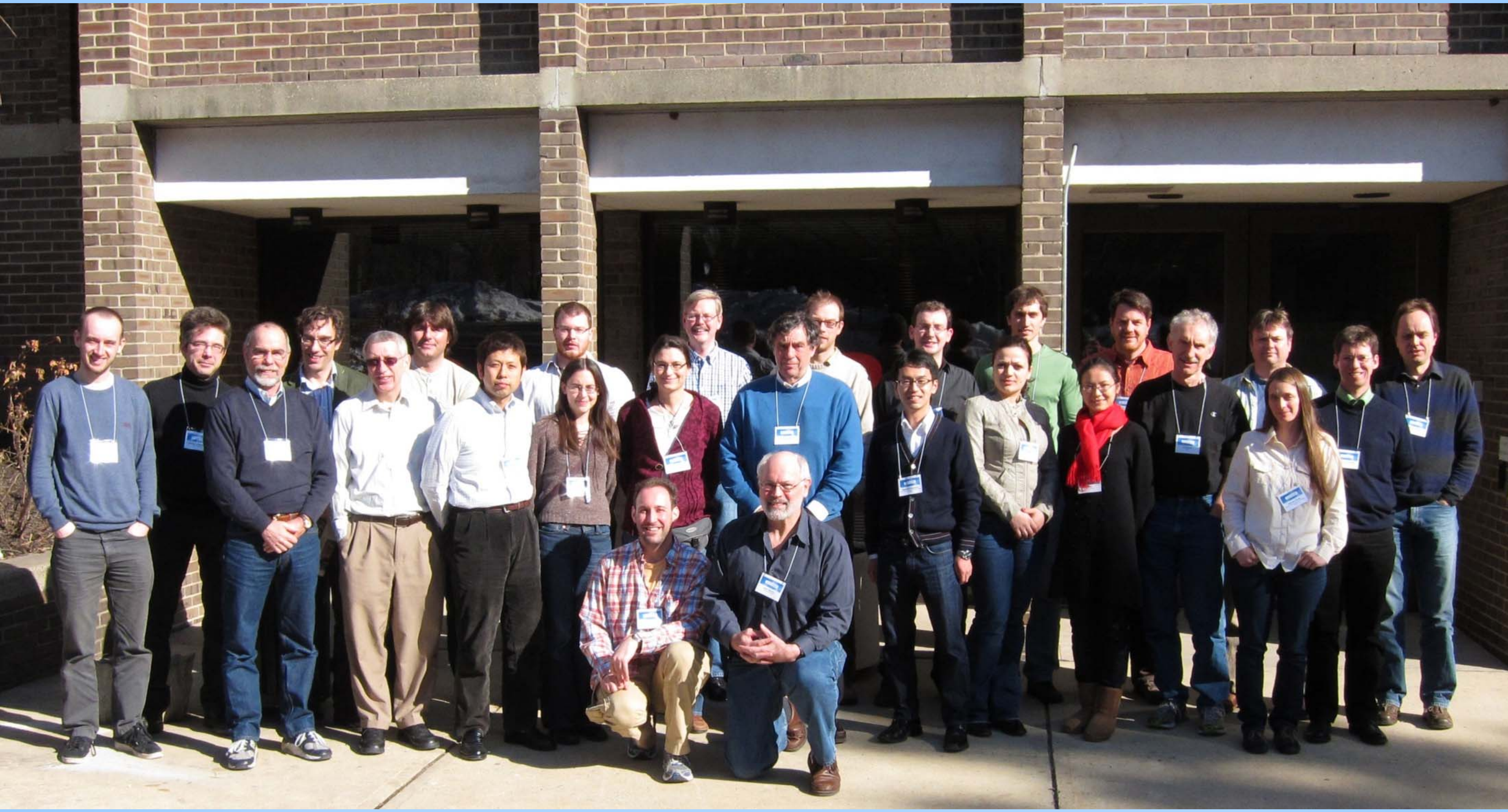
WCRP
World Climate Research Programme

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.

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

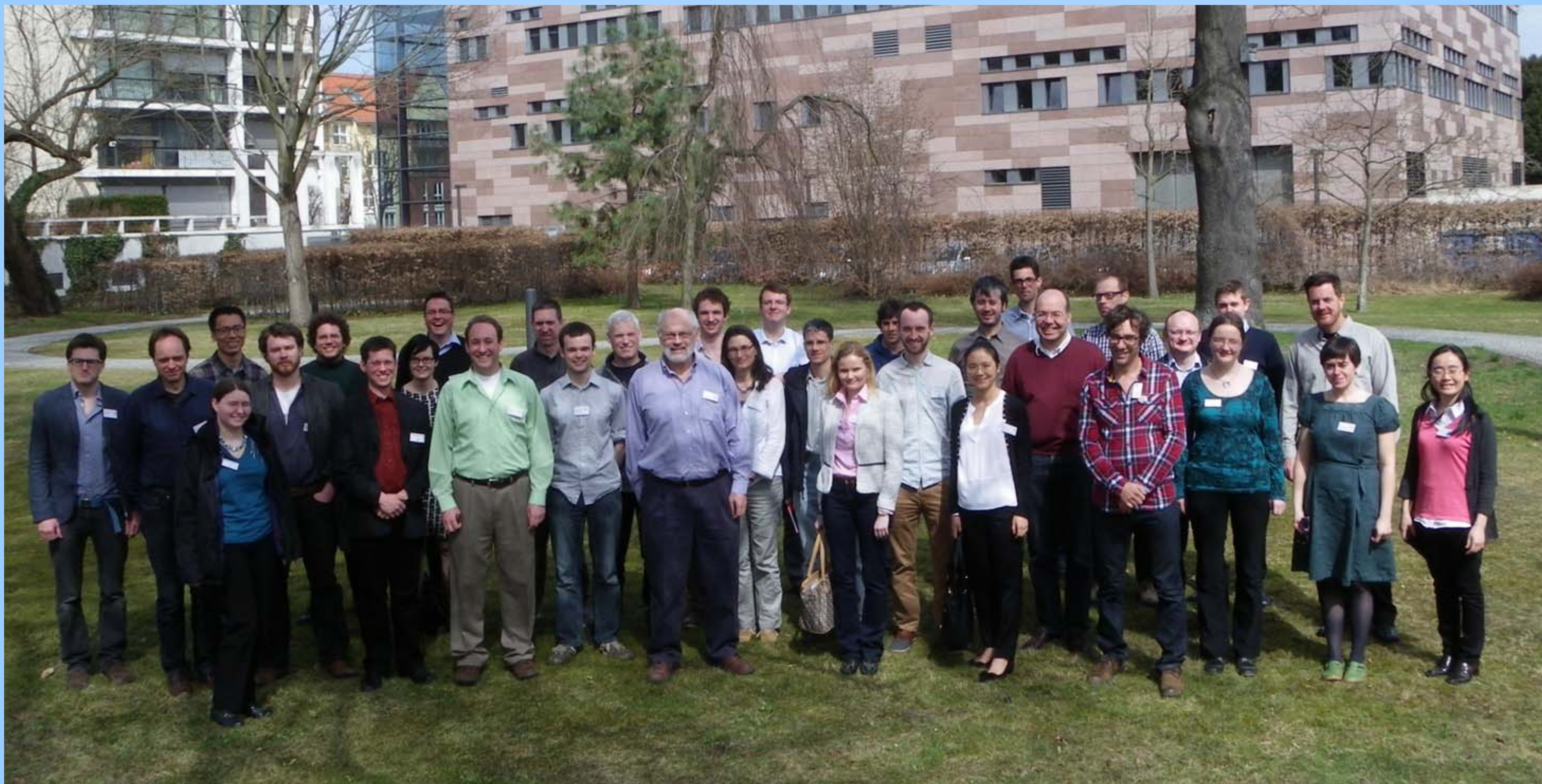
http://climate.envsci.rutgers.edu/GeoMIP/events/exetermarch2012.html

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.

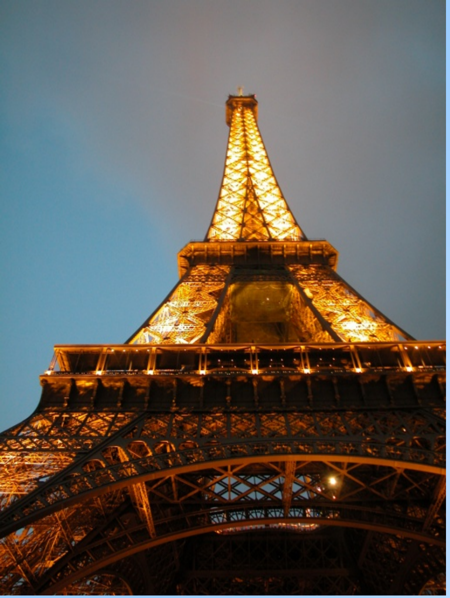
Third GeoMIP Workshop, Institute for Advanced Sustainability Studies, Potsdam, Germany, April 15-16, 2013

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.



Fourth GeoMIP Workshop

Paris, France, April 24-25, 2014

To be sponsored by NSF

Climate Engineering Conference 2014

August 18-21, Berlin, Germany

http://www.ce-conference.org/

'14 CEC Critical Global Discussions

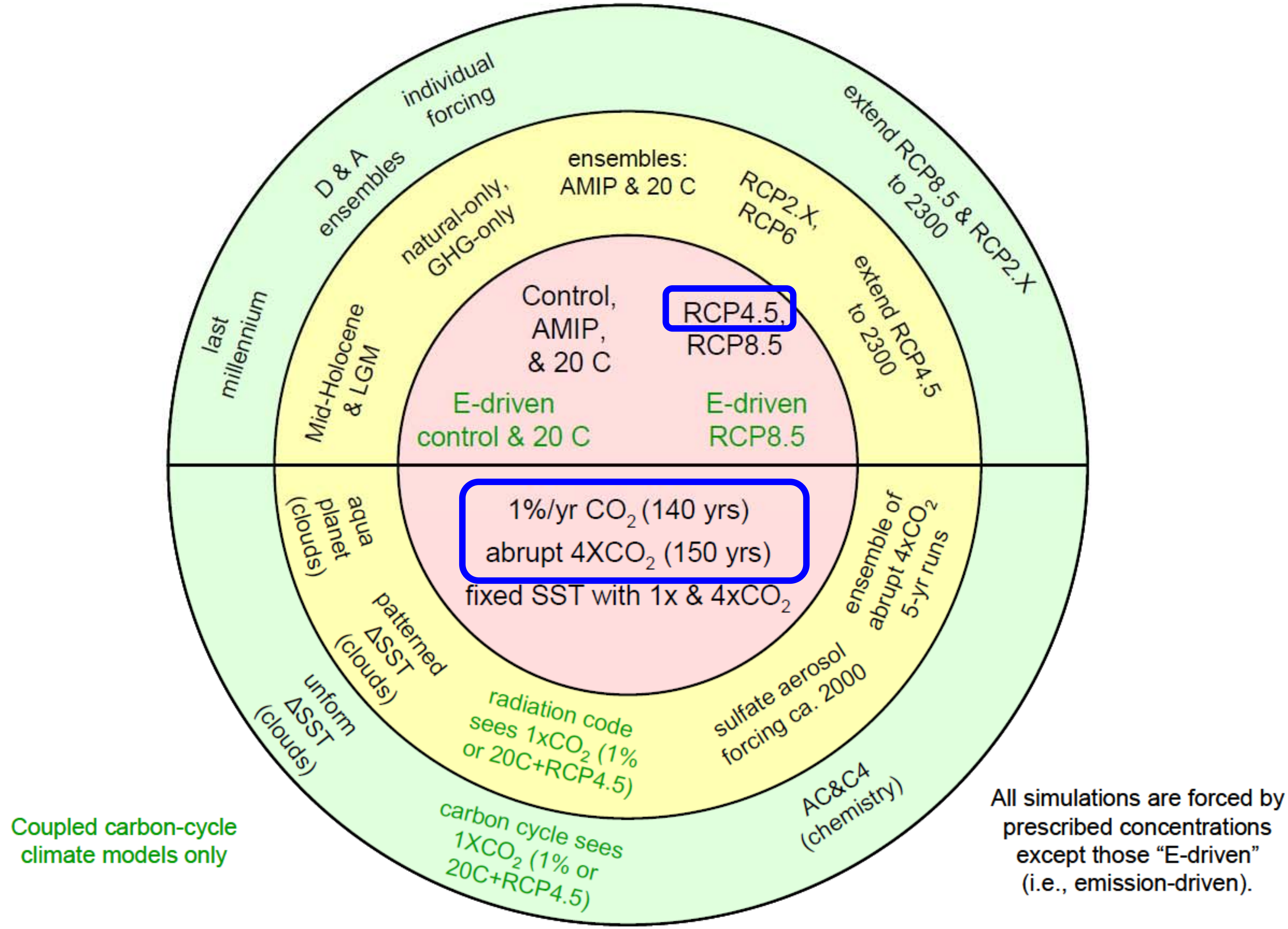
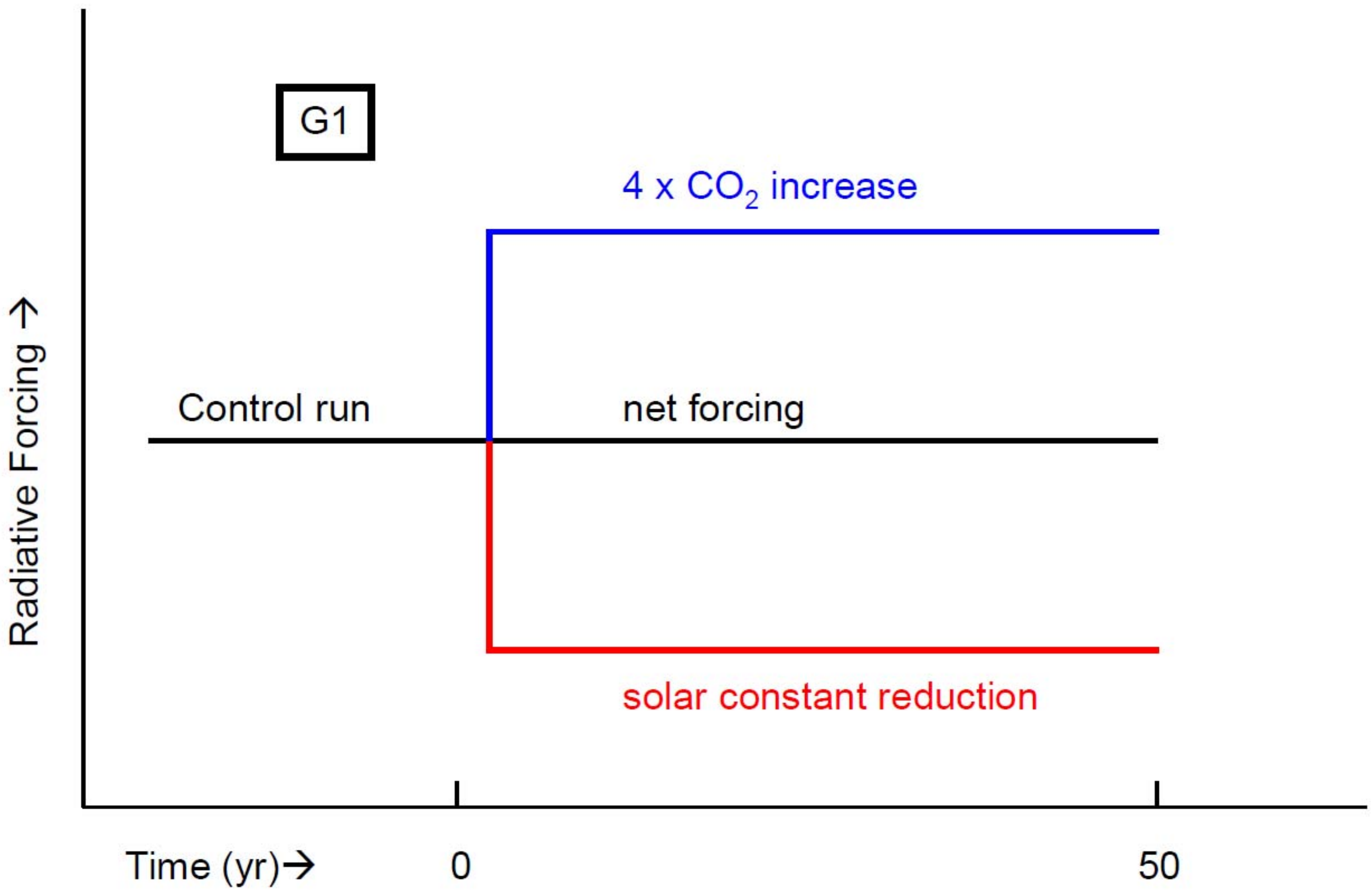
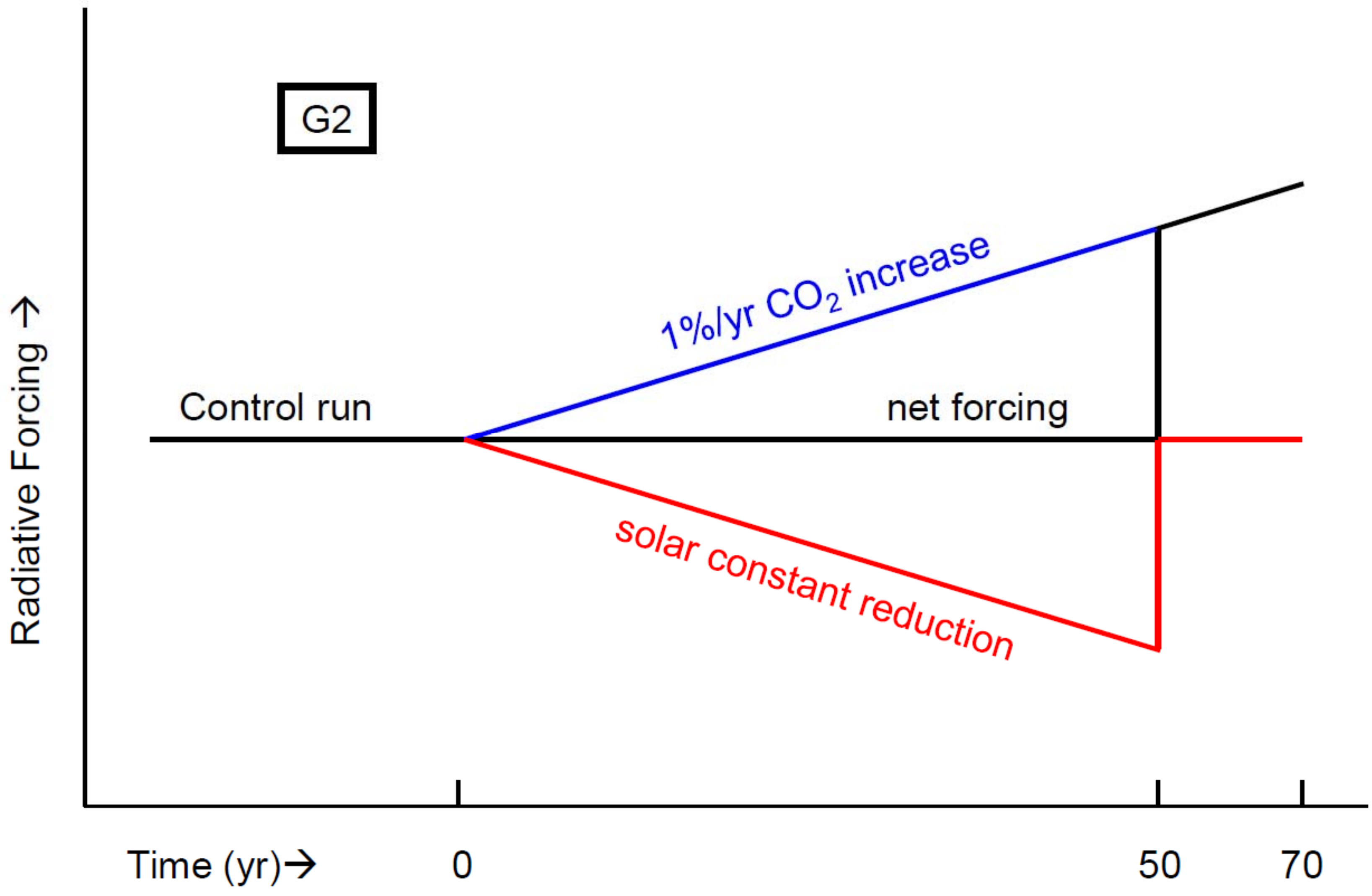


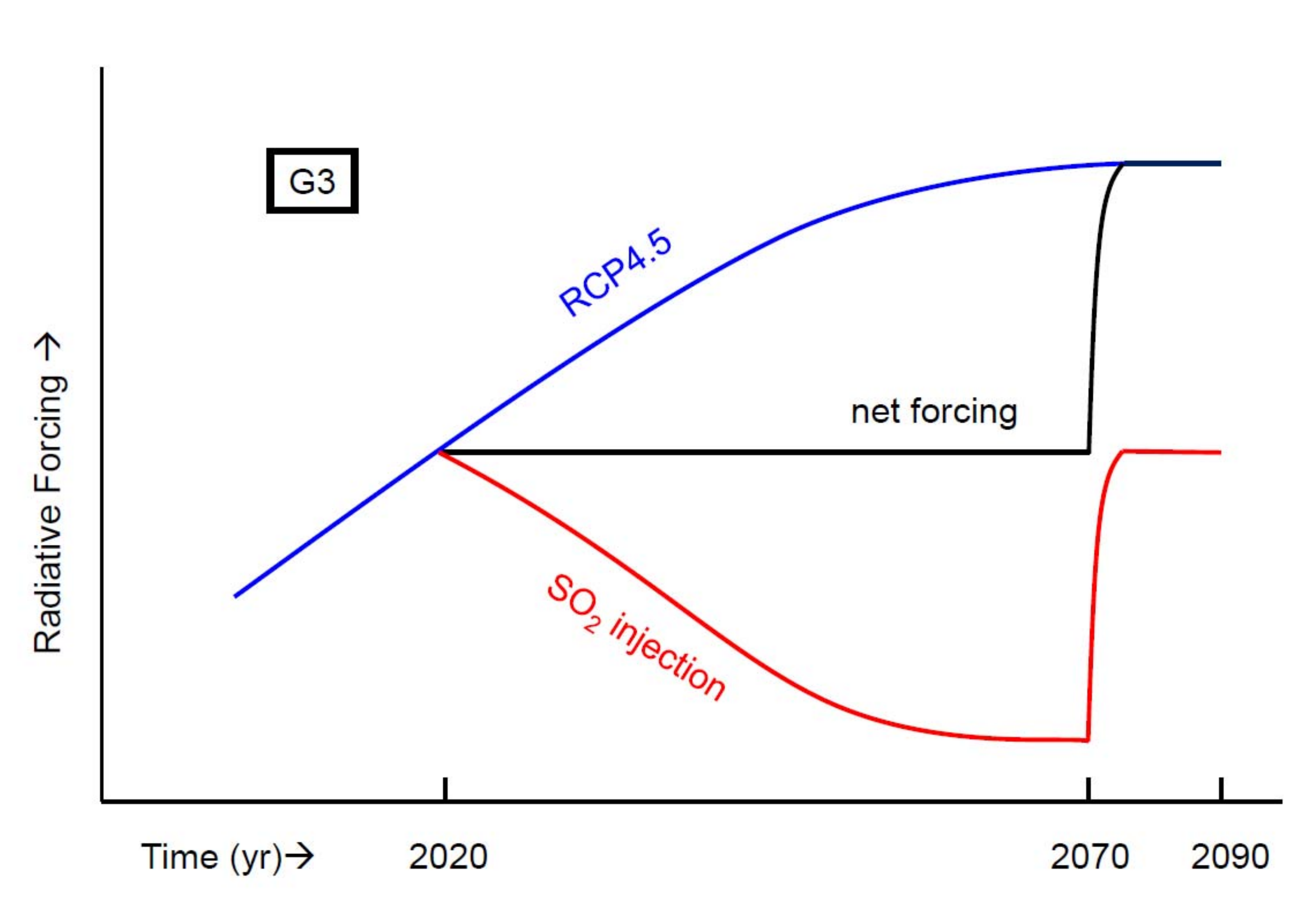
Figure 3: Schematic summary of CMIP5 long-term experiments.



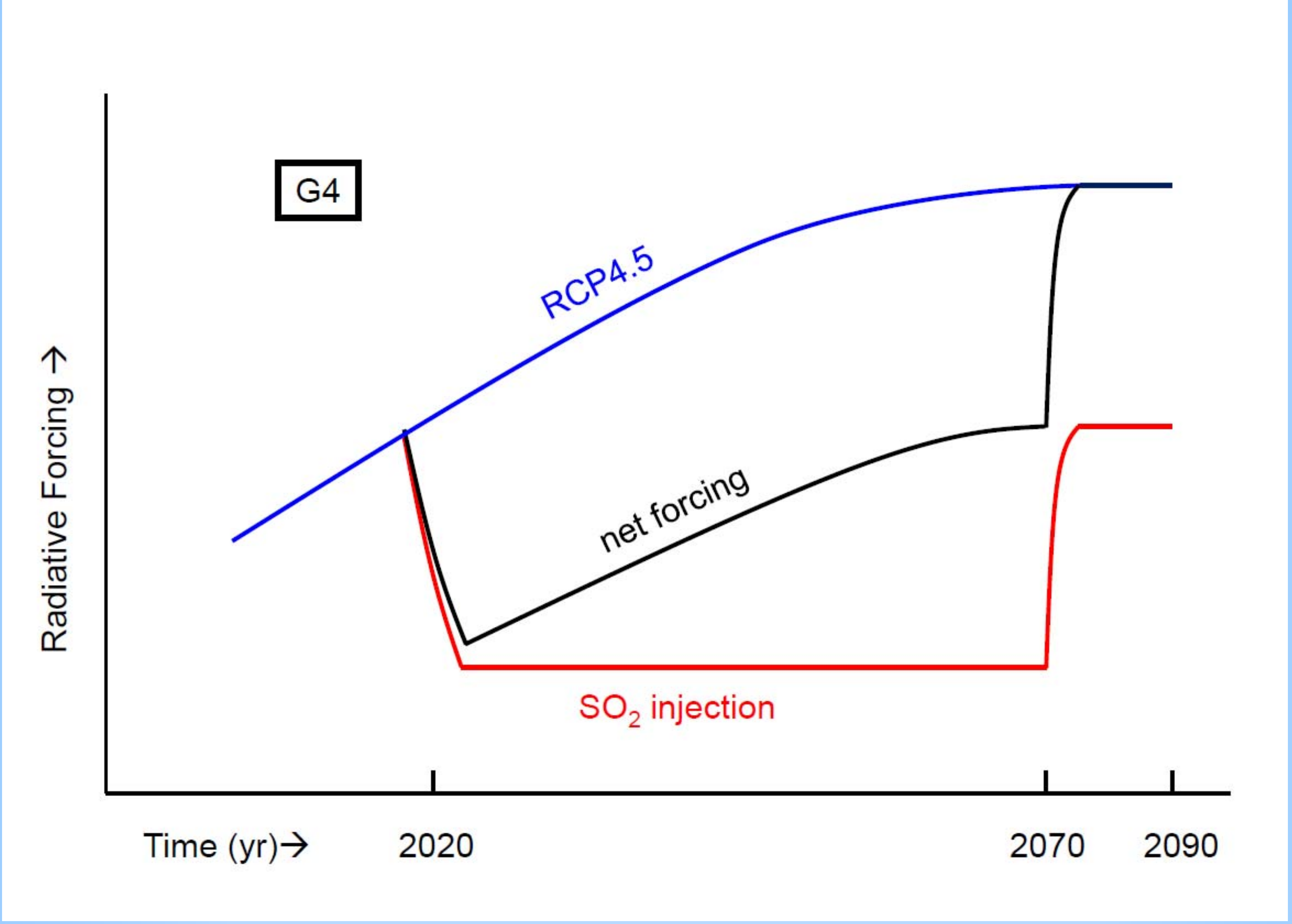
G1: Instantaneously quadruple CO_2 concentrations (as measured from preindustrial levels) while simultaneously reducing the solar constant to counteract this forcing.



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



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.



G4: (optional) 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).

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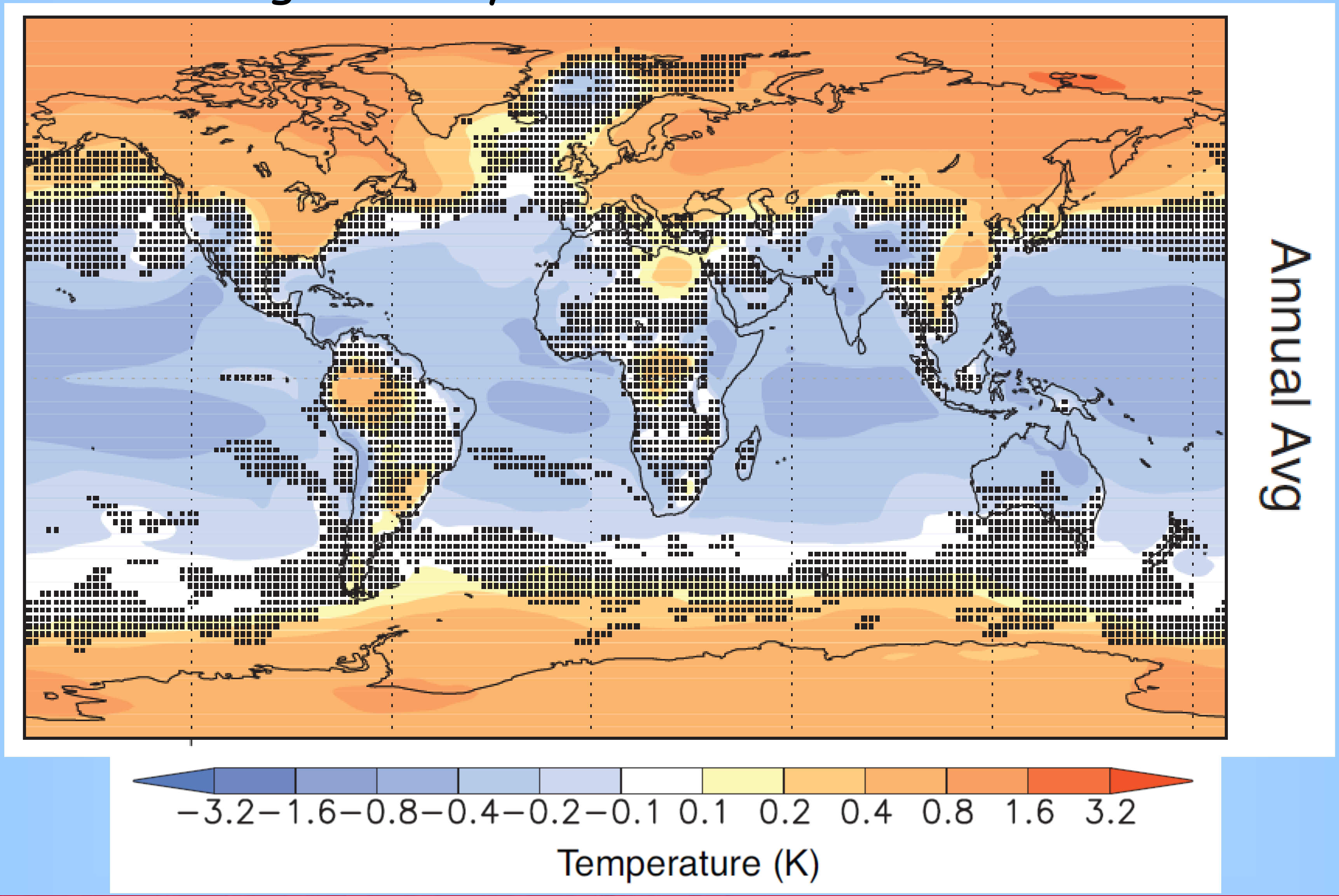
Surface air temperature differences (*G1-piControl*), averaged over years 11-50 of the simulation.



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

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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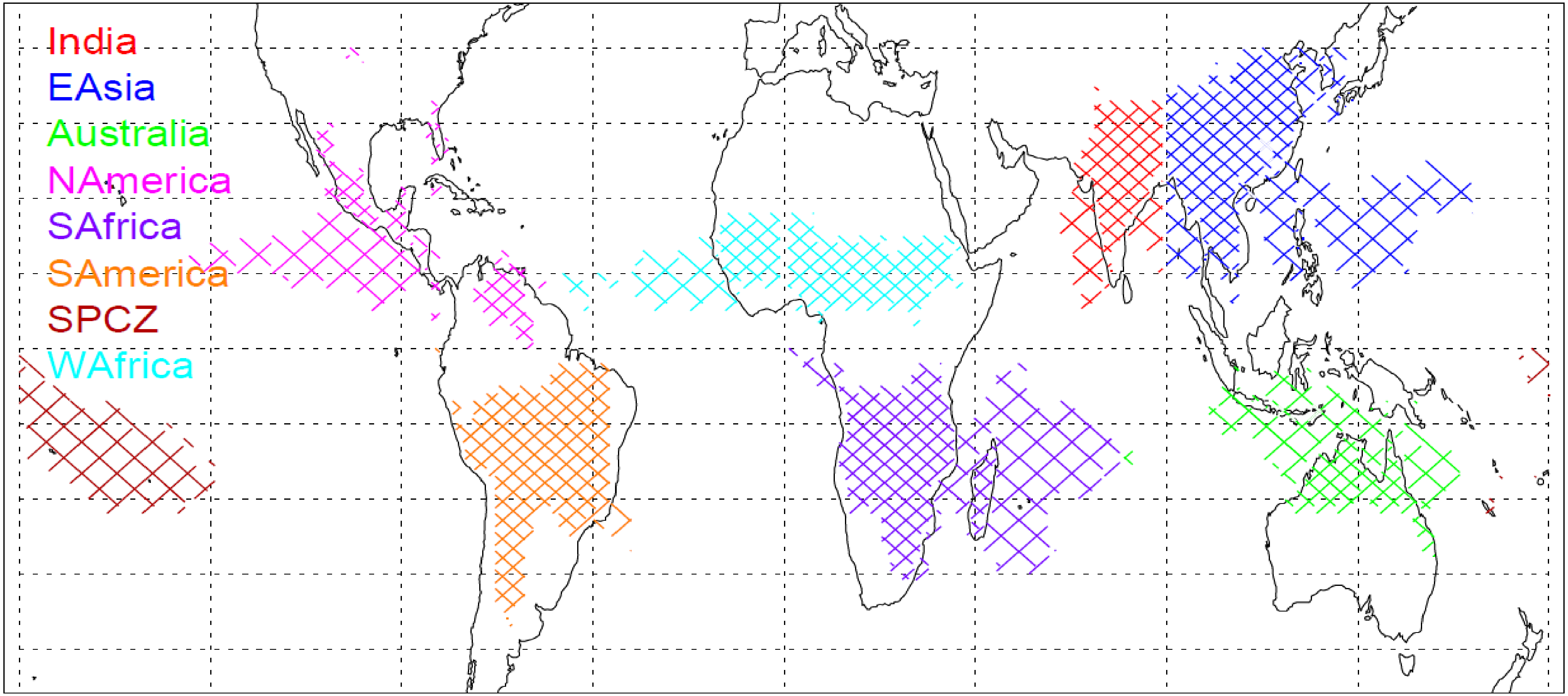
Monsoon regions



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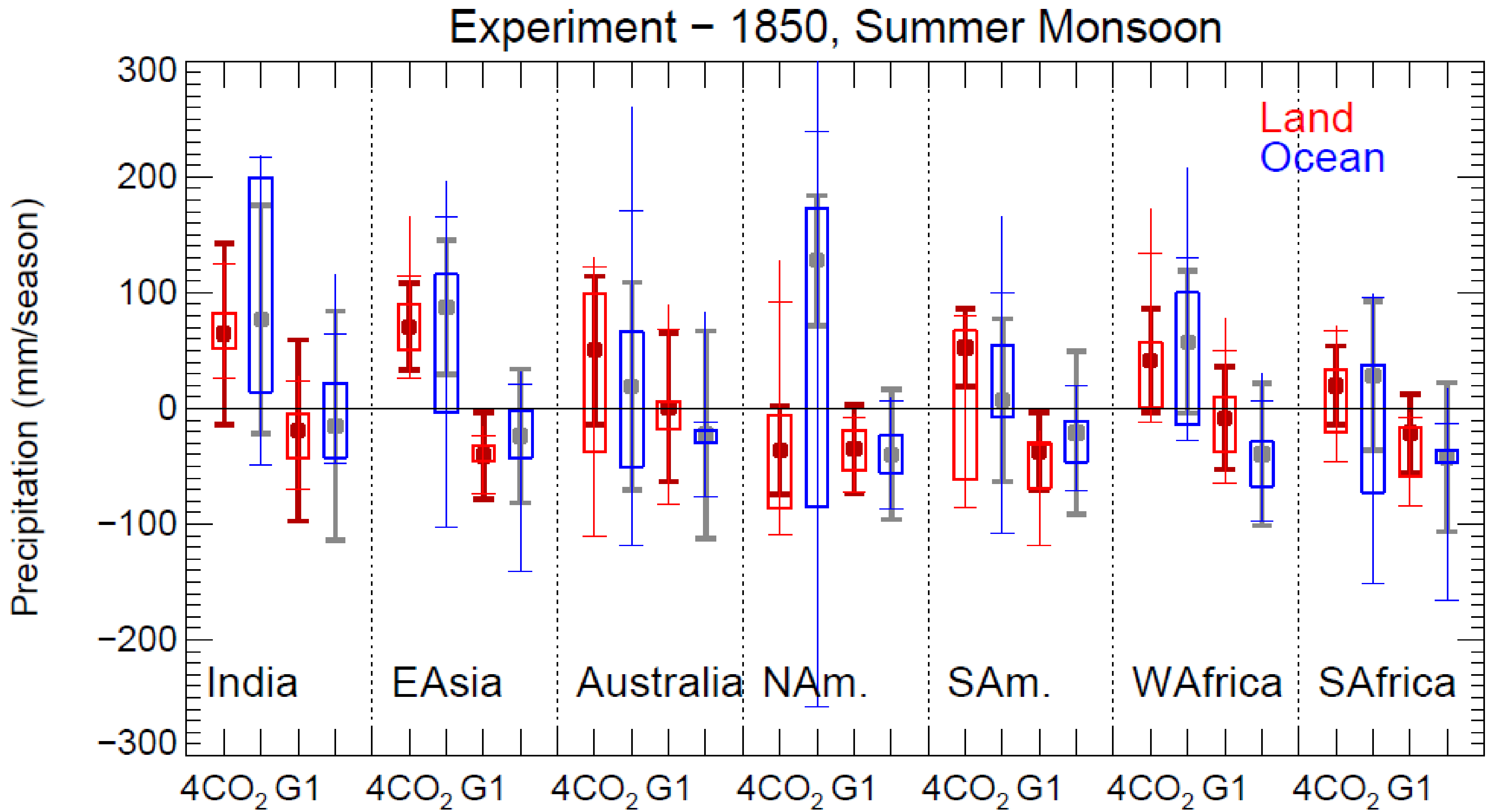

Years 11-50

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Results from G2 experiments by 12 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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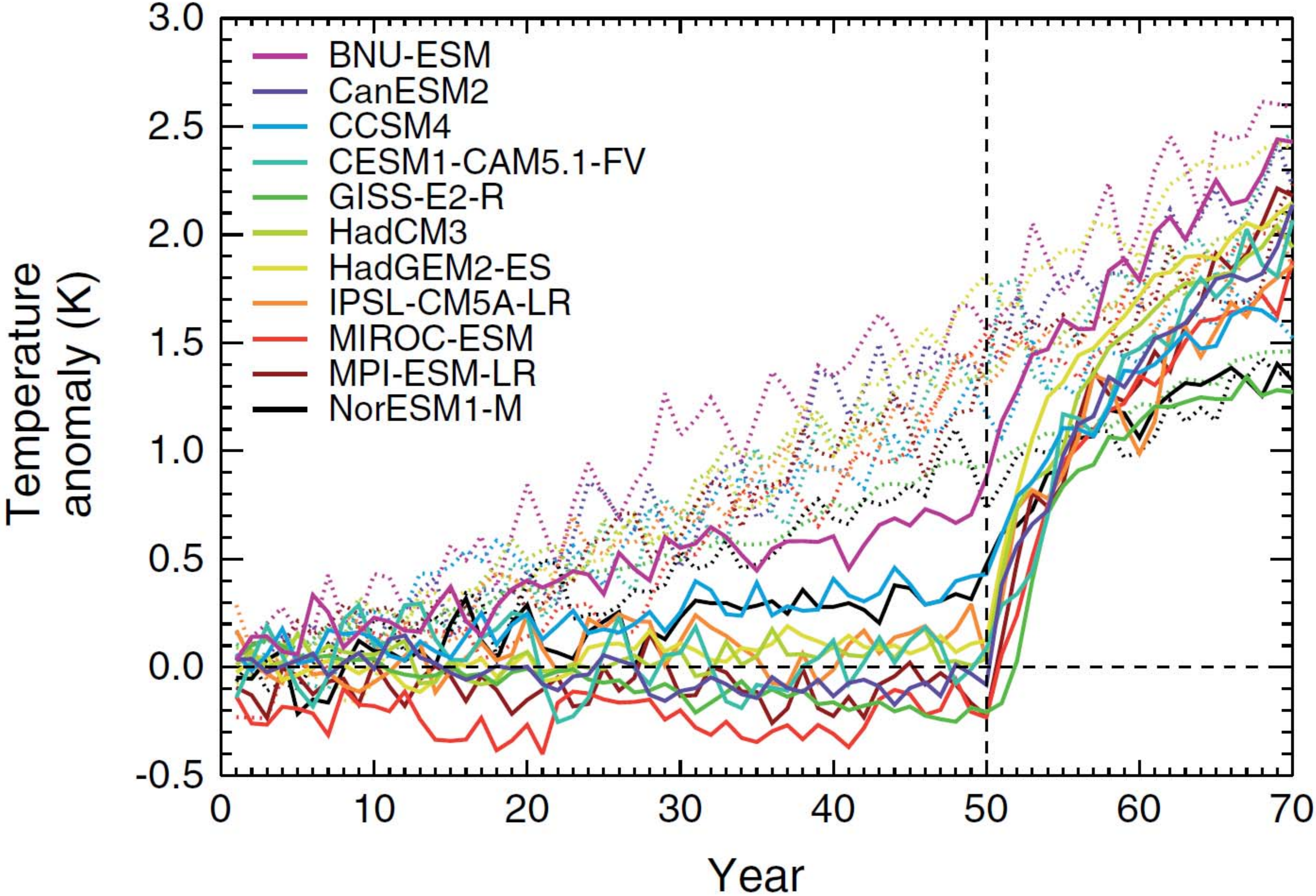
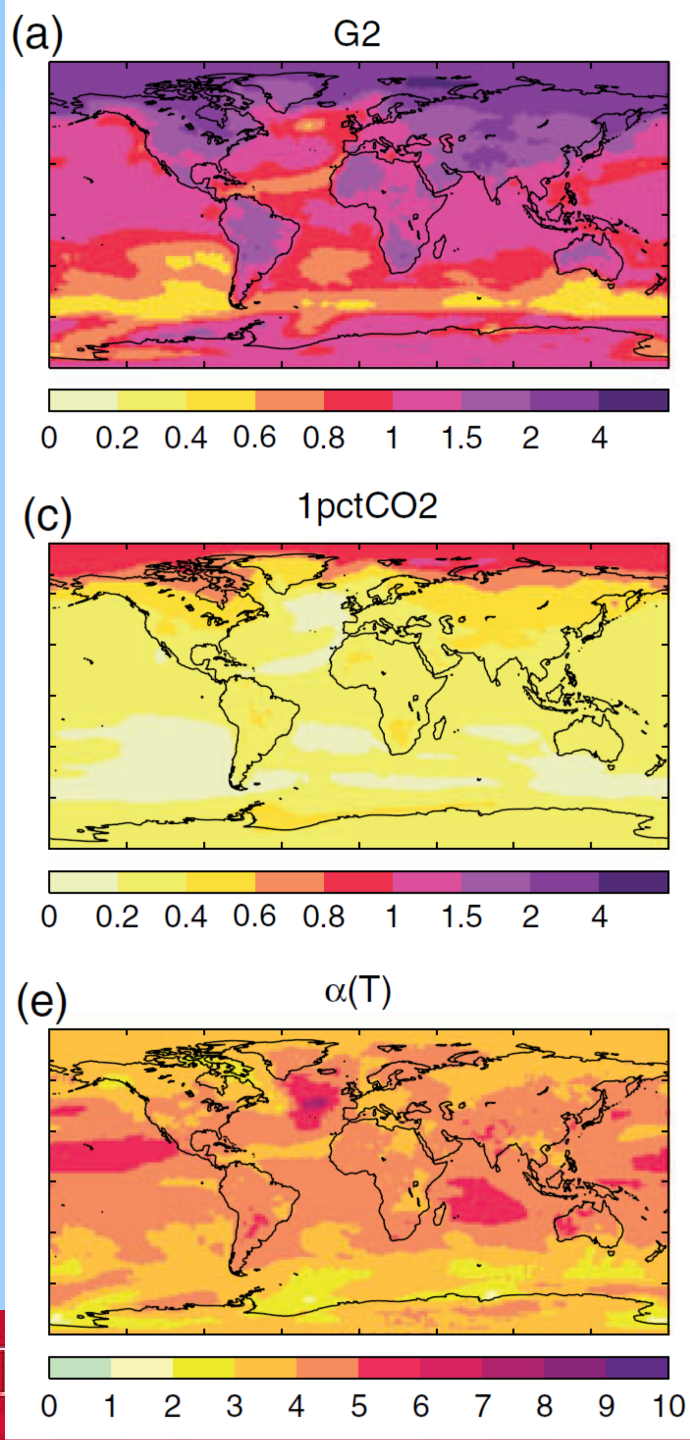


dotted lines are +1%/yr CO_2 solid lines are G2



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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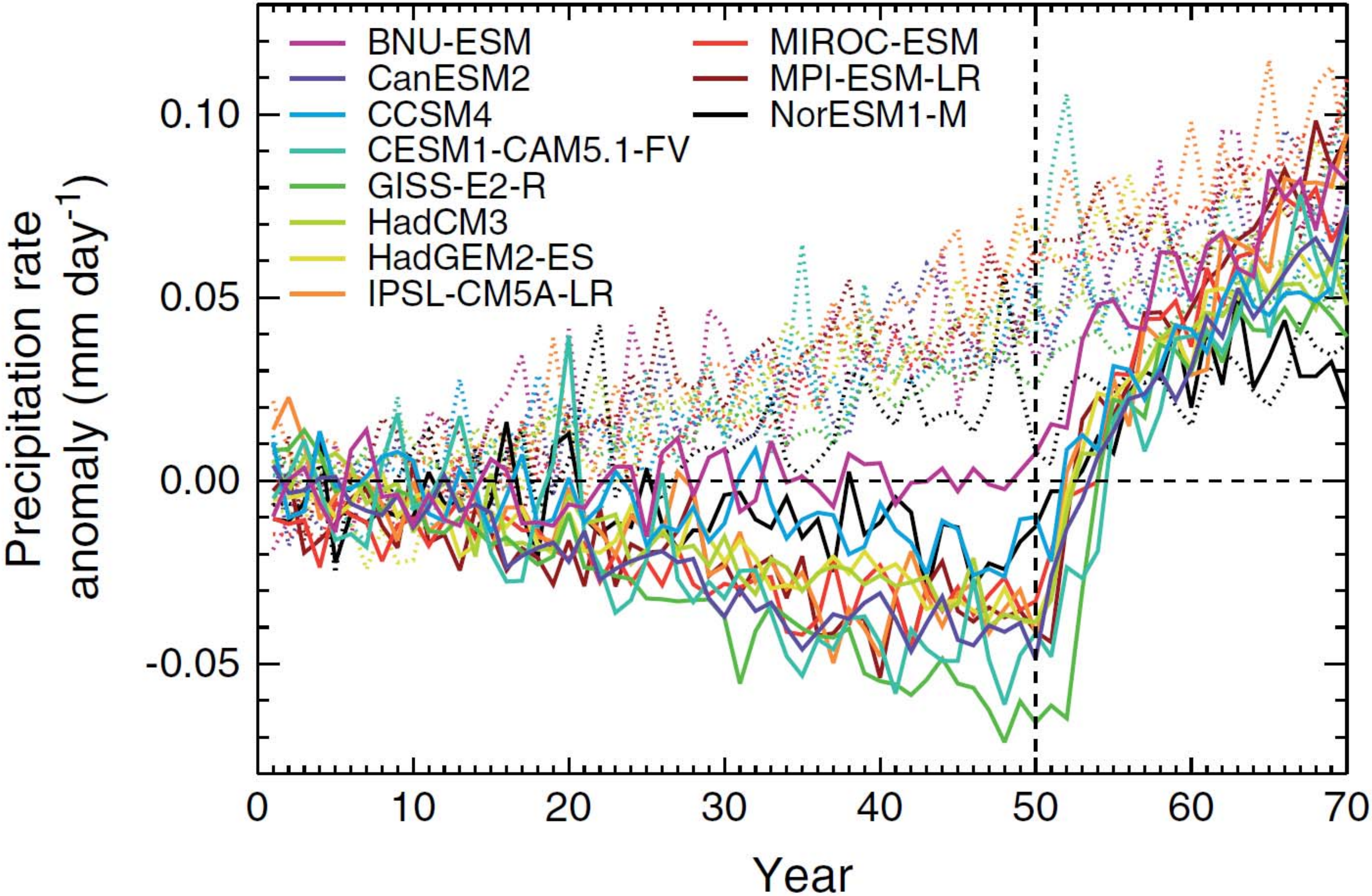
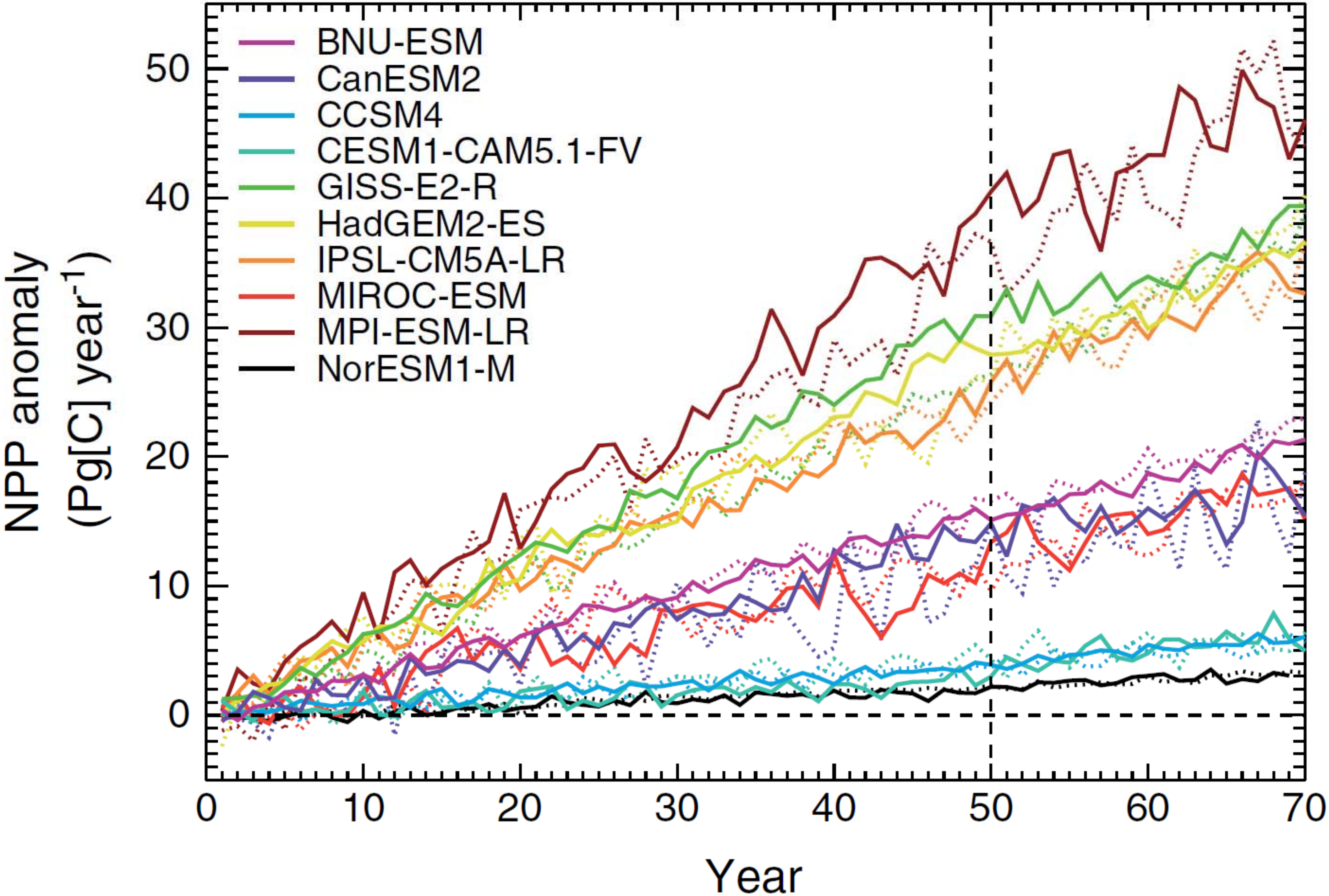
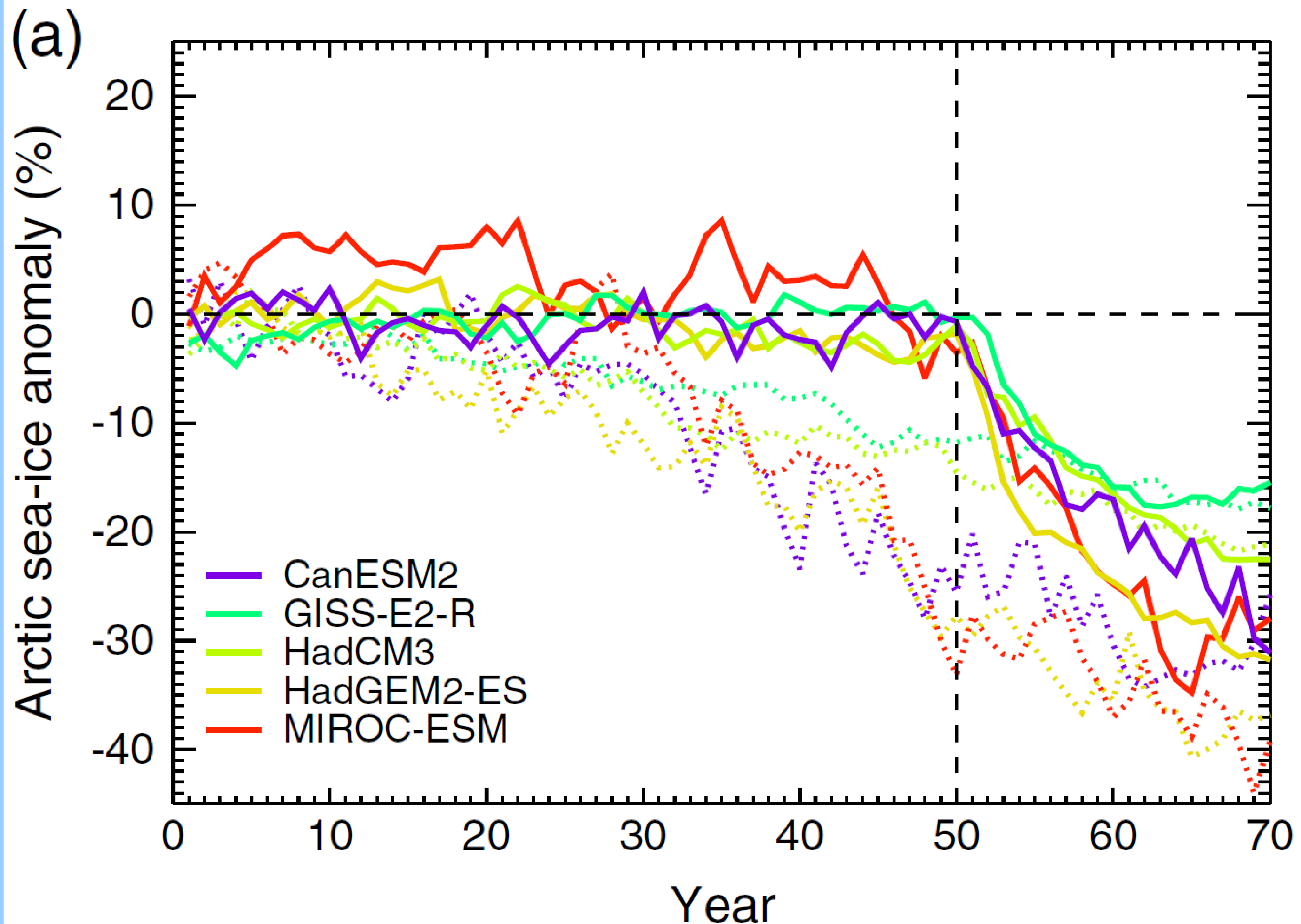


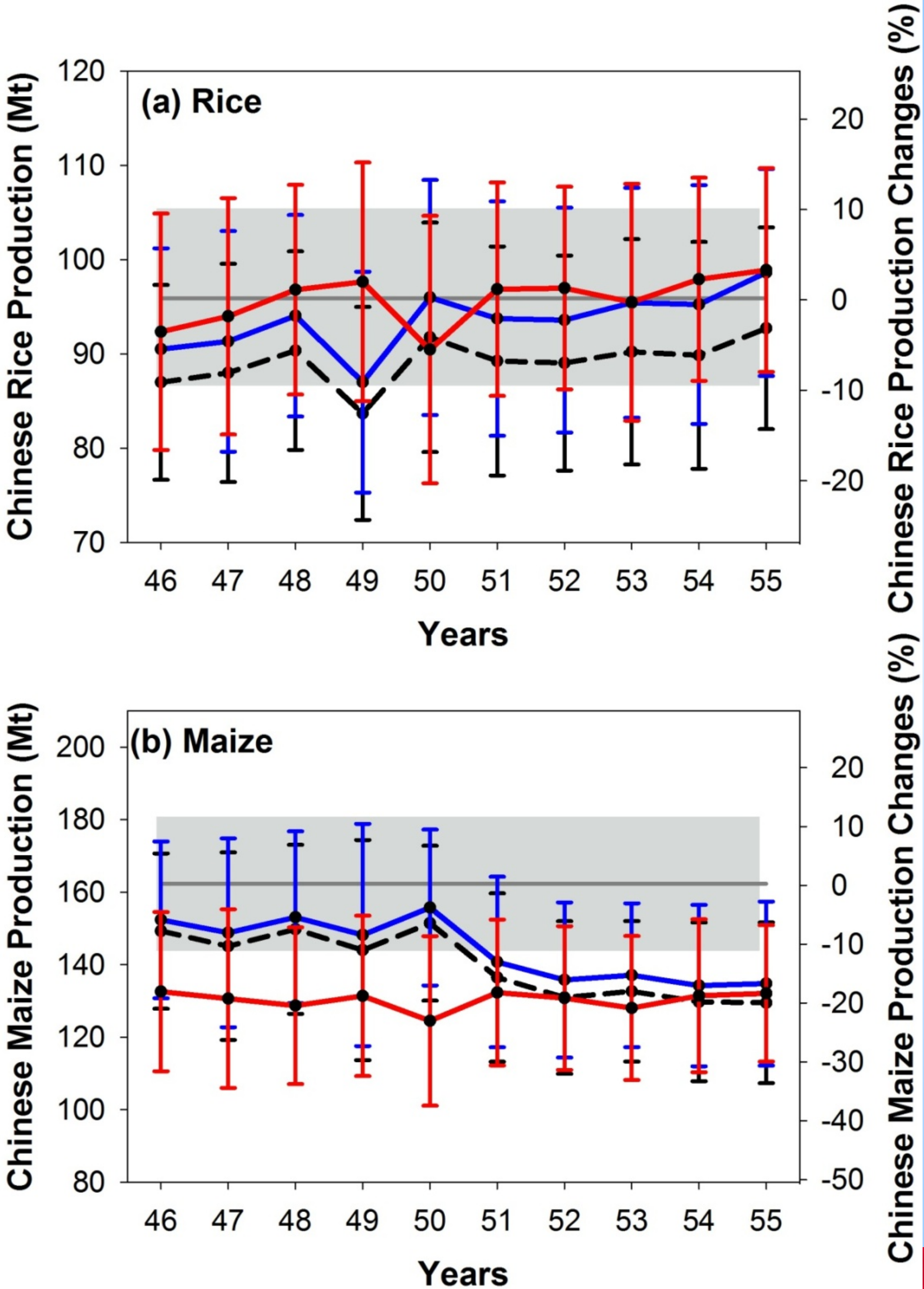
dotted lines are +1%/yr CO_2 solid lines are G2



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



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



$1pctCO_2$

G2

G2, constant CO_2

Xia, Lili, Alan Robock, Jason N. S. Cole, D. Ji, John C. Moore, Andy Jones, Ben Kravitz, Helene Muri, Ulrike Niemeier, B. Singh, Simone Tilmes, and Shingo Watanabe, 2013: Solar radiation management **impacts on agriculture in China**: A case study in the Geoengineering Model Intercomparison Project (GeoMIP). Submitted to *J. Geophys. Res. Atmos.*

Proposed GeoMIP Cloud Brightening Experiments

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

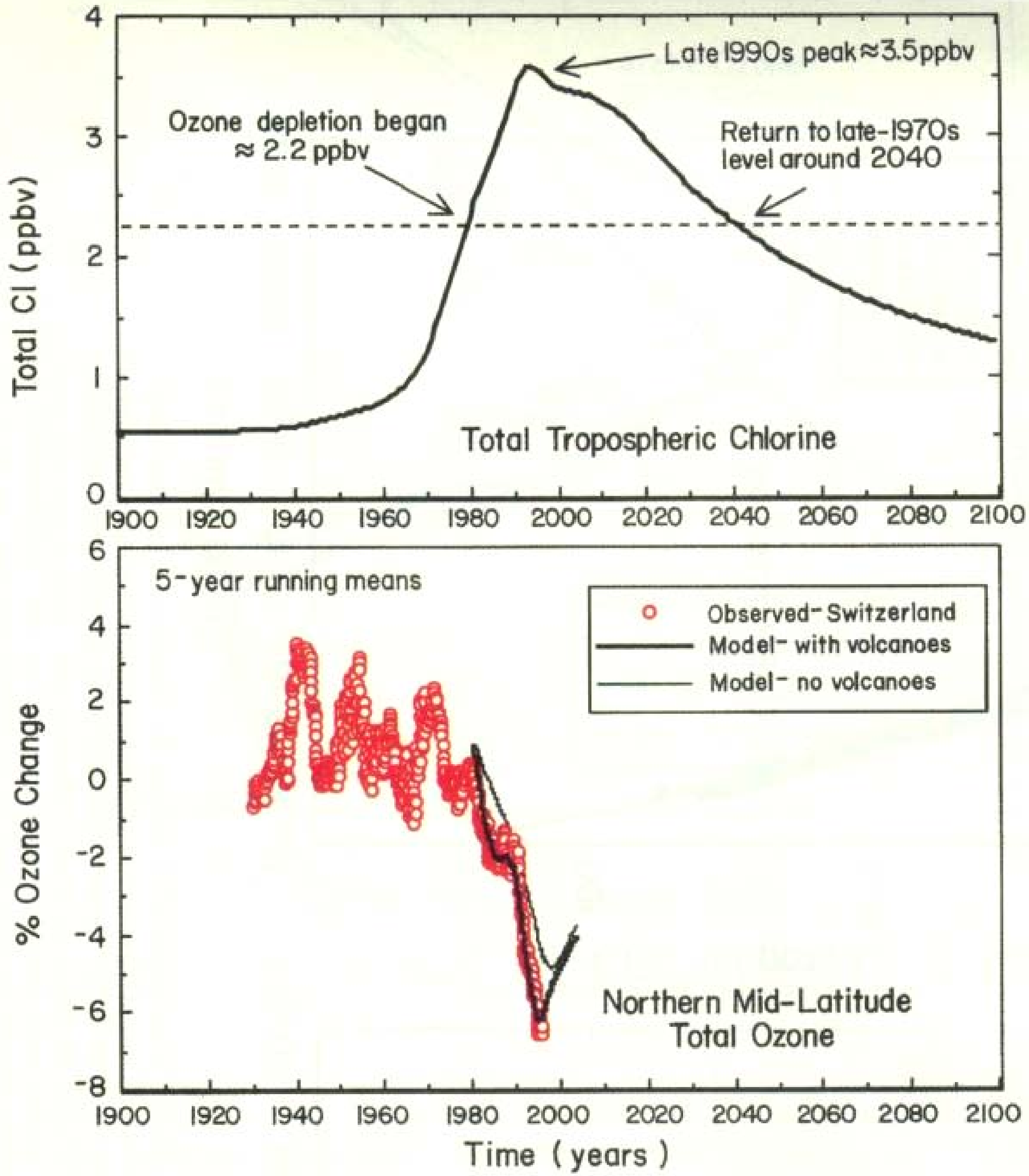
Experiment	*Description*
G1ocean-albedo	Instantaneously quadruple the preindustrial CO_2 concentration while simultaneously increasing ocean albedo to counteract this forcing.
G4cdnc	In combination with RCP4.5 forcing, starting in 2020, increase cloud droplet number concentration by 50% over the ocean.
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**, doi:10.1002/jgrd.50856, in press.

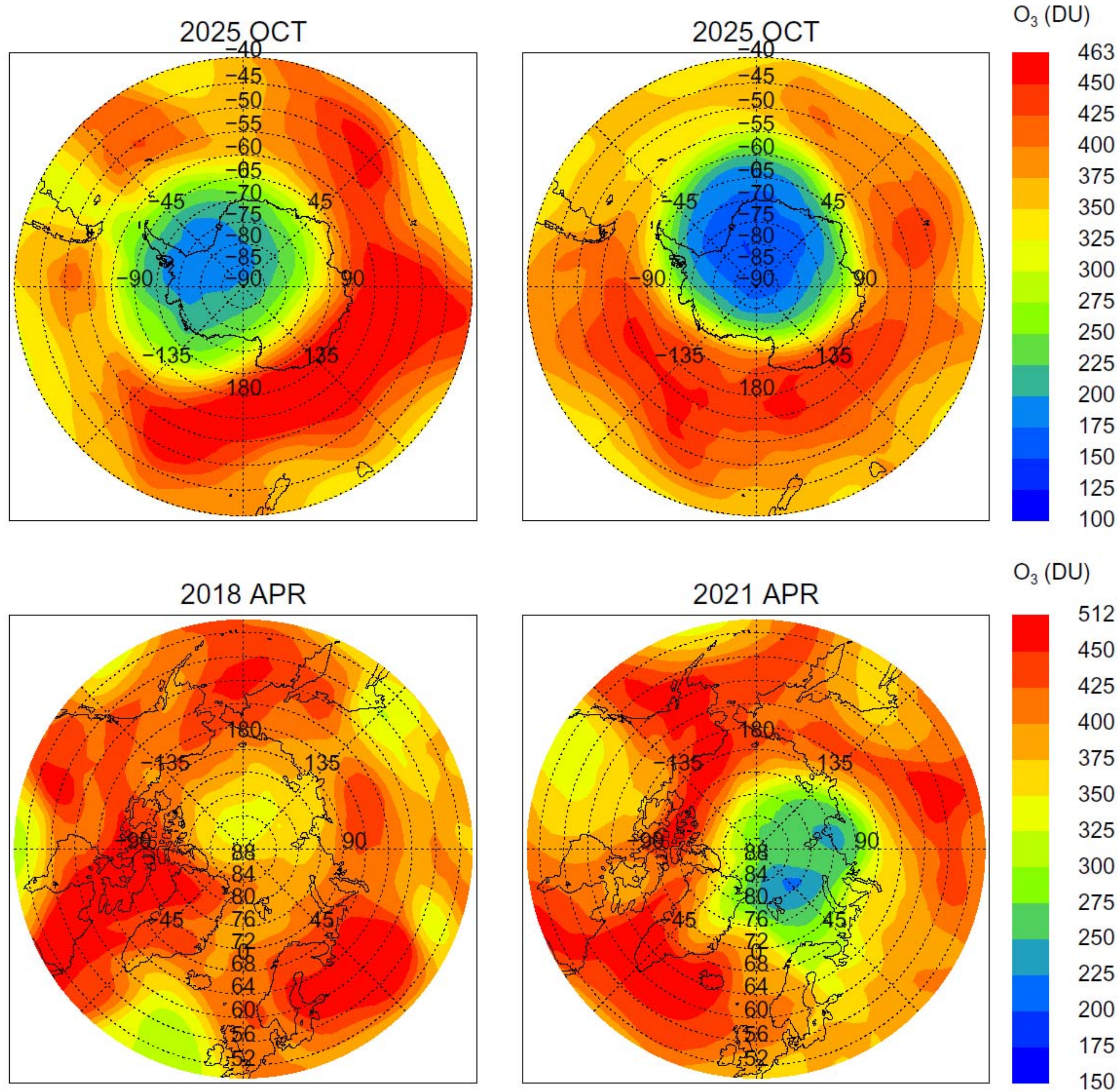
Tropospheric chlorine diffuses to stratosphere.

Volcanic aerosols make chlorine available to destroy ozone.

Solomon (1999)



Baseline Run   Geoengineering Run



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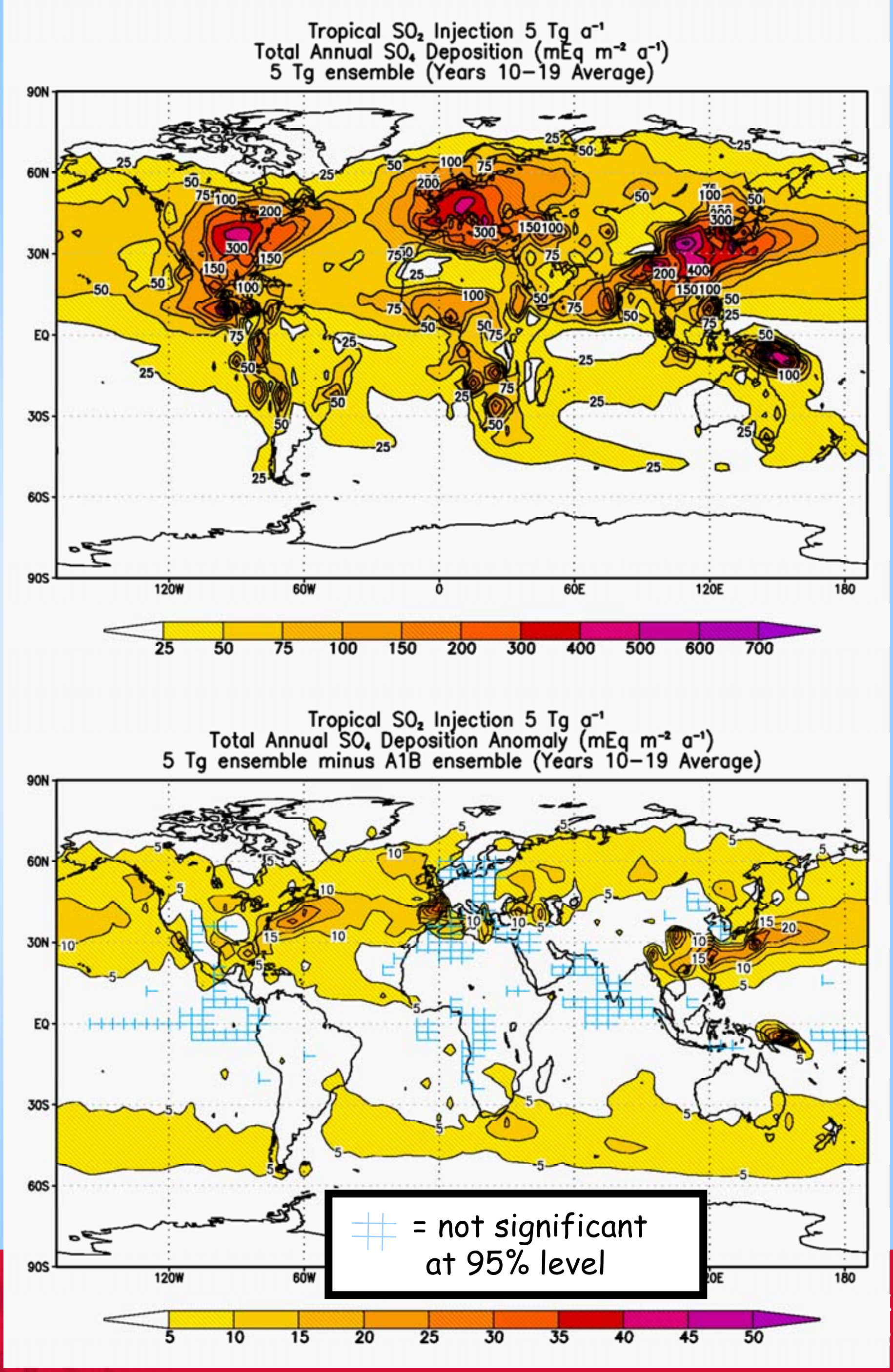
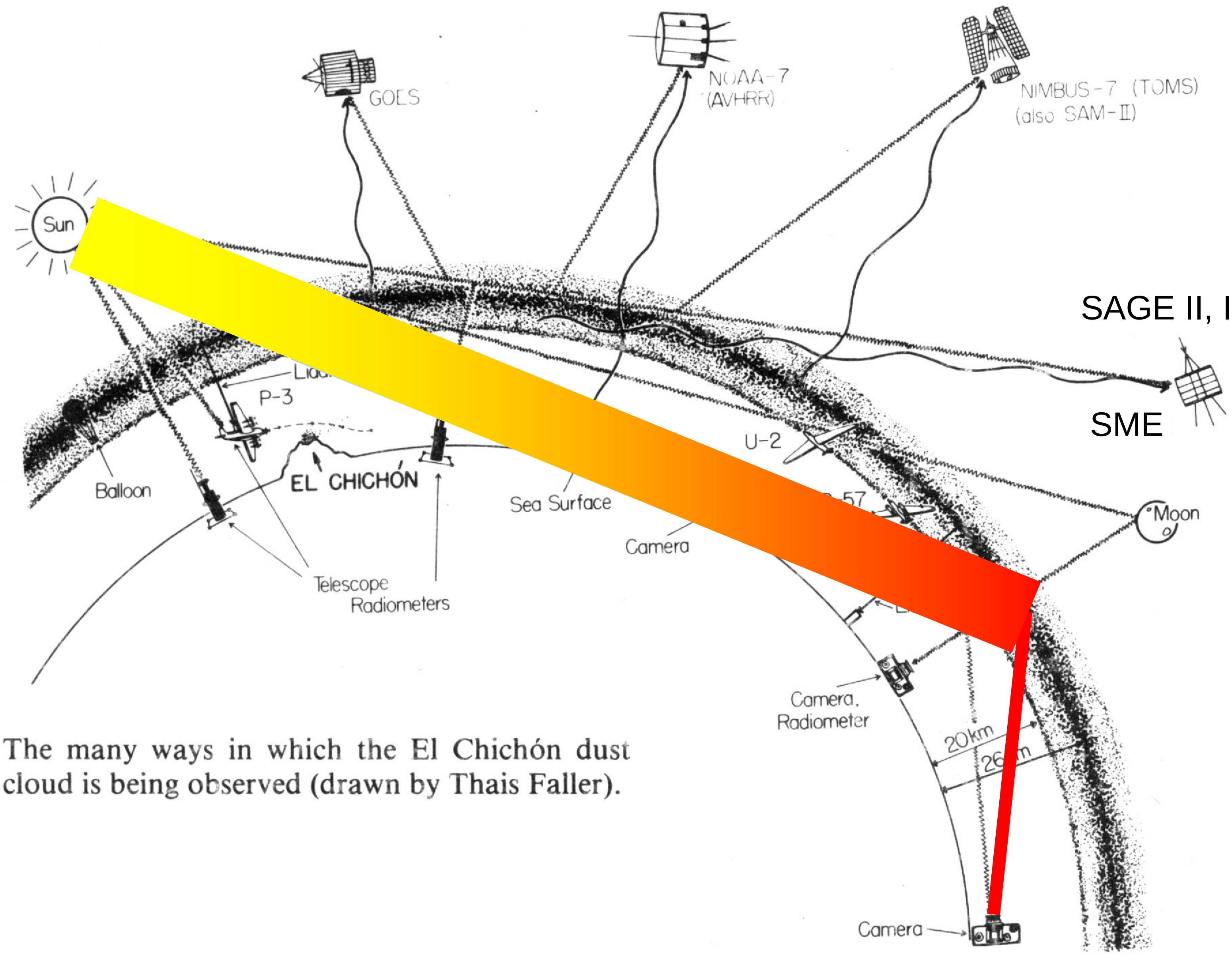
Ranges of critical loading of pollutant deposition (including sulfur) for various sites in Europe [*Skeffington*, 2006]

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.



The many ways in which the El Chichón dust cloud is being observed (drawn by Thais Faller).

Krakatau, 1883
Watercolor by William Ascroft

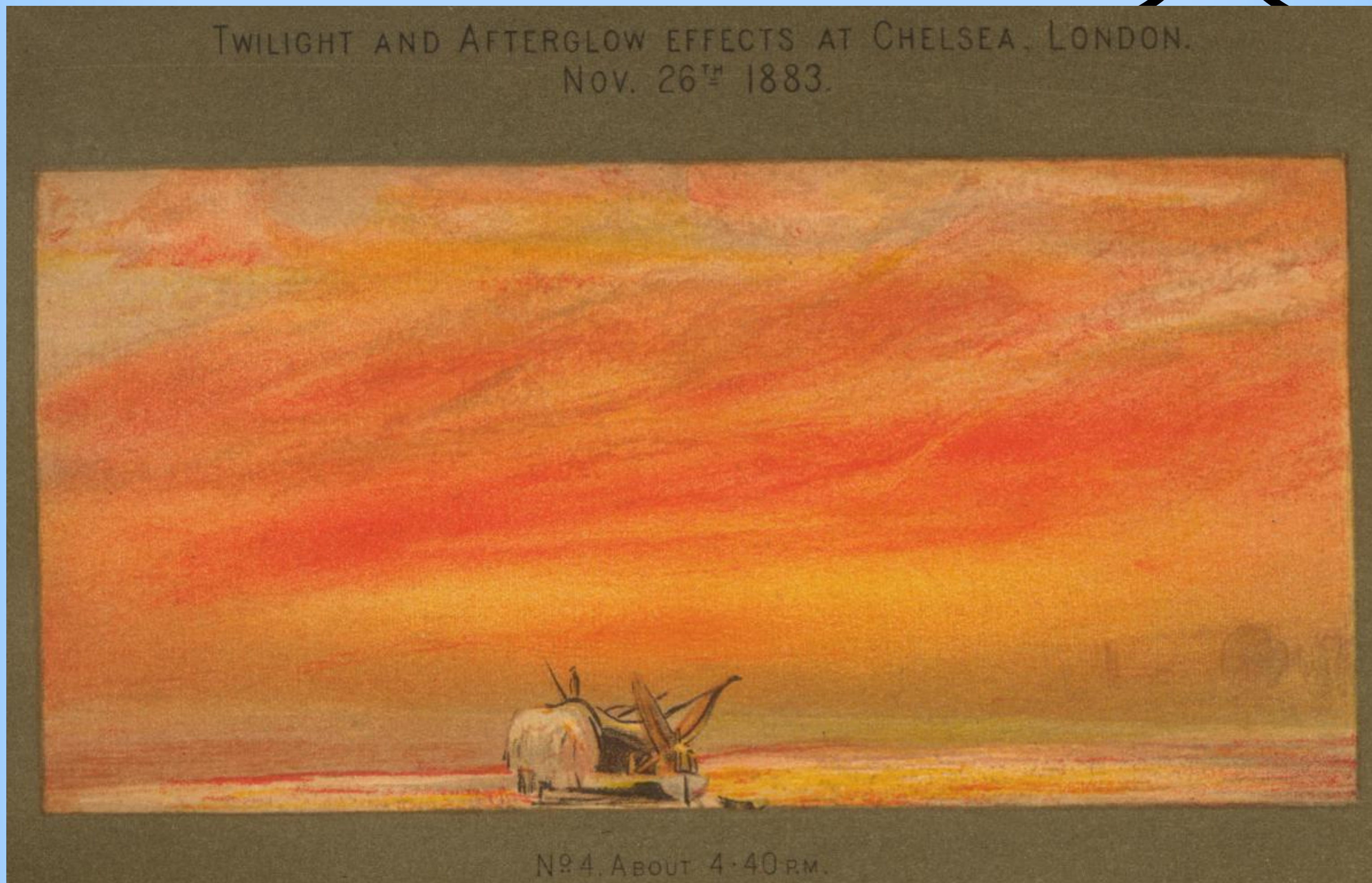


Figure from Symons (1888)

"The Scream"

Edvard Munch

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

Sunset over Lake Mendota, July 1982

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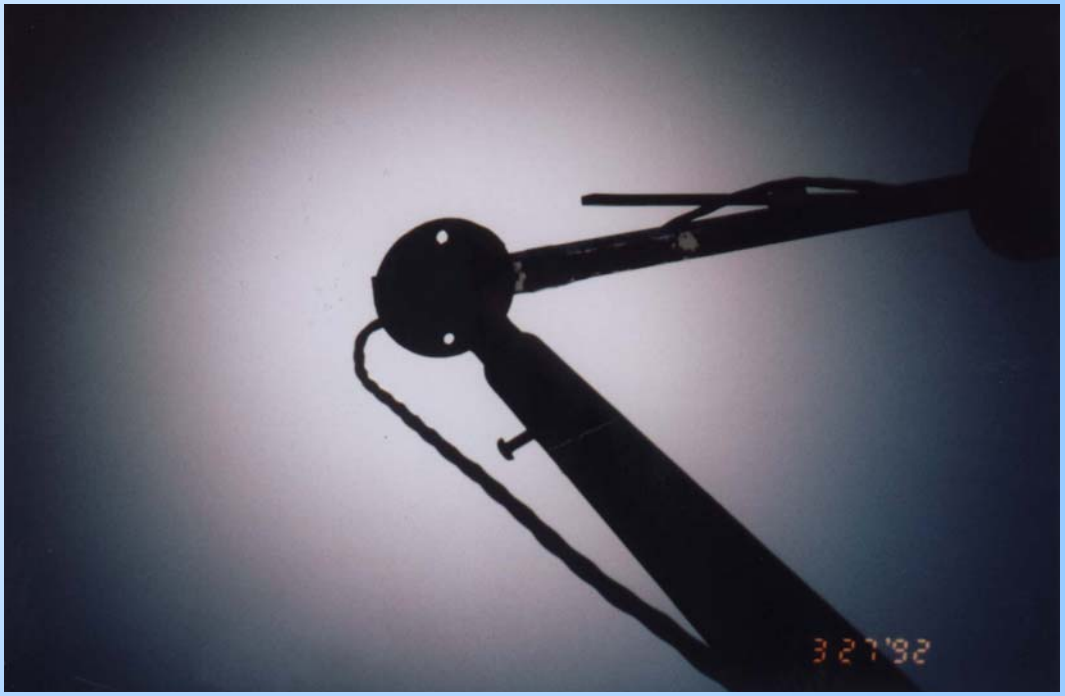
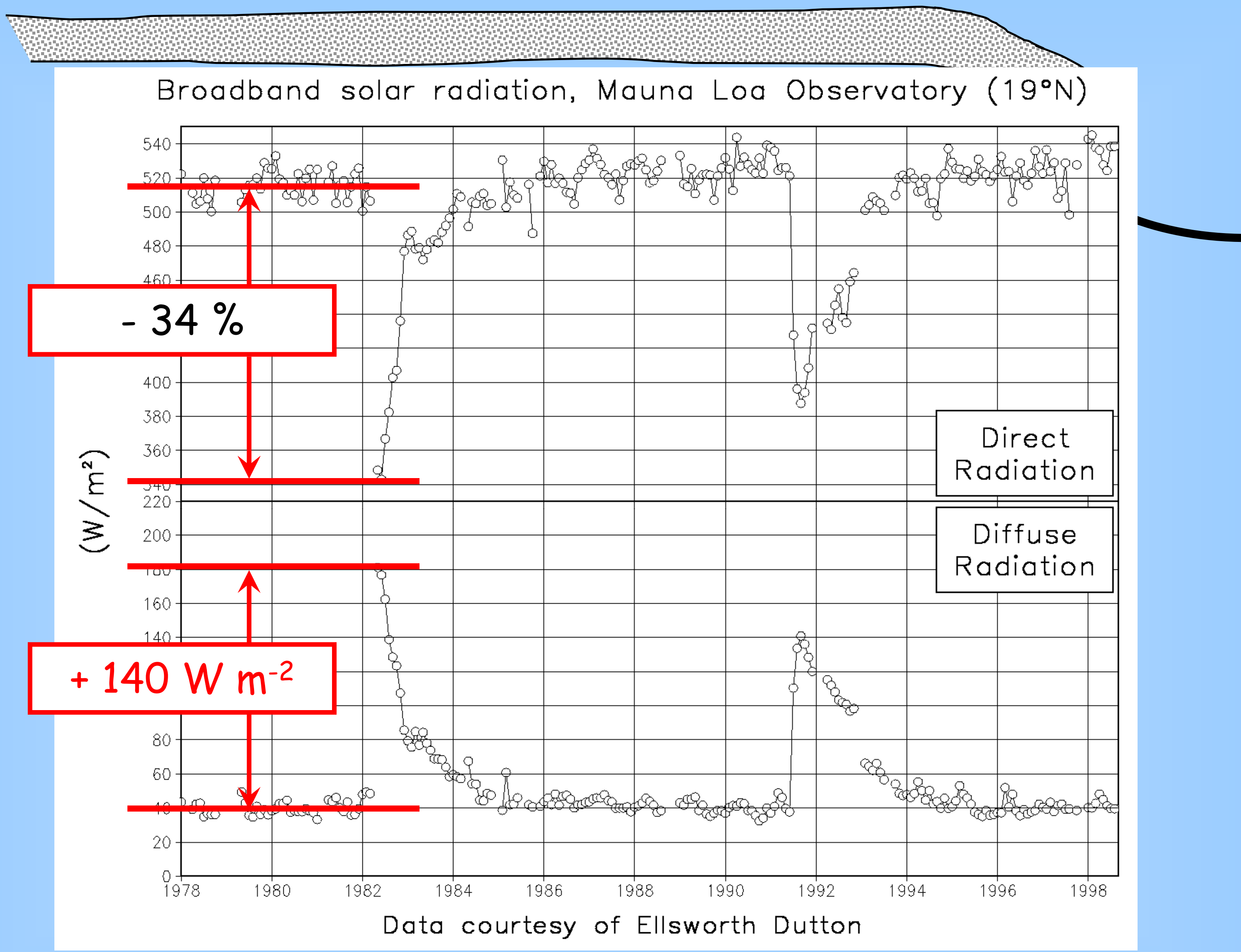
Diffuse Radiation from Pinatubo Makes a Whiter Sky



Photographs by Alan Robock



Robock (2000), Dutton and Bodhaine (2001)

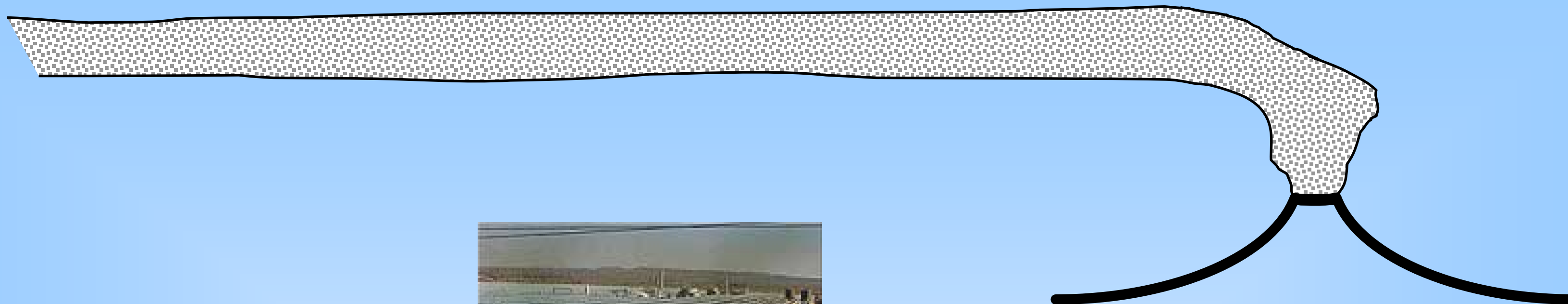
Geoengineering: Whiter skies?

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.



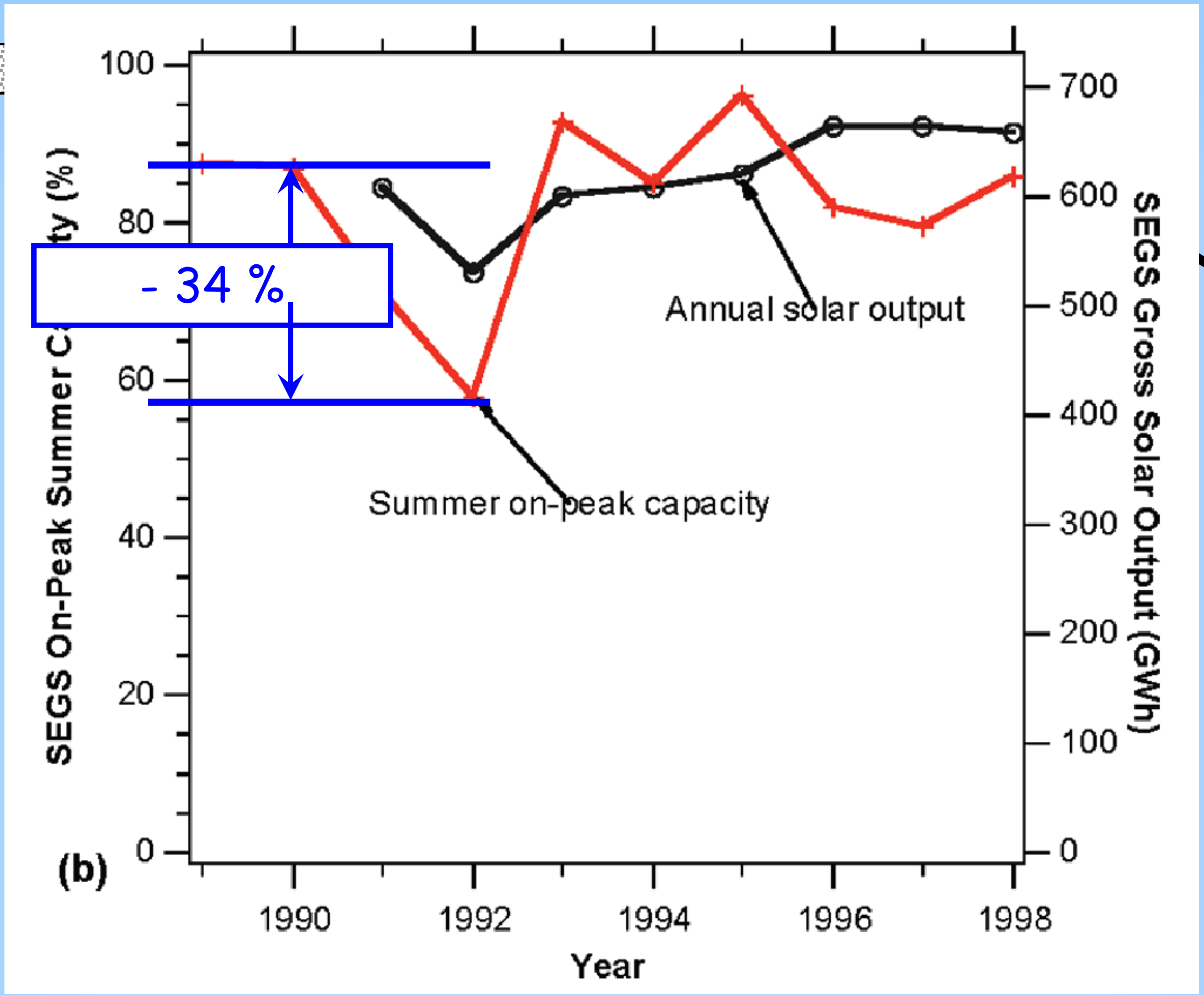
Nevada Solar One
64 MW

Solar steam generators
requiring direct solar

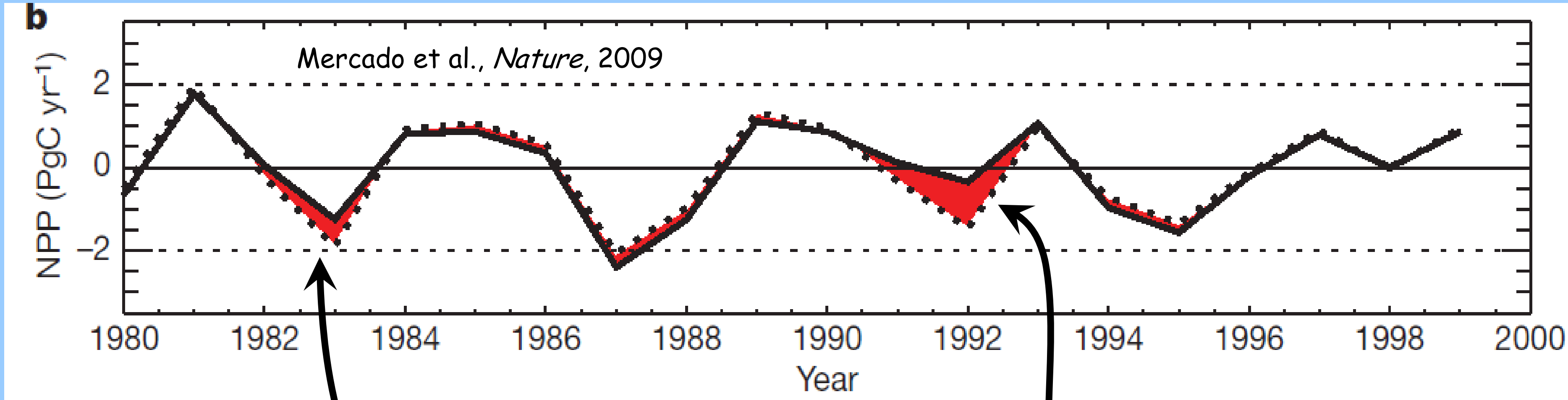
Seville, Spain
Solar Tower
11 MW

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

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



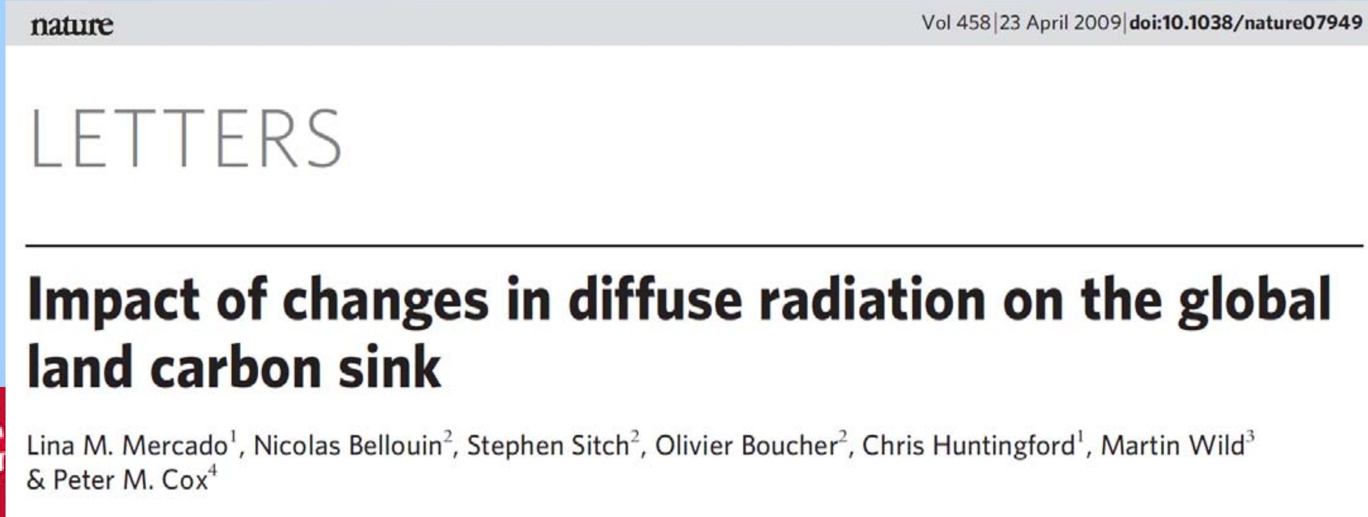
Output of solar electric generating systems (SEGS) solar thermal power plants in California (9 with a combined capacity of 354 peak MW). (Murphy, 2009, *ES&T*)



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 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]

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
X6. 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

Alan Robock
Department of Environmental Sciences

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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Department of Environmental Sciences

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.

Drawing by Brian West

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.

RUTGERS
Alan Robock
Department of Environmental Sciences


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

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.

Alan Robock
Department of Environmental Sciences

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, Chapter 5 of special issue "Geoengineering of the Climate System," *Issues Env. Sci. Tech.*, 38, in press.

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
11. Human error
12. Unexpected consequences
13. Commercial control
14. Military use of technology
15. Societal disruption, conflict between countries
16. Conflicts with current treaties
17. Whose hand on the thermostat?
18. Effects on airplanes flying in stratosphere
19. Effects on electrical properties of atmosphere
20. Environmental impact of implementation
21. Degrade terrestrial optical astronomy
22. Affect stargazing
23. Affect satellite remote sensing
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?

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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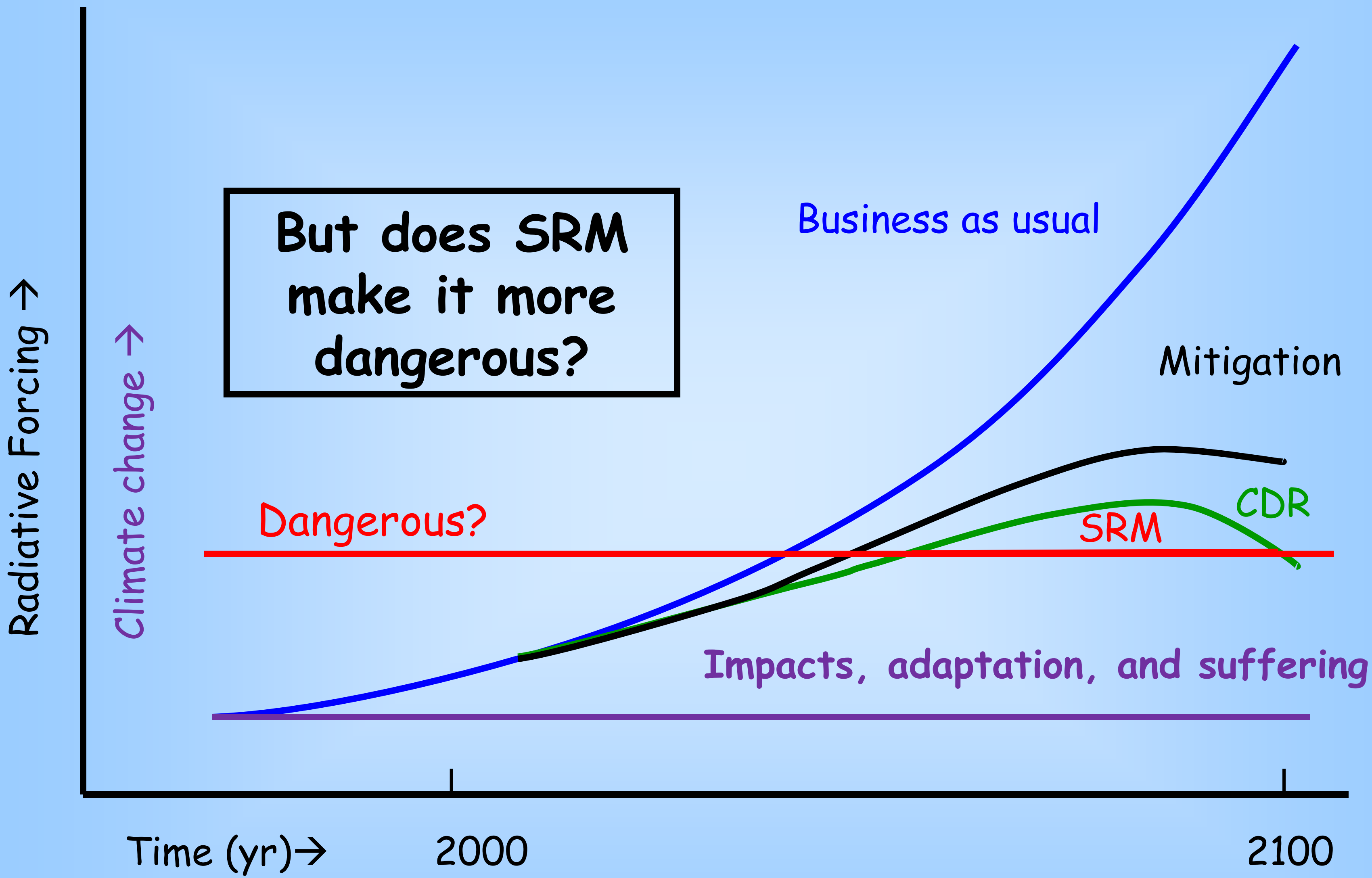

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Department of Environmental Sciences

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.

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.”

Alan Robock
Department of Environmental Sciences

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