Impacts of Climate Change and Geo-Engineering of Climate

AOSC 433/633 & CHEM 433/633

Ross Salawitch

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2013

Today:

- **Impacts of climate change: Arctic sea ice & sea level rise**
- **Geo-engineering of climate**
- **Lecture designed to serve as a "mini review" of class material**

Lecture 24

7 May 2013

Course Logistics

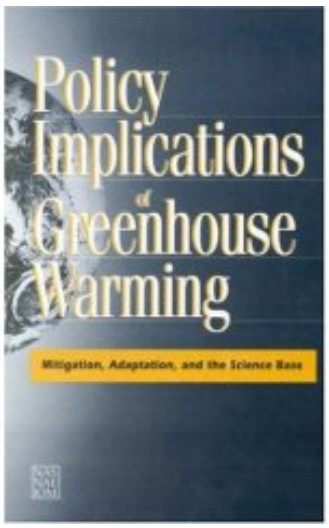
- Course evaluation now open
  - **Everyone** encouraged to participate :
    https://www.courseevalum.umd.edu/portal (open until Friday evening 10 May)
    As of this Mon morning: AOSC 433: 1 of 7 CHEM 433 : 9 of 20
- All grades have been entered into ELMS
  - Please let me know of any discrepancies on Thurs
  - Grades for P Set #6 and today's AT will be entered prior to Thurs
- Projects:
  - Presentations tomorrow, 8 Wed, 6 pm, this room
  - We will record and post, in case students would like to watch themselves in action ☺
  - **Everyone is welcome to attend**
  - Ross will lead with a 10 min presentation (2 mins for questions) mini-lecture on the impacts of climate change, Arctic sea ice, and sea level rise

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:



National Academy of Sciences, 1992

Chapter 28 (pages 433 to 464) and Appendix Q (pages 817 to 835) devoted to “geo-engineering of climate”

http://books.nap.edu/openbook.php?record_id=1605&page=433

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 19 that was skimmed over will be described today

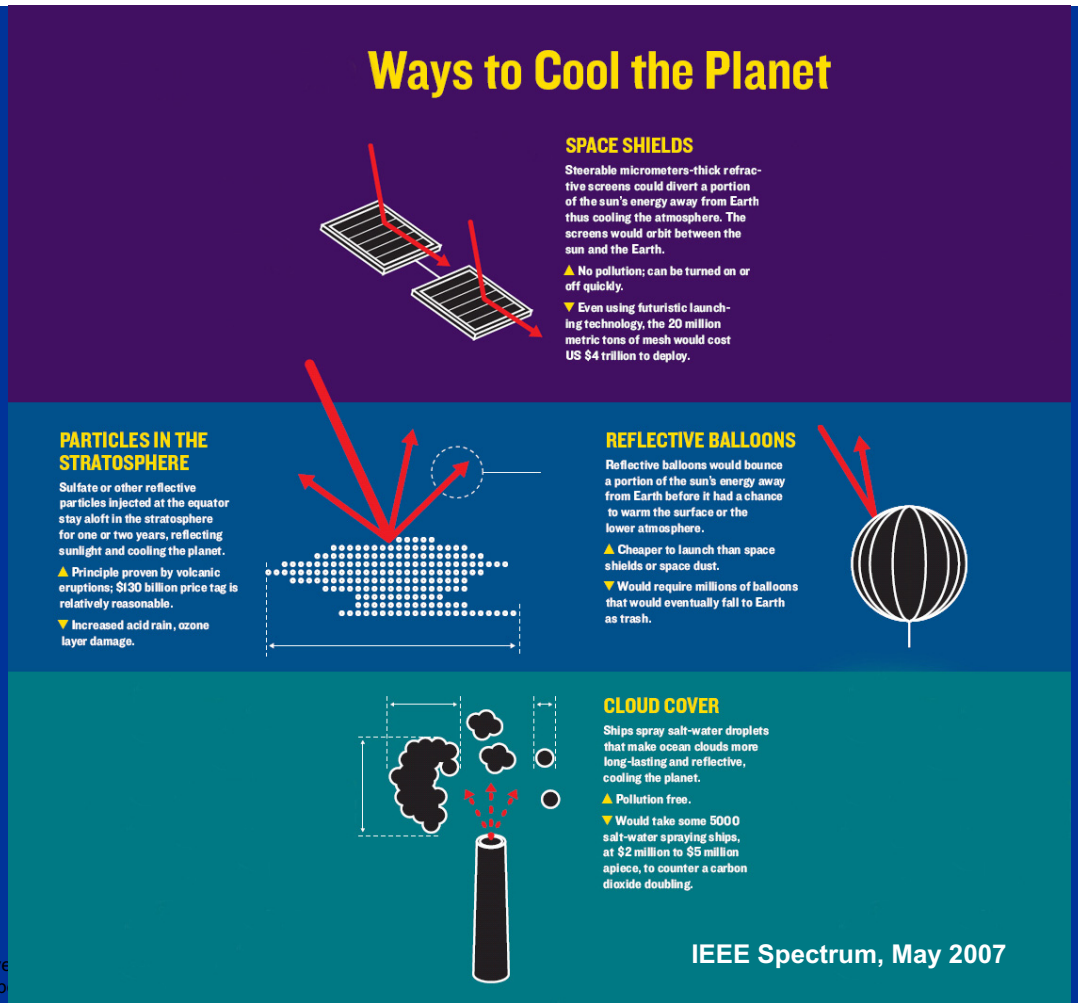
Since August 2006:

- **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.



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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

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

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

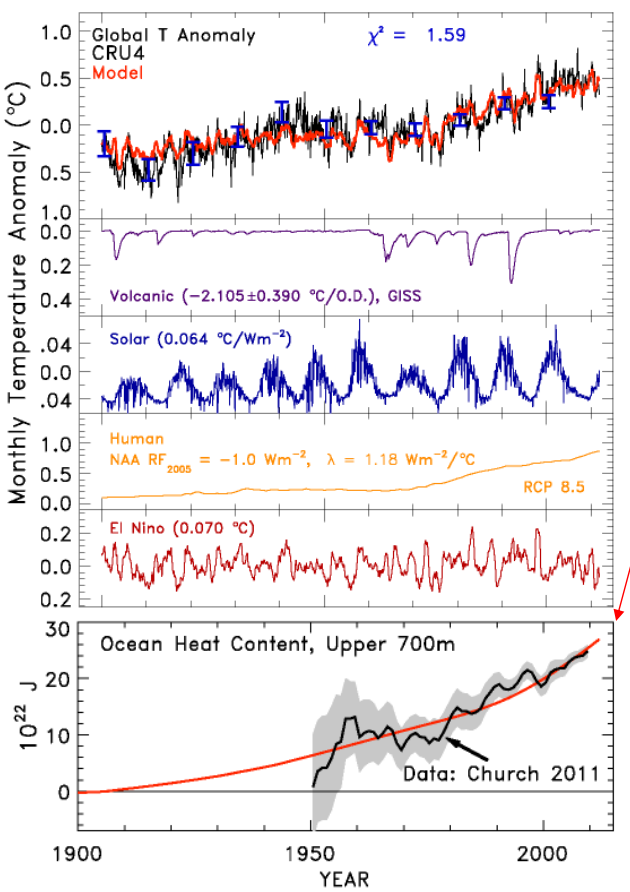
by Paul J. Crutzen : Climatic Change, 77, 211-219, 2006

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).

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

The most dramatic change in aerosol-produced reflecuvity 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

$\lambda_{BB} = 3.21\ W\ m^{-2}/°C$

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

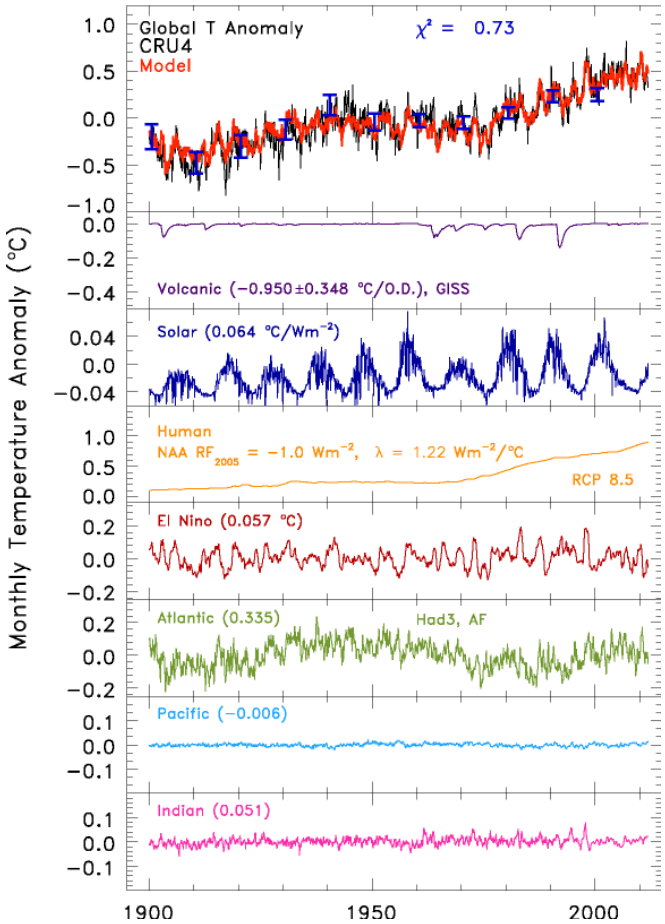
NAA RF = net RF due to anthropogenic aerosols

SOD = Stratospheric optical depth

TSI = Total solar irradiance

ENSO = Multivariate El Niño South. Osc Index

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



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where

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

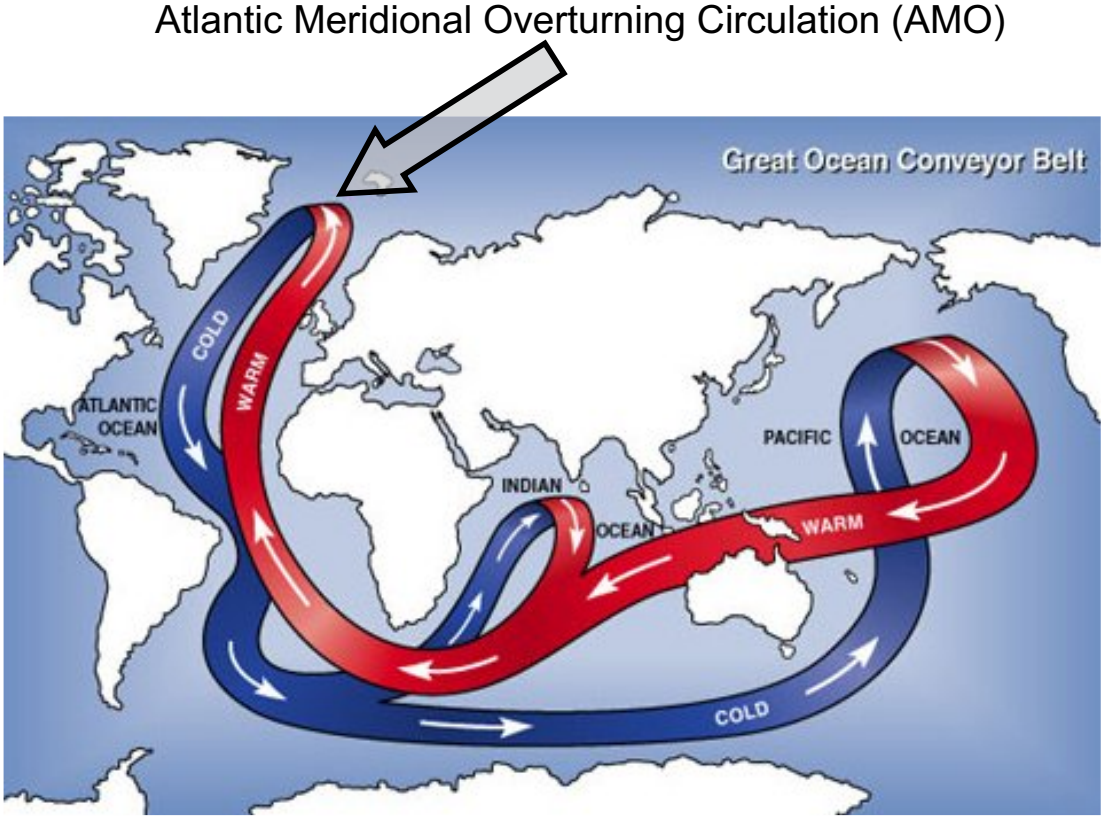
AMV = Atlantic Multidecdal Variation

PDO = Pacific Decadal Oscillation

IOD = Indian Ocean Dipole

Canty et al., ACP, 2013

Atlantic Meridional Overturning Circulation (AMO)



Lecture 5, Slide 26

AMOC: Atlantic Meridional Overturning Circulation

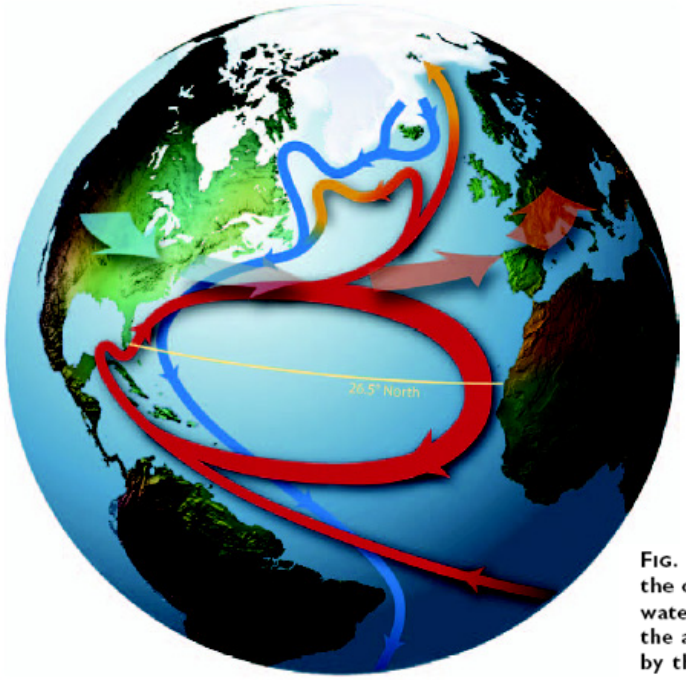


FIG. 1. A simplified schematic of the AMOC showing both the overturning and gyre recirculation components. Warm water flows north in the upper ocean (red), gives up heat to the atmosphere (atmospheric flow gaining heat represented by the changing color of broad arrows), sinks, and returns as a deep cold flow (blue). Latitude of the 26.5°N AMOC

Srokosz, M. et al., Past, Present, and Future Changes in the Atlantic Meridional Overturning Circulation, *BAMS*, November 2012.

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- 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

However, the recommendation by Myhre *et al.* (1998) is slightly different:

$$\Delta F = 5.35\, Wm^{-2} \ln \frac{C}{C_o}$$

5.35 × ln (2) = 3.7 W m^{-2}

Myhre *et al.* believed that the previous IPCC estimates had not been based on consistent model conditions. Using their evaluation, they found good agreement with high spectral resolution radiative transfer calculations.

Lecture 7, Slide 11

- Mt Pinatubo: $\Delta S_{STRATOSPHERE} \approx$ **6 Tg** $\Rightarrow$ **4.5 W m^{-2}** ↓ surface radiative forcing
  0.5 ºC cooling
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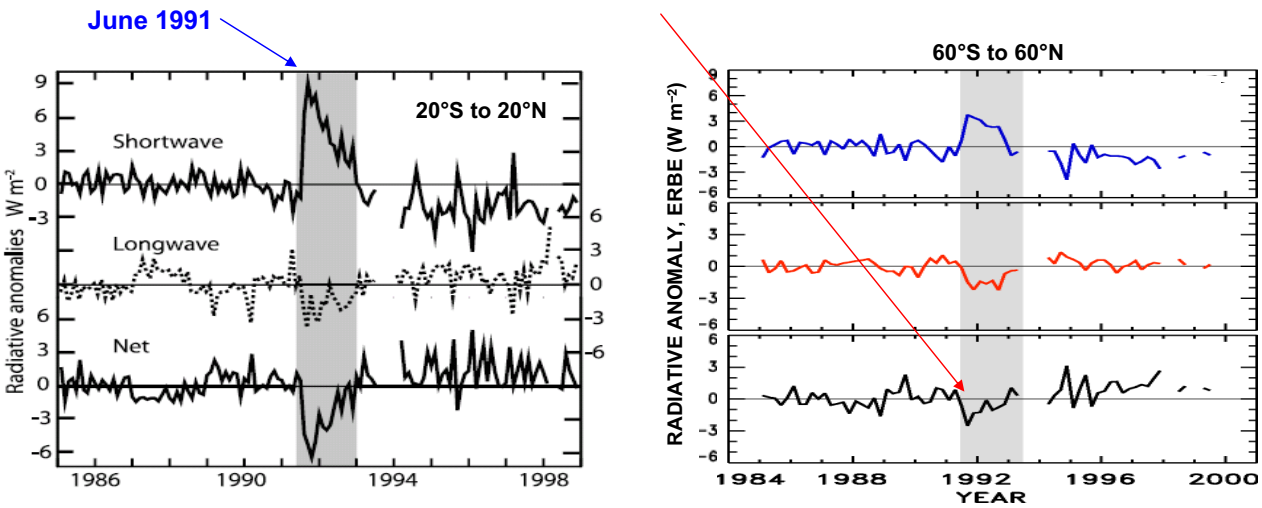
Global **RF anomaly due to Pinatubo was not as large as ~4.5 W m^{-2}**



Trenberth and Dai, *GRL*, 2007

Canty et al., *ACP*, 2013

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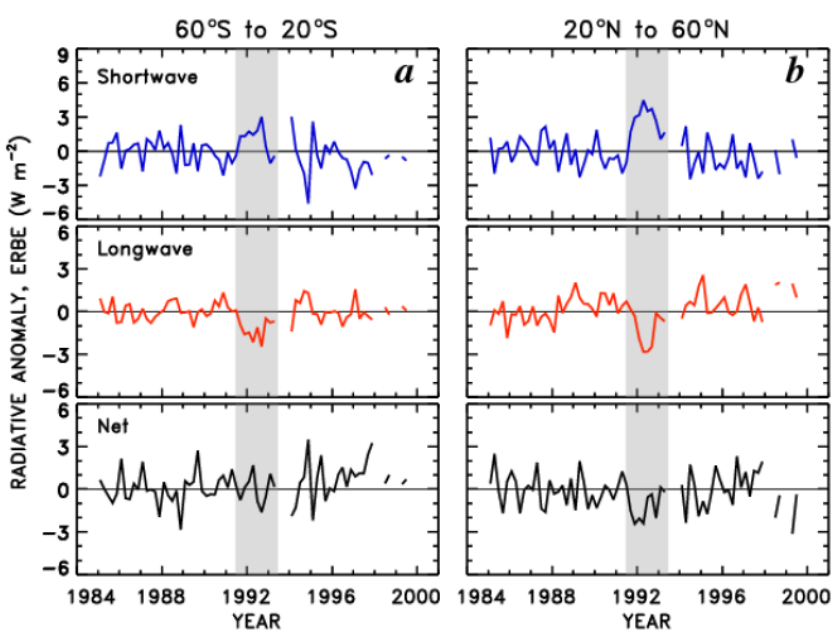
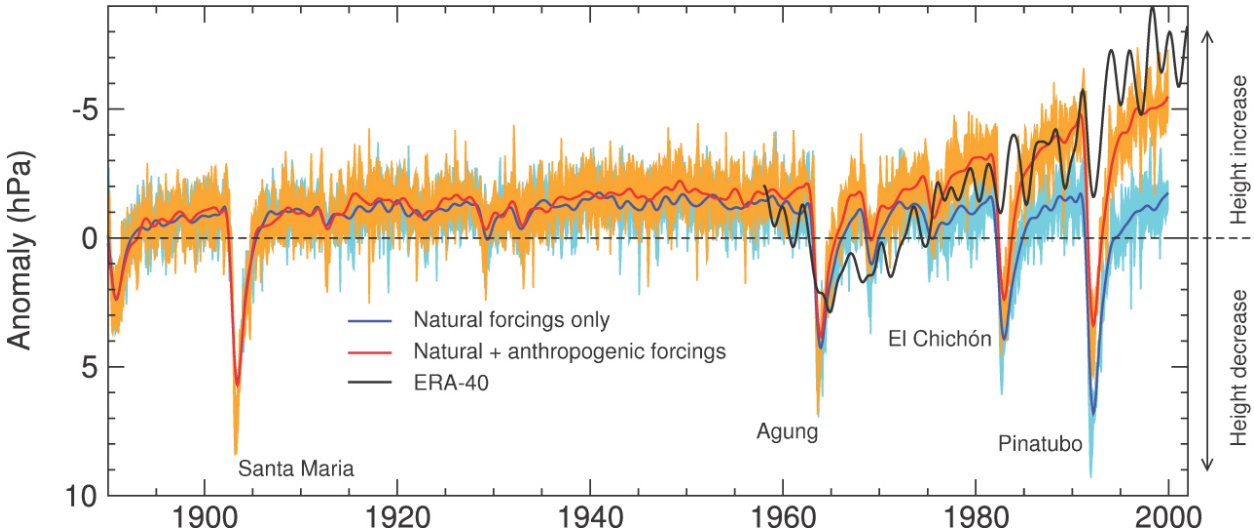
Almost no net RF anomaly due to Pinatubo outside of the tropics !



Canty et al., *ACP*, 2013



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

IPCC 2007, Fig 9.14

3. Reduced Impact of Volcanoes Upon Consideration of Ocean Circulation

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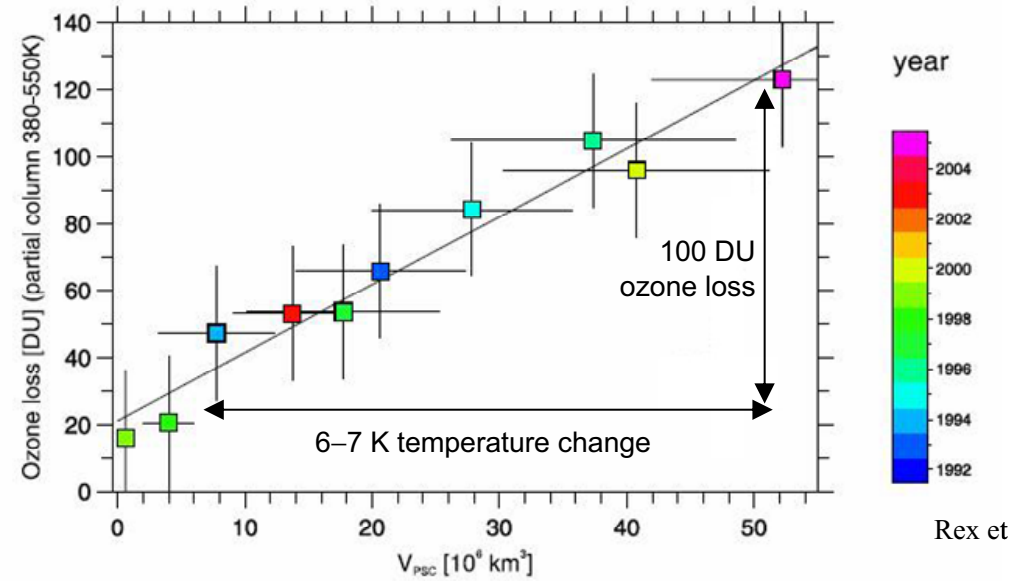
- Requires **5.3 Tg** perturbation to stratospheric S to counter
  - requires continuous injection of 2.65 to 5.3 Tg S per year (due to 2 or 1 yr $\tau_{STRATOSPHERE}$)
  - estimated cost $70 to 140 billion per year ($70 to 140 per capita of affluent world)
  - for comparison: annual military expenditures $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

Arctic Ozone Loss vs PSC Exposure

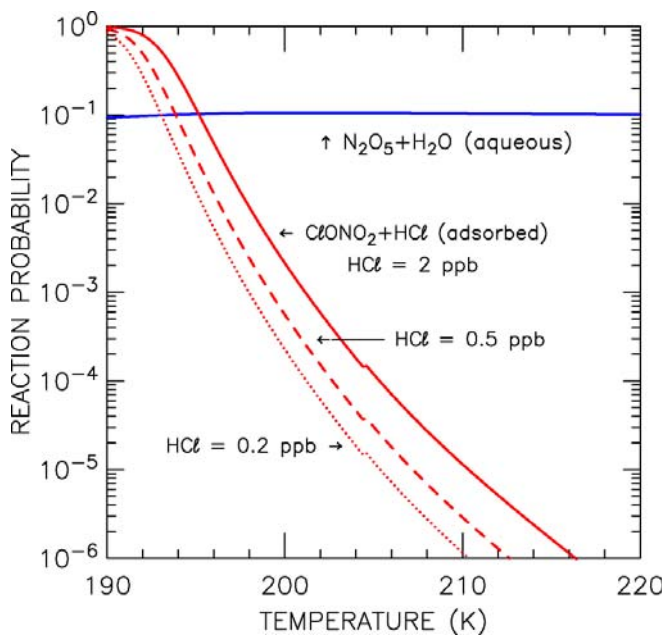


Rex et al., GRL, 2006

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

Lecture 16, Slide 27

Chlorine Activation

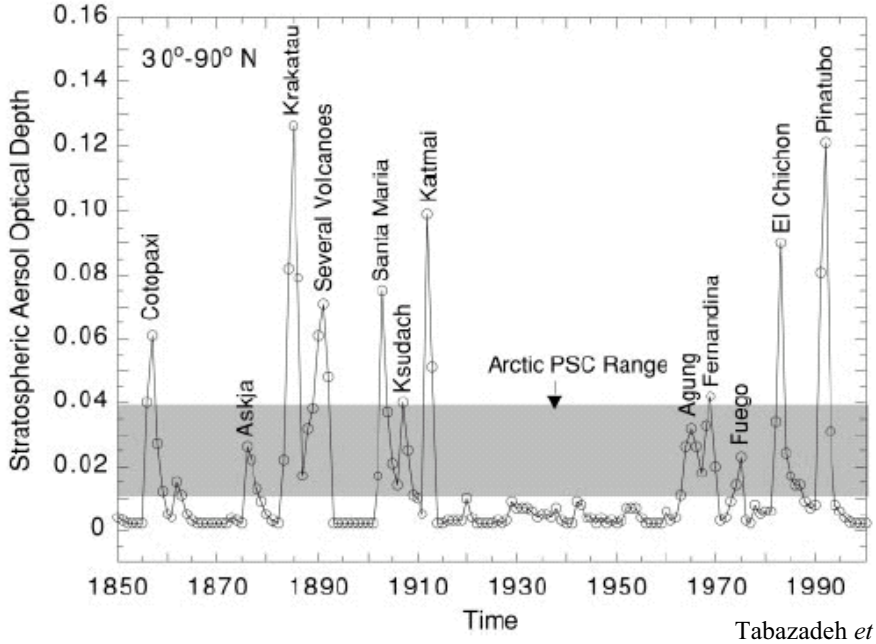


- **Chlorine activation reactions occur on cold aerosols**
- **Chlorine activation depends on T (which drives γ) as well as Surface Area**

Lecture 11, Slide 19

$$k = \frac{1}{4}\gamma(\mathbf{Velocity}_{ClONO2})(\mathbf{Aerosol\ Surface\ Area\ per\ Unit\ Volume})$$

Lecture 11, Slide 18

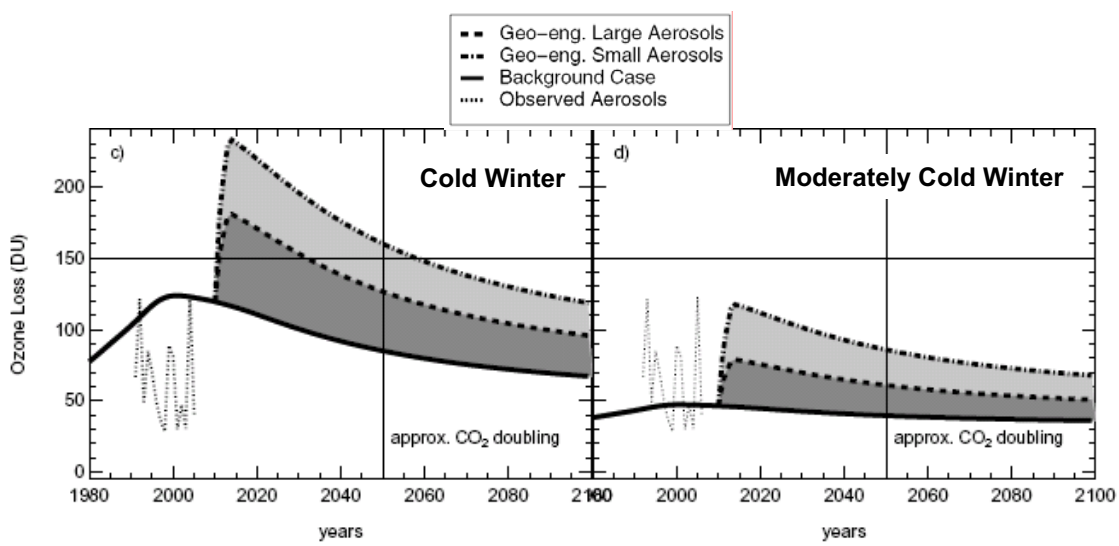


Tabazadeh *et al*., PNAS, 99, 2609, 2002

- **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

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  - Global column $O_3 \downarrow$ 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:

  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: 57 citations)

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"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."

Uptake of Atmospheric CO_2 by Oceans

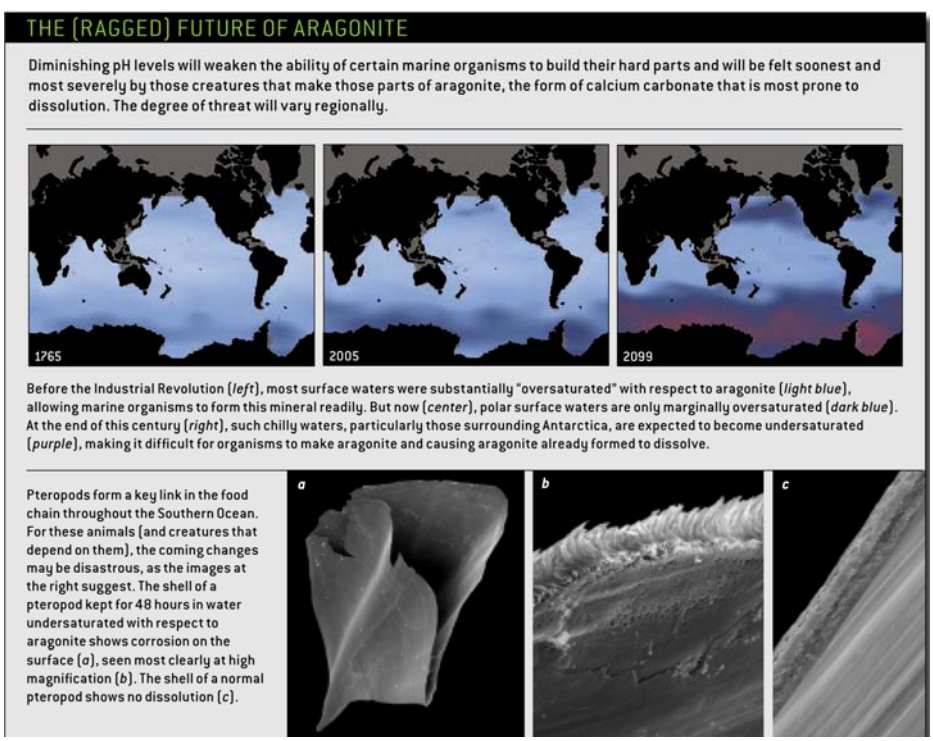
When CO_2 dissolves:

Net: $\mathbf{CO_2(aq) + CO_3^{2-} + H_2O \rightarrow 2\ HCO_3^-}$

Atmospheric CO_2	280 ppm Pre-Industrial	385 ppm Present Day	560 ppm 2 × Pre-Indus.
Ocean Carbon	2020×10^{-6} M	2070×10^{-6} M	2122×10^{-6} M
$[HCO_3^-]$	1772×10^{-6} M	1865×10^{-6} M	1957×10^{-6} M
$[CO_2\,(aq)]$	9.1×10^{-6} M	12.6×10^{-6} M	18.2×10^{-6} M
$[CO_3^{2-}]$	239×10^{-6} M	193×10^{-6} M	146×10^{-6} M
pH	8.32	8.20	8.06

Lecture 5, Slide 25

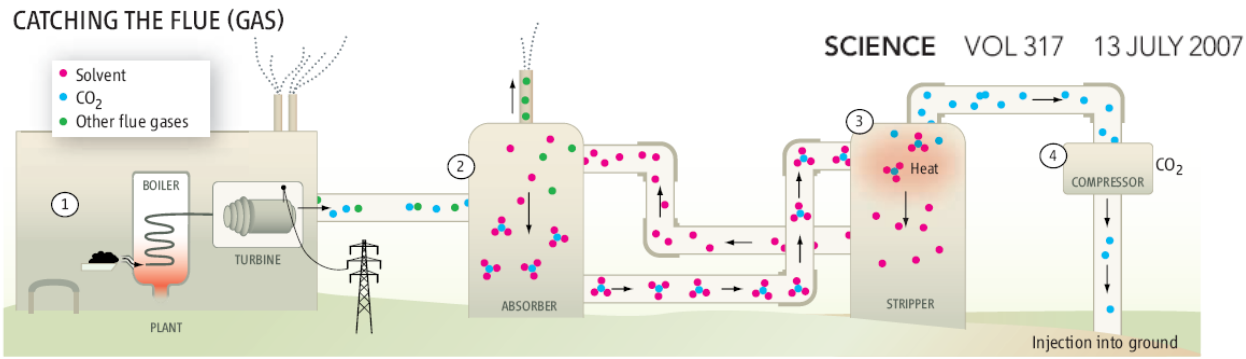
Ocean Acidification



Doney, The Dangers of Ocean Acidification, *Scientific American*, March, 2006

Lecture 5, Slide 31

Carbon Capture & Sequestration



How a retrofit works. (1) Most coal plants burn coal to create steam, running a turbine that produces electricity. After treatment for pollutants, the flue gas, a mixture of CO_2 (blue) and other emissions (green), goes out a smokestack. To collect CO_2 for storage, however, the mixture of gases is directed to an absorber (2), where a solvent like MEA (pink) bonds with the CO_2 molecules. The bonded CO_2–solvent complexes are separated in the stripper (3), which requires heat. More energy is needed for the next step (4), which produces a purified CO_2 stream for ground storage as well as solvent molecules that can be reused. (Schematic not to scale.)

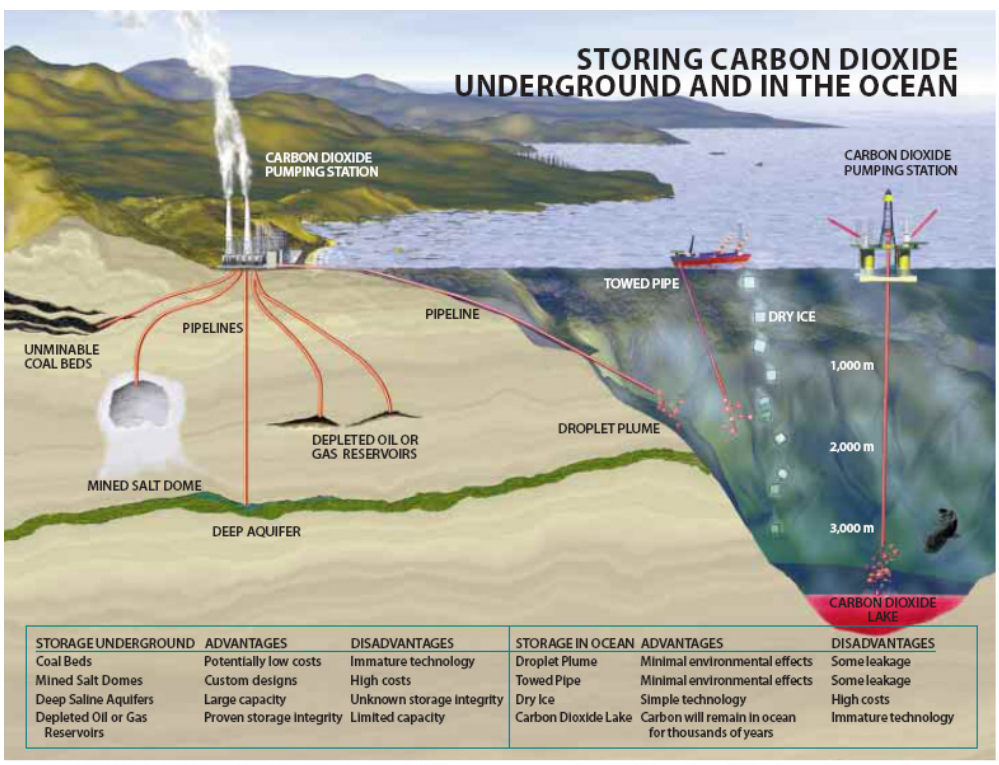
MEA-monoethanolamine $(CH_2CH_2OH)NH_2$ in an aqueous solution will absorb CO_2 to form ethanolammonium carbamate.

$$2RNH_2 + CO_2 + H_2O \rightarrow (RNH_3)_2CO_2$$

MEA is a weak base so it will re-release the CO_2 when heated

Kintisch, *Science*, 2007

Where to Place the Sequestered Carbon?



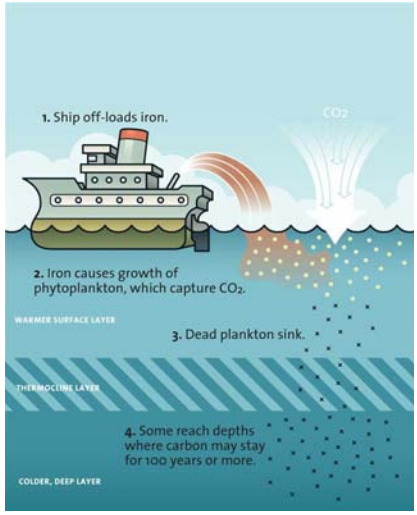
STORAGE UNDERGROUND	ADVANTAGES	DISADVANTAGES	STORAGE IN OCEAN	ADVANTAGES	DISADVANTAGES
Coal Beds	Potentially low costs	Immature technology	Droplet Plume	Minimal environmental effects	Some leakage
Mined Salt Domes	Custom designs	High costs	Towed Pipe	Minimal environmental effects	Some leakage
Deep Saline Aquifers	Large capacity	Unknown storage integrity	Dry Ice	Simple technology	High costs
Depleted Oil or Gas Reservoirs	Proven storage integrity	Limited capacity	Carbon Dioxide Lake	Carbon will remain in ocean for thousands of years	Immature technology

STORAGE SITES for carbon dioxide in the ground and deep sea should help keep the greenhouse gas out of the atmosphere where it now contributes to climate change. The various options must be scrutinized for cost, safety and potential environmental effects.

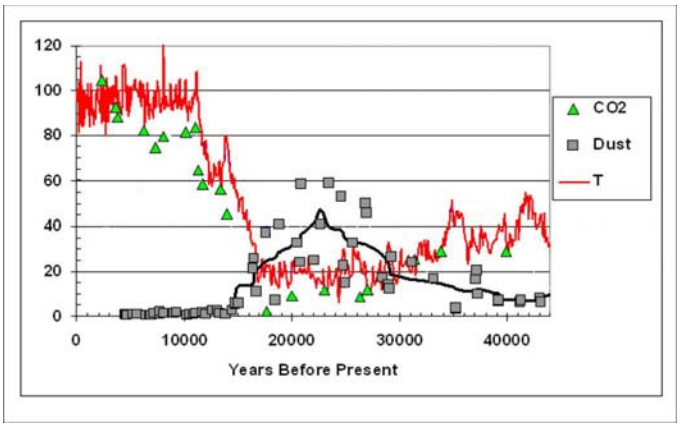
Herzog *et al.*, *Scientific American*, 2000

Sequestration of CO_2 from the Atmosphere: Oceanic 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: Oceanic Biology

- Numerous experiments have been conducted, many with "success": i.e., plankton blooms and increased ocean productivity, carbon export associated with regions that have been fertilized by iron
- A recent German study has shown that diatom population is limited by the availability of silica, as well as iron
- 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):

14 Jan 2009:

German science ministry halts iron fertilization in the Southern Ocean over concerns that environmental assessment must be completed before nutrient enhancement can begin.

UN Convention on Biological Diversity has called for a called for a moratorium on such experiments except at small scale in coastal waters

http://news.bbc.co.uk/2/hi/science/nature/7959570.stm

http://www.nature.com/news/2009/090114/full/news.2009.26.html

http://www.unesco.org/new/en/natural-sciences/ioc-oceans/single-view-oceans/news/ocean_fertilization_we_cannot_afford_to_gamble_with_the_ocean

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- 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:

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

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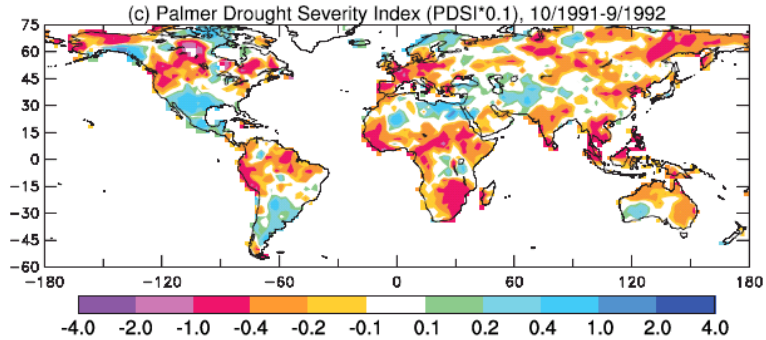
3.7 Ocean acidification

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

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**

Final Statements

It is difficult for people living now, who have become accustomed to the steady exponential growth in the consumption of energy from fossil fuels, to realize how transitory the fossil fuel epoch will eventually prove to be when it is viewed over a longer span of human history

M. King Hubbert, Scientific American, 1971
as quoted in foreword of
***When Oil Peaked* by Kenneth S. Deffeyes**

We believe that the development of renewable energy will be to students of your generation what the electronics & computer industry were to students of our generation: an opportunity for great innovation, entrepreneurial development, societal benefit, and also a very comfortable lifestyle for those who lead the "green revolution"

Ross Salawitch & Tim Canty