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THE STATE UNIVERSITY OF NEW JERSEY

Volcanic Eruptions as an Analog for Stratospheric Geoengineering

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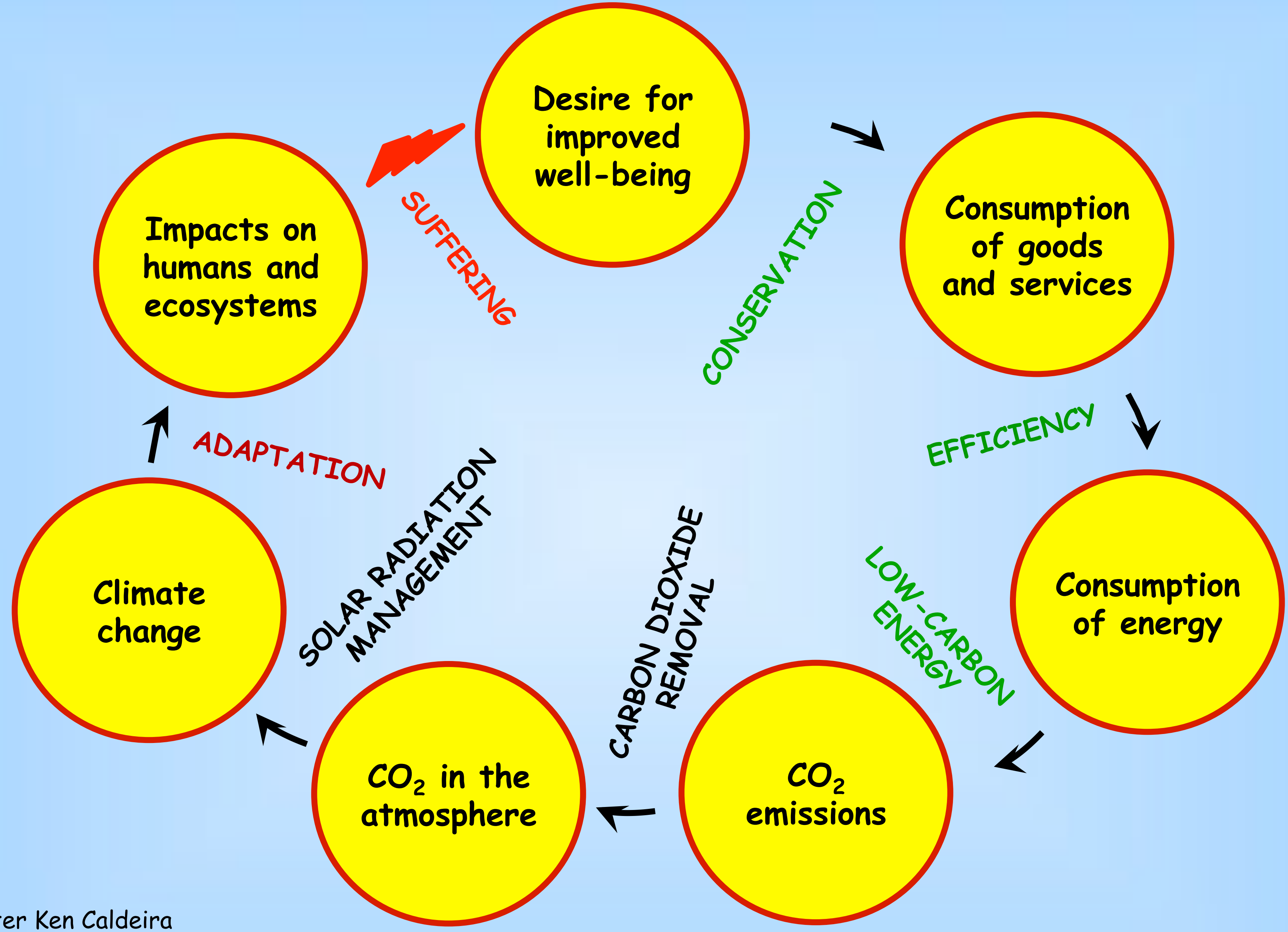

After Ken Caldeira

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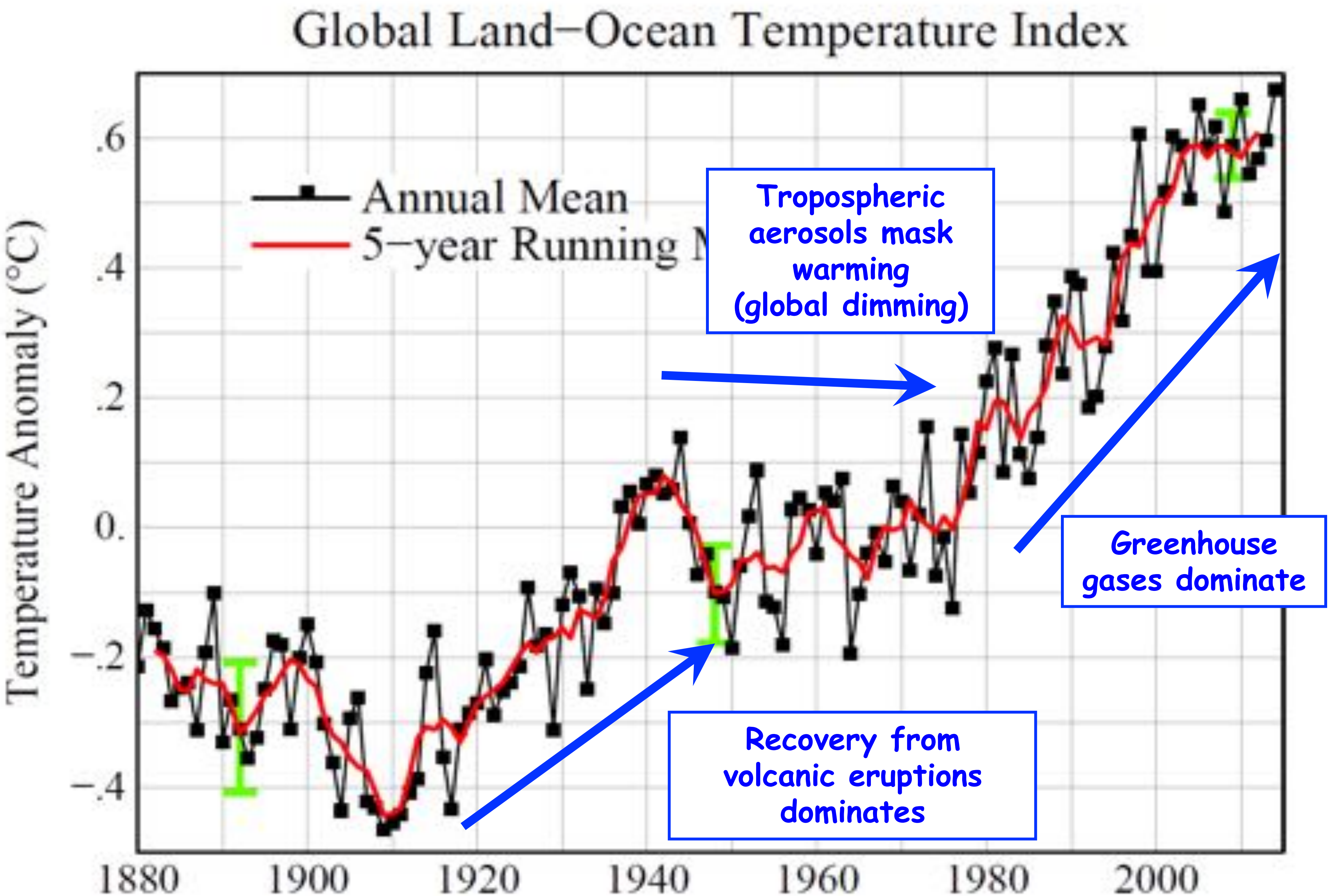


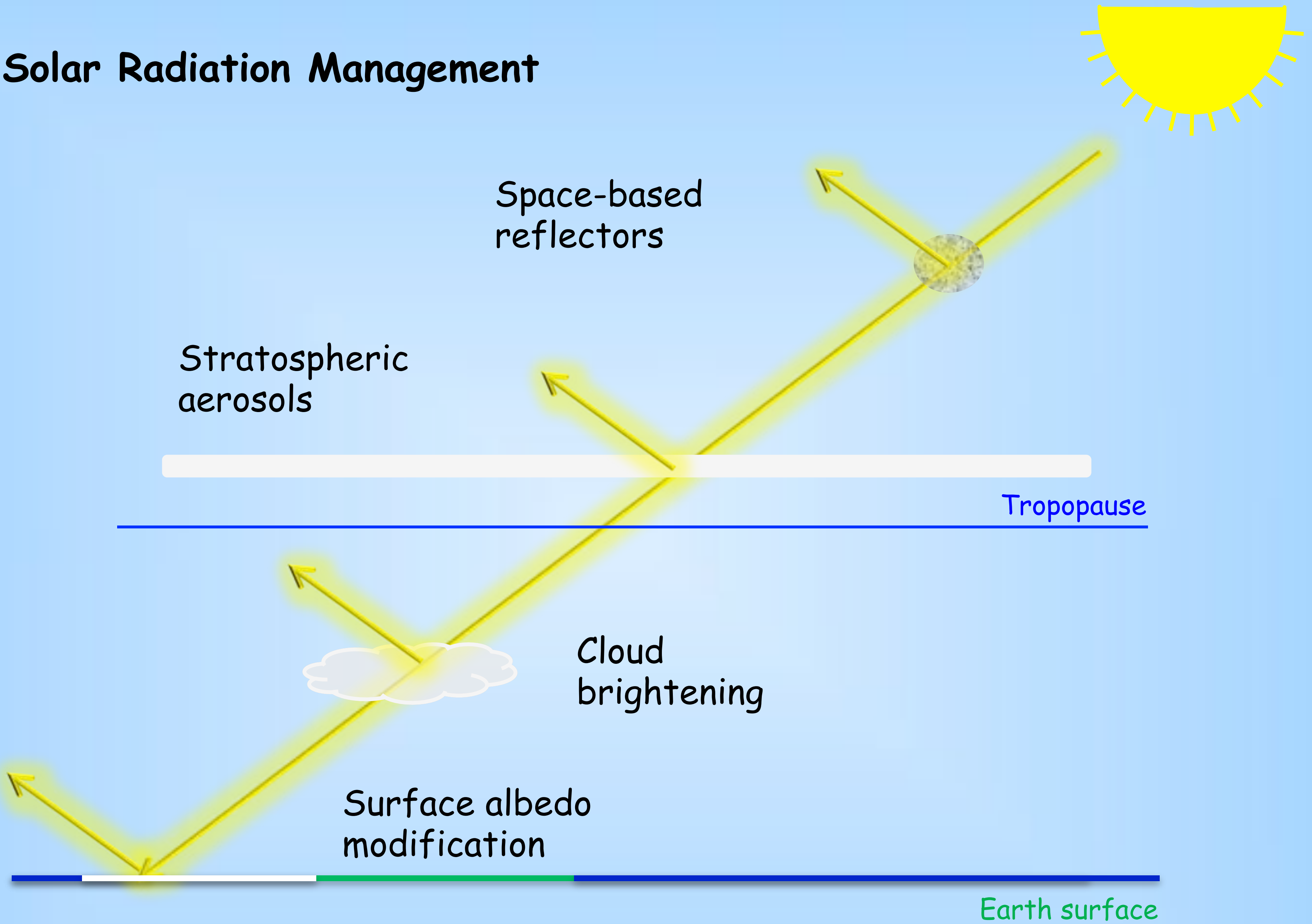
Global Land–Ocean Temperature Index
Annual Mean
5–year Running M
Temperature Anomaly (°C)
.6
.4
.2
0.
–.2
–.4
1880
1900
1920
1940
1960
1980
2000
Tropospheric aerosols mask warming (global dimming)
Greenhouse gases dominate
Recovery from volcanic eruptions dominates

Geoengineering is defined as

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

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

Solar Radiation Management



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Stratospheric geoengineering

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

Stratospheric Geoengineering

Benefits

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

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

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

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

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

Risks

1. Drought in Africa and Asia
2. Perturb ecology with more diffuse radiation
3. Ozone depletion
4. Continued ocean acidification
5. 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
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24. More sunburn
25. Moral hazard – the prospect of it working would reduce drive for mitigation
26. Moral authority – do we have the right to do this?

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Being addressed by GeoMIP

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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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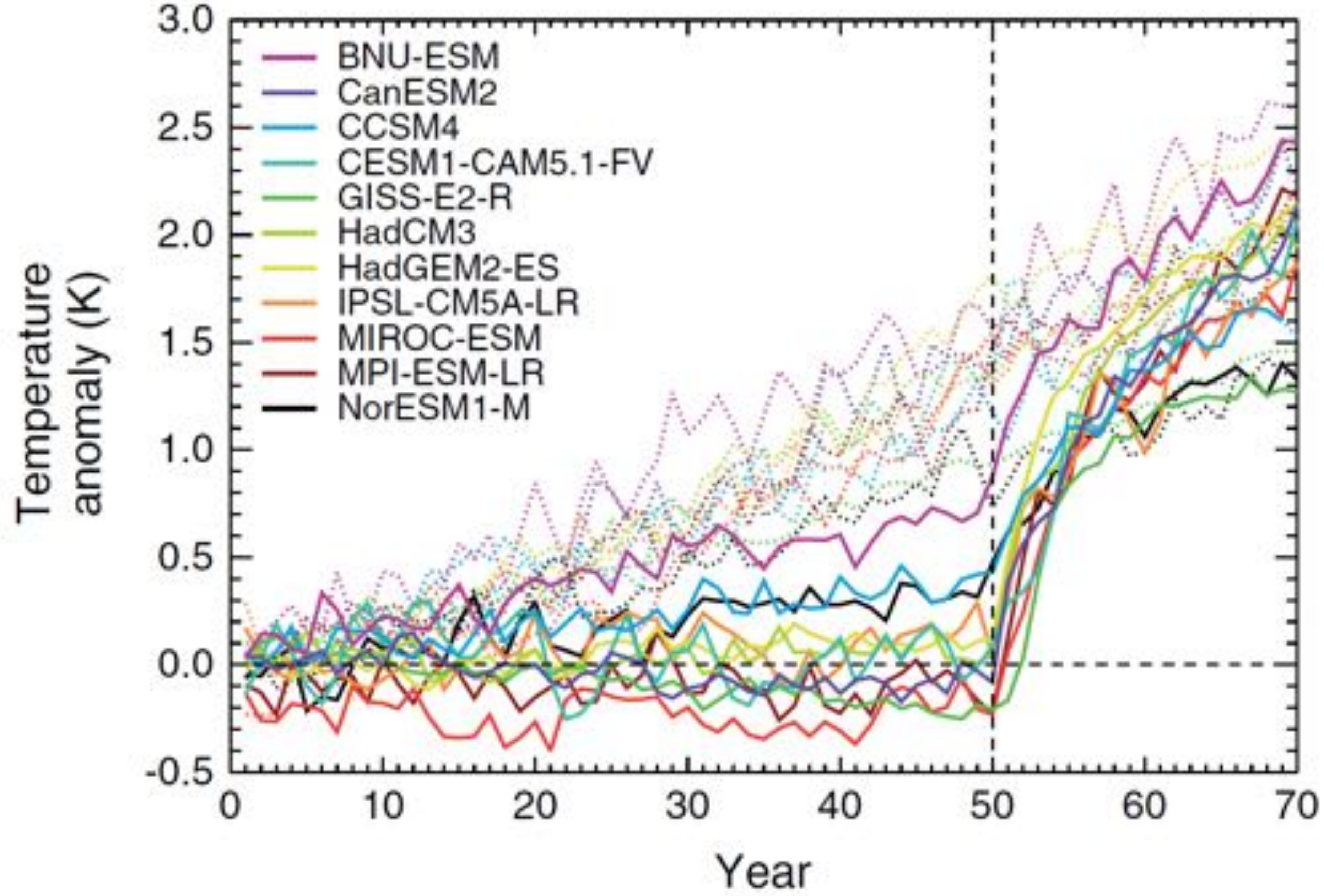
WCRP World Climate Research Programme

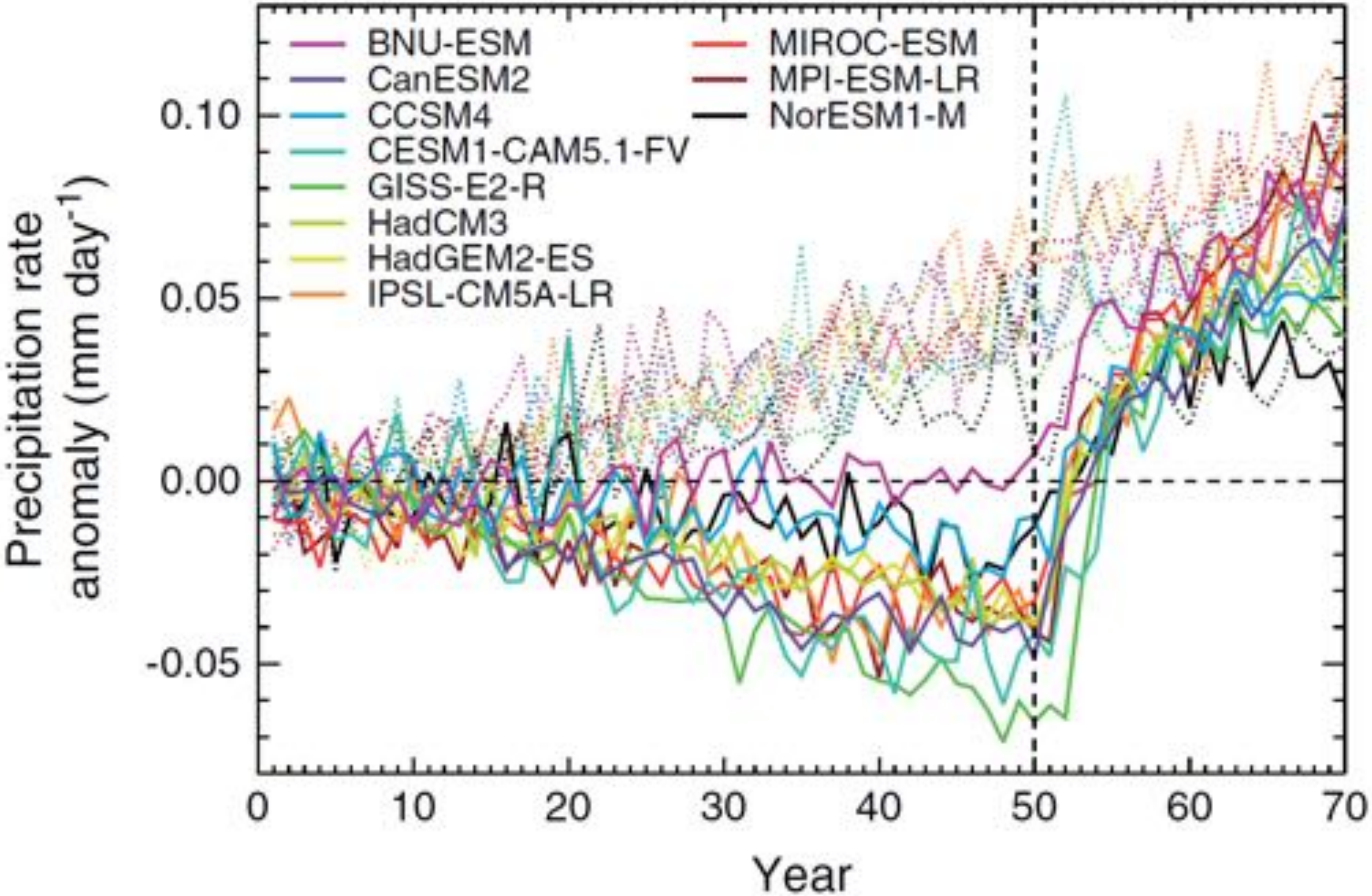
Results from G2 experiments by 11 climate models.

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

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



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



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

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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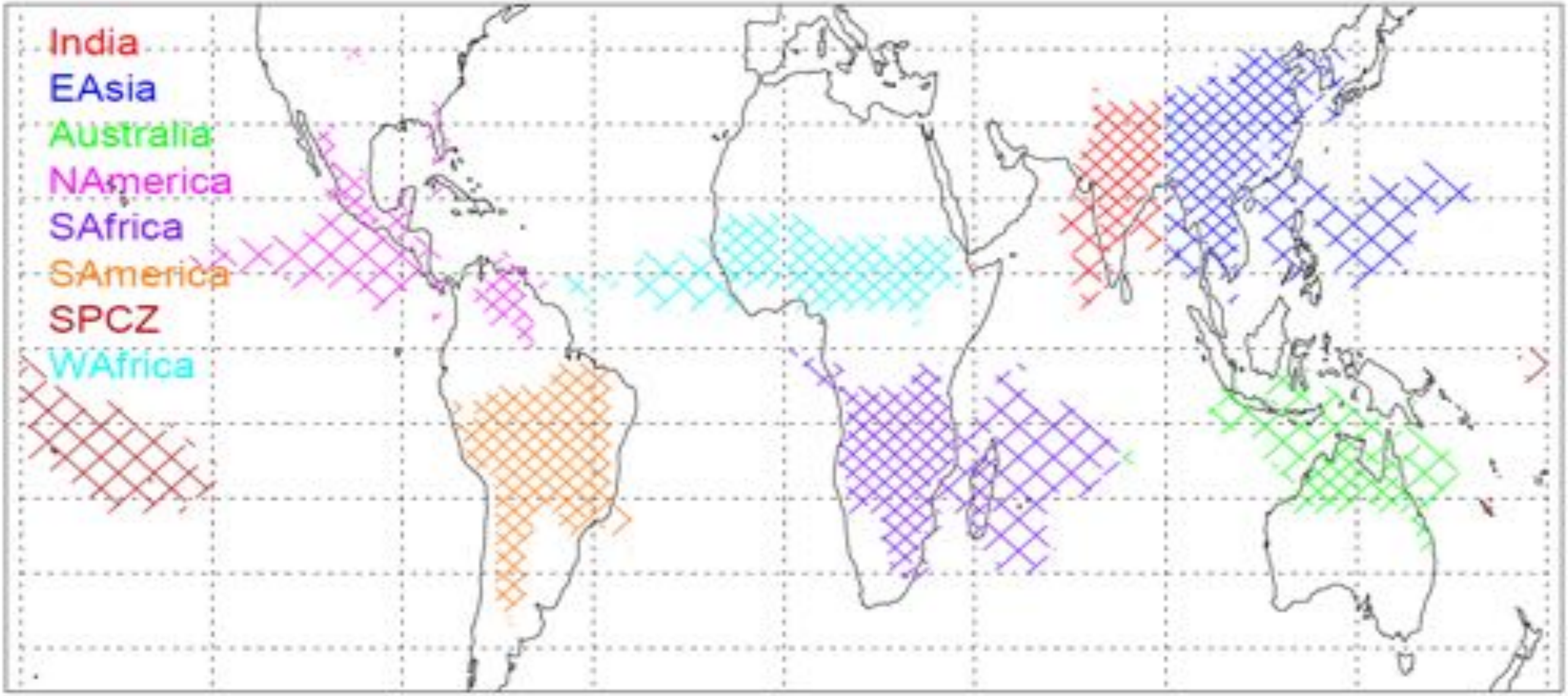
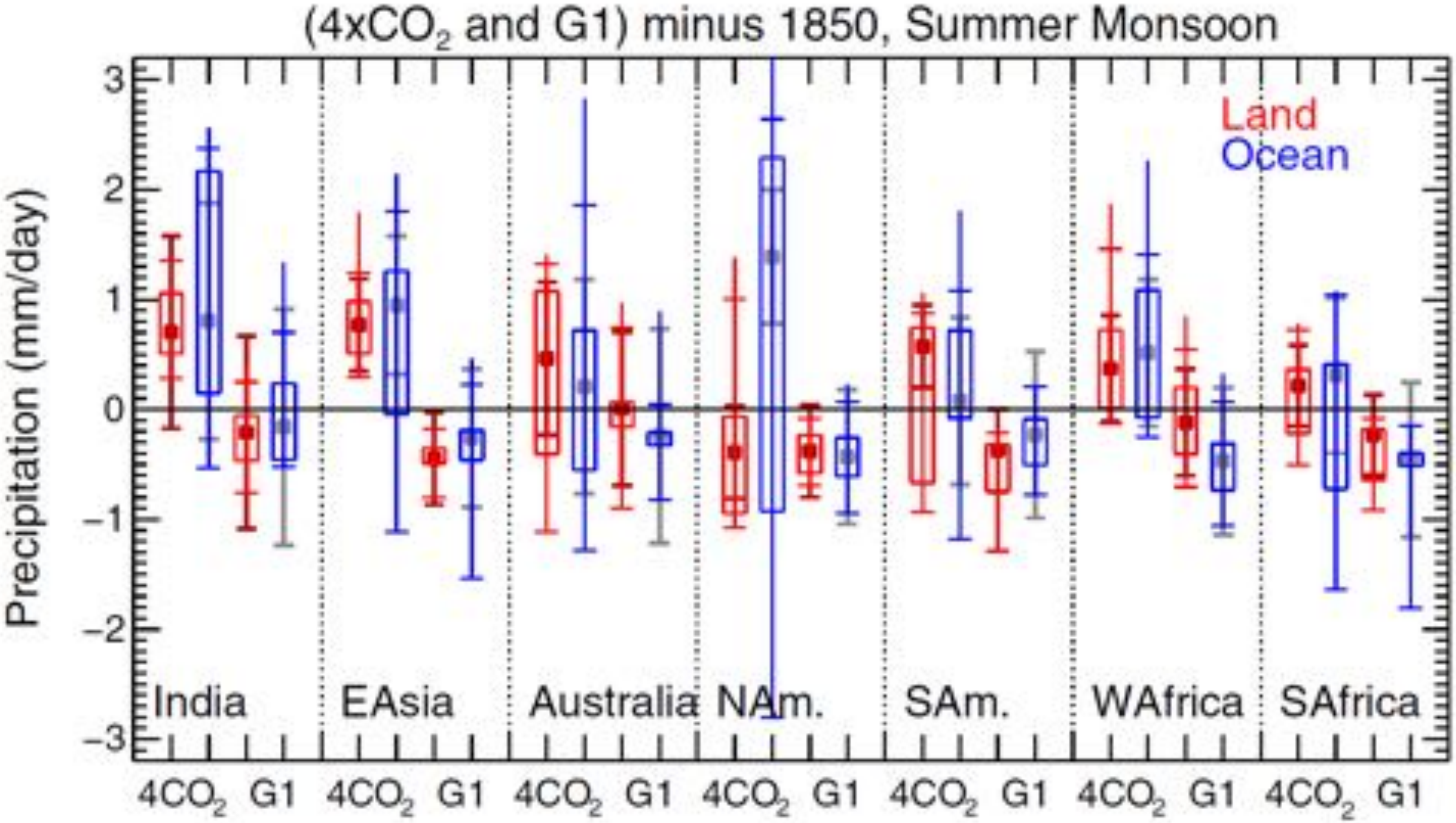
Monsoon regions





(4xCO2 and G1) minus 1850, Summer Monsoon
Land
Ocean
Precipitation (mm/day)
3
2
1
0
−1
−2
−3
India
EAsia
Australia
NAm.
SAm.
WAfrica
SAfrica
4CO2 G1 4CO2 G1 4CO2 G1 4CO2 G1 4CO2 G1 4CO2 G1 4CO2 G1

Years 11-50

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Volcanic analog

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

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

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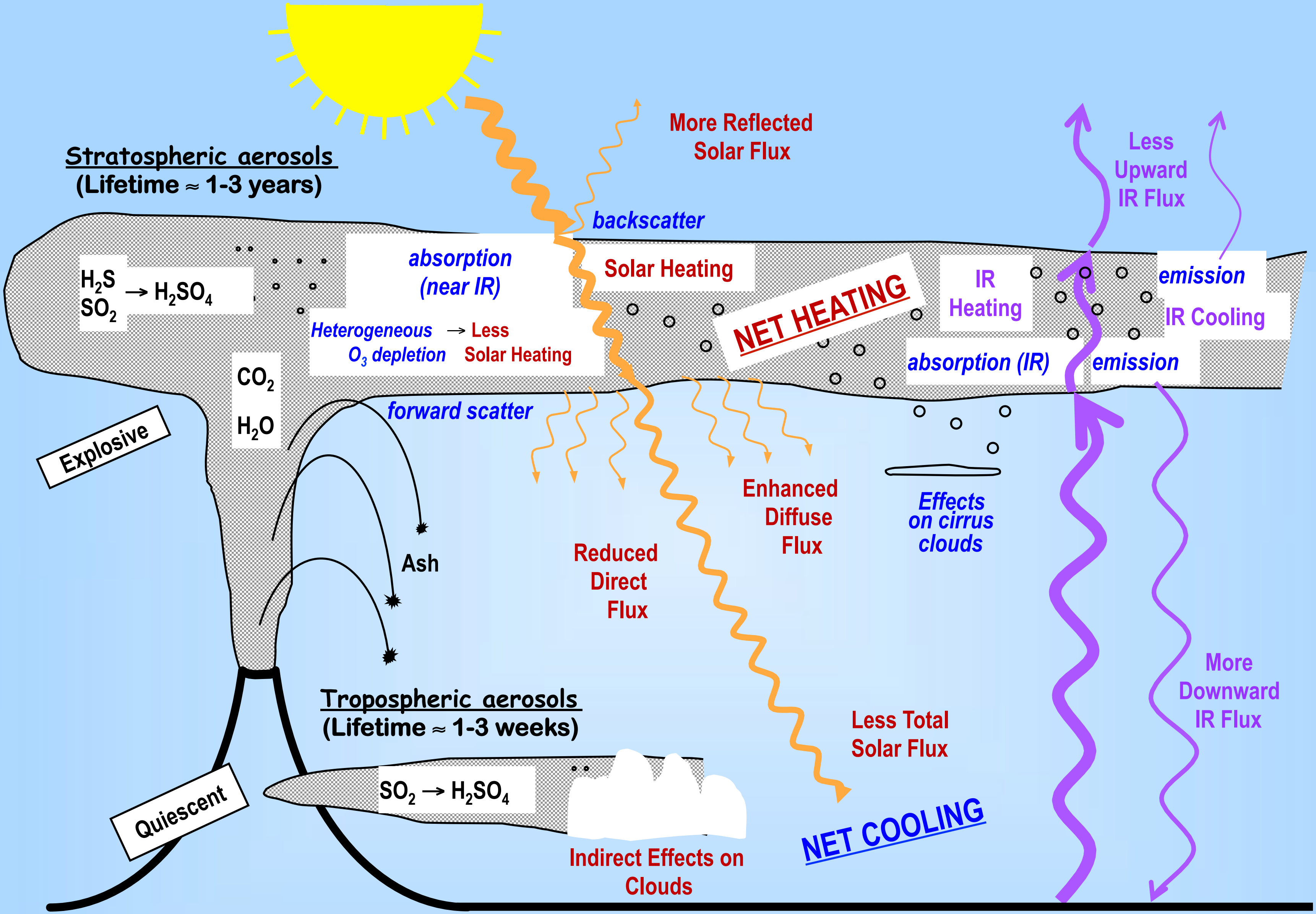

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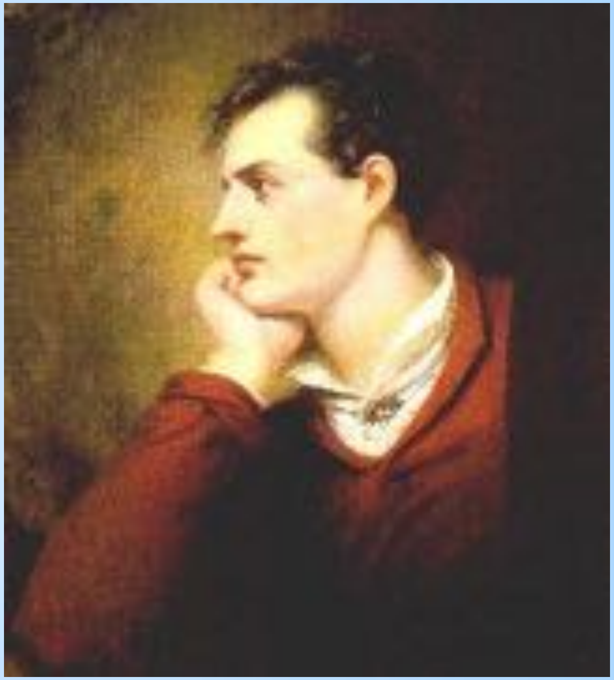
Tambora, 1815, produced the "Year Without a Summer" (1816)

Percy Bysshe Shelley

Mary Shelley

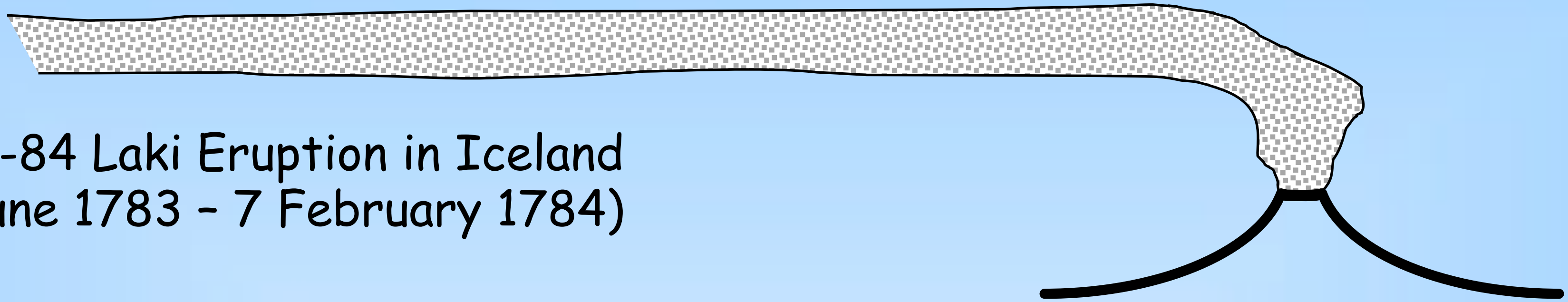


George Gordon, Lord Byron

Alan Robock
Department of Environmental Sciences


LORD BYRON
POÊTE ANGLAIS
AUTEUR DU
PRISONER of CHILLON
HABITA LA
VILLA DIODATI
EN 1816
YCOMPOSA LE 3me CHANT
DE
CHILDE HAROLD

1783-84, Lakagígar (Laki), Iceland



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

Second largest flood lava eruption in historical time

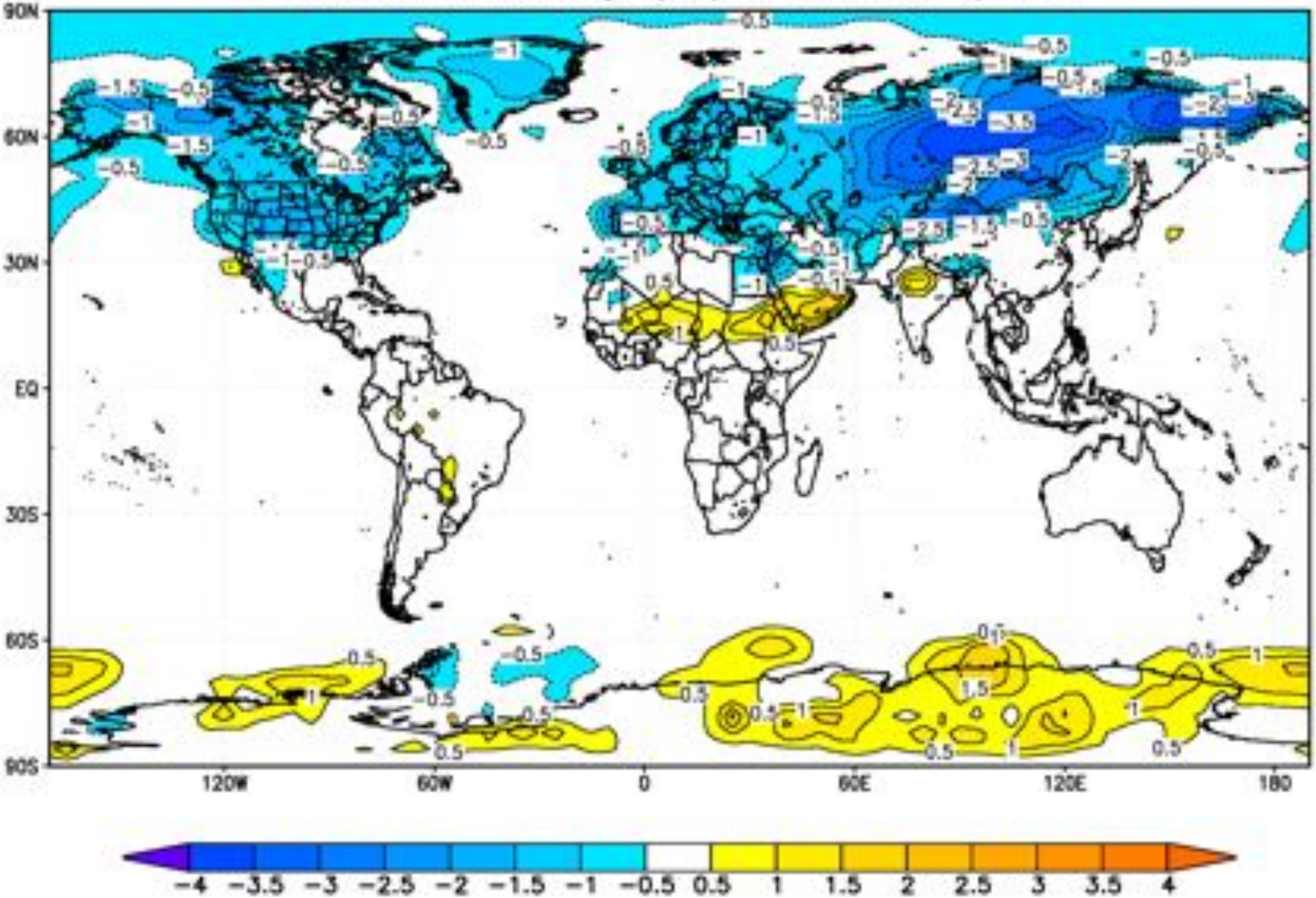
Iceland's biggest natural disaster

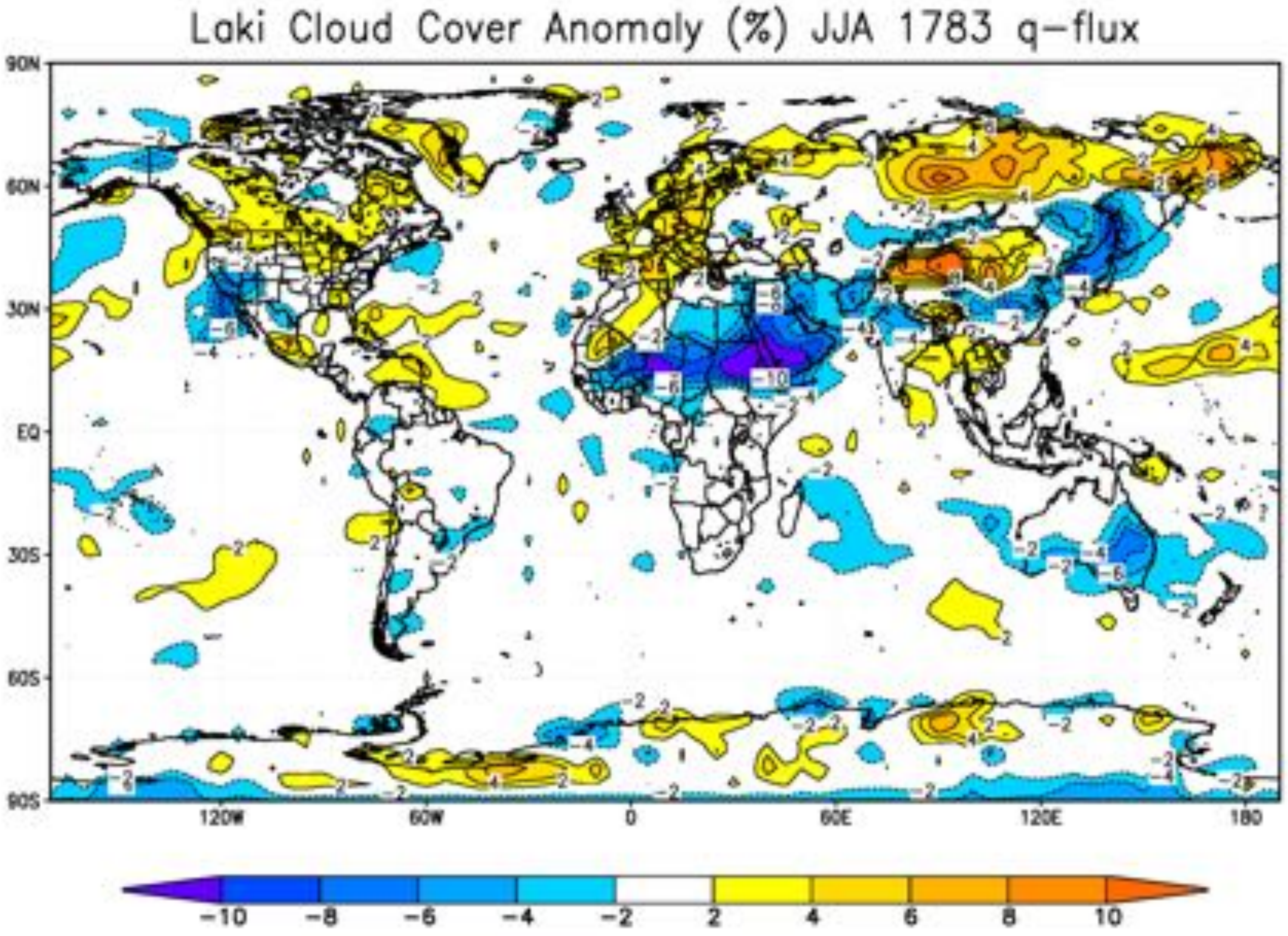
Lava = 14.7 km^3
Tephra = 0.4 km^3

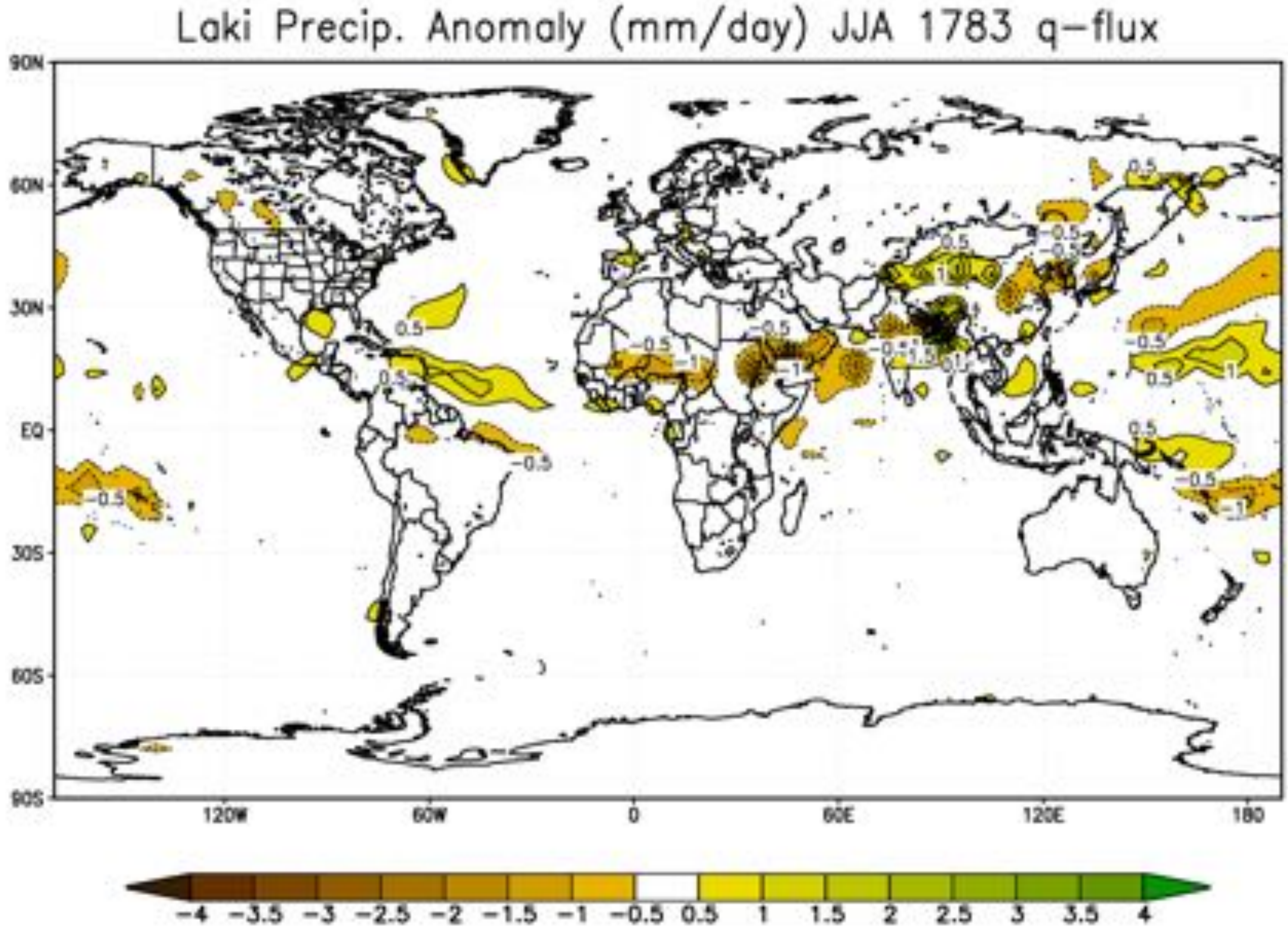
WVZ, EVZ, NVZ are Western, Eastern and Northern Volcanic Zones

Fig. 1 from Thordarson and Self (2003)

Laki SAT Anomaly (°C) JJA 1783 q-flux




Laki Cloud Cover Anomaly (%) JJA 1783 q-flux
90N
60N
30N
EQ
30S
60S
90S
120W
60W
0
60E
120E
180
-10
-8
-6
-4
-2
2
4
6
8
10

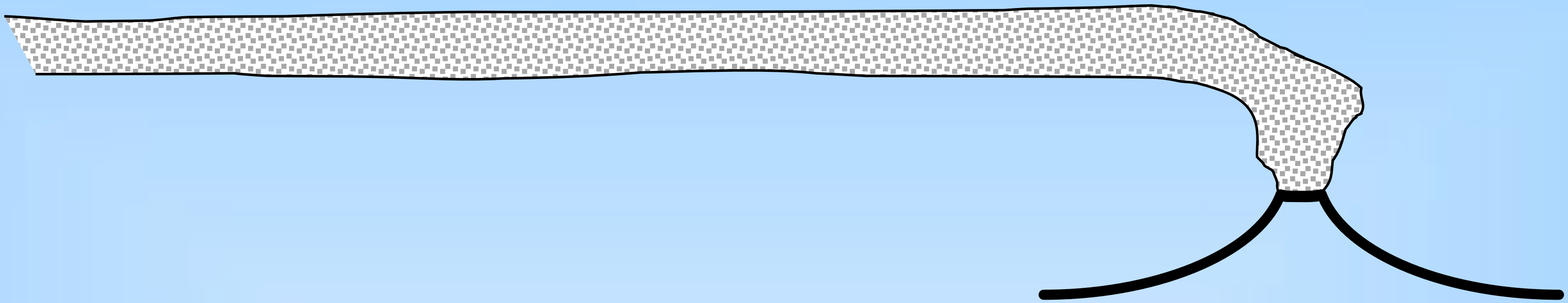

Laki Precip. Anomaly (mm/day) JJA 1783 q-flux
90N
60N
30N
EQ
30S
60S
90S
120W
60W
0
60E
120E
180
-4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0.5 1 1.5 2 2.5 3 3.5 4

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.

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.

What about other high latitude eruptions?

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

939 Eldgjá, Iceland - Tropospheric and stratospheric

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

1912 Novarupta (Katmai), Alaska - Stratospheric only

Photo by George C. Martin

KATMAI VILLAGE, LOOKING NORTH TOWARD KATMAI VOLCANO, WHICH IS CONCEALED IN THE CLOUD BEYOND THE HILLS
AUGUST 13, 1912

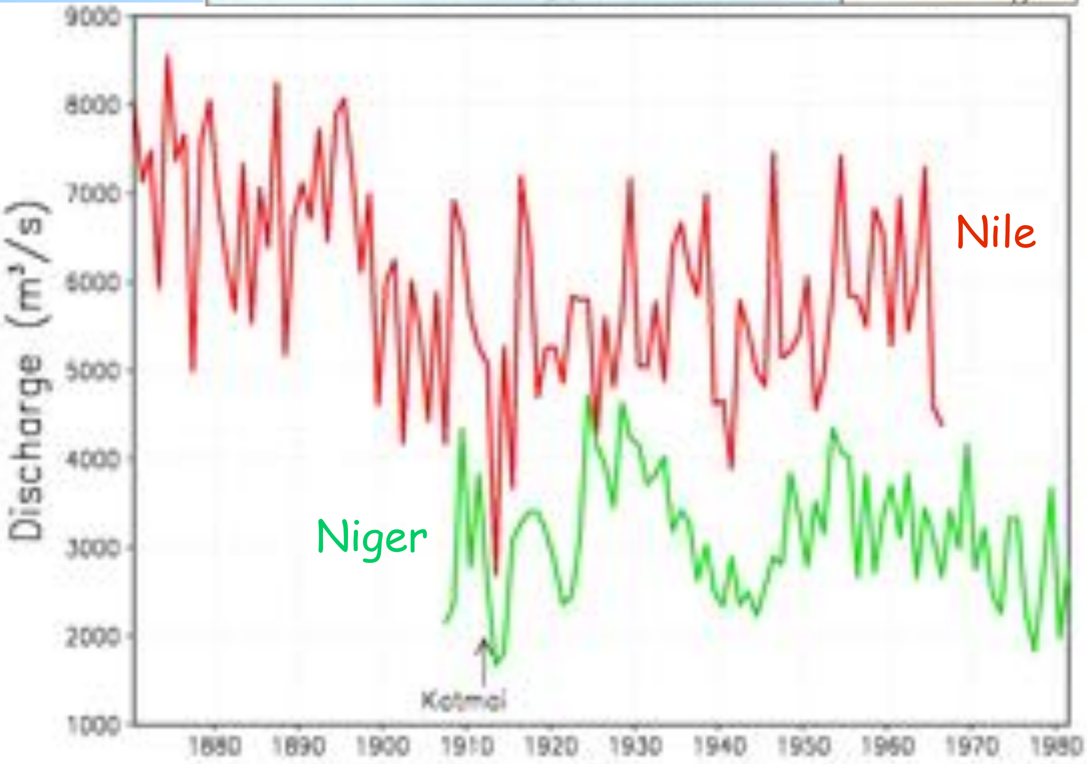
The eruption of Katmai Volcano, though one of the most violent explosions recorded, did not cause the loss of a single life, owing to the sparse settlement of the neighborhood. The town of Katmai was deserted at the time of the eruption, most of the inhabitants being away, engaged in the summer fishing.

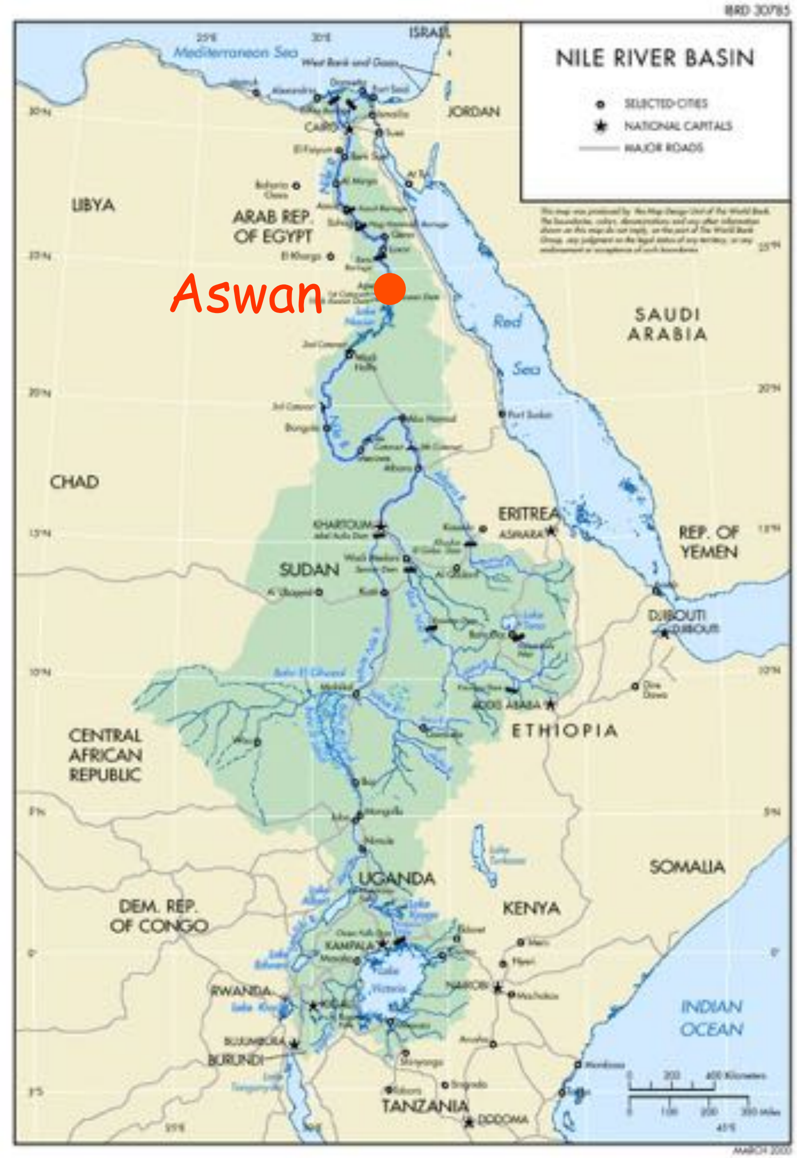
Katmai village, buried by ash from the June 6, 1912 eruption
Katmai volcano in background covered by cloud

Simulations showed same reduction in African summer precipitation.

http://www.festivalsegou.org

Niger Basin





http://www.isiimm.agropolis.org

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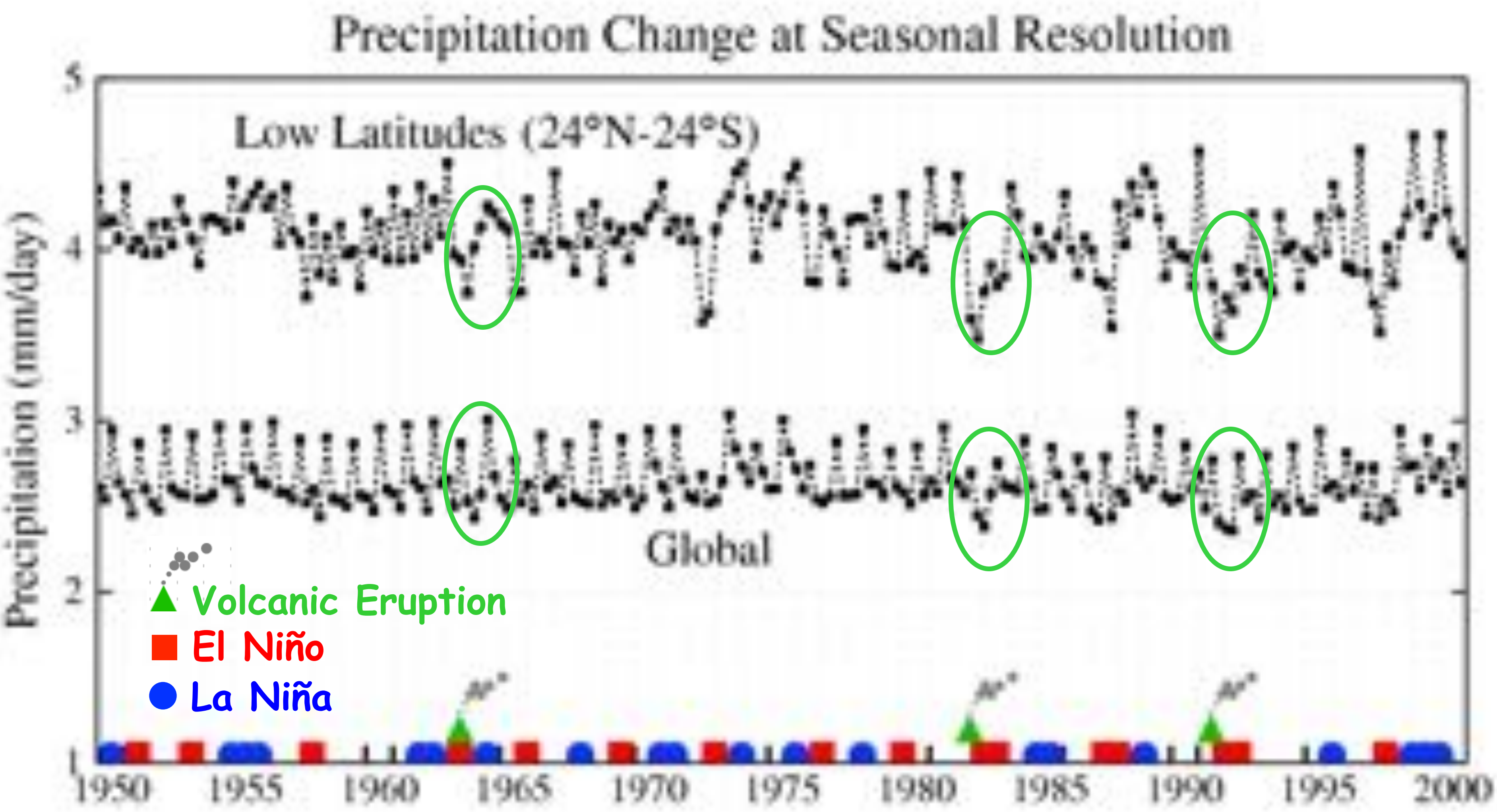

Drawn by Makiko Sato (NASA GISS) using CRU TS 2.0 data

Trenberth and Dai (2007)

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

Geophys. Res. Lett.

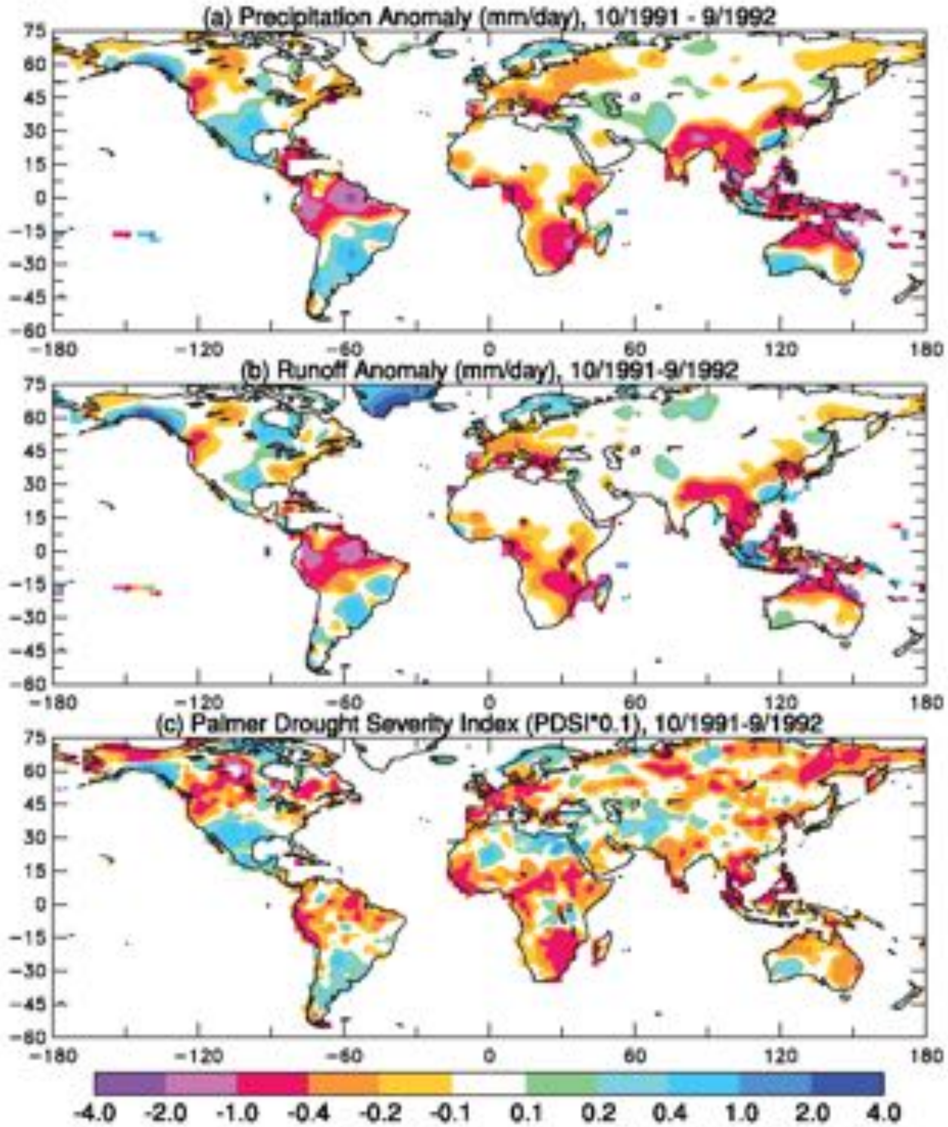

Figure 3. (a) Observed precipitation anomalies (relative to 1950–2004 mean) in mm/day during October 1991–September 1992 over land. Warm colors indicate below normal precipitation. (b) As for Figure 3a but for the simulated runoff [*Qian et al.*, 2006] using a comprehensive land surface model forced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

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Summer monsoon drought index pattern using tree rings for 750 years

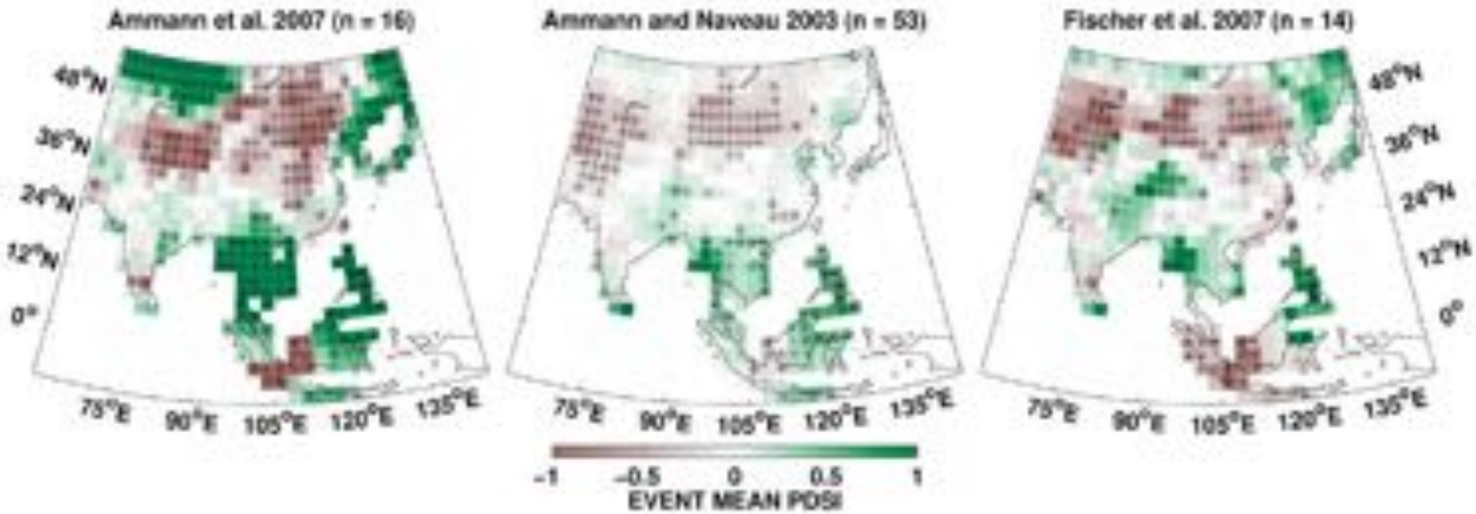


Figure 2. Superposed epoch analysis using the reconstructed PDSI values from the Monsoon Asia Drought Atlas (MADA) [*Cook et al.*, 2010] and the sets of events years shown in Table 1. Statistically significant (90% one-tailed) epochal anomalies based on Monte Carlo resampling (n = 10,000) are indicated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

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

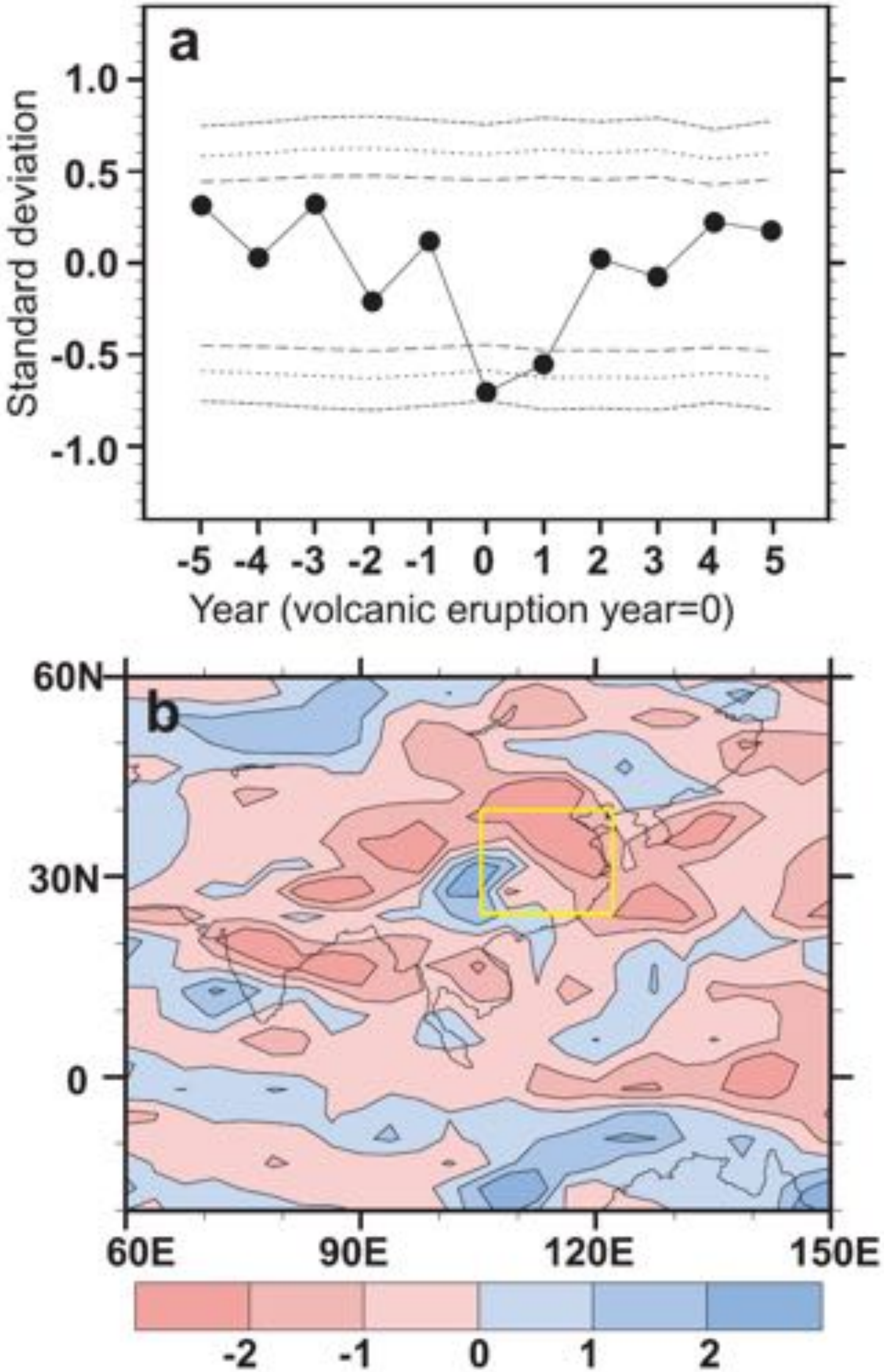


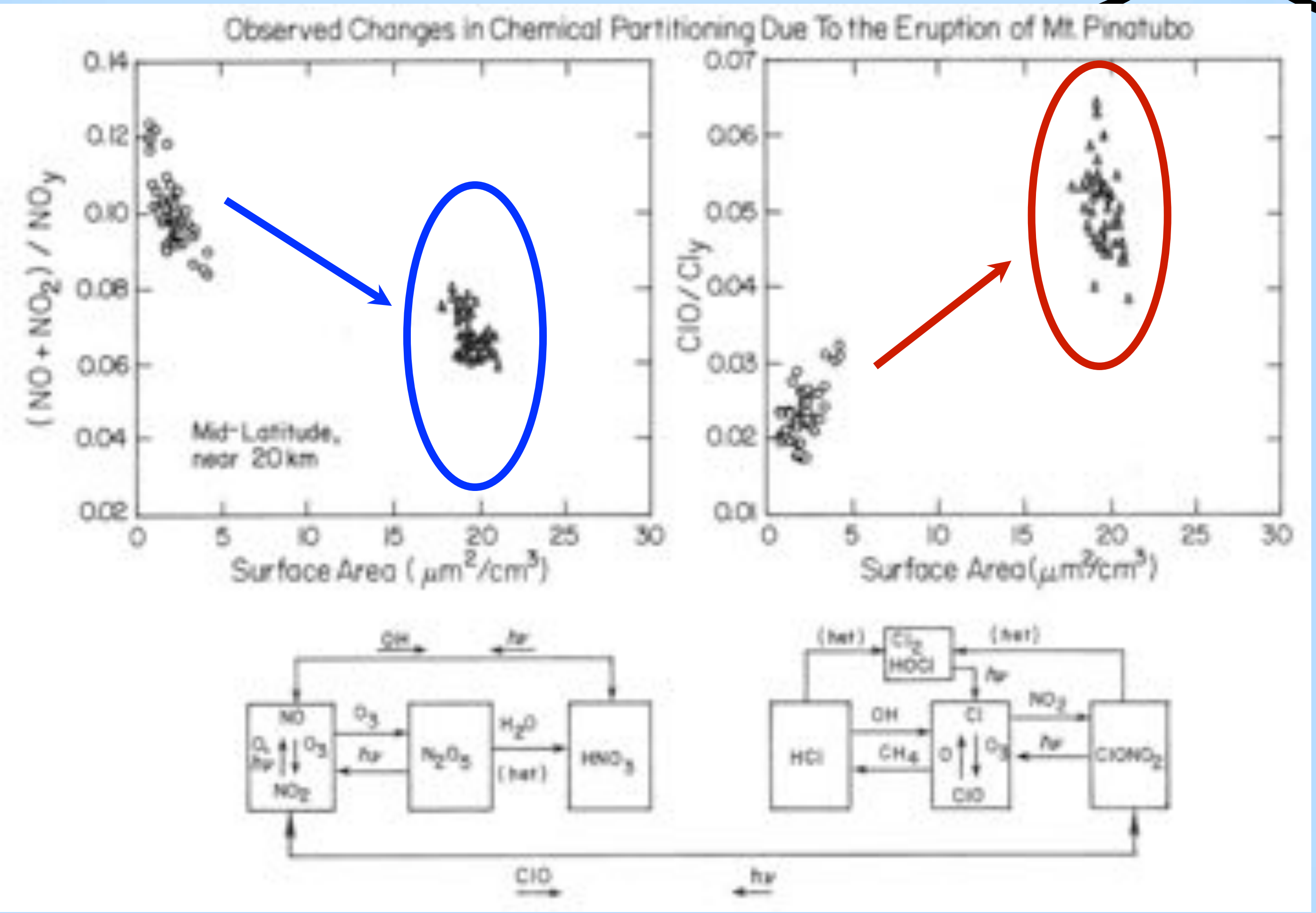
FIG. 1. (a) Results of superposed epoch analysis of modeled summer precipitation for 18 cases of large volcanic eruption showing the response of summer precipitation over eastern China. Bootstrapping procedures are used to assess the statistical significance of summer precipitation above and below the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

NCAR CCSM 2.0.1 simulation for past 1000 years

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

Volcanic aerosols produce more reactive chlorine

NO_x

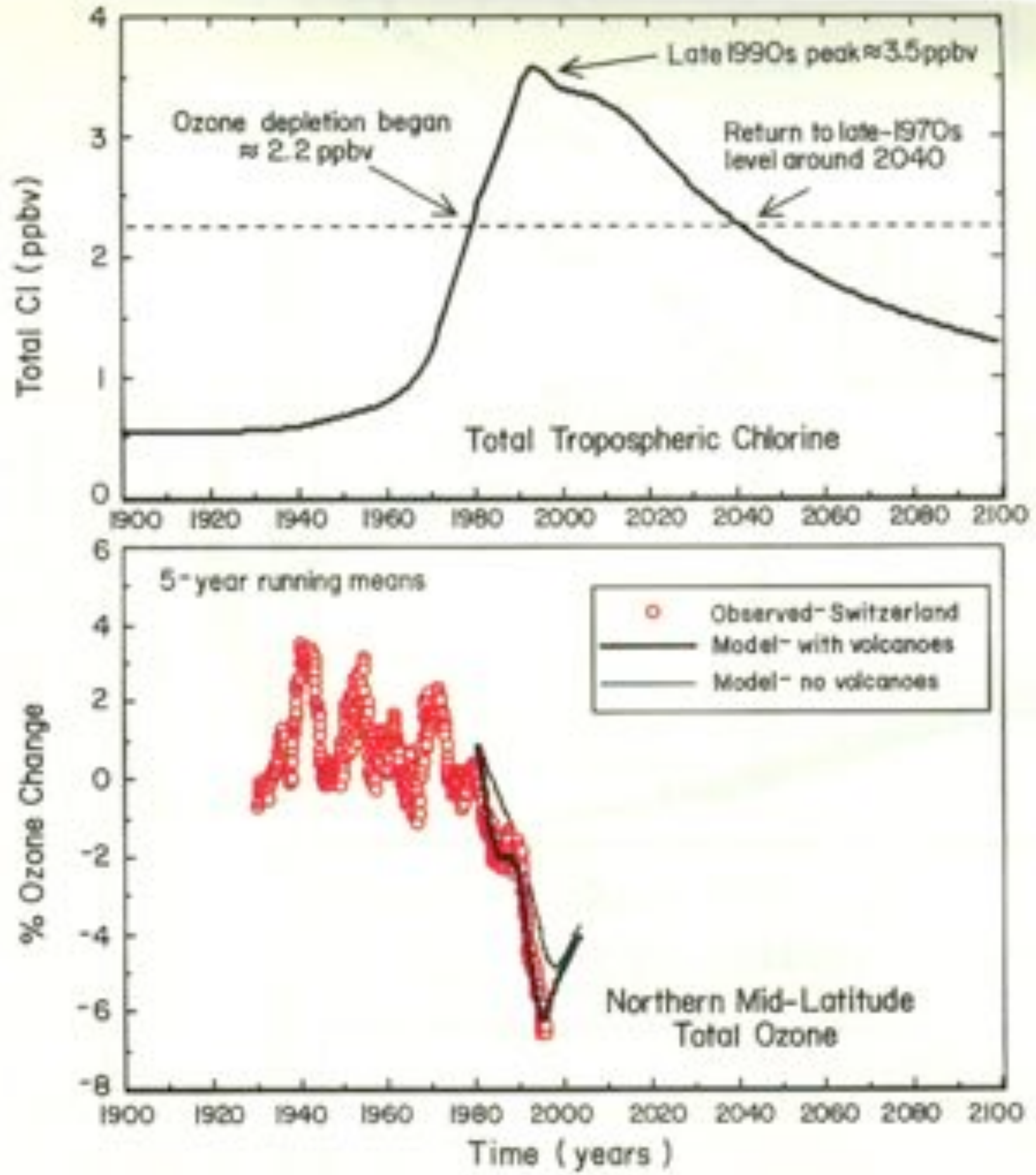


ClO

Tropospheric chlorine diffuses to stratosphere.

Volcanic aerosols make chlorine available to destroy ozone.

Solomon (1999)



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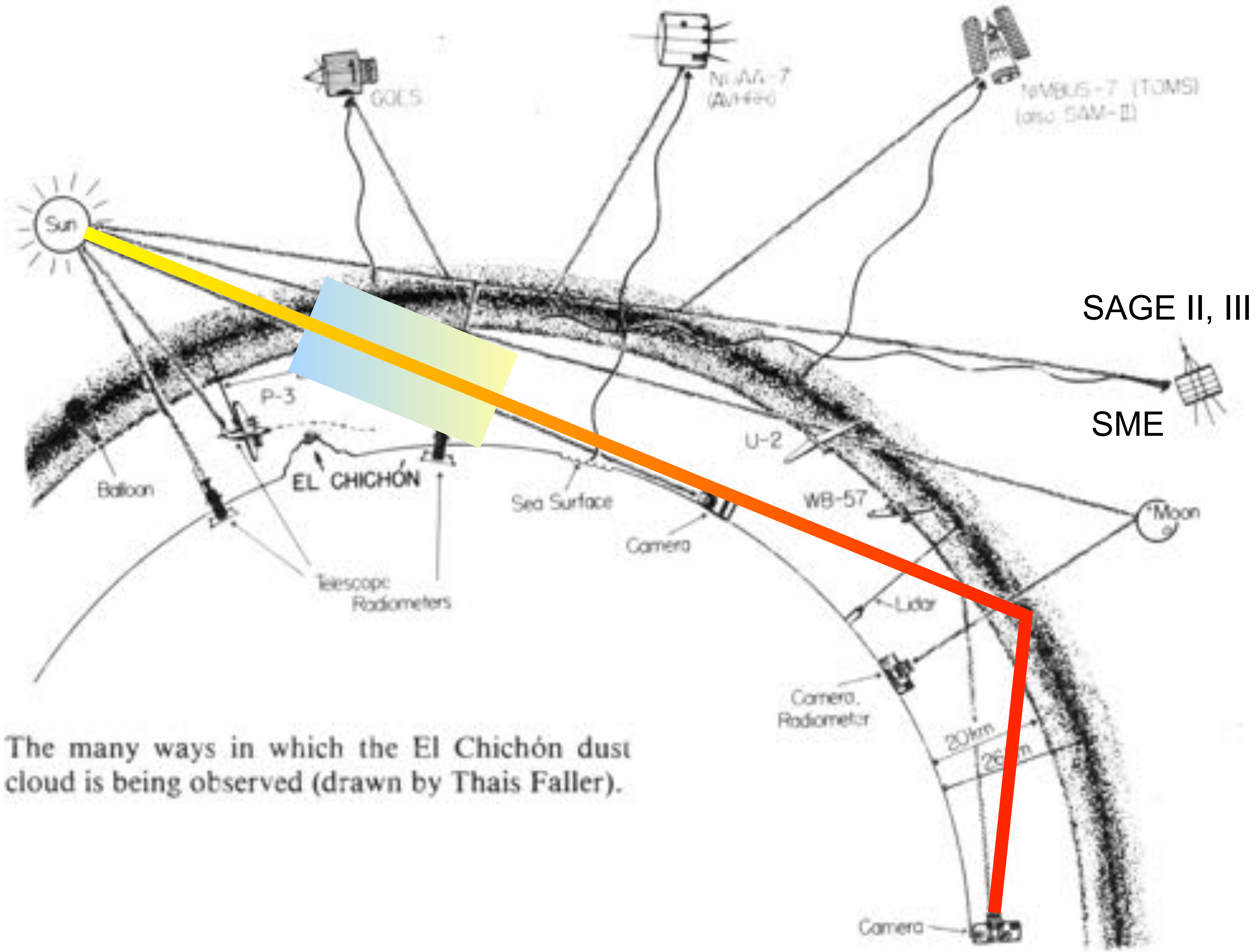

The many ways in which the El Chichón dust cloud is being observed (drawn by Thais Faller).

Robock (1983)

Krakatau, 1883
Watercolor by William Ascroft

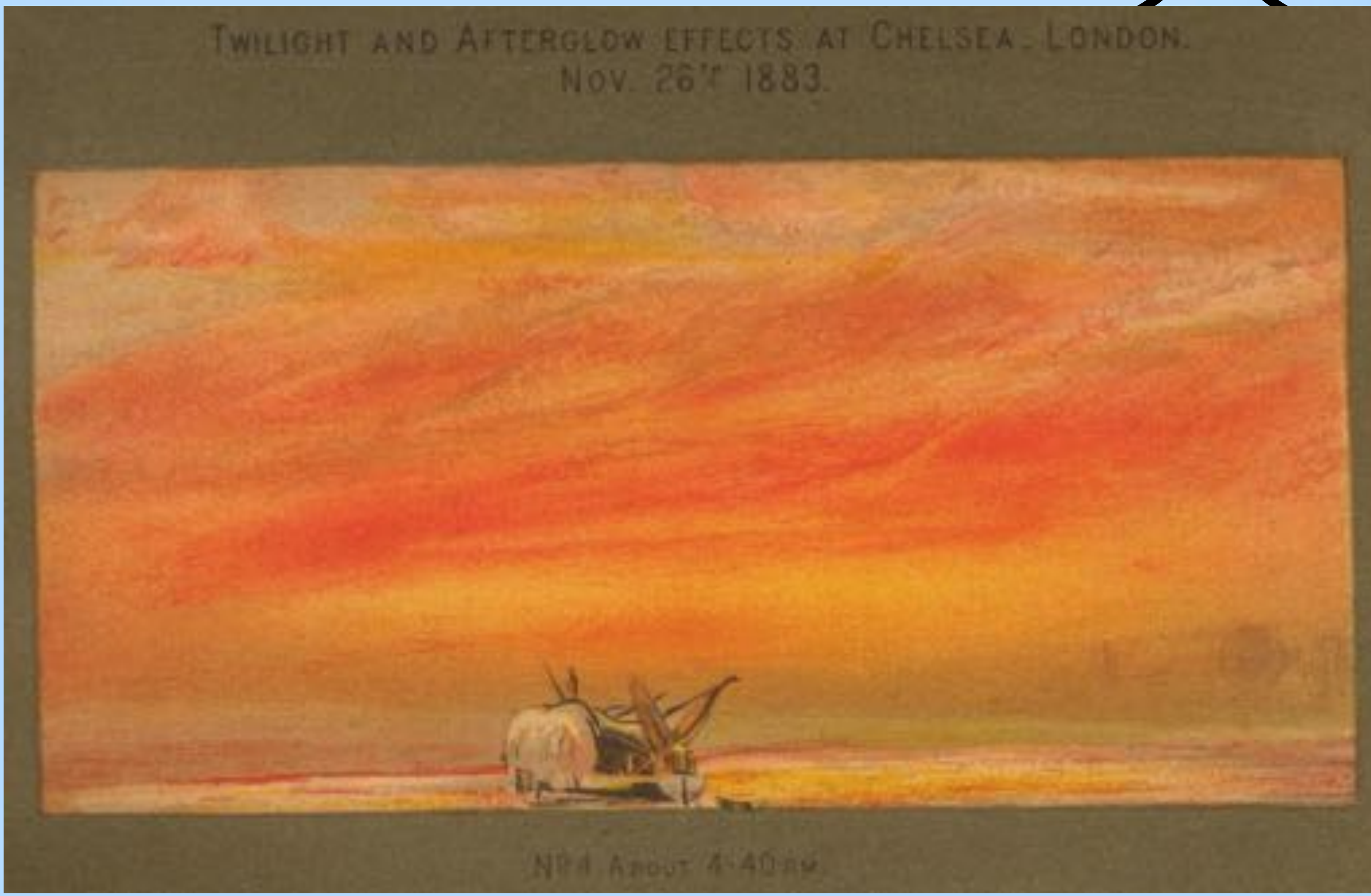

Figure from Symons (1888)

“The Scream”

Edvard Munch

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

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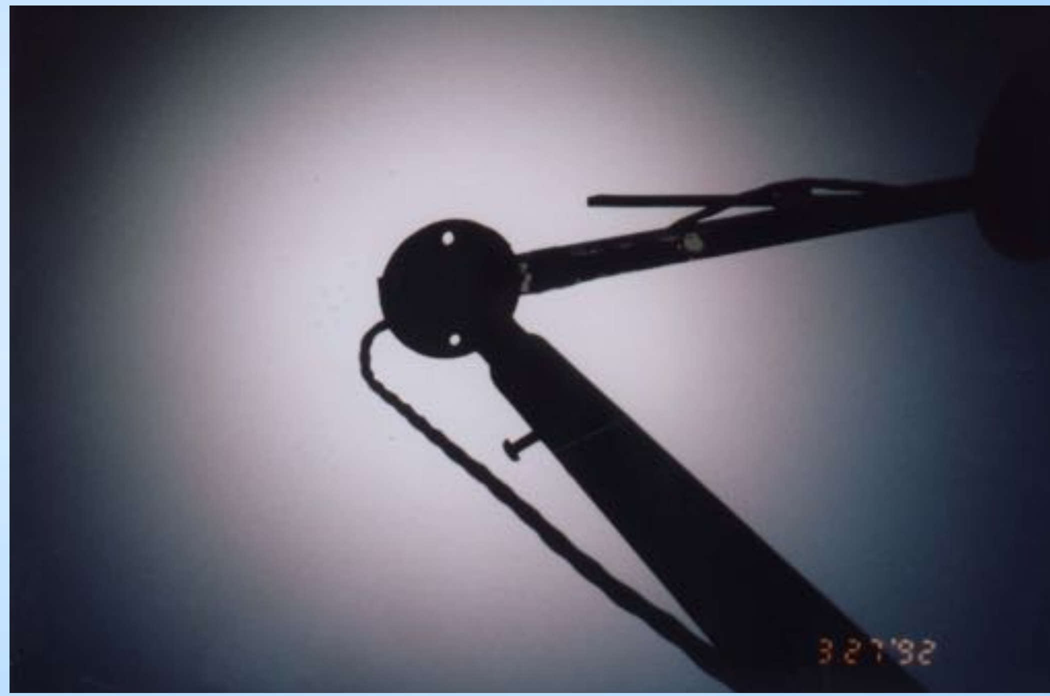
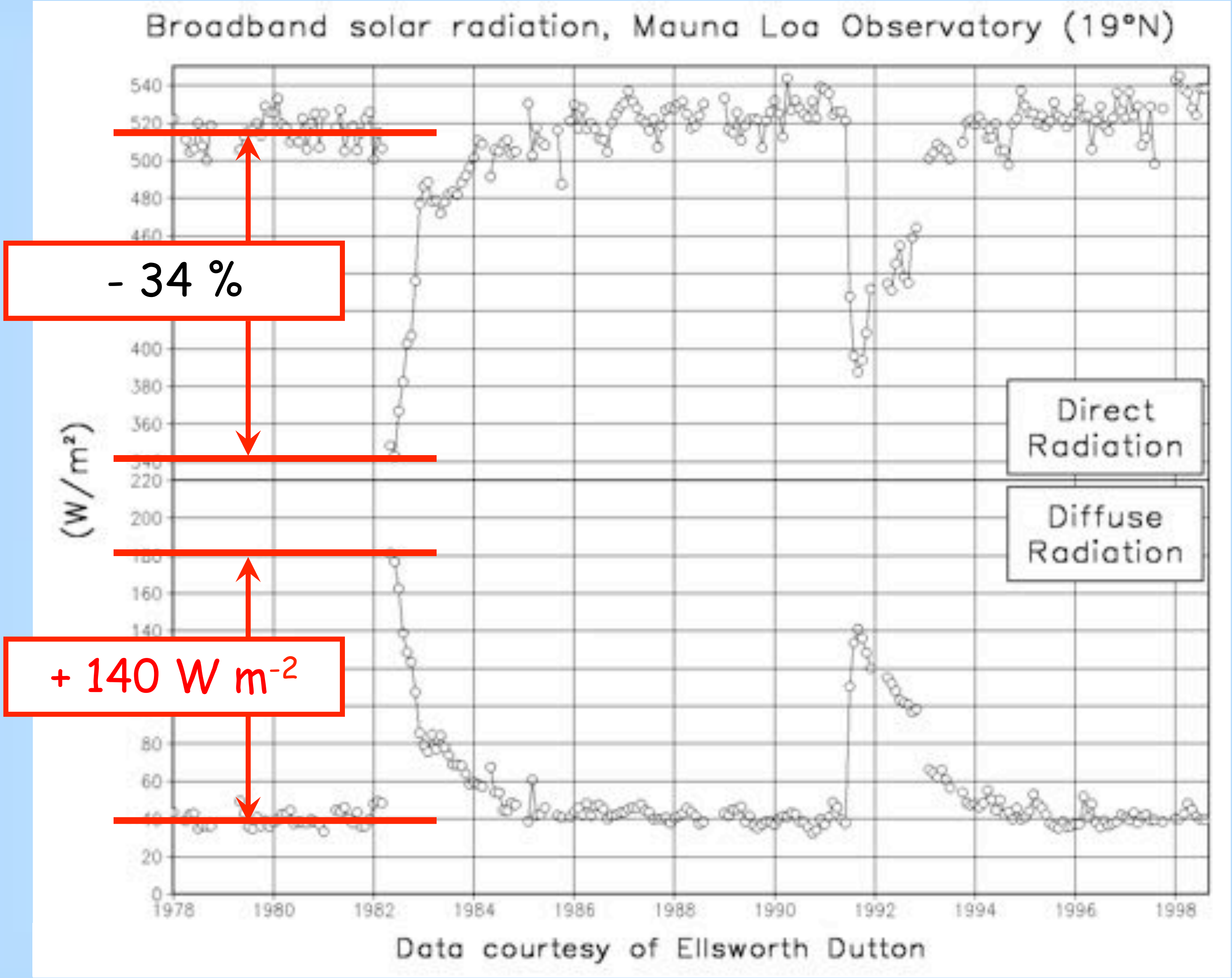
Department of Environmental Sciences

Diffuse Radiation from Pinatubo Makes a Whiter Sky



Photographs by Alan Robock



Robock (2000), Dutton and Bodhaine (2001)

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Geoengineering: Whiter skies?

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

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

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

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

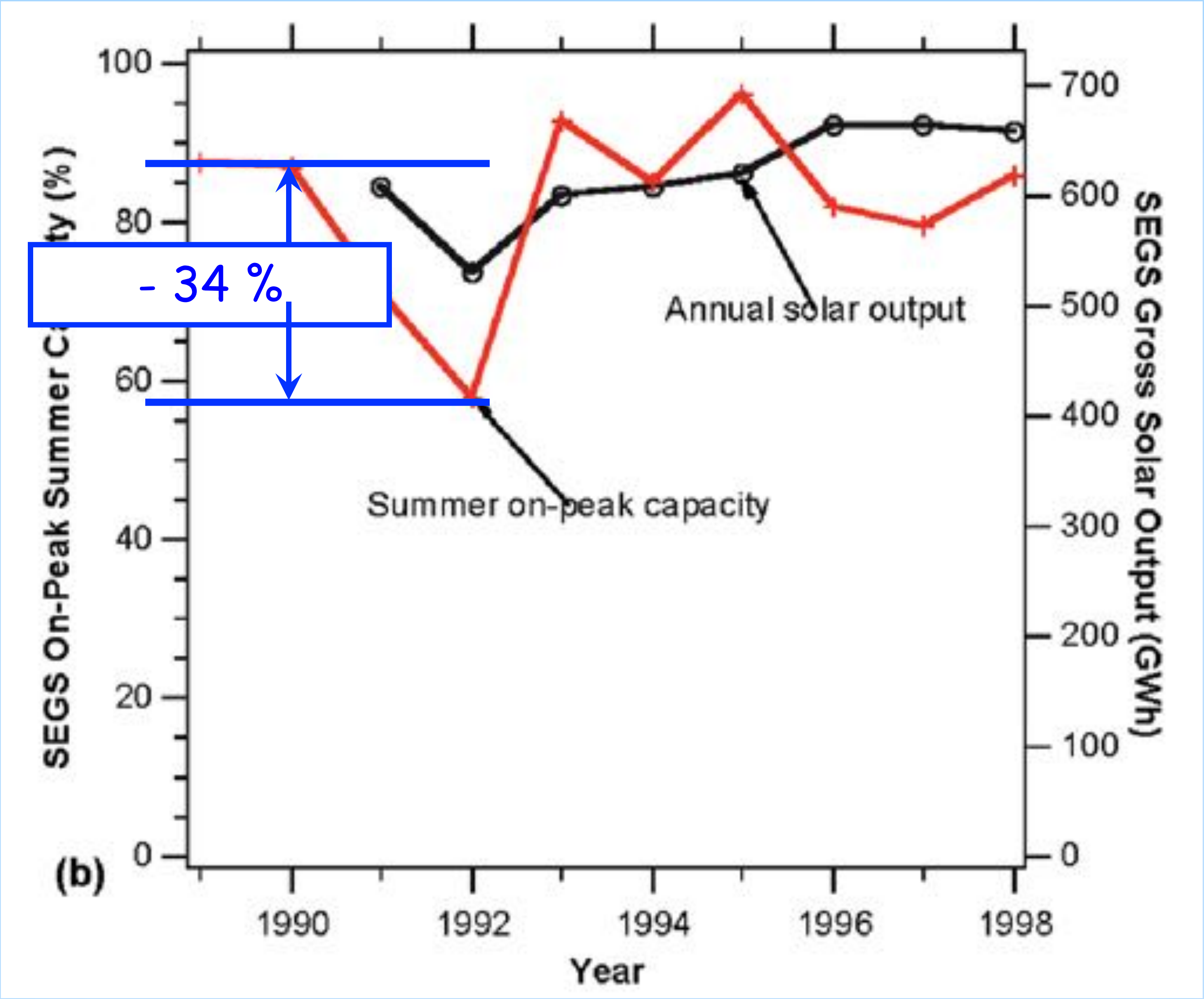
Nevada Solar One
64 MW

Solar steam generators requiring direct solar

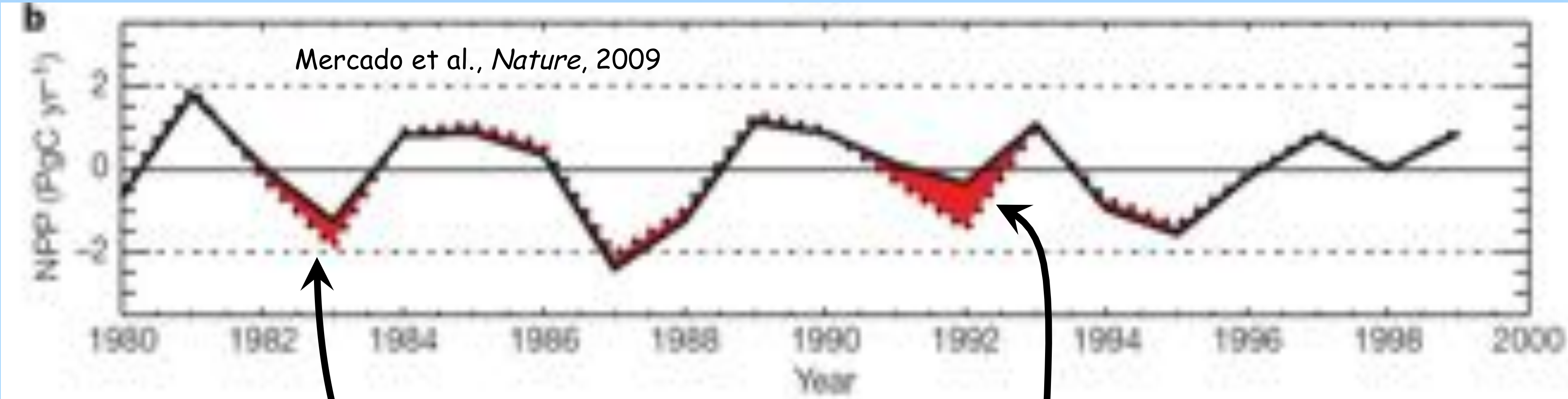
Seville, Spain
Solar Tower
11 MW

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

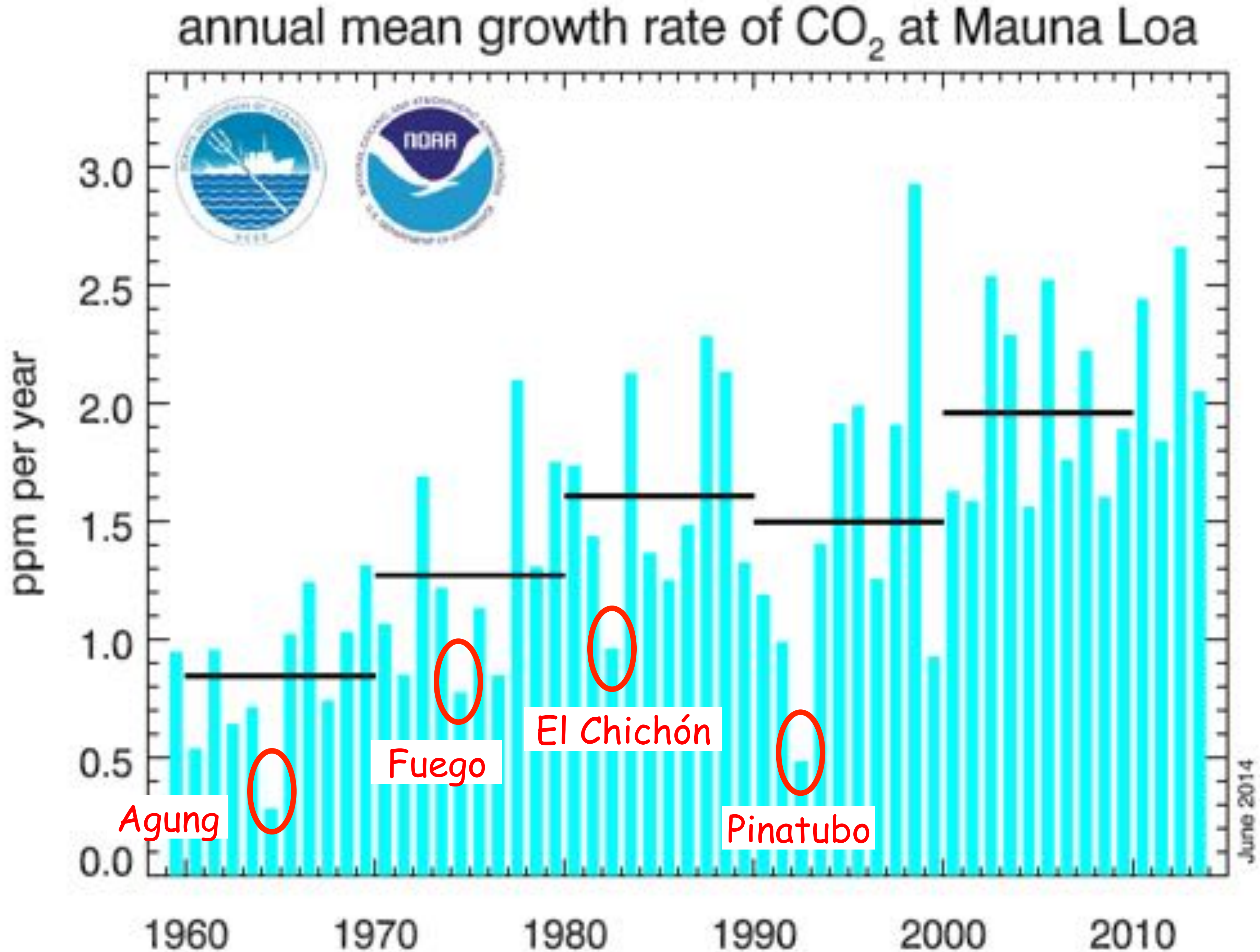
Additional carbon sequestration after volcanic eruptions because of the effects of diffuse radiation, but certainly will impact natural and farmed vegetation.

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

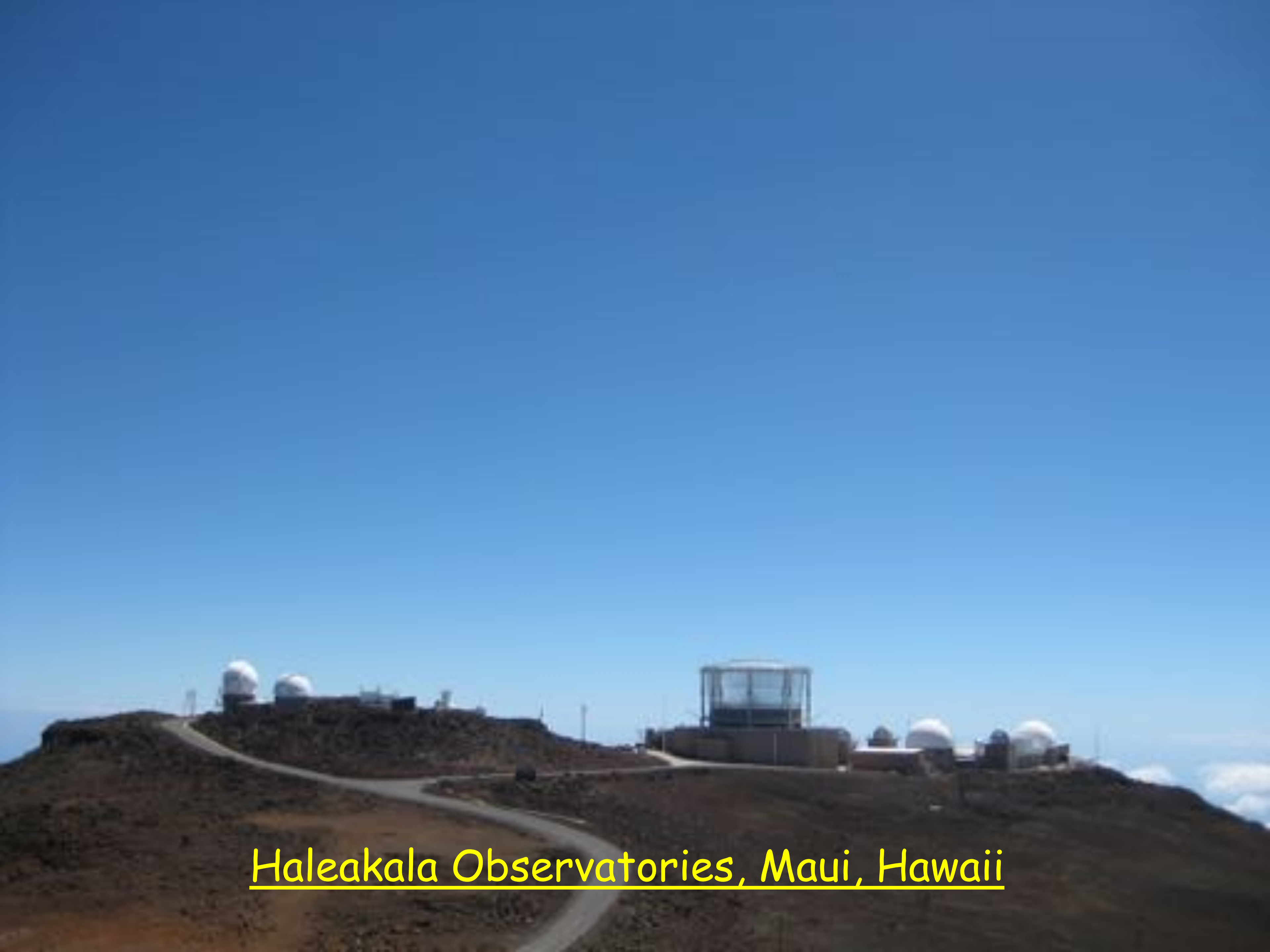
LETTERS

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]


annual mean growth rate of CO_2 at Mauna Loa
ppm per year
0.0
0.5
1.0
1.5
2.0
2.5
3.0
1960
1970
1980
1990
2000
2010
Agung
Fuego
El Chichón
Pinatubo
June 2014


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



Haleakala Observatories, Maui, Hawaii

Are We Ready for the Next Big Volcanic Eruption?

Scientific questions to address:

What will be the size distribution of sulfate aerosol particles created by geoengineering?

How will the aerosols be transported throughout the stratosphere?

How do temperatures change in the stratosphere as a result of the aerosol interactions with shortwave (particularly near IR) and longwave radiation?

Are there large stratospheric water vapor changes associated with stratospheric aerosols? Is there an initial injection of water from the eruption?

Is there ozone depletion from heterogeneous reactions on the stratospheric aerosols?

As the aerosols leave the stratosphere, and as the aerosols affect the upper troposphere temperature and circulation, are there interactions with cirrus and other clouds?

How will tropospheric chemistry be affected by stratospheric geoengineering?

Do stratospheric aerosols grow with large SO_2 injections?

"Successively larger SO_2 injections do not create proportionally larger optical depths because successively larger sulfate particles are formed."

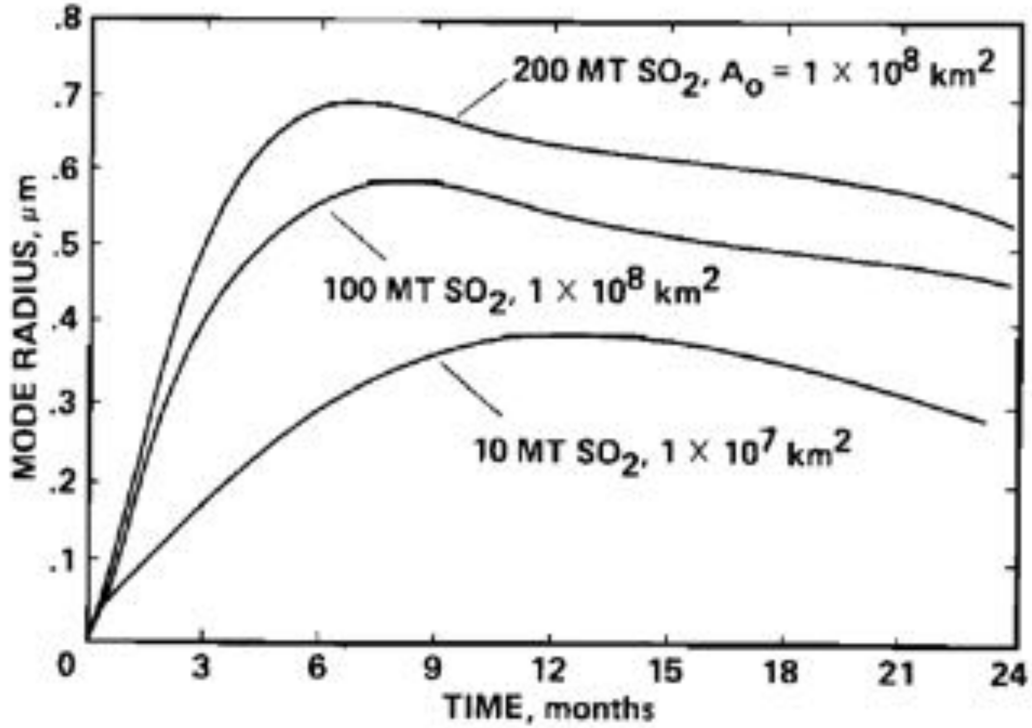


Fig. 3. The lognormal mode radius of the aerosol number size distribution for the SO_2 injections shown in Figure 2, as a function of time. Areas refer to the initial area of the cloud over which oxidation is assumed to occur.

Pinto, J. R., R. P. Turco, and O. B. Toon, 1989: Self-limiting physical and chemical effects in volcanic eruption clouds. *J. Geophys. Res.*, **94**, 11,165–11,174, doi:10.1029/JD094iD08p11165.

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

Environ. Res. Lett. 4 (2009) 045108

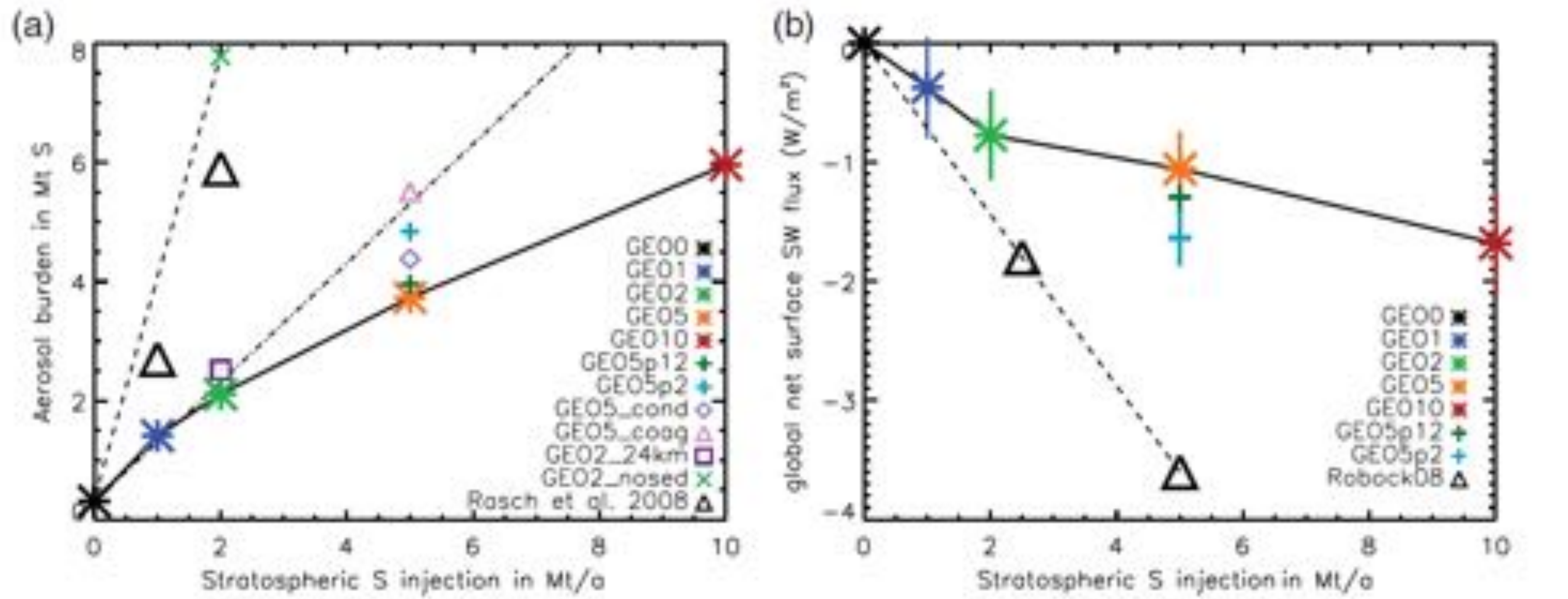


Figure 4. (a) Total aerosol burden as function of sulfur injected annually into the stratosphere (0, 1, 2, 5 and 10 Mt/a S) calculated by the AER model. Dash–dotted line: aerosol burden, if the aerosol residence time were 1 year irrespective of injection strength. Dashed line: aerosol burden when aerosol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

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Column averaged effective radius (Pinatubo)

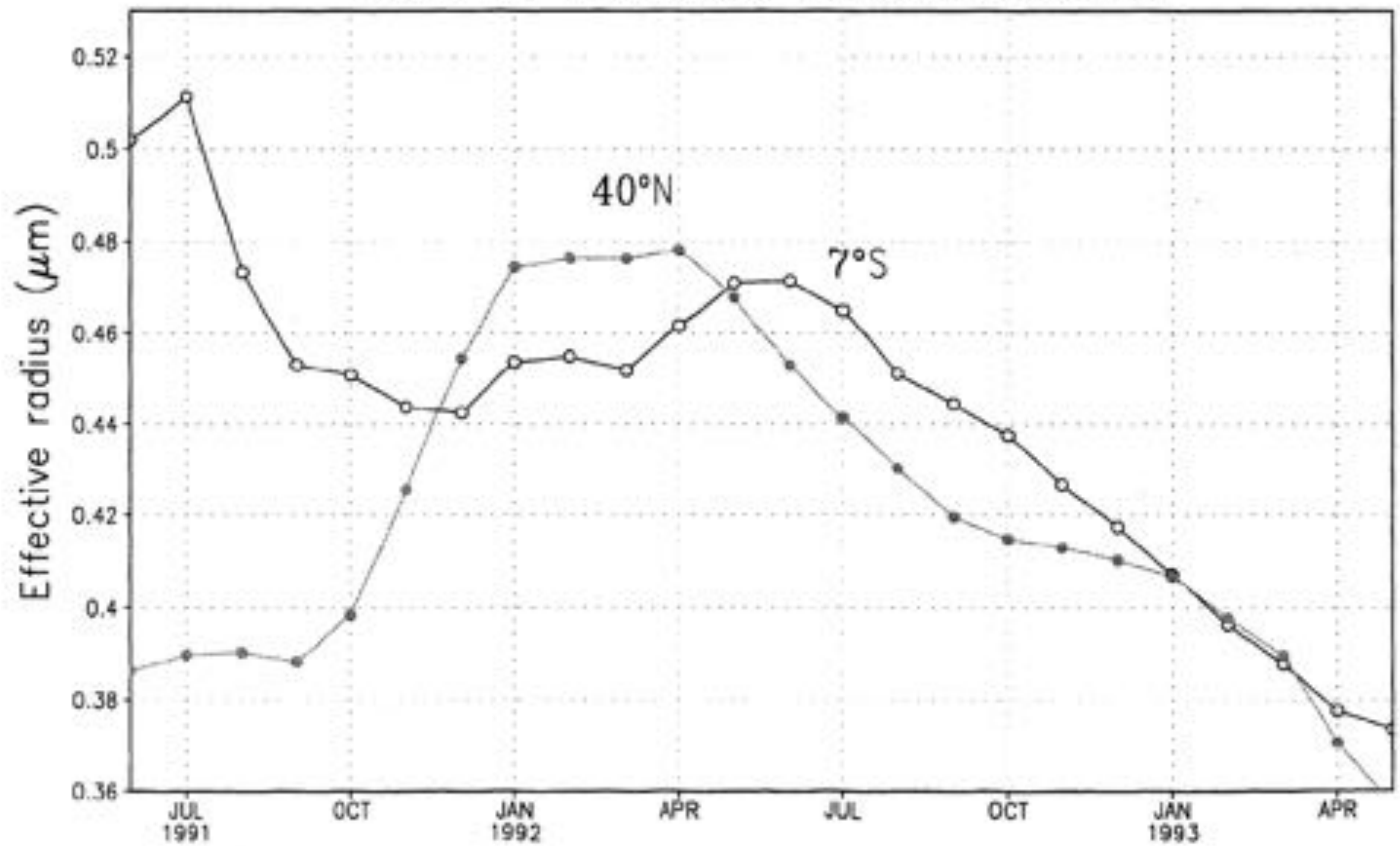

Figure 4. Column averaged aerosol effective radius (μm) for 7°S and 40°N.

"It combines both particle density, calculated from SAGE II extinctions, and effective radii, calculated for different altitudes from ISAMS [Improved Stratospheric And Mesospheric Sounder on UARS] measurements."

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Stenchikov, Georgiy L., Ingo Kirchner, Alan Robock, Hans-F. Graf, Juan Carlos Antuña, R. G. Grainger, Alyn Lambert, and Larry Thomason, 1998: Radiative forcing from the 1991 Mount Pinatubo volcanic eruption. *J. Geophys. Res.*, **103**, 13,837-13,857.

Are We Ready for the Next Big Volcanic Eruption?

Desired observations or outdoor experiments:

Balloons

Airships (blimps in the stratosphere)

Aircraft and drones (up to 20 km currently)

Lidar (ground-based and on satellites)

Satellite radiometers, both nadir and limb pointing

Spraying a small amount of SO_2 into the volcanic aerosol cloud to see if you get more or larger particles?

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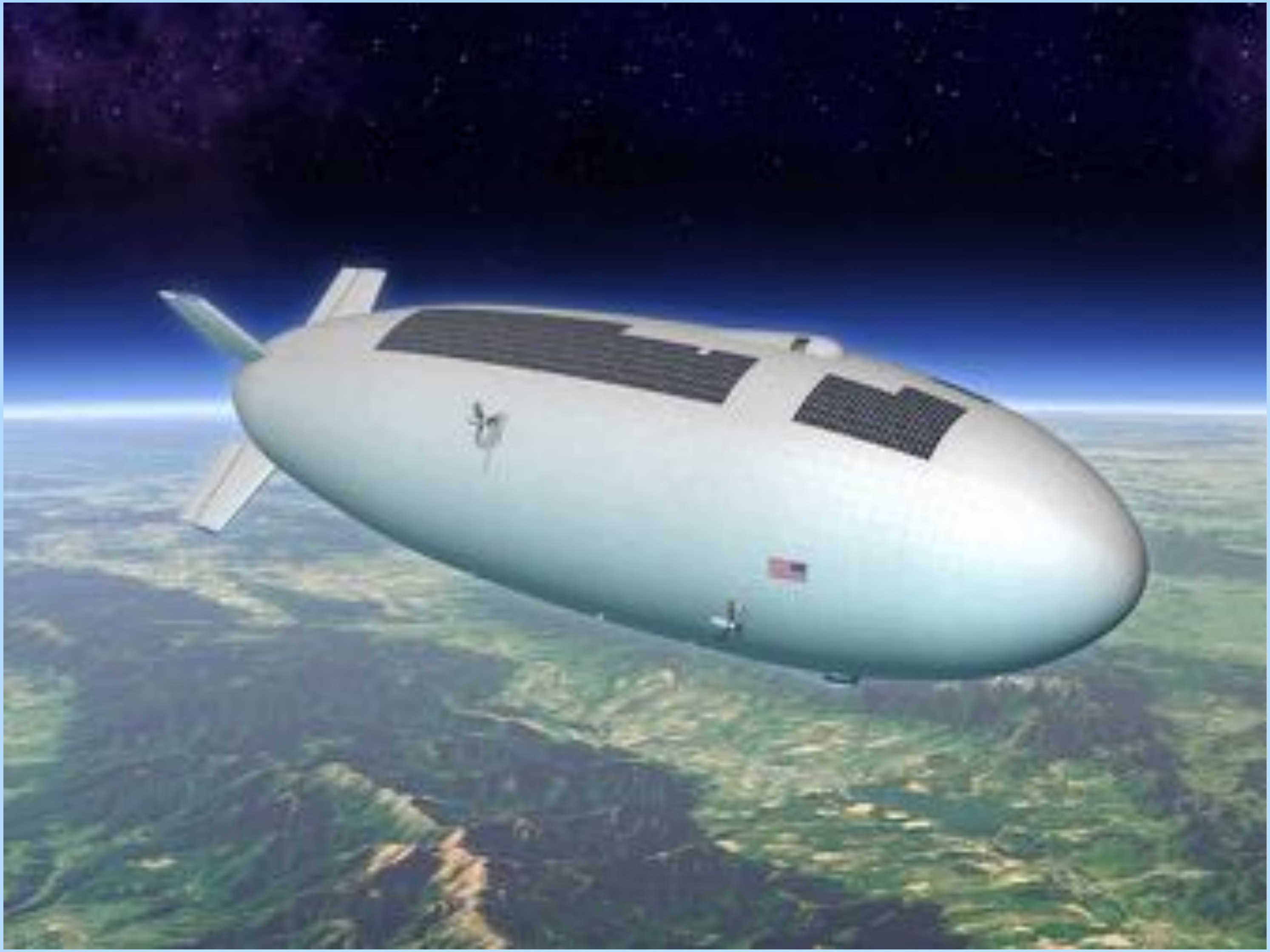

An artist's rendering of a stratospheric airship in flight.
Credit Keck Institute for Space Studies/Eagre Interactive

http://www.nytimes.com/2014/08/26/science/airships-that-carry-science-into-the-stratosphere.html

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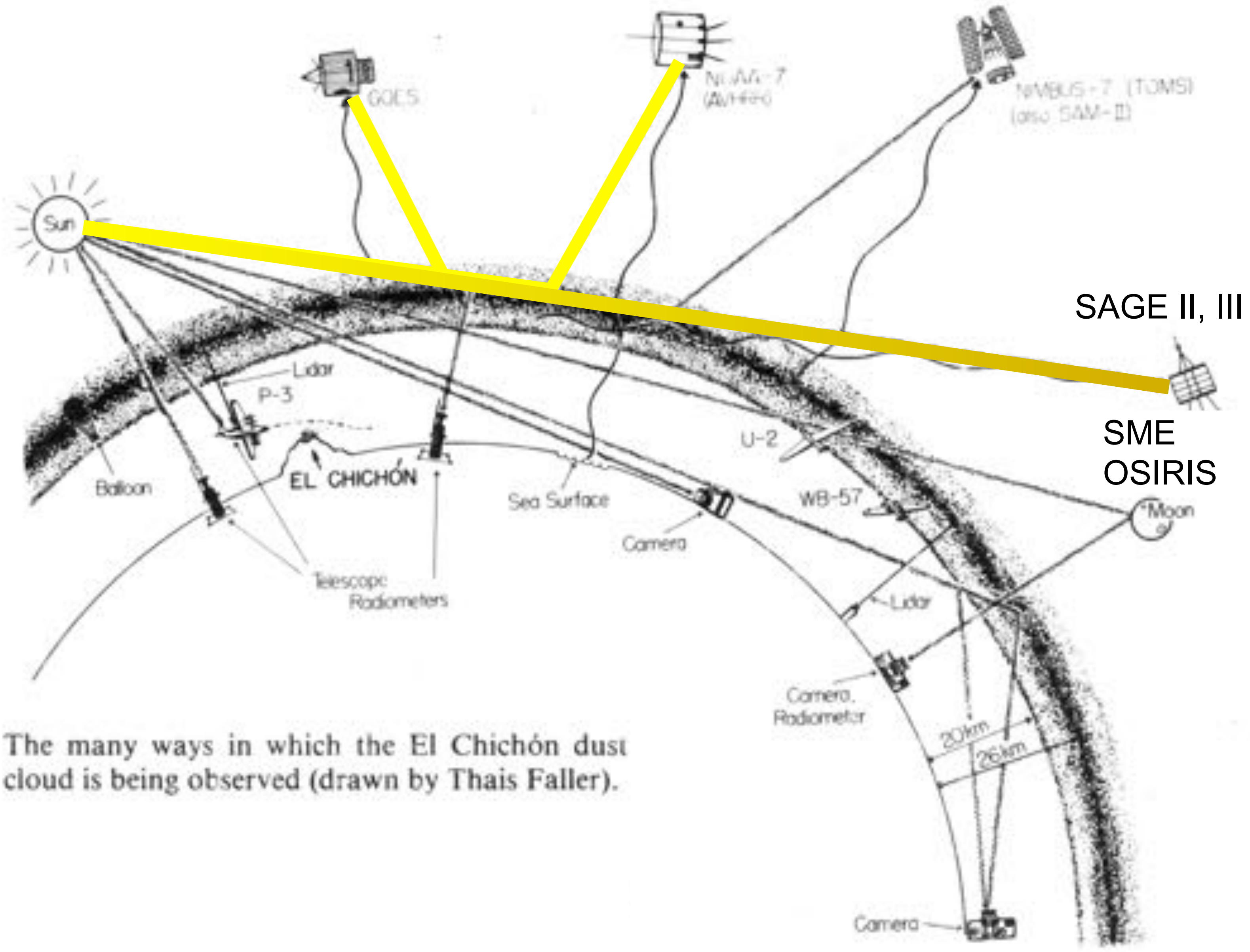

The many ways in which the El Chichón dust cloud is being observed (drawn by Thais Faller).

Robock (1983)

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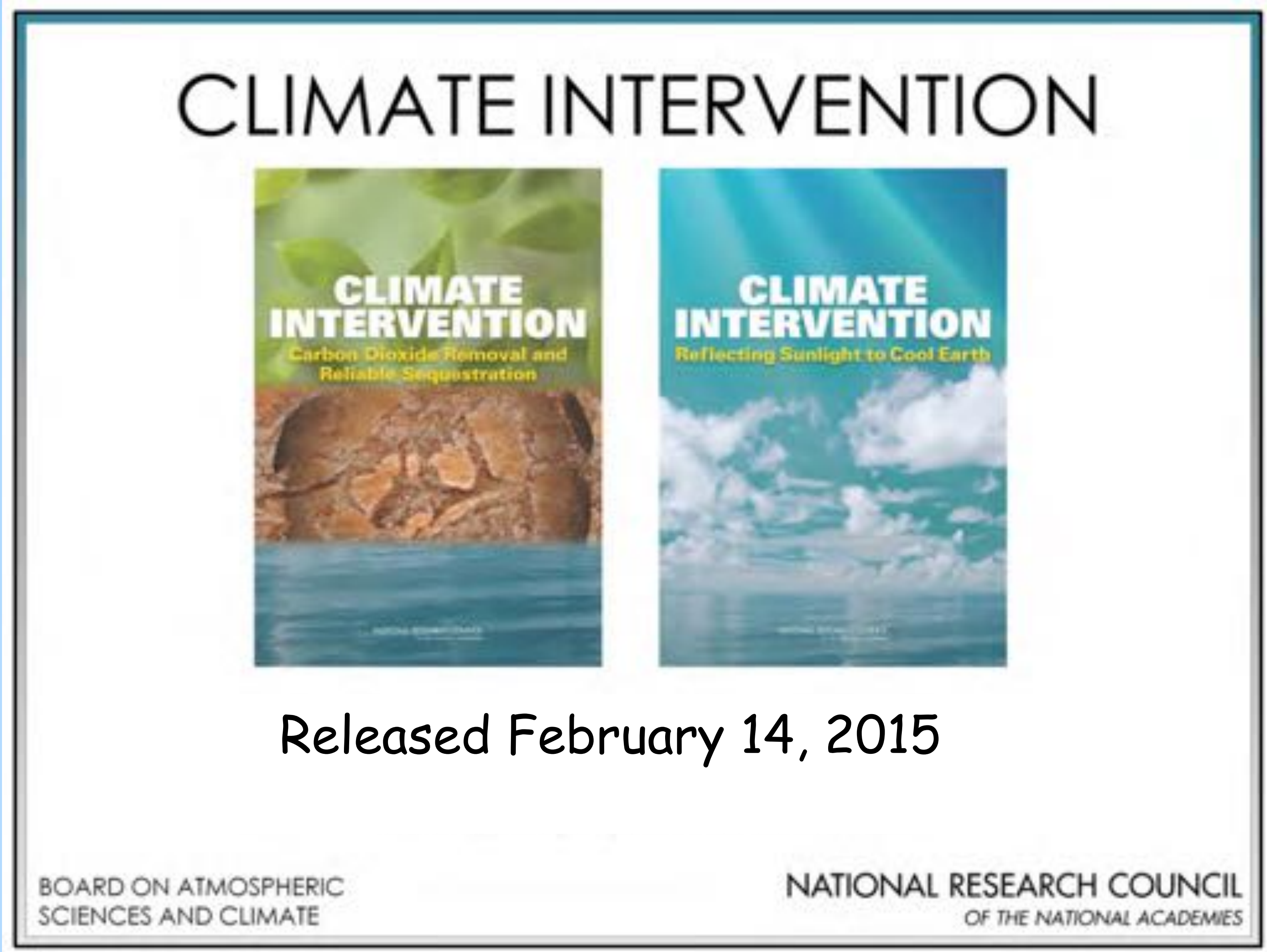

Sponsors: U.S. National Academy of Sciences, U.S. intelligence community, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, and U.S. Department of Energy

CLIMATE INTERVENTION

Carbon Dioxide Removal (CDR)

Solar Radiation Management (SRM)

Released February 14, 2015

BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

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OF THE NATIONAL ACADEMIES

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

THERE IS NO SUBSTITUTE FOR MITIGATION AND ADAPTATION

Recommendation 1:

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

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

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WHY "CLIMATE INTERVENTION"?

There are several meanings to the term "geoengineering"

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

Intervention is an action intended to improve a situation

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CARBON DIOXIDE REMOVAL READY FOR INCREASED RESEARCH AND DEVELOPMENT

Recommendation 2:

The Committee recommends research and development investment to

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

in particular to

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

ALBEDO MODIFICATION POSES SIGNIFICANT RISKS

Environmental risks – both known and poorly known

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

Significant potential for unanticipated, unmanageable, and regrettable consequences

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

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

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ALBEDO MODIFICATION RESEARCH

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

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

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

Recommendation 4:

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

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

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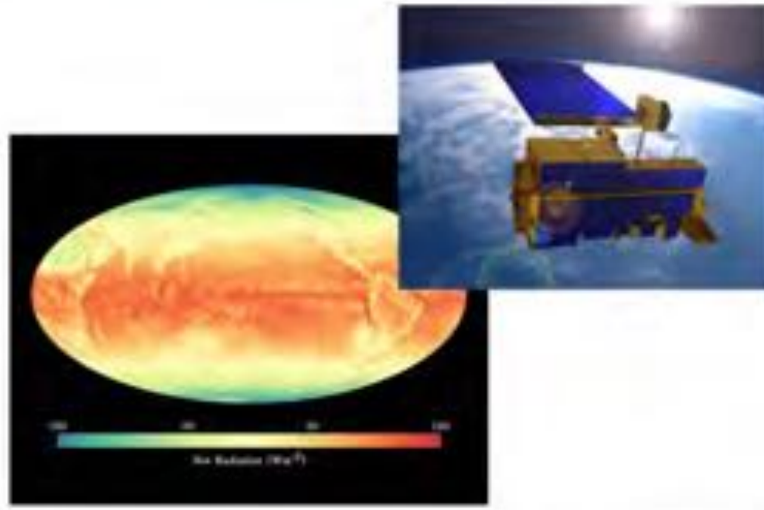
ALBEDO MODIFICATION RESEARCH

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



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

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GOVERNANCE CONSIDERATIONS

Recommendation 6:

The Committee recommends the initiation of a serious deliberative process to examine:

(a) what types of research governance, beyond those that already exist, may be needed for albedo modification research, and

(b) the types of research that would require such governance, potentially based on the magnitude of their expected impact on radiative forcing, their potential for detrimental direct and indirect effects, and other considerations

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

Not testable with GeoMIP or the volcanic analog

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

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

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

Risks

1. Drought in Africa and Asia
2. Perturb ecology with more diffuse radiation
3. Ozone depletion
4. Continued ocean acidification
5. 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?

London Sunset After Krakatau
4:40 p.m., Nov. 26, 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.