Geo-Engineering of Climate

AOSC 433/633 & CHEM 433/633

Ross Salawitch

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2015

Today:

- **Geo-engineering of climate**
- **Lecture designed to serve as a "mini review" of class material**

Lecture 23

7 May 2015

Course Logistics

- Course evaluation open https://www.courseevalum.umd.edu until 13 May

Course Evaluations Currently Open*	Evaluation Start Date	Deadline	Enroll	Invited	Resp
201501-AOSC633-0101-ATMSPHRC CHEM & CLIMATE	April 28, 2015	May 13, 2015	9	11	2
201501-CHEM433-0101-ATMSPHRC CHEM & CLIMATE	April 28, 2015	May 13, 2015	6	6	0
201501-AOSC433-0101-ATMSPHRC CHEM & CLIMATE	April 28, 2015	May 13, 2015	12	14	3

- Projects:
  - Paper due Monday, 11 May
  - Presentations Monday, 11 May, 6:30 pm (this room)
  - All are welcome to attend
  - Delighted to provide comments on either a draft paper and/or draft presentation provided **sent draft midnight Thurs (7 May)**
    Received only 1 draft paper ☹
  - **Please either email Ross, Austin, and Tim a PDF or PPT of your presentation by 6 pm or else arrive with presentation on memory stick by 6:15 pm**
  - **14 students x 10 mins / students = 140 mins ⇨ each student will have 10 mins**

    Suggest 6 to 8 slides, *absolute maximum of 10 slides*:
    - *** No need for outline or background**
    - *** Cut to the chase with a focus on figures illustrating what you learned**
    - *** A single conclusion slide of some sort is probably warranted**

Geo-engineering of weather & climate has a long history:

- 1945: John von Neumann and other leading scientists meet at Princeton and agreed that modifying weather deliberately might be possible (motivation was “next great war”)
- 1958: US Congress funded expanded rainmaking research (Irving Langmuir, GE)
- Cold War: U.S. military agencies devoted significant funds to research on what came to be called "climatological warfare”
  - one aim was to make the Arctic Ocean navigable by eliminating the ice pack
  - extensive cloud-seeding conducted over Ho Chi Minh Trail during Vietnam war, to increase rainfall and bog down the North Vietnamese Army's supply line in mud
- 1975: Mikhail Budyko calculated that if global warming ever became a serious threat, we could counter with just a few airplane flights a day in the stratosphere, burning sulfur to make aerosols that would reflect sunlight away
- 1977: N.A.S. report looked at a variety of schemes to reduce global warming, should it ever become dangerous, and concluded a turn to renewable energy was a more practical solution than geo-engineering of climate

Source: S. Weart, The Discovery of Global Warming, Harvard University Press, 2003
http://www.aip.org/history/climate/

Geo-engineering of weather & climate has a long history:

Stephen Schneider, Geo-engineering: could –or should – we do it ?, Climatic Change, **33**, *291*, 1996:

> Although I believe it would be irresponsible to implement any large-scale geo-engineering scheme until scientific, legal, and management uncertainties are substantially narrowed, I do agree that, given the potential for large inadvertent climatic changes now being built into the earth system, more systematic study of the potential for geo-engineering is probably needed.

Geo-engineering of weather & climate has a long history:

Two general classifications:

- **Modification of surface radiative forcing as CO_2 rises**
  - **space shield blocking portion of solar irradiance**
  - **stratospheric balloons blocking portion of solar irradiance**
  - **injection of sulfate particles into stratosphere to ↑ albedo**
  - **modification of tropospheric clouds to ↑ albedo**

- **Carbon control and / or sequestration**
  - **iron fertilization of oceans**
  - **carbon burial**

⇐ Material from Lecture 5 will be further described

Since August 2006:

- **Nov 2006: Geo-engineering workshop, NASA Ames**
  - led by Robert Chatfield and Max Loewenstein
  - 40 page workshop report (http://event.arc.nasa.gov/main/home/reports/SolarRadiationCP.pdf)
- **Oct 2007: Ken Caldeira, NY Times Op Ed**
  - Seeding the stratosphere might not work perfectly … but is cheap, easy and worth investigating…
  - Think of it as an insurance policy, a backup plan for climate change.
  - Which is the more environmentally sensitive thing to do: let the Greenland ice sheet collapse and polar bears become extinct, or throw a little sulfate in the stratosphere? The second option is at least worth looking into.

    http://www.nytimes.com/2007/10/24/opinion/24caldiera.html
- **Nov 2007: Geo-engineering meeting, Harvard University**
  - covered by Science (**http://sciencenow.sciencemag.org/cgi/content/full/2007/1109/1**)

    Harvard climate researcher James Anderson told the group that the arctic ice was "holding on by a thread" and that more carbon emissions could tip the balance. The delicacy of the system, he said "convinced me of the need for research into geo-engineering" And 5 years ago? "I would have said it's a very inappropriate solution"
- **June 2009: National Academy of Sciences (NAS) Geo-engineerimg meeting**
  - Chapter 15, Solar Radiation Management (SRM) of NAS America Climate Choice's 2010 report:

Little is currently known about the efficacy or potential unintended consequences of SRM approaches, particularly how to approach difficult ethical and governance questions. Therefore, research is needed to better understand the feasibility of different approaches; the potential consequences of such approaches on different human and environmental systems; and the related physical, ecological, technical, social, and ethical issues, including research that could inform societal debates about what would constitute a "climate emergency" and on governance systems that could facilitate whether, when, and how to intentionally intervene in the climate system.

Since August 2006:

- **Feb 2015: Two "Climate Intervention" reports issued by the prestigious National Academy of Sciences**

Box 2. ***Carbon Dioxide Removal Strategies Considered in This Study***

- Changes in land use management to enhance natural carbon sinks such as forests and agricultural lands
- Accelerated weathering in the ocean and on land to enhance natural processes that remove carbon dioxide from the atmosphere
- Bioenergy with carbon capture and sequestration
- Direct air capture and sequestration of carbon dioxide
- Ocean iron fertilization to boost phytoplankton growth and enhance take-up of carbon dioxide

Box 3. ***Albedo Modification Strategies Considered in This Study***

- Stratospheric aerosols that help reflect sunlight back into space
- Marine cloud brightening to enhance reflection of sunlight

Since August 2006:

- **Feb 2015: Two "Climate Intervention" reports issued by the prestigious National Academy of Sciences**

Six recommendations:

1. Efforts to address climate change should continue to focus most heavily on mitigating GHG 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

2. Research and development investment to improve methods of CO_2 removal and disposal at scales that would have a global impact on reducing greenhouse warming, in particular to minimize energy and materials consumption, identify and quantify risks, lower costs, and develop reliable sequestration and monitoring

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

4. An albedo modification research program be developed and implemented that emphasizes multiple benefit research that also furthers both basic understanding of the climate system and its human dimensions

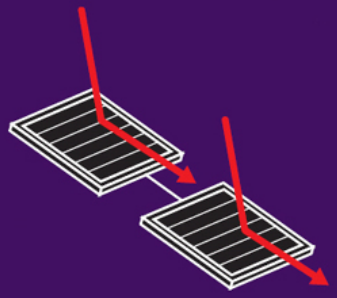
5. United States improve its capacity to detect and measure changes in radiative forcing and associated changes in climate

6. 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;

   (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

Ways to Cool the Planet



SPACE SHIELDS

Steerable micrometers-thick refractive screens could divert a portion of the sun's energy away from Earth thus cooling the atmosphere. The screens would orbit between the sun and the Earth.

▲ No pollution; can be turned on or off quickly.

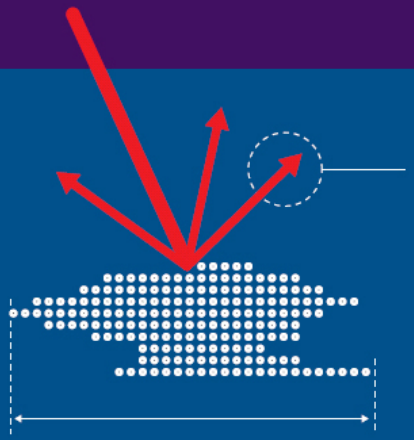
▼ Even using futuristic launching technology, the 20 million metric tons of mesh would cost US $4 trillion to deploy.

PARTICLES IN THE STRATOSPHERE

Sulfate or other reflective particles injected at the equator stay aloft in the stratosphere for one or two years, reflecting sunlight and cooling the planet.

▲ Principle proven by volcanic eruptions; $130 billion price tag is relatively reasonable.

▼ Increased acid rain, ozone layer damage.

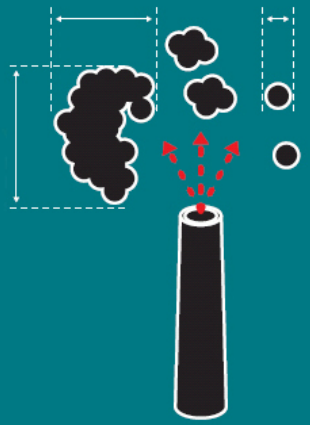


REFLECTIVE BALLOONS

Reflective balloons would bounce a portion of the sun's energy away from Earth before it had a chance to warm the surface or the lower atmosphere.

▲ Cheaper to launch than space shields or space dust.

▼ Would require millions of balloons that would eventually fall to Earth as trash.



CLOUD COVER

Ships spray salt-water droplets that make ocean clouds more long-lasting and reflective, cooling the planet.

▲ Pollution free.

▼ Would take some 5000 salt-water spraying ships, at $2 million to $5 million apiece, to counter a carbon dioxide doubling.

IEEE Spectrum, May 2007

Geo-engineering of climate garnered lots of renewed attention with the publication, in August 2006, of an article entitled:

Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolved a Policy Dilemma?

by Paul J. Crutzen : Climatic Change, 77, 211-219, 2006

According to model calculations … complete ***improvement in air quality*** could lead to a decadal global average surface air temperature increase by 0.8 K on most continents and 4 K in the Arctic. Further studies indicate that global average climate warming during this century may even surpass the highest values in the projected IPCC global warming range of 1.4–5.8ºC

What aspect of air quality improvement might lead to a large increase in surface air temperature?

Volcanic Cooling used as a Surrogate for Geo-Engineering of Climate

Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolved a Policy Dilemma?

by Paul J. Crutzen : Climatic Change, 77, 211-219, 2006

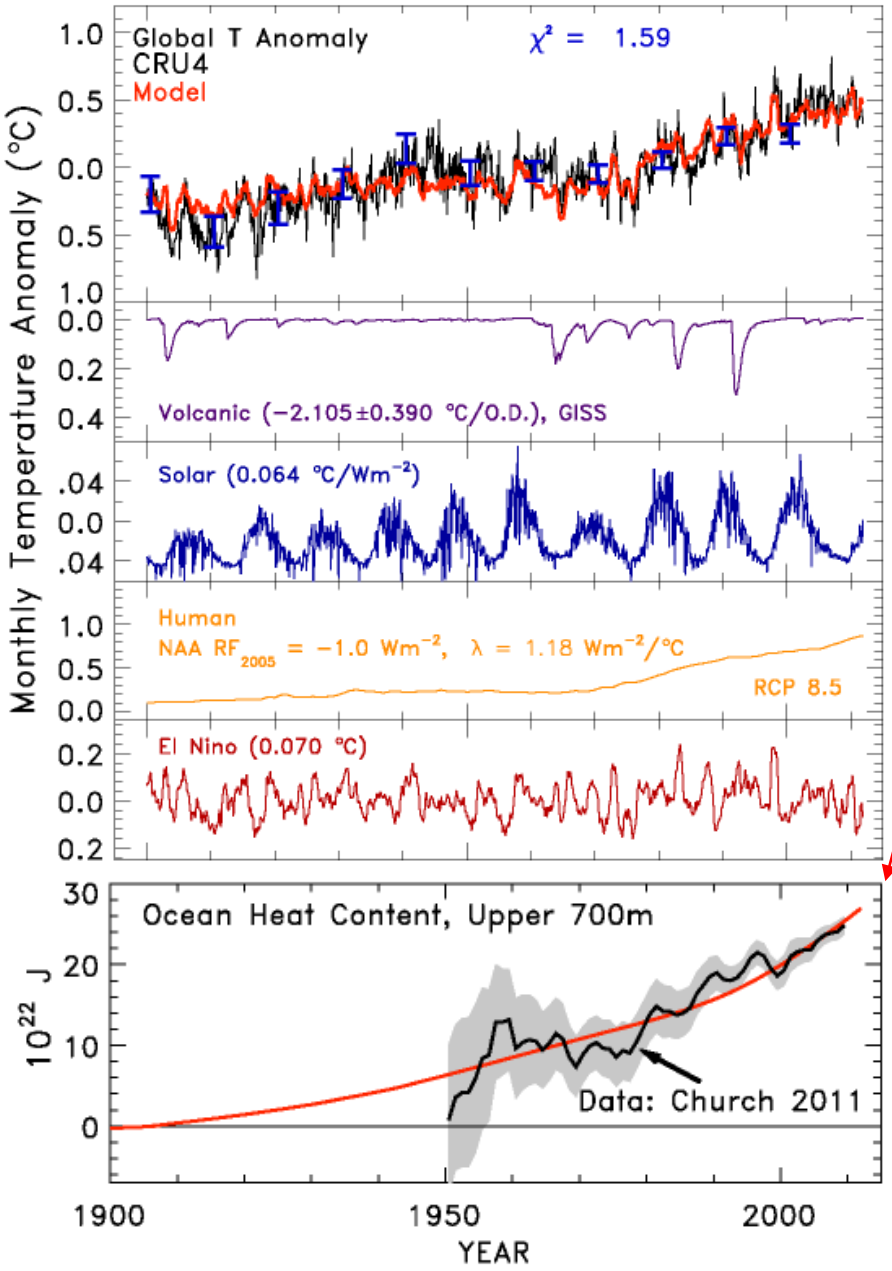
Mount Pinatubo in June, 1991, which injected some 10 Tg S, initially as SO_2, into the tropical stratosphere (Wilson et al., 1993; Bluth et al., 1992). In this case enhanced reflection of solar radiation to space by the particles cooled the earth's surface on average by 0.5 °C in the year following the eruption (Lacis and Mishchenko, 1995).

1. Introduction

Scientific Echo Chamber: Major Volcanic Eruptions Cause ~0.5°C Drop In Global Surface Temperature

The most dramatic change in aerosol-produced reflectivity comes when major volcanic eruptions eject material very high into the atmosphere. Rain typically clears aerosols out of the atmosphere in a week or two, but when material from a violent volcanic eruption is projected far above the highest cloud, these aerosols typically influence the climate for about a year or two before falling into the troposphere and being carried to the surface by precipitation. Major volcanic eruptions can thus cause a drop in mean global surface temperature of about half a degree celsius that can last for months or even years.

page 97, Chapter 1,
Historical Overview of Climate Change Science,
IPCC Physical Science Basis, 2007



Canty et al., ACP, 2013

First shown in Lecture 8

$$\Delta T_{MDL\,i} = (1+\gamma)\,(GHG\ RF_i + NAA\ RF_i) / \lambda_{BB} + C_0 + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2} - Q_{OCEAN\,i} / \lambda_{BB}$$

where

$\lambda_{BB} = 3.21\ W\ m^{-2} / °C$

$1+\gamma = \{1 - \Sigma(\text{Feedback Parameters}) / \lambda_{BB}\}^{-1}$

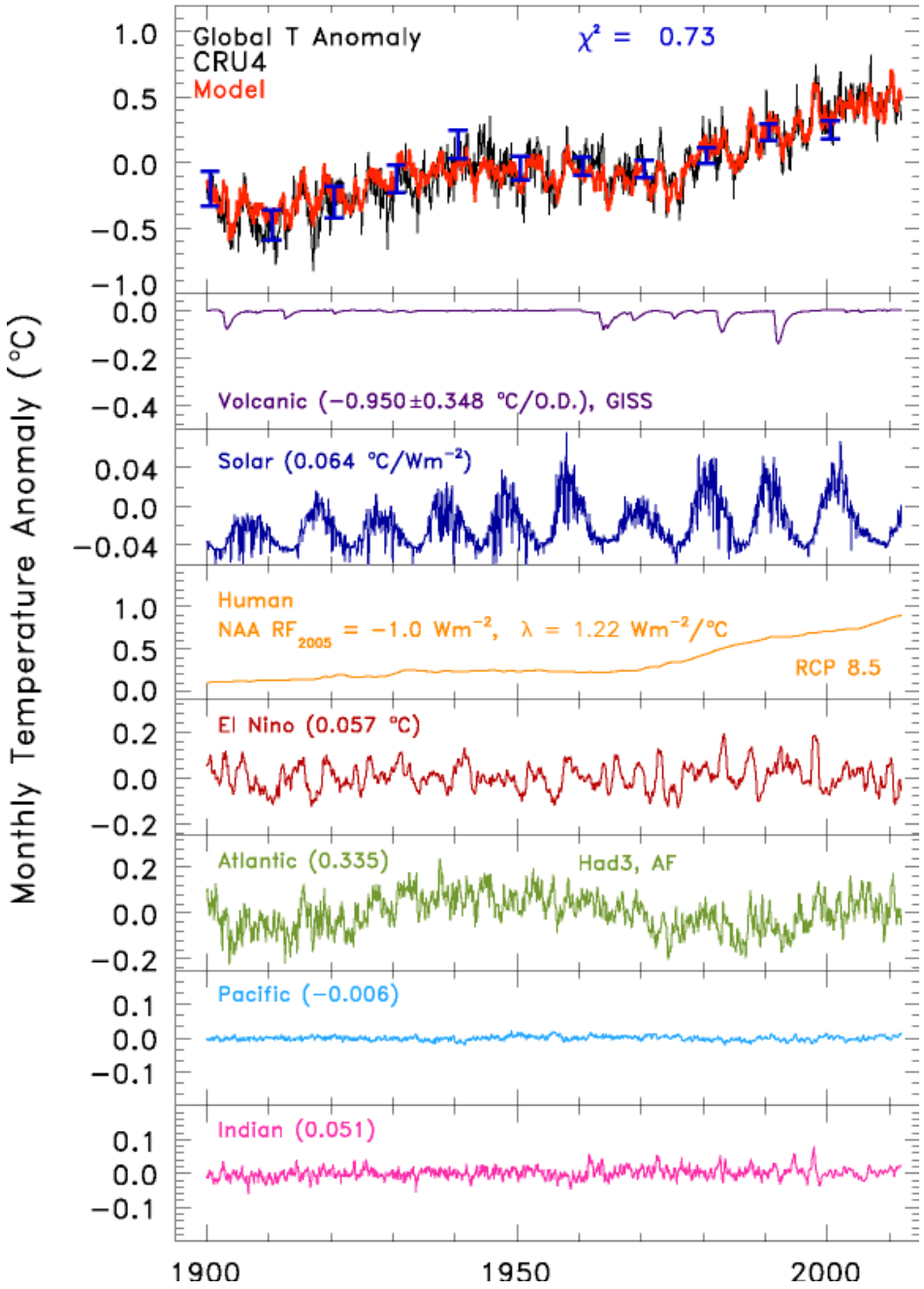
NAA RF = net RF due to anthropogenic aerosols

SOD = Stratospheric optical depth

TSI = Total solar irradiance

ENSO = Multivariate El Niño South. Osc Index

Q_{OCEAN} = Export of heat from atmosphere to ocean



First shown in Lecture 8

$$\Delta T_{MDL\,i} = (1+\gamma)\,(GHG\ RF_i + NAA\ RF_i) / \lambda_{BB} + C_0 + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2} + C_4 \times AMV_i + C_5 \times PDO_i + C_6 \times IOD_i - Q_{OCEAN\,i} / \lambda_{BB}$$

where

$\lambda_{BB} = 3.21\ W\ m^{-2} / °C$

$1+\gamma = \{1 - \Sigma(\text{Feedback Parameters}) / \lambda_{BB}\}^{-1}$

NAA RF = net RF due to anthropogenic aerosols

SOD = Stratospheric optical depth

TSI = Total solar irradiance

ENSO = Multivariate El Niño South. Osc Index

Q_{OCEAN} = Export of heat from atmosphere to ocean

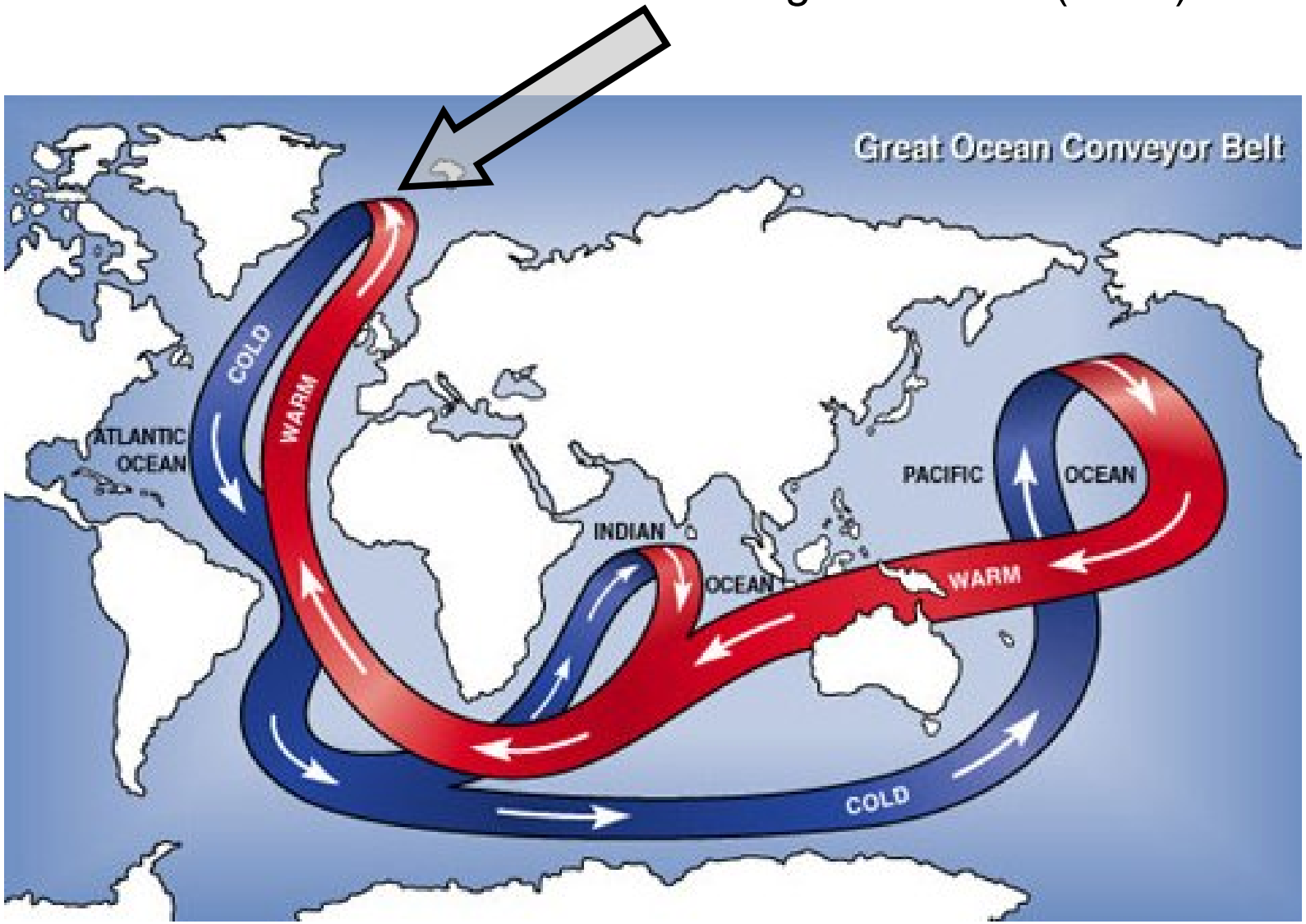
AMV = Atlantic Multidecdal Variation

PDO = Pacific Decadal Oscillation

IOD = Indian Ocean Dipole

Canty et al., ACP, 2013

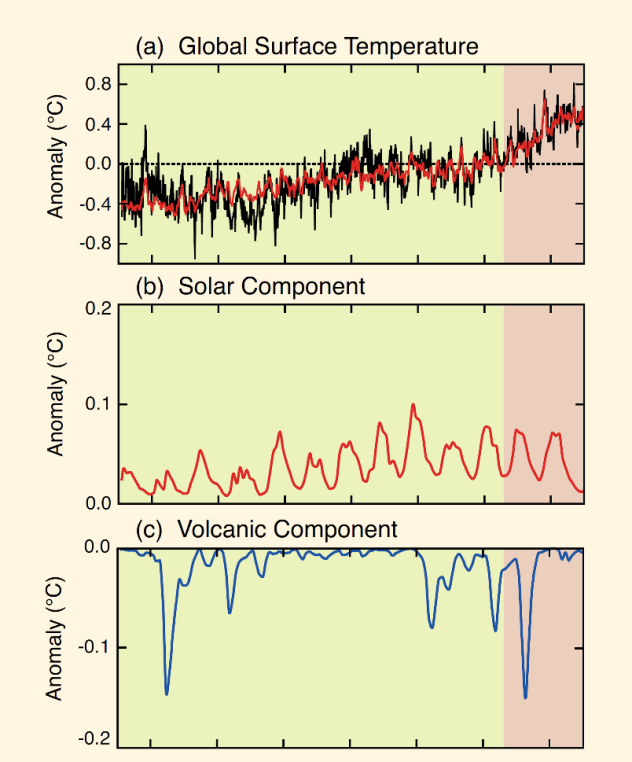
Atlantic Meridional Overturning Circulation (AMO)

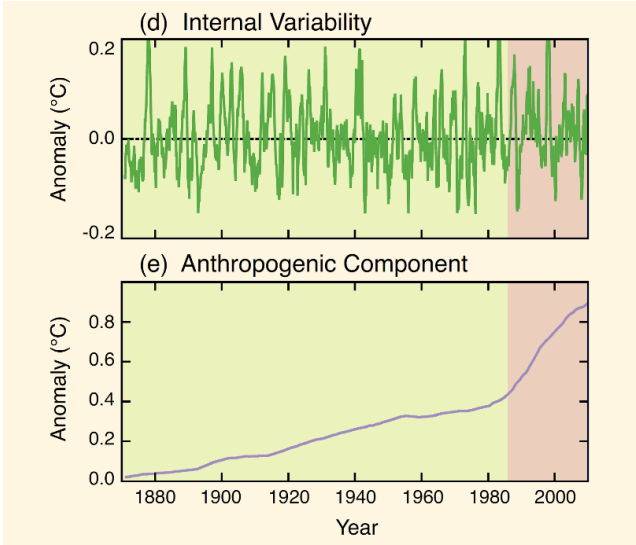


Lecture 5, Slide 25

0.5°C cooling after Pinatubo is Science Fiction !

IPCC (2013) states Pinatubo caused global surface T to fall by 0.1 to 0.3°C, consistent with our work





FAQ 5.1, Figure 1

IPCC 2013 WG1, pg 392 & 393

Volcanic eruptions contribute to global surface temperature change by episodically injecting aerosols into the atmosphere, which cool the Earth's surface (FAQ 5.1, Figure 1c). Large volcanic eruptions, such as the eruption of Mt. Pinatubo in 1991, can cool the surface by around 0.1°C to 0.3°C for up to three years. *(continued on next page)*

Geo-engineering of climate garnered lots of renewed attention with the publication, in <u>August 2006</u>, of an article entitled:

Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolved a Policy Dilemma? by Paul J. Crutzen : Climatic Change, 77, 211-219, 2006

- Mt Pinatubo: $\Delta S_{STRATOSPHERE} \approx$ **6 Tg** $\Rightarrow$ **4.5 W m^{-2}** $\downarrow$ surface radiative forcing
  0.5 ºC cooling
- Doubling CO_2 will result in ~ **3.7 W m^{-2}** $\uparrow$ surface radiative forcing

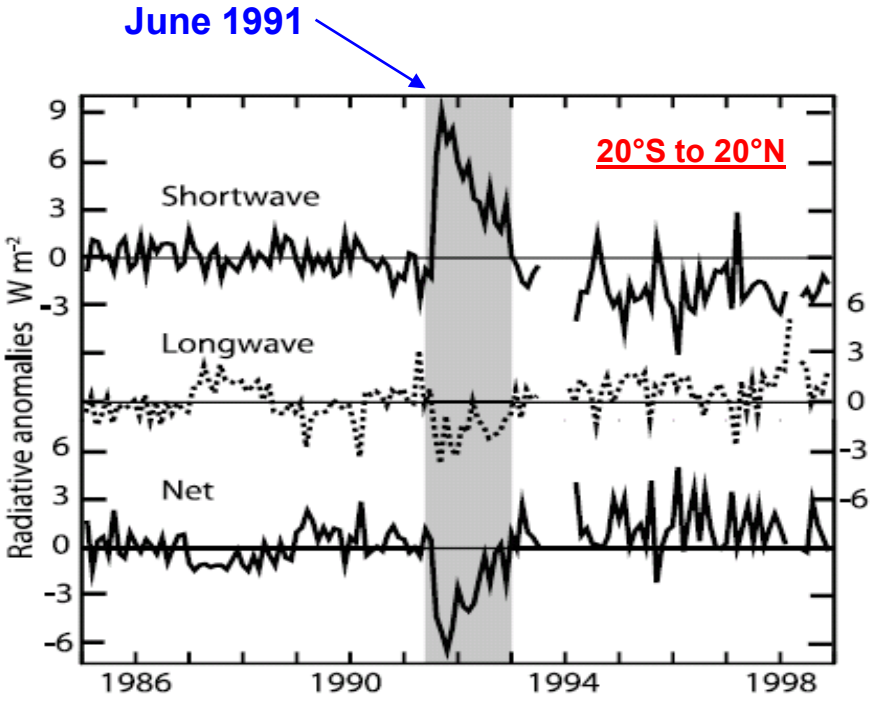
$$\Delta F \approx 5.35 \text{ W m}^{-2} \ln\left(\frac{CO_2^{Final}}{CO_2^{Initial}}\right)$$

Lecture 4, Slide 31

Geo-engineering of climate garnered lots of renewed attention with the publication, in August 2006, of an article entitled:

Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolved a Policy Dilemma? by Paul J. Crutzen : Climatic Change, 77, 211-219, 2006

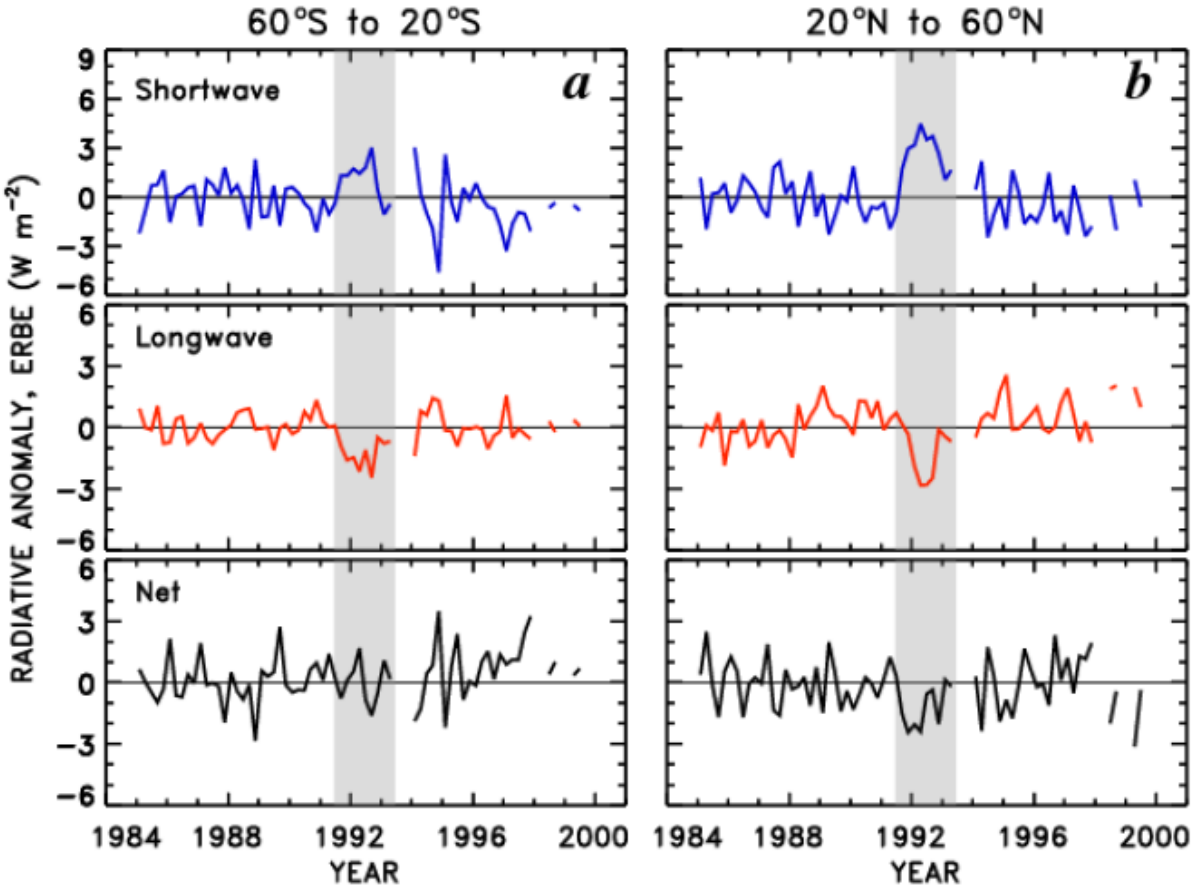
- Mt Pinatubo: $\Delta S_{STRATOSPHERE} \approx$ **6 Tg** $\Rightarrow$ **4.5 W m^{-2}** $\downarrow$ surface radiative forcing
  0.5 ºC cooling
- Doubling CO_2 will result in ~ **3.7 W m^{-2}** $\uparrow$ surface radiative forcing



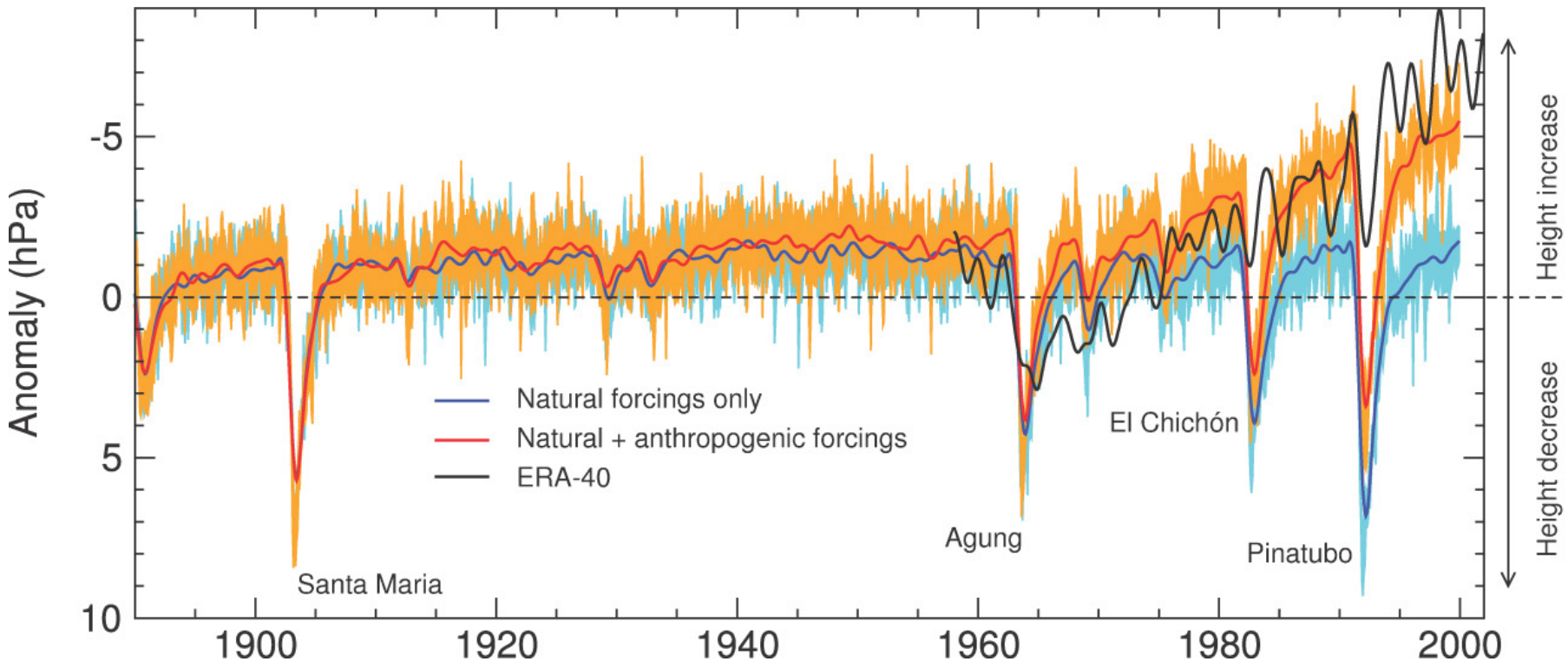
Trenberth and Dai, *GRL*, 2007

- Mt Pinatubo: $\Delta S_{STRATOSPHERE} \approx$ **6 Tg** $\Rightarrow$ **4.5 W m^{-2}** $\downarrow$ surface radiative forcing
  0.5 ºC cooling
- Doubling CO_2 will result in ~ **3.7 W m^{-2}** $\uparrow$ surface radiative forcing

Almost no net RF anomaly due to Pinatubo outside of the tropics !



Canty et al., *ACP*, 2013



Comparison of reanalysis (BLACK LINE) and modeled global, monthly mean tropopause height anomalies.

IPCC 2007, Fig 9.14

Geo-engineering of climate garnered lots of renewed attention with the publication, in <u>August 2006</u>, of an article entitled:

Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolved a Policy Dilemma? by Paul J. Crutzen : Climatic Change, 77, 211-219, 2006

- Requires **5.3 Tg** perturbation to stratospheric S to counter
  - requires continuous injection of 2.65 to 5.3 Tg S per year (due to 2 or 1 yr $\tau_{STRATOSPHERE}$)
  - estimated cost $70 to 140 billion per year ($70 to 140 per capita of affluent world)
  - for comparison: annual military expenditures $1000 billion per year
  - advocates manufacture & surface release of a special gas (insoluble, non-toxic, un-reactive with OH, and zero GWP) that is processed photochemically only in the stratosphere to yield sulfate aerosols (he's an atmospheric chemist!)
- Ozone depletion
  - Global column O_3 declined by ~2.5% following eruption of Mt. Pinatubo
  - Compensating for CO_2 doubling would lead to less ozone loss than followed Pinatubo
  - Stratospheric chlorine is declining, so enhanced O_3 loss less worrisome in the future

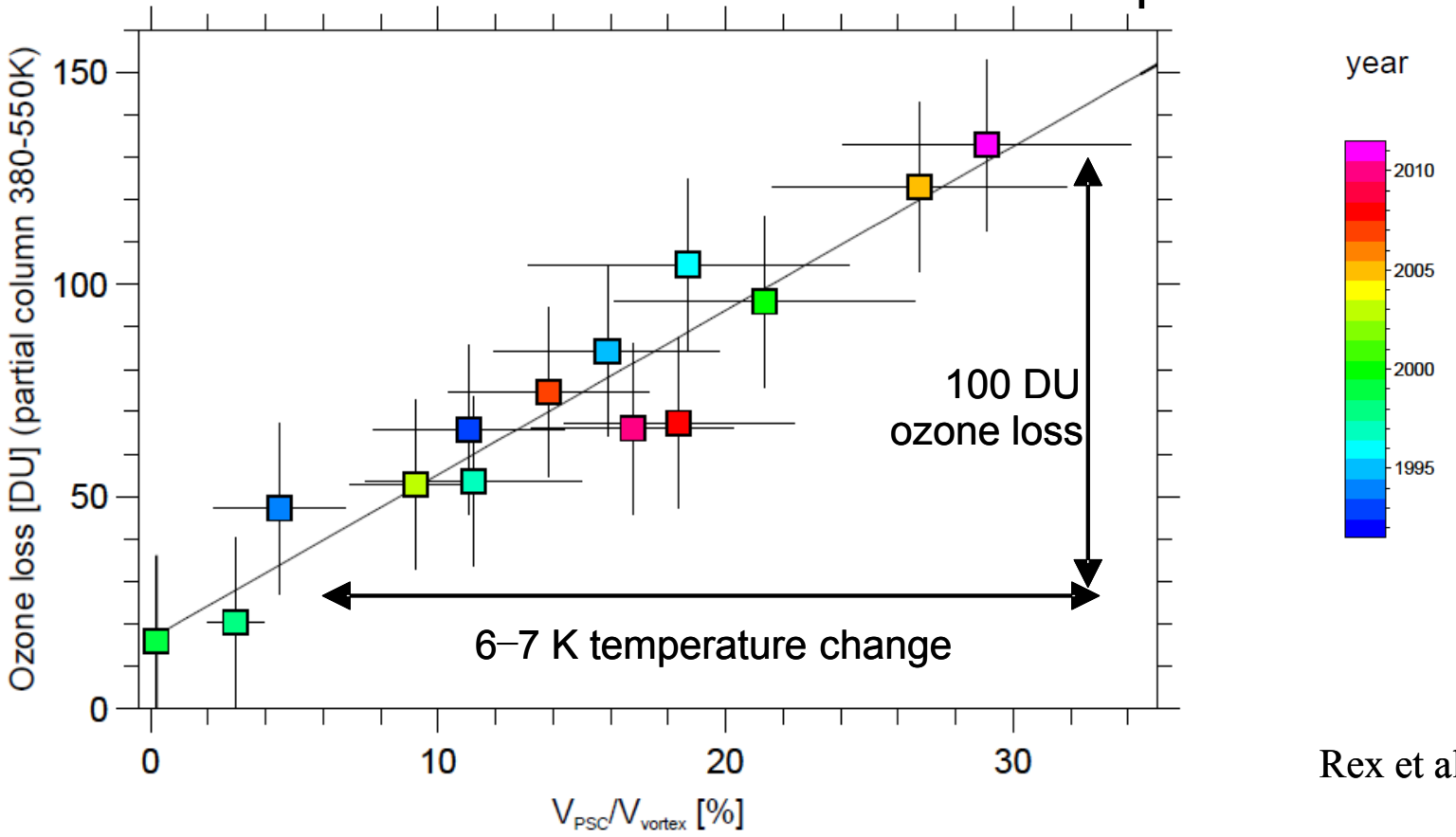
Geo-engineering of climate garnered lots of renewed attention with the publication, in August 2006, of an article entitled:

Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolved a Policy Dilemma? by Paul J. Crutzen : Climatic Change, 77, 211-219, 2006

- Requires **5.3 Tg** perturbation to stratospheric S to counter
  - requires continuous injection of 2.65 to 5.3 Tg S per year (due to 2 or 1 yr $\tau_{STRATOSPHERE}$)
  - estimated cost $70 to 140 billion per year ($70 to 140 per capita of affluent world)
  - for comparison: annual military expenditures $1000 billion per year
  - advocates manufacture & surface release of a special gas (insoluble, non-toxic, un-reactive with OH, and zero GWP) that is processed photochemically only in the stratosphere to yield sulfate aerosols (he's an atmospheric chemist!)
- Ozone depletion
  - Global column O_3 declined by ~2.5% following eruption of Mt. Pinatubo
  - Compensating for CO_2 doubling would lead to less ozone loss than followed Pinatubo
  - Stratospheric chlorine is declining, so enhanced O_3 loss less worrisome in the future

Will the response of *polar ozone* to stratospheric sulfur injection be as modest as suggested by the response of global ozone to Mt. Pinatubo aerosol?

Arctic Ozone Loss vs PSC Exposure

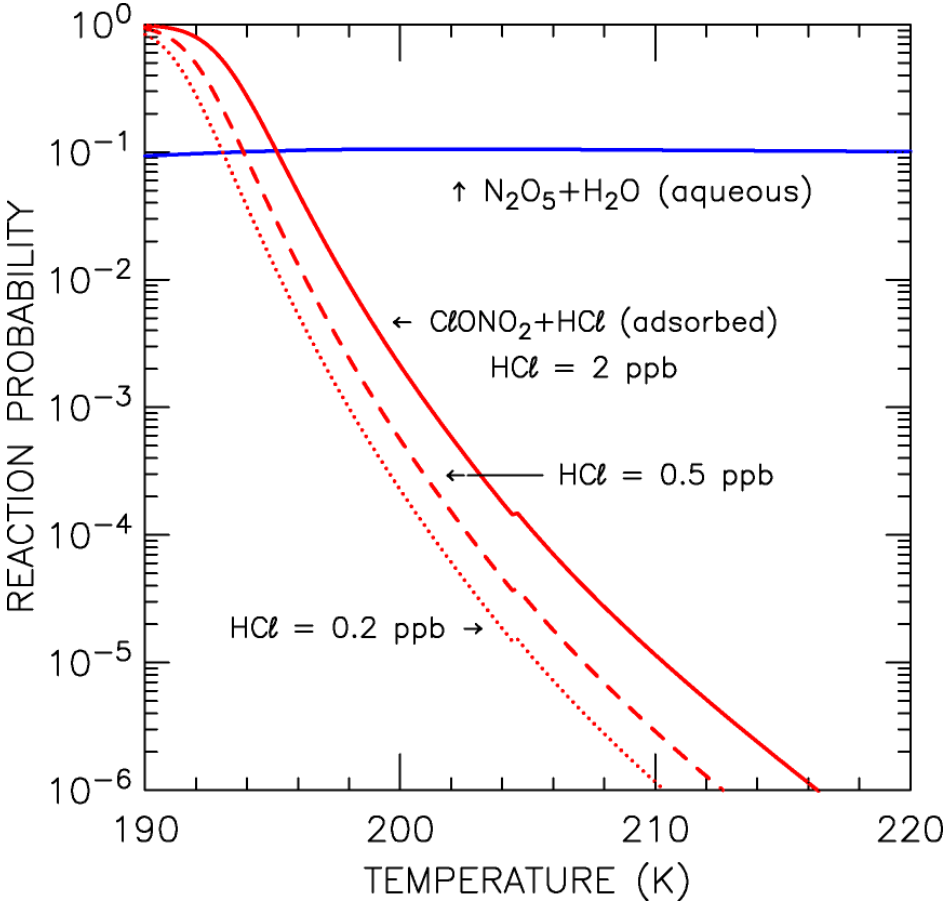


Rex et al., GRL, 2006

PSCs ⇨ polar stratospheric clouds: provide ***surfaces*** for heterogeneous conversion of HCl and $ClNO_3$ to ClO

Lecture 15, Slide 37

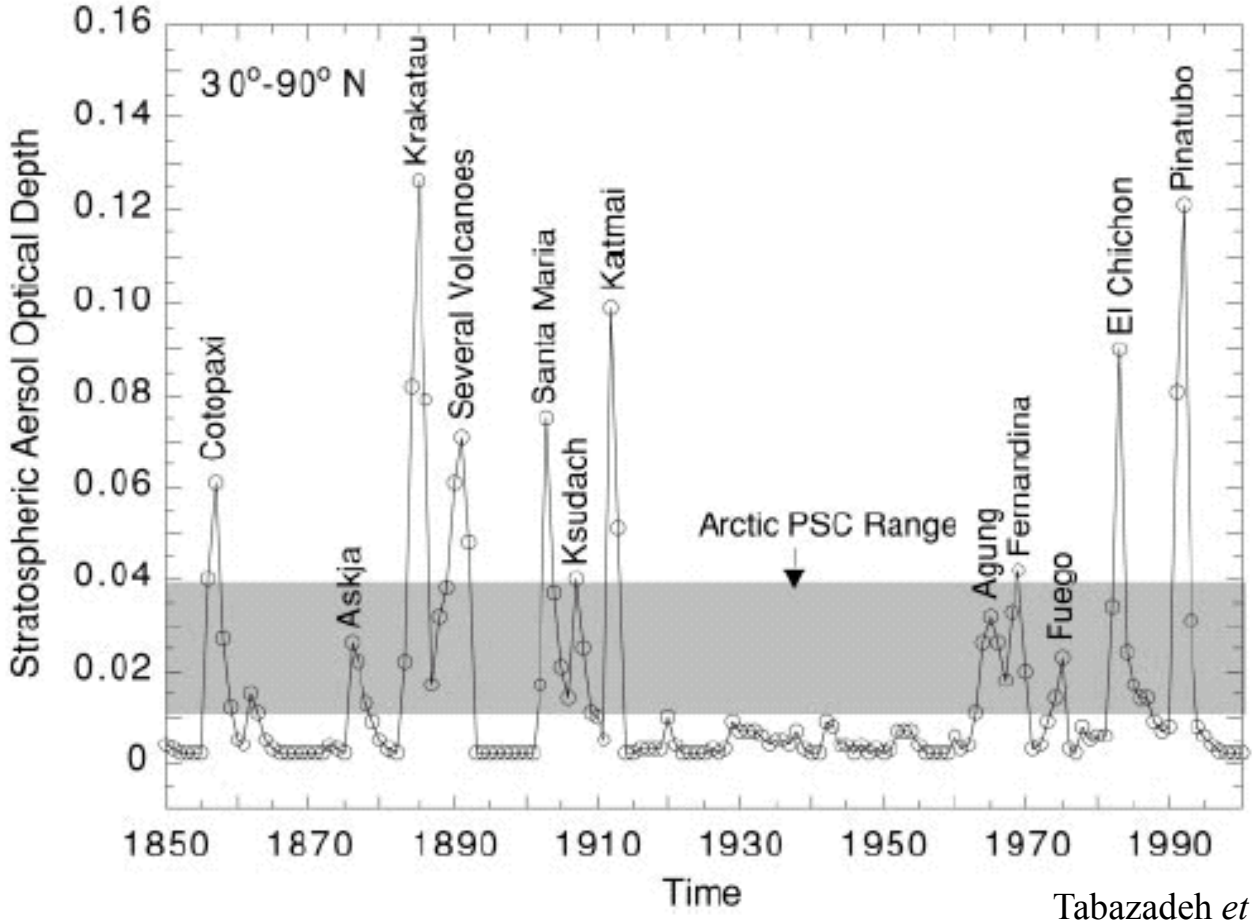
Chlorine Activation



- **Chlorine activation reactions occur on cold aerosols**
- **Chlorine activation depends on T (which drives γ) as well as Surface Area**

$$k = \frac{1}{4}\gamma\,(\text{Velocity}_{ClONO_2})\,(\text{Aerosol Surface Area per Unit Volume})$$

Lecture 11, Slides 24 & 25

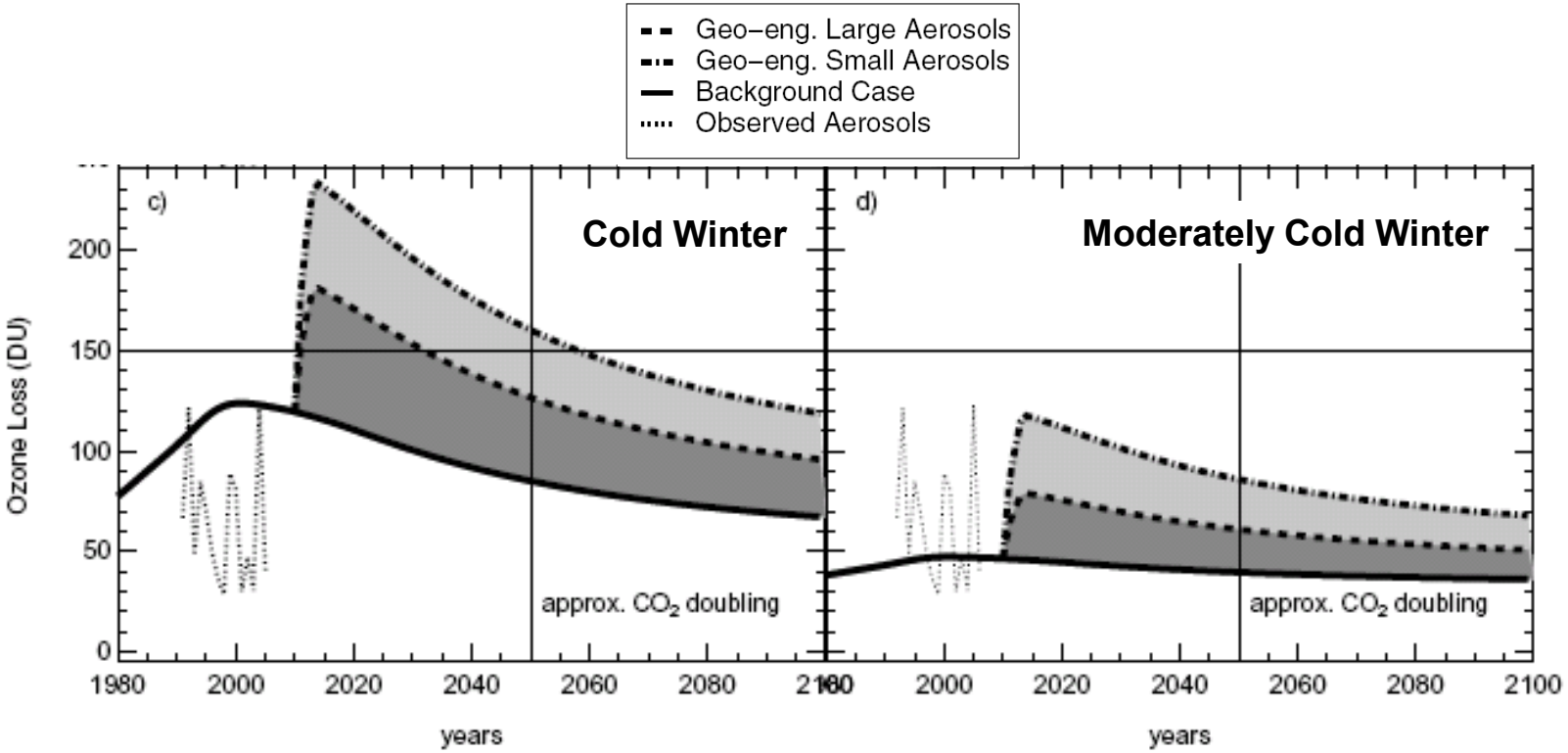


Tabazadeh *et al.*, PNAS, 99, 2609, 2002

- **Chlorine activation reactions occur on cold aerosols**
- **Chlorine activation depends onT (which drives γ) as well as Surface Area**
- **Volcanoes provide more reactive surface area than PSCs !**

Similar to *Lecture 7, Slide 25*

Effect of Geo-Engineering on Arctic O_3 Loss



Enhancement of stratospheric aerosols due to geo-engineering risks:

a) future *Arctic Ozone Hole* in "cold" winters (i.e., 1995, 1996, 2000, 2005)

b) 30 to 70 year delay in the recovery of the Antarctic ozone hole

Tilmes *et al.*, *Science*, 2008

Geo-engineering of climate garnered lots of renewed attention with the publication, in August 2006, of an article entitled:

Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolved a Policy Dilemma?

by Paul J. Crutzen : Climatic Change, 77, 211-219, 2006

- Ozone depletion
  - Global column O_3 ↓ 2.5% following eruption of Mt. Pinatubo
  - Compensating for CO_2 doubling would lead to less ozone loss than followed Pinatubo
  - Stratospheric chlorine is declining, so enhanced O_3 loss less worrisome in the future

- National Academy of Sciences (2009):

  For the injection of sulfate aerosols, ***an additional concern exists***: the potential for increased concentrations of stratospheric aerosols to enhance the ability of residual chlorine, left from the legacy of chlorofluorocarbon use, to damage the ozone layer, especially in the early spring months at high latitudes. A sudden increase in stratospheric sulfate aerosol ***could strongly enhance chemical loss of stratospheric polar ozone for several decades, especially in the Arctic*** (Tilmes *et al*., 2008: 86 citations !)

Geo-engineering of climate garnered lots of renewed attention with the publication, in August 2006, of an article entitled:

Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolved a Policy Dilemma?

by Paul J. Crutzen : Climatic Change, 77, 211-219, 2006

- Ozone depletion
  - Global column O_3 ↓ 2.5% following eruption of Mt. Pinatubo
  - Compensating for CO_2 doubling would lead to less ozone loss than followed Pinatubo
  - Stratospheric chlorine is declining, so enhanced O_3 loss less worrisome in the future

- National Academy of Sciences (2015):

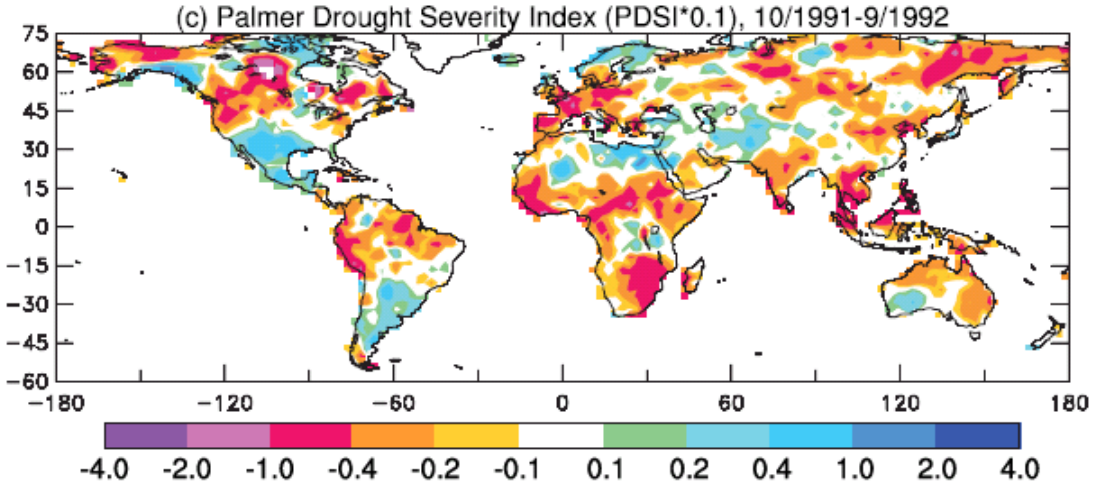
  Tilmes et al. (2009; 2008), Heckendorn et al. (2009) and Pitari (2014) explored the impact of SAAM on ozone depletion, and concluded that SAAM (Stratospheric Aerosol Albedo Modification) sufficient to counter a doubling of CO_2 would **delay ozone recovery** (due to the decrease in halogens) by a few decades

Quote from a geo-engineering email thread:

Paul Crutzen's Nobel prize was for his work on the ozone layer;
he is in a good position to claim the effect on ozone would not be excessive

Solar Radiation Management: Other Issues

- **Enhanced acid precipitation (sulfate will ultimately reach the surface)**
- **Reducing solar radiation at surface (short wave) may lead to decreased evaporation and precipitation**
  - ***Precipitation anomalies after Pinatubo suggest risk of widespread drought***



Trenberth and Dai, *GRL*, 2007

Palmer Drought Severity Index for October 1991 to September 1992; warm colors indicate drying. Values less than 0.2 indicate moderate drought, values less than 0.3 indicate severe drought

- **Model calculations (NASA GISS Model E) indicate stratospheric sulfate injections injections would disrupt the Asian and African summer monsoons, reducing precipitation to area that supply food to billions of people (Robock *et al.*)**
- **If we ever do implement geo-engineering, rapid warming would likely ensue if the perturbation were to stop**

Geo-engineering of climate garnered lots of renewed attention with the publication, in August 2006, of an article entitled:

Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolved a Policy Dilemma?

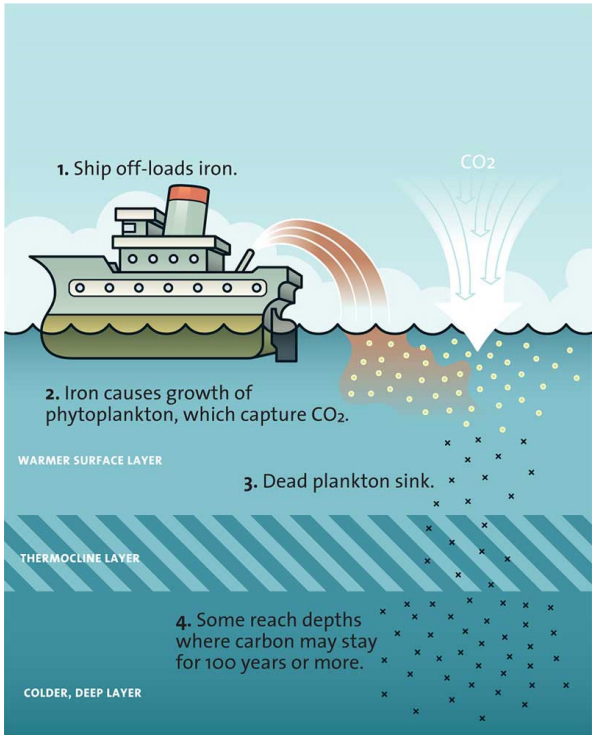
by Paul J. Crutzen : Climatic Change, 77, 211-219, 2006

"Very best if emissions of GHGs could be reduced so that the stratospheric sulfur release experiment would not need to take place. Currently, this looks like a pious wish."

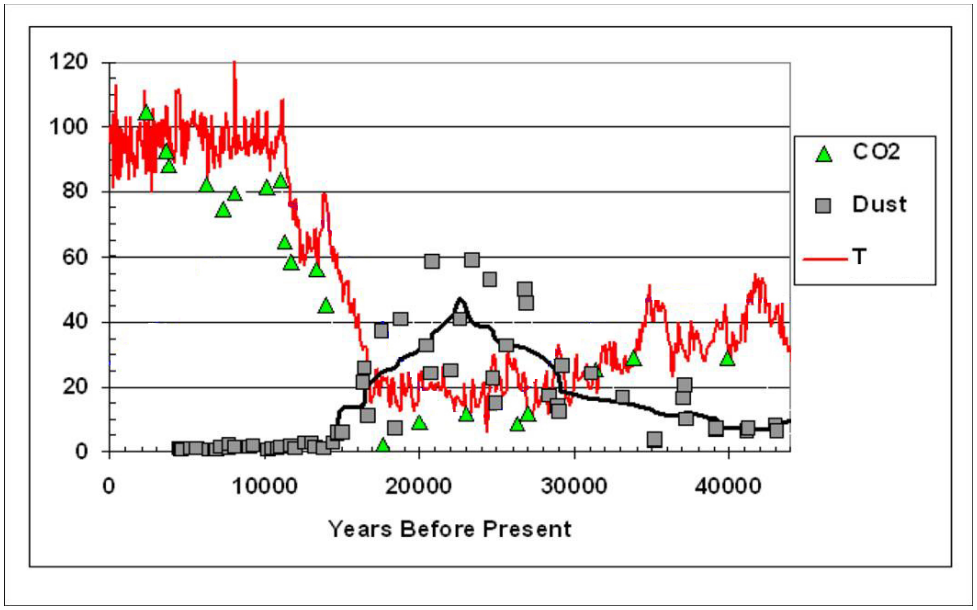
If society is able to successfully "manage solar radiation" reaching the surface, what ecological impact of rising CO_2 would still occur ?

Sequestration of CO_2 from the Atmosphere: Ocean Biology

- Iron's importance to phytoplankton growth and photosynthesis in the ocean dates back to the 1930s, when English biologist Joseph Hart speculated that the ocean's great "desolate zones" (areas apparently rich in nutrients, but lacking in plankton activity or other sea life) might be due to an iron deficiency
- This observation has led to speculation by numerous scientists that “tanker loads” of iron powder, deposited in the right place and time, would increase oceanic dissolved iron content enough to turn these “desolate regions” into oceanic biological havens



http://www.motherjones.com/files/legacy/news/outfront/2008/03/dumping-iron-1000.jpg



Vostok ice core data for ***changes*** in temperature (units of 0.1 K), CO_2 (ppmv), and dust aerosols (linear scale normalized to unity for Holocene) Black line shows 5 point running mean of dust.

Chylek and Lohmann, *GRL*, 2008

Lecture 4, Slide 32

GLACIAL-INTERGLACIAL CO_2 CHANGE: THE IRON HYPOTHESIS

PALEOCEANOGRAPHY, VOL.5, NO.1, PAGES 1-13 1990

John H. Martin

In contrast, atmospheric dust Fe supplies were 50 times higher during the last glacial maximum (LGM). Because of this Fe enrichment, phytoplankton growth may have been greatly enhanced, larger amounts of upwelled nutrients may have been used, and the resulting stimulation of new productivity may have contributed to the LGM drawdown of atmospheric CO_2 to levels of less than 200 ppm. Background information and arguments in support of this hypothesis are presented.

Lecture 5, Slide 30

Sequestration of CO_2 from the Atmosphere: Ocean Biology

BOX 3.2
Historical Context of Ocean Iron Fertilization

"Give me half a tanker of iron, and I'll give you an ice age," biogeochemist John Martin reportedly quipped in a Dr. Strangelove accent at a conference at Woods Hole in 1988 (Fleming, 2010). Martin and his colleagues at Moss Landing Marine Laboratories proposed that iron was a limiting nutrient in certain ocean waters and that adding it stimulated explosive and widespread phytoplankton growth. They tested their iron deficiency, or "Geritol," hypothesis in bottles of ocean water, and subsequently experimenters added iron to the ocean in a dozen or so ship-borne "patch" experiments extending over hundreds of square miles (see text for discussion). OIF was shown to be effective at inducing phytoplankton growth, and the question became—was it possible that the blooming and die-off of phytoplankton, fertilized by the iron in natural dust, was the key factor in regulating atmospheric carbon dioxide concentrations during glacial-interglacial cycles? Dust bands in ancient ice cores encouraged this idea, as did the detection of natural plankton blooms by satellites.

This realization led to further questions. Could OIF speed up the biological carbon pump to sequester carbon dioxide? And could it be a solution to climate change? Because of this possibility, Martin's hypothesis received widespread public attention. What if entrepreneurs or governments could turn patches of ocean green and claim that the carbonaceous carcasses of the dead plankton sinking below the waves constituted biological "sequestration" of undesired atmospheric carbon? Several companies—Climos,[18] Planktos (now out of the business), GreenSea Ventures, and the Ocean Nourishment Corporation[19]—have proposed entering the carbon-trading market by dumping either iron or urea into the oceans to stimulate both plankton blooms and ocean fishing (Climos, 2007; Freestone and Rayfuse, 2008; Powell, 2008; Rickels et al., 2012; Schiermeier, 2003).

OIF projects could be undertaken unilaterally and without coordination by an actor out to make a point; in fact, one such incident took place off the coast of Canada in 2012 (Tollefson, 2012). However, as this section describes, there are still unresolved questions with respect to the effectiveness and potential unintended consequences of large-scale ocean iron fertilization.

NAS, 2015

Sequestration of CO_2 from the Atmosphere: Ocean Biology

- Some scientists have long argued that the iron fertilization vision is flawed because:
  a) lack of iron not always the limiting factor for growth
  b) the diatoms that form are much larger than phytoplankton that populate typical surface waters (top of the oceanic food chain)

- Academic research continues:

Biogeosciences, 7, 4017–4035, 2010

Side effects and accounting aspects of hypothetical large-scale Southern Ocean iron fertilization

A. Oschlies[1], W. Koeve[1], W. Rickels[2], and K. Rehdanz[2]

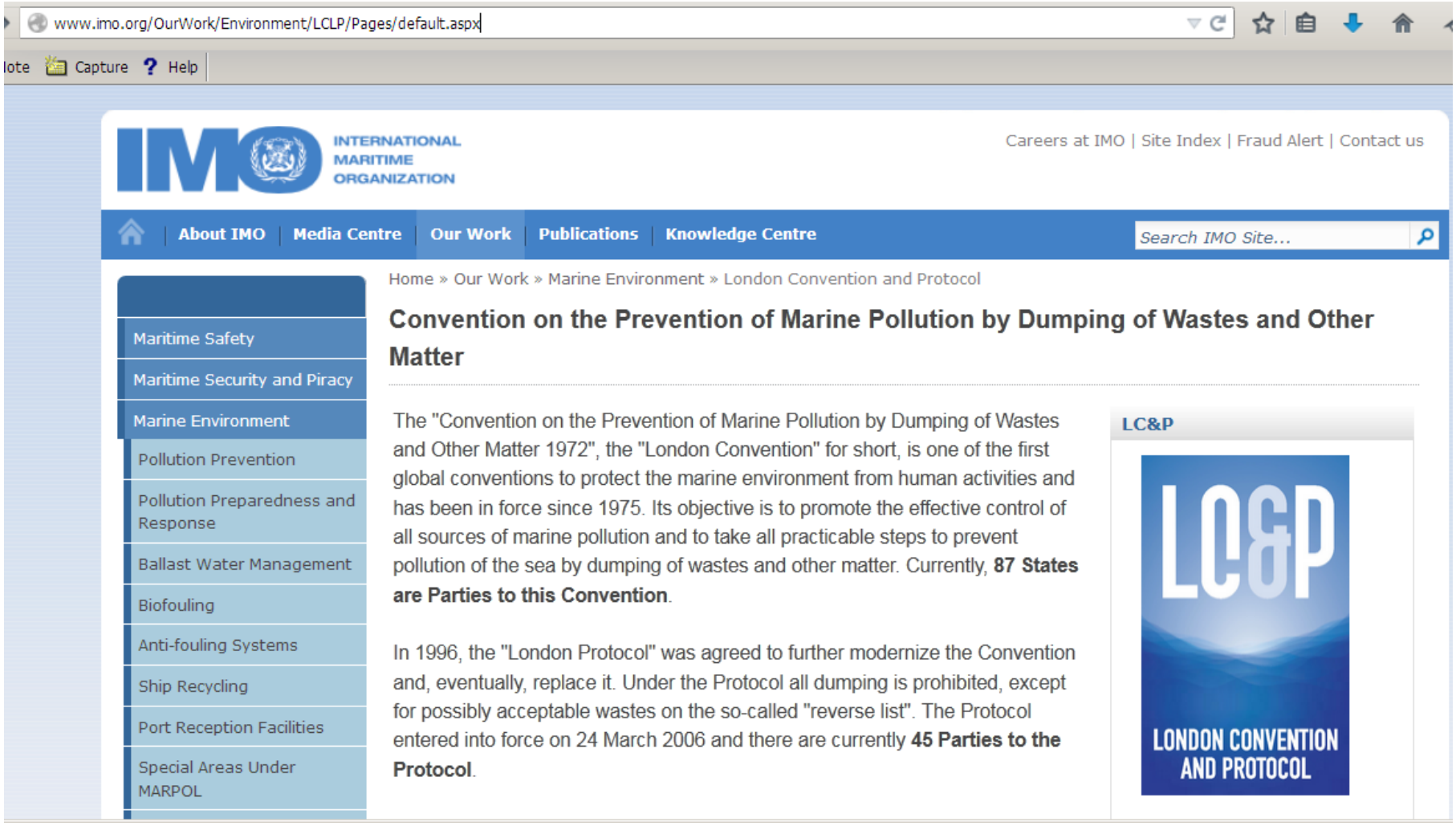
[1]IFM-GEOMAR, Leibniz-Institut für Meereswissenschaften, Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany
[2]Kiel Inst. for the World Economy at the Christian-Albrechts Univ. of Kiel, Hindenburgufer 66, 24105, Kiel, Germany

3.7 Ocean acidification

To the extent that OIF sequesters additional CO_2 in the ocean, it will also amplify ocean acidification (Denman, 2008). This is most pronounced in areas where the sequestered CO_2 is stored.

http://www.biogeosciences.net/7/4017/2010/bg-7-4017-2010.html

Sequestration of CO_2 from the Atmosphere: Ocean Biology



http://www.imo.org/OurWork/Environment/LCLP/Pages/default.aspx

http://www.imo.org/OurWork/Environment/LCLP/Documents/Map%20of%20Parties%20Sept%202014.pdf

National Academy of Sciences (2015) Summary Table

TABLE S.1 Overview of general differences between Carbon Dioxide Removal (CDR) proposals and Albedo Modification proposals. GHG stands for greenhouse gases released by human activities and natural processes and include carbon dioxide, methane, nitrous oxide, chlorofluorocarbons and others. The Committee intends to limit discussion to proposals that raise the fewest problematic issues, thus excluding ocean iron fertilization from the CDR list. Each statement may not be true of some proposals within each category.

Carbon Dioxide Removal proposals…	Albedo Modification proposals…
… address the cause of human-induced climate change (high atmospheric GHG concentrations).	…do not address cause of human-induced climate change (high atmospheric GHG concentrations).
…do not introduce novel global risks.	… introduce novel global risks.
…are currently expensive (or comparable to the cost of emission reduction).	…are inexpensive to deploy (relative to cost of emissions reduction).
…may produce only modest climate effects within decades.	…can produce substantial climate effects within years.
…raise fewer and less difficult issues with respect to global governance.	…raise difficult issues with respect to global governance.
…will be judged largely on questions related to cost.	…will be judged largely on questions related to risk.
…may be implemented incrementally with limited effects as society becomes more serious about reducing GHG concentrations or slowing their growth.	…could be implemented suddenly, with large-scale impacts before enough research is available to understand their risks relative to inaction.
…require cooperation by major carbon emitters to have a significant effect.	…could be done unilaterally.
…for likely future emissions scenarios, abrupt termination would have limited consequences.	…for likely future emissions scenarios, abrupt termination would produce significant consequences.