Geo-Engineering of Climate

AOSC / CHEM 433 & AOSC 633

Ross Salawitch & Walt Tribett

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2019

Today:

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

Lecture 23
9 May 2019

Course Logistics

- Problem Set #4 due today
  - Review will be held on Mon, 13 May, 6:30 pm
- Energy Plan (assigned only to 433 students) has also been posted
  - Several will be selected for presentation in class on 14 May
- Presentations/Paper (assigned to 633 students; 433 students can participate)
  - Mon, 13 May, 2 pm: Atlantic 3400
- Final Exam
  - Mon, 20 May, 10:30 am to 12:30 pm
  - **Please return *Chemistry in Context* to receive refund of your $20**
- Course evaluation website http://CourseEvalUM.umd.edu open until 15 May, 11:59 pm
  - No evaluations submitted as of last night
  - 70% of students must submit, in order for future students to see evaluations
  - ***Please complete evaluations for all of your classes***

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

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

Geo-engineering of climate garnered *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

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-engineering 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

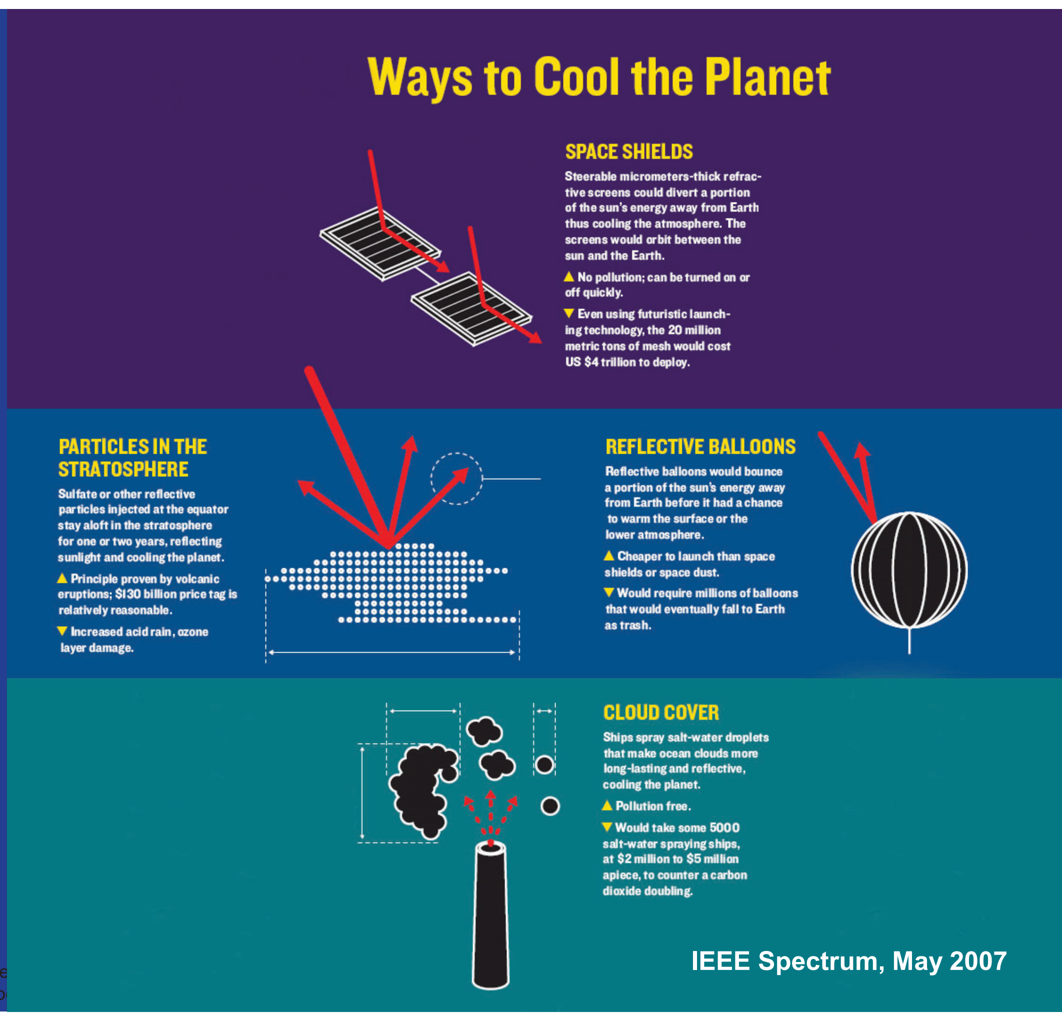
4. An albedo modification research program be developed and implemented that emphasizes multiple benefit research that also furthers both basic understanding of the climate system and its human dimensions

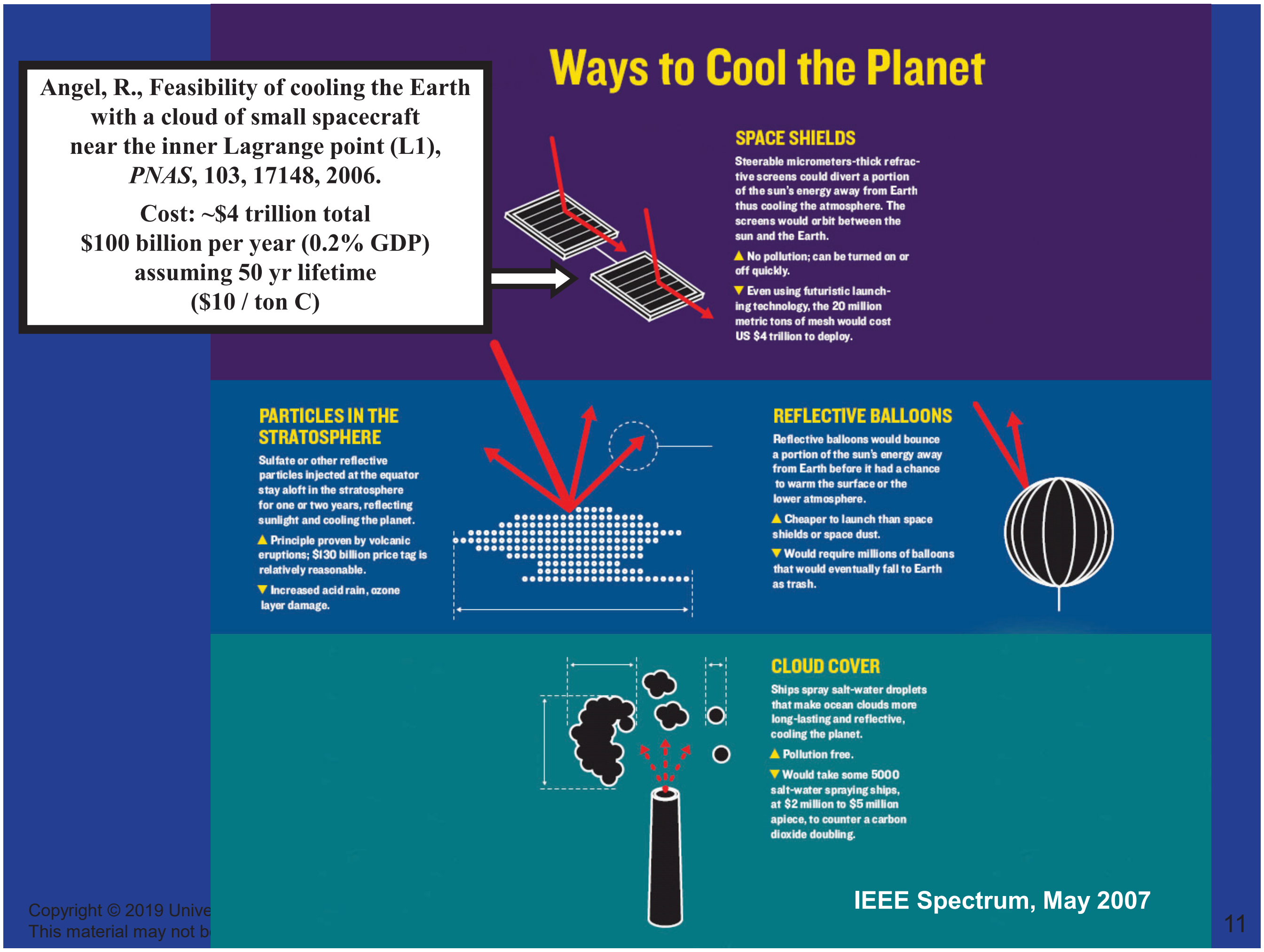
5. United States improve its capacity to detect and measure changes in radiative forcing and associated changes in climate

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




Angel, R., Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1), PNAS, 103, 17148, 2006.
Cost: ~$4 trillion total
$100 billion per year (0.2% GDP)
assuming 50 yr lifetime
($10 / ton C)
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
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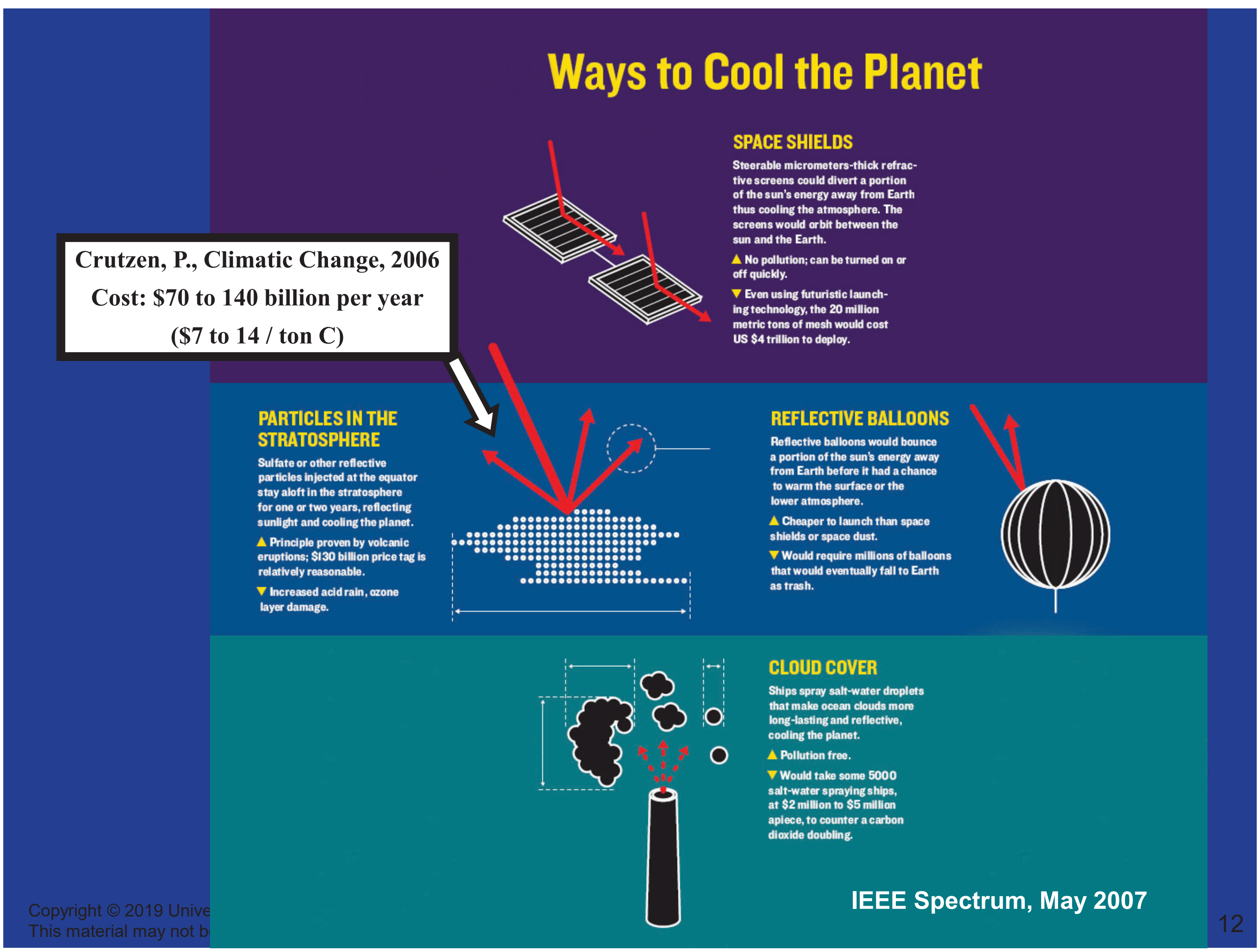
Crutzen, P., Climatic Change, 2006
Cost: $70 to 140 billion per year
($7 to 14 / ton C)
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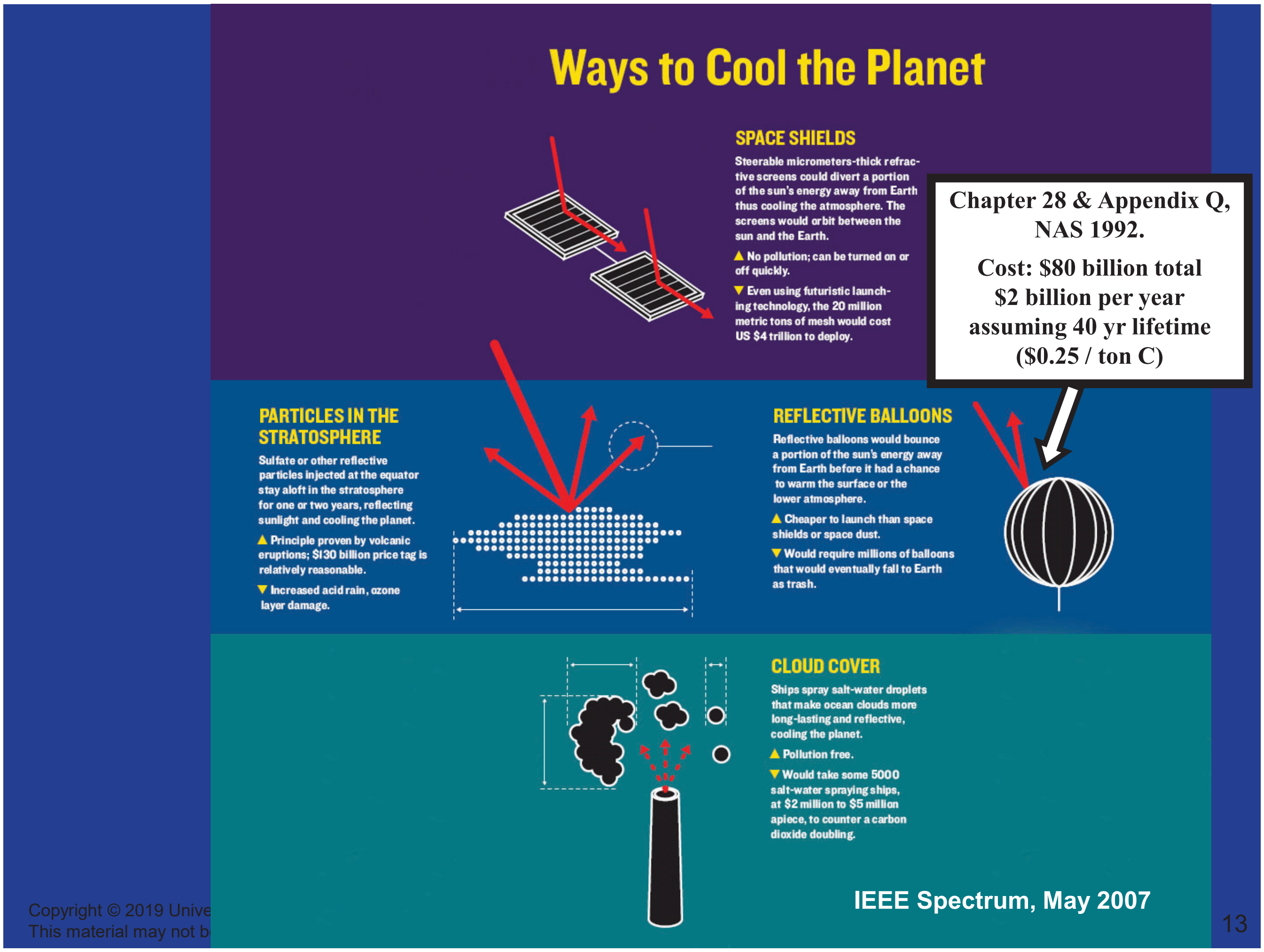
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Chapter 28 & Appendix Q, NAS 1992.
Cost: $80 billion total
$2 billion per year
assuming 40 yr lifetime
($0.25 / ton C)
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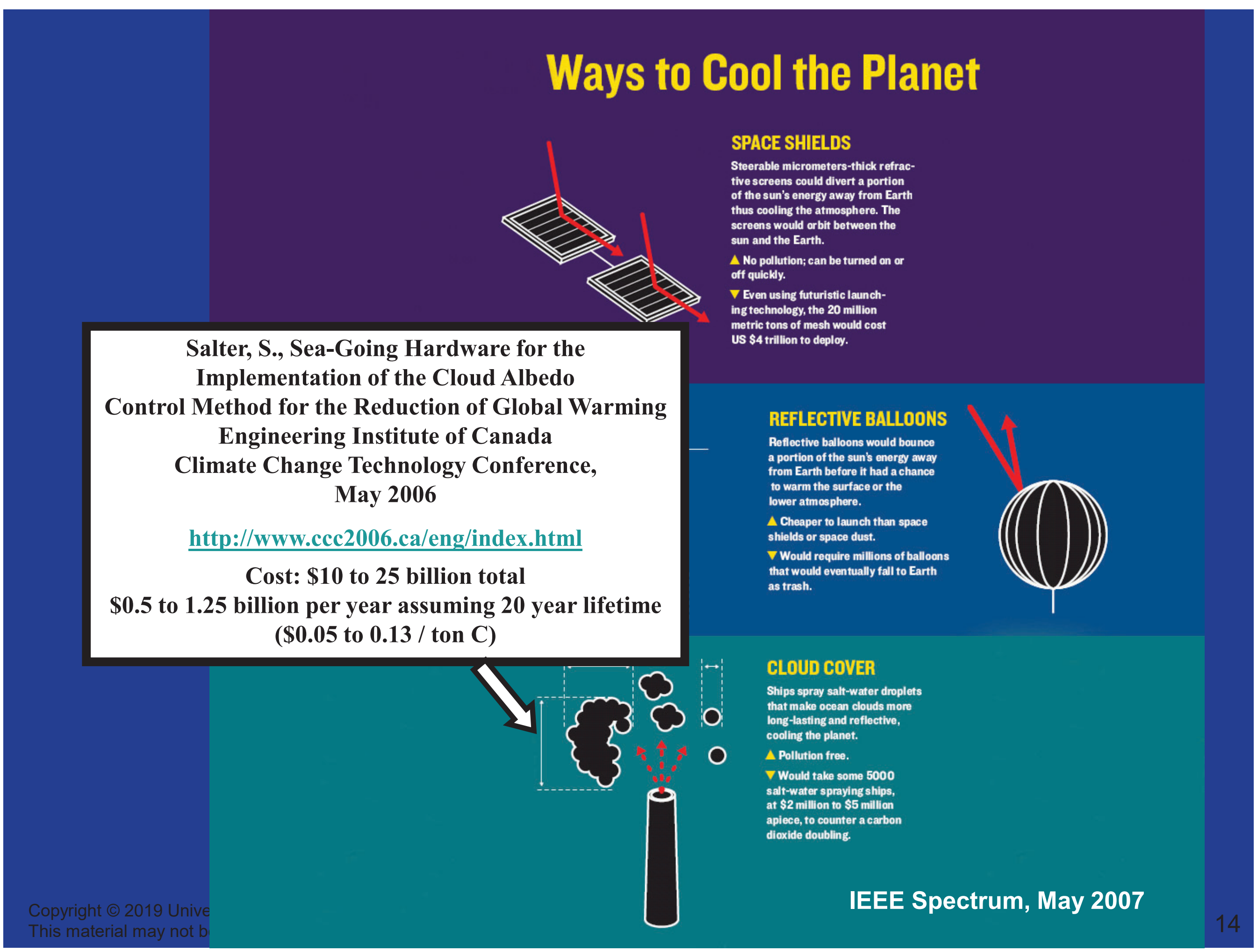
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Salter, S., Sea-Going Hardware for the Implementation of the Cloud Albedo Control Method for the Reduction of Global Warming
Engineering Institute of Canada
Climate Change Technology Conference, May 2006
http://www.ccc2006.ca/eng/index.html
Cost: $10 to 25 billion total
$0.5 to 1.25 billion per year assuming 20 year lifetime
($0.05 to 0.13 / ton C)
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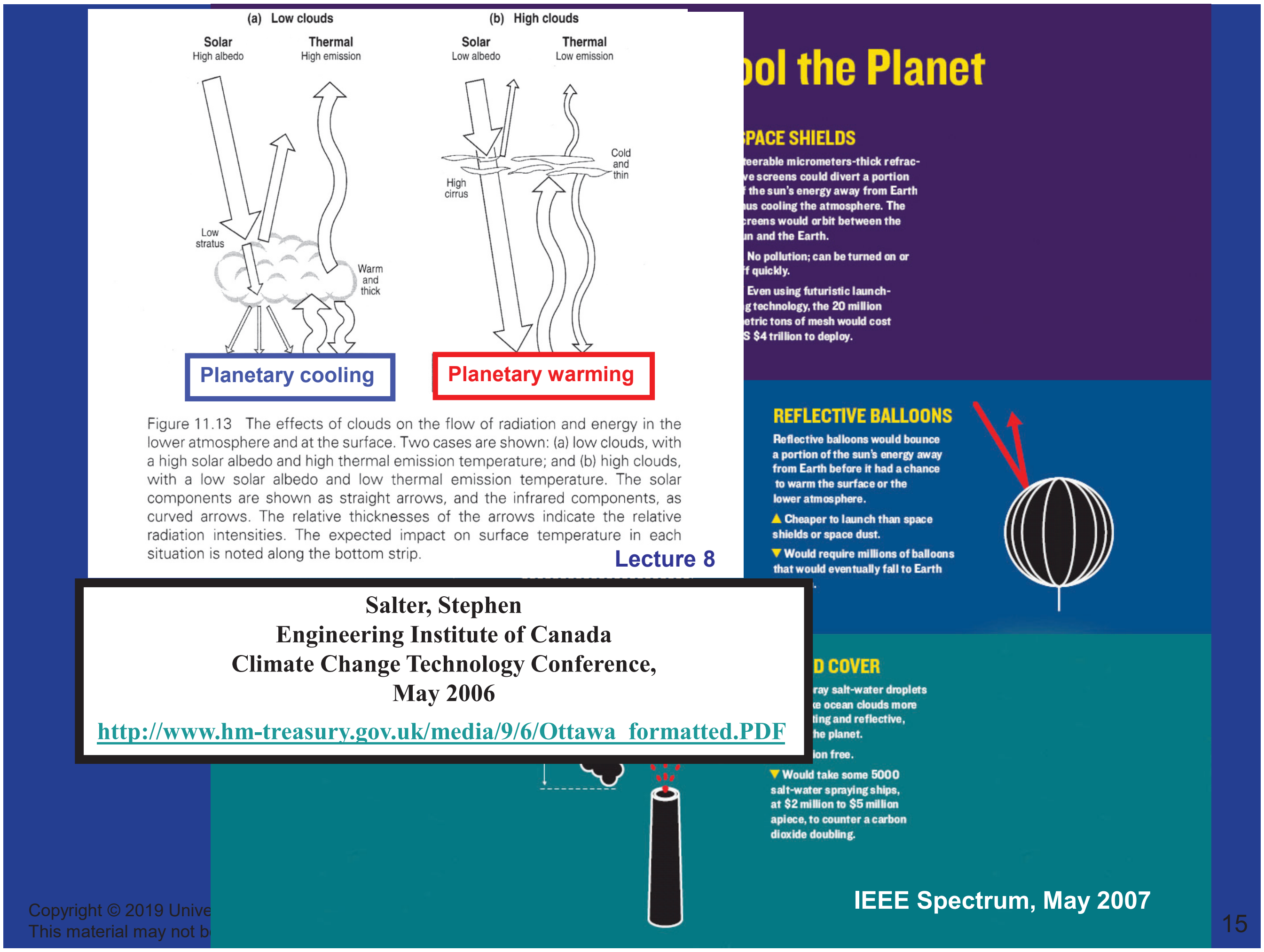


Geo-engineering of climate garnered lots of renewed attention with the publication, in August 2006, of an article entitled:

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?

RF of Climate due to GHGs and Aerosols

Lecture 8

- Past: tropospheric aerosols have offset some *unknown* fraction of GHG warming
- Future: this "mask" is going away due to air quality concerns

71 plausible scenarios for RF of climate due to Tropospheric aerosols (direct & indirect effect) from Smith and Bond (2012)

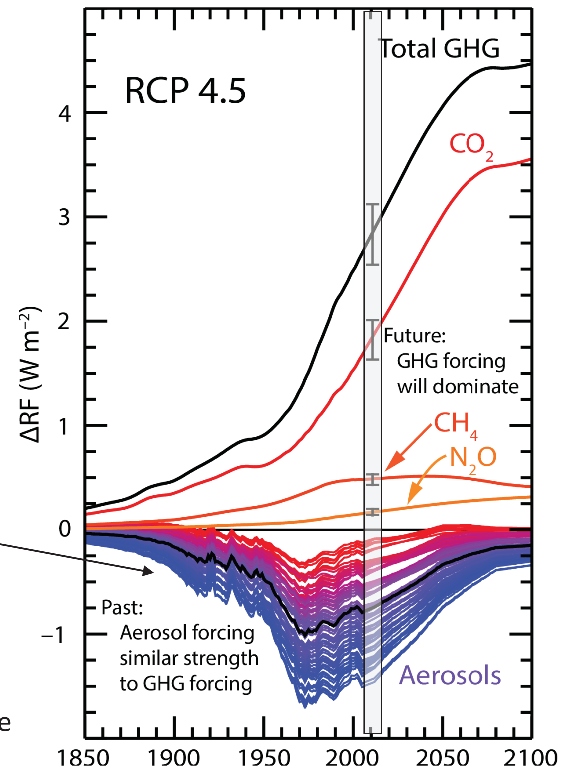


Figure 1-10, Paris Beacon of Hope

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

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

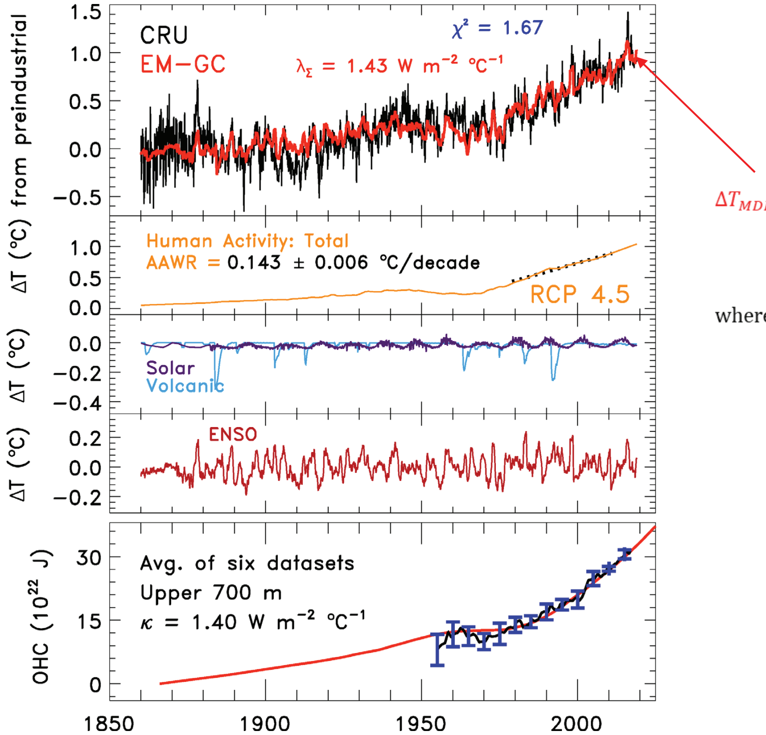
by Paul J. Crutzen : Climatic Change, 77, 211-219, 2006

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 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



$$\Delta T_{MDL\,i} = (1+\gamma)\left(\frac{GHG\ RF_i + LUC\ RF_i + Aerosol\ RF_i}{\lambda_p}\right) + C_0 + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2} + C_4 \times AMOC_i - \left(\frac{Q_{OCEAN\,i}}{\lambda_p}\right)$$

where:

i denotes month

λ_p = 3.2 W m^{-2}°C^{-1}

$1+\gamma = \{1 - \lambda_\Sigma/\lambda_p\}^{-1}$

GHG RF = RF due to all anthropogenic GHGs

LUC RF = RF due to Land Use Change

Aerosol RF = RF due to Tropospheric Aerosols

SOD = Stratospheric Optical Depth

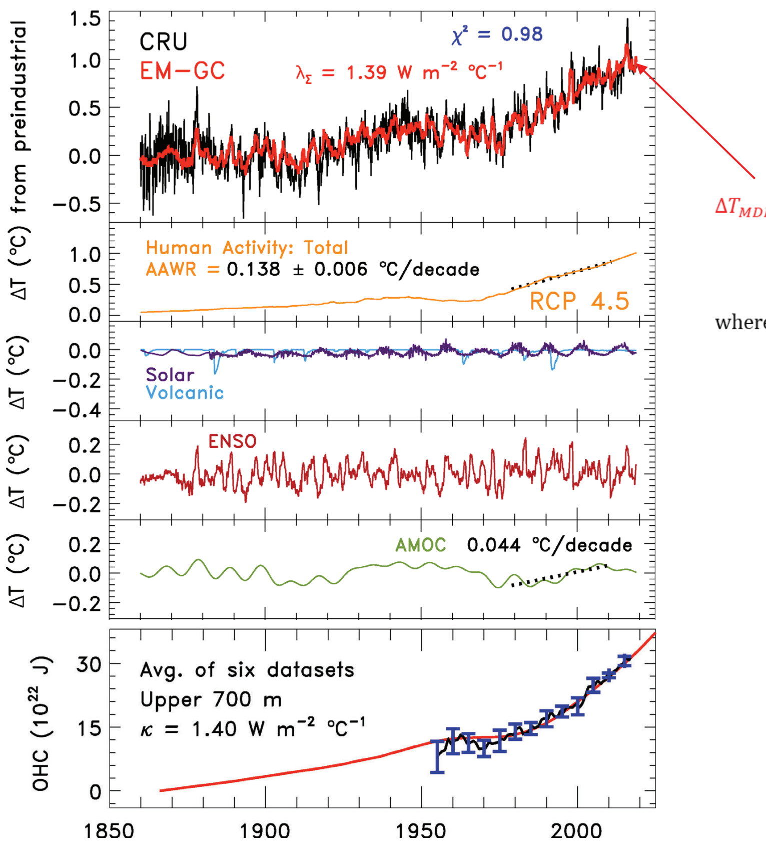
TSI = Total Solar Irradiance

ENSO = El Niño Southern Oscillation

Q_{OCEAN} = Ocean heat export = $\kappa(1+\gamma)\{\Delta T_{MDL\,i} - \Delta T_{OCEAN\ SURFACE\,i}\}$

After Canty *et al.*, *ACP*, 2013

First shown in Lecture 2. Also shown in Lectures 7 & 8



$$\Delta T_{MDL\,i} = (1+\gamma)\left(\frac{GHG\ RF_i + LUC\ RF_i + Aerosol\ RF_i}{\lambda_p}\right) + C_0 + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2} + C_4 \times AMOC_i - \left(\frac{Q_{OCEAN\,i}}{\lambda_p}\right)$$

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AMOC = Atlantic Meridional Overturning Circulation

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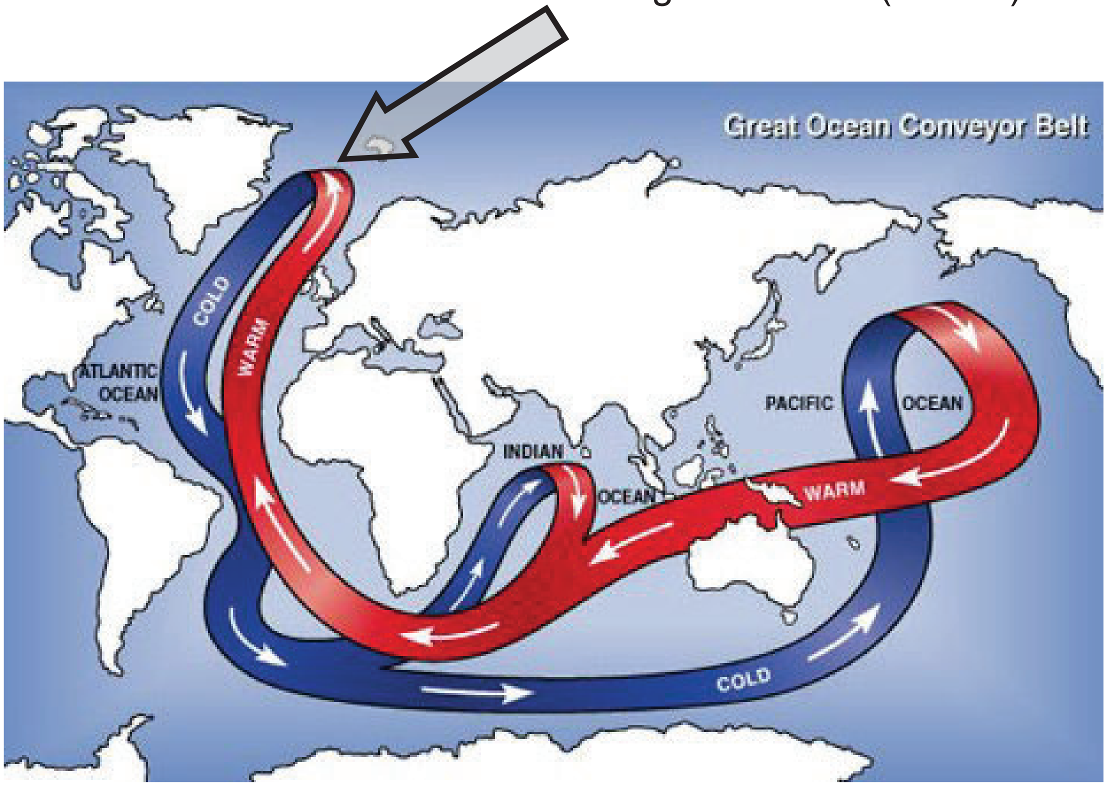
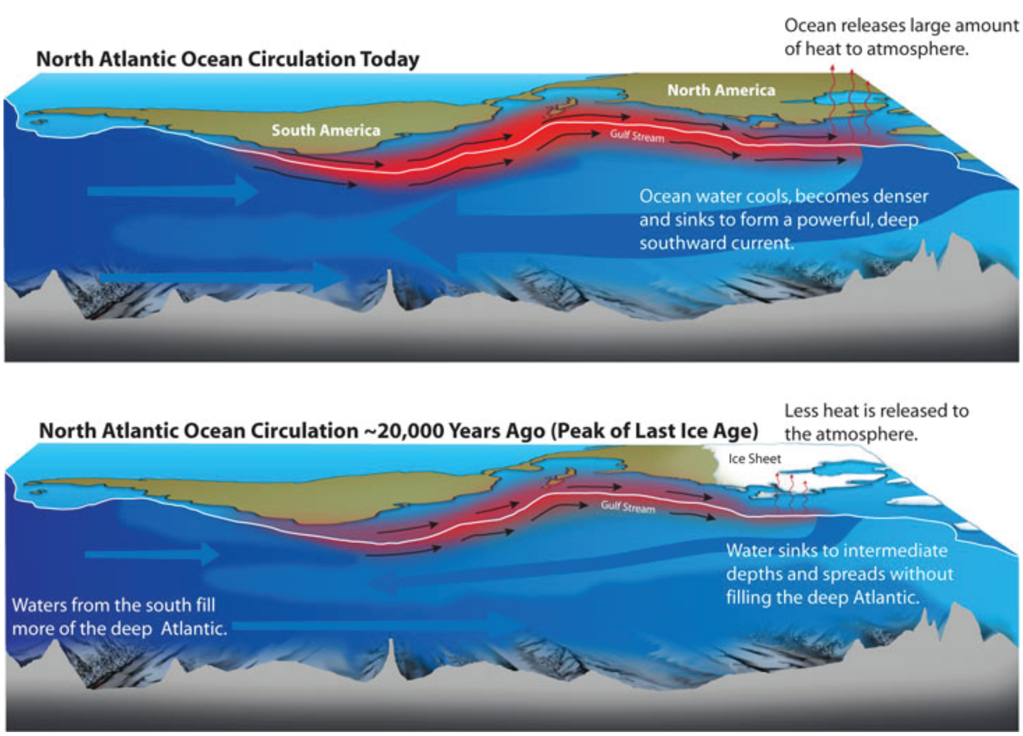
Atlantic Meridional Overturning Circulation (AMOC)



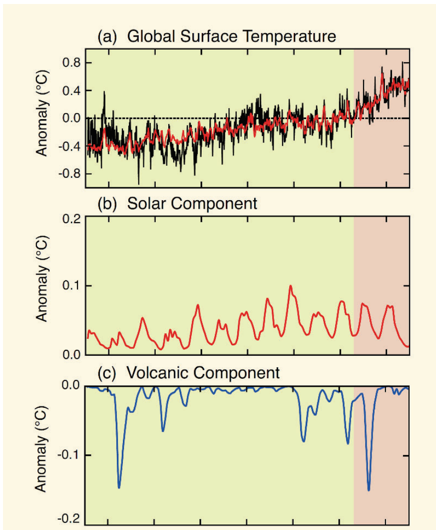
Atlantic Meridional Overturning Circulation (AMOC)

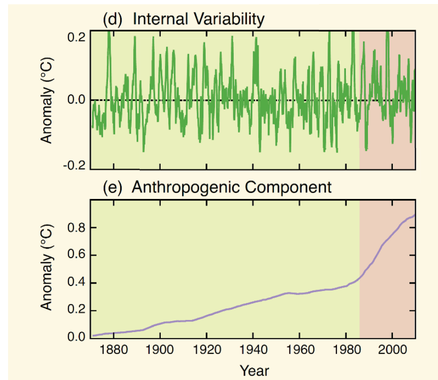


http://www.whoi.edu/cms/images/oceanus/2006/11/nao-en_33957.jpg

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 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}** ↓ surface radiative forcing
  0.5 ºC cooling
- Doubling CO_2 will result in ~ **3.7 W m^{-2}** ↑ surface radiative forcing

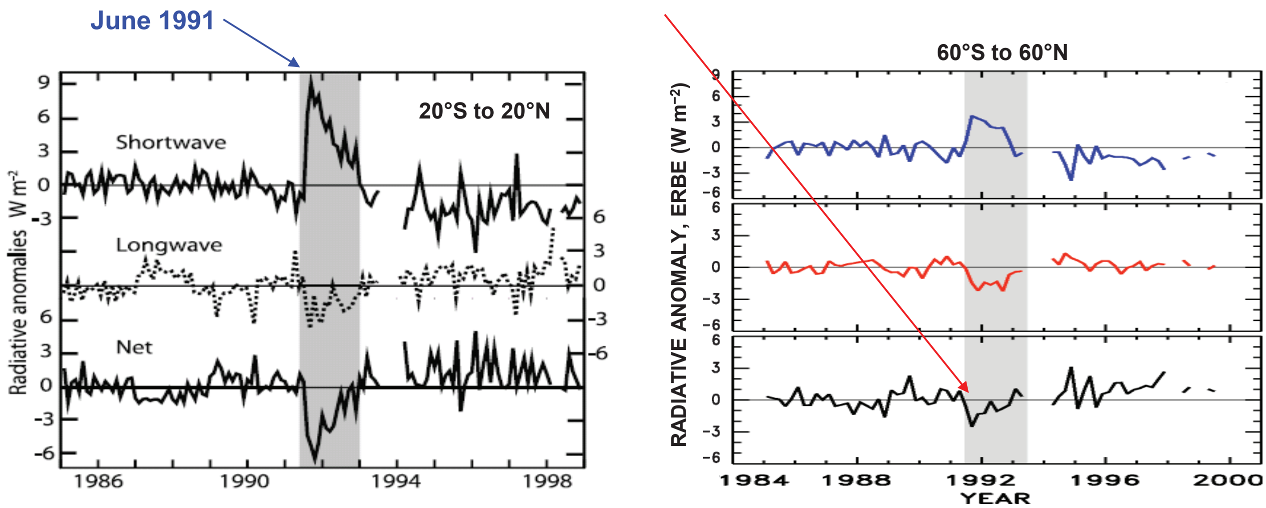
$$\Delta F \approx 5.35 \text{ W m}^{-2} \ln\left(\frac{CO_2^{\ Final}}{CO_2^{\ Initial}}\right) = 5.35 \text{ W m}^{-2} \ln(2) =$$

Lecture 4

• Mt Pinatubo: $\Delta S_{STRATOSPHERE} \approx$ **6 Tg** $\Rightarrow$ **4.5 W m^{-2}** ↓ surface radiative forcing
0.5 ºC cooling

• Doubling CO_2 will result in ~ **3.7 W m^{-2}** ↑ surface radiative forcing

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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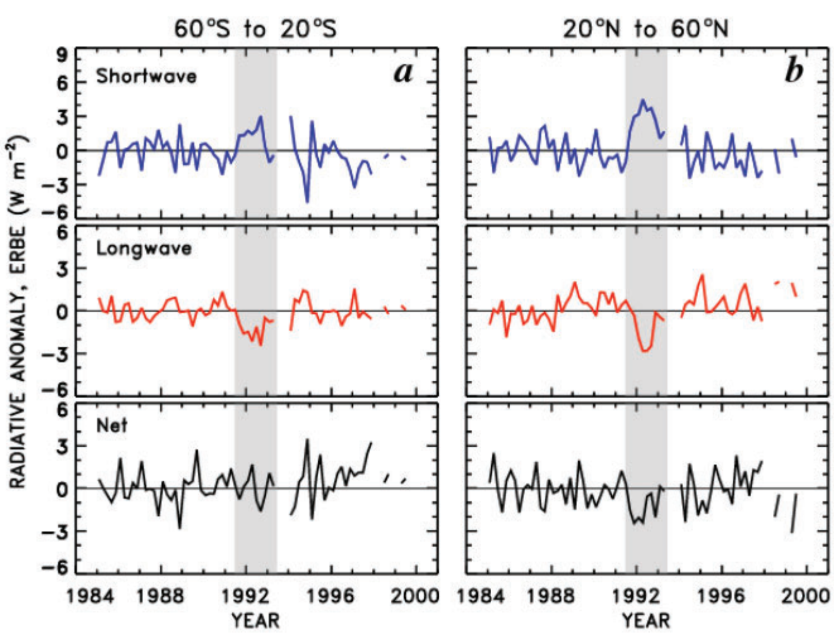
0.5 ºC cooling

• Doubling CO_2 will result in ~ **3.7 W m^{-2}** ↑ surface radiative forcing

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



Canty et al., *ACP*, 2013

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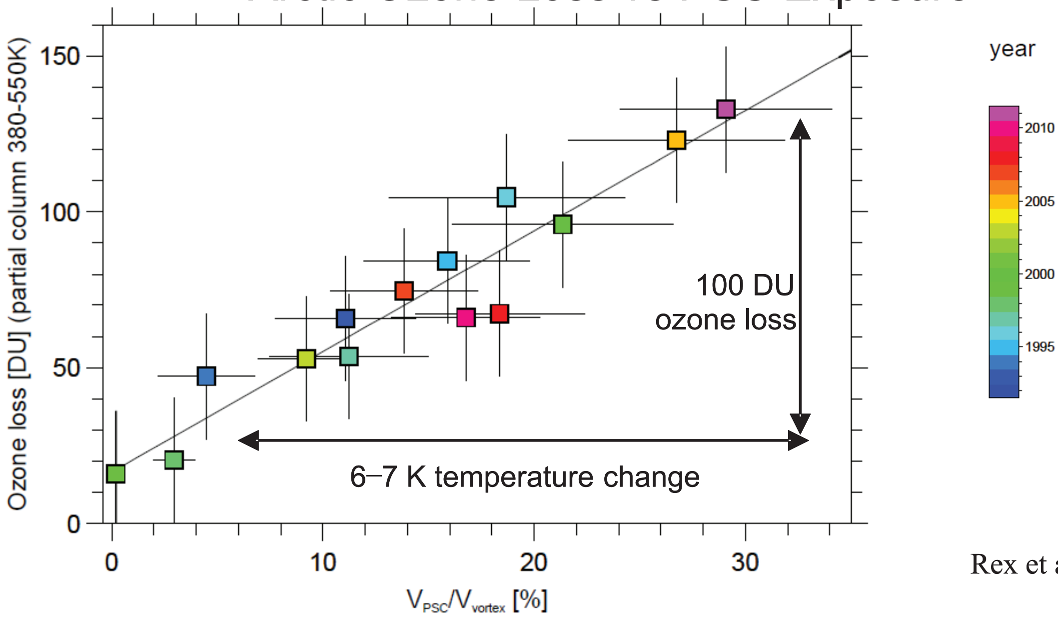
- Requires **5.3 Tg** perturbation to stratospheric S to counter
  - requires continuous injection of 2.65 to 5.3 Tg S per year (due to 2 or 1 yr $\tau_{STRATOSPHERE}$)
  - estimated cost \$70 to 140 billion per year (\$70 to 140 per capita of affluent world)
  - for comparison: annual military expenditures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

Will the response of *<u>polar ozone</u>* 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

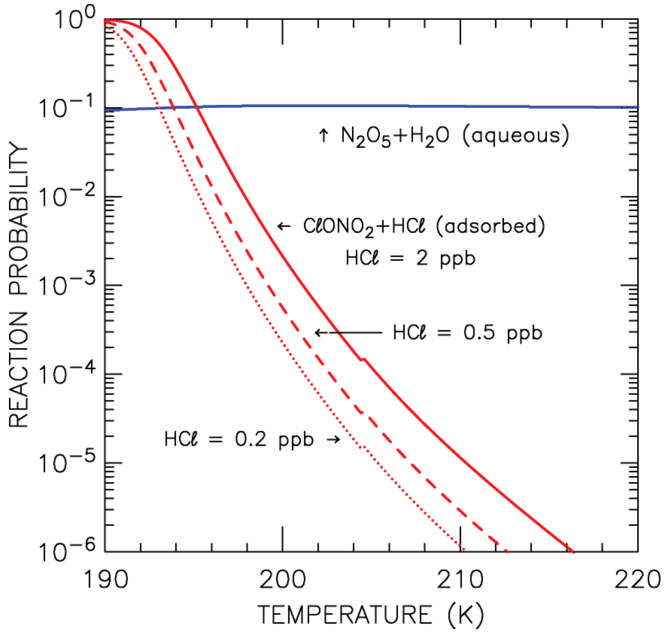


Rex et al., GRL, 2006

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

Lecture 15

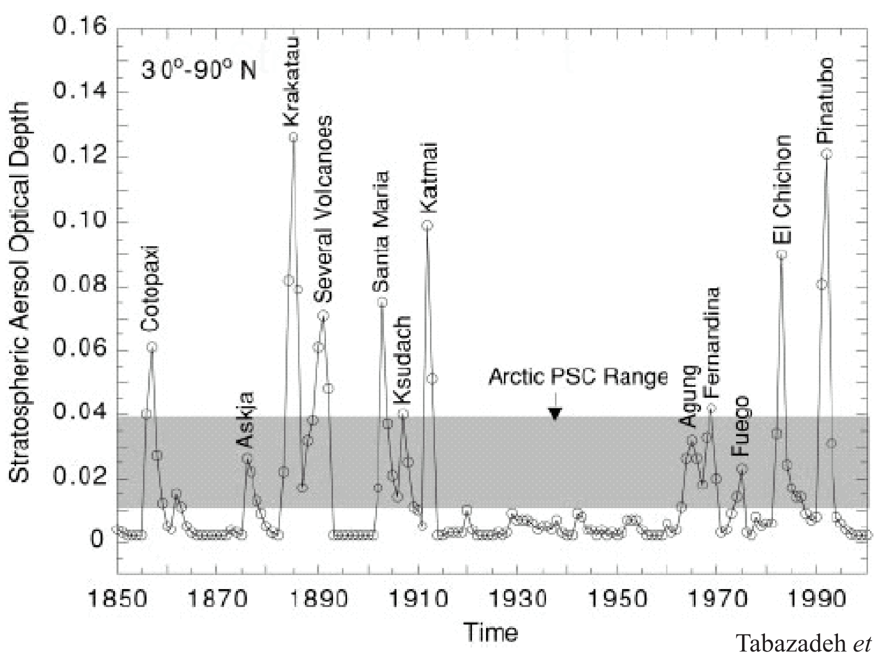
Chlorine Activation



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

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

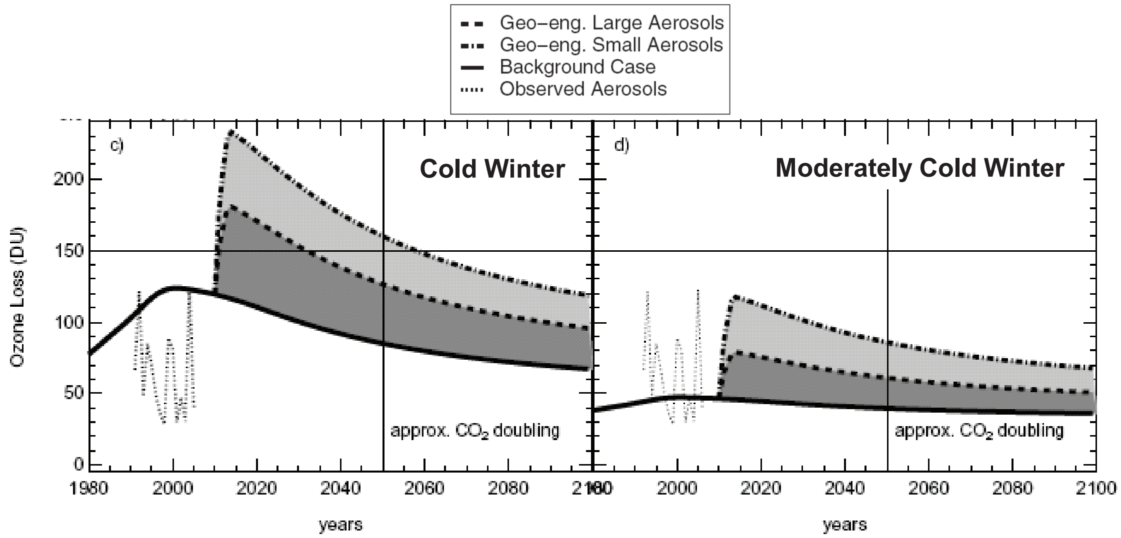
Lecture 11



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 !**

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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- 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: cited 256 times, and counting!)

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?

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- National Academy of Sciences (2015):

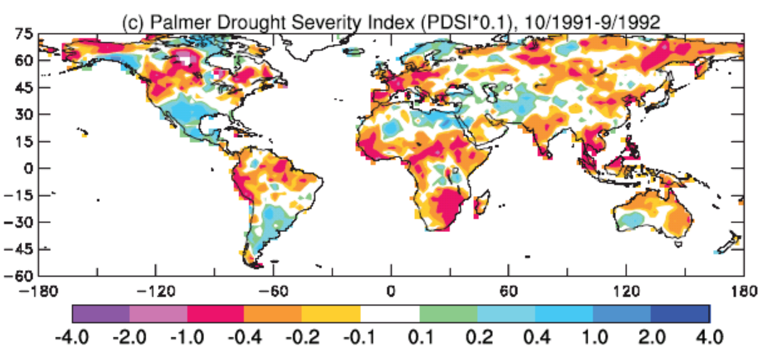
Tilmes et al. (2009; 2008), Heckendorn et al. (2009) and Pitari (2014) explored the impact of SAAM on ozone depletion, and concluded that SAAM (Stratospheric Aerosol Albedo Modification) sufficient to counter a doubling of CO_2 would **delay ozone recovery** (due to the decrease in halogens) by a few 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 <u>good position</u> 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**
- **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 <u>August 2006</u>, of an article entitled:

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

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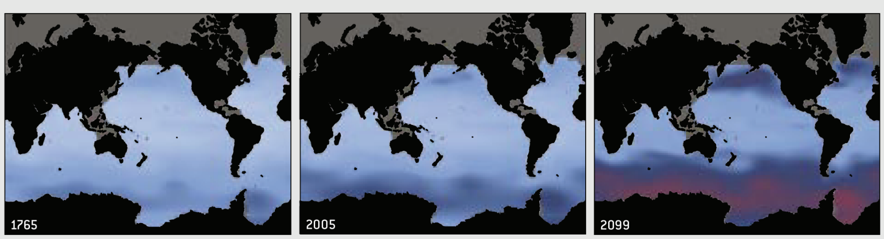
"Very best if emissions of GHGs could be reduced so that the stratospheric sulfur release experiment would not need to take place. Currently, this looks like a pious wish."

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

Ocean Acidification

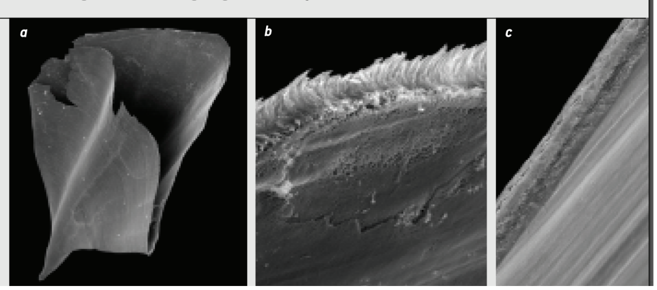
THE (RAGGED) FUTURE OF ARAGONITE

Diminishing pH levels will weaken the ability of certain marine organisms to build their hard parts and will be felt soonest and most severely by those creatures that make those parts of aragonite, the form of calcium carbonate that is most prone to dissolution. The degree of threat will vary regionally.



Before the Industrial Revolution (*left*), most surface waters were substantially "oversaturated" with respect to aragonite (*light blue*), allowing marine organisms to form this mineral readily. But now (*center*), polar surface waters are only marginally oversaturated (*dark blue*). At the end of this century (*right*), such chilly waters, particularly those surrounding Antarctica, are expected to become undersaturated (*purple*), making it difficult for organisms to make aragonite and causing aragonite already formed to dissolve.

Pteropods form a key link in the food chain throughout the Southern Ocean. For these animals (and creatures that depend on them), the coming changes may be disastrous, as the images at the right suggest. The shell of a pteropod kept for 48 hours in water undersaturated with respect to aragonite shows corrosion on the surface (*a*), seen most clearly at high magnification (*b*). The shell of a normal pteropod shows no dissolution (*c*).

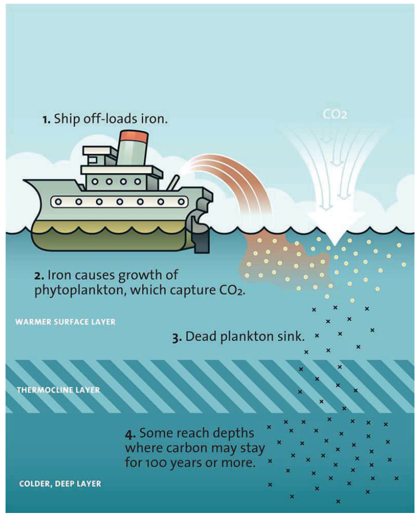


Doney, The Dangers of Ocean Acidification, *Scientific American*, March, 2006

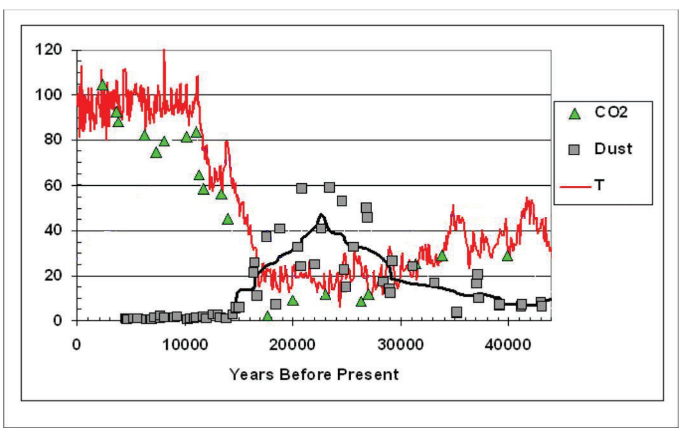
Lecture 5

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

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 4

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)

Biogeosciences, 7, 4017–4035, 2010

- Academic research continues:

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

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  - Particularly Sensitive Sea Areas

Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter

The "Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972", the "London Convention" for short, is one of the first global conventions to protect the marine environment from human activities and has been in force since 1975. Its objective is to promote the effective control of all sources of marine pollution and to take all practicable steps to prevent pollution of the sea by dumping of wastes and other matter. Currently, 87 States are Parties to this Convention.

In 1996, the "London Protocol" was agreed to further modernize the Convention and, eventually, replace it. Under the Protocol all dumping is prohibited, except for possibly acceptable wastes on the so-called "reverse list". The Protocol entered into force on 24 March 2006 and there are currently 48 Parties to the Protocol.

These pages include general information for the public and for States interested in becoming Parties to the London Protocol 1996. Please click on the links to the left for further information on related issues.

Information about the Convention and the Protocol can also be found in the information leaflet (currently available in English only) which contains details on what the London Convention is, achievements to date, the potential benefits and cost of membership, a shortlist of the current activities under the instruments and their relationship with other international agreements.

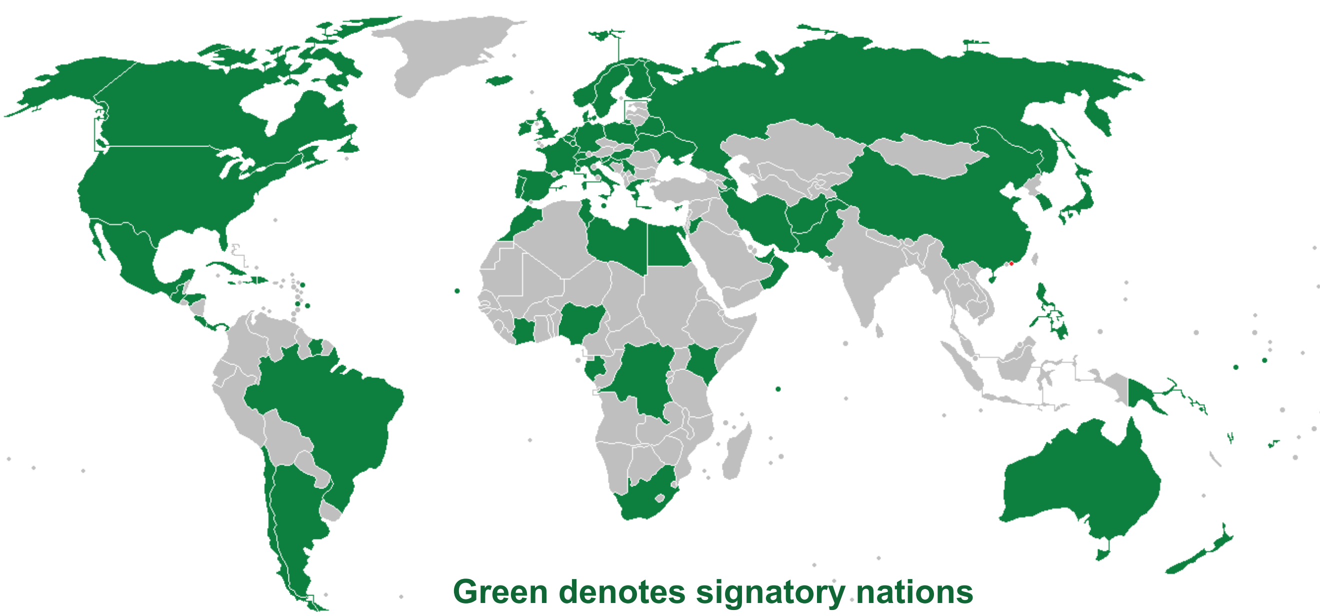
LC&P

LC&P LONDON CONVENTION AND PROTOCOL

Related Documents

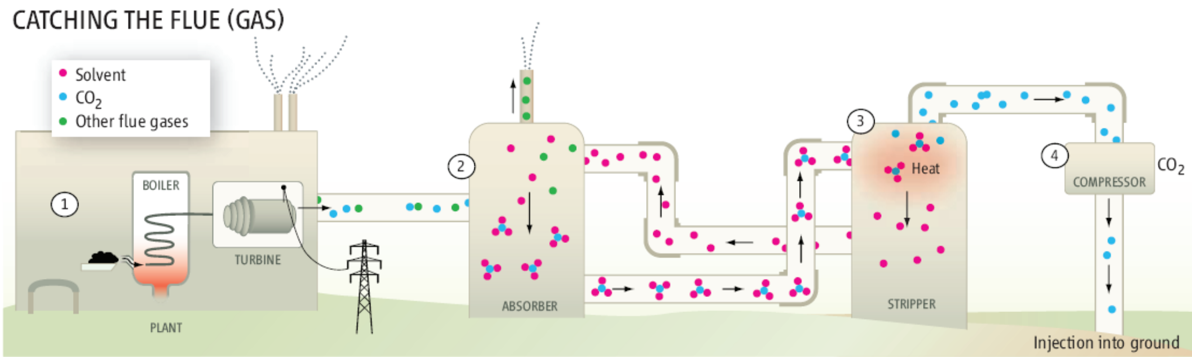
http://www.imo.org/OurWork/Environment/LCLP/Pages/default.aspx

Sequestration of CO_2 from the Atmosphere: Ocean Biology



https://en.wikipedia.org/wiki/London_Convention_on_the_Prevention_of_Marine_Pollution_by_Dumping_of_Wastes_and_Other_Matter#/media/File:London_Convention_signatories.png

Sequestration of CO_2 from Power Plants



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.)

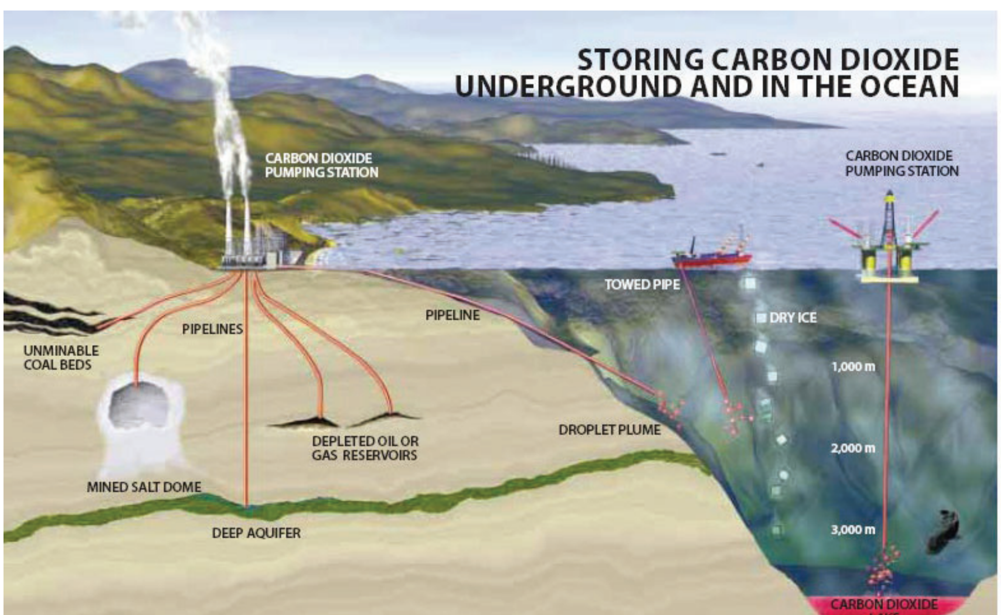
MEA-monoethanolamine $(CH_2CH_2OH)NH_2$ in an aqueous solution will absorb CO_2 to form ethanolammonium carbamate.

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

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

Kintisch, *Science*, 2007

Sequestration of CO_2 from Power Plants



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 Power Plants

Sleipner, Norway

National Geographic, June 2008

- North Sea natural gas field: enormous capacity
- Captures ~90% of CO_2 that is generated
- CO_2 pumped into 200 m thick sandstone layer 720 m below sea floor
- Project initiated in response to **$50 ton tax on CO_2 emissions** instituted by Norwegian Government in 1996
- Investment in capital cost paid off in about one and a half years !

Sequestration of CO_2 from Power Plants: Cost

CCS component	Cost range	
Capture from a power plant	15–75 US$/t$CO_2$ net captured	~$45/ tonne
Capture from gas processing or ammonia production	5–55 US$/t$CO_2$ net captured	
Capture from other industrial sources	25–115 US$/t$CO_2$ net captured	
Transportation	1–8 US$/t$CO_2$ transported per 250km	~$4.5/ tonne
Geological storage	0.5–8 US$/t$CO_2$ injected	~$4.5/ tonne
Ocean storage	5–30 US$/t$CO_2$ injected	
Mineral carbonation	50–100 US$/t$CO_2$ net mineralized	

Cost of capture: **~$54 / ton** CO_2 × 11 × 10^9 tonne C / yr × (44/12) × 0.5 = **$ 1.1 trillion**
Global GDP, 2017: **$ 75 trillion** CO_2 capture = **1.5 % of world GDP**

⇦ Back of the envelope analysis ⇧

Revised estimate is ~**$80 per ton of CO_2** (median) for capture, transport, and storage, based on the work of the group of Professor Edward Rubin at Carnegie Mellon University:
https://www.cmu.edu/epp/people/faculty/edward-s-rubin.html

Cost of capture: **~$80 / ton** CO_2 × 11 × 10^9 tonne C / yr × (44/12) × 0.5 = **$ 1.6 trillion**
Global GDP, 2017: **$ 75 trillion** CO_2 capture = **2.1 % of world GDP**

Regional Greenhouse Gas Initiative “RGGI”

http://www.rggi.org

- RGGI caps CO_2 emissions from region’s fossil fuel power plants (> 25 Mega Watt)
  - Regional CO_2 emissions held constant from 2009 through 2014
  - Beginning 2014 regional CO_2 emissions decrease for a total reduction of 10% by 2018
  - All fossil fuel fired facilities must own allowances equal to their annual CO_2 emissions
- **9 States are now part of RGGI**
  - Each state has an emissions cap
  - Regional market for CO_2 emission allowances
  - New Jersey is about to rejoin
- Maryland joined on 20 April 2007
  - Bill passed in Annapolis
  - Participation governed by Md Dept of the Environment (MDE)

2018

State	Emissions Cap (Tons CO_2)
CT	3,905,571
DE	2,761,772
MA	9,739,612
ME	2,173,277
NH	3,149,261
NY	23,494,281
RI	971,486
VT	447,824
MD	*13,701,106*
TOTAL	60,344,190

https://www.rggi.org/sites/default/files/Uploads/Allowance-Tracking/2018_Allowance-Distribution.xls
https://www.outdoors.org/articles/blogs/conservation-blog/new-jersey-rggi

Regional Greenhouse Gas Initiative “RGGI”

http://www.rggi.org

Allowance Distribution

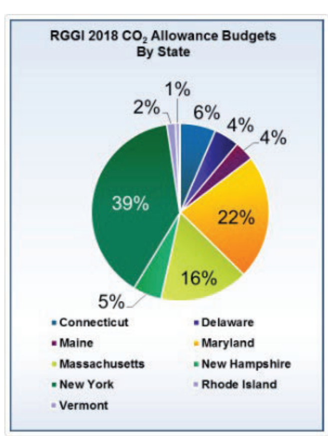
CO_2 allowances are issued by each RGGI state in an amount defined in each state's applicable statute and/or regulations. Together, all the CO_2 allowances issued by all the RGGI states comprise the RGGI cap.

Most allowances are distributed at auction, but a limited amount may be held in set-aside accounts and distributed according to state-specific programs. For a list of state-specific set-aside programs, see this summary document.

The trackers below offer more detail on the distribution of allowances, organized by allocation year. Note that the allocation year of the allowance does not necessarily equal the year that the allowance was distributed. Trackers are updated to account for any changes to the status of past allocation years' allowances (such as retirement or distribution from set-aside accounts).

Distribution of 2018 Allocation Year CO_2 Allowances

The RGGI 2018 cap is 82.2 million short tons. The RGGI 2018 adjusted cap is 60.3 million short tons. For more details on the distribution of CO_2 allowances by state, download the full data here: [PDF] [XLS]



https://www.rggi.org/allowance-tracking/allowance-distribution

How Do the RGGI Auctions Operate?

The auctions operate in a single-round, uniform-price sealed-bid format. Each participant has one opportunity to submit one or more undisclosed bids as well as the quantity of allowances (in multiples of 1,000) that they are willing to purchase at that price.

The bids are then ranked from high to low and allowances are tentatively awarded in this order until cumulative demand is greater than the supply of allowances offered for sale. All allowances are then sold at a clearing price determined by the value of the highest rejected bid.

Bidder	Bidder's Offering price	Number of Allowances	Cumulative Demand
Edward	$7.50	10,000 ✓	10,000
Ann	$6.25	10,000 ✓	20,000
Charlie	$6.10	5,000 ✓	25,000
Edward	$5.50	15,000 ✓	40,000
Diane	$4.75	10,000 ✓	50,000
Charlie	$4.75	10,000 ✓	60,000
Bernie	$4.50	15,000 ✓	75,000
Ann	$4.10	20,000 ✓	95,000
Edward	$3.95	10,000 /	105,000
Bernie	$3.70	20,000 ✗	125,000
Diane	$3.50	20,000 ✗	145,000

100,000 CO_2 allowances are available for sale at auction.

Cumulative demand is met at Edward's $3.95 bid, so all bids above this are winning bids, and allowances will be awarded in the full amount requested. Edward will also be awarded the remaining 5,000 allowances toward his $3.95 bid.

This auction has awarded all 100,000 CO_2 allowances which were offered; with an additional 45,000 more allowances being sought for purchase than were available.

All 100,000 allowances will be awarded at the clearing price of $3.95. The total proceeds from this auction are $395,000.

http://www.mde.state.md.us/programs/Air/ClimateChange/RGGI/Pages/RGGI-Auctions.aspx

Cost of Fossil Fuels

- Fuel cost per ton of CO_2 released to the atmosphere (U.S., summer 2018):
  - Coal: $18
  - Natural Gas: $67
  - Gasoline: $290
- Current Regional Greenhouse Gas Initiative (RGGI) auction price: $5.27 per ton of CO_2

Allowance Prices and Volumes

Auction	Date	Quantity Offered	CCR Sold	Quantity Sold	Clearing Price	Total Proceeds
Auction 43	2019-03-13	12,883,436	0	12,883,436	$5.27	$67,895,707.72
Auction 42	2018-12-05	13,360,649	0	13,360,649	$5.35	$71,479,472.15
Auction 41	2018-09-05	13,590,107	0	13,590,107	$4.50	$61,155,481.50
Auction 40	2018-06-13	13,771,025	0	13,771,025	$4.02	$55,359,520.50
Auction 39	2018-03-14	13,553,767	0	13,553,767	$3.79	$51,368,776.93
Auction 38	2017-12-06	14,687,989	0	14,687,989	$3.80	$55,814,358.20
Auction 37	2017-09-06	14,371,585	0	14,371,585	$4.35	$62,516,394.75
Auction 36	2017-06-07	14,597,470	0	14,597,470	$2.53	$36,931,599.10
Auction 35	2017-03-08	14,371,300	0	14,371,300	$3.00	$43,113,900.00
Auction 34	2016-12-07	14,791,315	0	14,791,315	$3.55	$52,509,168.25
Auction 33	2016-09-07	14,911,315	0	14,911,315	$4.54	$67,697,370.10
Auction 32	2016-06-01	15,089,652	0	15,089,652	$4.53	$68,356,123.56
Auction 31	2016-03-09	14,838,732	0	14,838,732	$5.25	$77,903,343.00

Afforestation

- If 100,000 km^2 (size of Ireland) was re-planted every year, for 40 years (size of Australia) would sequester between 20 and 50 Gt of C from the atmosphere
- ⇨ between **5** and **10** % of emissions, 2015 to 2055
- Land available ✓ Cost ✓
- But:
  - forests are dark … as albedo declines, T rises, particularly in winter
  - once trees are fully grown, sequestration stops (yikes)
  - offset is small fraction of total projected C emission and we have used an area the size of Australia (yikes yikes)

http://www.worldlandtrust.org/images/places/brazil/wetland-before-after-joy-and-mick-braker-vl.jpg

Sequestration of CO_2 from the Atmosphere: Burial of Trees

- Prof Ning Zeng (UMCP) advocates planting, harvesting, and burial of rapidly growing trees (proposal is to collect dead trees on forest floor and selectively log live trees)
- Meetings have been held to discuss this idea:
- A UMd Gemstone Project has addressed this issue
  http://teams.gemstone.umd.edu/classof2010/carbonsinks

- Statements from Zeng, Carbon Sequestration Via Wood Burial, *Carbon Balance and Management*, 2008 http://www.cbmjournal.com/content/3/1/1 :

  – Here I suggest an approach in which wood from old or dead trees in the world's forests is harvested & buried in trenches under a layer of soil, where the anaerobic condition slows the decomposition of the buried wood.

  – Because of low oxygen below the soil surface, decomposition of buried wood is expected to be slow