

Stratospheric Sulfur Geoengineering - Benefits and Risks

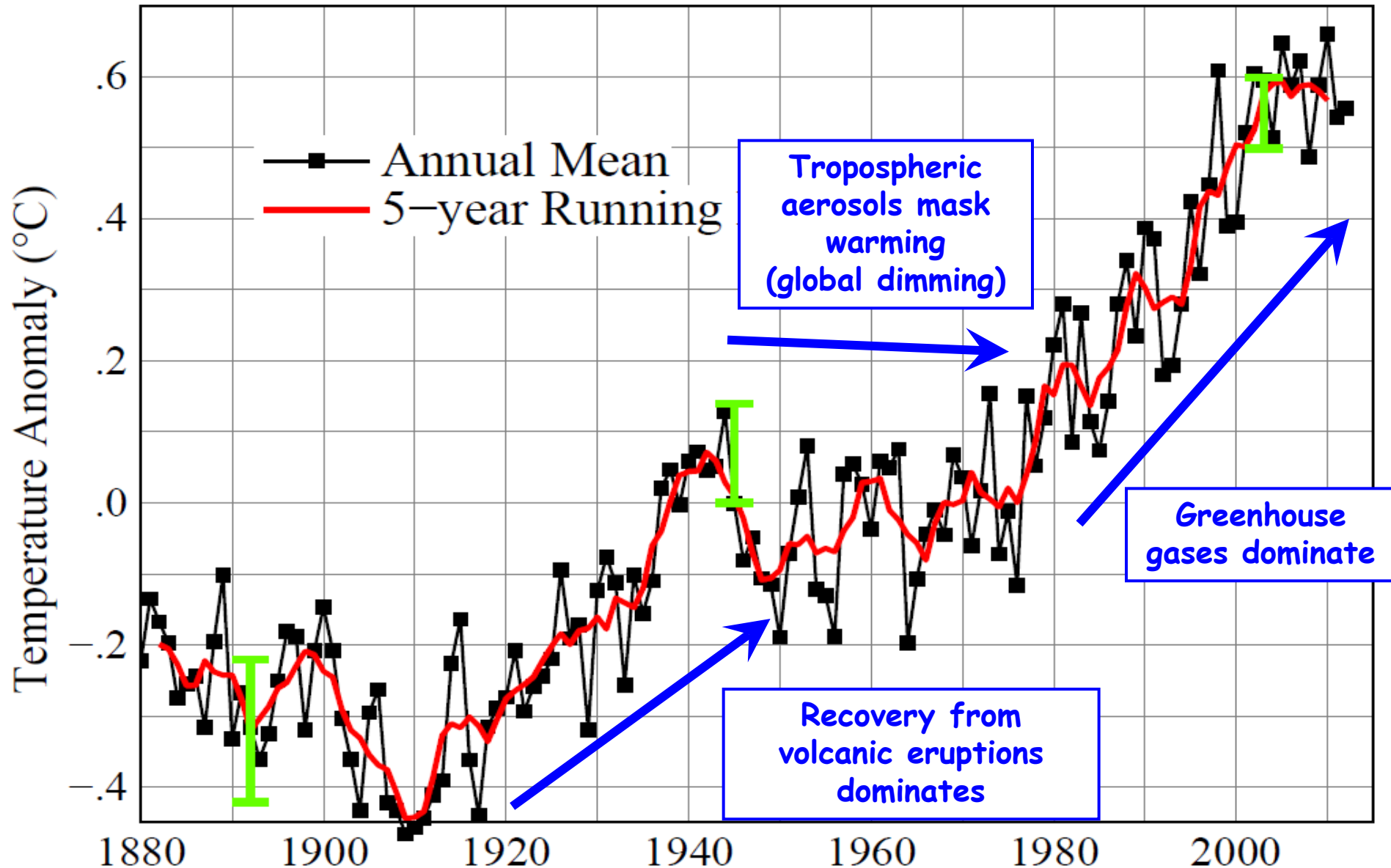
Alan Robock

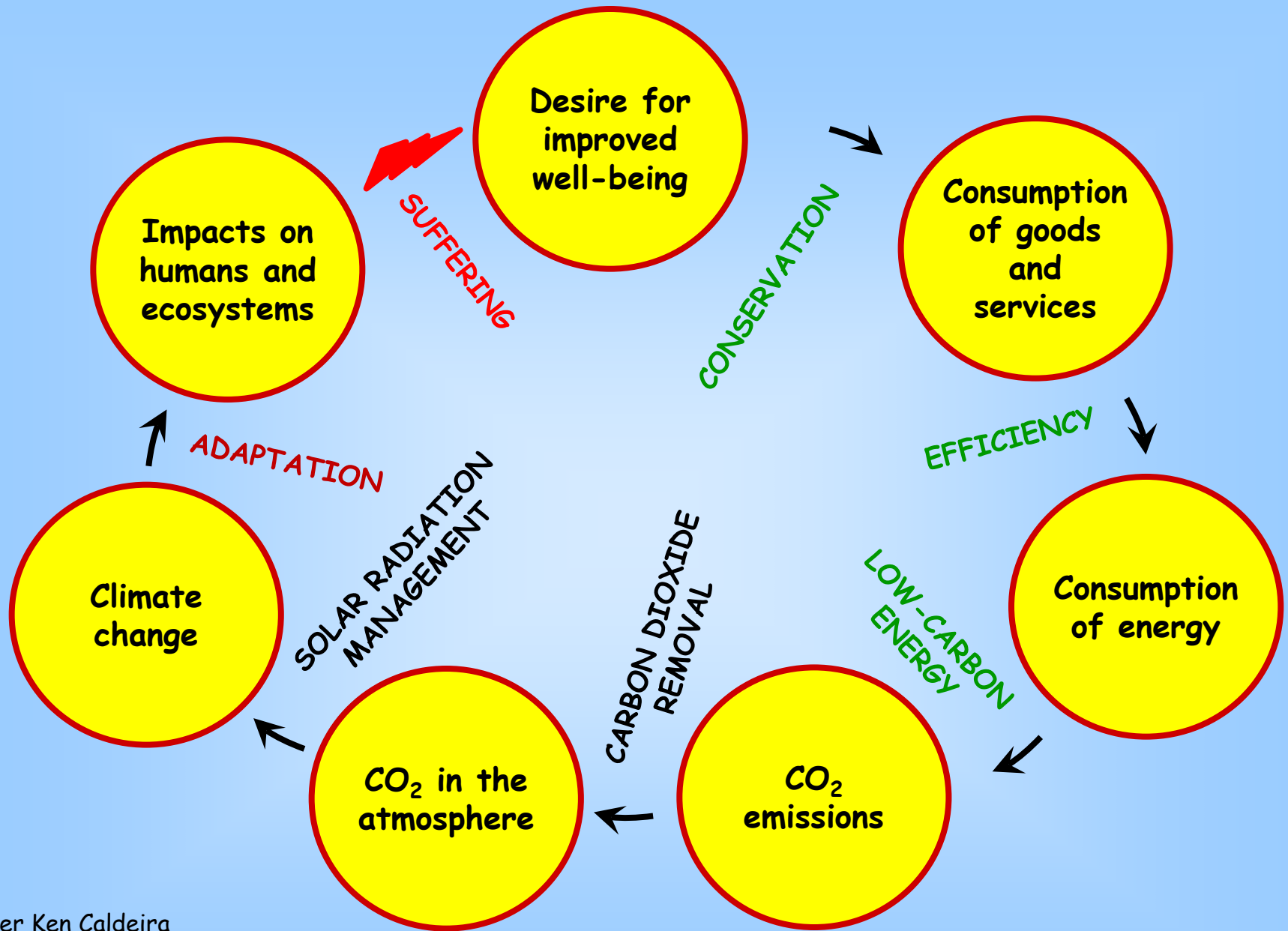
Department of Environmental Sciences
Rutgers University, New Brunswick, New Jersey

robock@envsci.rutgers.edu

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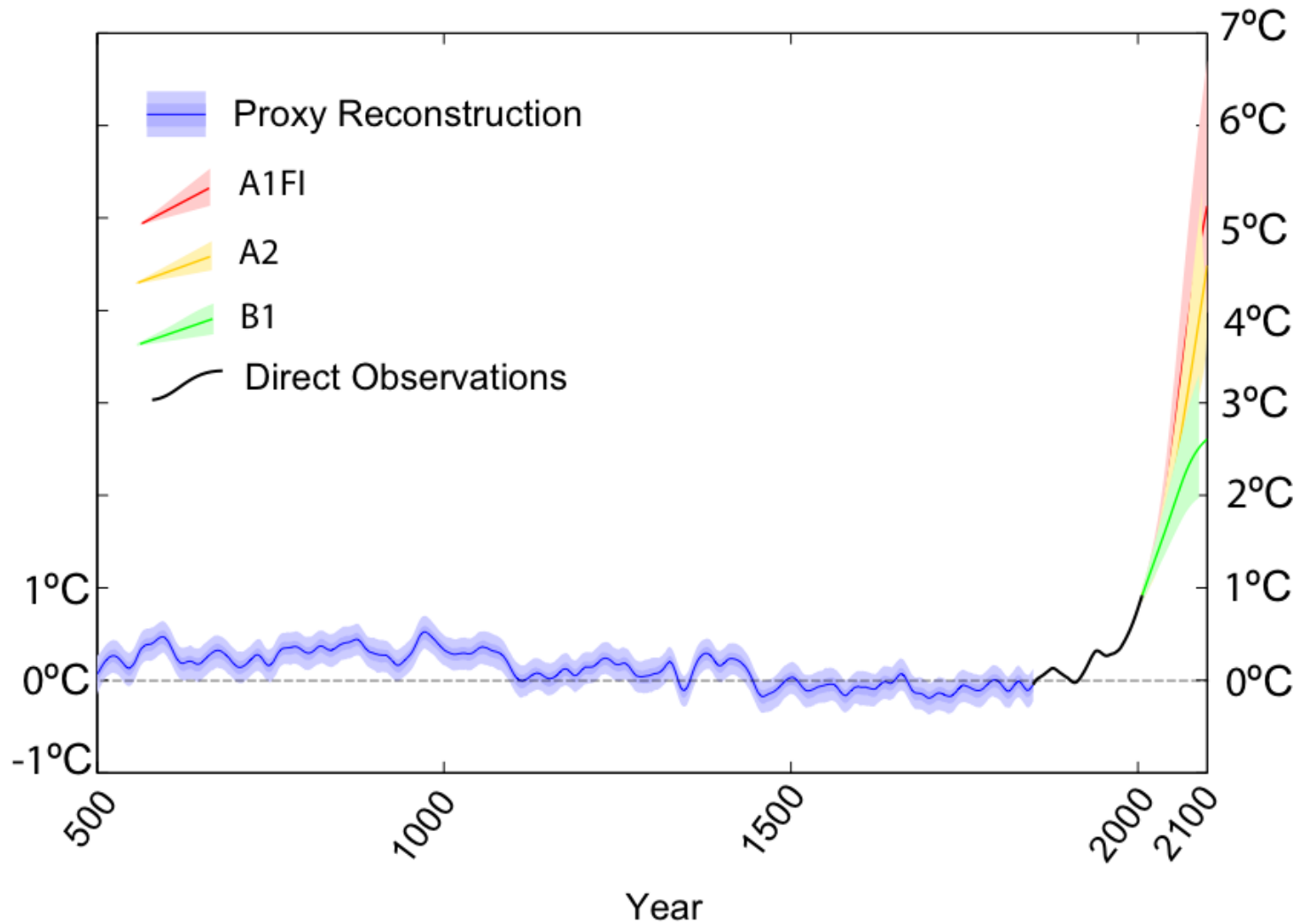
Global Land–Ocean Temperature Index



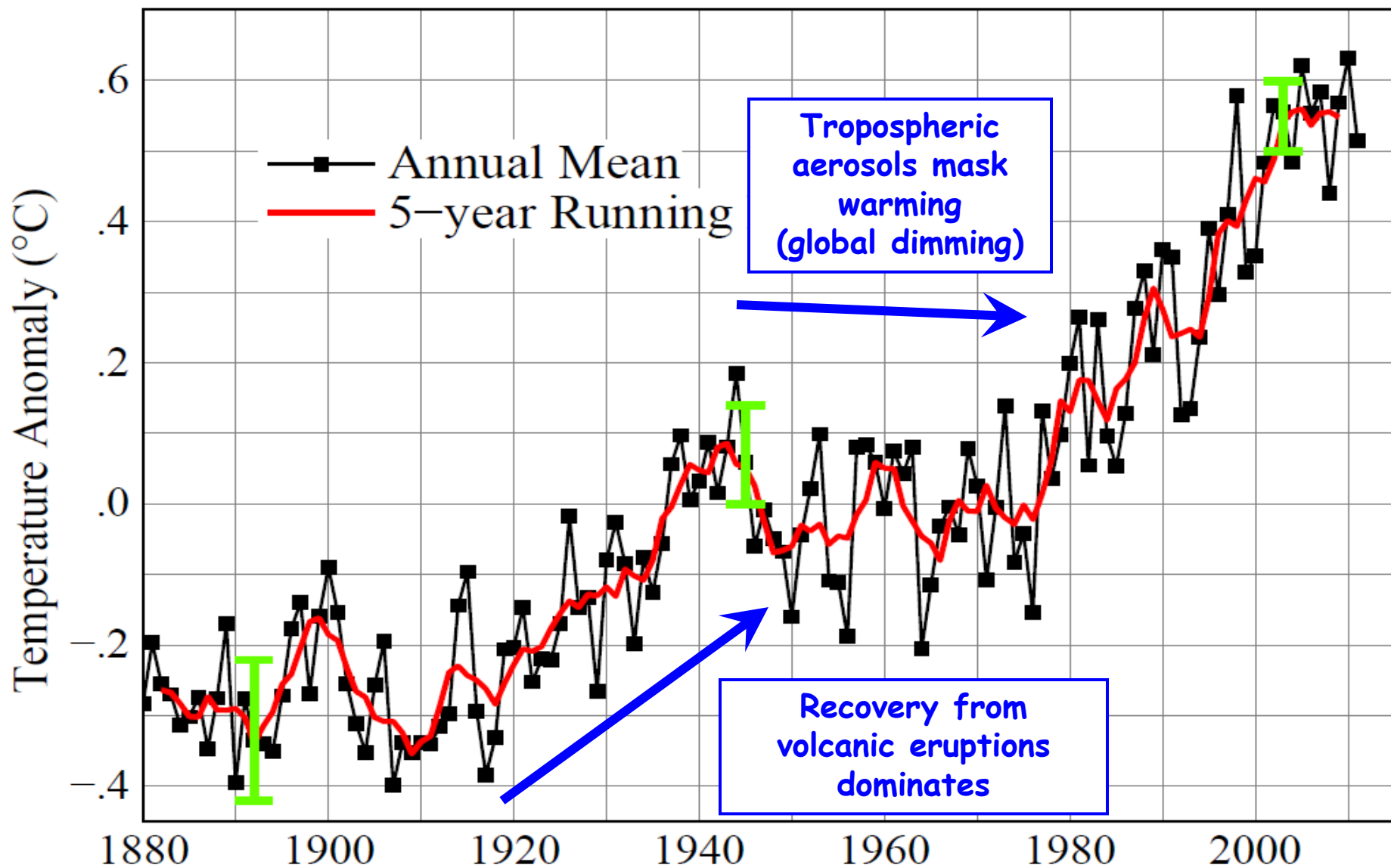


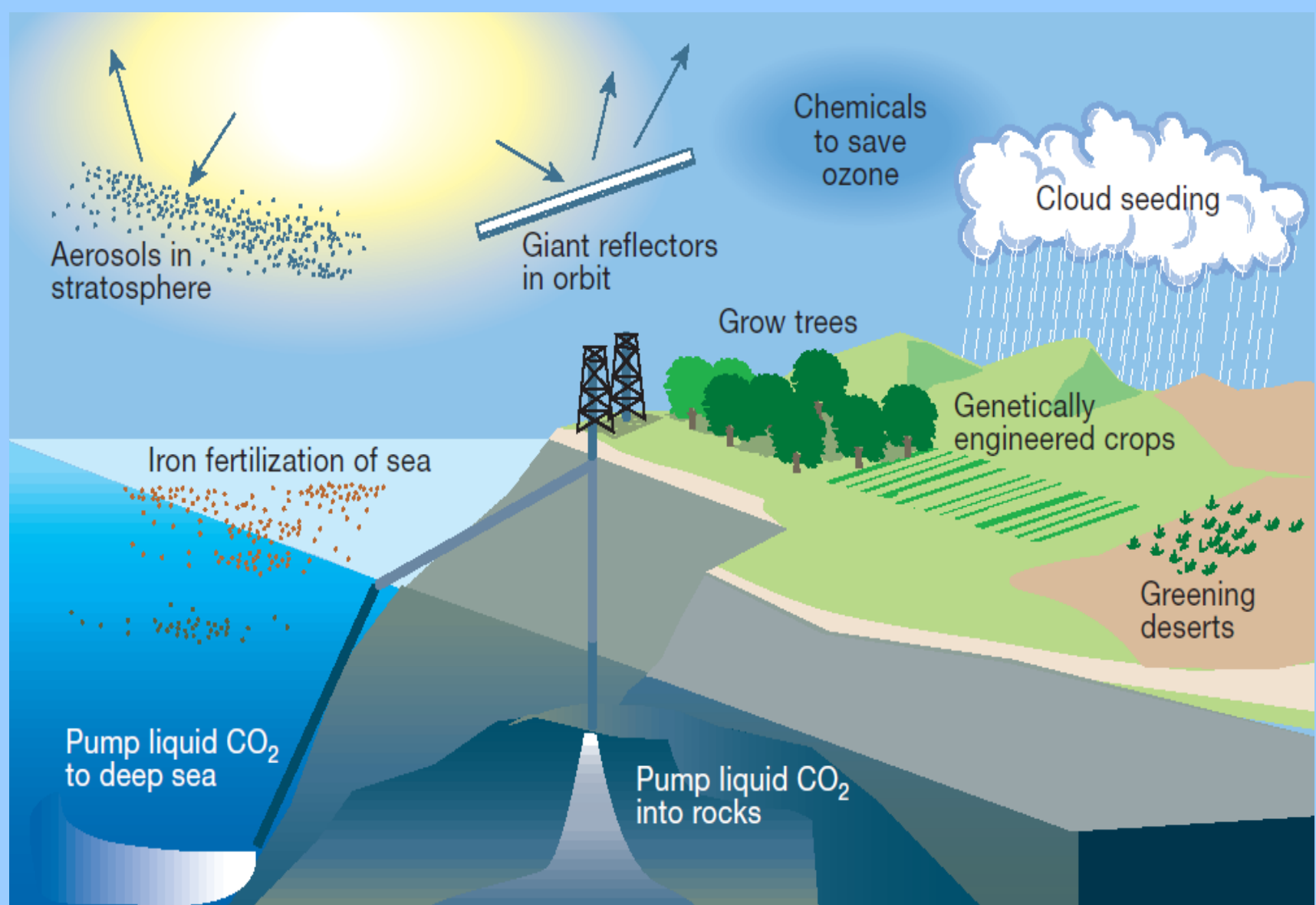
After Ken Caldeira

Global Temperature Relative to 1800-1900 (°C)



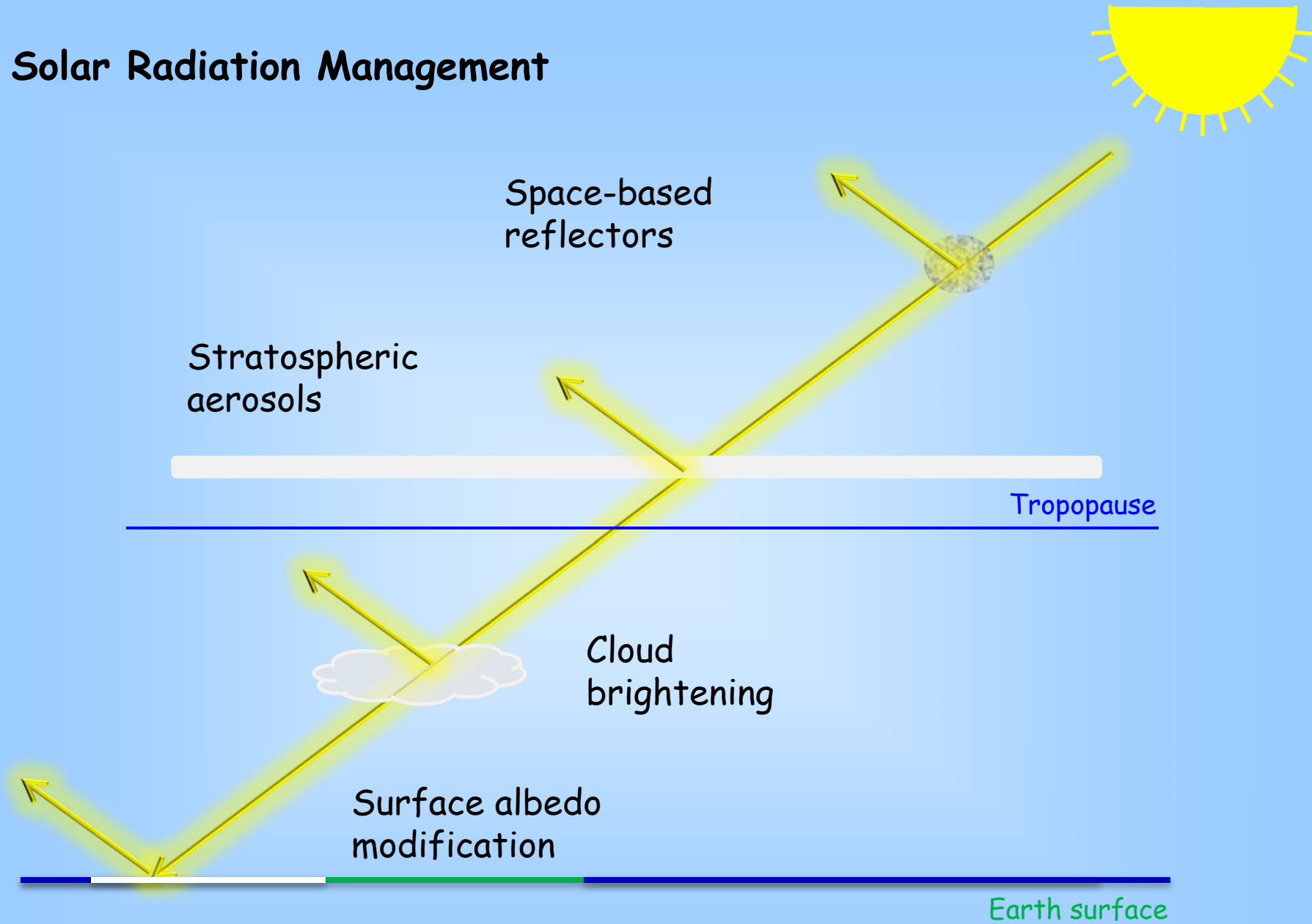
Global Land–Ocean Temperature Index



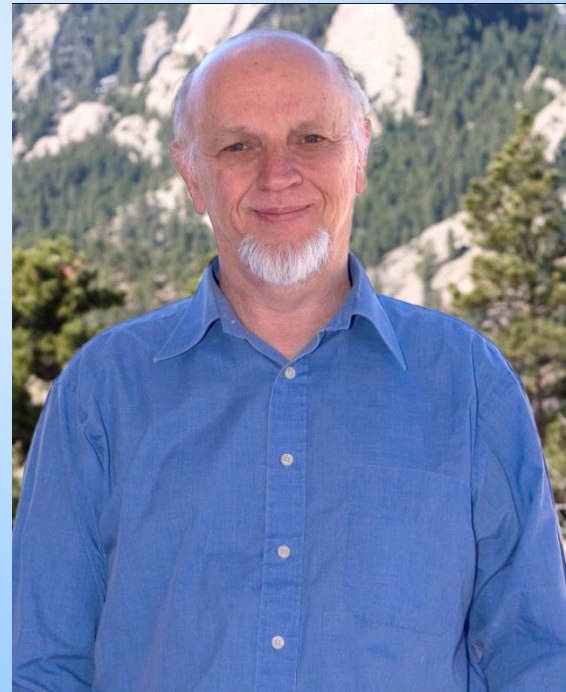


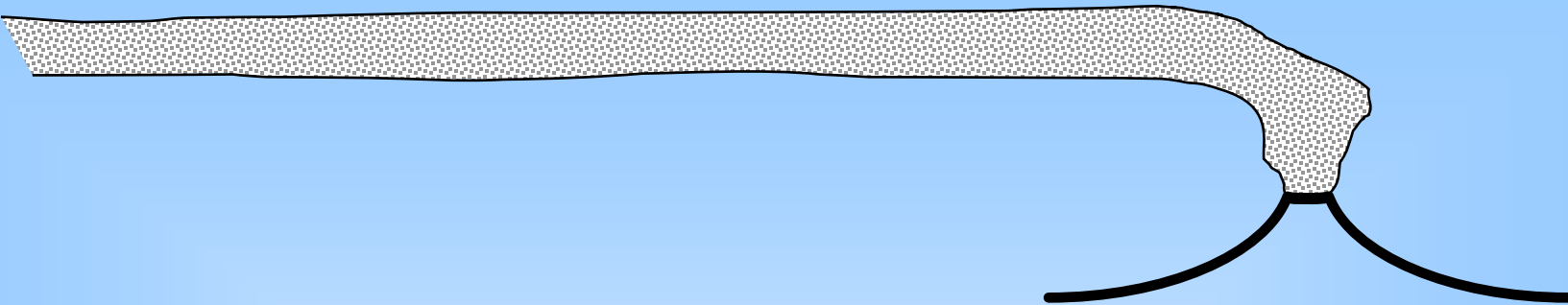
Schematic representation of various climate-engineering proposals (courtesy B. Matthews).

Solar Radiation Management



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 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.**

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.

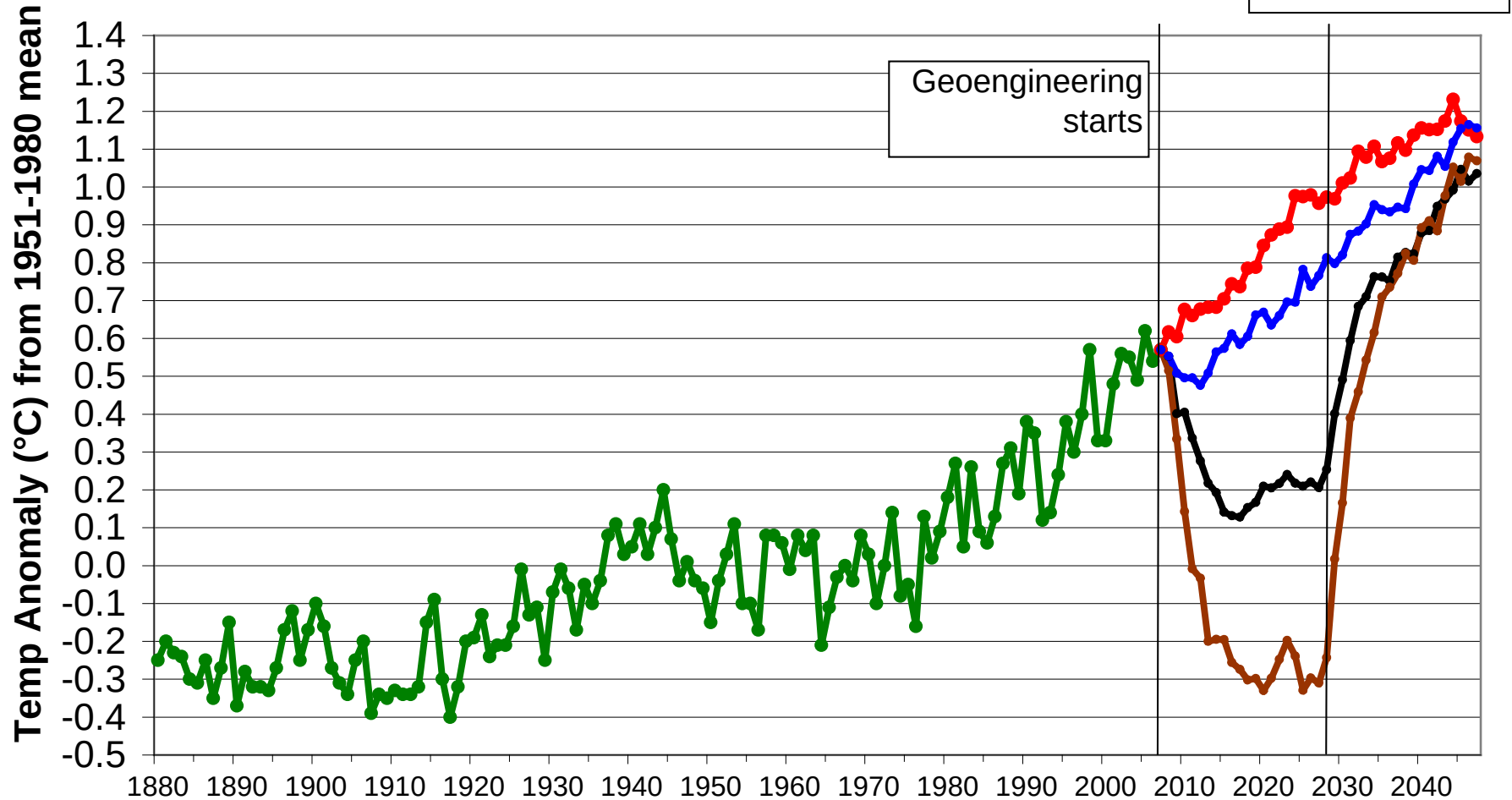
We conducted the following geoengineering simulations with the NASA GISS ModelE atmosphere-ocean general circulation model run at $4^\circ \times 5^\circ$ horizontal resolution with 23 vertical levels up to 80 km, coupled to a $4^\circ \times 5^\circ$ dynamic ocean with 13 vertical levels and an online 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

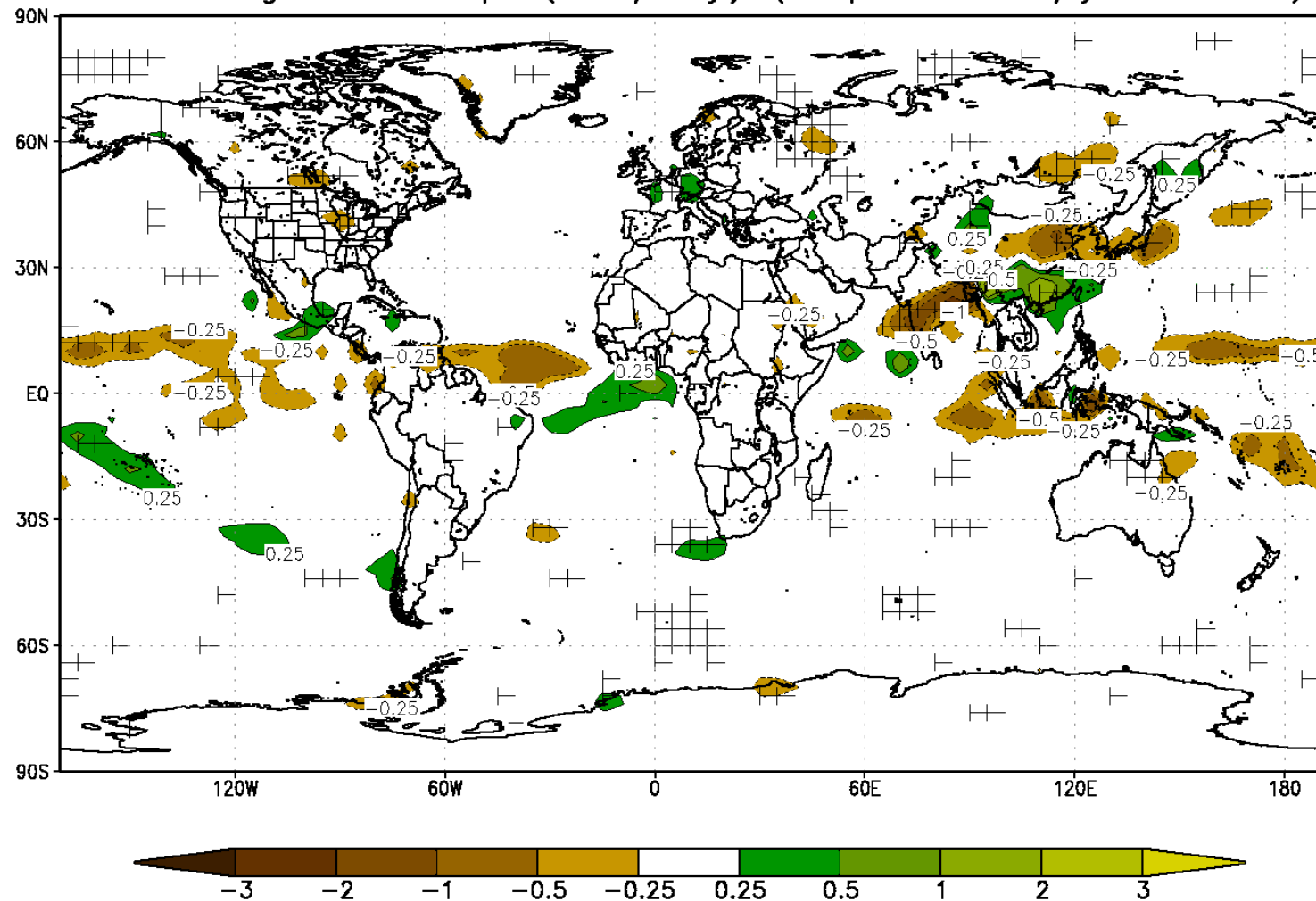
Robock, Alan, Luke Oman, and Georgiy Stenchikov, 2008: Regional climate responses to geoengineering with tropical and Arctic SO_2 injections. *J. Geophys. Res.*, **113**, D16101, doi:10.1029/2008JD010050

GISS Global Average Temperature Anomaly

+ Anthro Forcing, 3 Mt/yr Arctic,
5 Mt/yr Tropical, 10 Mt/yr Tropical



JJA Change in Precip. (mm/day) (Tropical 5 Mt/yr–Control)



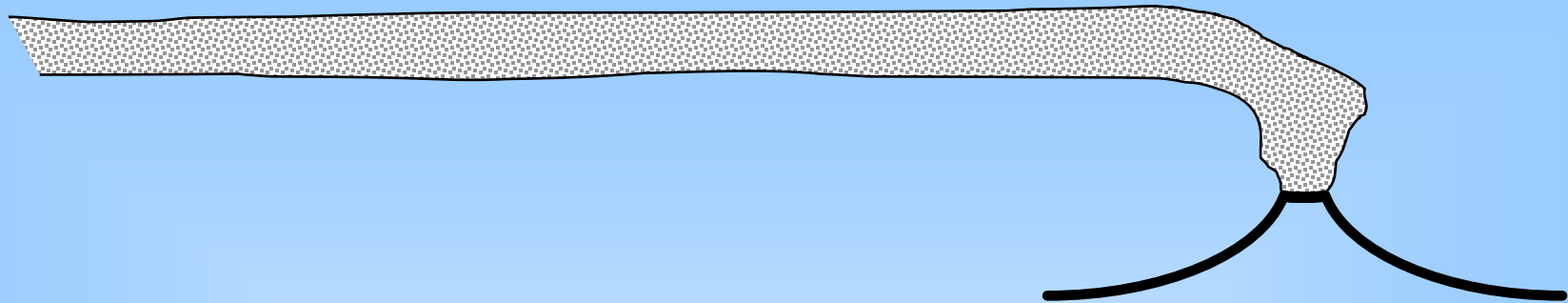
= significant at the 95% level

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.



FAMINE IN INDIA AND CHINA IN 1783

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

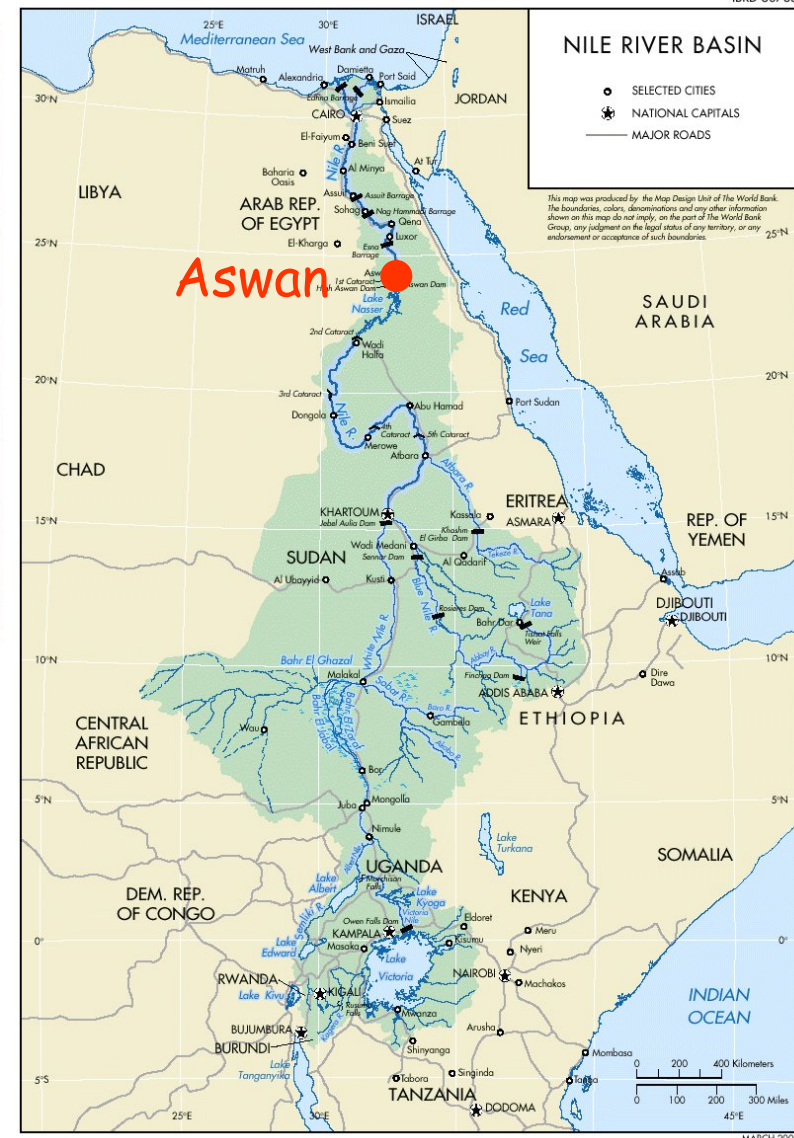
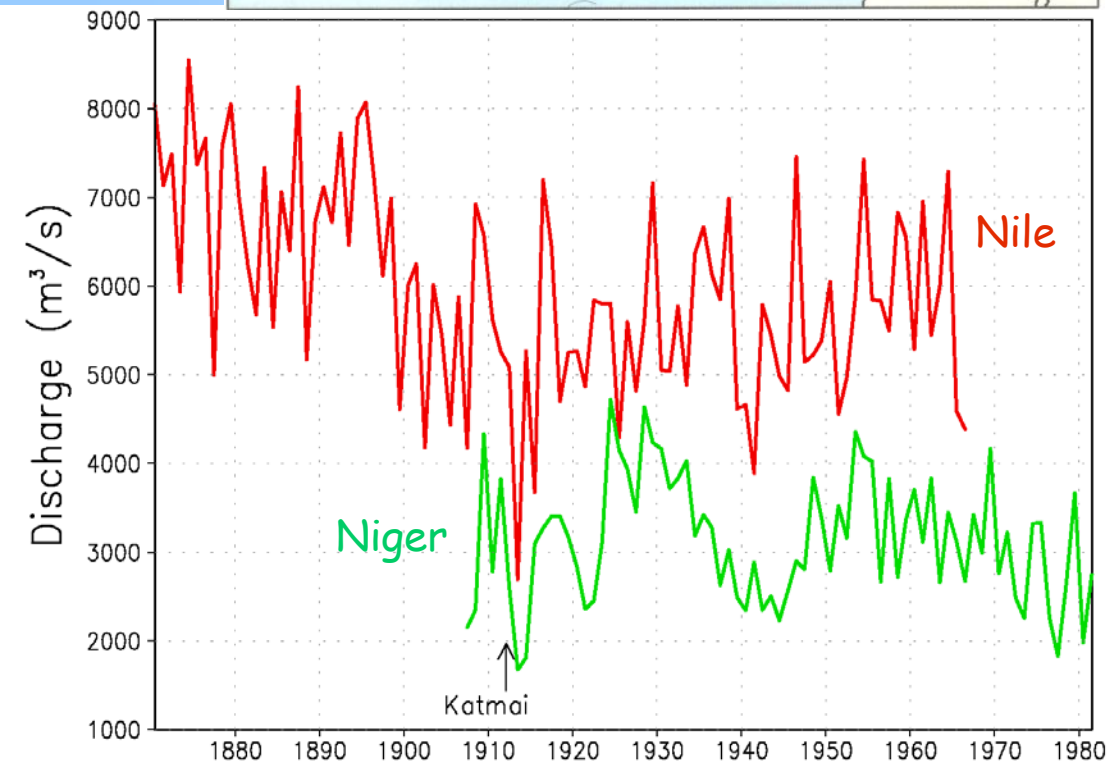
There was also the Great Tenmei Famine in Japan in 1783-1787, which was locally exacerbated by the Mount Asama eruption of 1783.

<http://www.festivalsegou.org>



Koulikoro

Niger
Basin

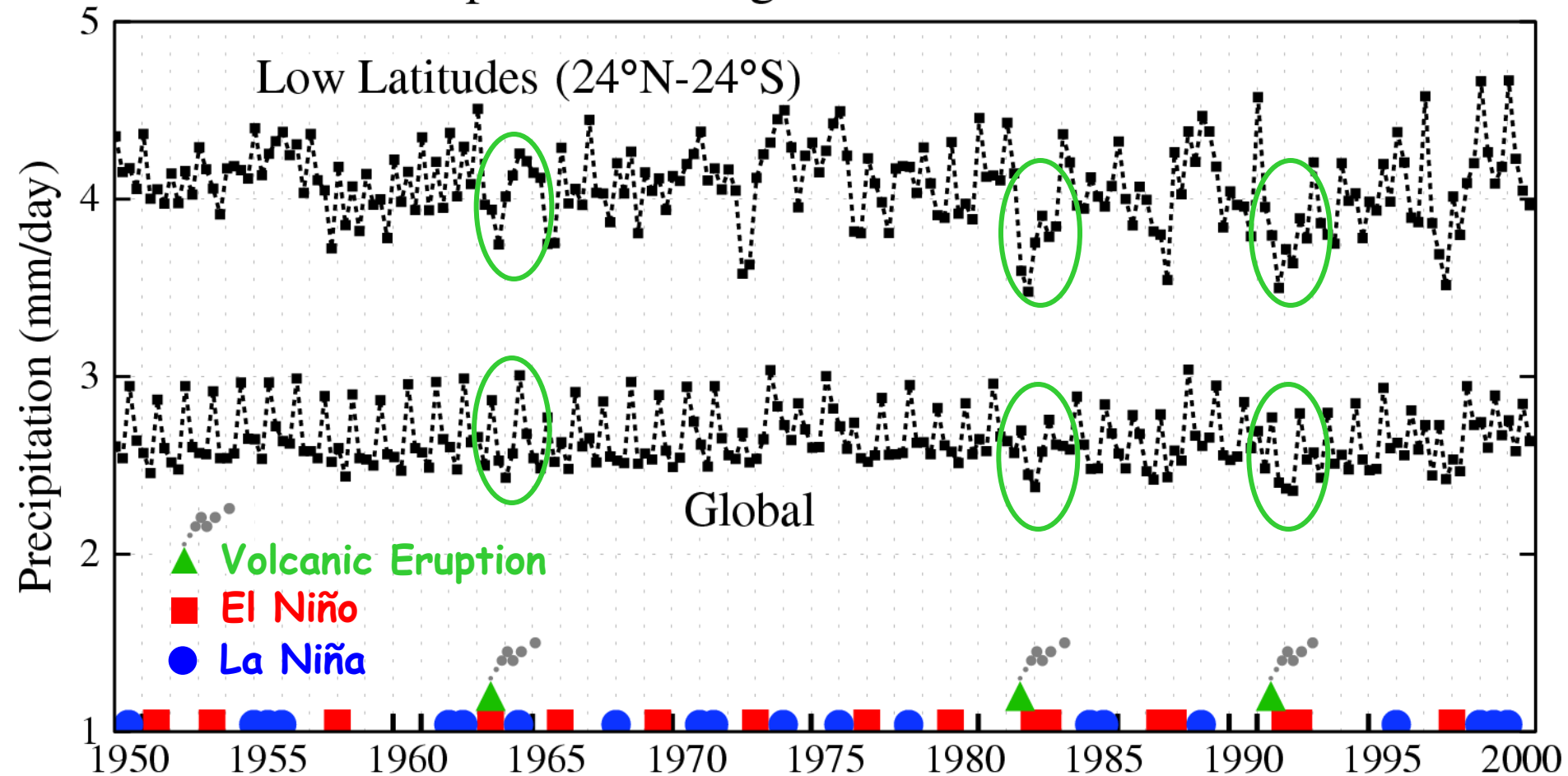


Aswan

<http://www.isiimm.agropolis.org>

Alan Robock
Department of Environmental Sciences

Precipitation Change at Seasonal Resolution



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.

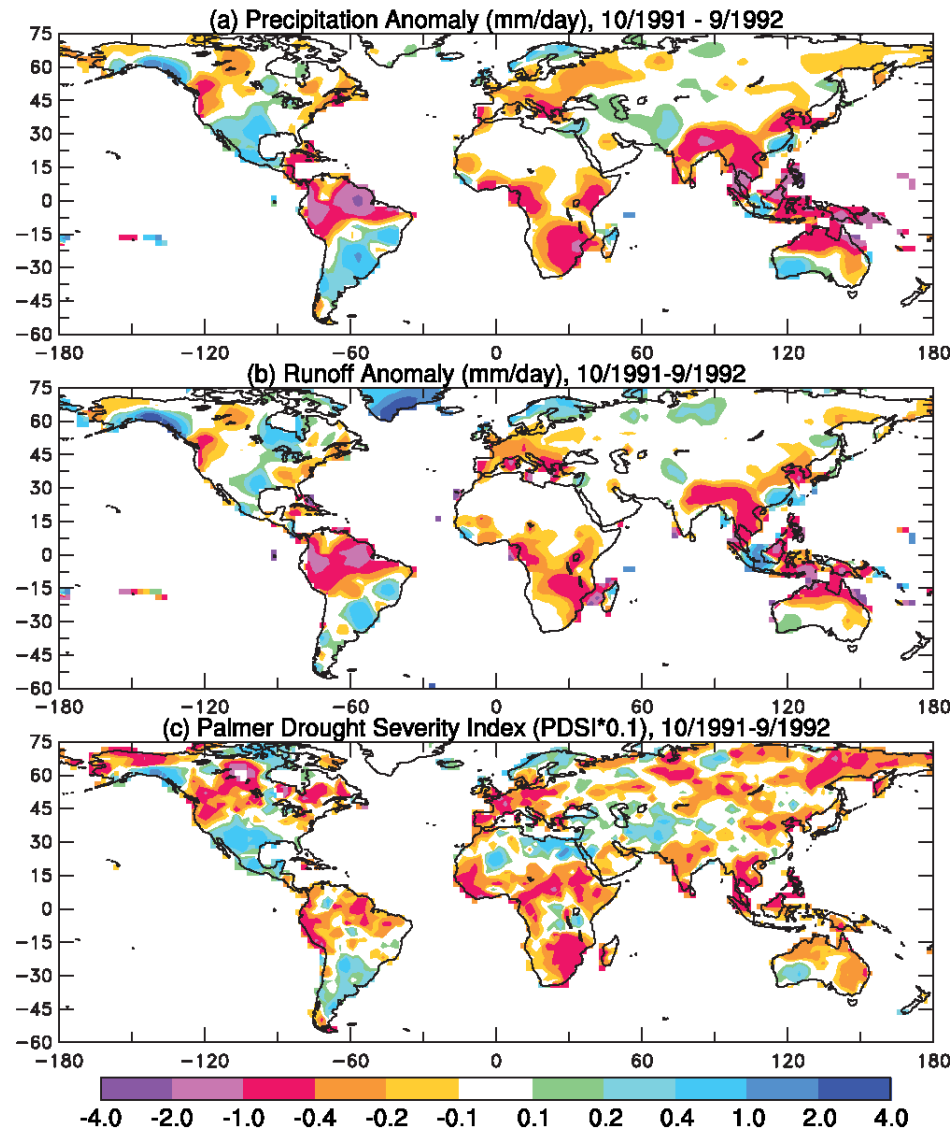


Figure 3. (a) Observed precipitation anomalies (relative to 1950–2004 mean) in mm/day during October 1991–September 1992 over land. Warm colors indicate below normal precipitation. (b) As for Figure 3a but for the simulated runoff [Qian *et al.*, 2006] using a comprehensive land surface model forced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

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.

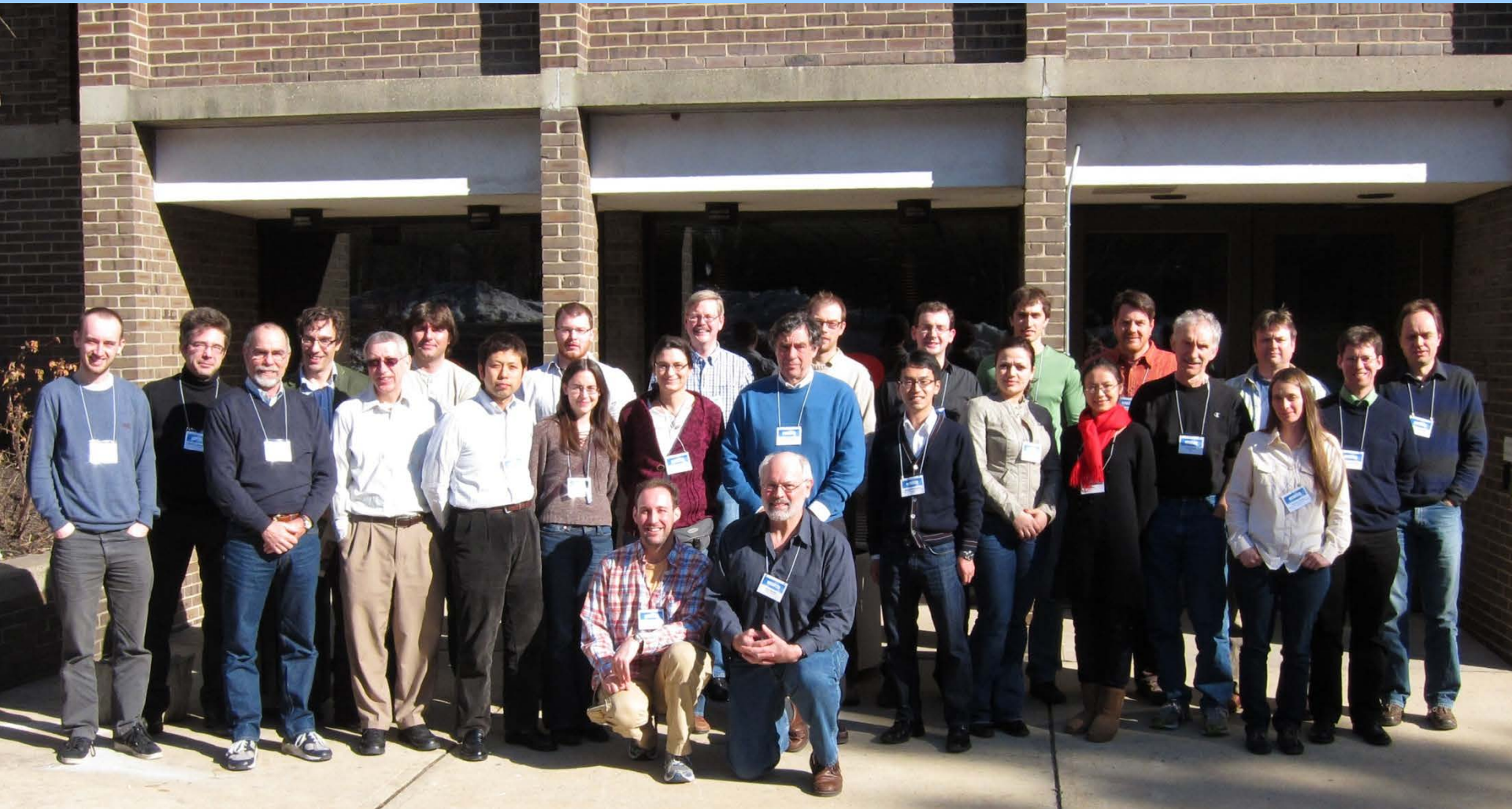
For example, how will the hydrological cycle respond to stratospheric geoengineering? Will there be a significant reduction of Asian monsoon precipitation? How will ozone and UV change?

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).

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>

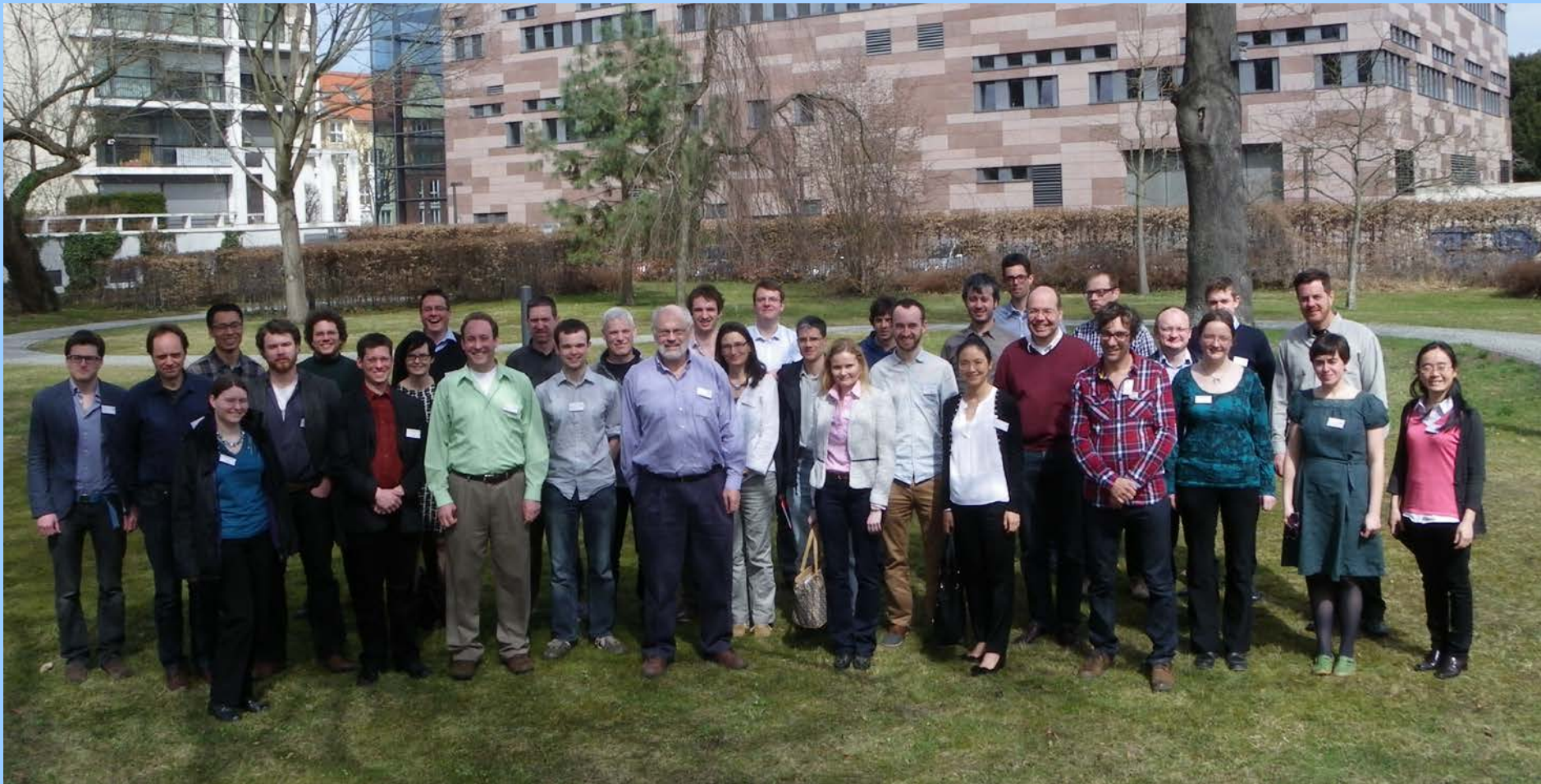


Workshop was sponsored by the Integrated Assessment of Geoengineering Proposals project.

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/>



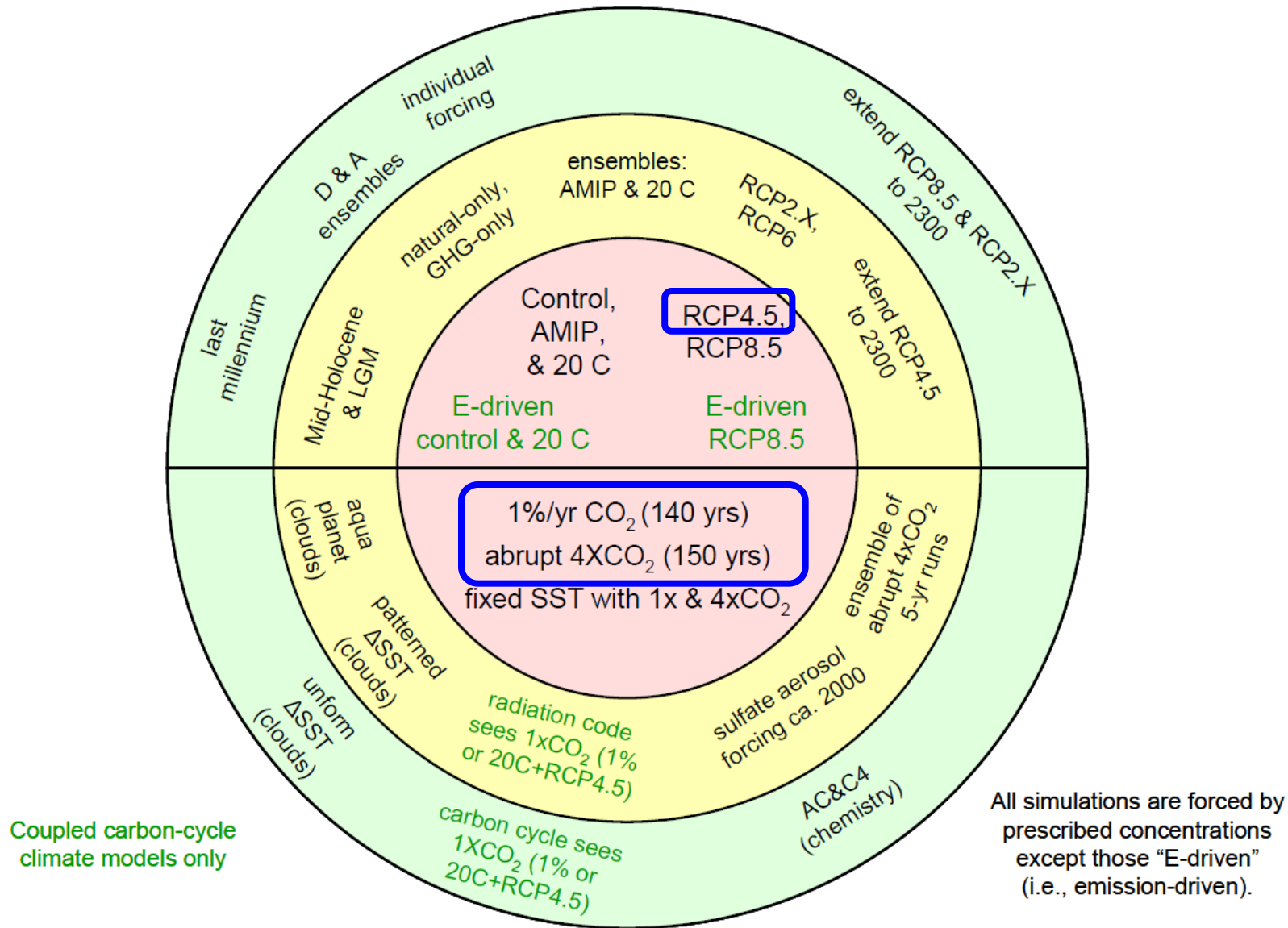
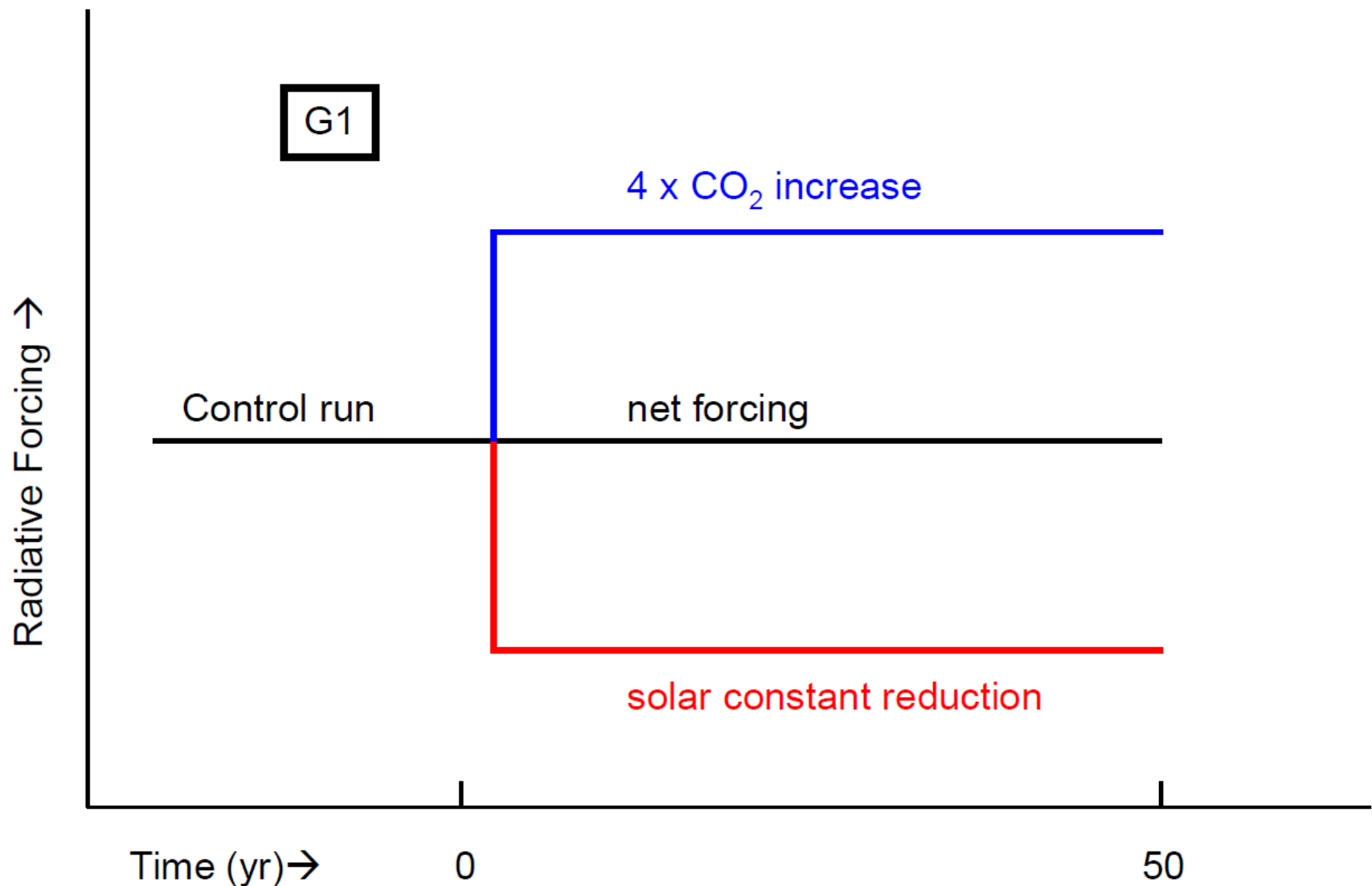
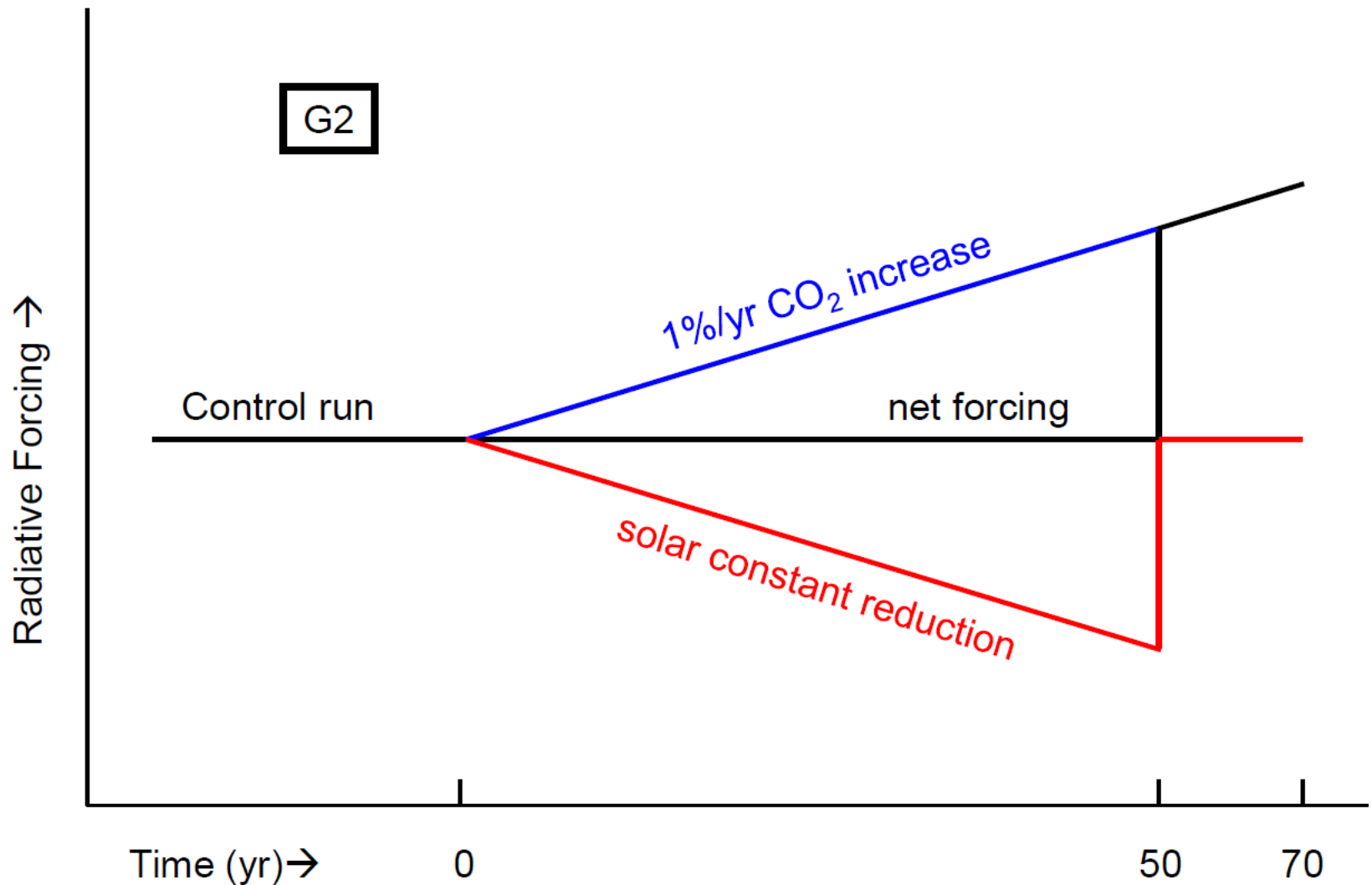


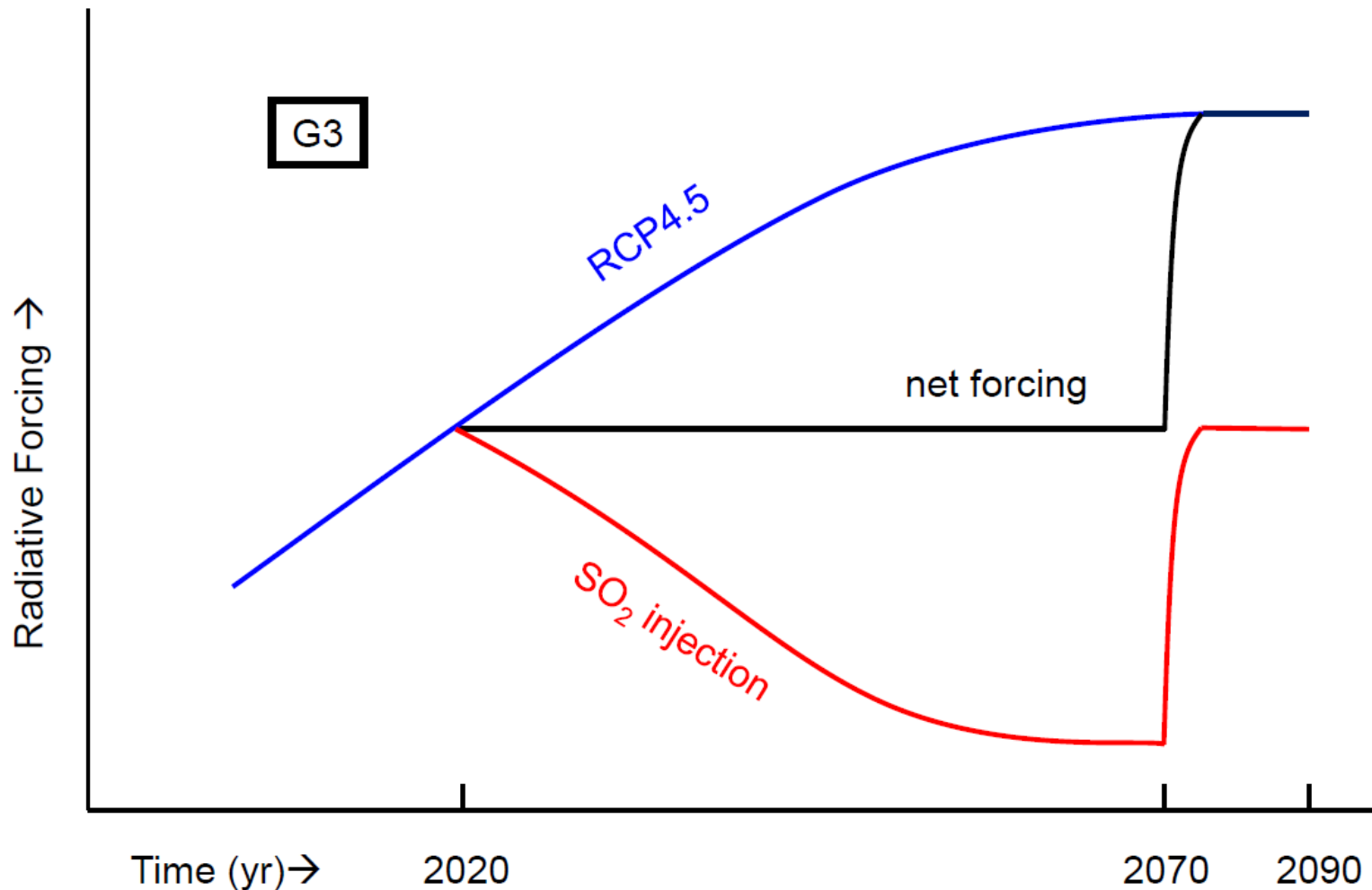
Figure 3: Schematic summary of CMIP5 long-term experiments.



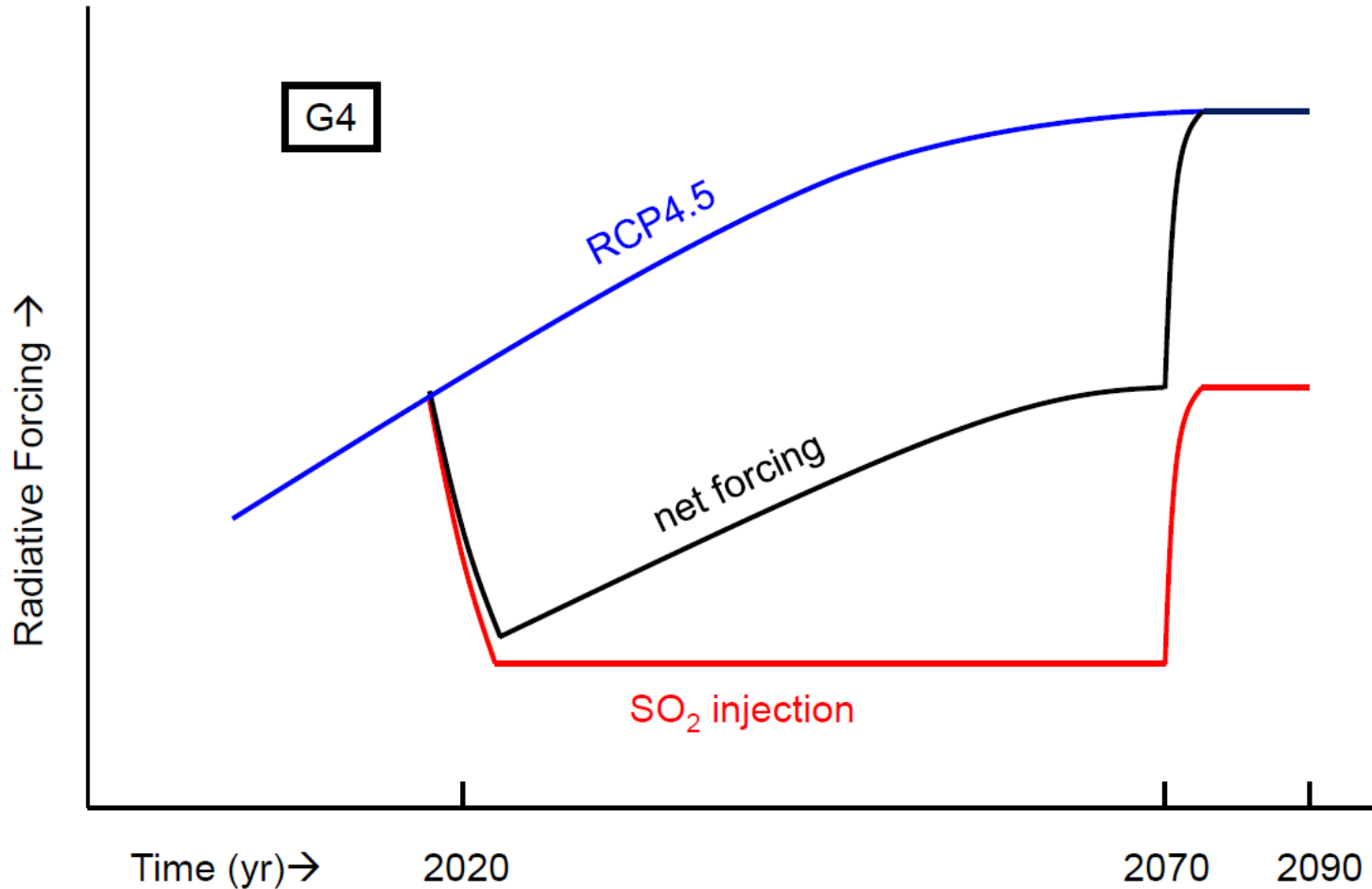
G1: Instantaneously quadruple CO₂ concentrations (as measured from preindustrial levels) while simultaneously reducing the solar constant to counteract this forcing.



G2: In combination with 1% CO₂ 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 SO₂ 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 SO₂ at a rate of 5 Tg SO₂ per year at one point on the Equator through the lower stratosphere (approximately 16-25 km in altitude).

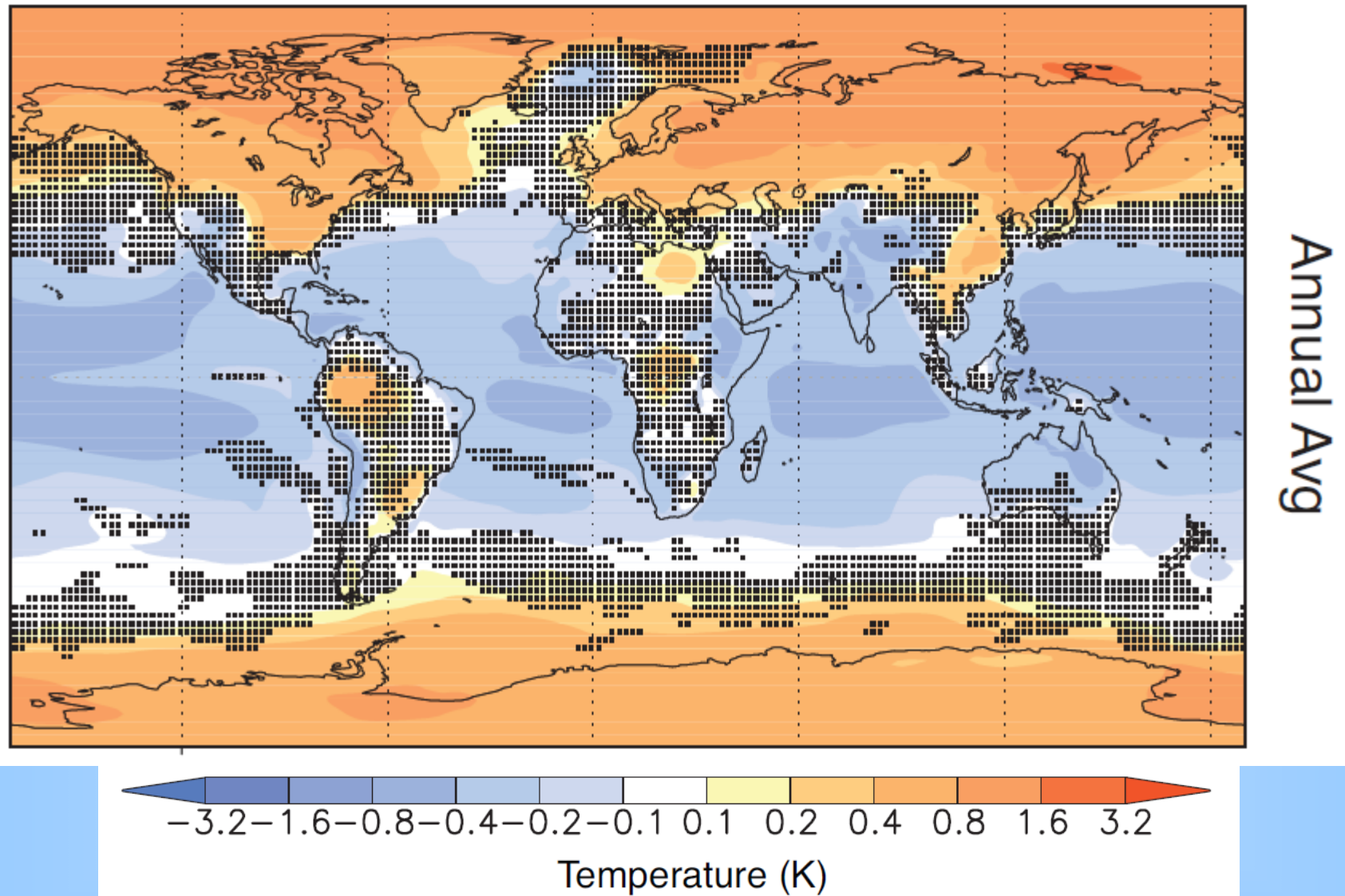
Results from G1 experiments by 12 climate models.

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 $4\times\text{CO}_2$ 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.

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.

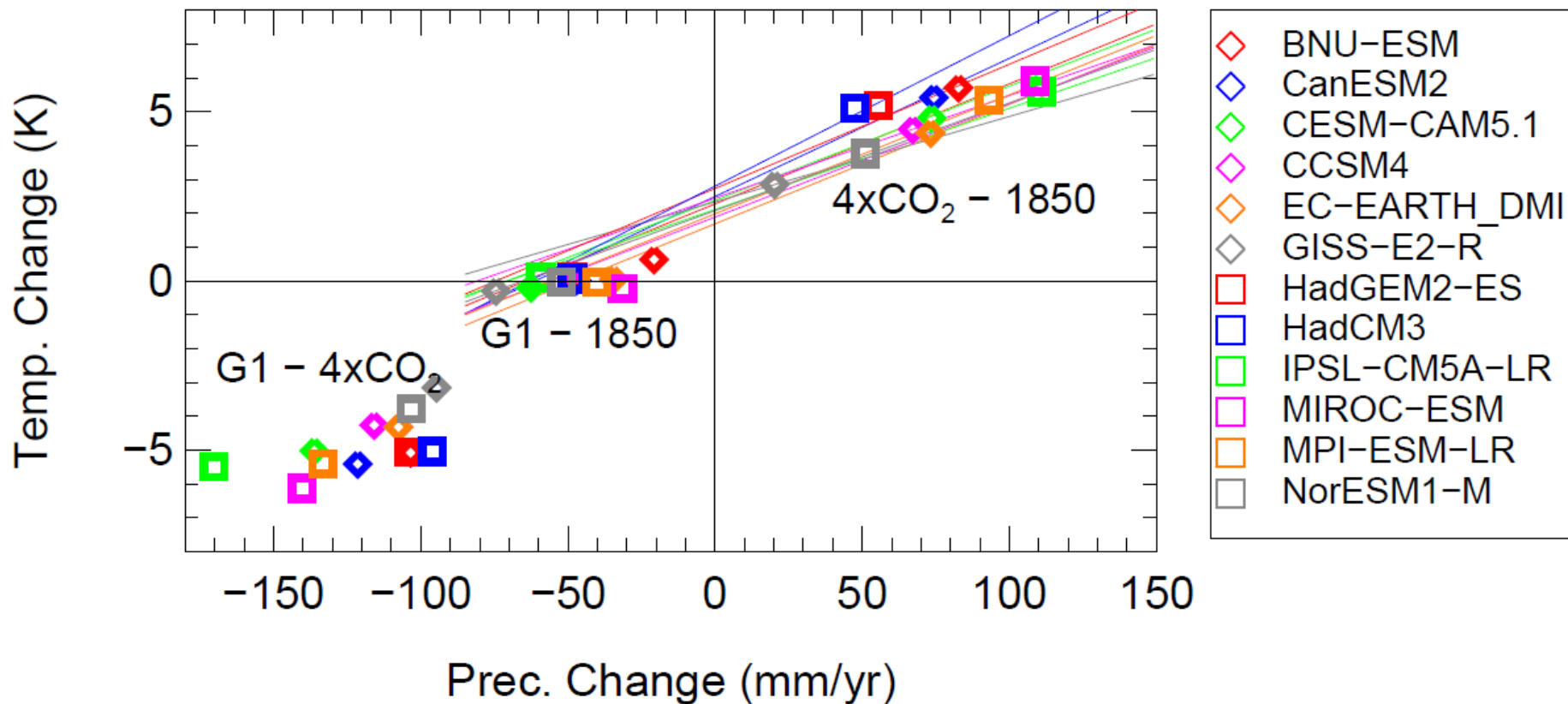
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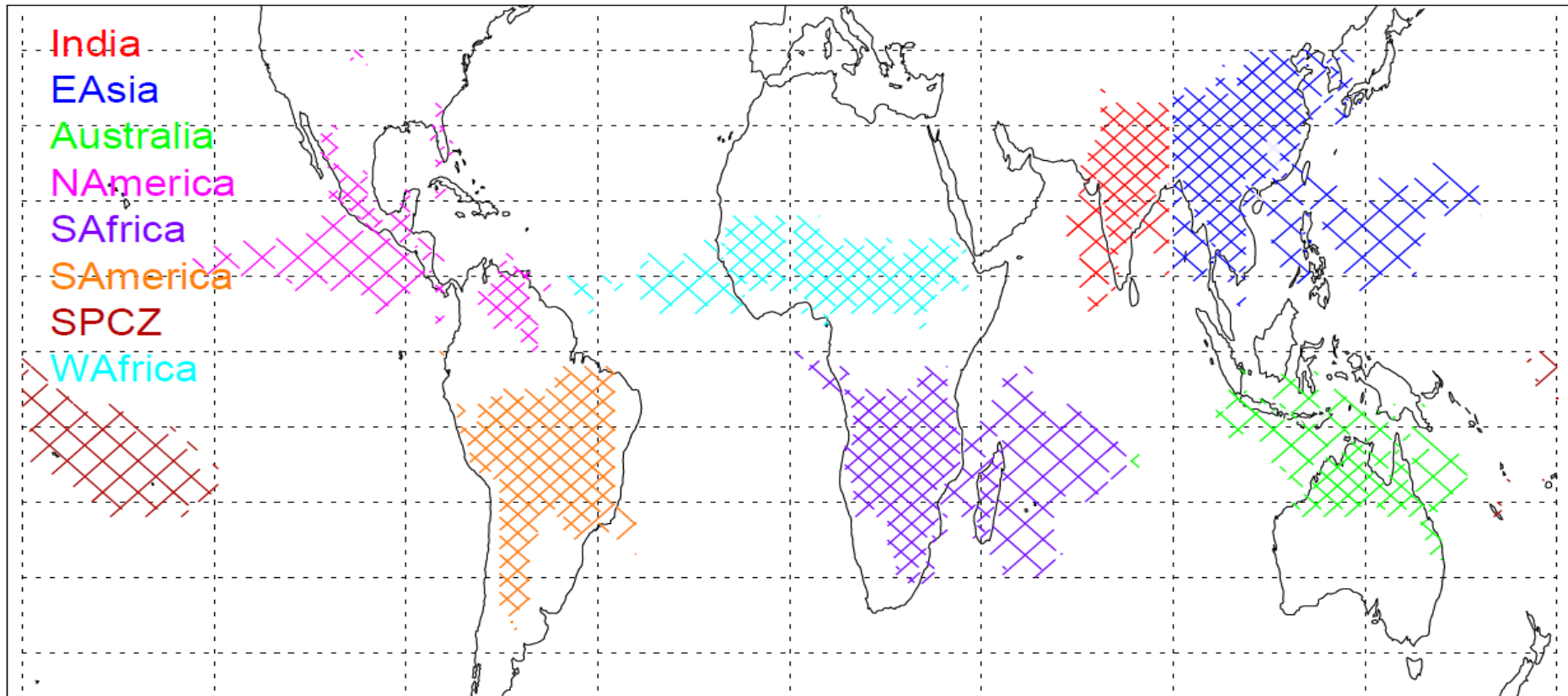
Shown are averages from years 11-50 of the simulations, balancing $4\times\text{CO}_2$ with solar radiation reduction to achieve global average radiation balance.

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

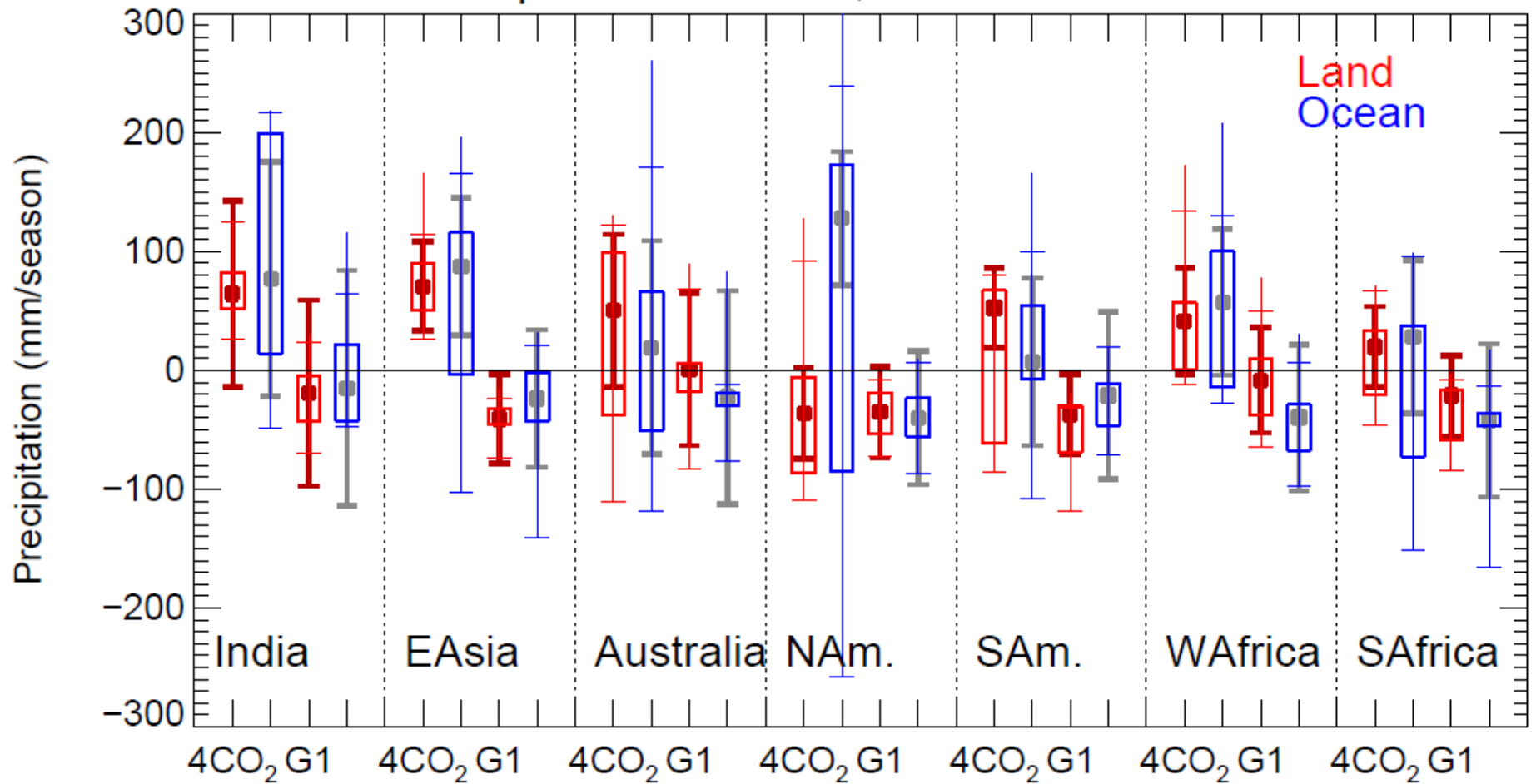
Global average results for all years for G1 and for years 11-50 of simulation for 4xCO₂



Monsoon regions



Experiment – 1850, Summer Monsoon



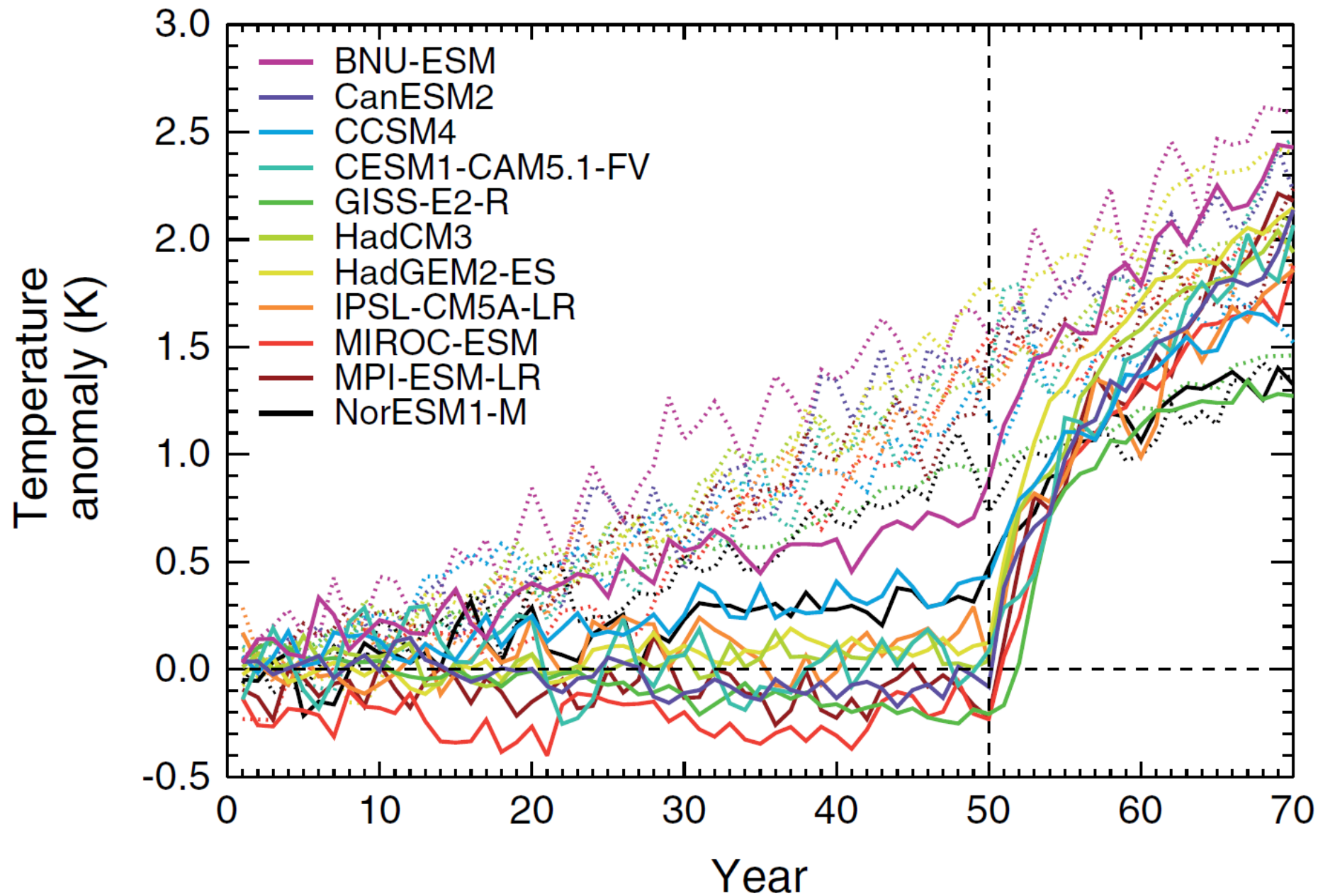
Years 11-50

Results from G2 experiments by 12 climate models.

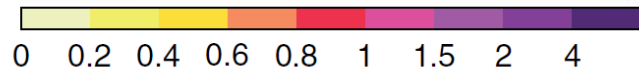
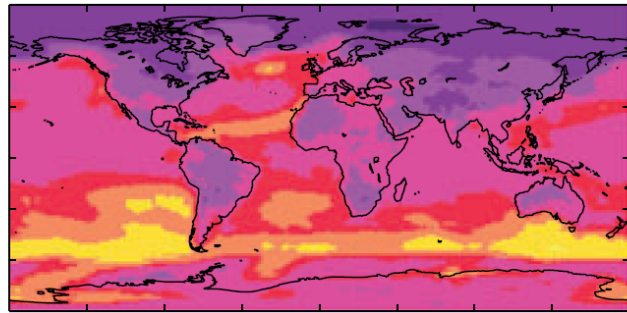
This is a 1%/year increase of CO_2
balanced by a reduction of insolation.

Shown are averages from years 11-50.

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.

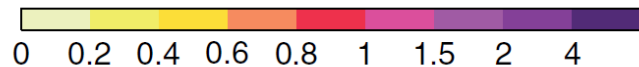
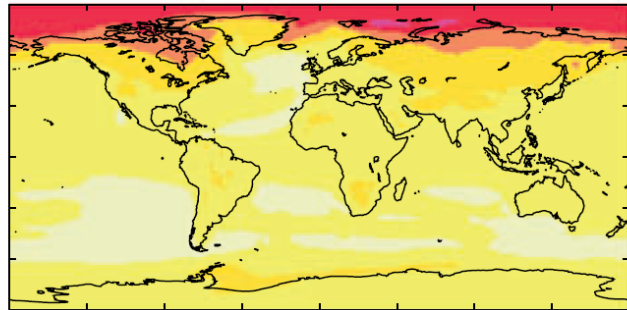


(a) G2



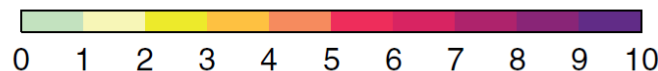
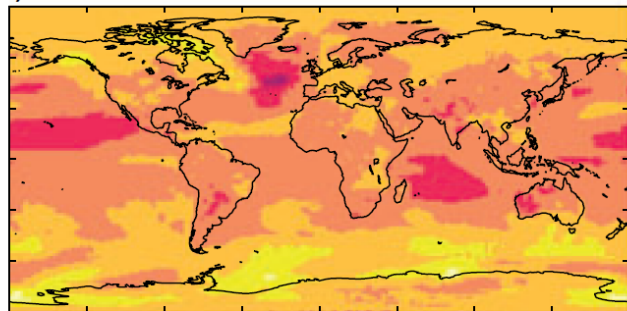
Rate of change of
temperature in first 10
years of G2 (K/decade)

(c) 1pctCO2

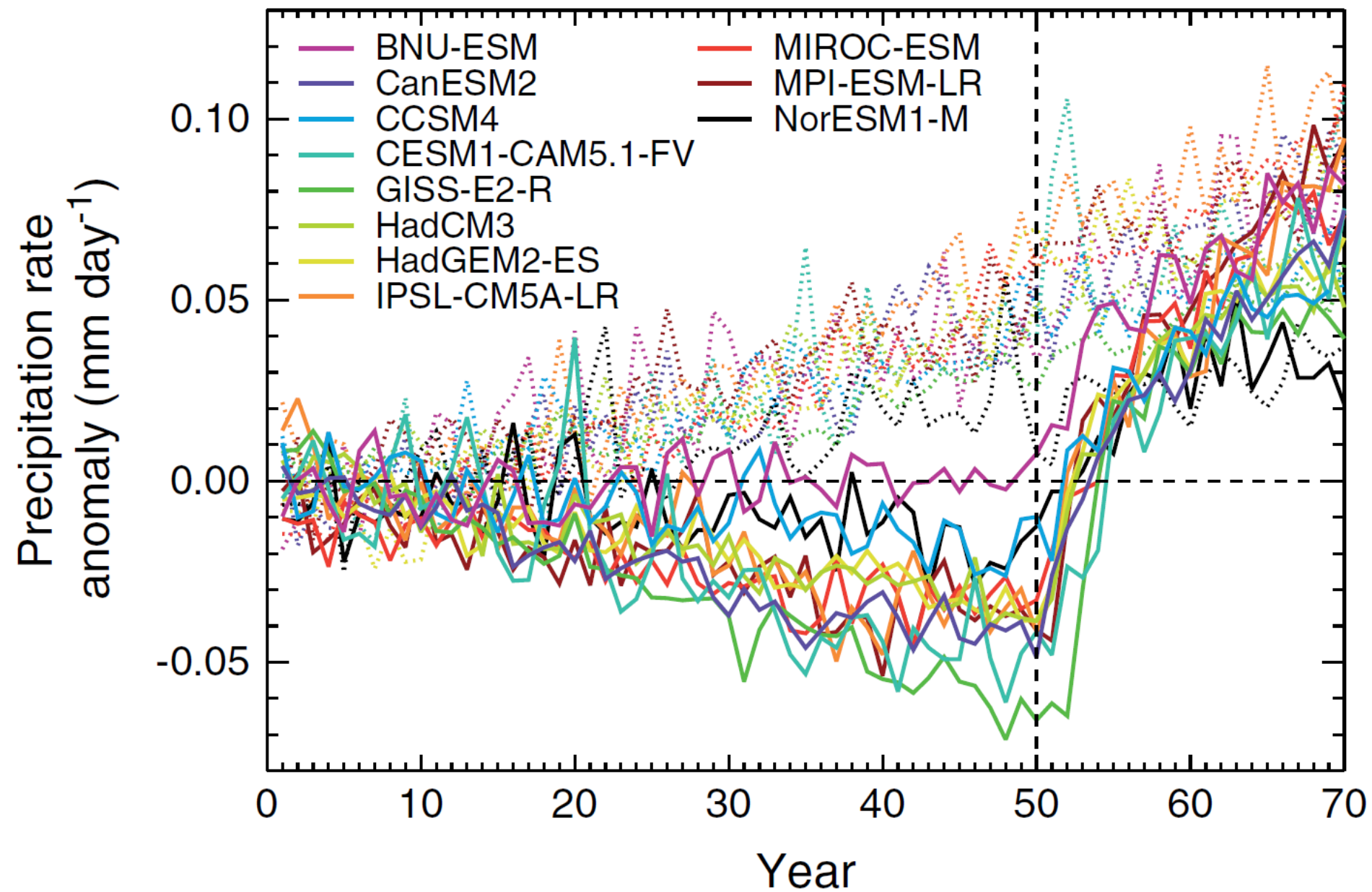


Rate of change of
temperature in 70 years of
+1%/yr CO₂ (K/decade)

(e) $\alpha(T)$

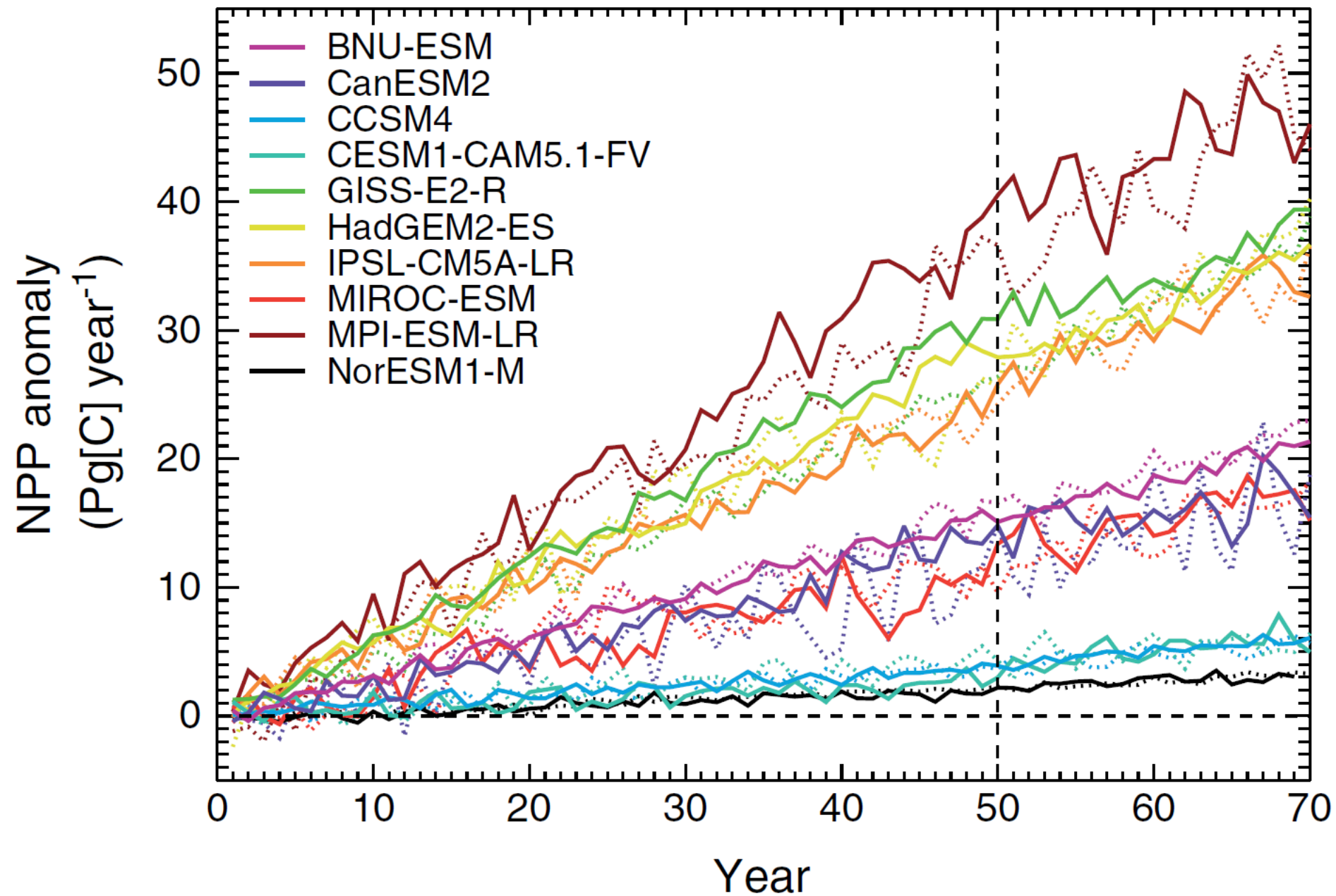


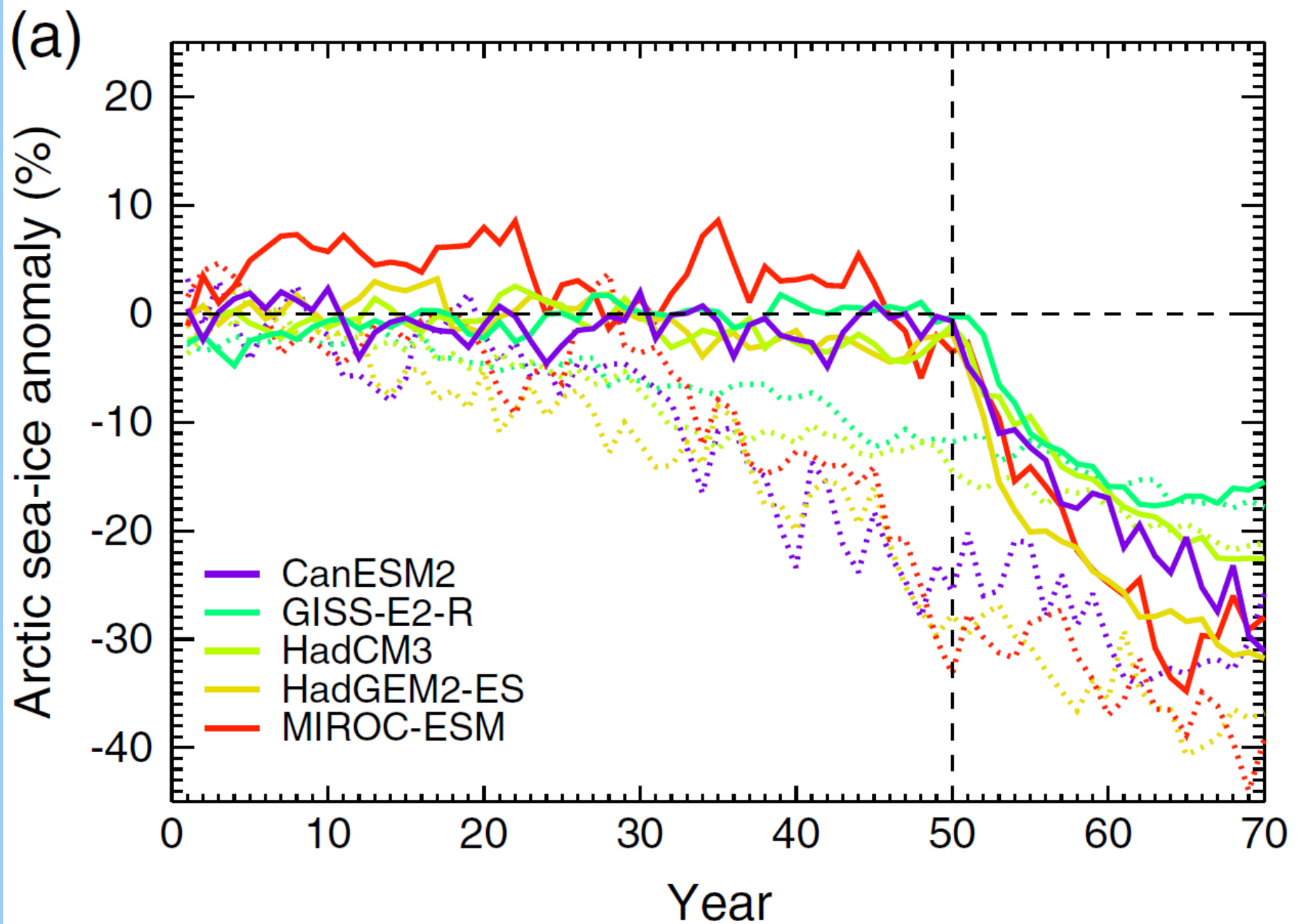
Ratio of G2 to +1%/yr CO₂

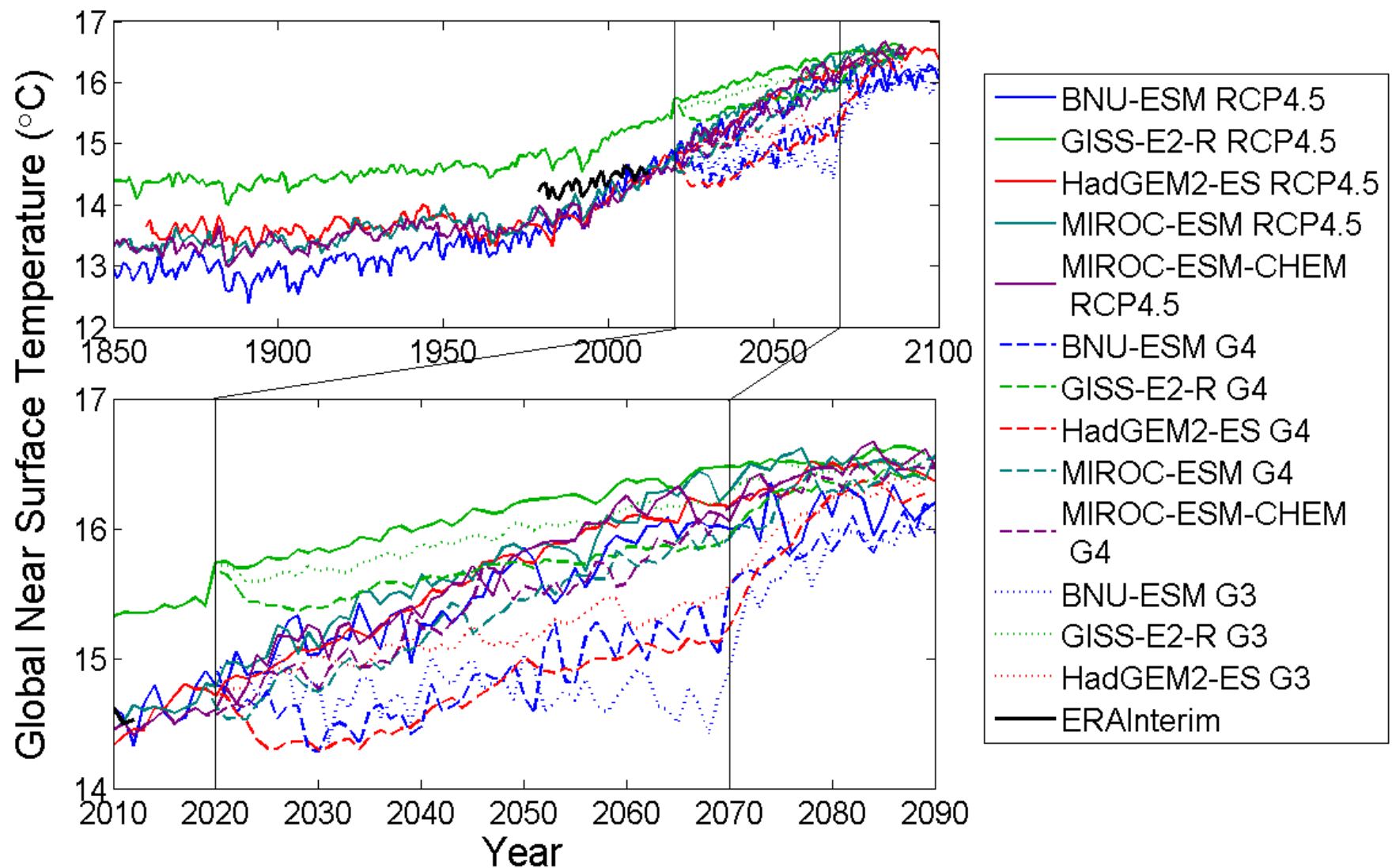


dotted lines are $+1\%/yr$ CO_2

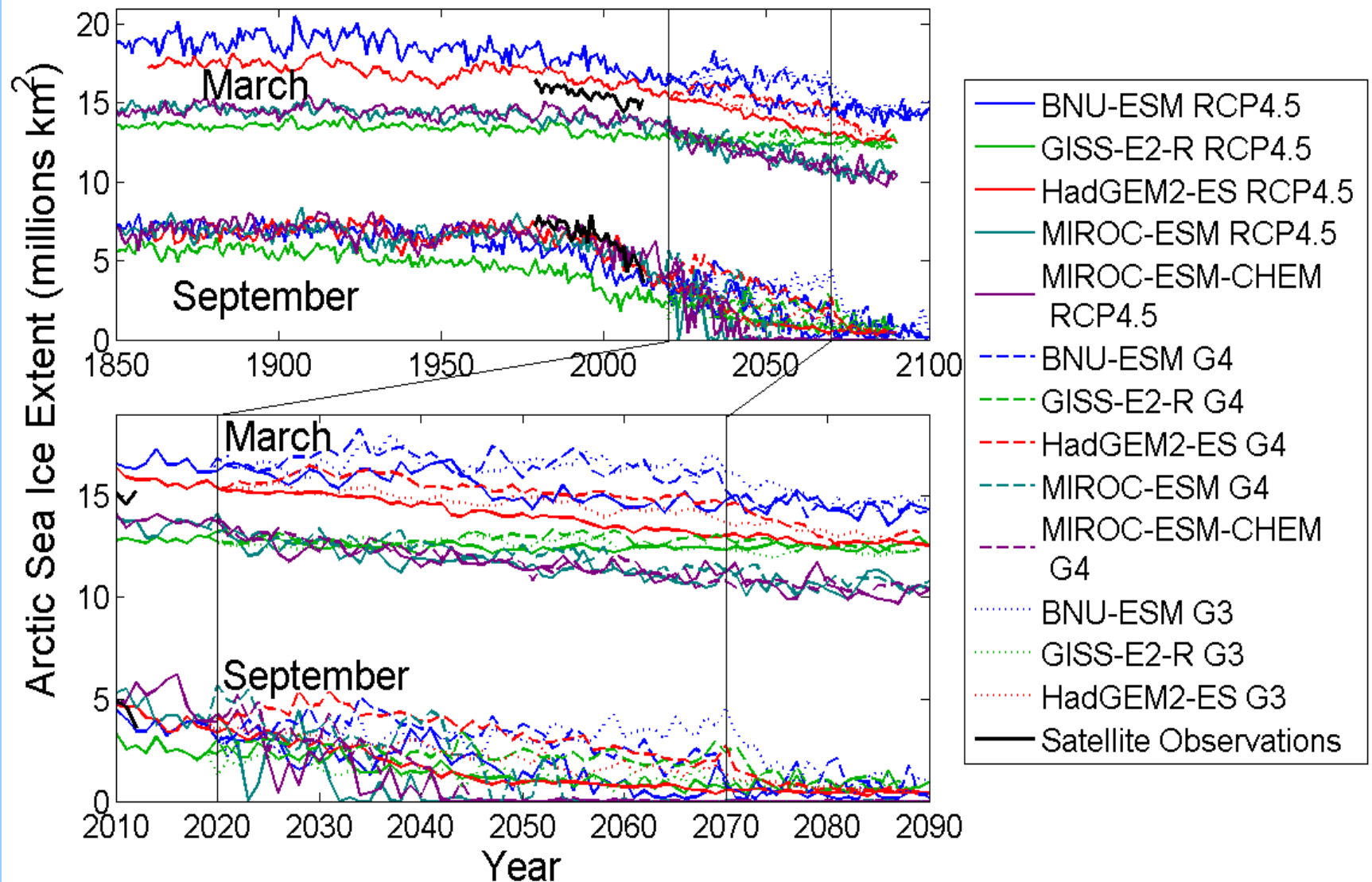
solid lines are $G2$



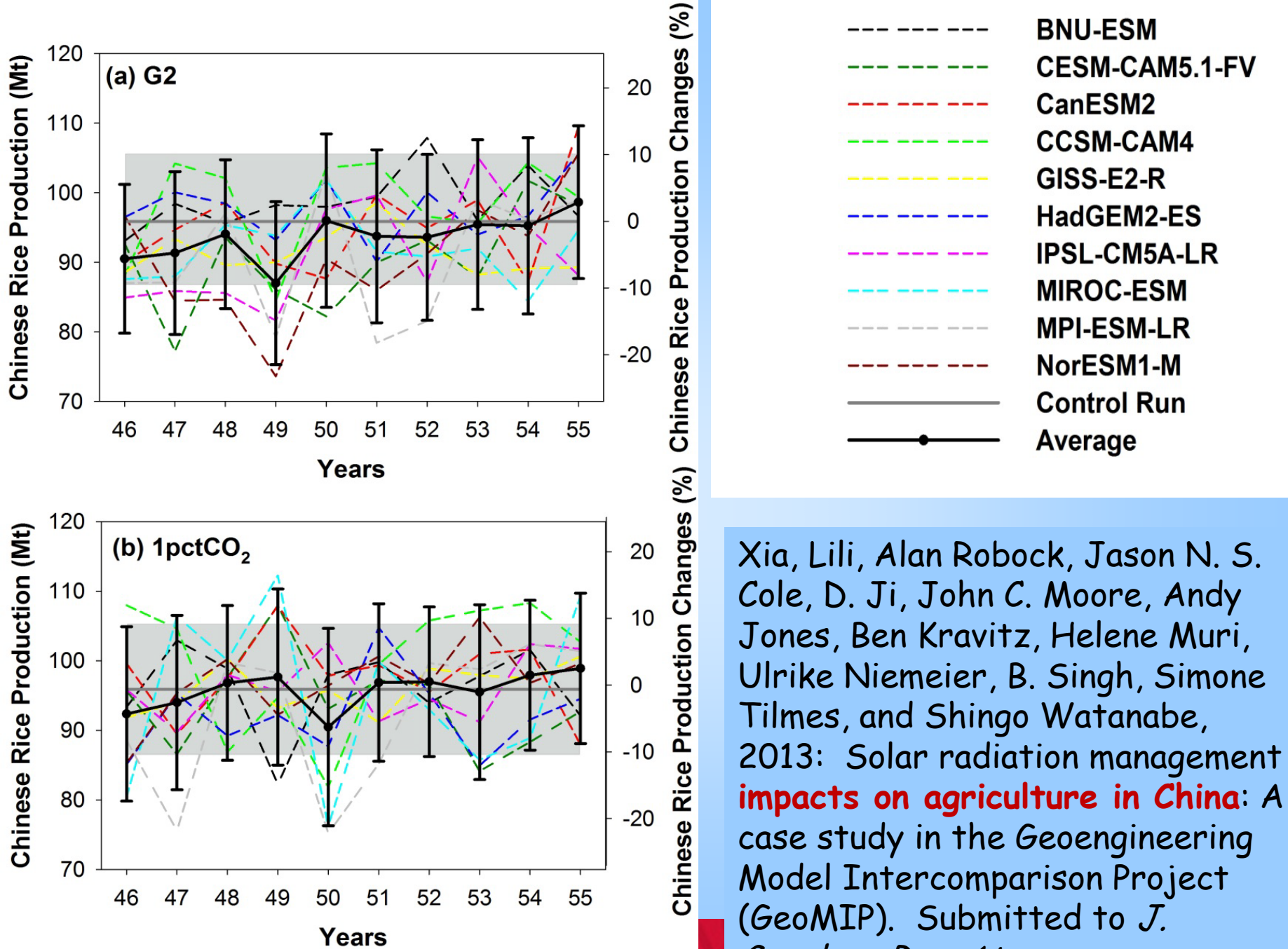




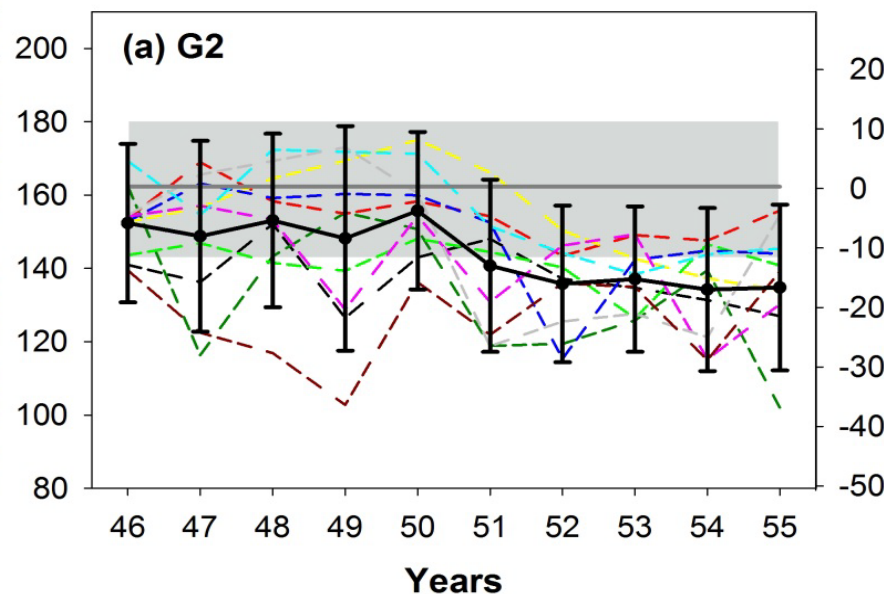
Berdahl, Mira, Alan Robock, Duoying Ji, Andy Jones, Ben Kravitz, John C. Moore, and Shingo Watanabe (2013), Arctic cryosphere response in the Geoengineering Model Intercomparison Project (GeoMIP) G3 and G4 scenarios. Submitted to *J. Geophys. Res. Atmos.*



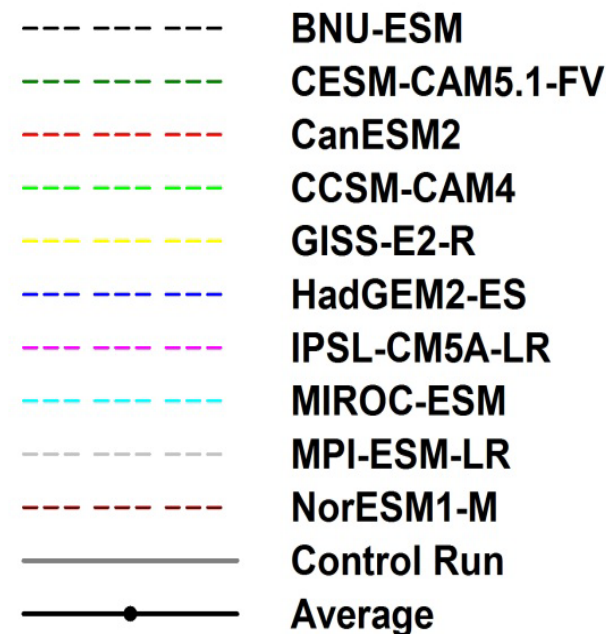
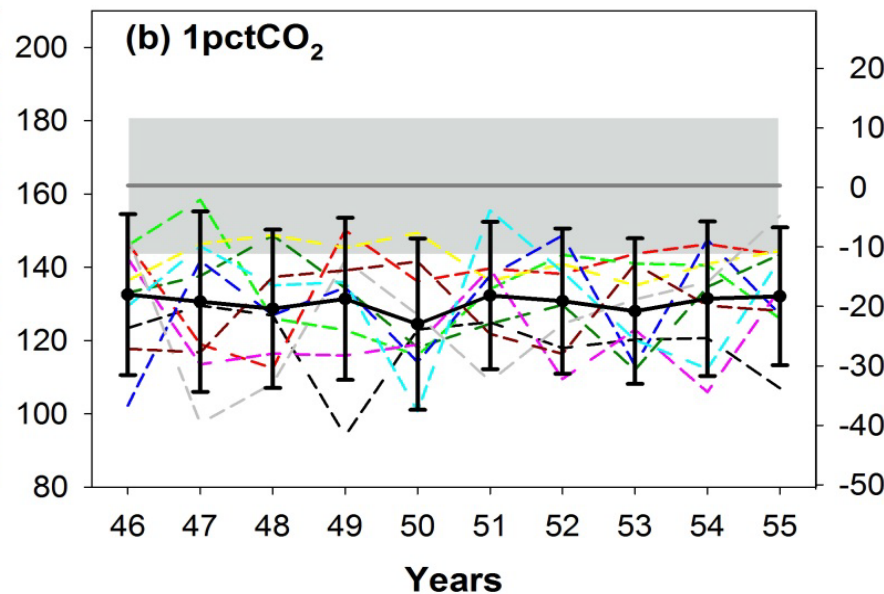
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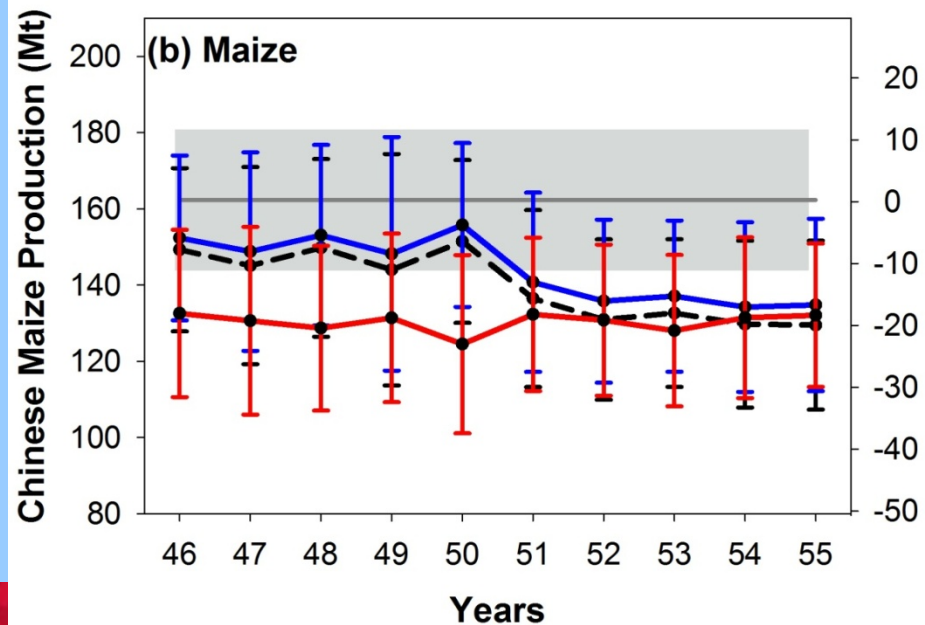
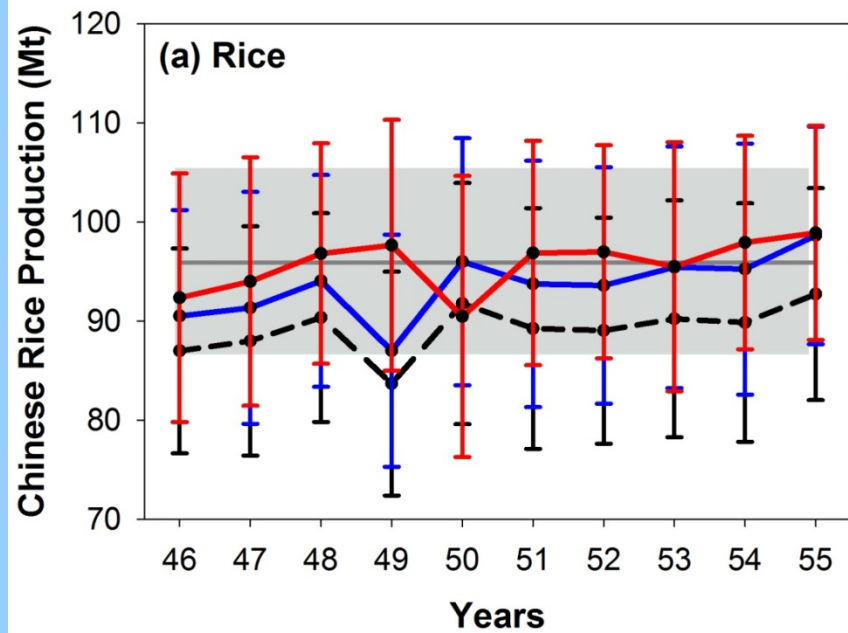
Chinese Maize Production (Mt)



Chinese Maize Production (Mt)



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.*



— 1pctCO₂

— G2

- - - G2, constant CO₂

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

<u>Experiment</u>	<u>Description</u>
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.

Reasons geoengineering may be a bad idea

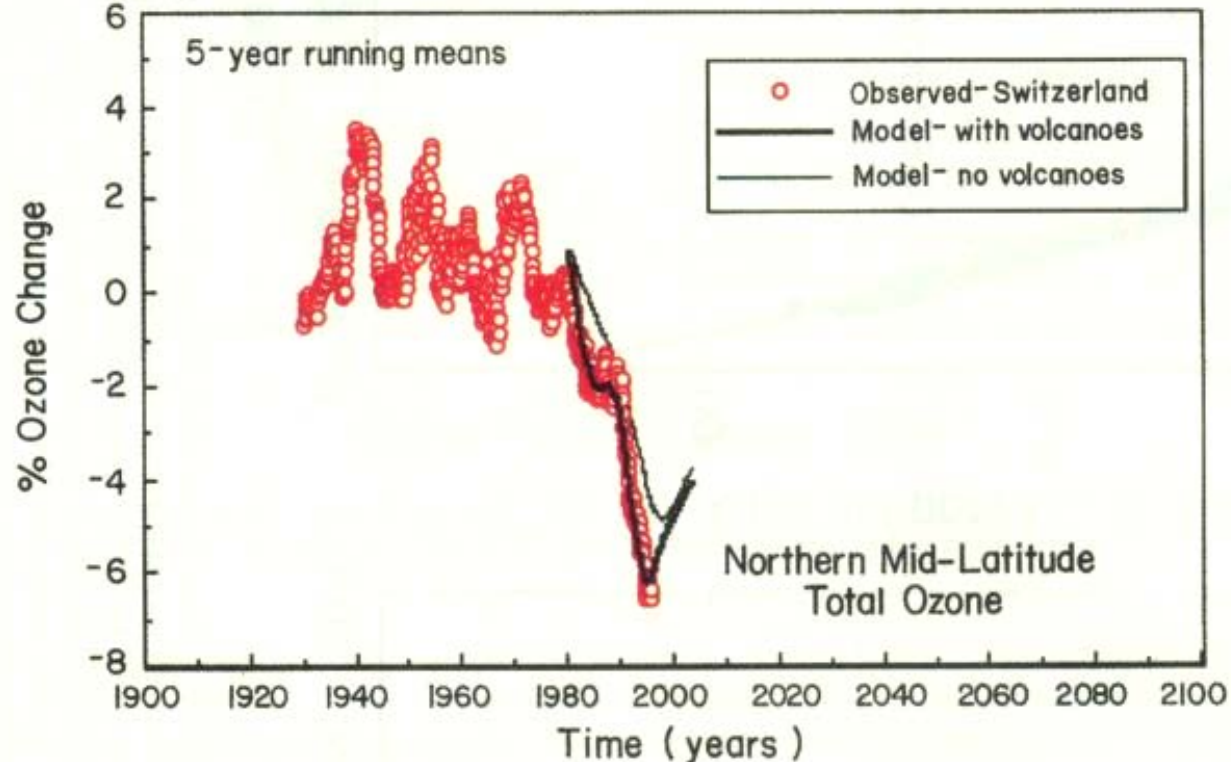
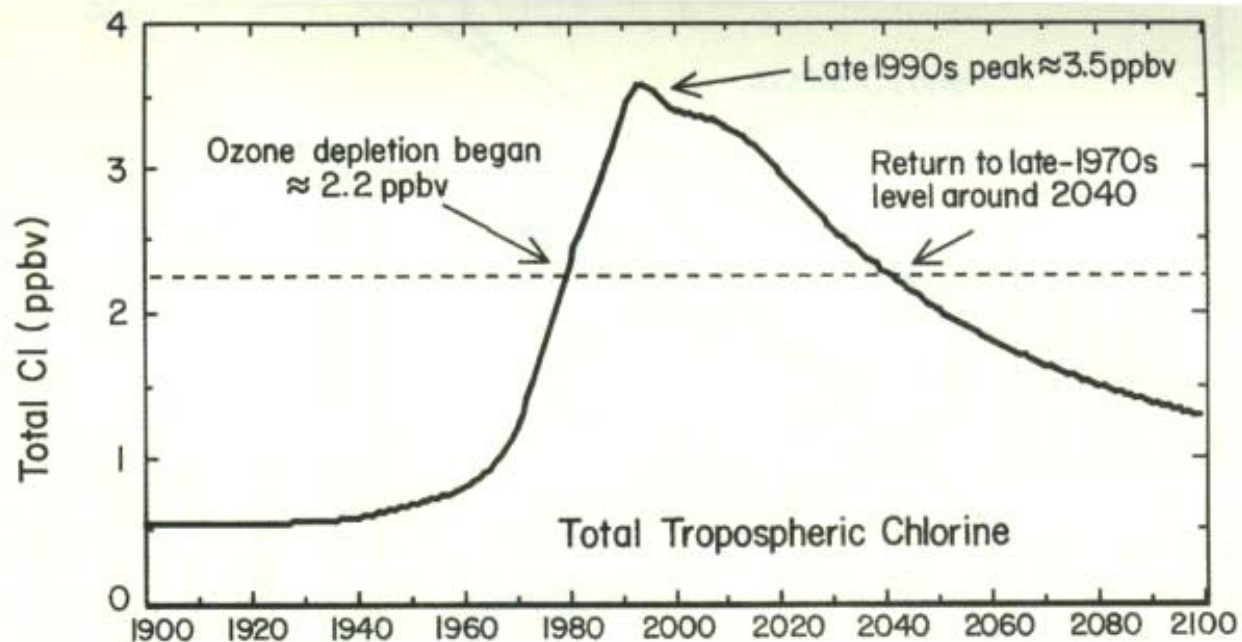
Climate system response

- ✓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

Tropospheric chlorine diffuses to stratosphere.

Volcanic aerosols make chlorine available to destroy ozone.

Solomon (1999)



SH

Rasch et al.
(2008)

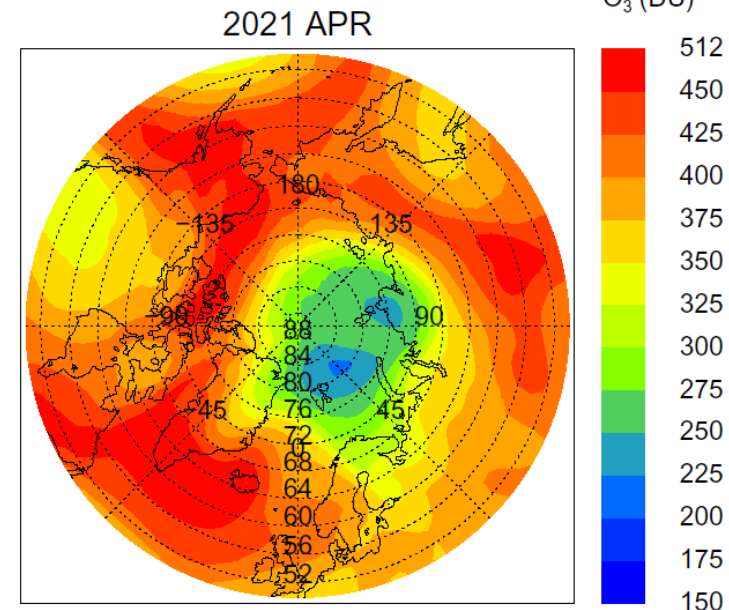
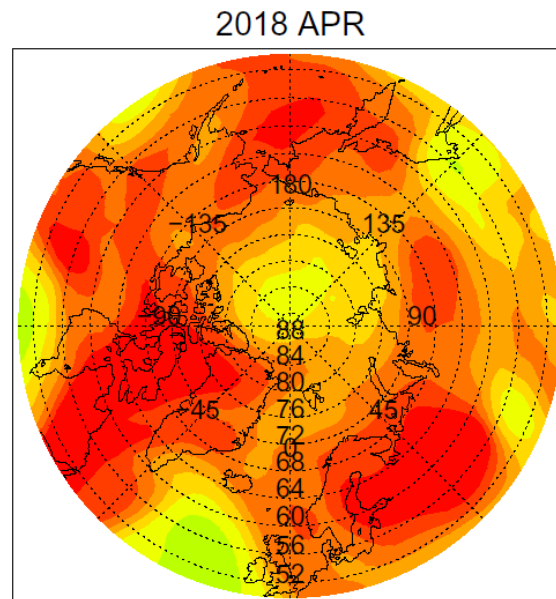
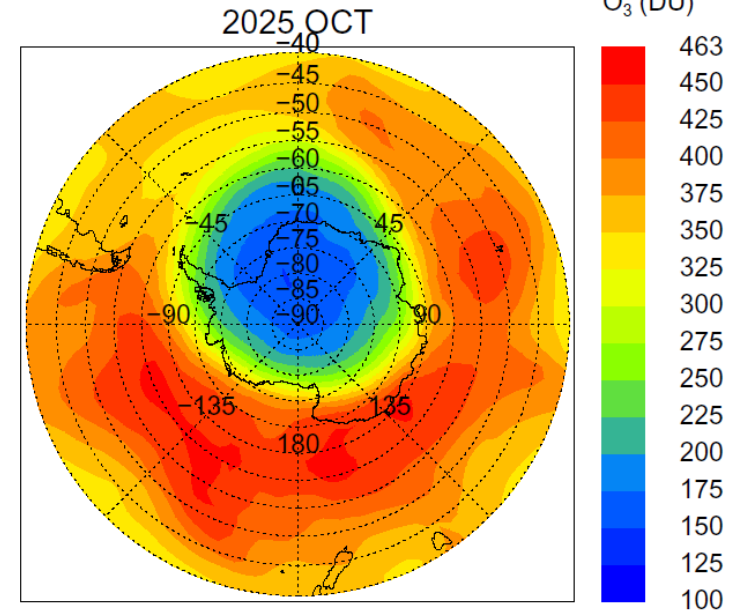
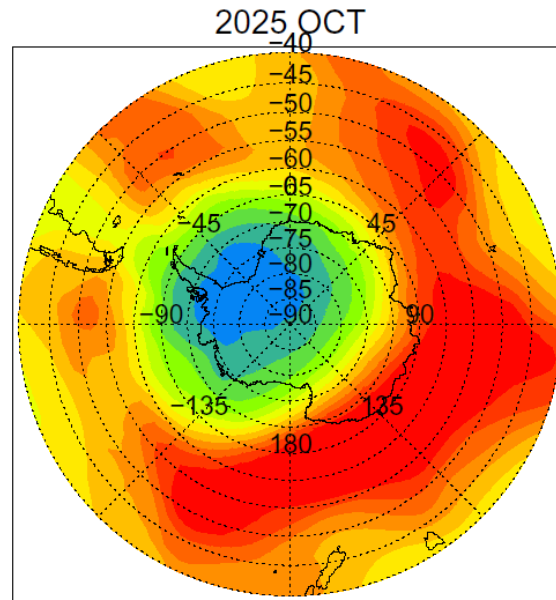
Ozone concentration
for coldest winters
with and without
geoengineering

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

NH

Baseline Run

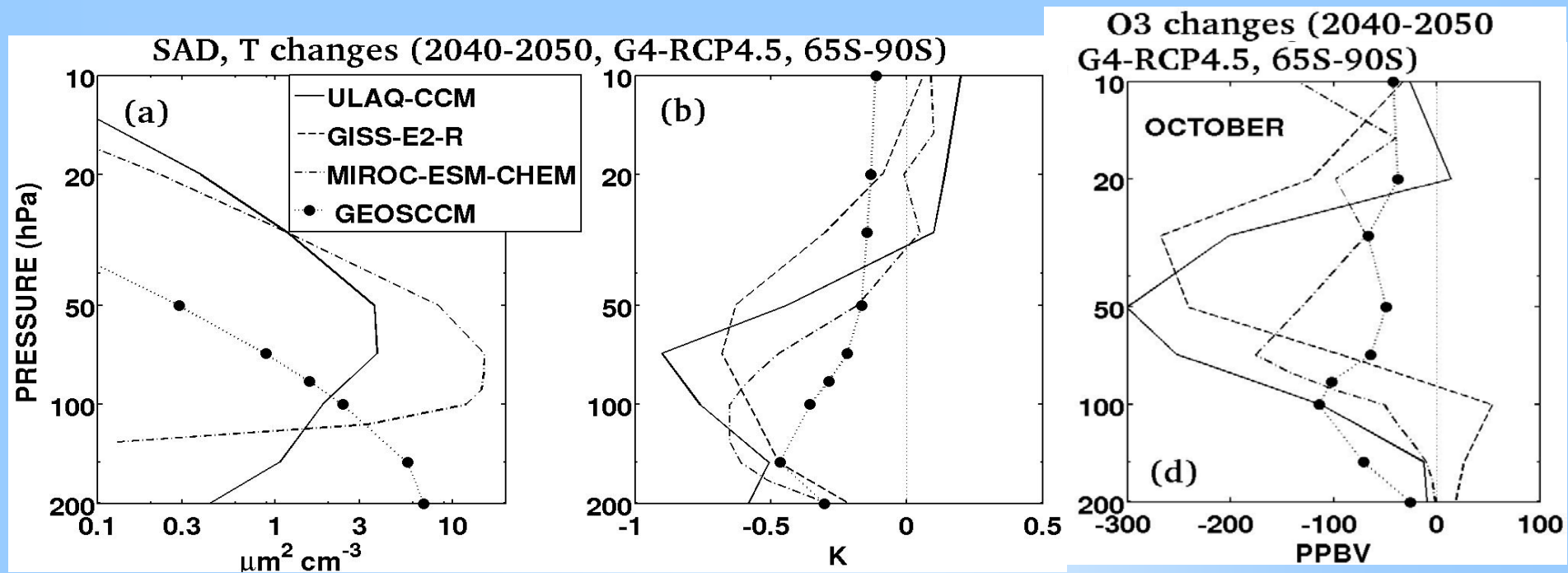
Geoengineering Run



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 NO_x cycle, and increases of surface area density.

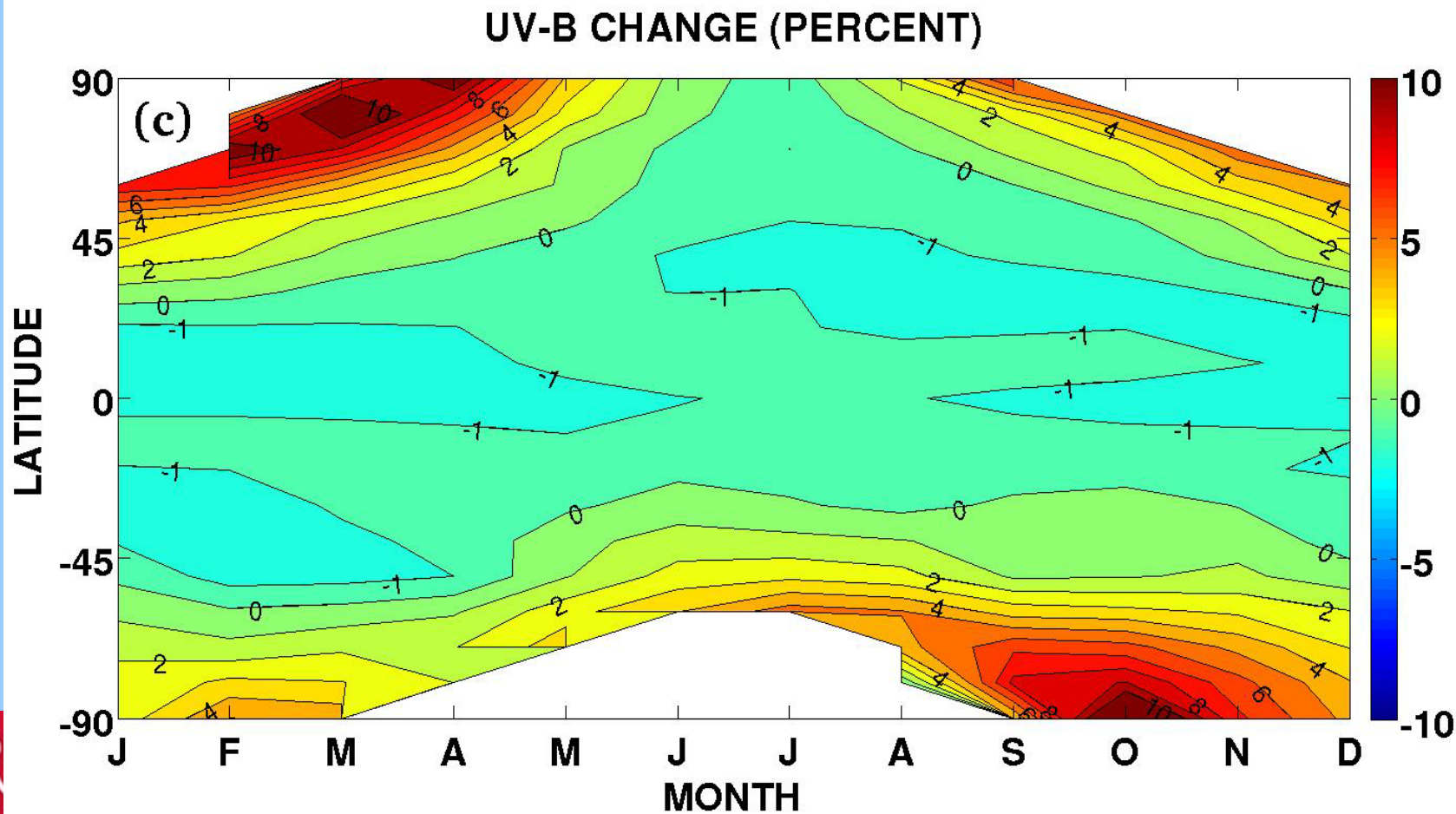
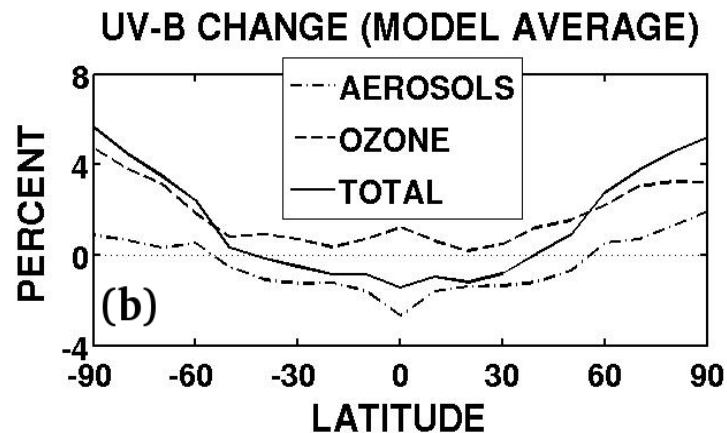
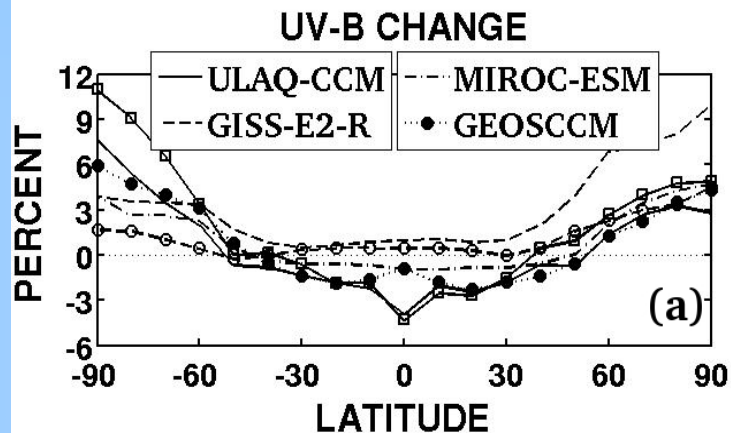
The net effect for a tropical injection rate of 5 Tg SO₂ per year is a decrease in globally averaged ozone by 1.1-2.1 DU in the years 2040-2050 for three models which include heterogeneous chemistry on the sulfate aerosol surfaces. GISS-E2-R, a fully coupled general circulation model, performed simulations 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, 2013: Stratospheric ozone response in experiments G3 and G4 of the Geoengineering Model Intercomparison Project (GeoMIP). Submitted to *J. Geophys. Res. Atmos.*, doi:10.1029/2013JD020566.



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, 2013: Stratospheric ozone response in experiments G3 and G4 of the Geoengineering Model Intercomparison Project (GeoMIP). Submitted to *J. Geophys. Res. Atmos.*, doi:10.1029/2013JD020566.



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

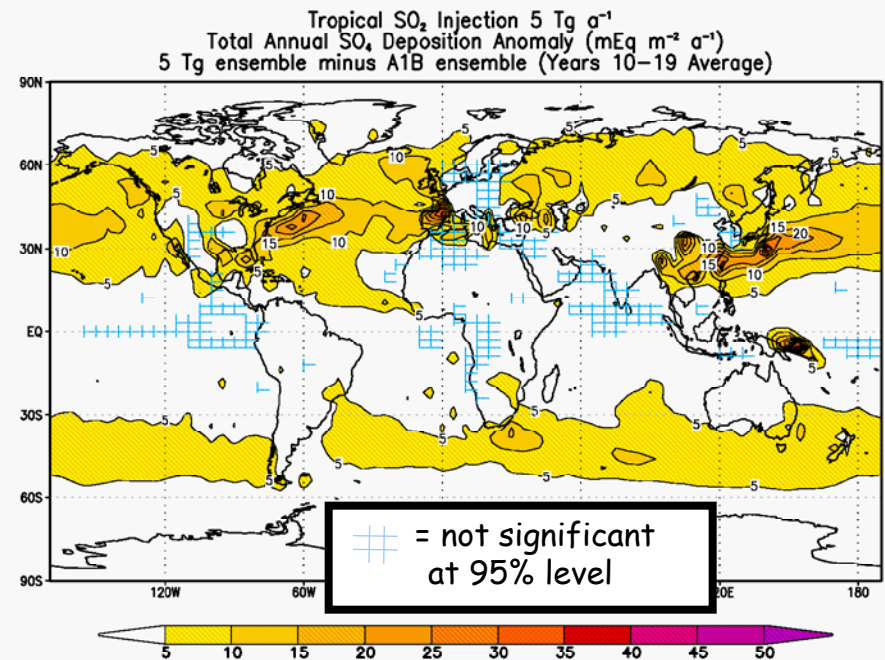
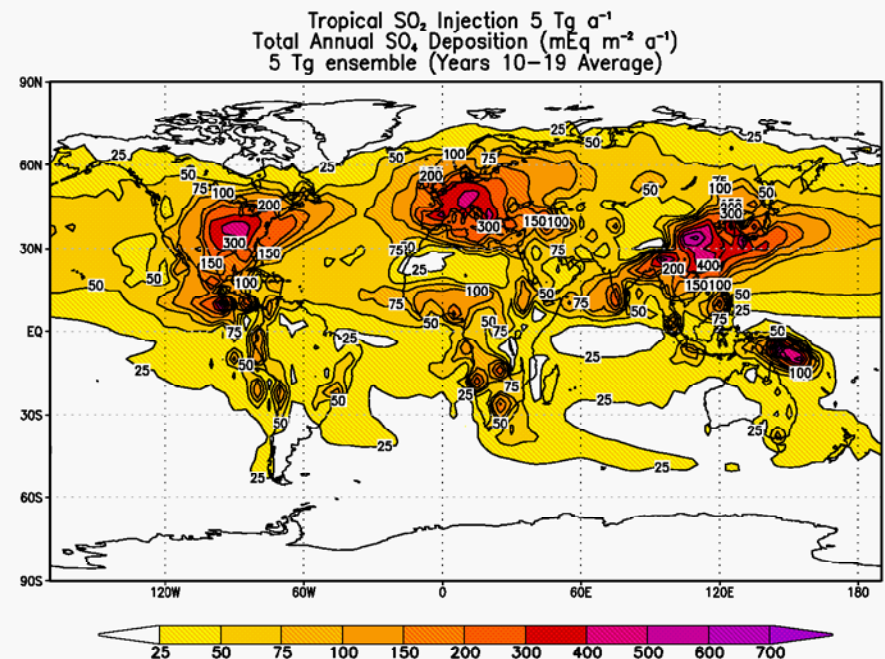
Robock, Alan, 2008: Whither geoengineering? *Science*, **320**, 1166-1167.

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

Region	Critical Load ($\text{mEq m}^{-2} \text{ a}^{-1}$)
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
Fåråhall 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.

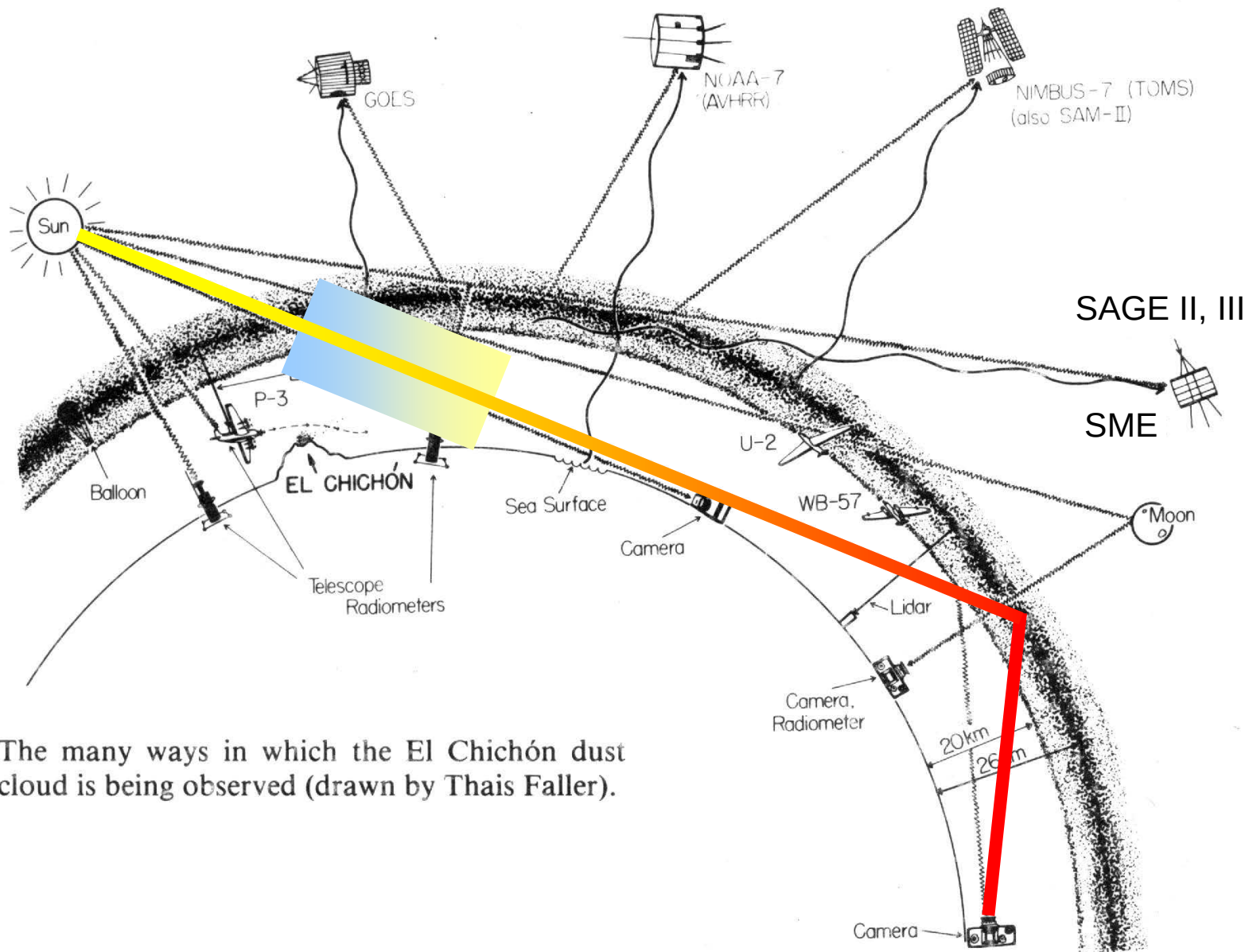
Kravitz, Ben, Alan Robock, Luke Oman, Georgiy Stenchikov, and Allison B. Marquardt, 2009: Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols. *J. Geophys. Res.*, **114**, D14109, doi:10.1029/2009JD011918, corrected.



Reasons geoengineering may be a bad idea

Climate system response

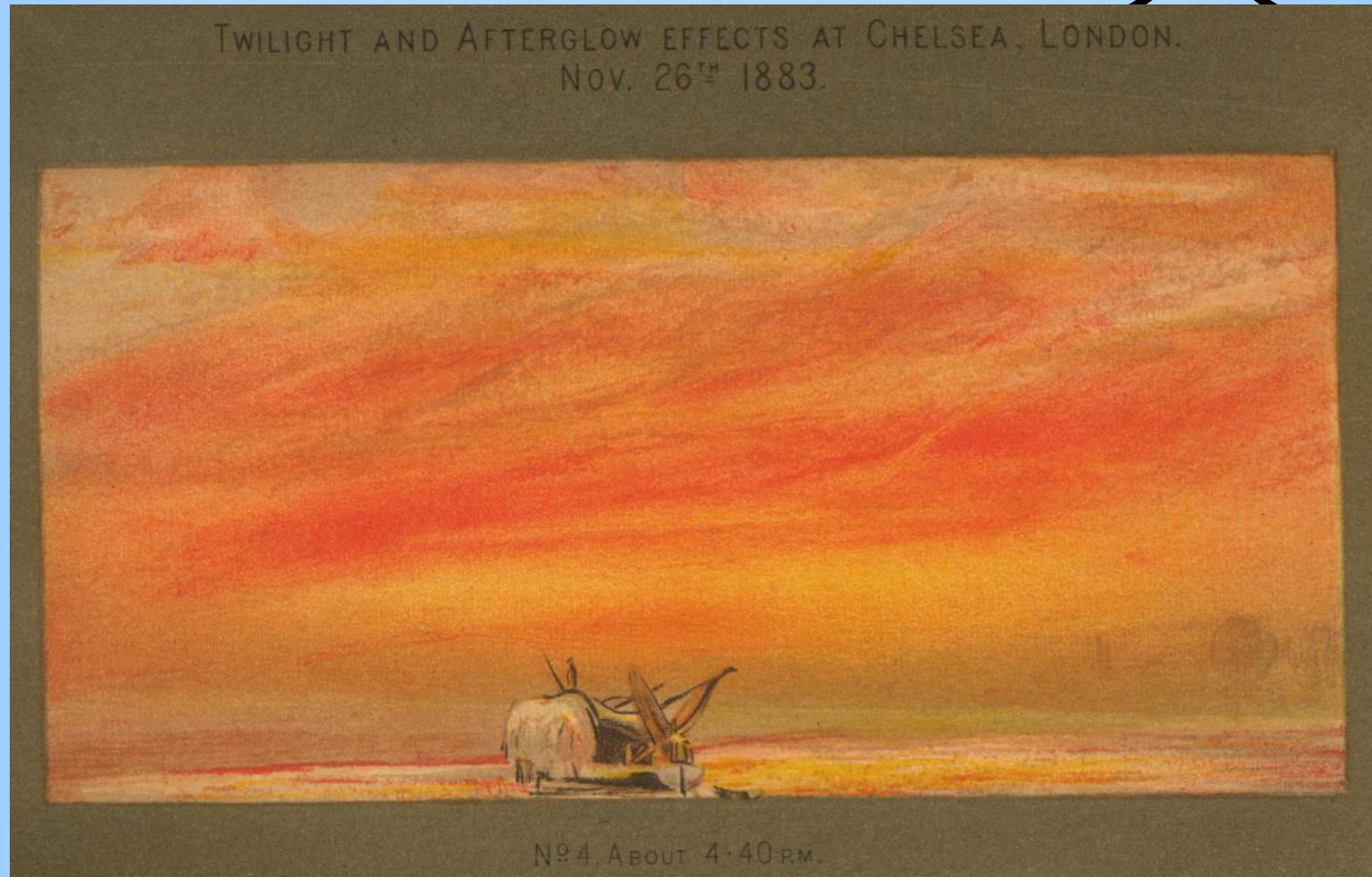
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The many ways in which the El Chichón dust cloud is being observed (drawn by Thais Faller).

Krakatau, 1883

Watercolor by William Ascroft



“The Scream”

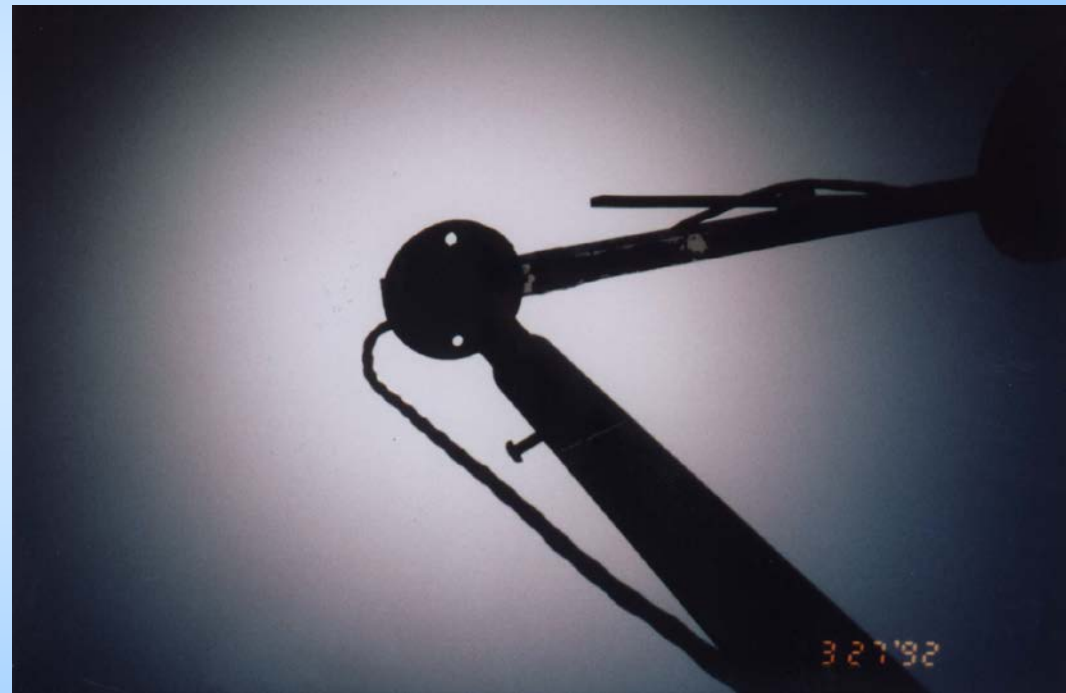
Edvard Munch

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



Sunset over Lake Mendota, July 1982

Diffuse Radiation from Pinatubo Makes a Whiter Sky



Photographs by Alan Robock

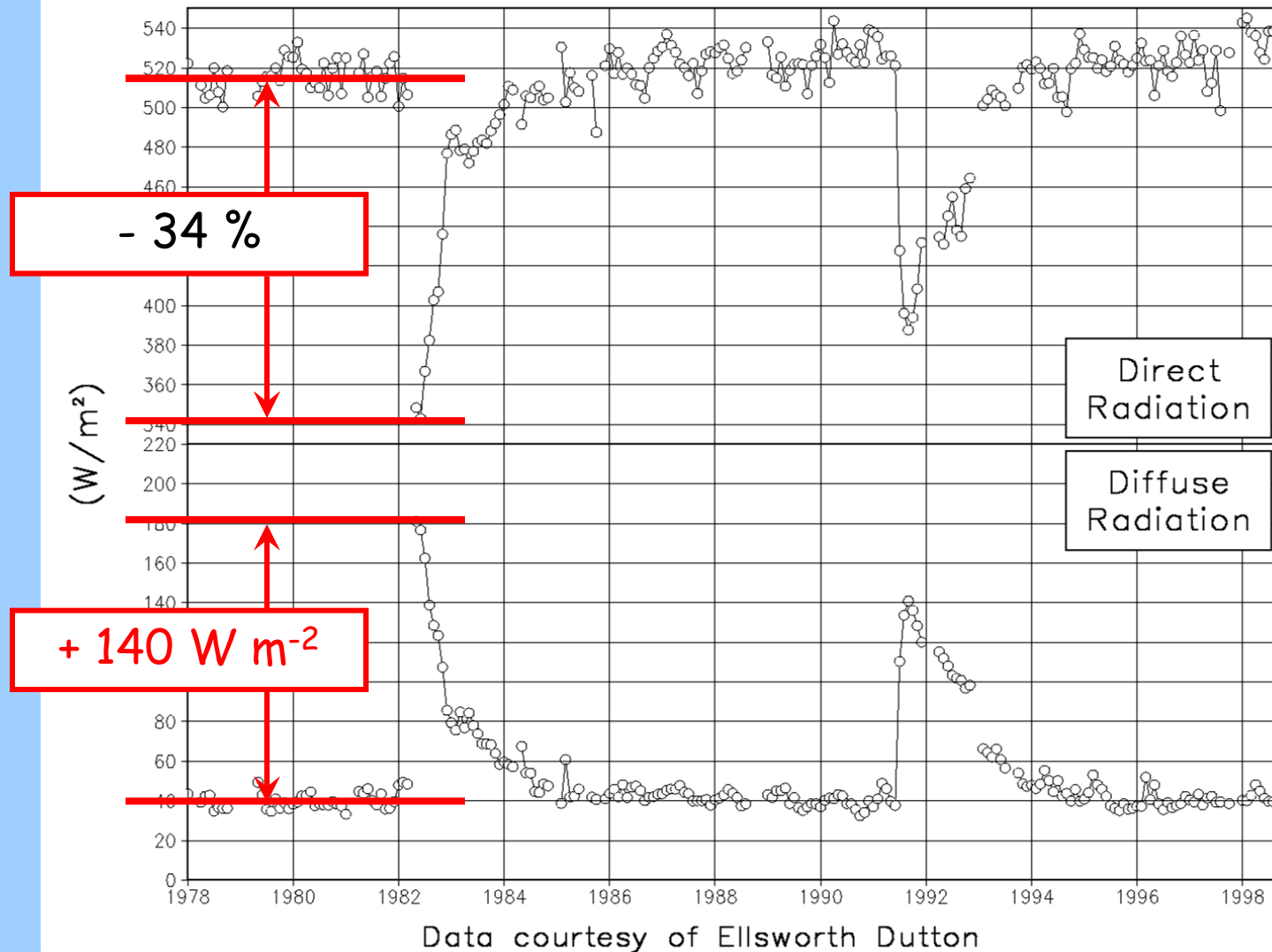
Geoengineering: Whiter skies?

Ben Kravitz,¹ Douglas G. MacMartin,² and Ken Caldeira¹

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 CO₂ 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 $\sim 0.5 \mu\text{m}$ preferentially increase diffuse irradiance in red wavelengths, whereas large particles ($\sim 0.9 \mu\text{m}$) 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.

Broadband solar radiation, Mauna Loa Observatory (19°N)



Nevada Solar One
64 MW



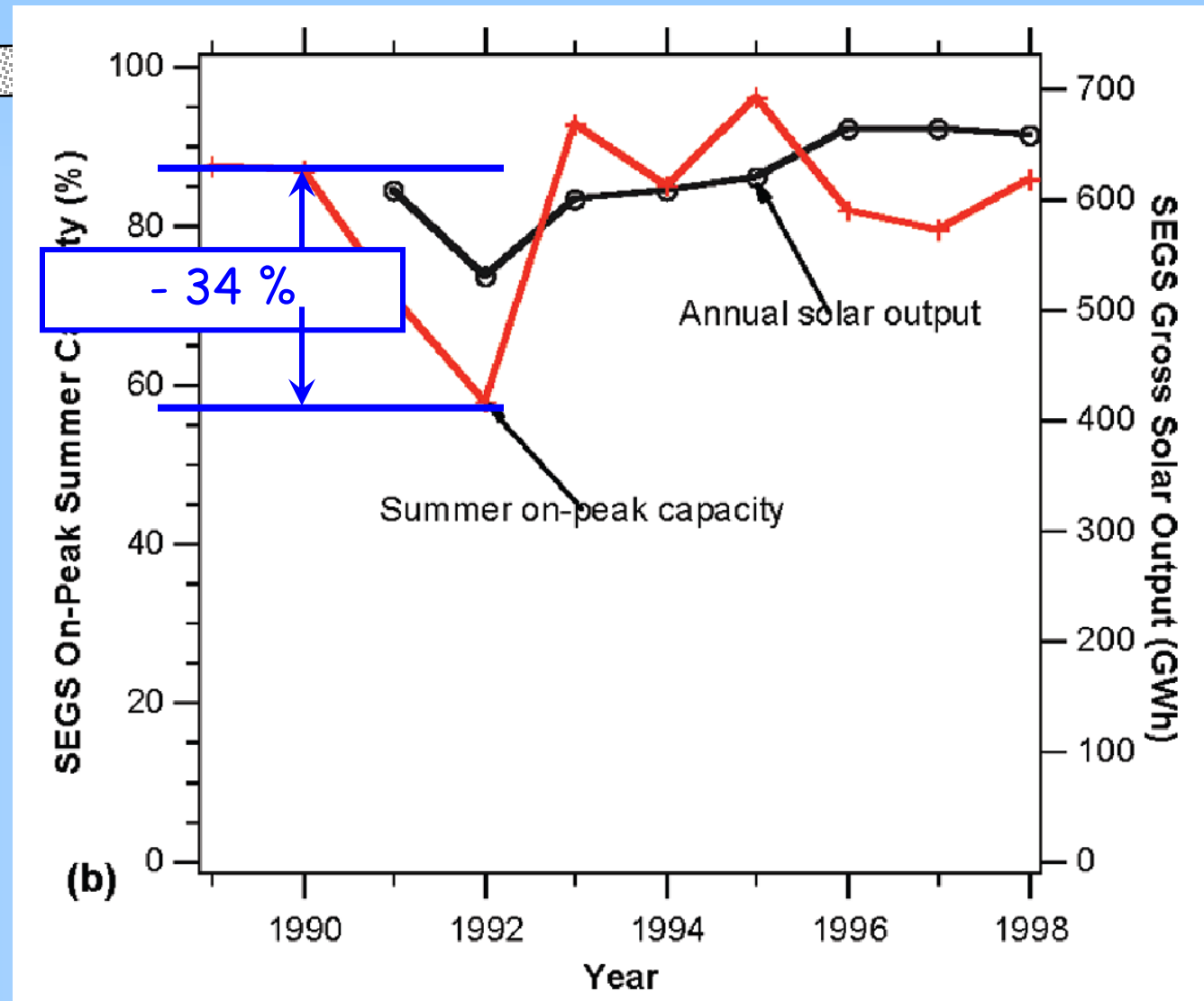
Solar steam generators
requiring direct solar

Seville, Spain
Solar Tower
11 MW



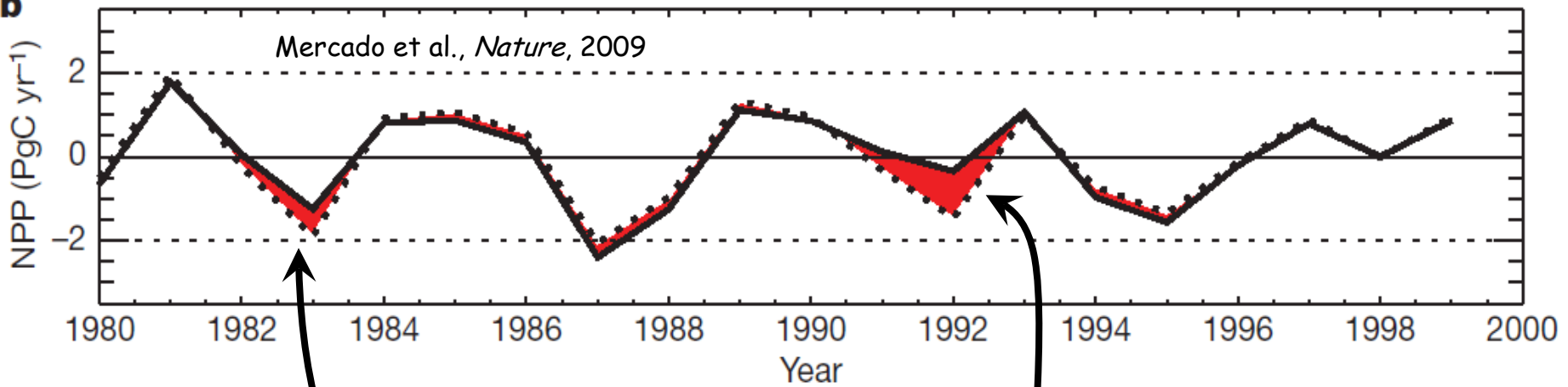
http://www.electronichealing.co.uk/articles/solar_power_tower_spain.htm

<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*)

b Mercado et al., *Nature*, 2009



Additional carbon sequestration after volcanic eruptions because of the effects of diffuse radiation, but certainly will impact natural and farmed vegetation.

nature

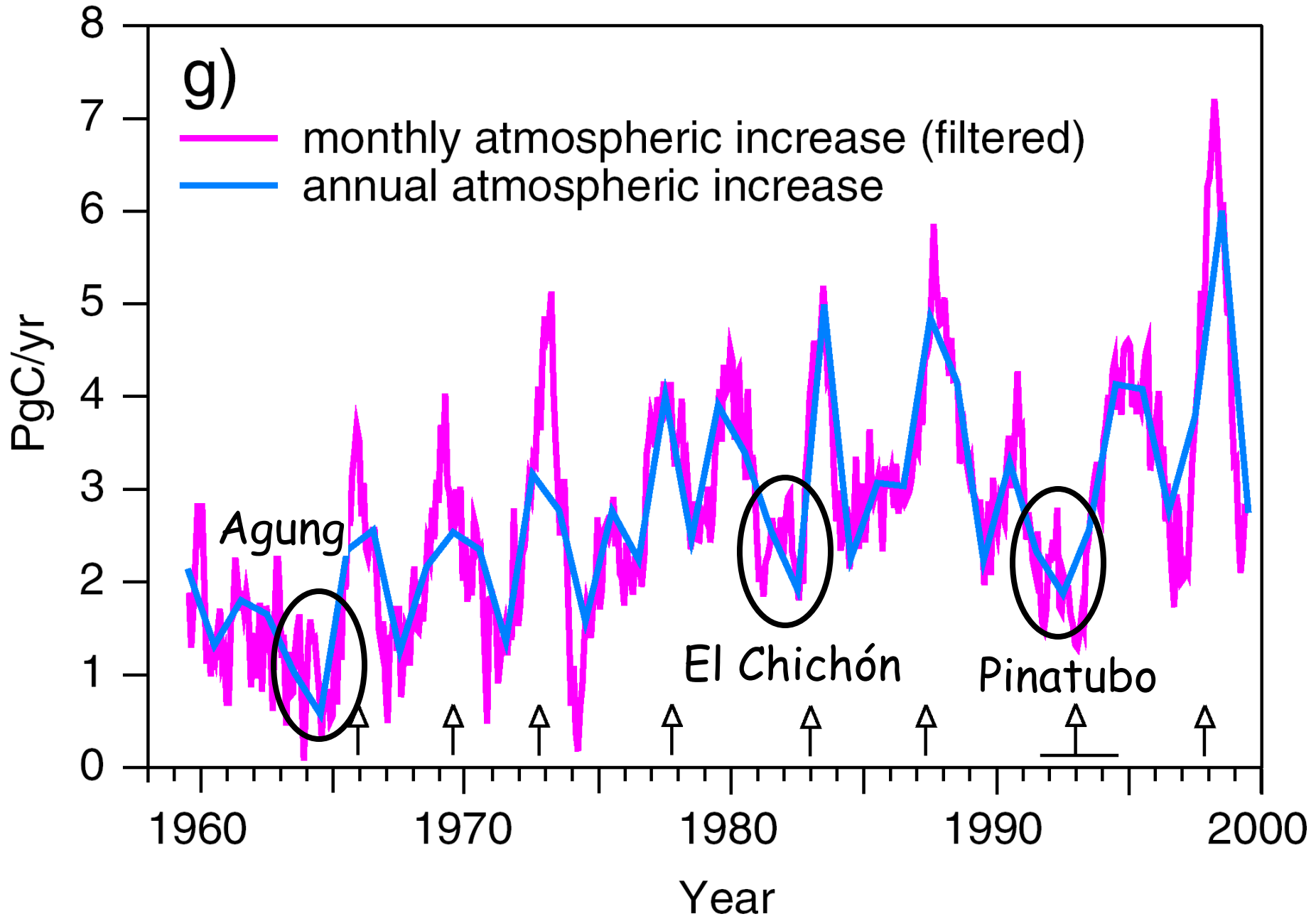
Vol 458 | 23 April 2009 | doi:10.1038/nature07949

LETTERS

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

Lina M. Mercado¹, Nicolas Bellouin², Stephen Sitch², Olivier Boucher², Chris Huntingford¹, Martin Wild³ & Peter M. Cox⁴

Rate of increase of CO₂ in the atmosphere



Reasons geoengineering may be a bad idea

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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?

- 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.

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.



© New York Times
Henning Wagenbreth
Oct. 24, 2007

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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.**

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 CO₂ 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.

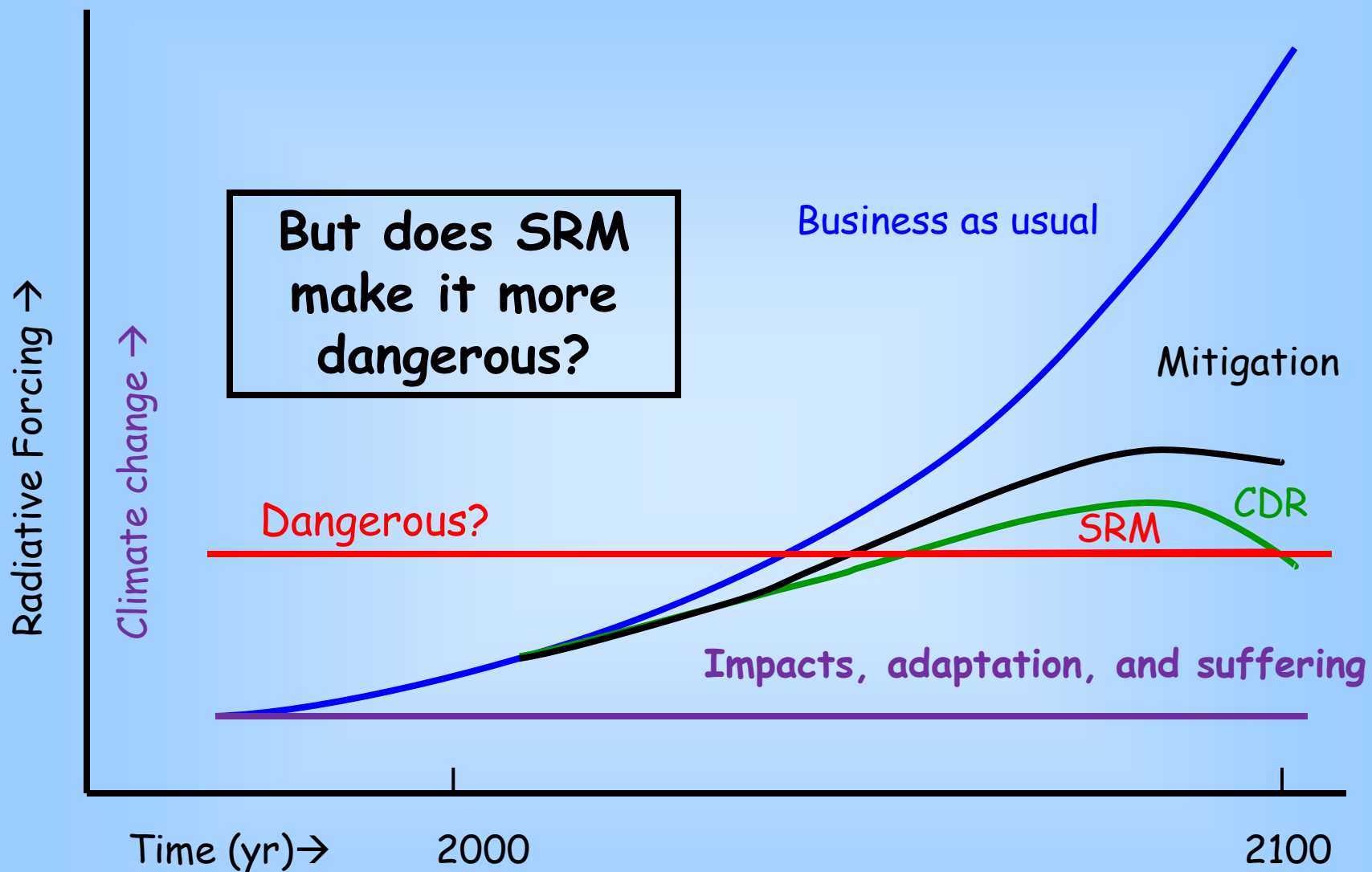
Robock, Alan, Allison B. Marquardt, Ben Kravitz, and Georgiy Stenchikov, 2009: The benefits, risks, and costs of stratospheric geoengineering. *Geophys. Res. Lett.*, **36**, L19703, doi:10.1029/2009GL039209.

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 CO₂ 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



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.”



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

