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Smoke and mirrors: Is geoengineering a solution to global warming?

Alan Robock

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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 12.364 in the 2011 Journal Citation Reports, highest in the geosciences.

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Department of Environmental Sciences

This work is done in collaboration with

Luke Oman and Georgiy Stenchikov

NASA Goddard Space Flight Center

King Abdullah University of Science and Technology

Ben Kravitz, Lili Xia, and Allison Marquardt

Rutgers University

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Supported by NSF grant
ATM-0730452

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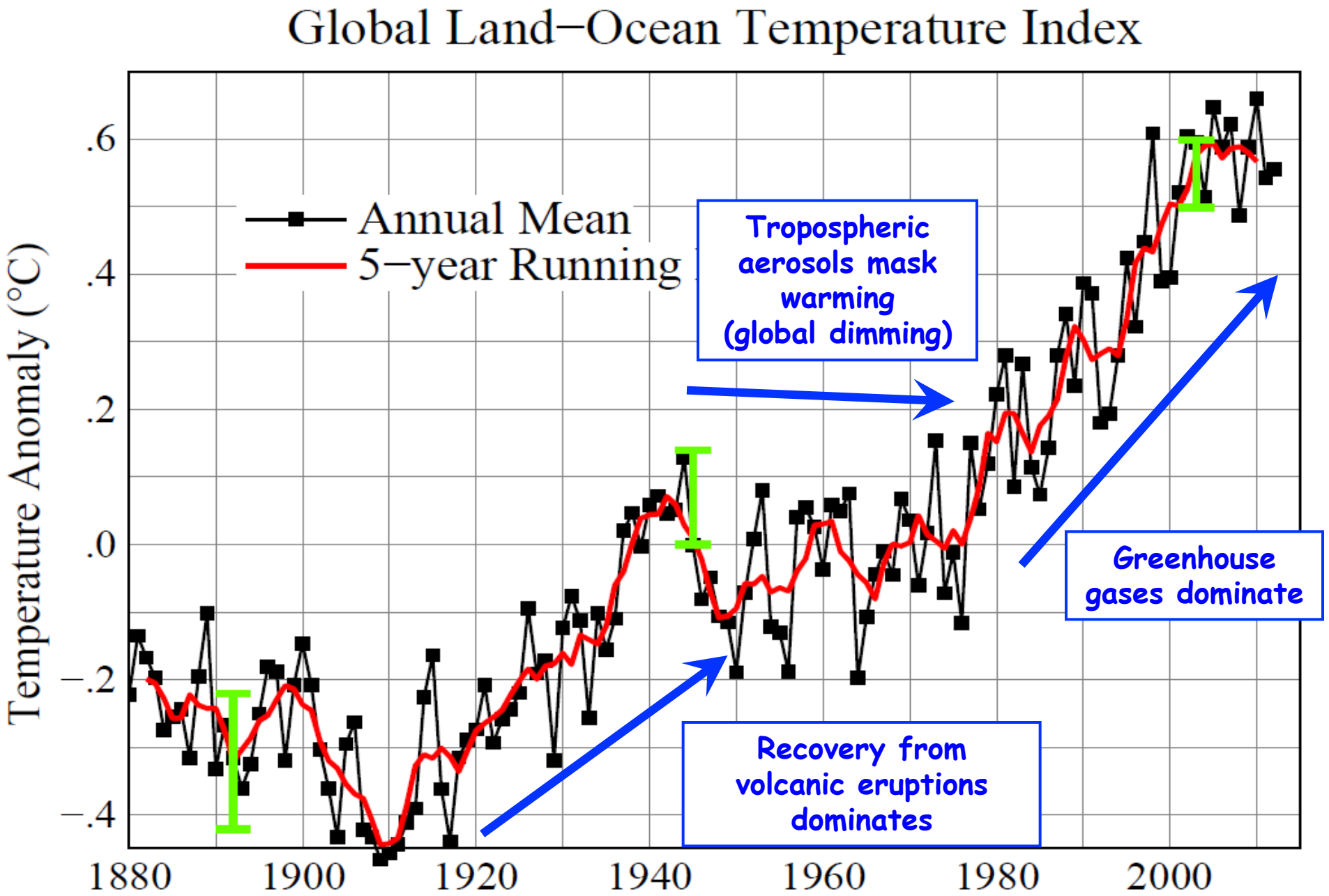
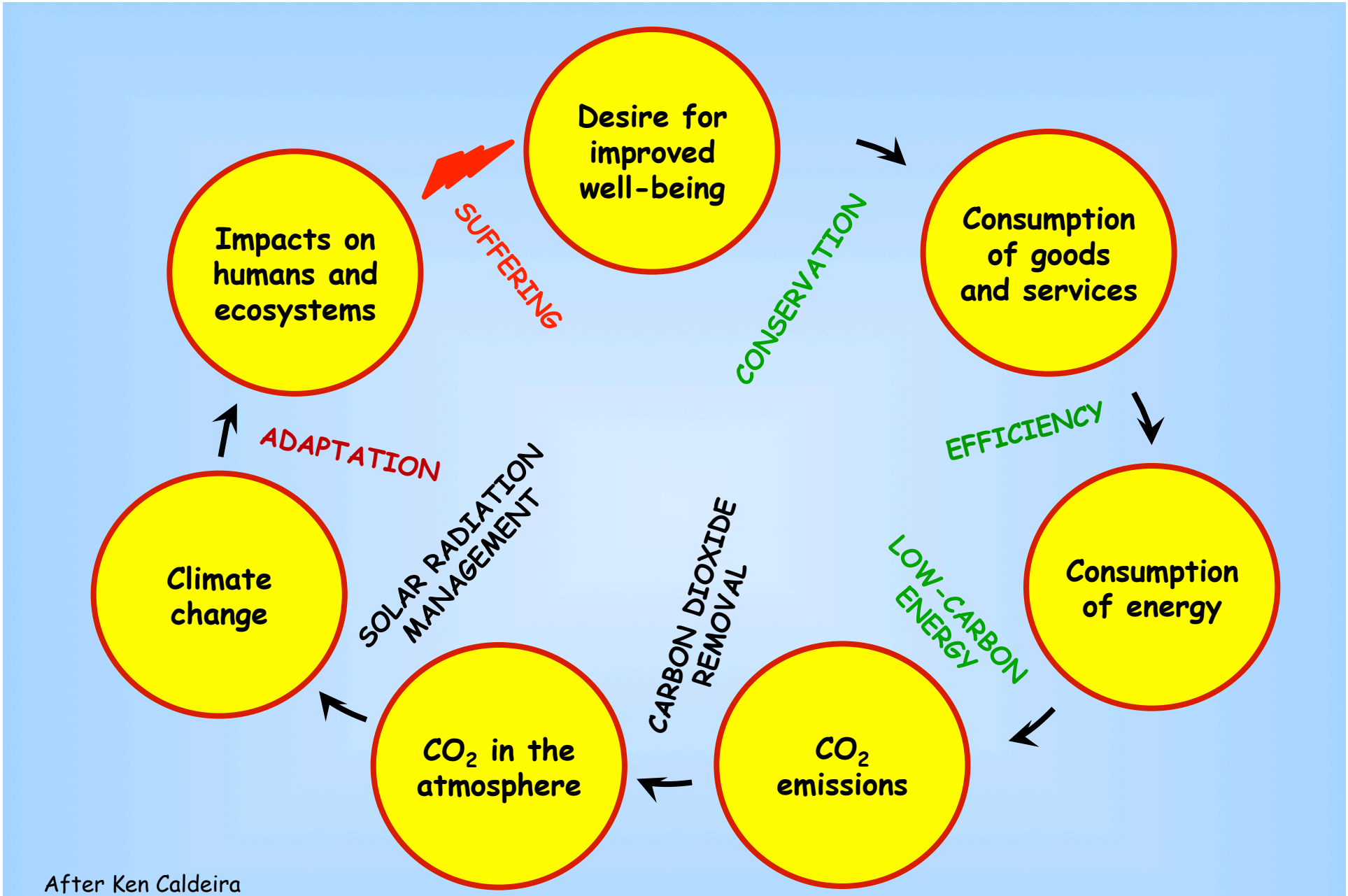

Global Land–Ocean Temperature Index
Annual Mean
5–year Running
Temperature Anomaly (°C)
.6
.4
.2
.0
–.2
–.4
1880
1900
1920
1940
1960
1980
2000
Tropospheric aerosols mask warming (global dimming)
Greenhouse gases dominate
Recovery from volcanic eruptions dominates



After Ken Caldeira

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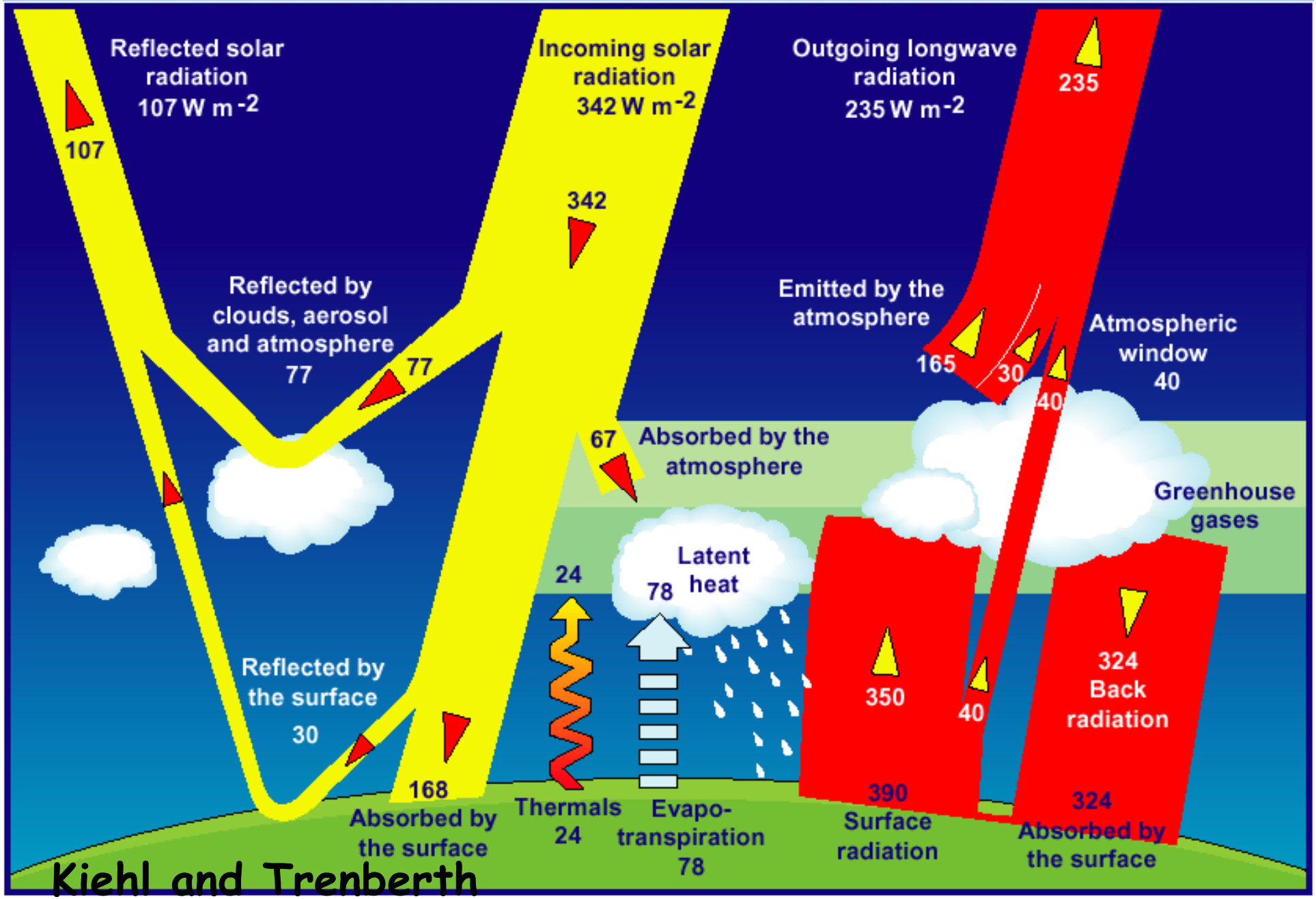
Climate System Energy Balance



Global Warming Fundamental Questions

1. How will climate change in the future?
   Considerable warming, glacier retreat, more precipitation, floods, droughts, extinctions, stronger storms, and sea level rise
2. How will climate change affect us?
   Some winners but more losers, including water, agriculture, pests, national security
3. What should we do about it?
   Mitigation (reduce emissions) now is cheaper than waiting, study impacts, adapt, but not stratospheric geoengineering

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2nd Polar Shipping Summit

30 - 31 March 2011 Montreal, Canada

ACI

Taking Advantage of Commercial Opportunities & Next Generation Ship Technologies

WHY YOU CANNOT MISS THIS EVENT?

With the opening up of new sea routes, maritime issues in the Arctic are becoming much more prominent. **2nd Polar Shipping Summit** will focus on **technological, operational, and logistical challenges** encountered by ship owners in harsh arctic conditions. It will address **key developments in transport and exploration in Arctic, commercial, environmental and safety issues**. Particular emphasis will be put on evaluating commercial potential of the North West Passage and the Northern Sea Route. This summit through interactive discussions and case studies will examine practical solutions and the latest innovations of technology in this specialized area.

THE AGENDA

- Discover the commercial prospects of Arctic shipping routes
- Examine operational strategies in harsh environments
- Consider new design solutions for ice going vessels
- Hear about latest developments in technologies
- Examine the future of the industry
- Learn about the local communities in the Arctic Circle

AN INTERACTIVE 2 DAYS

- Hear from an outstanding line-up of the industry's leading **decision makers**, coming from all sides of the argument over the future of Arctic Shipping
- Network informally with a relatively small, targeted group of senior-level **ship owners** and decision-makers from the **arctic maritime and natural resource** industries
- Discuss the latest challenges and developments in this rapidly changing and growing sector of the industry
- Participate in roundtable sessions – giving you the chance to discuss the latest issues with your colleagues – and the speakers - in an open, informal and intimate setting

WHO WILL ATTEND?

Delegates will be drawn from the Maritime industry's leading companies and include:

- Presidents
- VPs
- Directors
- Managers

There will also be representation from different stakeholders within arctic shipping which include oil and gas and mining organisations.

For more information or to register for this exclusive event,

contact Mohammad Ahsan

By calling +44 (0) 207 981 2503

Emailing mahsan@acieu.net

ORGANIZATIONS PREVIOUSLY ATTENDED POLAR SHIPPING SUMMIT INCLUDE

Anglo-Eastern Ship Management

Biglift Shipping

Canadian Coastguard

Fednav

Finnish Shipowners Association

Groupe Desgagnes

International Ice Charting Working Group

Krylov Shipbuilding Research Institute

Maersk Line

Ministry of Foreign Affairs of the Russian Federation

Nordic Bulk Carriers

Nunavut Eastern Arctic Shipping (NEAS)

Pompeii Shipping

Rio Tinto

Royal Norwegian Embassy in Canada

Spliethoff

and many others...

OPPORTUNITIES TO MEET YOUR TARGET AUDIENCE

Companies can gain direct access to our senior level audience and have an increased level of visibility through branding and networking at the summit. For information on available sponsorship and commercial opportunities, please contact

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hubert@acieu.net

Sponsored by

ATLANTIC TOWING LIMITED

2nd Polar Shipping Summit

30 - 31 March 2011 Montreal, Canada

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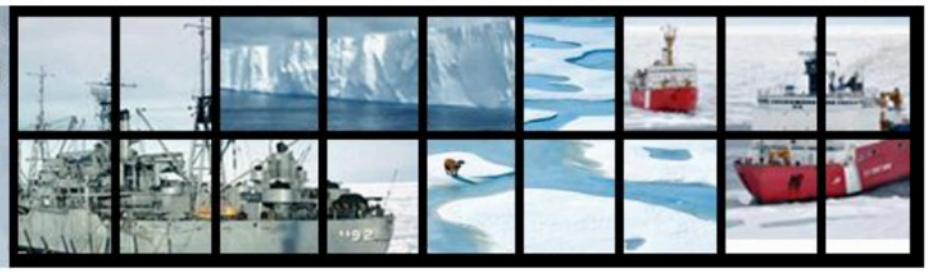

Prices and Payment Information

Summit (Includes Documentation Packet)	**30th and 31st March 2011**	**£1,495**
Documentation Packet	Copies of all Summit Proceedings	£420

Documentation Packet Available

You can purchase the **Polar Shipping** papers at just £420. Simply tick the box on the booking form, send it with payment and your copy will be on its way to you after the meeting. This important manual will be a source of invaluable reference for the future.

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Members and customers of all supporting organisations are entitled to a 15% discount off their conference package.
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canadian shipowners association

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ARCTIC PORTAL

Global Warming Fundamental Questions

1. How will climate change in the future?

   Intergovernmental Panel on Climate Change (IPCC) Working Group I (WG I)

2. How will climate change affect us?

   IPCC WG II

3. What should we do about it?

   IPCC WG III

Alan Robock
Department of Environmental Sciences

Intergovernmental Panel on Climate Change (IPCC)

Established in 1988 jointly by the World Meteorological Organization and the UN Environment Programme

2500 scientists from more than 150 nations

Winner of 2007 Nobel Peace Prize

First Assessment Report (FAR), 1990

Second Assessment Report (SAR), 1996

Third Assessment Report (TAR), 2001

Fourth Assessment Report (4AR), 2007

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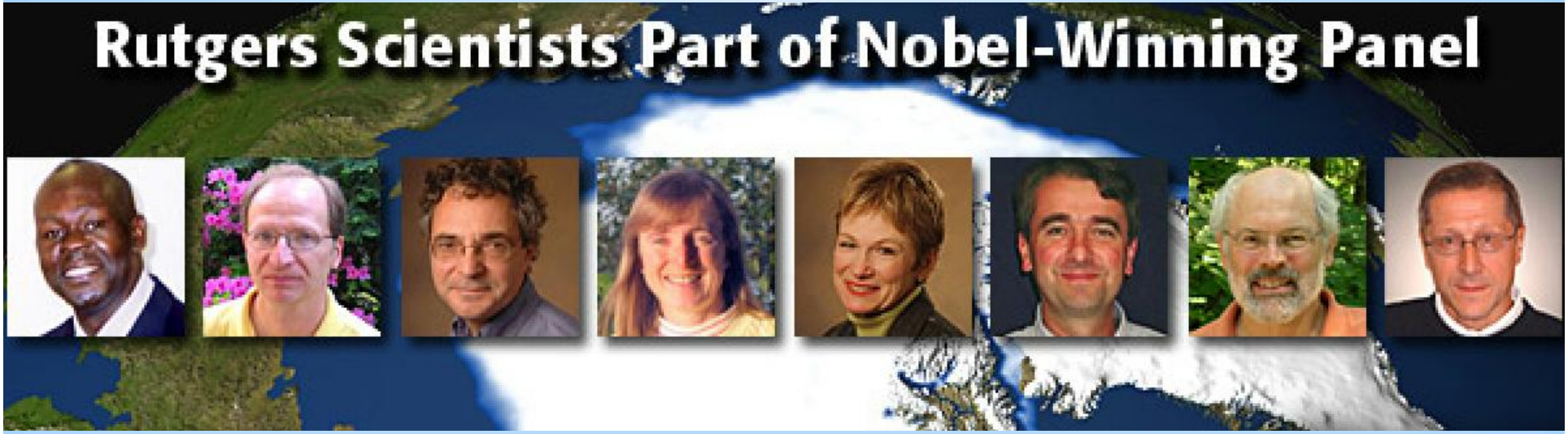

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In this Summary for Policymakers, the following terms have been used to indicate the assessed likelihood, using expert judgment, of an outcome or a result:

Virtually certain > 99% probability of occurrence
Extremely likely > 95%
Very likely > 90%
Likely > 66%
More likely than not > 50%
Unlikely < 33%,
Very unlikely < 10%
Extremely unlikely < 5%

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What is new: It is now very likely that humans caused recent climate change.

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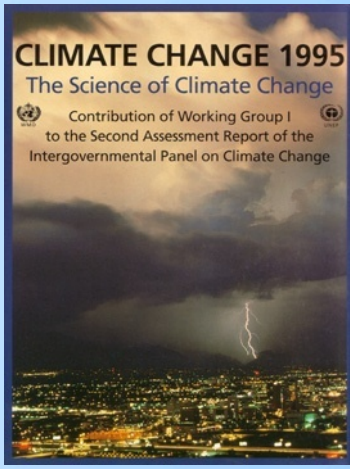
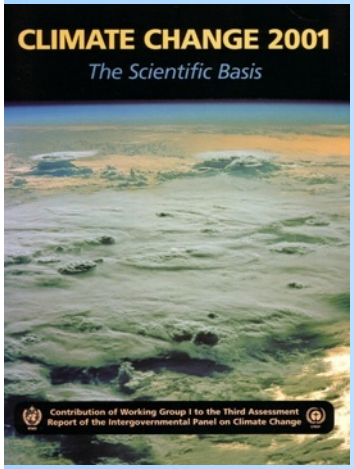
"The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more."

Climate Change – *The IPCC Scientific Assessment (1990)*



"The balance of evidence suggests a discernible human influence on global climate."

Climate Change 1995 – *The Second IPCC Assessment*

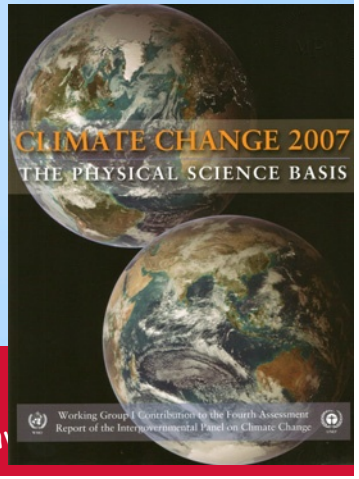


"Most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations."

Climate Change 2001 – *The Third IPCC Assessment*

"Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."

Climate Change 2007 – *The Fourth IPCC Assessment*



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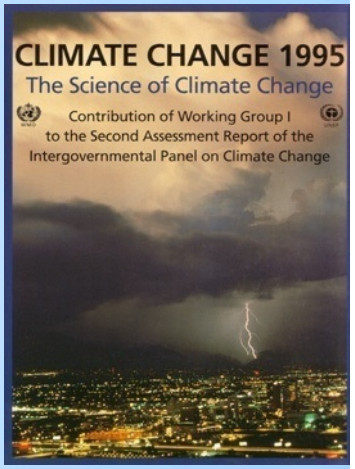

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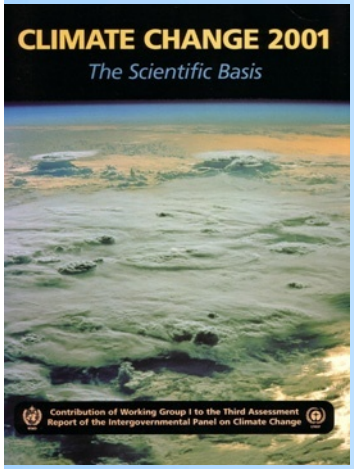

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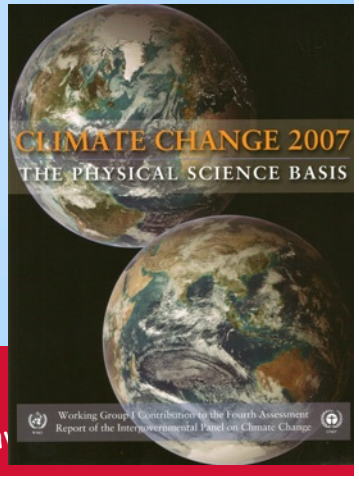


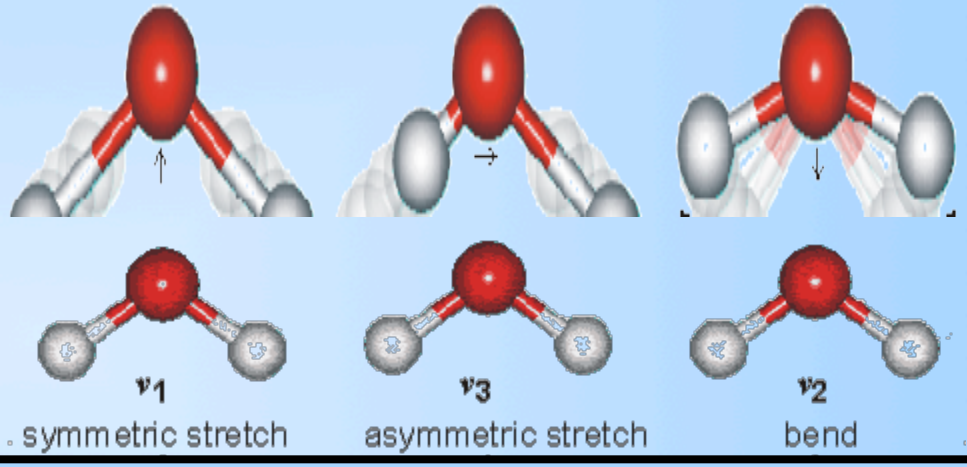
But, what is a "greenhouse gas" anyway?

Nitrogen (N_2), oxygen (O_2), and argon (Ar) make up for 99% of the atmosphere, but **are not** greenhouse gases.

Water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), ozone (O_3), and nitrous oxide (N_2O) **are** greenhouse gases.

A greenhouse gas absorbs infrared radiation, which creates molecular vibration and bending.

Collisions transfer energy to heat the surrounding gas.



Water vapor (H_2O) vibration modes

http://www.lsbu.ac.uk/water/vibrat.html

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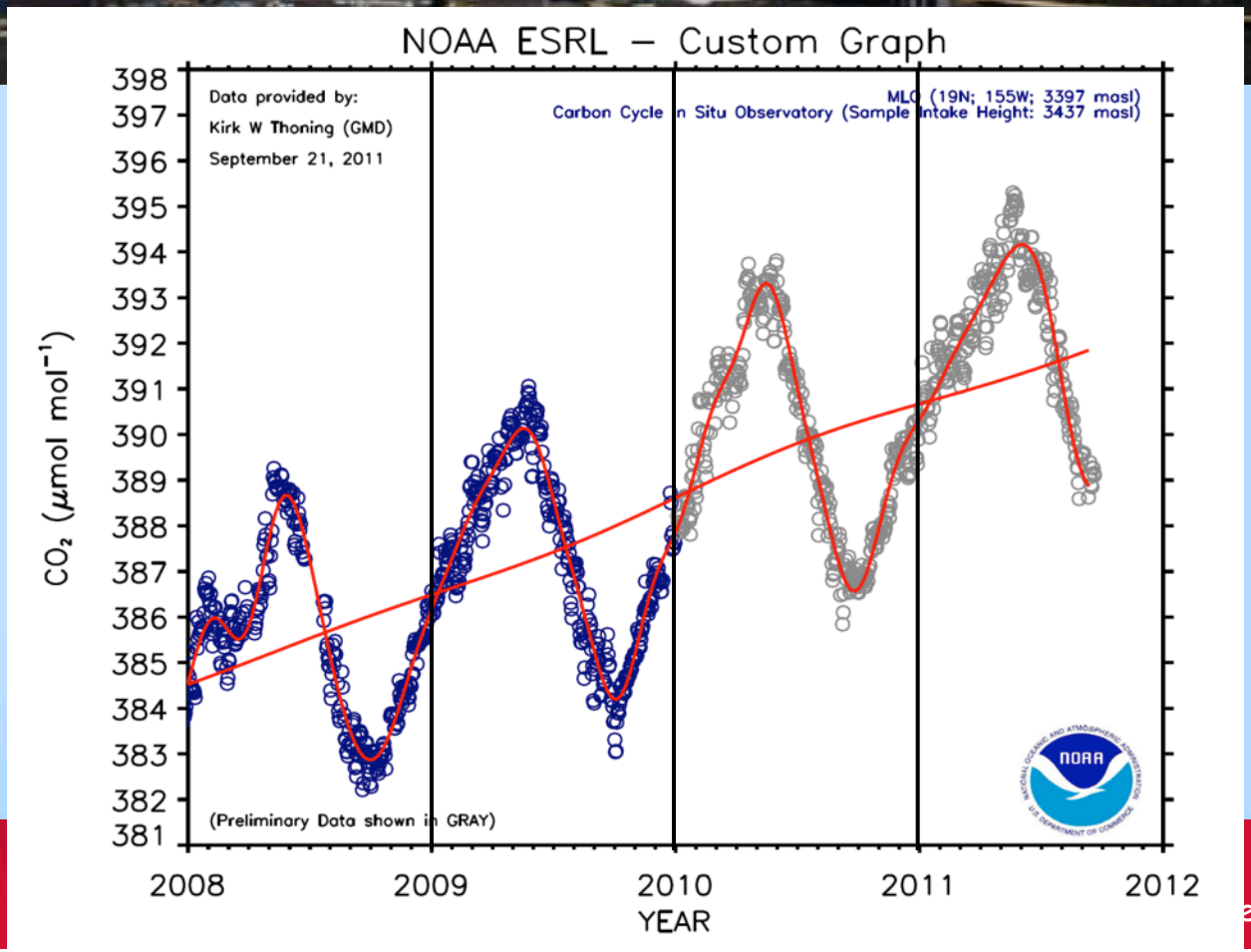

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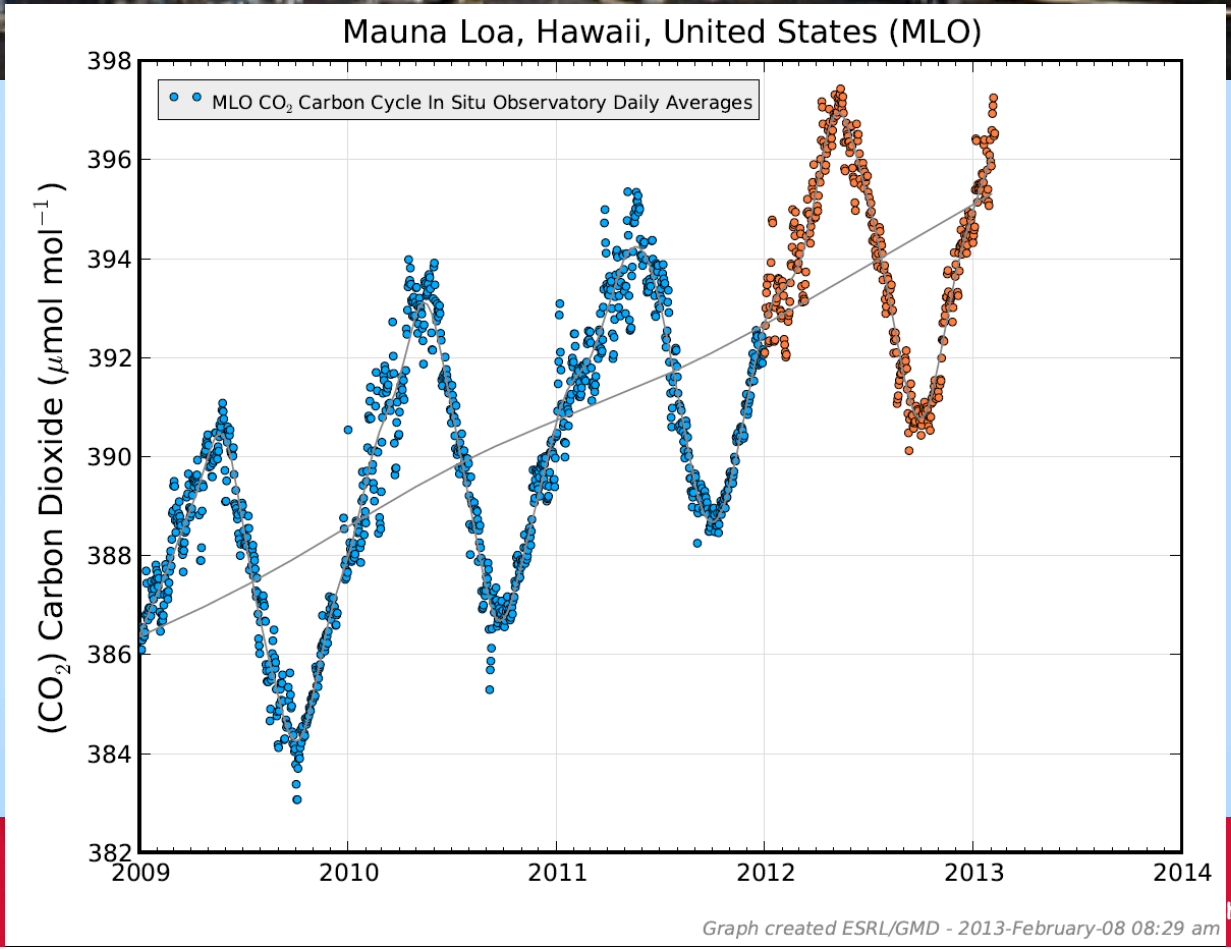

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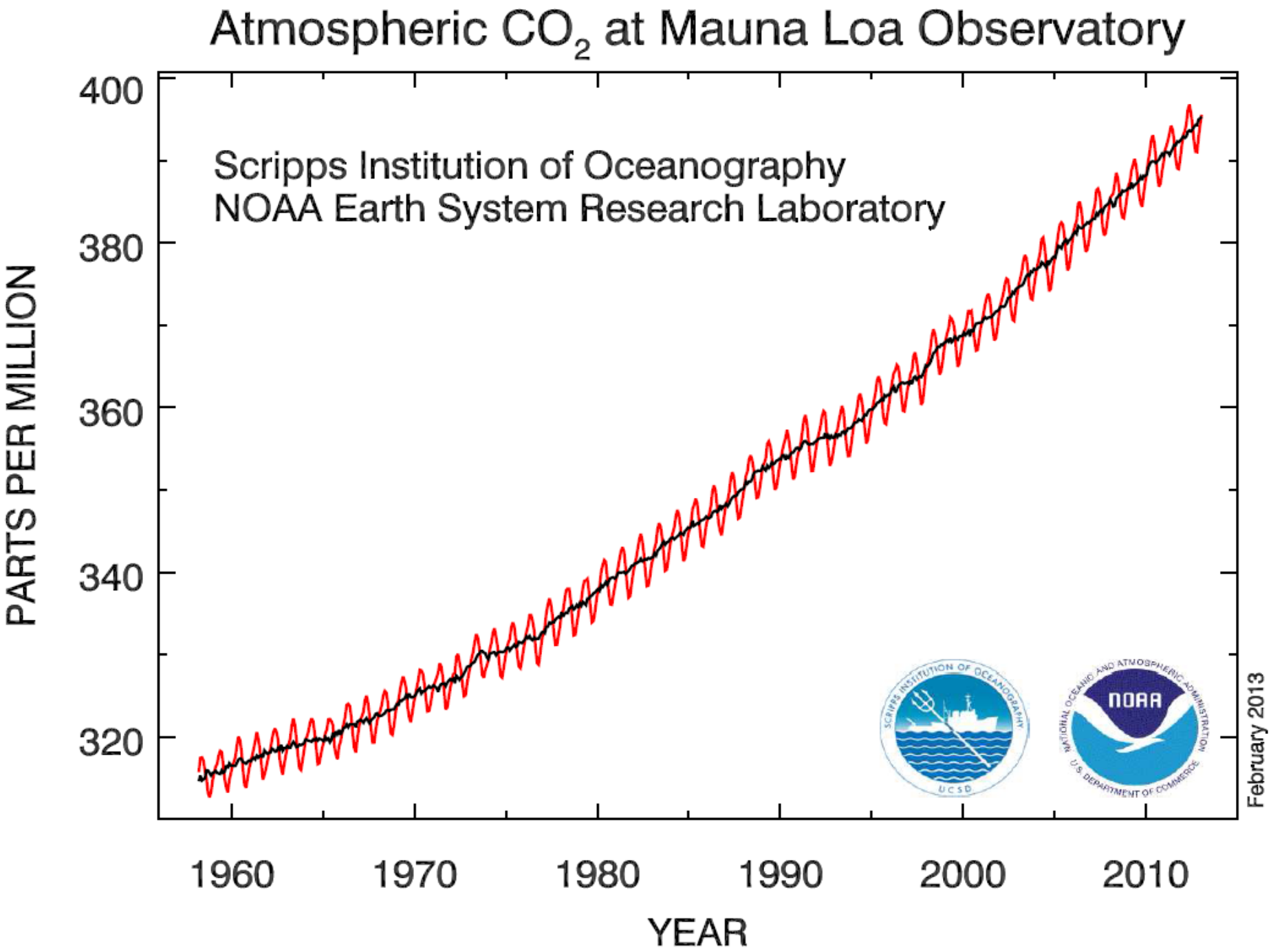

Atmospheric CO_2 at Mauna Loa Observatory
Scripps Institution of Oceanography
NOAA Earth System Research Laboratory
PARTS PER MILLION
400
380
360
340
320
1960
1970
1980
1990
2000
2010
YEAR
February 2013

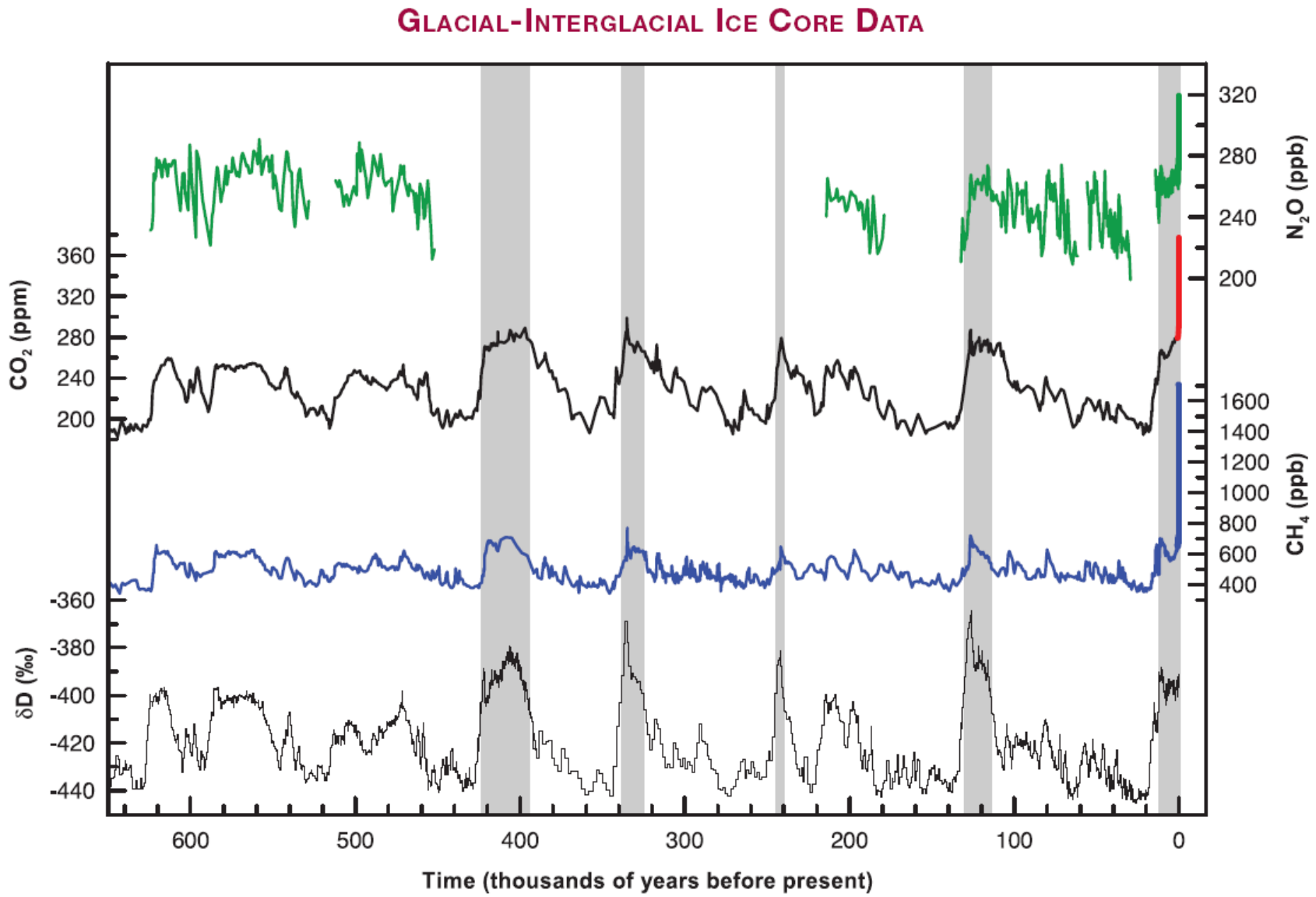
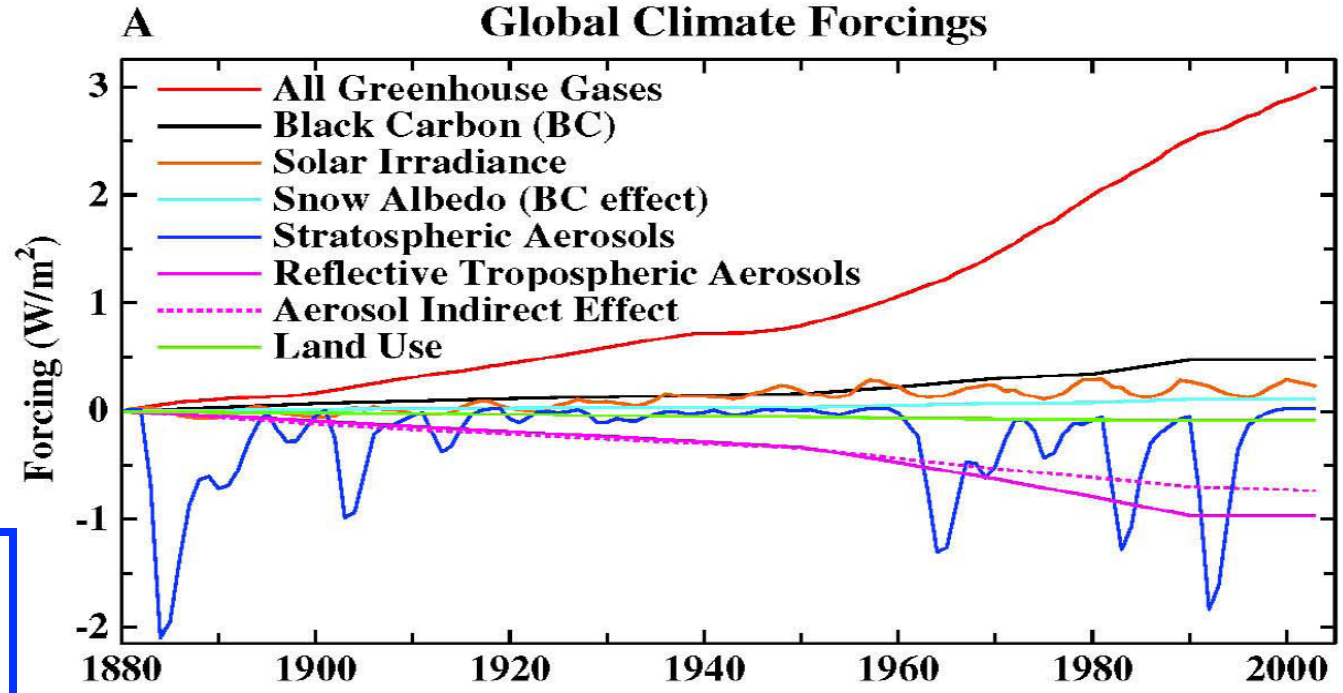


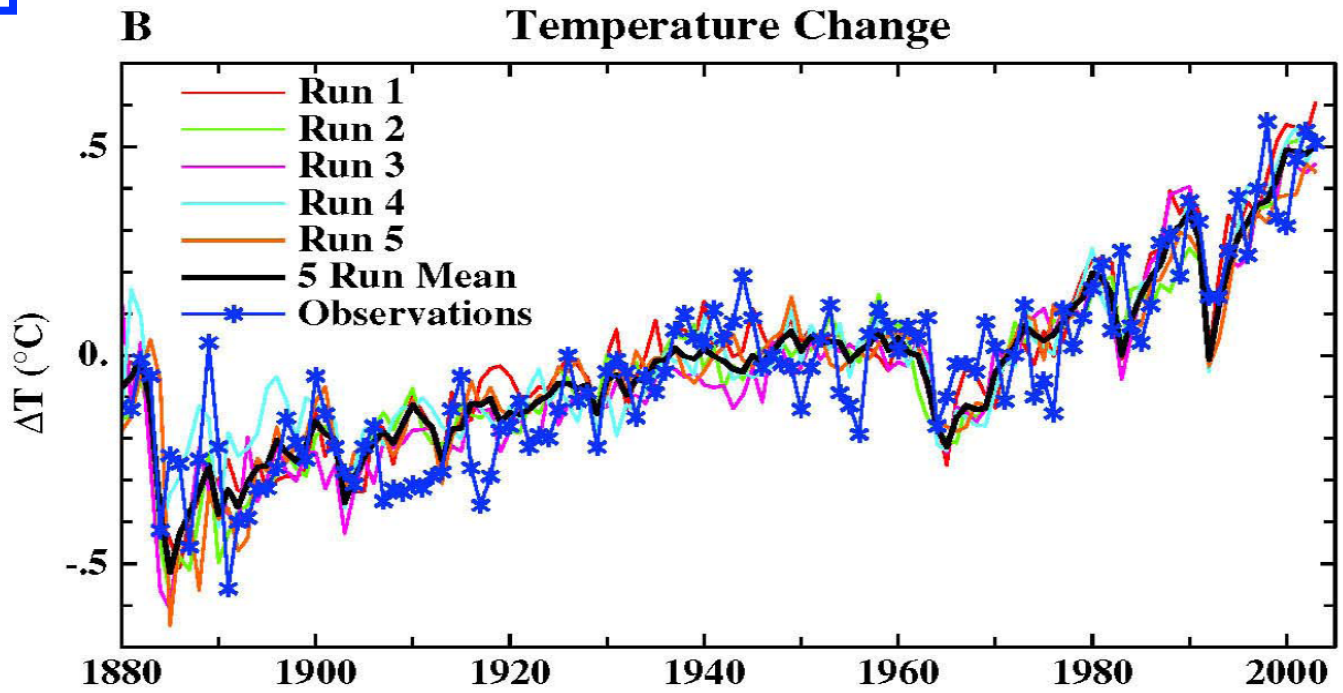
Figure TS.1. *Variations of deuterium (δD) in antarctic ice, which is a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in air trapped within the ice cores and from recent atmospheric measurements. Data cover 650,000 years and the shaded bands indicate current and previous interglacial warm periods.*

(A) Forcings used to drive climate simulations.

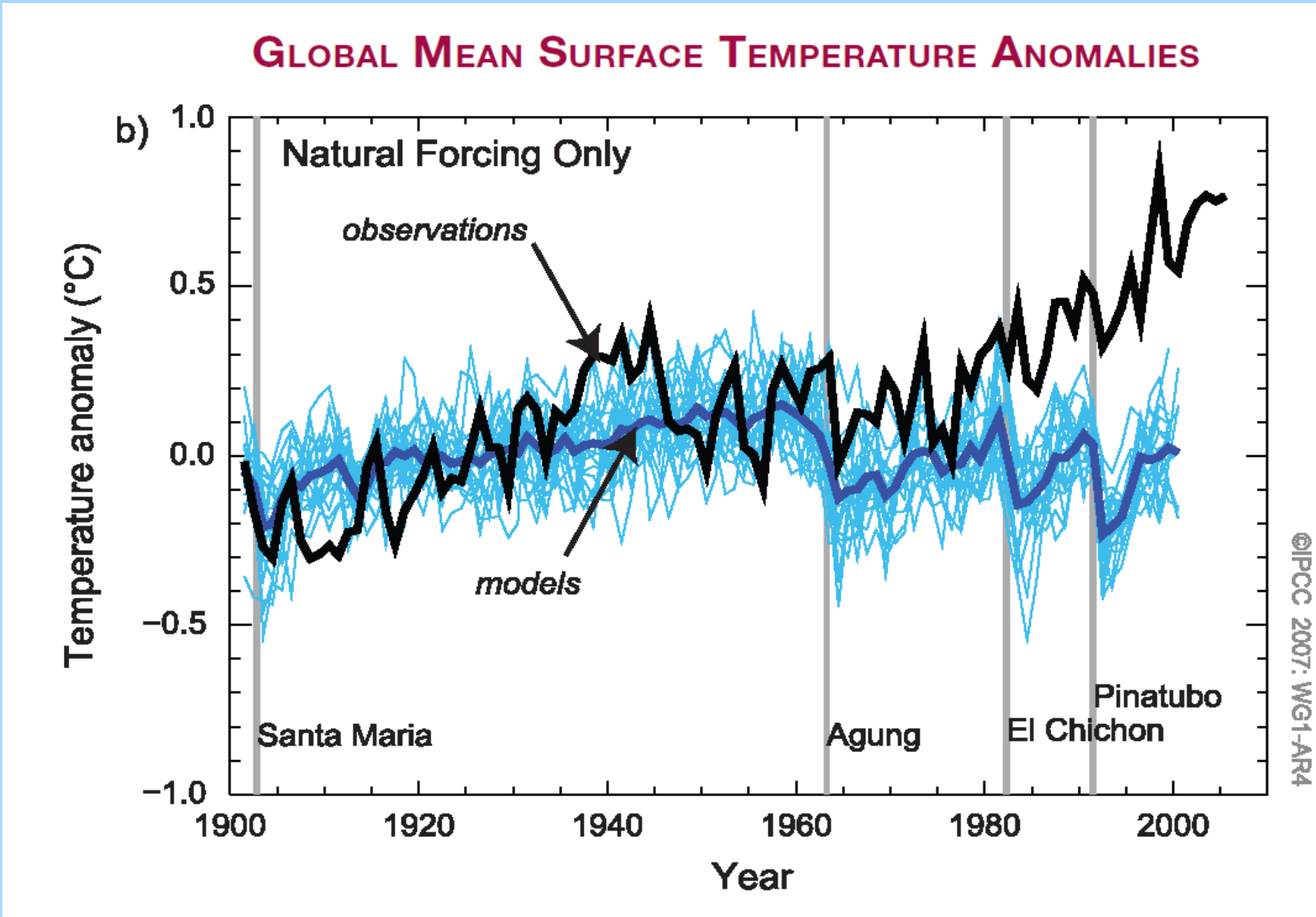
NASA GISS climate model

(B) Simulated and observed surface temperature change.





Source: Earth's energy imbalance: Confirmation and implications. *Science* **308**, 1431, 2005.



IPCC AR4 Simulations (from 13 different climate models from around the world)

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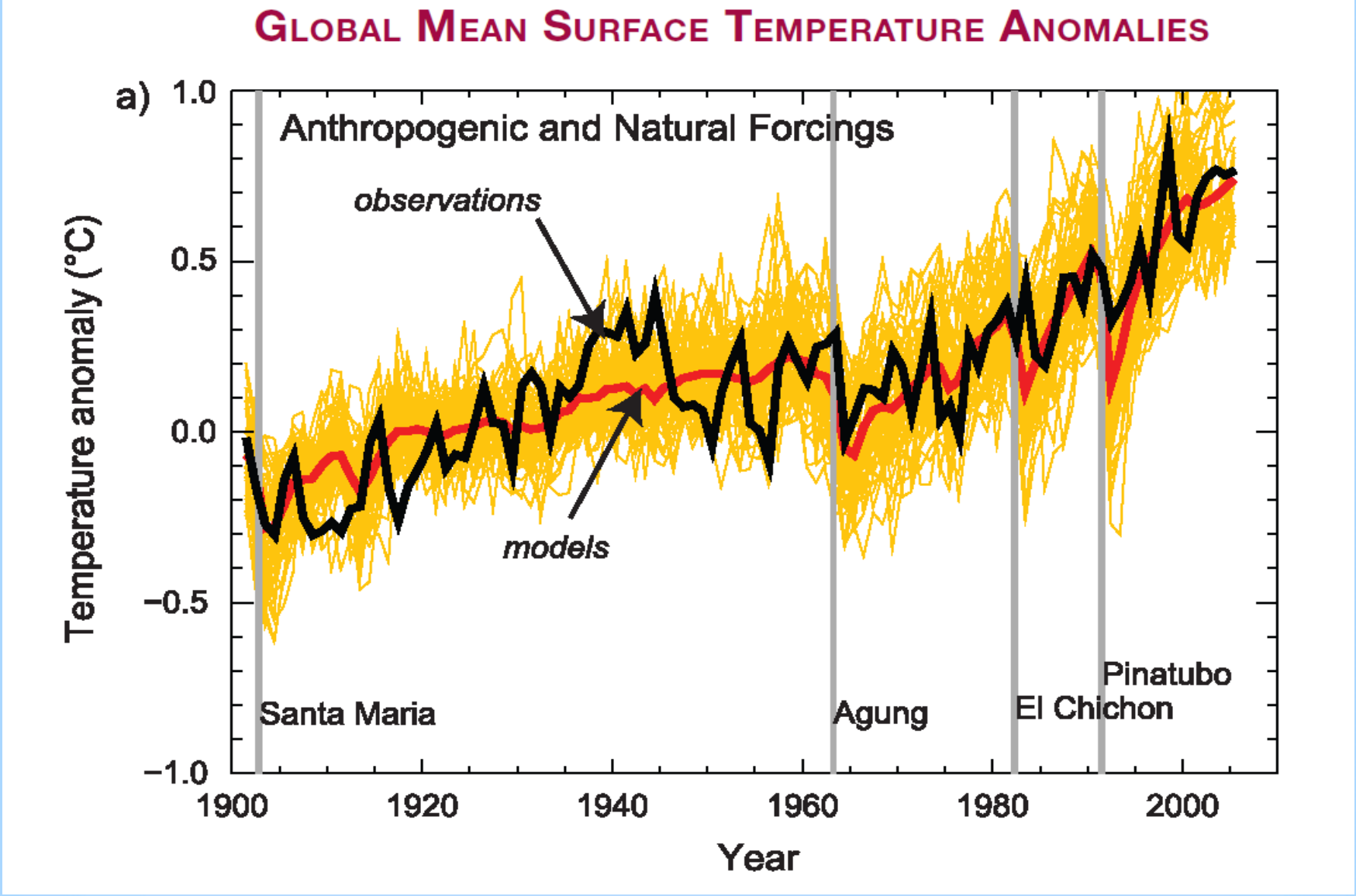

IPCC AR4 Simulations (from 13 different climate models from around the world)

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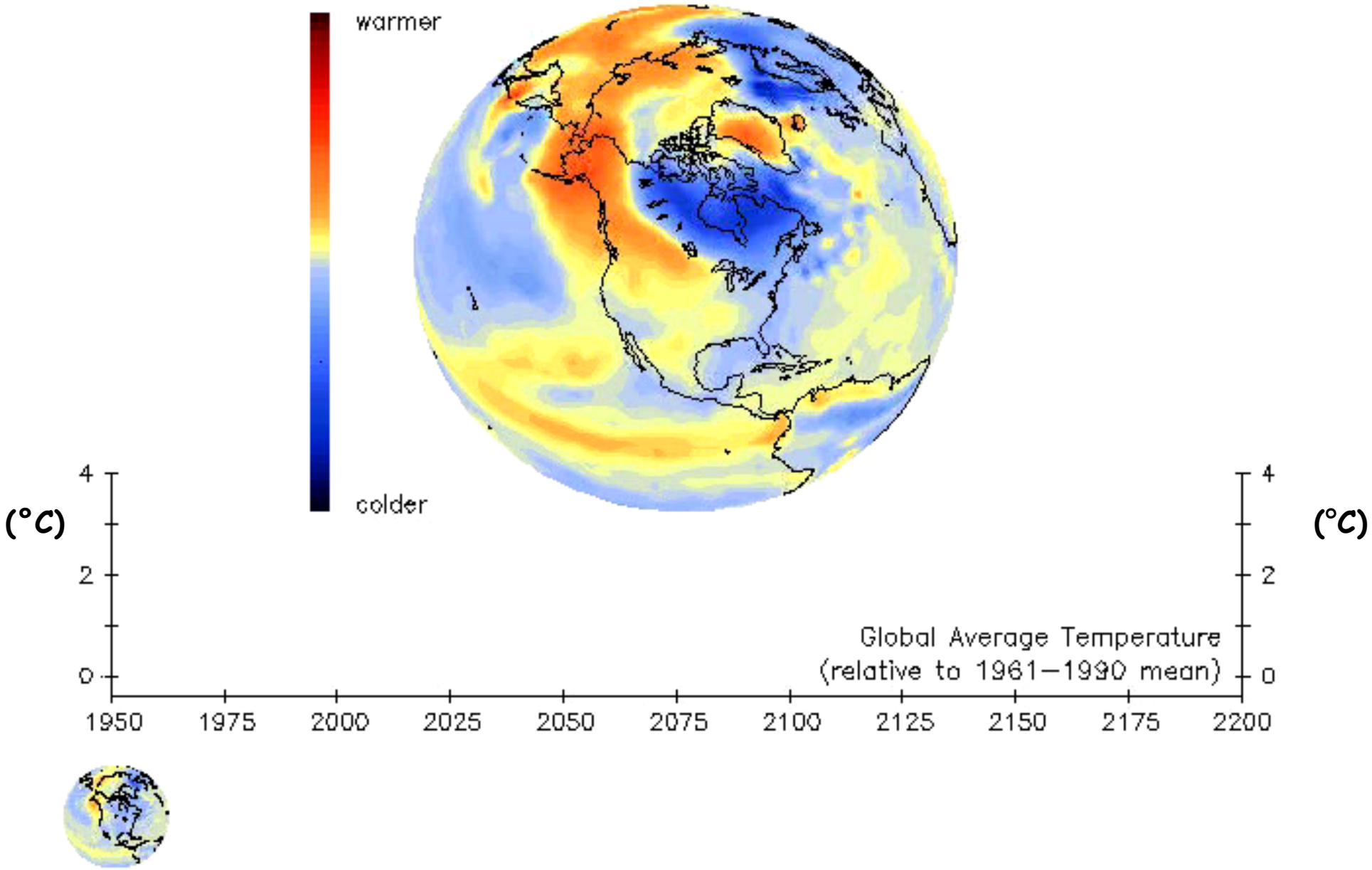
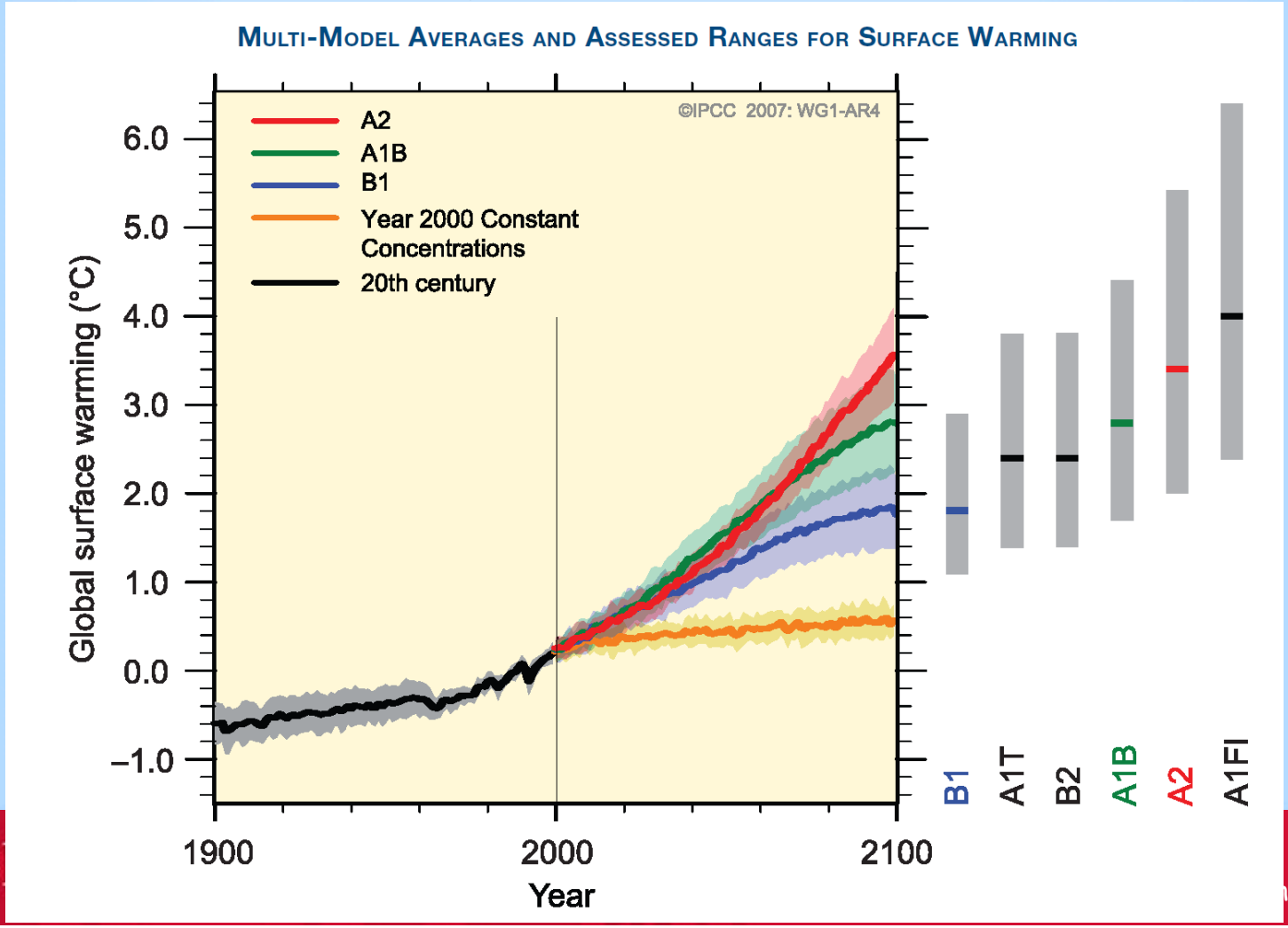
CCSM Climate "Forecasts"



"For the next two decades a warming of about 0.2°C per decade is projected for a range of SRES emission scenarios.

"Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected."



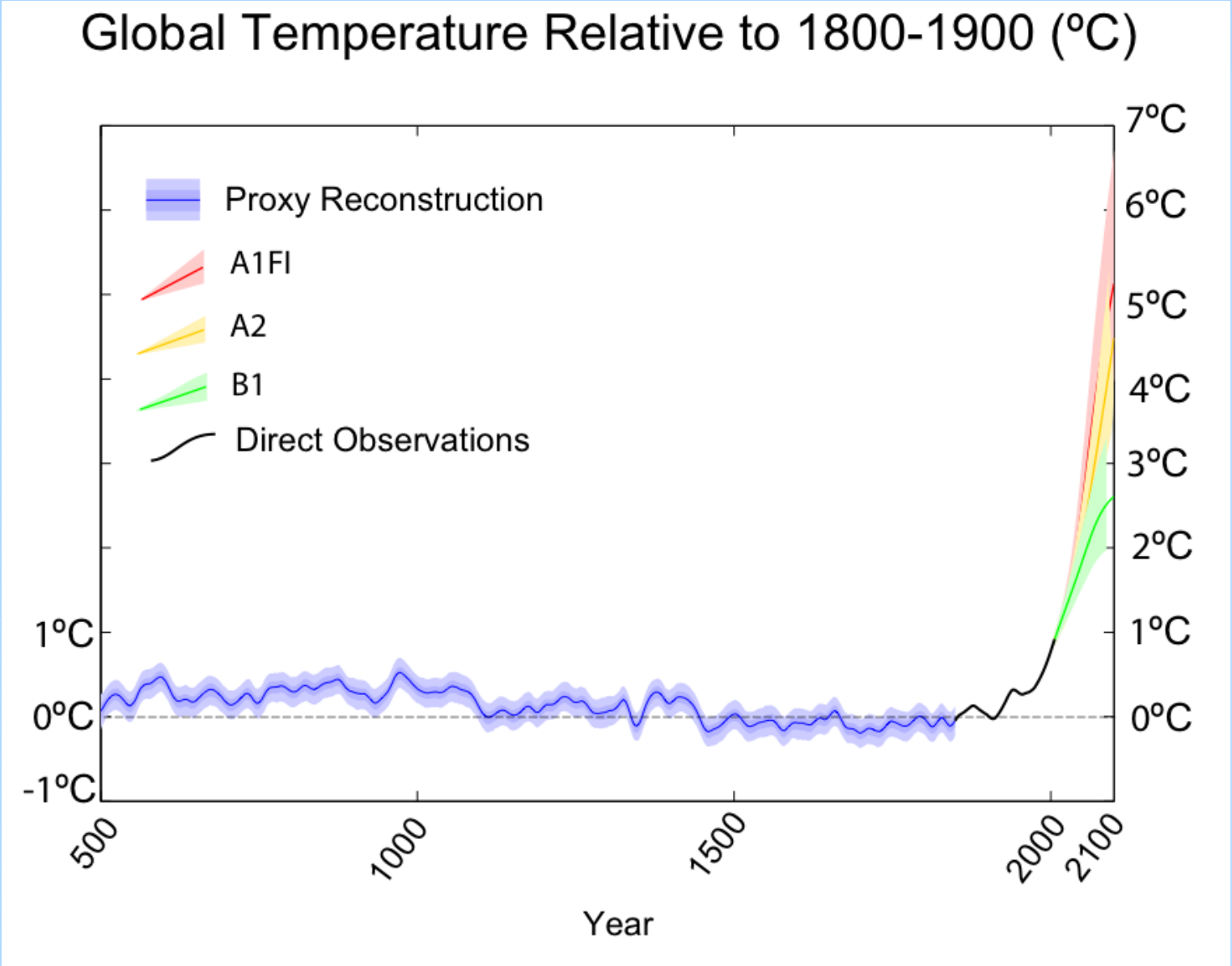


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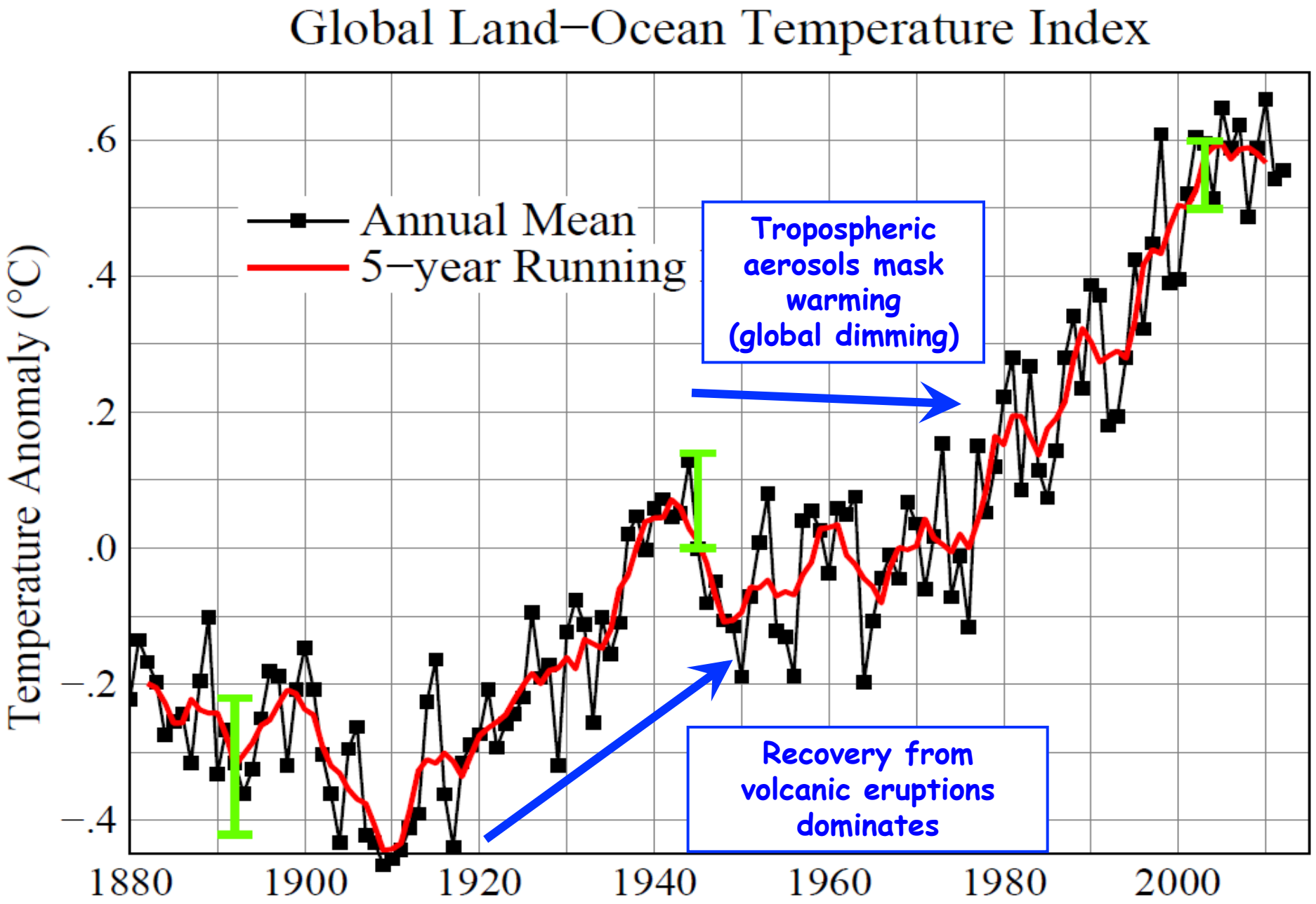
Figure 21: Reconstructed, observed and future warming projections

The Copenhagen Diagnosis

Updating the World on the Latest Climate Science


Global Land–Ocean Temperature Index
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.0
–.2
–.4
1880
1900
1920
1940
1960
1980
2000
Tropospheric aerosols mask warming (global dimming)
Recovery from volcanic eruptions dominates

Some Proposed Geoengineering Schemes:

A. Space
Modifier of solar radiation at L1 point

B. Stratospheric
Stratospheric aerosols (sulfate, soot, dust)
Stratospheric balloons or mirrors

C. Tropospheric
Modifying total reflection from marine Sc

D. Surface
Making deserts more reflective
Modifying ocean albedo

Solar Radiation Management (SRM)

Reforestation (CO_2 and evapotranspiration effects, but albedo effect causes warming)
Direct absorption of CO_2
Ocean fertilization

Carbon Capture and Sequestration (CCS)

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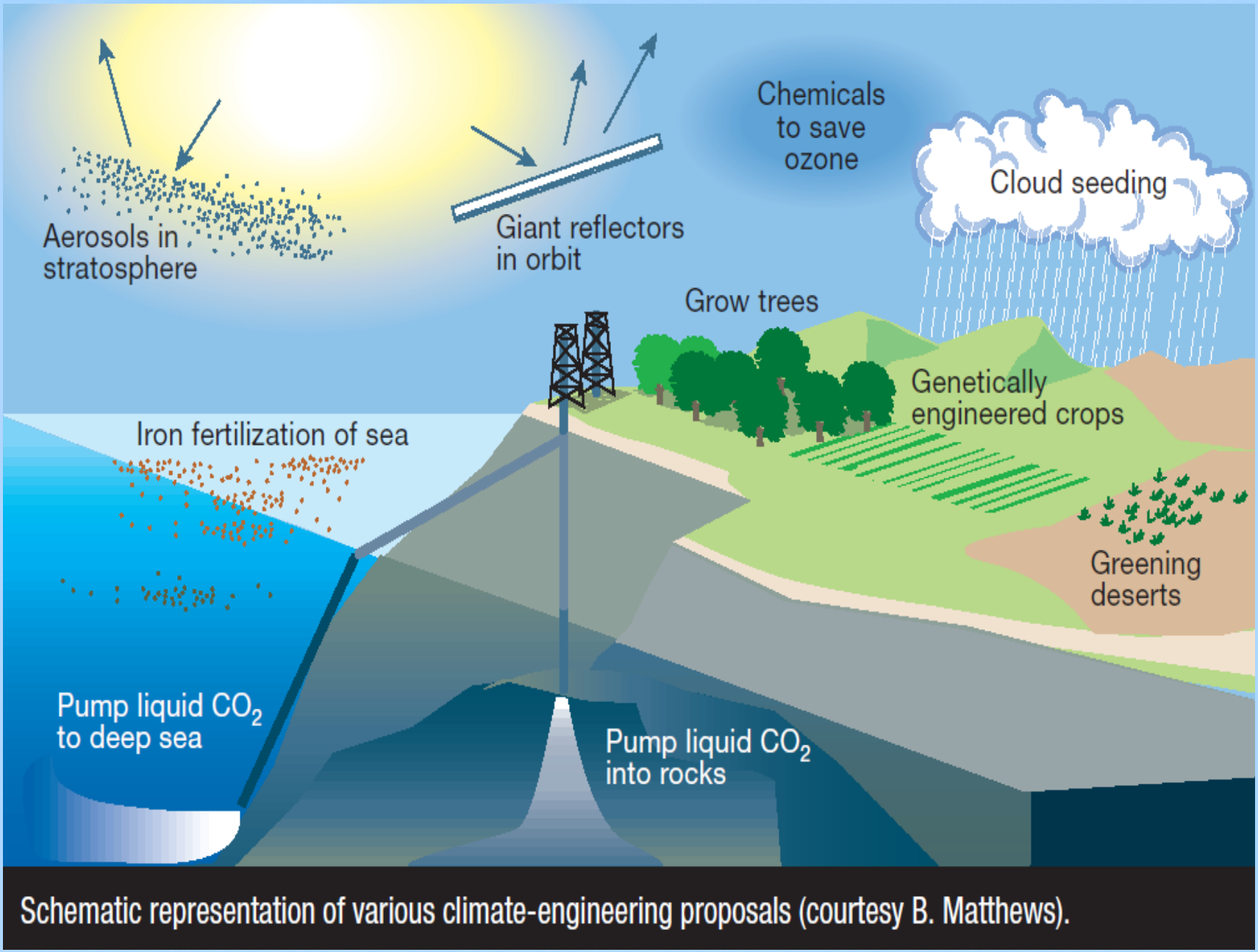

Schematic representation of various climate-engineering proposals (courtesy B. Matthews).

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

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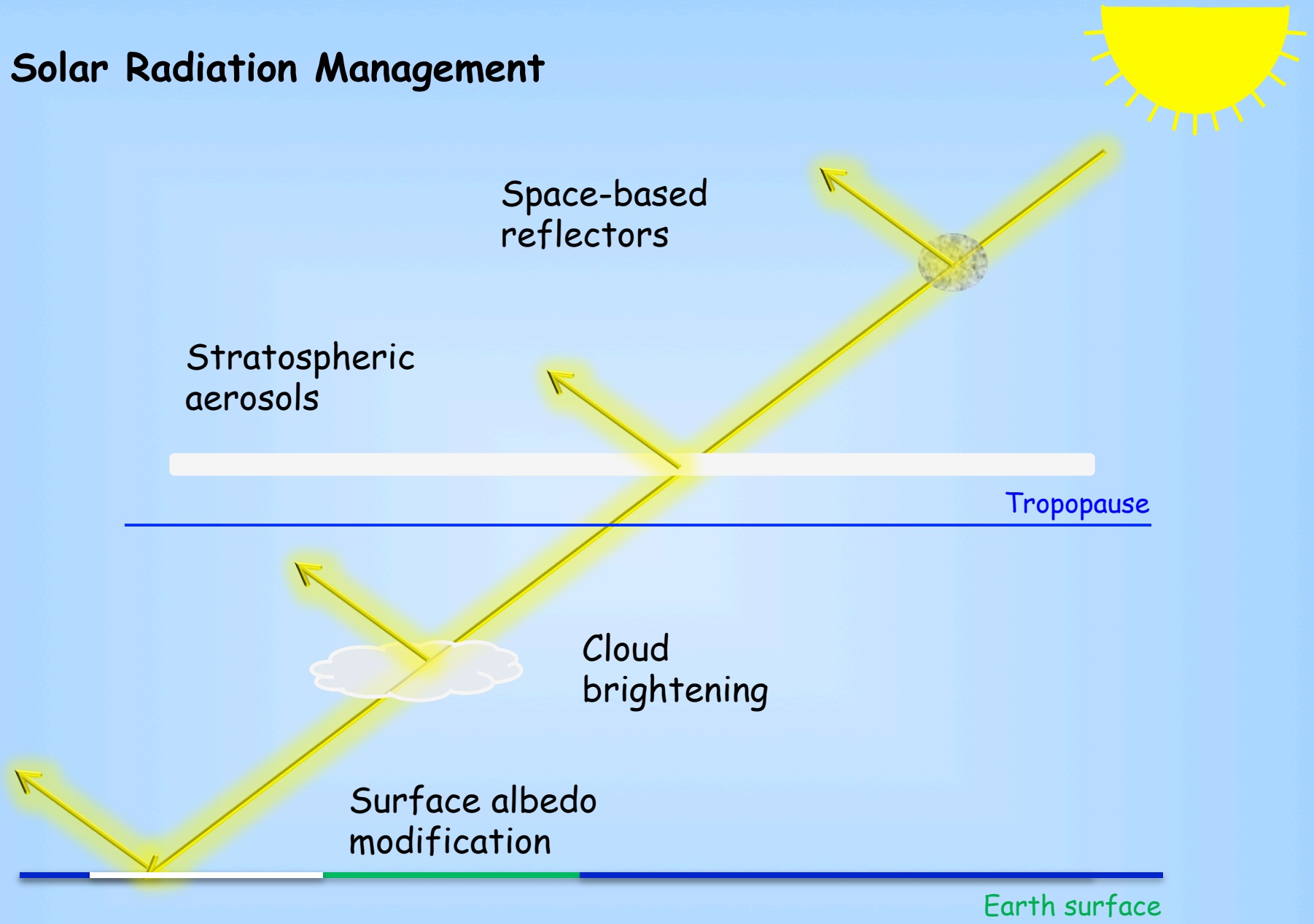
Solar Radiation Management



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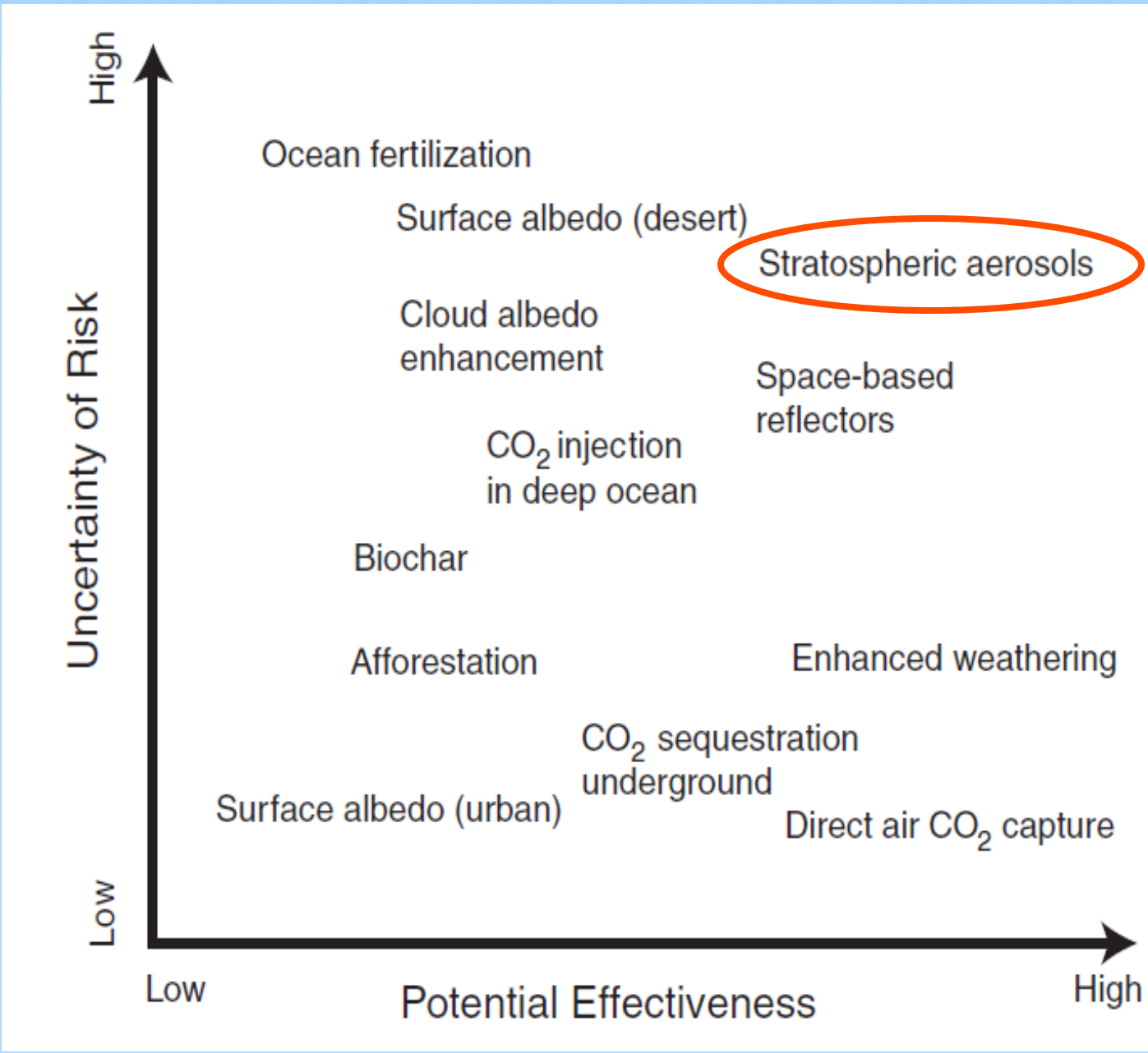

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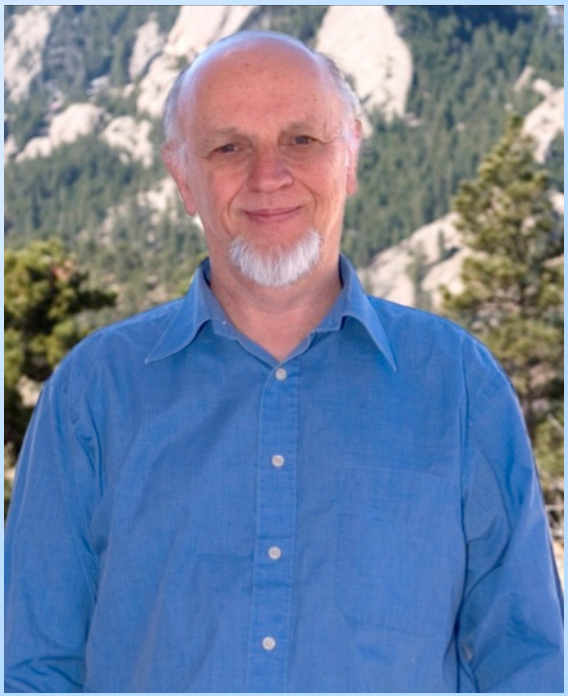
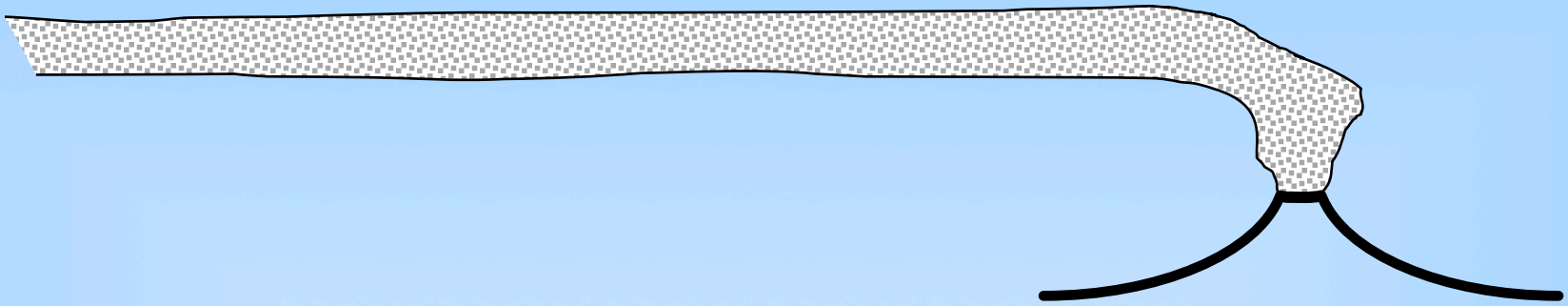
Matthews, H. Damon and Sarah E. Turner, 2009: Of mongooses and mitigation: ecological analogues to geoengineering. *Environ. Res. Lett.*, **4**, doi: 10.1088/1748-9326/4/4/045105.

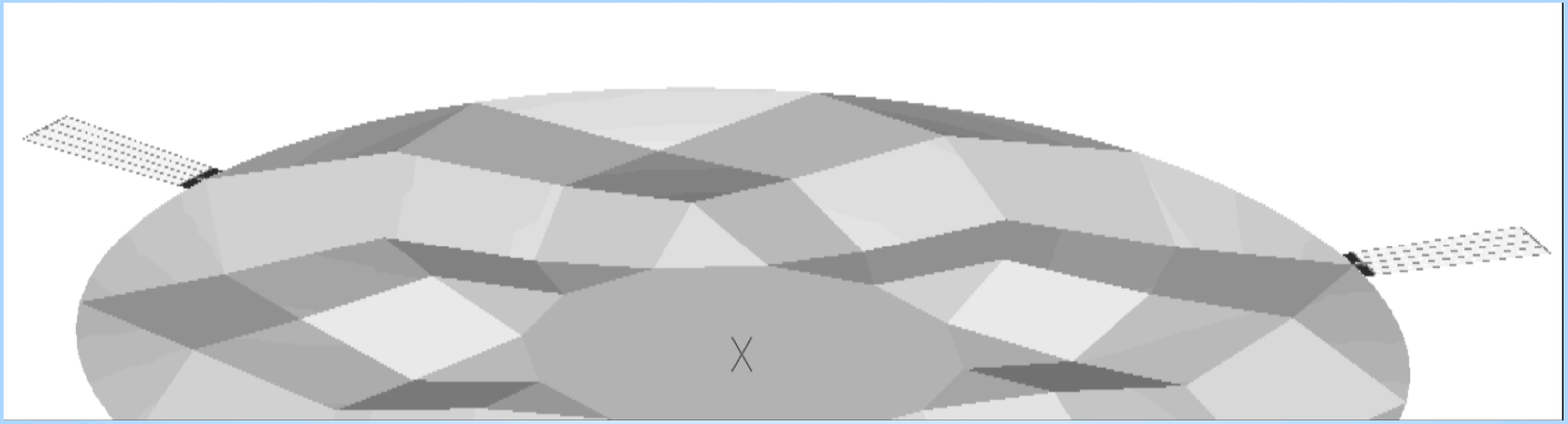
Despairing of prompt political response to global warming, in August and September 2006, Paul Crutzen (Nobel Prize in Chemistry) and Tom Wigley (NCAR) suggested that we consider temporary geoengineering as an emergency response.





This talk focuses on injecting sulfate aerosol precursors into the stratosphere to reduce insolation to counter global warming, which brings up the question:

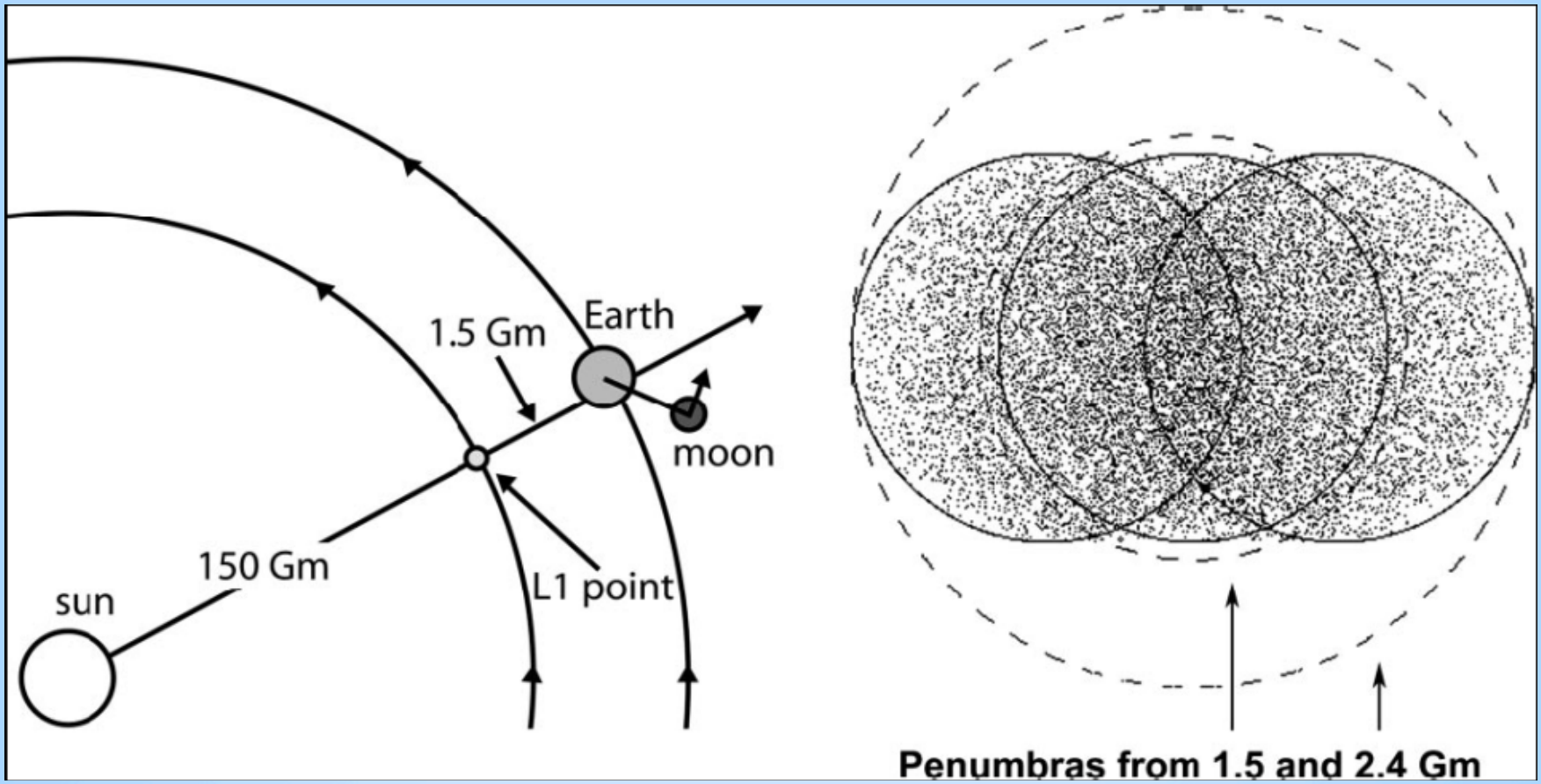
Are volcanic eruptions an innocuous example that can be used to demonstrate the safety of geoengineering? **No.**



Flyer concept. The 0.6 m diameter, 5 μm thick refracting disc is faceted to improve stiffness. The three 100 μm thick tabs have 2% of the disc area, and contain the MEMS solar sails, tracker cameras, control electronics and solar cells.

He envisions over a 10-yr period, vertical 2-km magnetic launchers with 800,000 flyers each, every 5 min from 20 sites simultaneously to put 20 Mt of flyers into orbit.

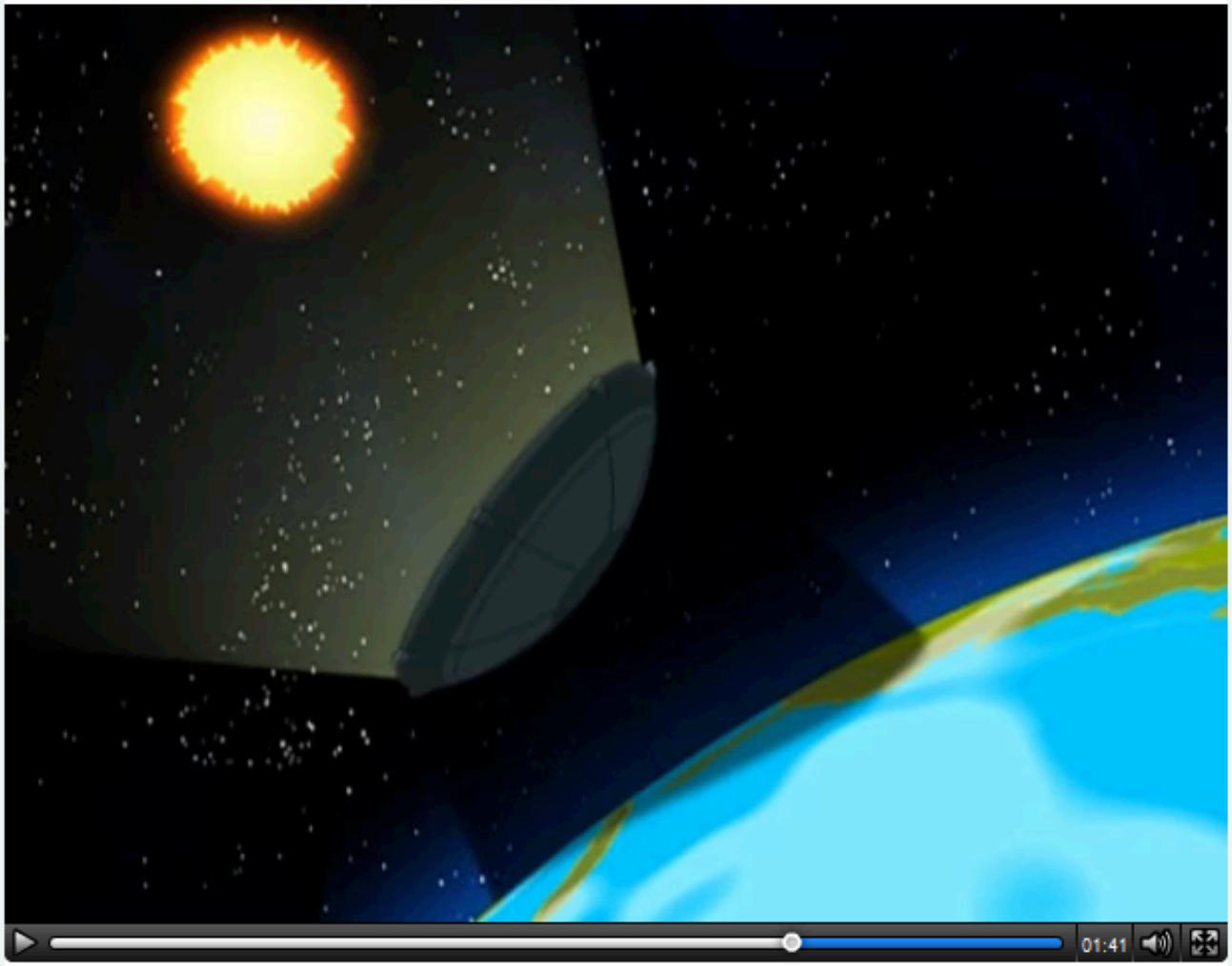
Angel, Roger, 2006: Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proc. Nat. Acad. Sci.*, **103**, 17,184-17,189.



Angel, Roger, 2006: Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proc. Nat. Acad. Sci.*, **103**, 17,184-17,189.

And then on *Futurama*...

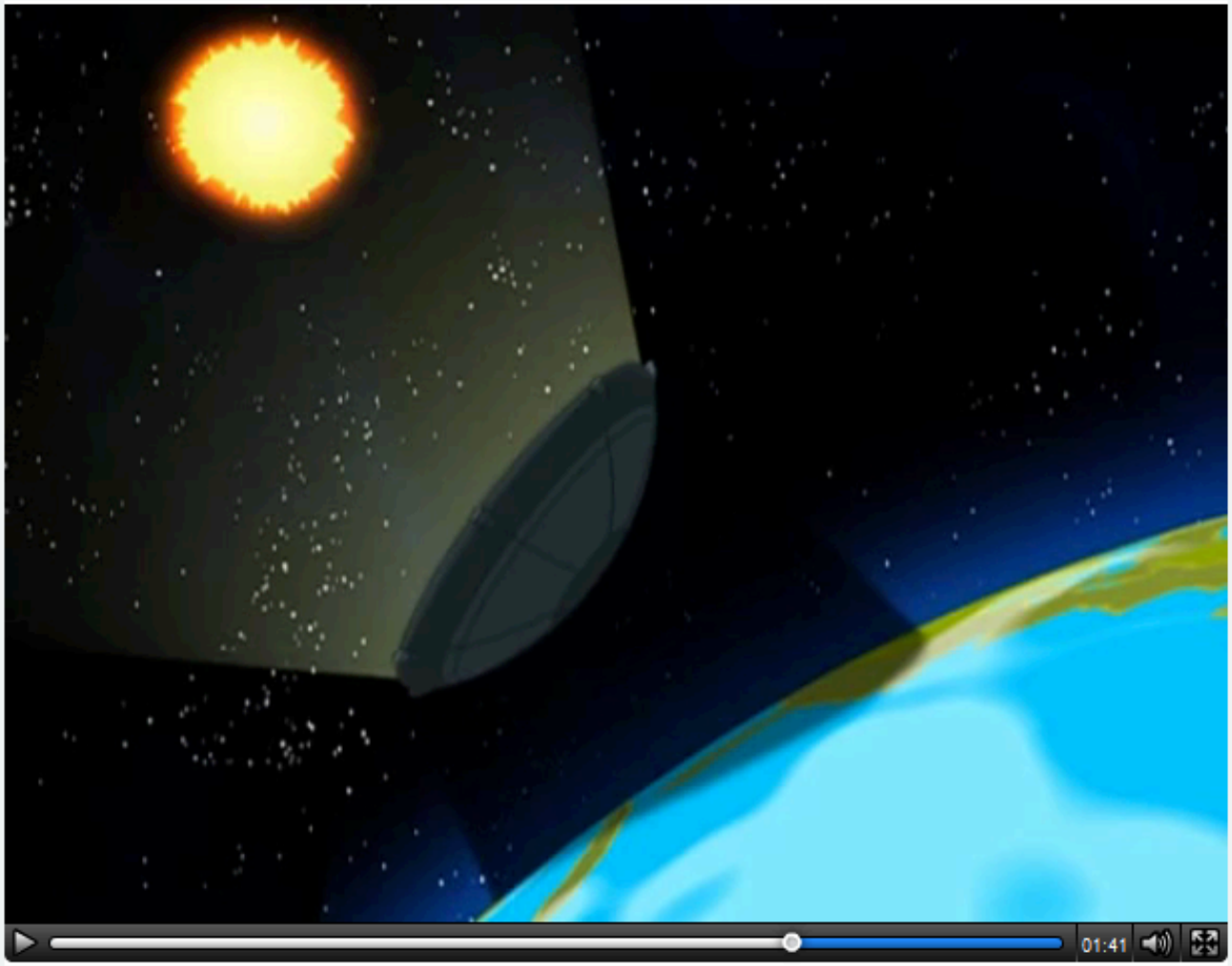
From Web



http://io9.com/5665736/blotting-out-the-sun-to-slow-down-global-warming-could-be-outlawed

And then on *Futurama*...

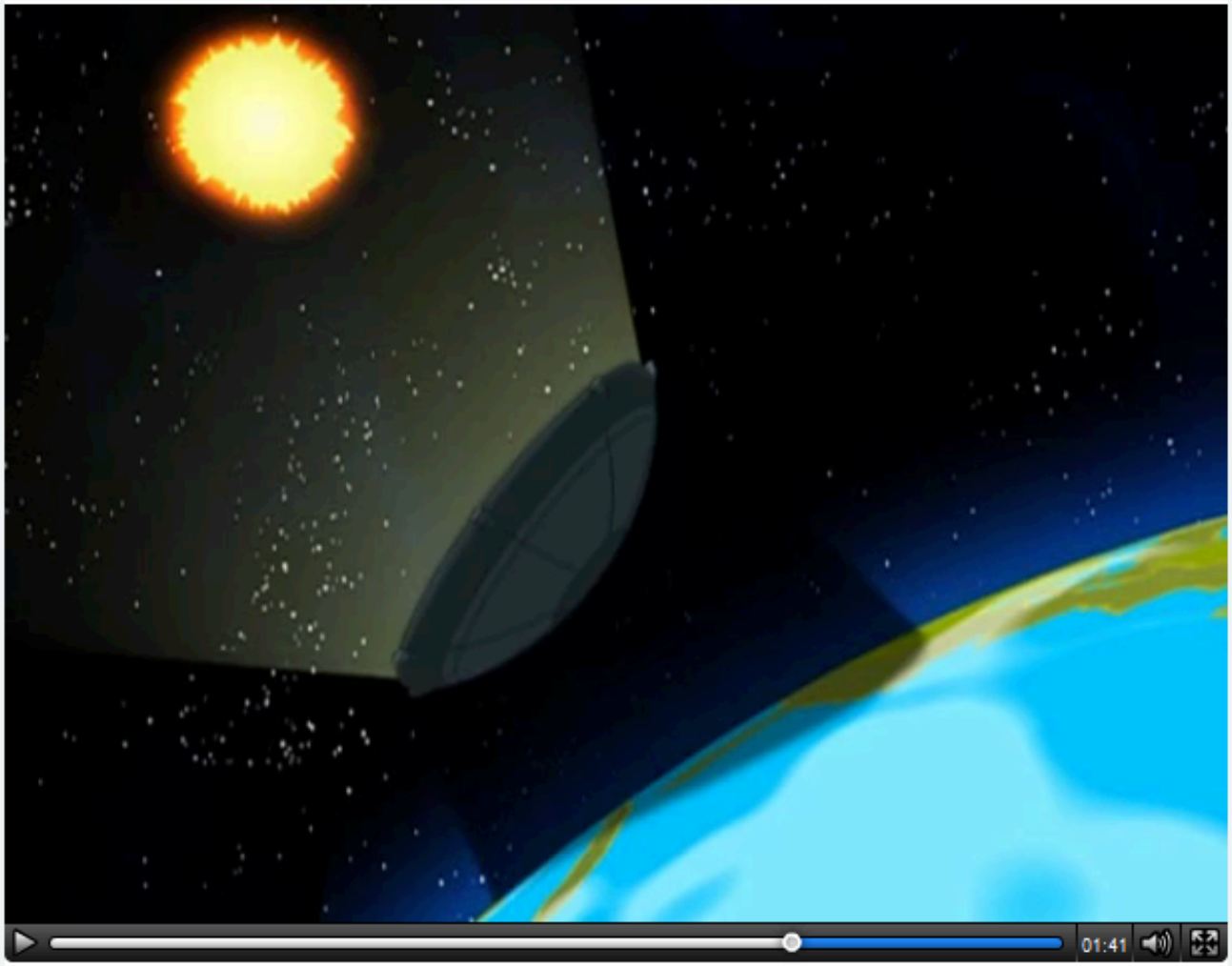
RealPlayer



http://io9.com/5665736/blotting-out-the-sun-to-slow-down-global-warming-could-be-outlawed

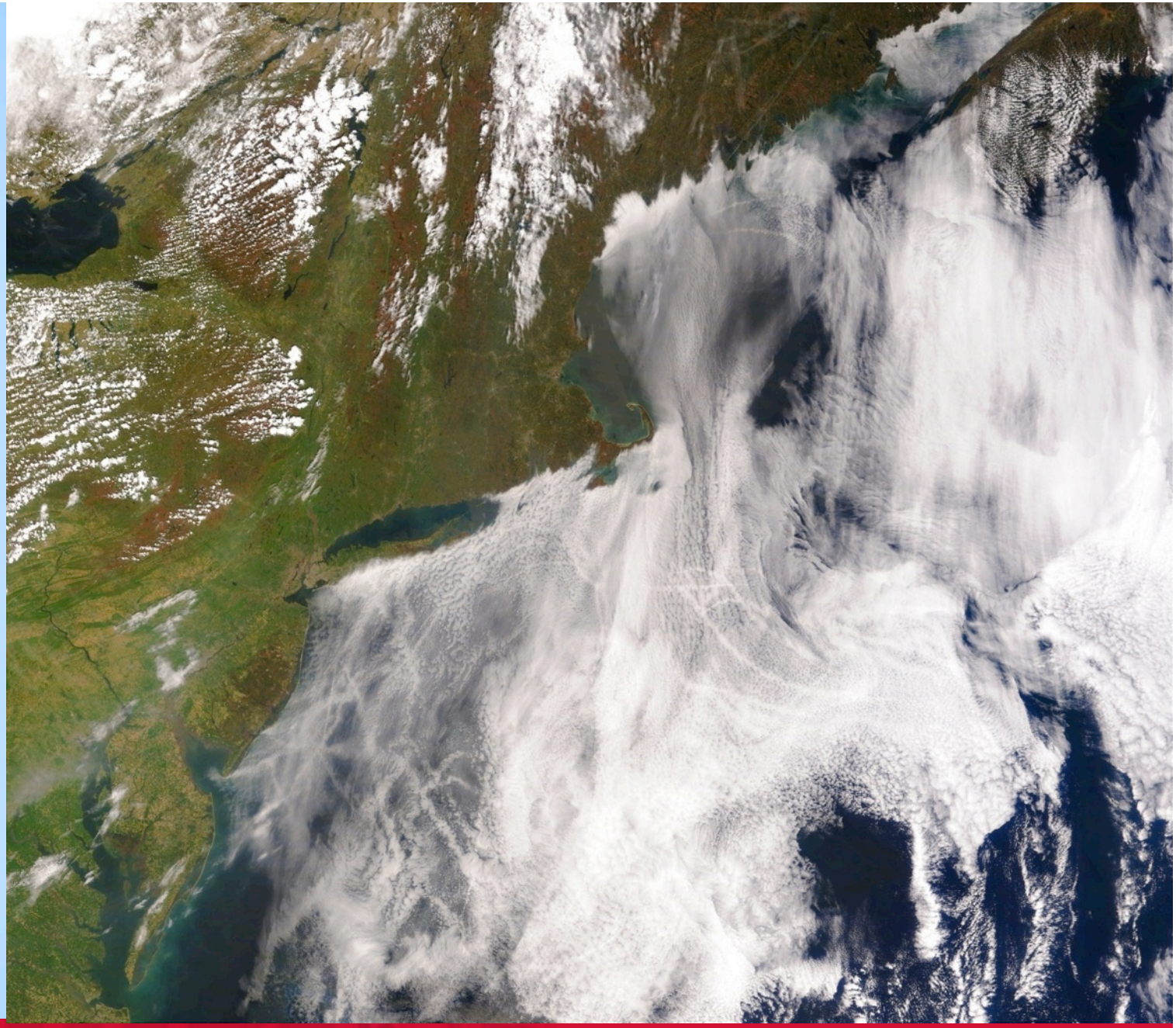
And then on *Futurama*...

Media Player



http://io9.com/5665736/blotting-out-the-sun-to-slow-down-global-warming-could-be-outlawed

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



http://eobglossary.gsfc.nasa.gov/Newsroom/NewImages/Images/ShipTracks_TMO_2005131_lrg.jpg

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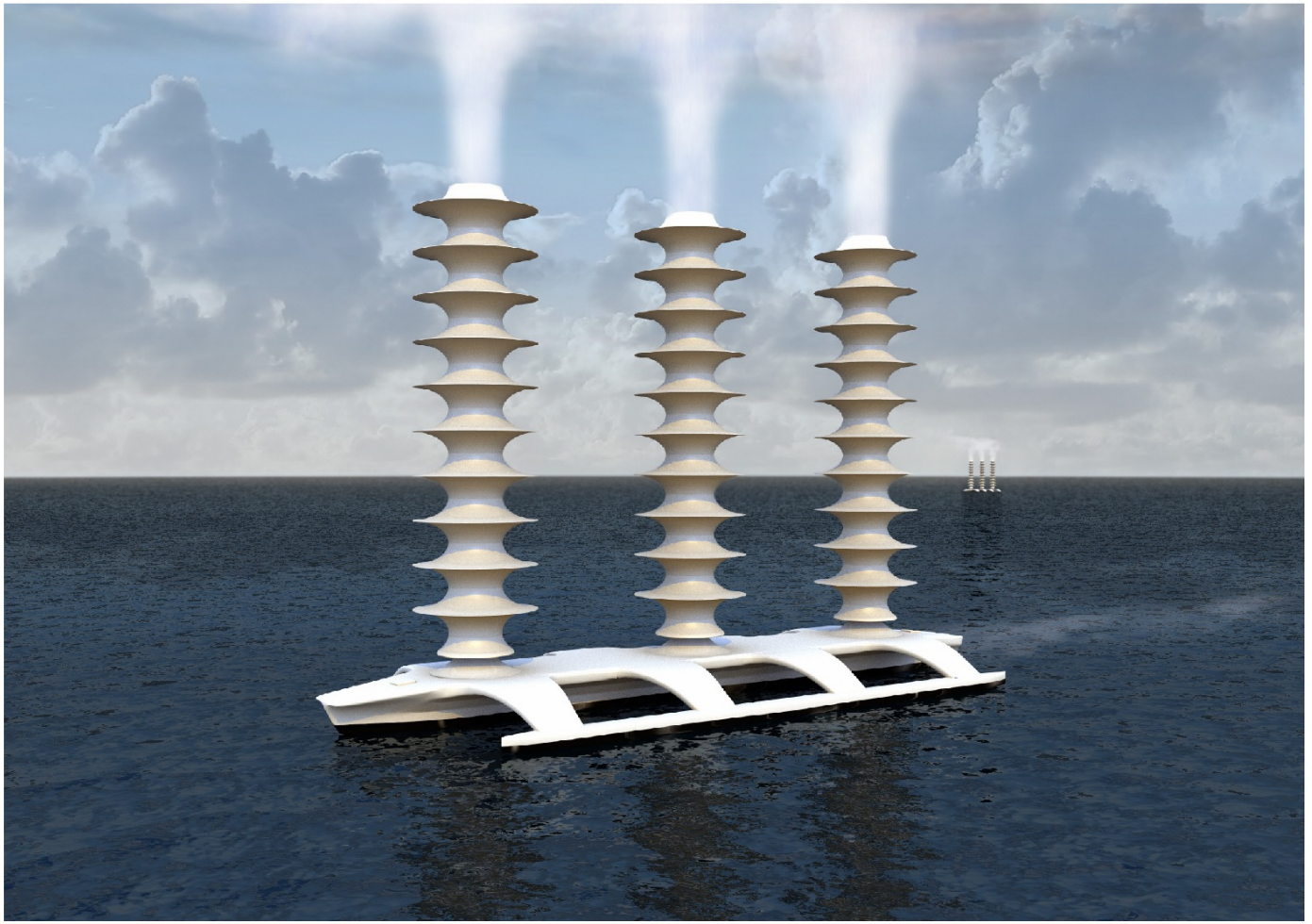
Scheme by John Latham (University of Manchester, NCAR) and Steve Salter (University of Edinburgh) to increasing cloud albedo with by injecting more sea salt cloud condensation nuclei into marine stratus clouds.



RUTGERS

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

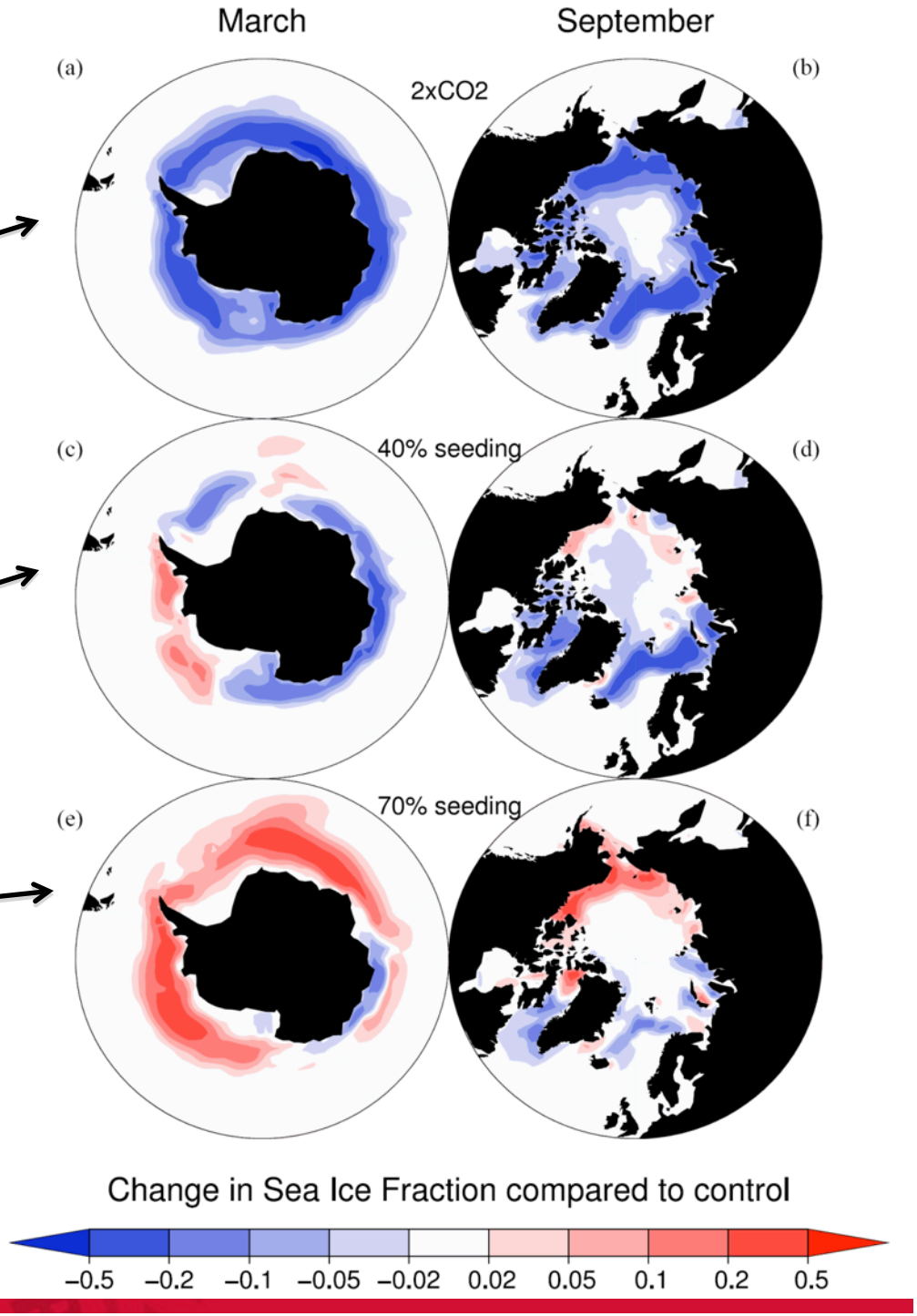
Sea ice is affected by global warming and geoengineering

Summer sea ice goes away with a doubling of CO_2

Ice returns with geoengineering

It is possible to overdo the effect

Rasch et al. (2009)



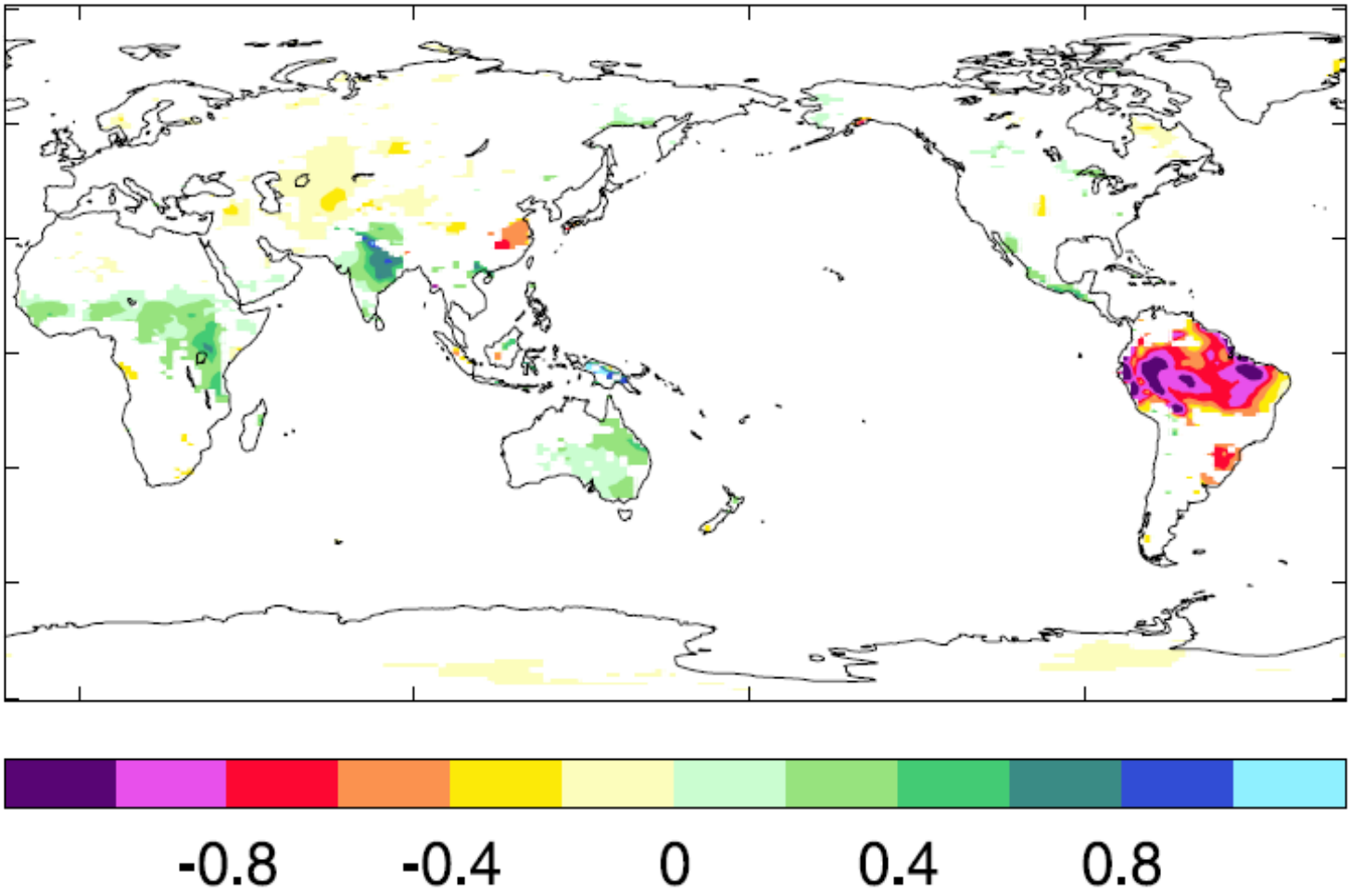


Figure 4. Mean 2030–2059 land precipitation (mm day^{-1}): ALL – A1B. Land areas in Figure 4b where the change is not statistically significant at the 5% level are in white.

Precipitation change for geoengineering with brighter marine stratocumulus clouds.

Damage to Amazon would not be reversible.

(Jones et al., 2009)

Jones, Andy, Jim Haywood, and Olivier Boucher (2009), Climate impacts of geoengineering marine stratocumulus clouds, *J. Geophys. Res.*, **114**, D10106, doi:10.1029/2008JD011450.

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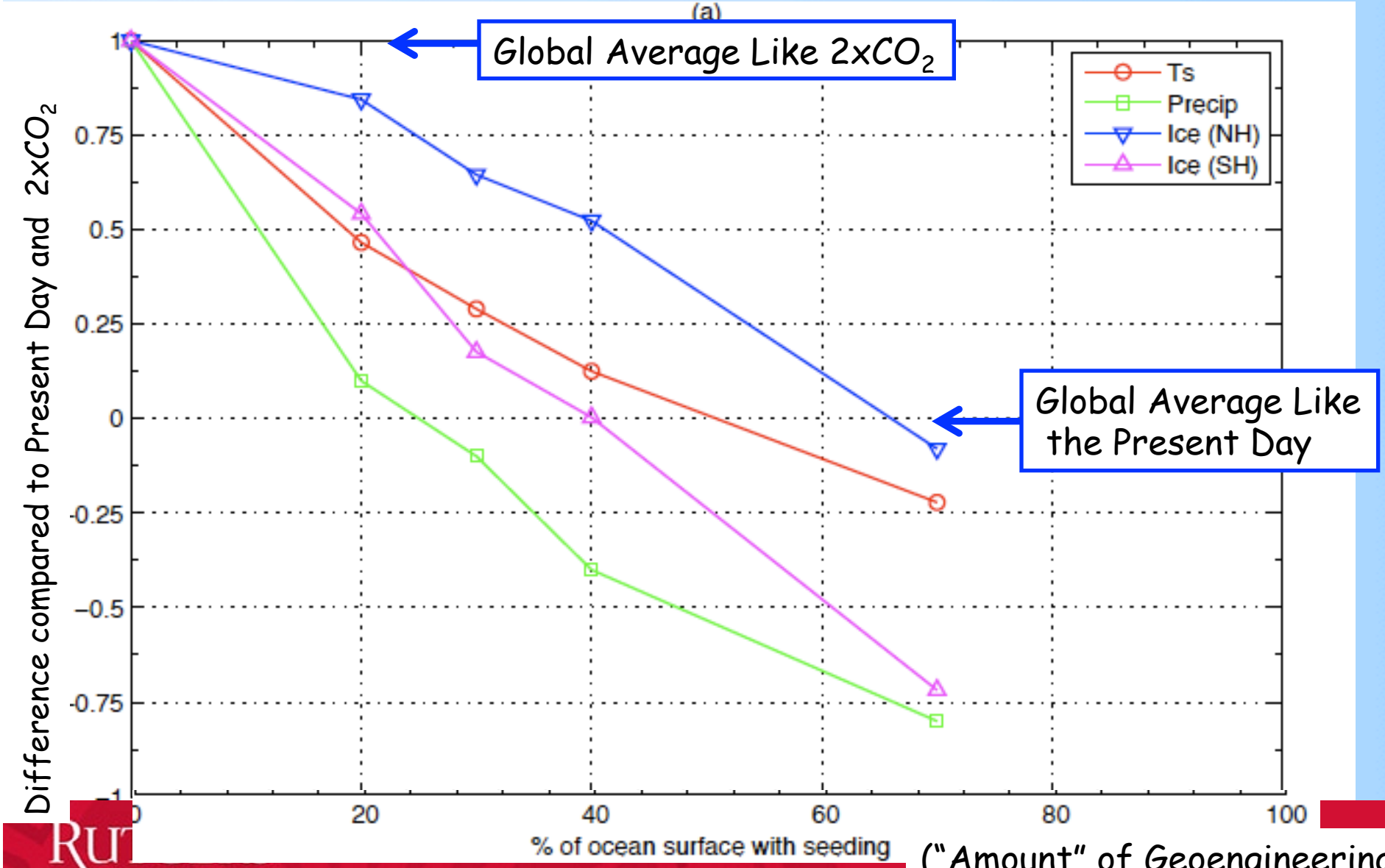
SRM will not operate "uniformly" (even for global averages) (Rasch et al., 2009)



("Amount" of Geoengineering)

Making the surface brighter?

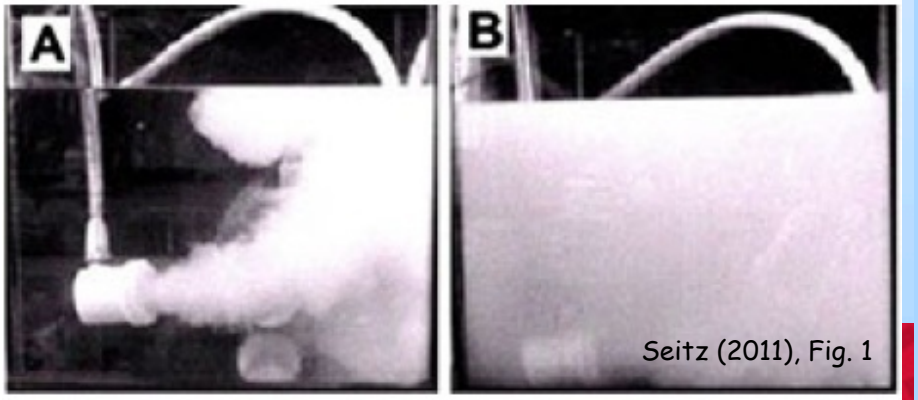
http://www.treehugger.com/white-roof.jpg

Oleson et al. (2010) found minimal global impacts of urban white roofs.

Oleson, K., G. Bonan, and J. Feddema, 2010: Effects of white roofs on urban temperature in a global climate model, *Geophys. Res. Lett.*, **37**, L03701, doi:10.1029/2009GL042194.

Doughty et al. (2011) found leaf brightening would have minimal effect.

Doughty, C. E., C.B. Field, and A. M. S. McMillan, 2011: Can crop albedo be increased through the modification of leaf trichomes, and could this cool regional climate? *Climatic Change*, **104**, 379–387, doi: 10.1007/s10584-010-9936-0



Seitz (2011), Fig. 1

Seitz (2011) proposed bubbles to brighten the ocean, but Robock (2011) found many issues with proposal.

Seitz, R., 2011: Bright water: hydrosols, water conservation and climate change. *Climatic Change*, **105**, 365-381, doi:10.1007/s10584-010-9965-8.

Robock, Alan, 2011: Bubble, bubble, toil and trouble. An editorial comment. *Climatic Change*, **105**, 383-385, doi:10.1007/s10584-010-0017-1.

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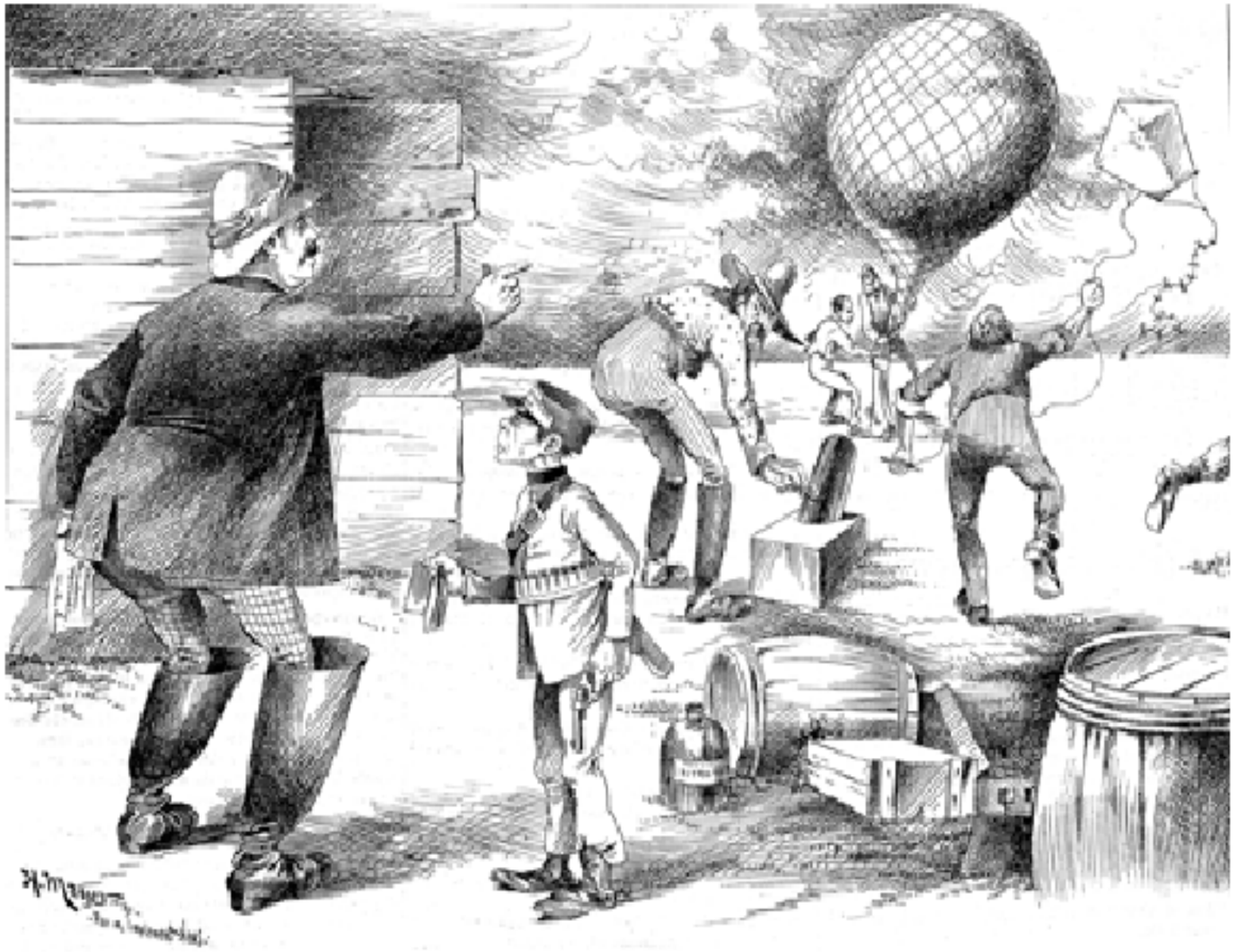
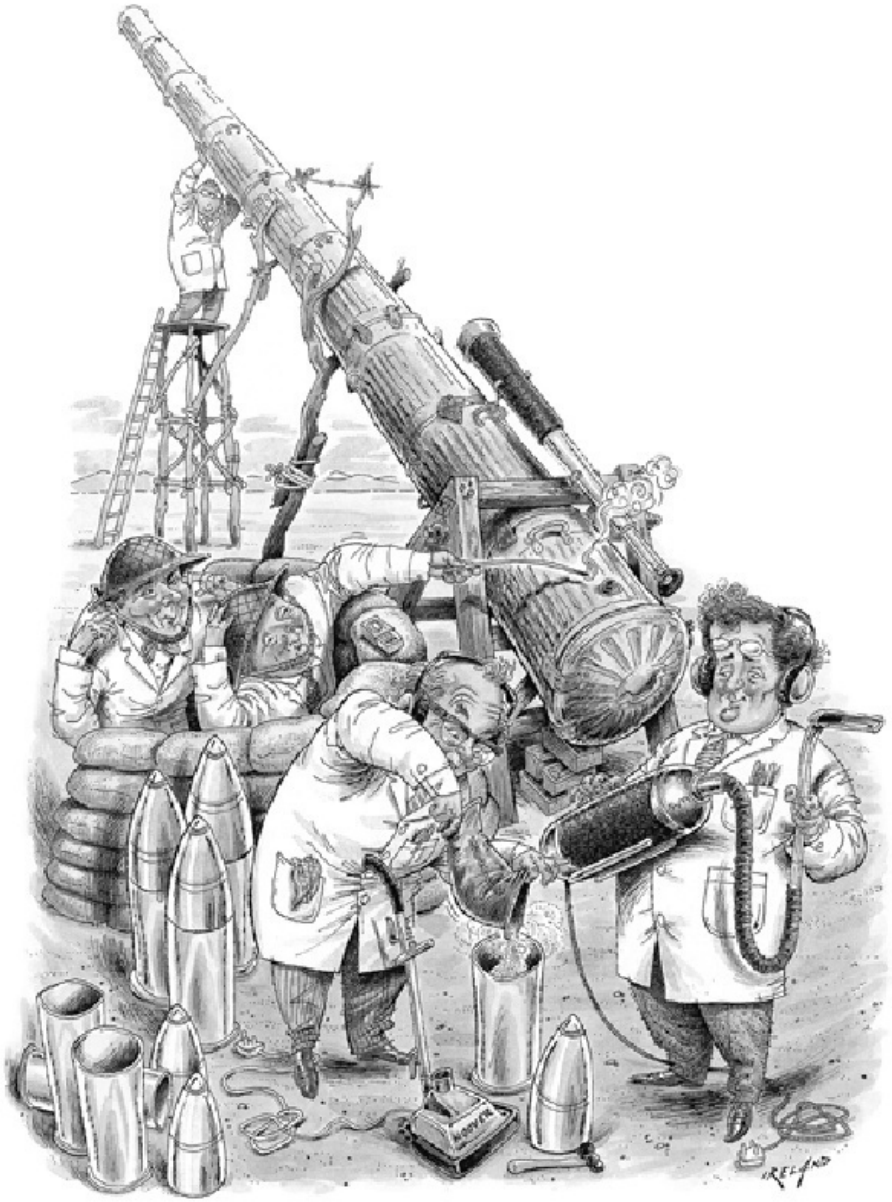


Robert St. George Dyrenforth claimed success after his federally funded rainmaking mission to Texas in 1891, but in this cartoon from a local magazine he is shown ordering his assistants to speed up: "Here's a telegram announcing a storm. If we don't hurry, it will be on before we raise our racket."

Experiments with cloud seeding during the Cold War inspired fantastic predictions about America's ability to control the weather, as in this 1954 article, and use it as a weapon against its communist adversaries.



Ridicule greeted a 1992 proposal to combat global warming by shooting reflective particles into the atmosphere. The response could be different today.

Can Dr. Evil Save The World?

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

Jeff Goodell
Rolling Stone
November 3, 2006

Reasons geoengineering may be a bad idea

Climate system response

1. Regional climate change, including temperature and precipitation
2. Rapid warming when it stops
3. How rapidly could effects be stopped?
4. Continued ocean acidification
5. Ozone depletion
6. Enhanced acid precipitation
7. Whitening of the sky (but nice sunsets)
8. Less solar radiation for solar power, especially for those requiring direct radiation
9. Effects on plants of changing the amount of solar radiation and partitioning between direct and diffuse
10. Effects on cirrus clouds as aerosols fall into the troposphere
11. Environmental impacts of aerosol injection, including producing and delivering aerosols

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

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

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

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Department of Environmental Sciences

Arctic geoengineering

(In response to New York Times Op-Ed "How to Cool the Globe" by Ken Caldeira, October 24, 2007)

Screwing (with) the Planet

James Fleming
Colby College, Waterville, ME

We would all like to see the polar bears flourish, but Ken Caldiera's suggestion to "seed" the Earth's stratosphere with acidic particles using military technology is not the way to do this.

Naval artillery, rockets, and aircraft exhaust are all "manly" ways to declare "war" on global warming. "A fire hose suspended from a series of balloons" alludes to the proposal by Edward Teller's protégé Lowell Wood to attach a 25-mile long phallus to a futuristic military High Altitude Airship. If the geoengineers can't keep it up, imagine a "snake" filled with more than a ton of acid ripping loose, writhing wildly, and falling out of the sky!

Arctic geoengineering: continued

(In response to New York Times Op-Ed "How to Cool the Globe" by Ken Caldeira, October 24, 2007)

Screwing (with) the Planet

James Fleming
Colby College, Waterville, ME

The pair of overheated polar bears in the cartoon alludes to such nonsense. And whose warships are those in the distance? Better check with Vladimir Putin before we screw (with) the Arctic.

The geoengineers have been playing such games with the planet since computerized general circulation models were developed back in the late 1950s. While this kind research will undoubtedly continue, it should remain indoors between consenting adults. What needs to be aired out are the underlying assumptions.

© New York Times, Henning Wagenbreth, Oct. 24, 2007

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

- 80-yr control run
- 40-yr anthropogenic forcing, IPCC A1B scenario: greenhouse gases (CO_2, CH_4, N_2O, O_3) and tropospheric aerosols (sulfate, biogenic, and soot), 3-member ensemble
- 40-yr IPCC A1B + Arctic lower stratospheric injection of 3 Mt SO_2/yr, 3-member ensemble
- 40-yr IPCC A1B + Tropical lower stratospheric injection of 5 Mt SO_2/yr, 3-member ensemble
- 40-yr IPCC A1B + Tropical lower stratospheric injection of 10 Mt SO_2/yr

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

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.

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

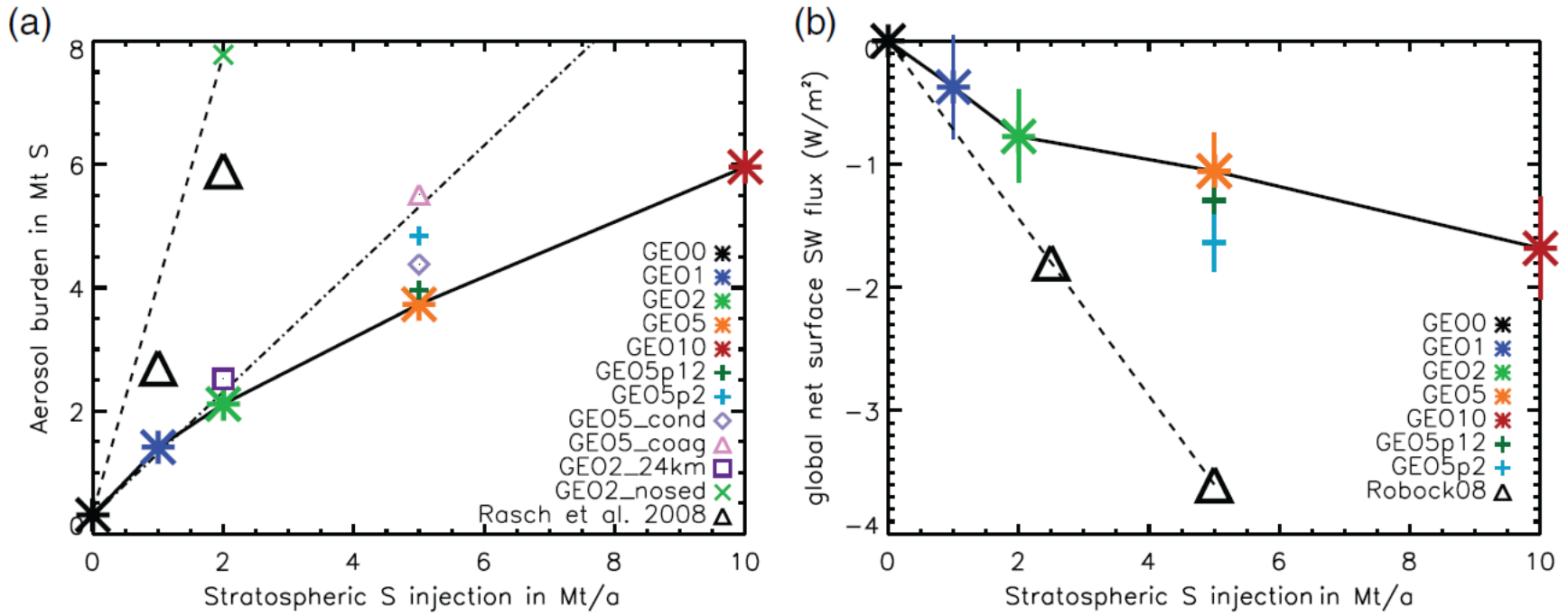

Figure 4. (a) Total aerosol burden as function of sulfur injected annually into the stratosphere (0, 1, 2, 5 and 10 Mt/a S) calculated by the AER model. Dash–dotted line: aerosol burden, if the aerosol residence time were 1 year irrespective of injection strength. Dashed line: aerosol burden when aerosol 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) showed emitting sulfuric acid directly and in dispersed pattern will produce larger particles, helping solve the problem of aerosol growth.

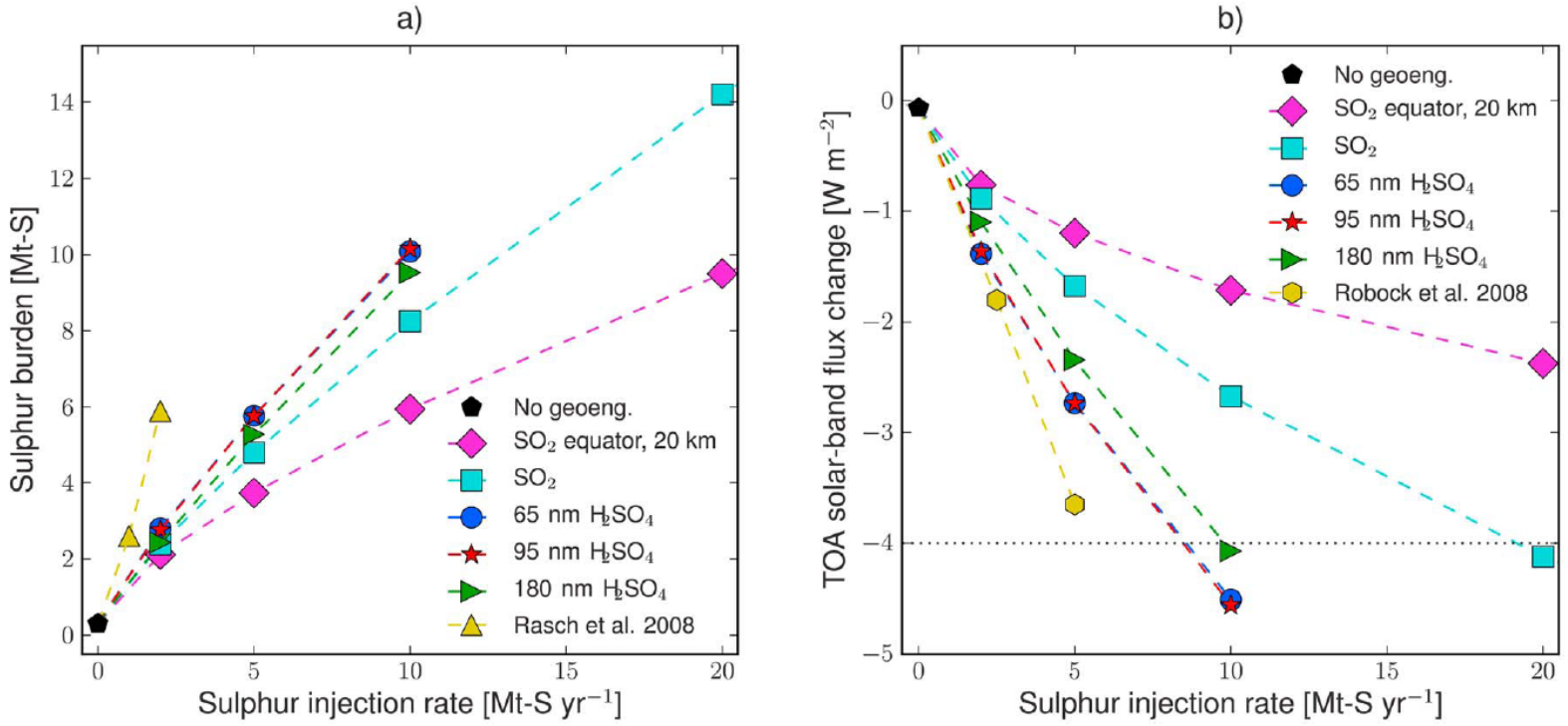

Figure 4. Steady-state (a) stratospheric sulfur burden and (b) top-of-atmospheric solar-band (shortwave) radiative flux change from the stratospheric aerosols as a function of sulfur injection rate. All simulations have emissions evenly distributed between 30°S–30°N and 20–25 km, except results for SO_2 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.