RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY

The Geoengineering Model Intercomparison Project (GeoMIP)

Alan Robock

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

robock@envsci.rutgers.edu

http://envsci.rutgers.edu/~robock

Reviews of Geophysics

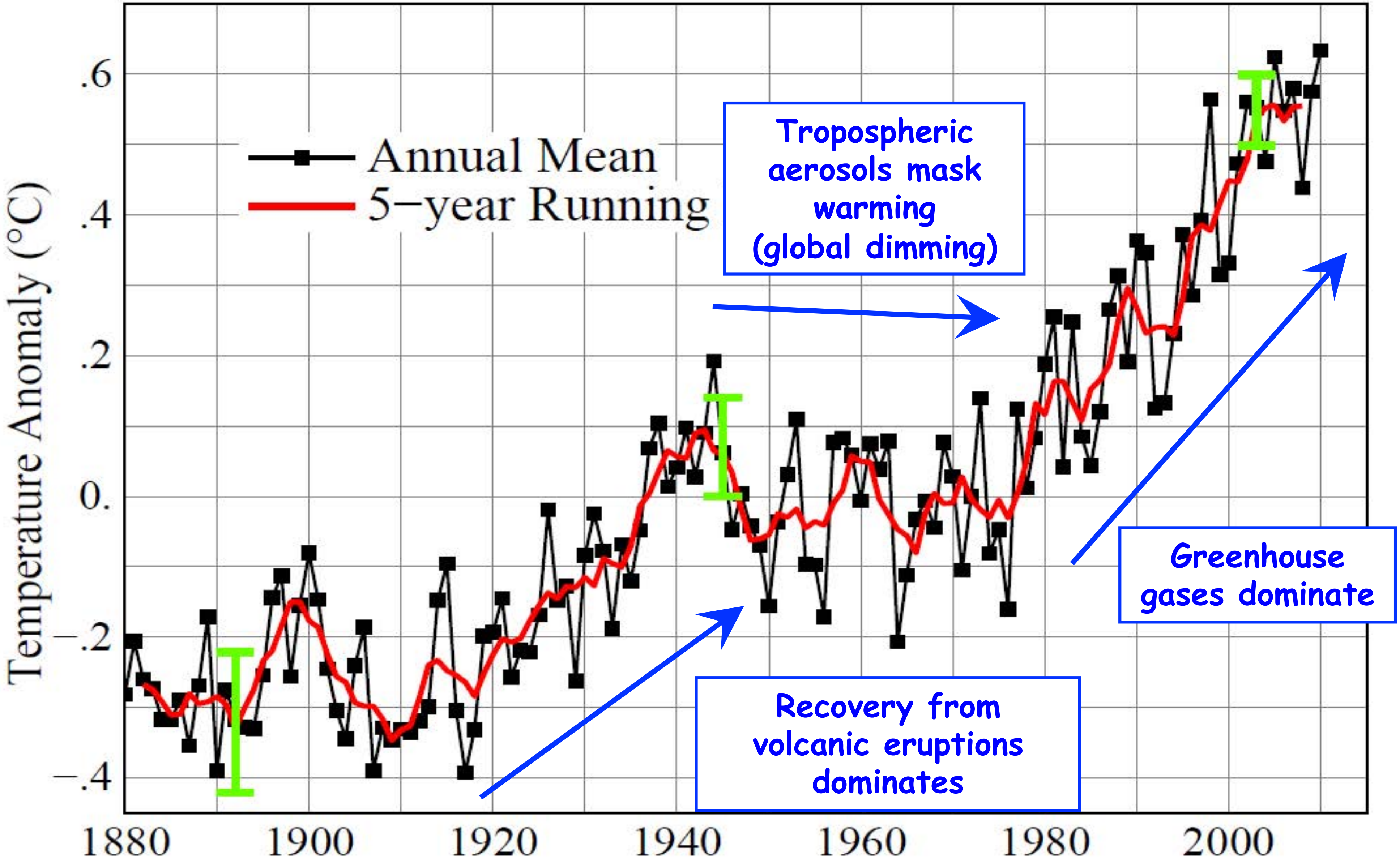
http://www.agu.org/journals/rg/

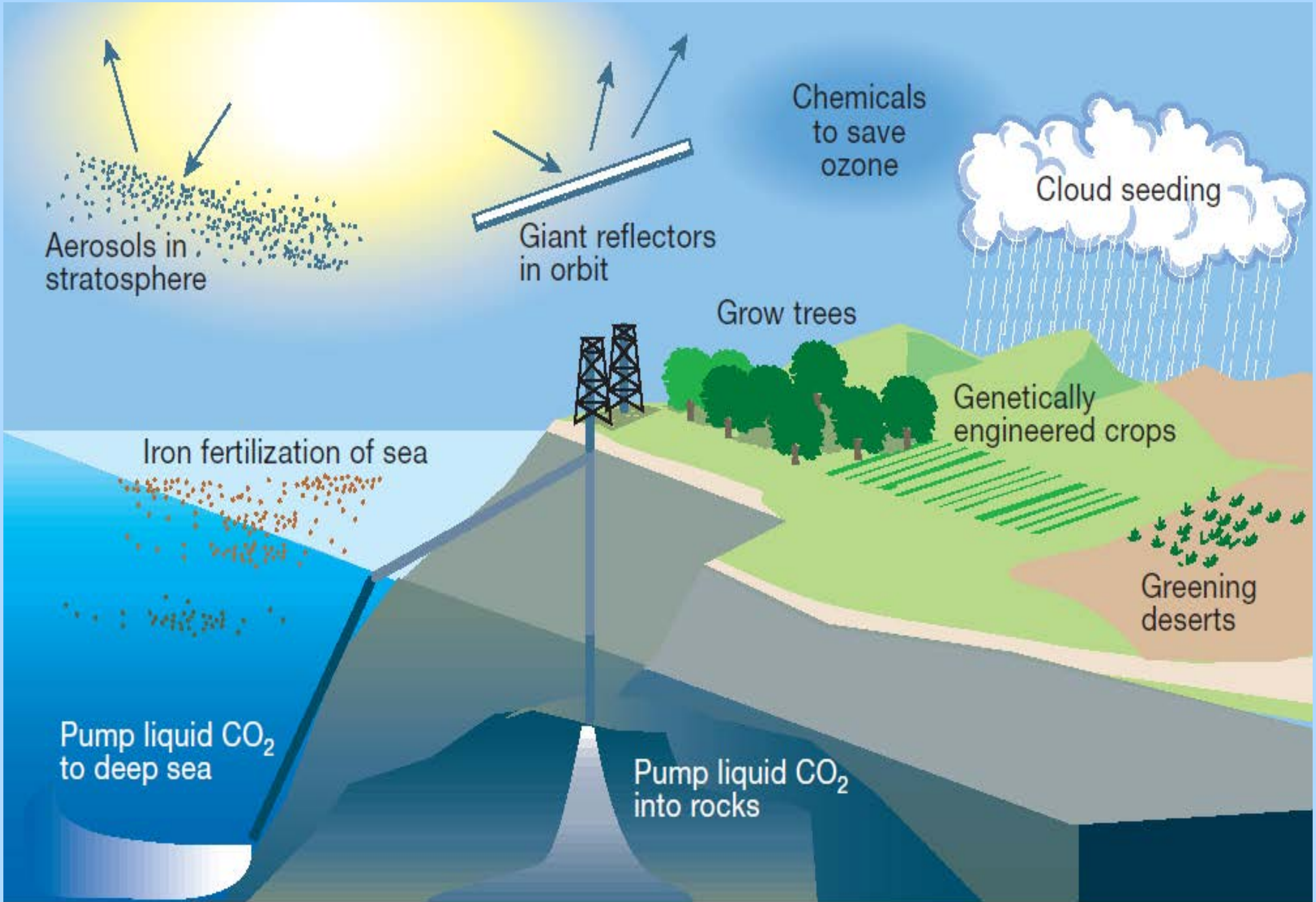
Reviews of Geophysics distills and places in perspective previous scientific work in currently active subject areas of geophysics. Contributions evaluate overall progress in the field and cover all disciplines embraced by AGU.

Authorship is by invitation, but suggestions from readers and potential authors are welcome. If you are interested in writing an article please talk with me, or write to reviewsgeophysics@agu.org, with an abstract, outline, and explanation of how the paper fits the goals of the journal.

Reviews of Geophysics has an impact factor of 9.538 in the 2010 Journal Citation Reports, highest in the geosciences.

Global Land–Ocean Temperature Index



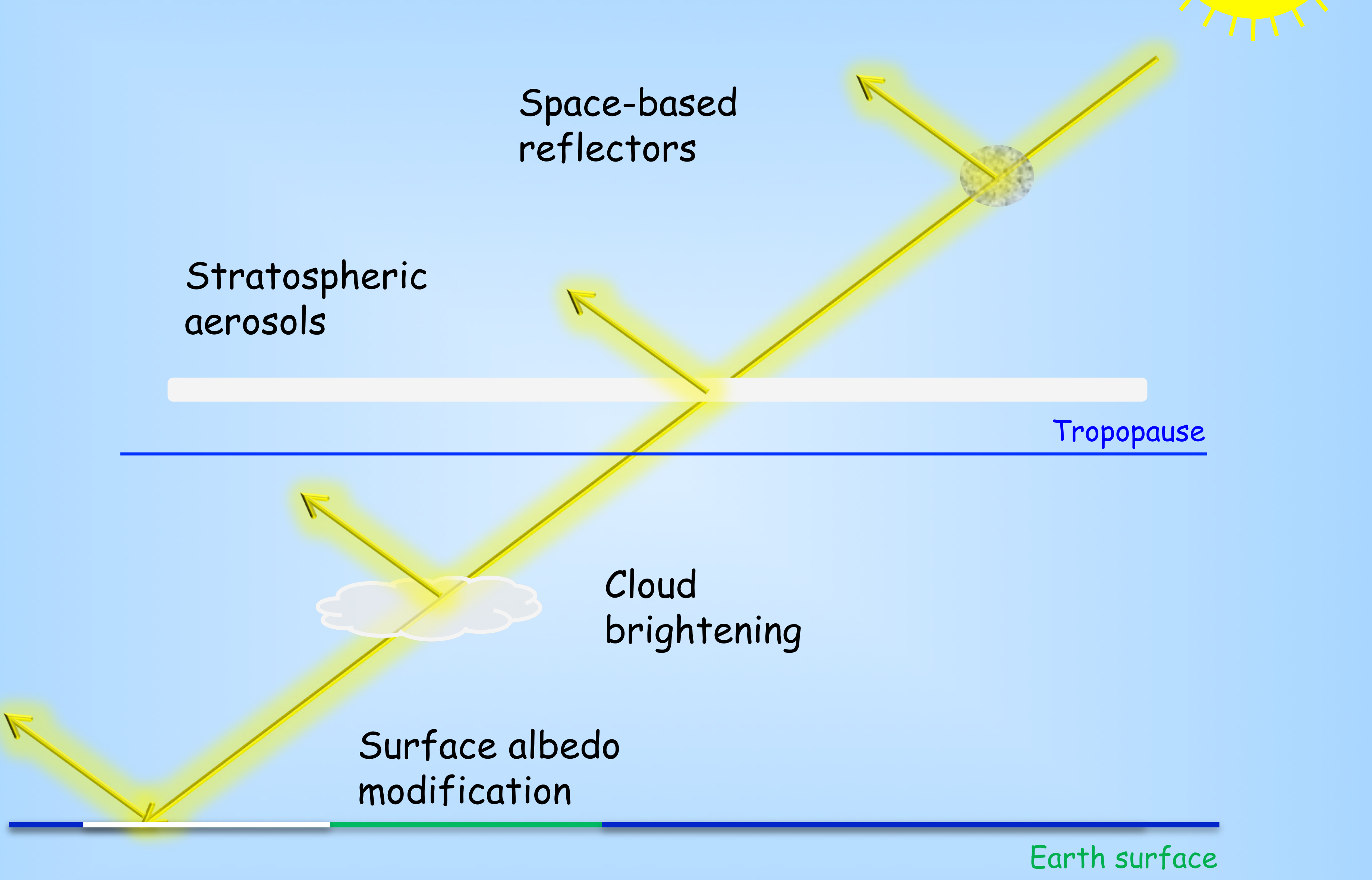


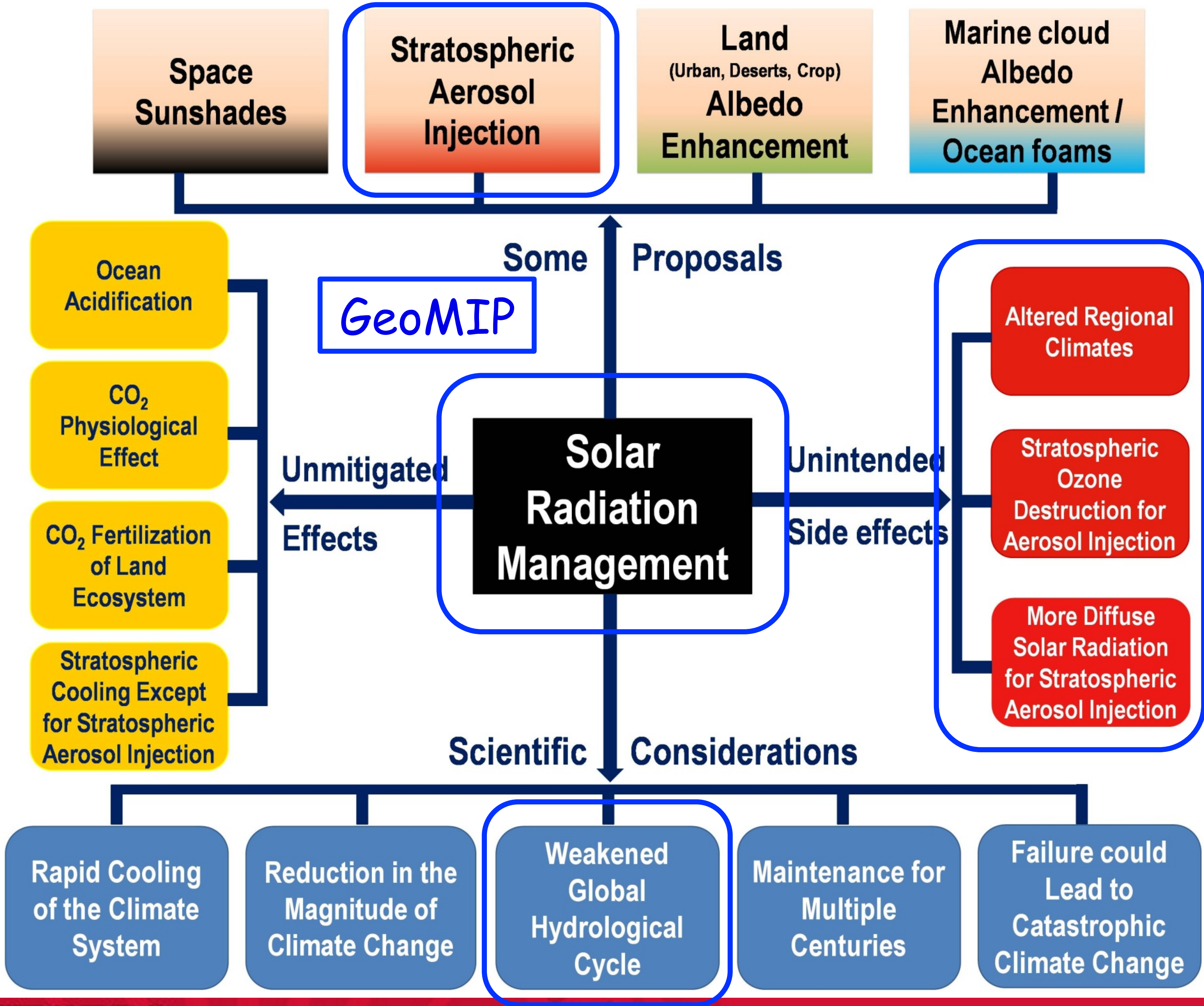
Schematic representation of various climate-engineering proposals (courtesy B. Matthews).

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

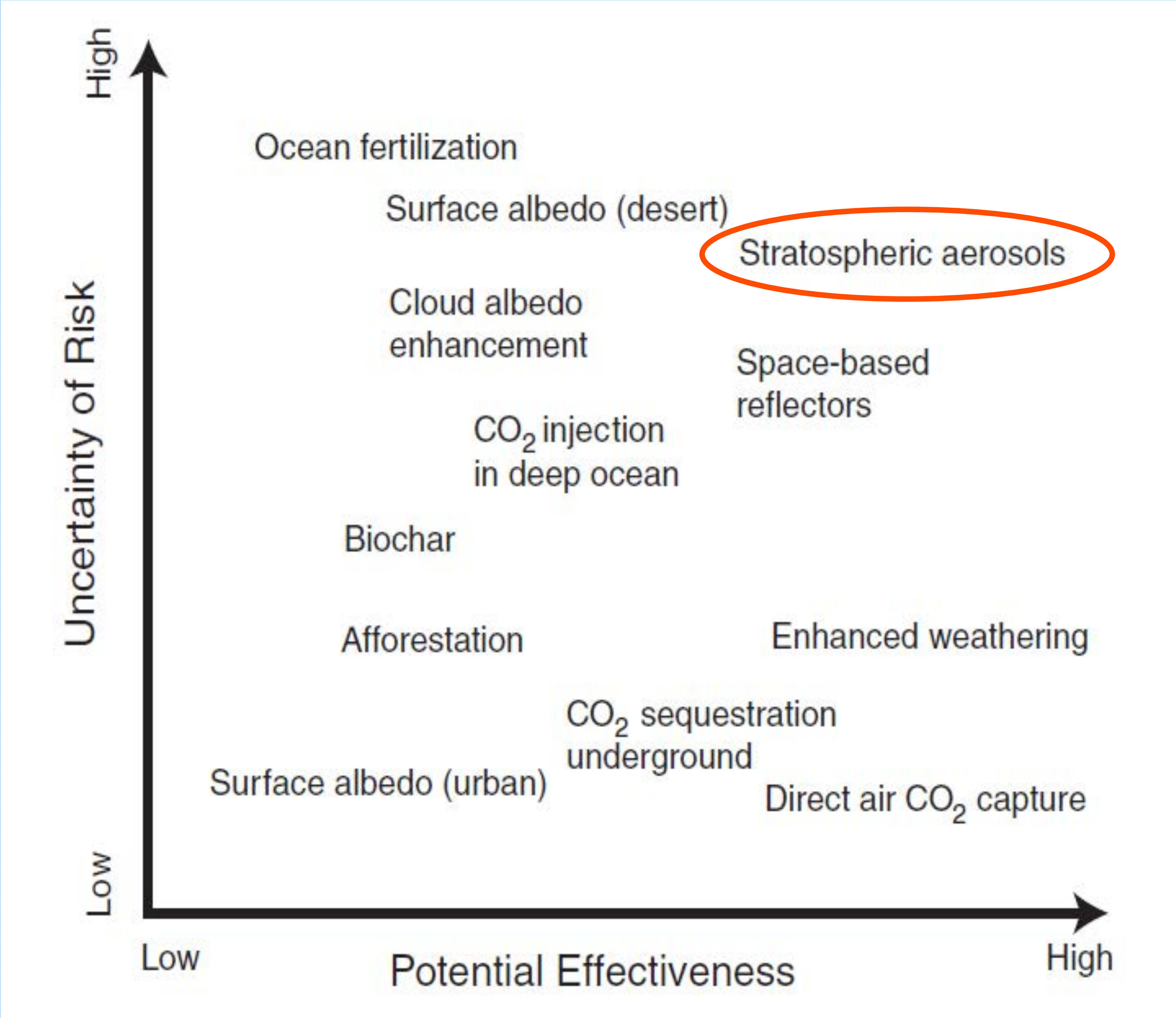
Alan Robock
Department of Environmental Sciences

Solar Radiation Management (SRM)





Space Sunshades
Stratospheric Aerosol Injection
Land (Urban, Deserts, Crop) Albedo Enhancement
Marine cloud Albedo Enhancement / Ocean foams
Some
Proposals
GeoMIP
Ocean Acidification
CO_2 Physiological Effect
CO_2 Fertilization of Land Ecosystem
Stratospheric Cooling Except for Stratospheric Aerosol Injection
Unmitigated
Effects
Solar Radiation Management
Unintended
Side effects
Altered Regional Climates
Stratospheric Ozone Destruction for Aerosol Injection
More Diffuse Solar Radiation for Stratospheric Aerosol Injection
Scientific
Considerations
Rapid Cooling of the Climate System
Reduction in the Magnitude of Climate Change
Weakened Global Hydrological Cycle
Maintenance for Multiple Centuries
Failure could Lead to Catastrophic Climate Change



RUTGERS

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

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

RUTGERS

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

Aerosol properties

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

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

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

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

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

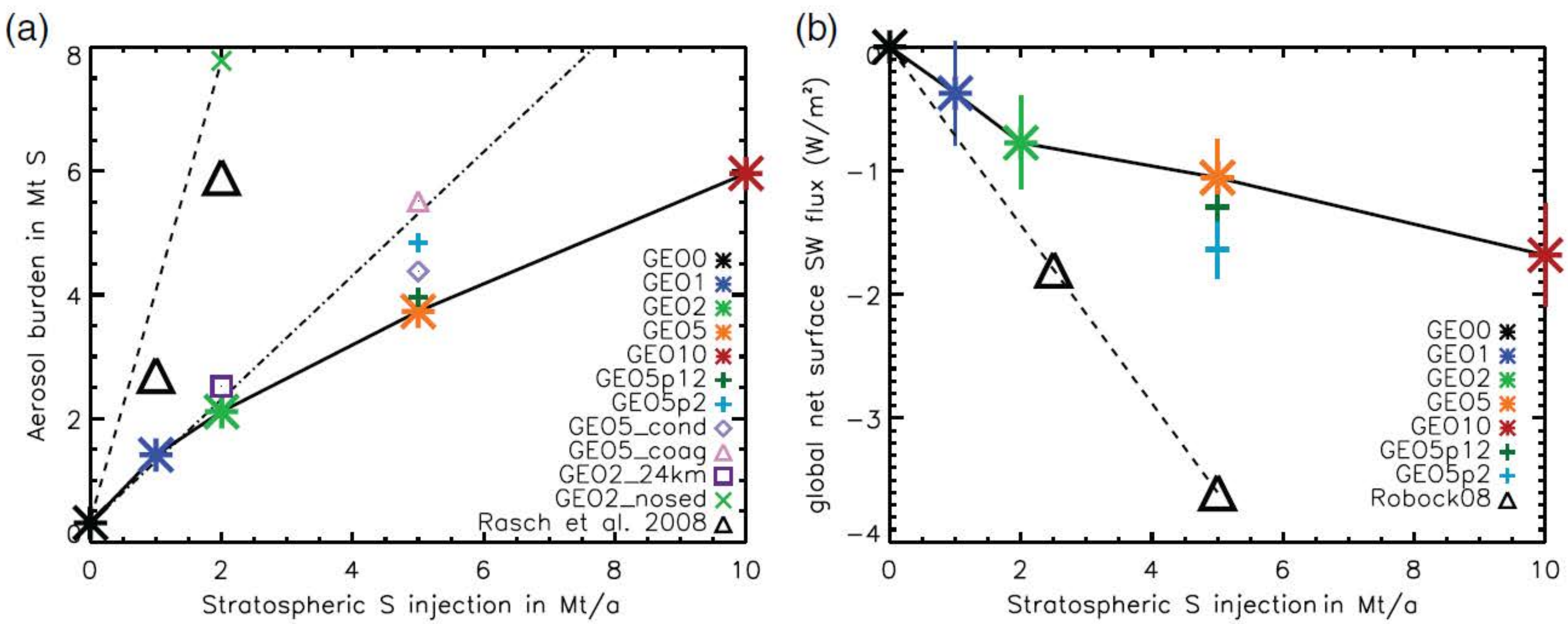


Figure 4. (a) Total aerosol burden as function of sulfur injected annually into the stratosphere (0, 1, 2, 5 and 10 Mt/a S) calculated by the AER model. Dash–dotted line: aerosol burden, if the aerosol residence time were 1 year irrespective of injection strength. Dashed line: aerosol burden when aerosol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

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

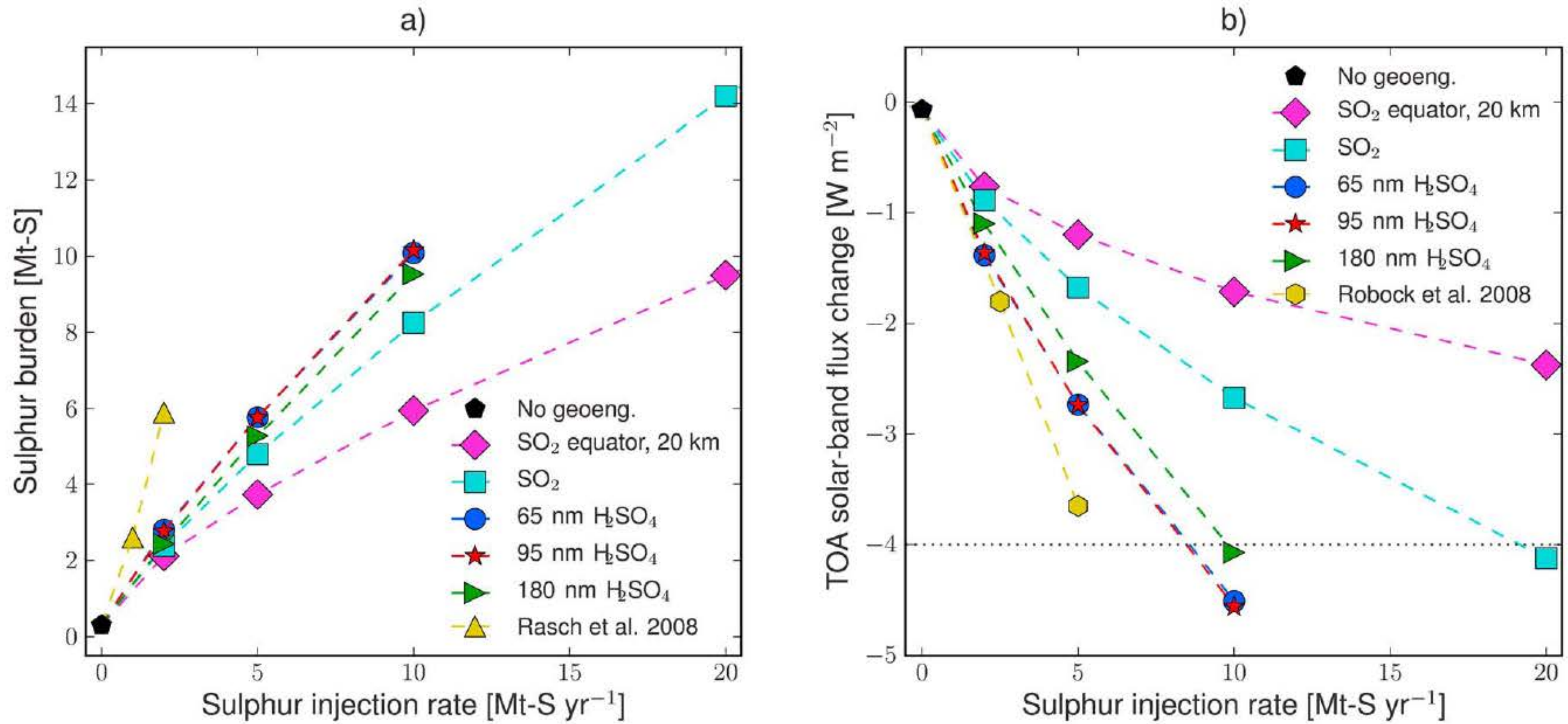


Figure 4. Steady-state (a) stratospheric sulfur burden and (b) top-of-atmospheric solar-band (shortwave) radiative flux change from the stratospheric aerosols as a function of sulfur injection rate. All simulations have emissions evenly distributed between 30°S–30°N and 20–25 km, except results for SO_2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

Aerosol properties

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

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

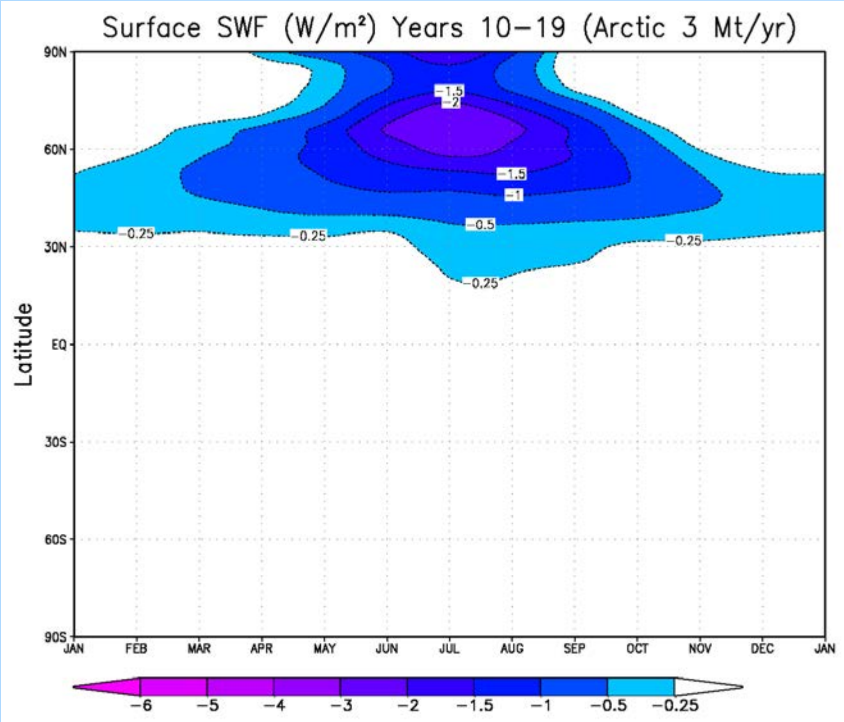
Latitudes and Altitudes

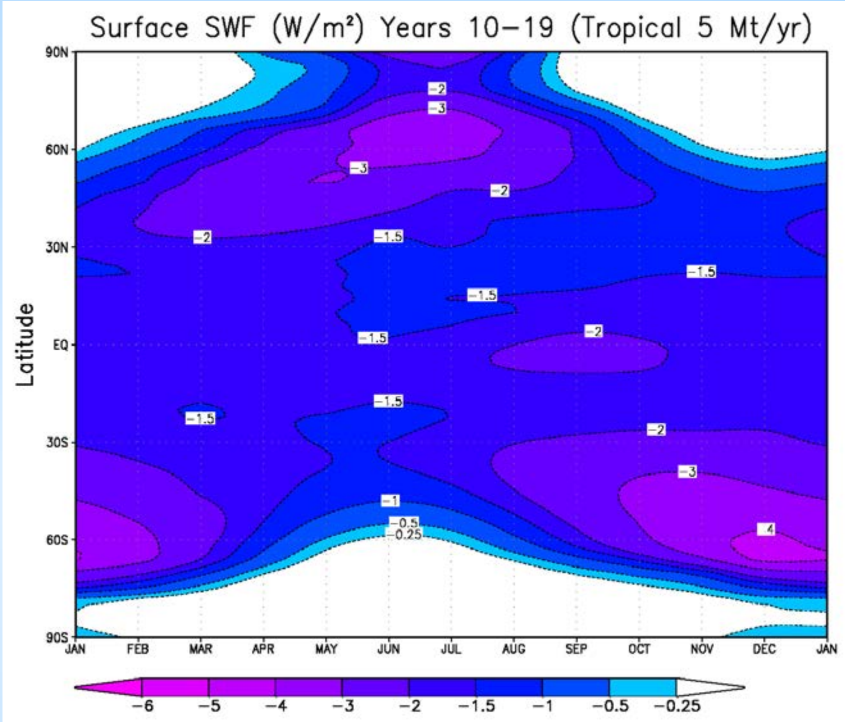
Tropical: We put SO_2 into the lower stratosphere (16-22 km) over the Equator at a daily rate equal to
5 Mt/yr (1 Pinatubo every 4 years) or
10 Mt/yr (1 Pinatubo every 2 years) for 20 years,
and then continue to run for another 20 years to see how fast the system warms afterwards.

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

Alan Robock
Department of Environmental Sciences

Change in downward solar radiation at Earth's surface





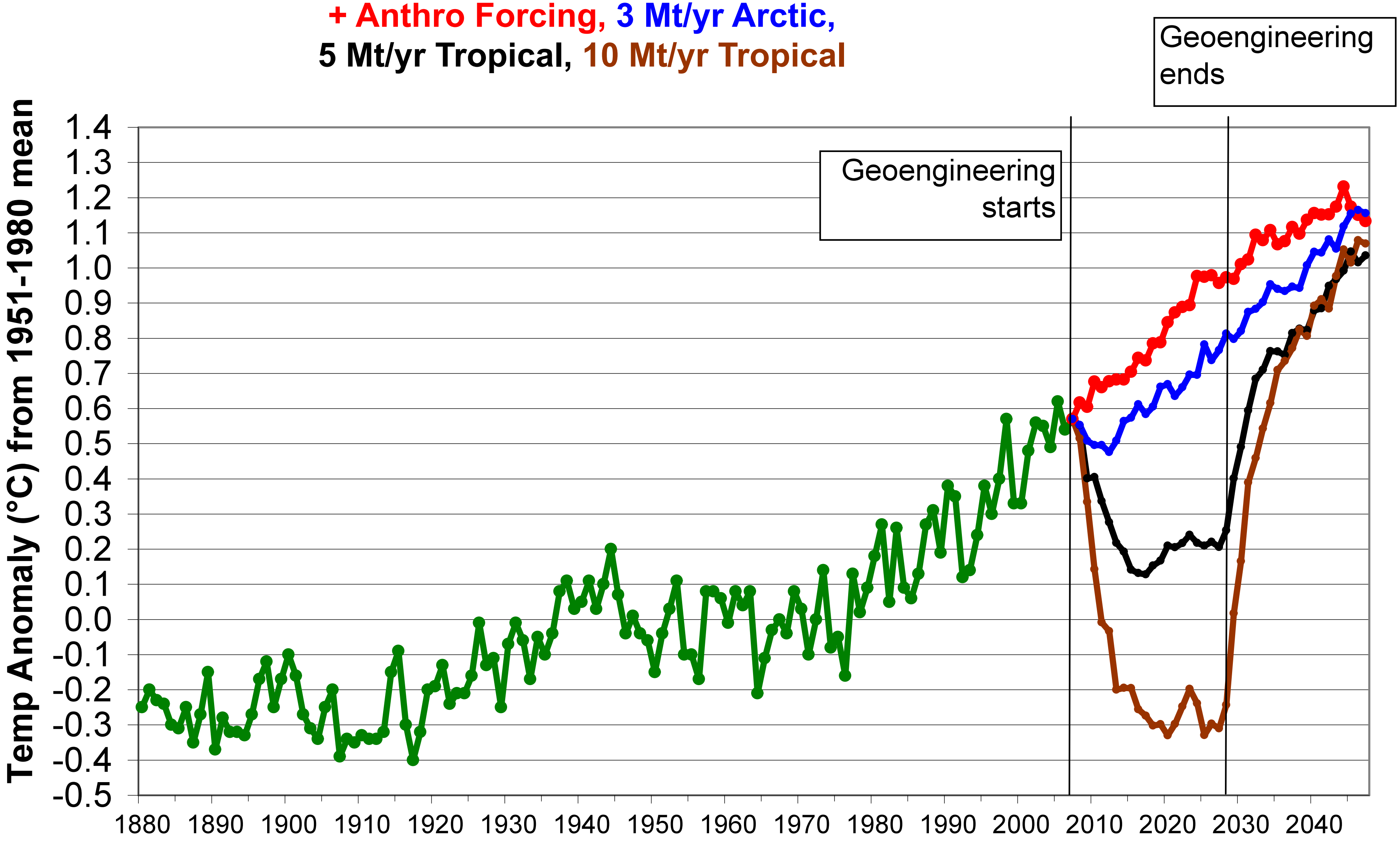
Arctic emission at 68°N leaks into the subtropics

Tropical emission spreads to cover the planet

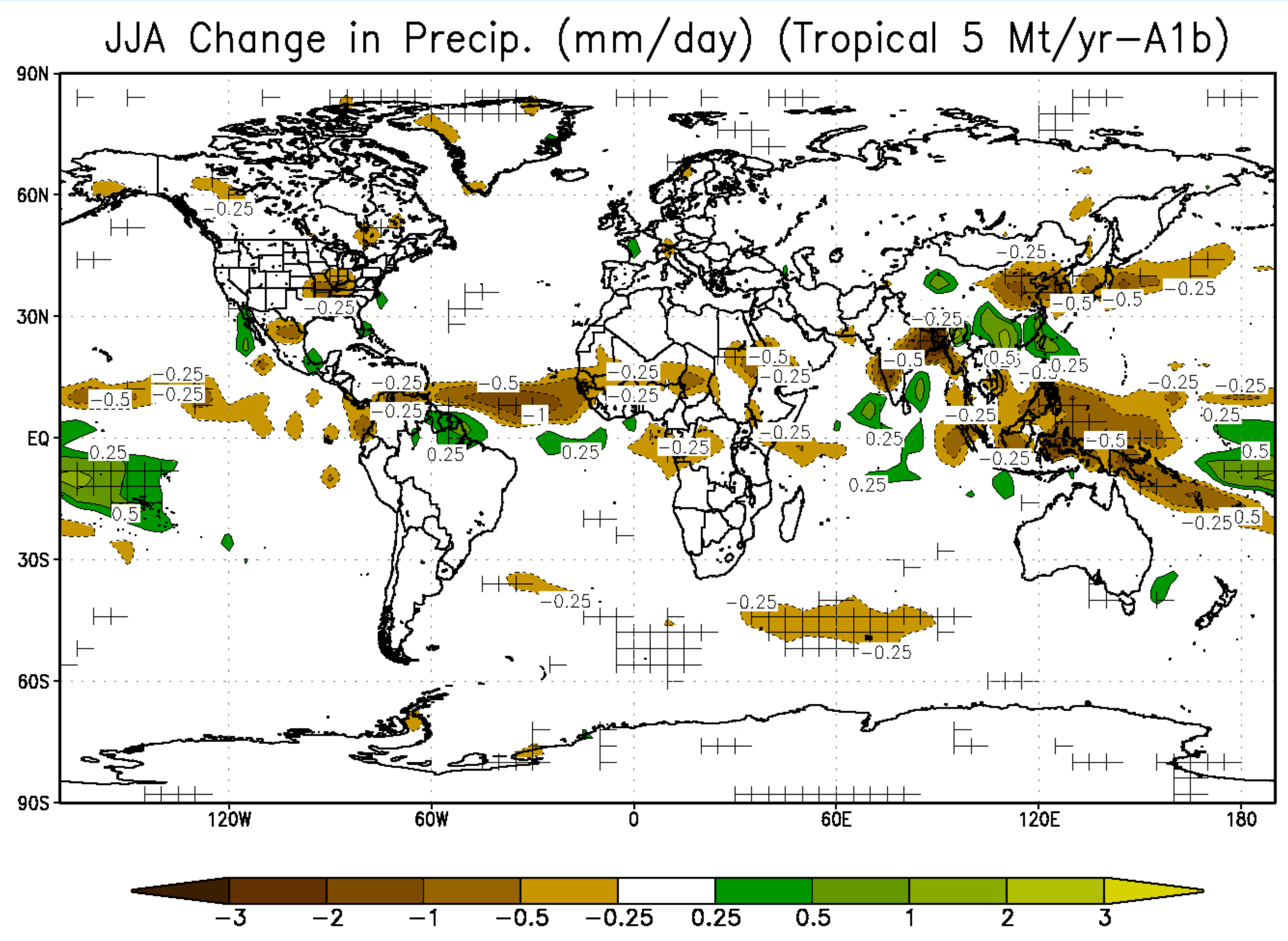
RUTGERS

Alan Robock
Department of Environmental Sciences

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



RUTGERS
Alan Robock
Department of Environmental Sciences



ǂǂǂ = significant at the 95% level

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.

Alan Robock
Department of Environmental Sciences

Trenberth and Dai (2007)

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

Geophys. Res. Lett.

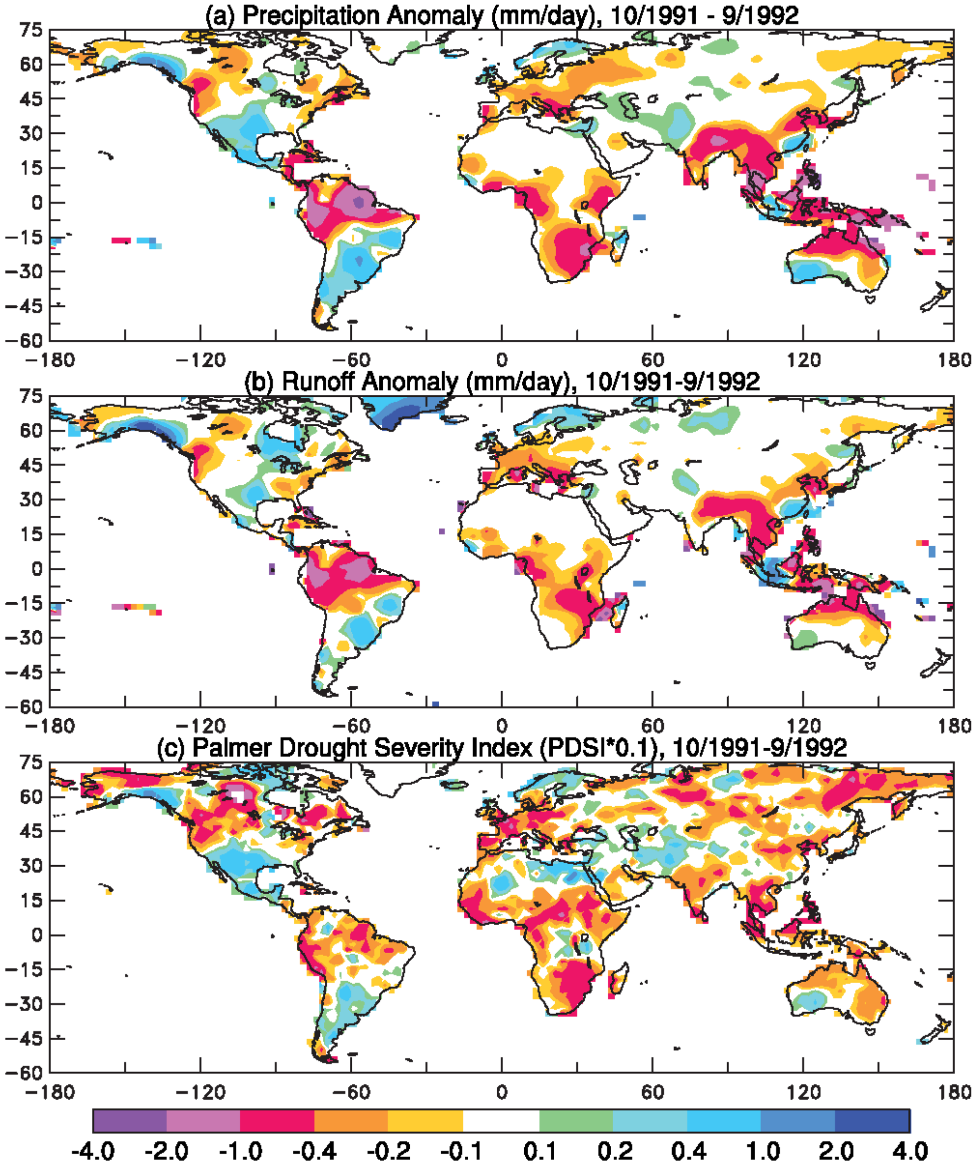
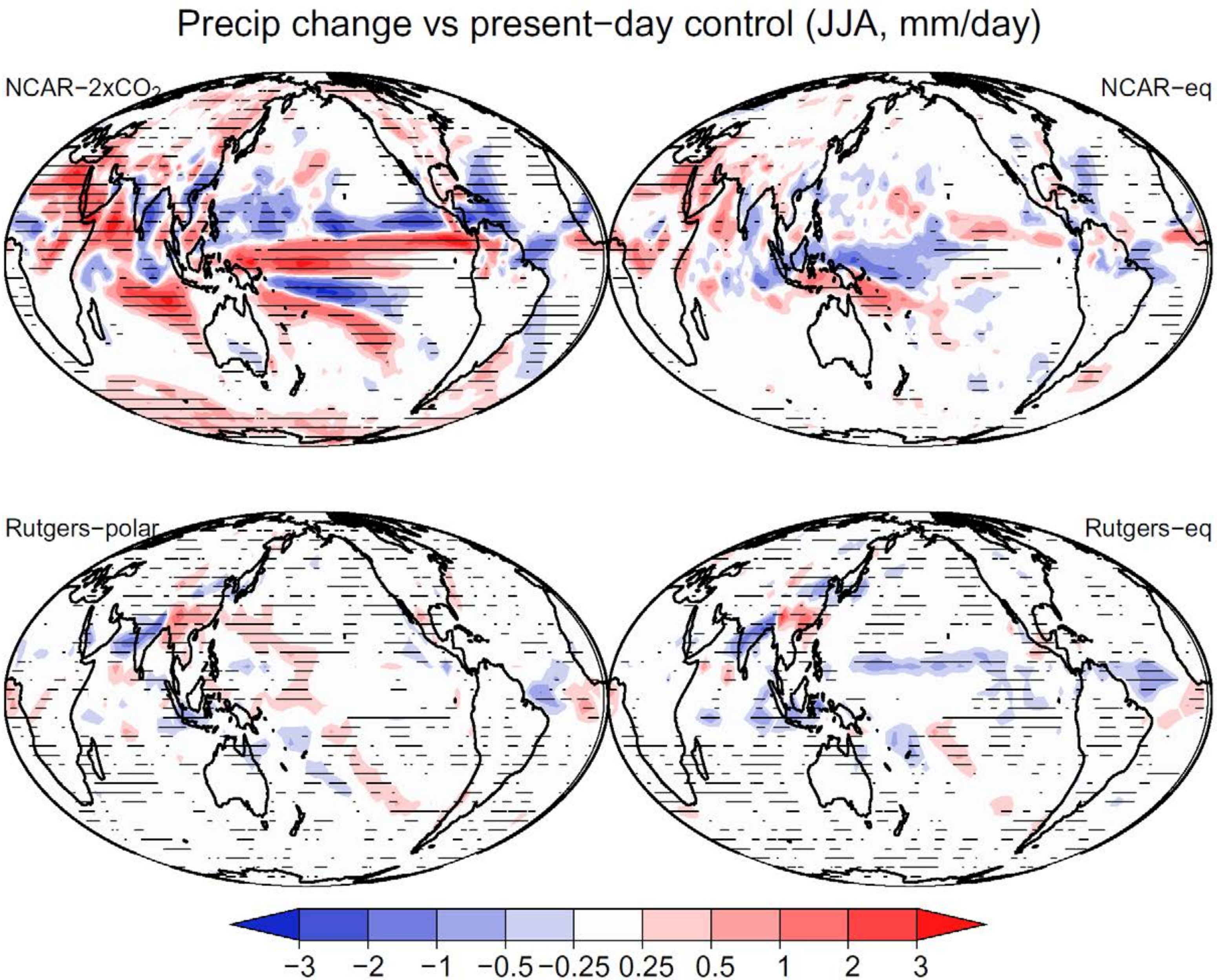


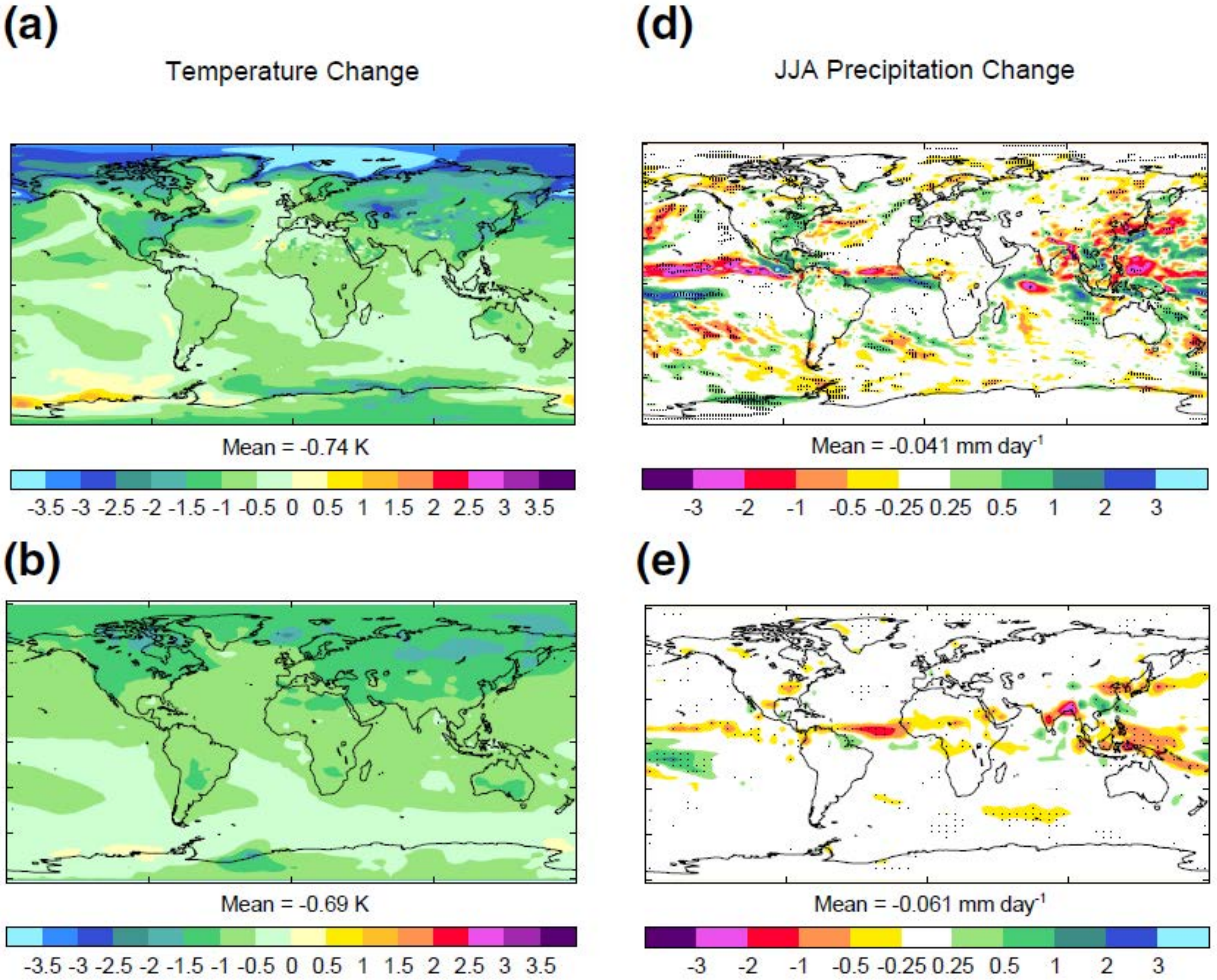
Figure 3. (a) Observed precipitation anomalies (relative to 1950–2004 mean) in mm/day during October 1991–September 1992 over land. Warm colors indicate below normal precipitation. (b) As for Figure 3a but for the simulated runoff [*Qian et al.*, 2006] using a comprehensive land surface model forced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

RUTGERS



RUTGERS

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



Met Office, Hadley Centre

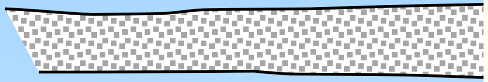
5Mt/yr – A1b

ModelE

5Mt/yr – A1b

RUTGERS

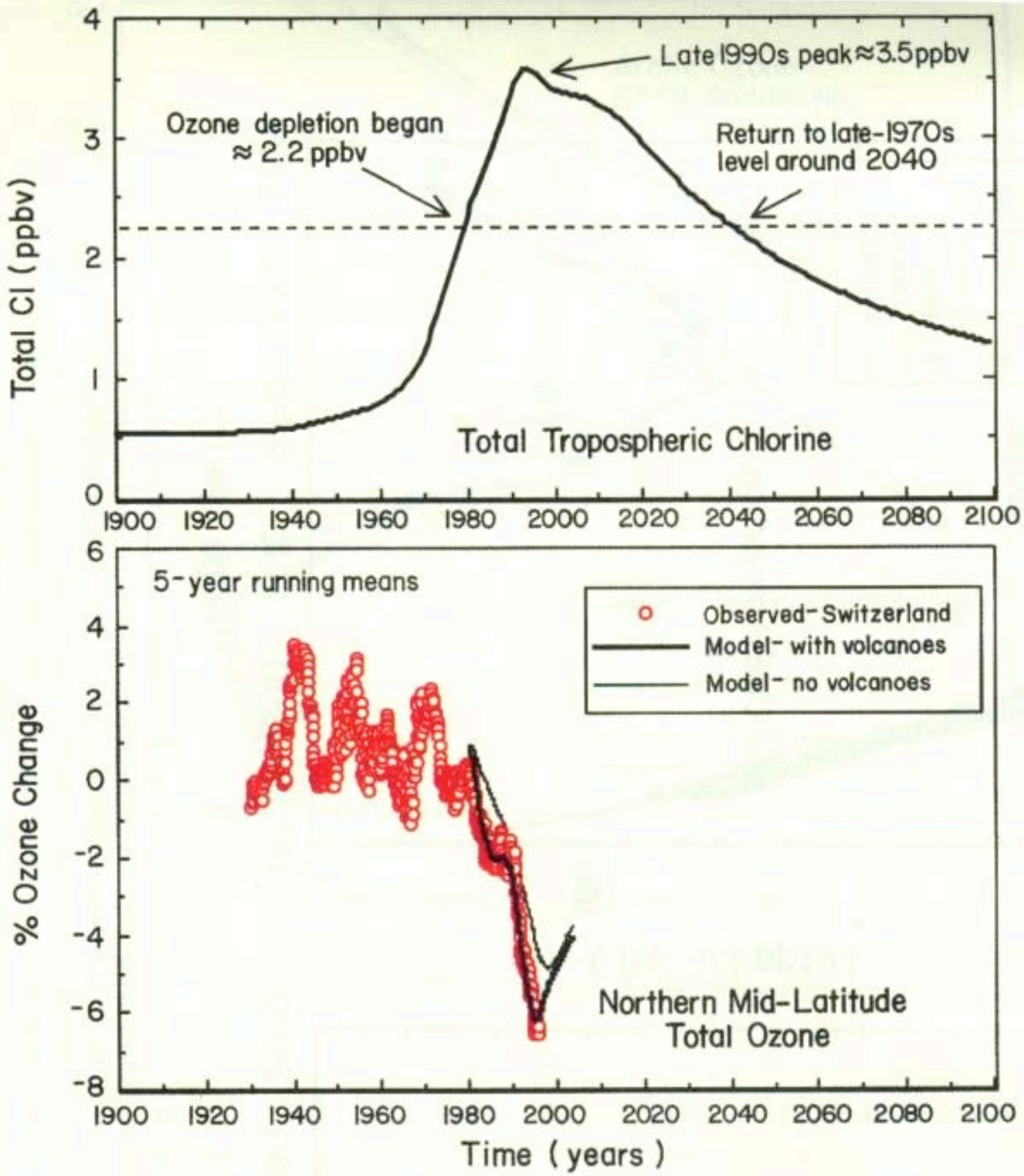
Jones, Andy, Jim Haywood, Olivier Boucher, Ben Kravitz, and Alan Robock, 2010: Geoengineering by stratospheric SO_2 injection: Results from the Met Office HadGEM2 climate model and comparison with the Goddard Institute for Space Studies ModelE. *Atmos. Chem. Phys.*, **10**, 5999-6006.



Tropospheric chlorine diffuses to stratosphere.

Volcanic aerosols make chlorine available to destroy ozone.

Solomon (1999)



RUTGERS

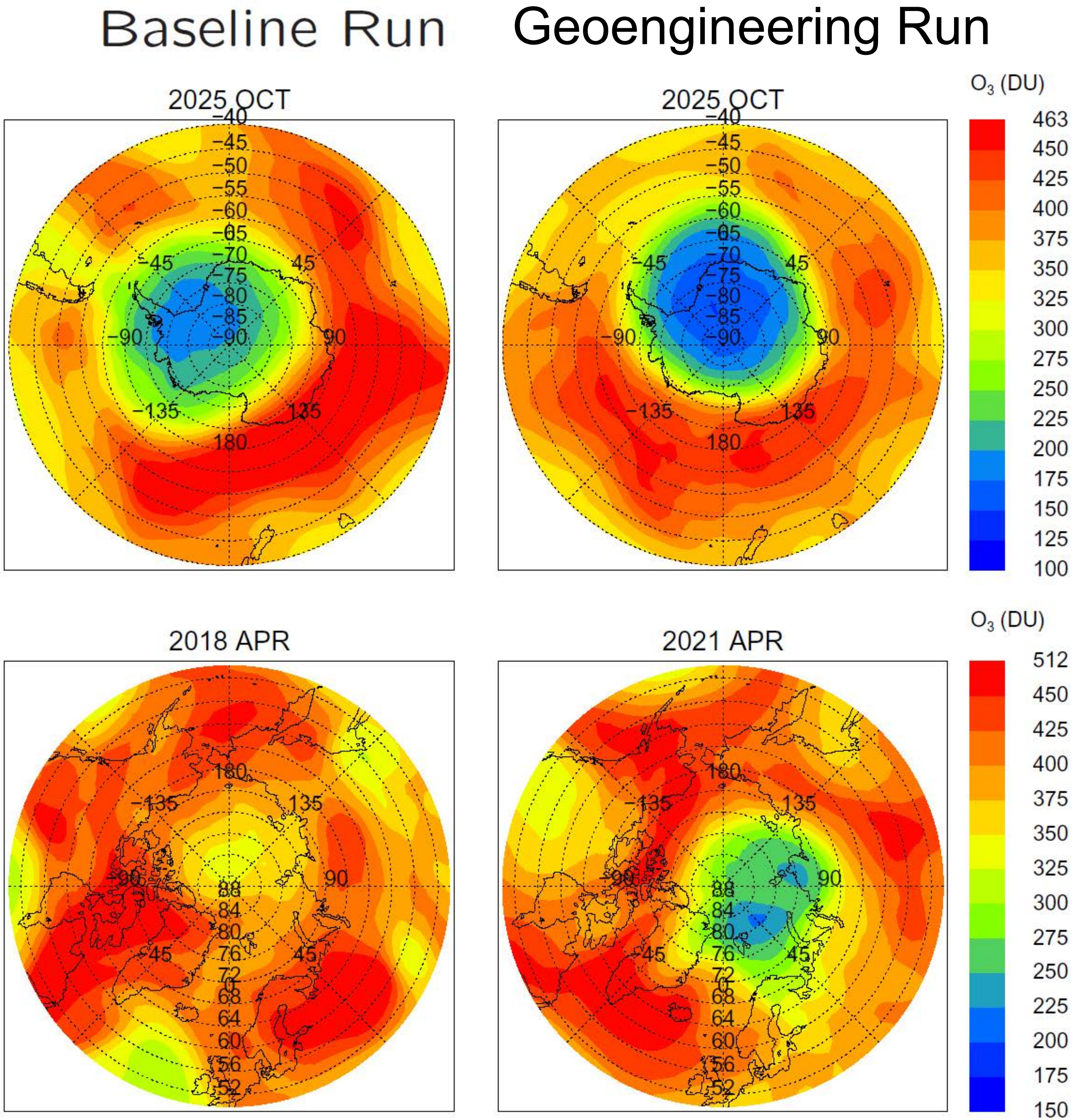
SH

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



RUTGERS

Stratospheric Geoengineering

Benefits

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

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. Conflicts with current treaties
16. Whose hand on the thermostat?
17. Effects on airplanes flying in stratosphere
18. Effects on electrical properties of atmosphere
19. Environmental impact of implementation
20. Degrade terrestrial optical astronomy
21. Affect stargazing
22. Affect satellite remote sensing
23. More sunburn
24. Moral hazard – the prospect of it working would reduce drive for mitigation
25. Moral authority – do we have the right to do this?

Stratospheric Geoengineering

Benefits

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

IPCC

WG I

WG II

WG III

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. Conflicts with current treaties
16. Whose hand on the thermostat?
17. Effects on airplanes flying in stratosphere
18. Effects on electrical properties of atmosphere
19. Environmental impact of implementation
20. Degrade terrestrial optical astronomy
21. Affect stargazing
22. Affect satellite remote sensing
23. More sunburn
24. Moral hazard – the prospect of it working would reduce drive for mitigation
25. Moral authority – do we have the right to do this?

GeoMIP

We proposed standard experiments with the new GCMs being run as part of CMIP5 to use the same global warming and same 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.

Alan Robock
Department of Environmental Sciences

GeoMIP

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

GeoMIP is also a SPARC CCMVal Geoengineering Model Intercomparison Project.

GeoMIP is led by Ben Kravitz (Stanford University), Alan Robock (Rutgers University), and Olivier Boucher (Laboratoire de Météorologie Dynamique).

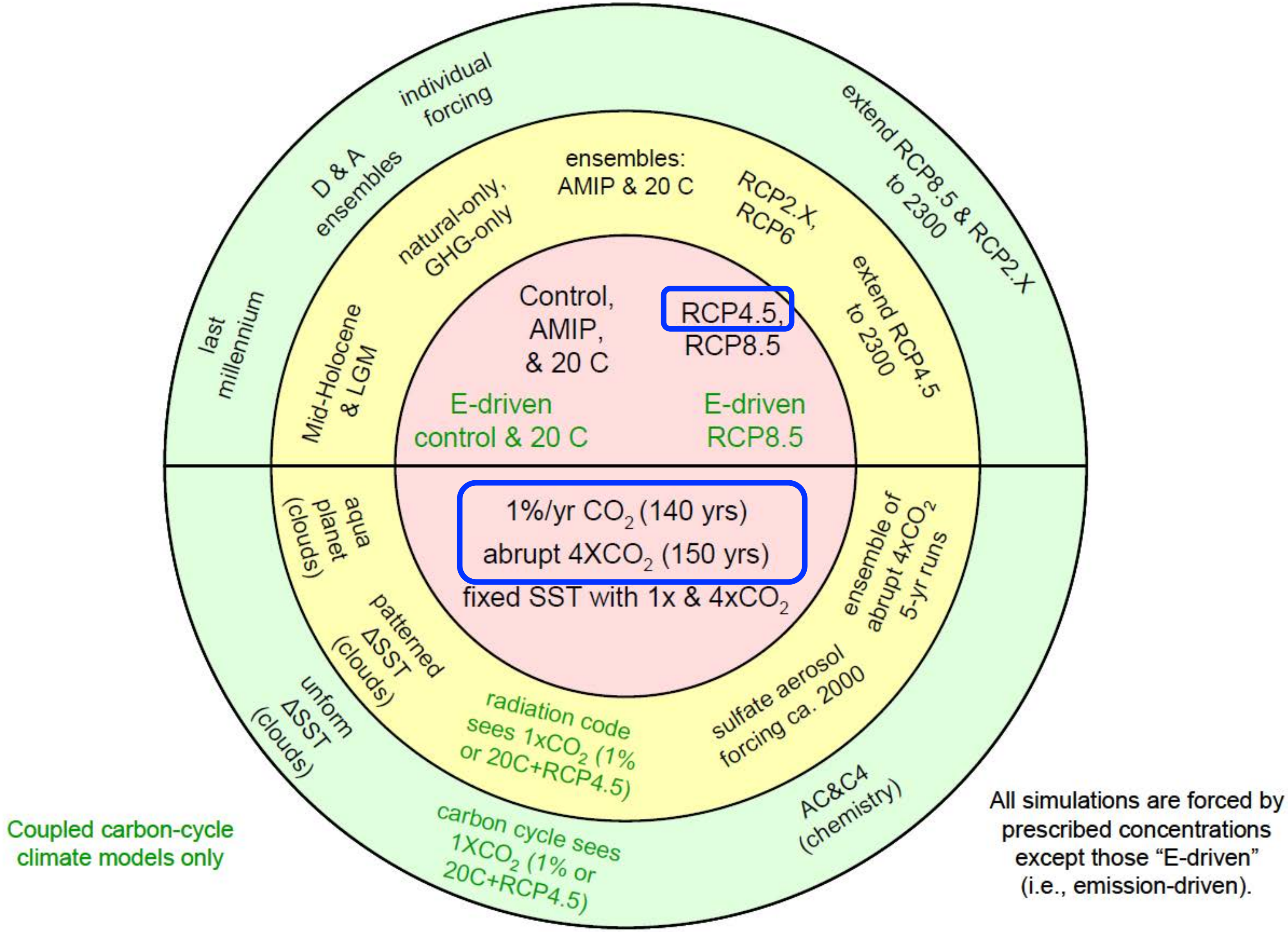
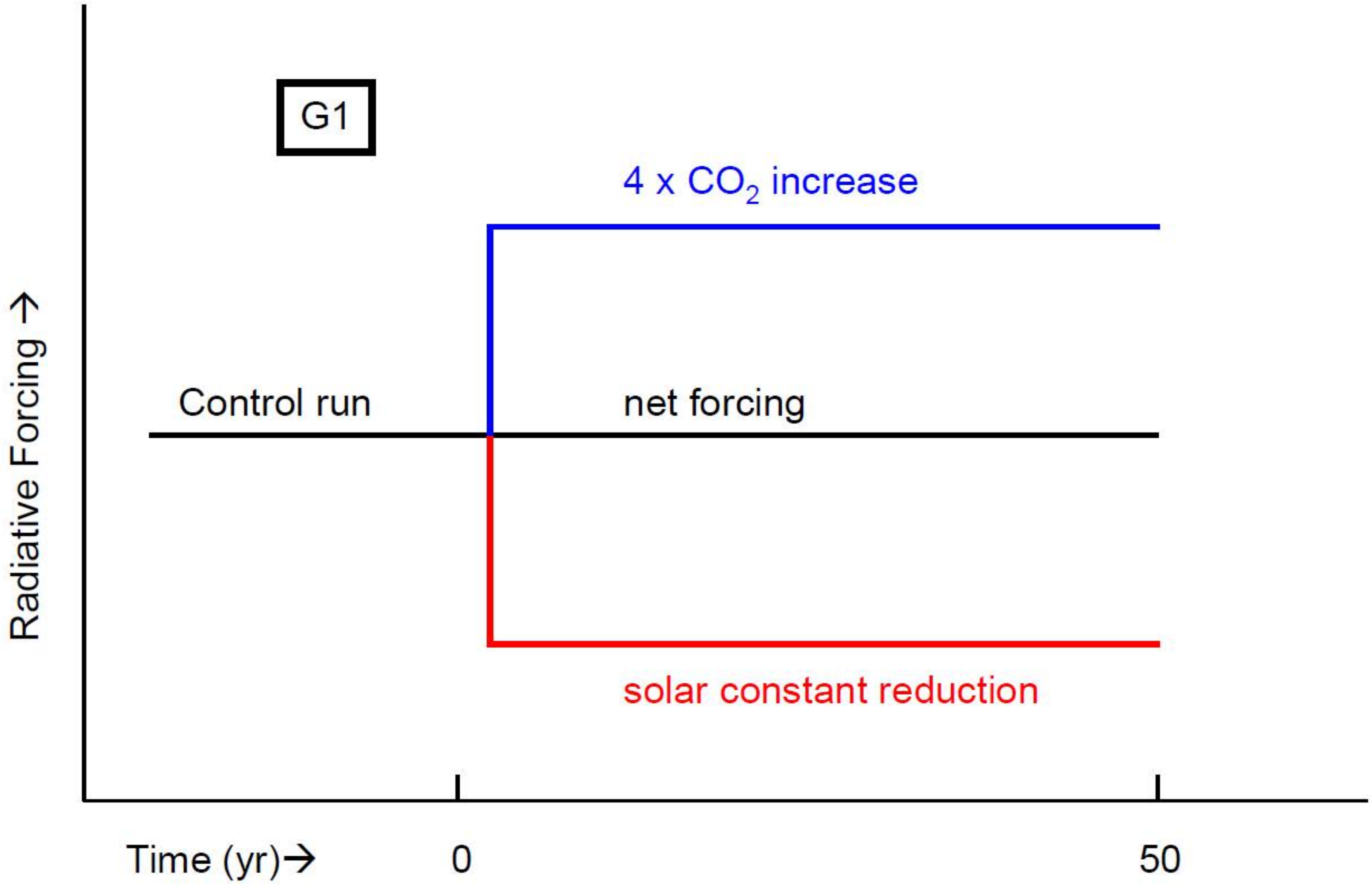
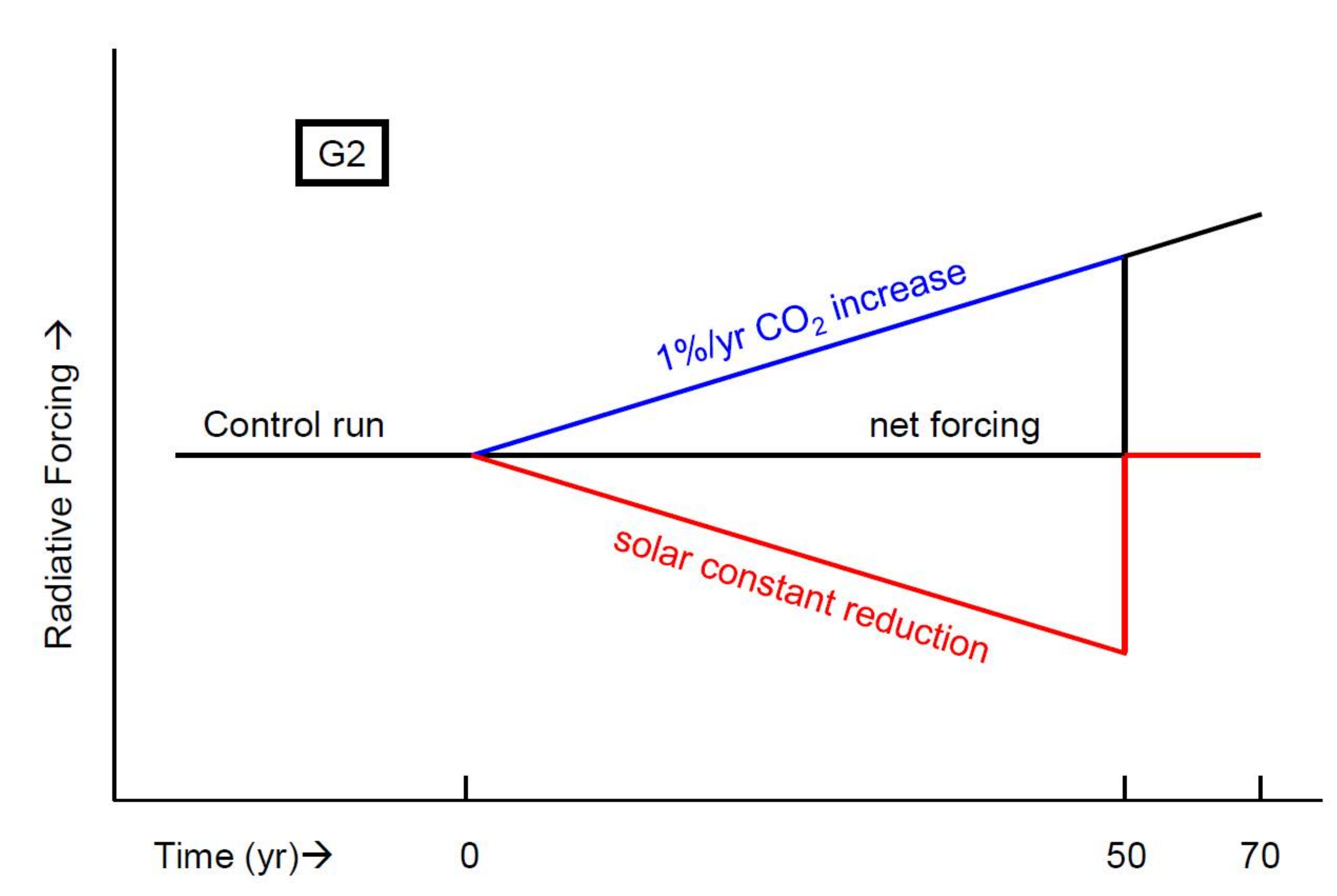


Figure 3: Schematic summary of CMIP5 long-term experiments.

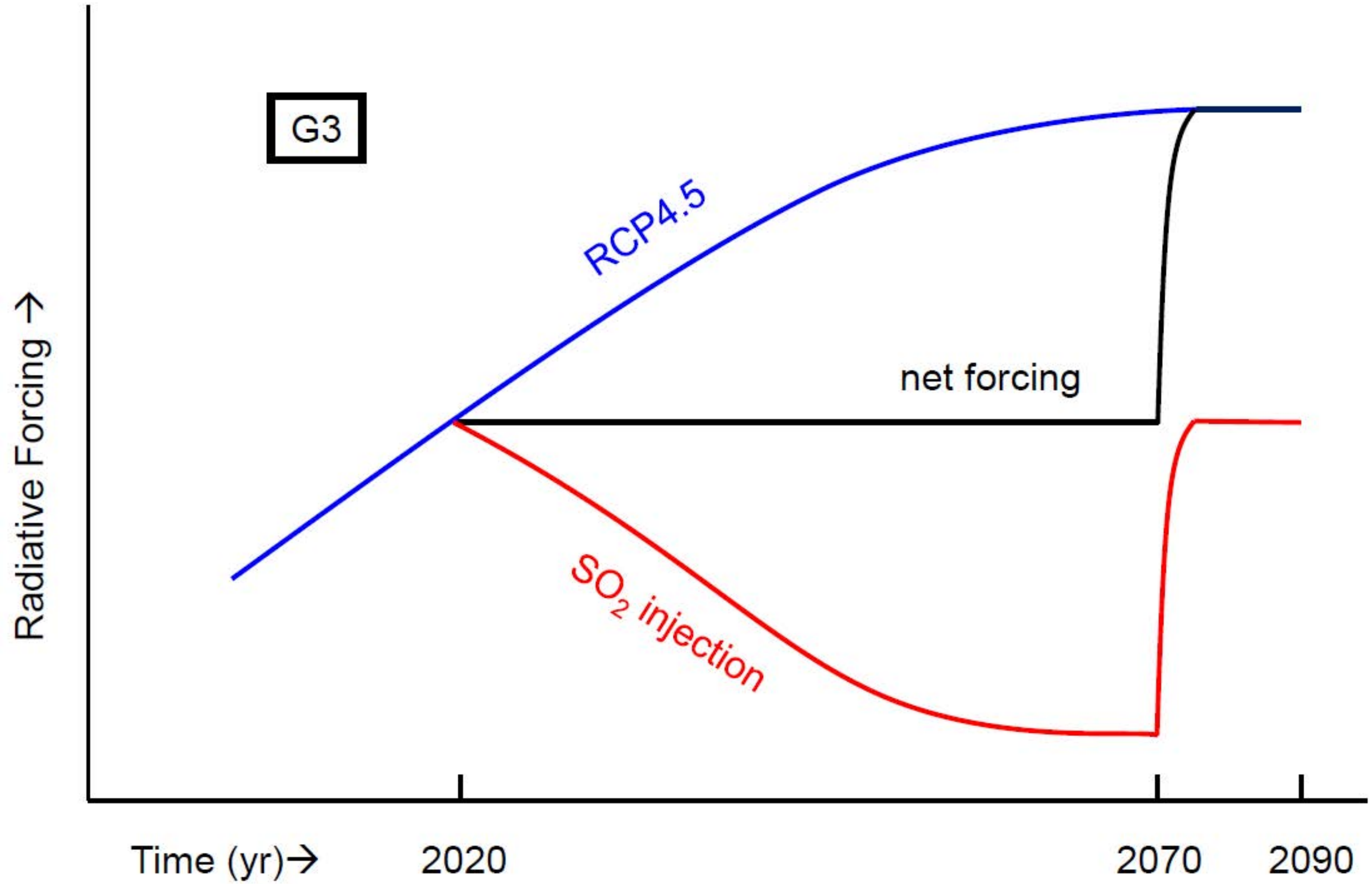
Taylor et al. (2008)



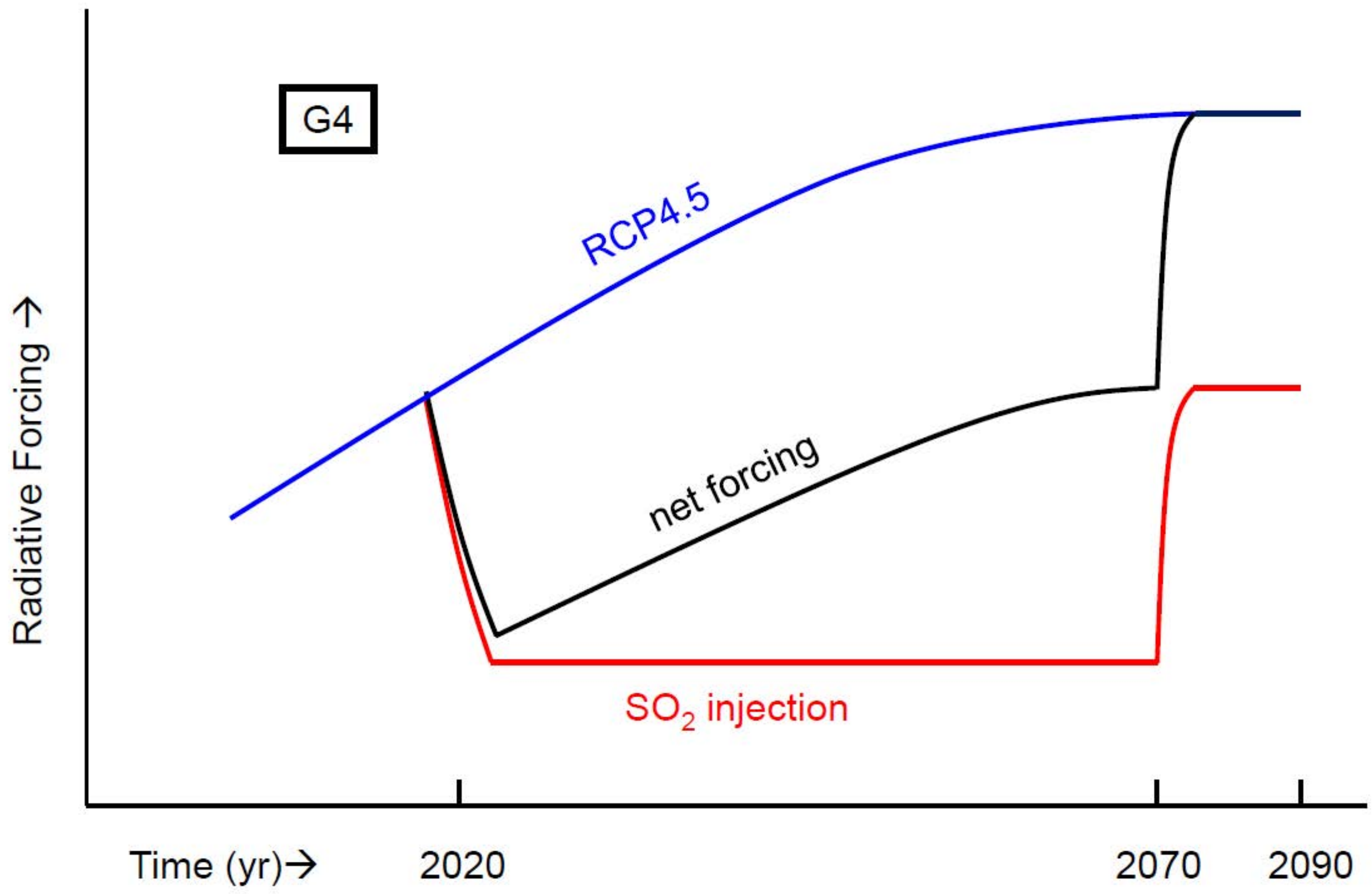
G1: Instantaneously quadruple CO_2 concentrations (as measured from preindustrial levels) while simultaneously reducing the solar constant to counteract this forcing.



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



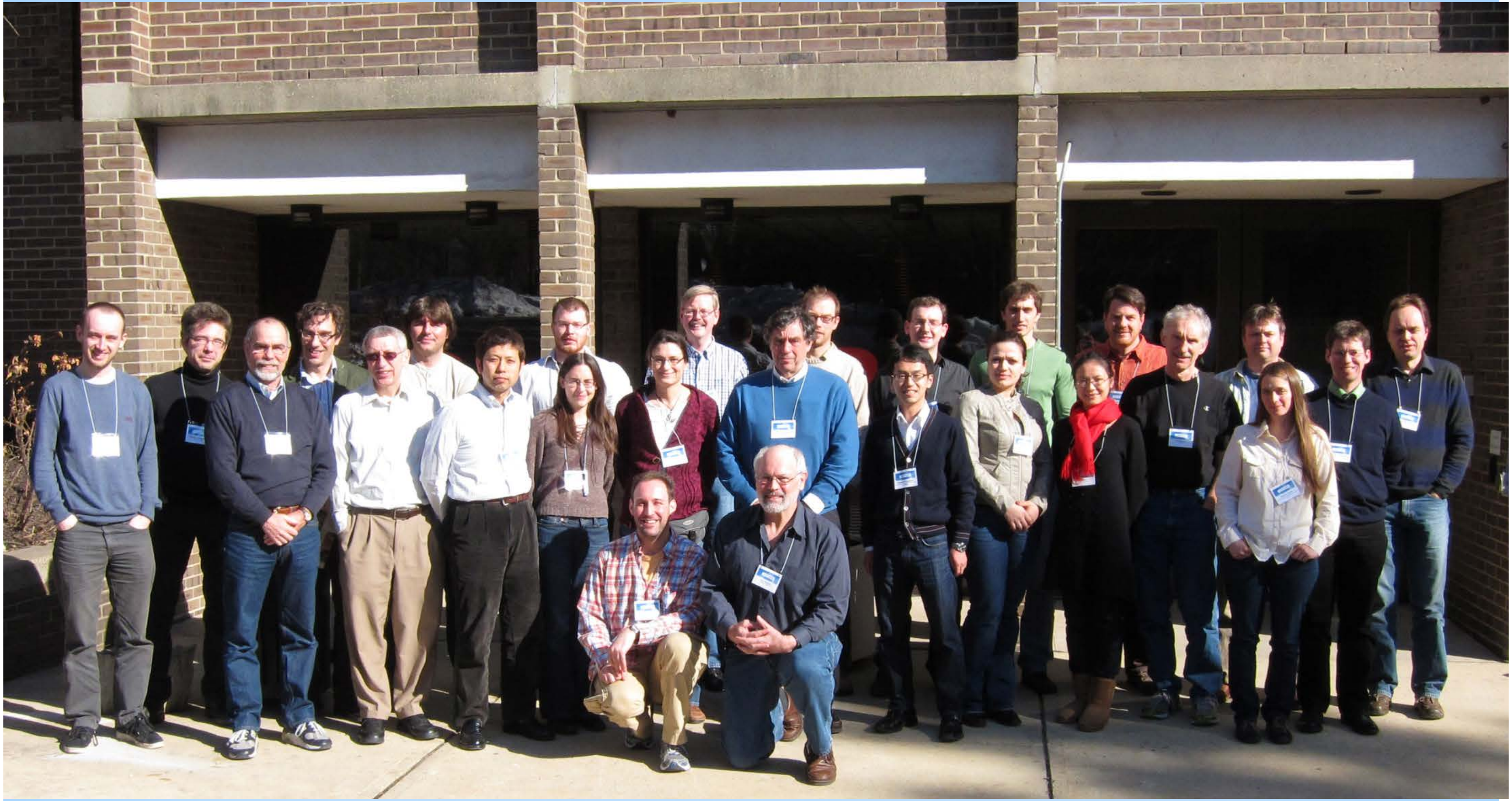
G3: In combination with RCP4.5 forcing, starting in 2020, gradual ramp-up the amount of SO_2 or sulfate aerosol injected, with the purpose of keeping global average temperature nearly constant. Injection will be done at one point on the Equator or uniformly globally.



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).

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.

					# of ensemble members (* in progress)							
Model (CMIP5 or CCMVal participant)	Contact	Atmospheric Model Resolution	Atmospheric Model Top	Oceanic Model Resolution	Stratospheric Aerosols	Ozone	G1	G2	G3	G3 solar	G4
MPI-ESM (ECHAM6)	Hauke Schmidt, Ulrike Niemeier	T63L47	0.01 mb	GR15 L40	Prescribed AOD and surface area	Prescribed	1	1	3		
IPSLCM5A	Michael Schulz, Diana Karam, Olivier Boucher	2.5° lat x 3.75° lon L39	0.1 mb (80 km)	2° lat X 2° lon	Prescribed AOD	Calculated	1	1	*		
GISS ModelE2	Ben Kravitz	2° lat X 2.5° lon L40	0.1 mb (80 km)	1° lat X 1.25° lon L32	Generated from SO_2 injection (Koch scheme)	Calculated	*	*	*		*
NorESM1-M	Jón Egill Kristjánsson, Kari Alterskjær	1.9° lat x 2.5° lon	42 km	~0.5° lat x ~1° lon, 1.125 degrees along the equator	Prescribed	Prescribed	1	1			
CESM-CAM5	Phil Rasch, Jin-Ho Yoon	1.9° lat x 2.5° lon L30	3.5 mb	gx1v6 (displaced pole)	Prescribed	Prescribed	1	1	*		
CESM-CAM4 (G1, G2, G3 solar)	Simone Tilmes, Jean-Francois Lamarque	0.9° lat x 1.25° lon	42 km	~1° lat x ~1° lon	Prescribed	Prescribed	3	3		3	
CESM-CAM4 Chem (G3 solar, G3, G4)	Simone Tilmes, Jean-Francois Lamarque	1.9° lat x 2.5° lon	42 km	~1° lat x ~1° lon	Generated from SO_2 injection (bulk aerosol scheme)	Calculated				*	
CESM-WACCM4	Michael Mills	1.9° lat x 2.5° lon	5.9603E-6 hPa (~145 km)	~1° lat x ~1° lon	Prescribed from SAGE, prognostic PSC growth	Calculated					
MIROC-ESM	Michio Kawamiya, Shingo Watanabe	2.8° x 2.8° (T42)	~85 km (80 levels)	0.56° ~1.4° lat x ~1.4° lon (44 levels)	Prescribed AOD	Prescribed	1	1			1
MIROC-ESM-CHEM	Michio Kawamiya, Shingo Watanabe	2.8° x 2.8° (T42)	~85 km (80 levels)	0.56° ~1.4° lat x ~1.4° lon (44 levels)	Prescribed AOD --> sulfate SAD	Calculated					4
HadGEM2-ES	Andy Jones	1.25° lat x 1.875° lon	39.3 km	30°N-S: 1/3°, 30°-90°N/S: 1°x1°	Generated from SO_2 injection	Prescribed	1	3	3		3
CanESM2	Jason Cole, Charles Curry	~ 2.81° x 2.81° (T63)	~1 hPa (35 layers)	0.94° lat x 1.4° lon	Prescribed	Prescribed	3	3			3
CMCC-CMS	Chiara Cagnazzo	~1.8° x 1.8° (T63)	0.01 hPa (95 levels)	2° lat X 2° lon (31 levels)	Prescribed SO_2 or AOD	Prescribed					
UMUKCA (future HadGEM3-ES)	Peter Braesicke, Luke Abraham	2.5° lat x 3.75° lon (N48) L60	~84 km (60 levels)	~2° L31	Prescribed	Calculated	*	*			
CCSRNIES / MIROC3.2	Hideharu Akiyoshi	T42	0.012 mb		Prescribed	Calculated					1
EMAC2 (DLR)	Martin Dameris, Patrick Jöckel, Veronika Eyring	T42L90MA	0.01 mb		Prescribed	Calculated					
LMDzrepro	Bekki/Marchand	2.5° lat x 3.75° lon)	0.07 mb		Prescribed	Calculated					
SOCOL	Eugene Rozanov	T30	0.01 mb		Prescribed	Calculated					
ULAQ	Pitari	R6/11.5° lat x 22.5° lon	0.04 mb		Prescribed	Calculated					
UMSLIMCAT	Martin Chipperfield	2.5° lat x 3.75° lon	0.01 mb		Prescribed	Calculated					
EMAC (ECHAM5/MESSy)	Mark Lawrence	ca. 2.8° X 2.8° (T42)	~80 km (1 Pa), 90 levels		Generated from SO_2 injection	Calculated					
HadCM3	Peter Irvine	2.5° lat X 3.75° lon L19	5 mb (28 km)	1.25° lat X 1.875° Lon L20	Prescribed SO_2 or AOD	Fixed	1	1			
HadCM3 [27-member perturbed physics ensemble]	Peter Irvine	2.5° lat X 3.75° lon L19	5 mb (28 km)	1.25° lat X 1.875° Lon L20	Prescribed SO_2 or AOD	Fixed	*	*			
IAPRASCM	Alexander Chernokulsky	4.5° lat X 6° lon L8	80 km	4.5° lat X 6° lon L3	Prescribed lifetime	Prescribed					
GCCESM	John Moore	2.8° x 2.8° (T42)	42 km	200 lat x 360 lon, 30°-90°N/S: 1°x1°	Prescribed	Prescribed					
CSIRO Mk3L	Andrew Lenton	5.6° x 3.2° (R21)	36 km (18 levels)	1.6° lat x 2.8° lon (21 levels)	Prescribed	Prescribed					

GeoMIP Participants

Possible GeoMIP publications:

Workshop report – EOS
Overview – model results and summary of gross features – Boucher et al.
What does GeoMIP tell us about how robust models need to be for geoengineering? –Rasch et al.
Fast responses – Forster et al.
Volcanic diagnosis of CMIP5 models to interpret GeoMIP results – Driscoll et al.
Precipitation, hydrology (e.g., monsoon response) G1, G2 – Kravitz, Robock, ...
Precipitation, hydrology (e.g., monsoon response) G3, G4 – Kravitz, Robock, ...
Radiation/energy budget – Schmidt et al.
Stratospheric dynamical responses – Tilmes et al.
Chemistry and ozone (stratospheric / tropospheric responses) – Tilmes et al.

Possible GeoMIP publications:

Snow cover /sea ice – Kravitz et al.
Diurnal cycle – Taylor et al.
Regional focus (e.g., Mediterranean, Asia)
Benefits and risks of geoengineering (including regional differences) – Irvine et al.
Agricultural responses – Xia et al.
Natural vegetation (ecosystem) responses to temperature, precipitation, diffuse/direct radiation – Forster et al.
Ocean circulation response – Stenchikov et al.
Aerosol microphysics (G3, G4) – Mann et al.
Volcanic eruptions (observations) as analogs for geoengineering – Haywood et al.
UTLS / tropopause response – Braesicke et al.
Cryosphere / sea level response – Irvine et al.

Alan Robock
Department of Environmental Sciences

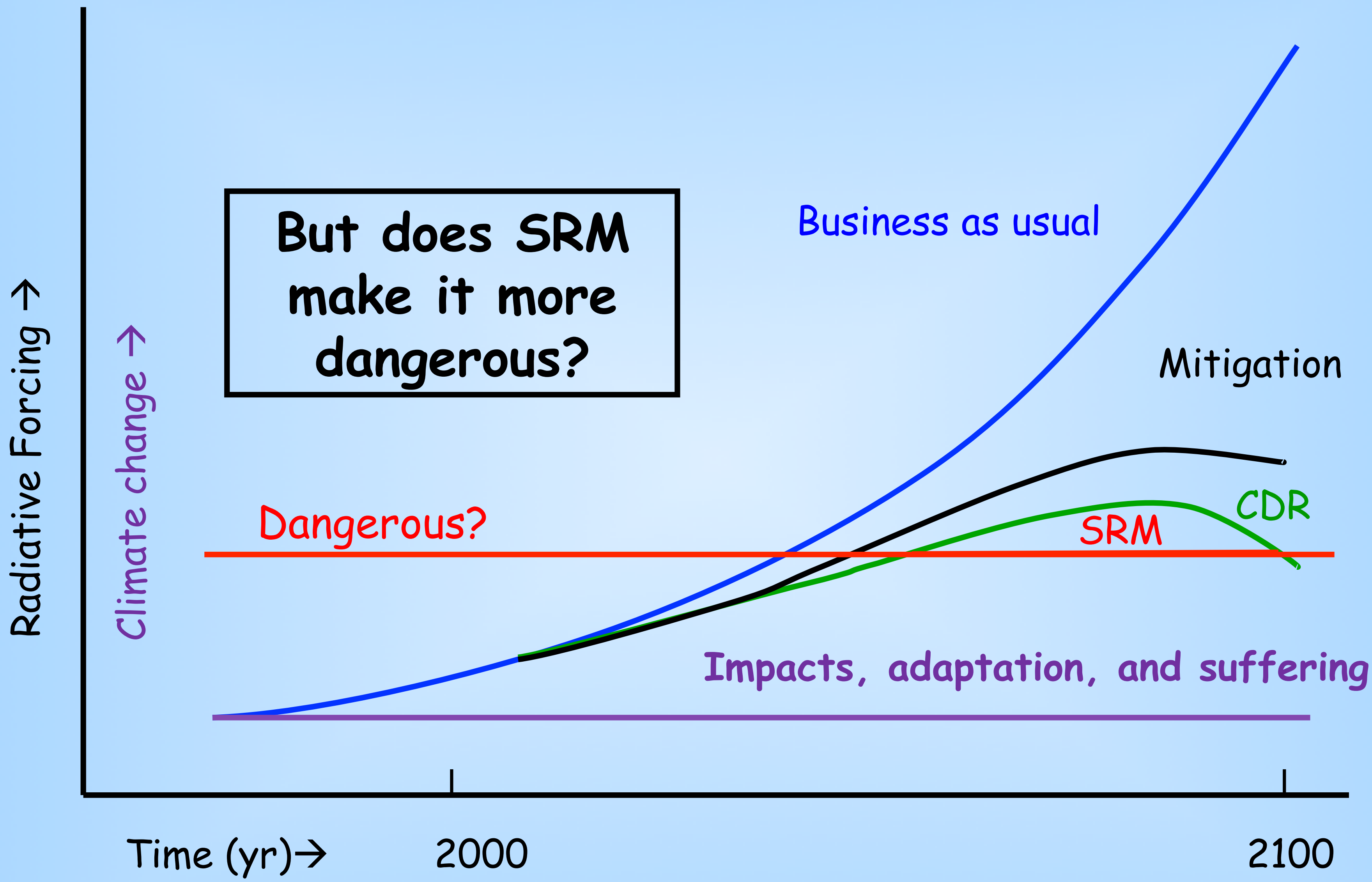
Next Workshop

Hadley Centre

Exeter, UK

March 30-31, 2012

Alan Robock
Department of Environmental Sciences



RUTGERS

Alan Robock
Department of Environmental Sciences