Geo-Engineering of Climate

AOSC / CHEM 433 & AOSC / CHEM 633

Ross Salawitch

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2020

Today:

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

Lecture 23

10 December 2020

Announcements: Class

Dear Ross Salawitch

The evaluation period for one or more of the courses you are teaching is now open. You can help improve response rates and the quality of feedback you receive by expressing interest to your students in their feedback, such as offering an example of how you've used evaluations to improve your course. You also can offer class time to have students complete evaluations on a computer or mobile device. Students are being sent emails announcing that evaluations are open, with instructions about how to access their evaluations.

Live, on-demand access to response rates for sections you teach is available within CourseEvalUM! Just login to CourseEvalUM using the link below, and click View Response Rate Monitor.

Login to CourseEvalUM: https://CourseEvalUM.umd.edu
CourseEvalUM Help Center: https://confluence.umd.edu/display/courseeval/

Course Evaluations Currently Open*	Evaluation Start Date	Deadline	Responses
202008-AOSC633-0101-ATMSPHRC CHEM & CLIMATE	December 03, 2020	December 15, 2020	0 of 2
202008-CHEM433-0101-ATMSPHRC CHEM & CLIMATE	December 03, 2020	December 15, 2020	0 of 6
202008-CHEM633-0101-ATMSPHRC CHEM & CLIMATE	December 03, 2020	December 15, 2020	5 of 8
202008-AOSC433-0101-ATMSPHRC CHEM & CLIMATE	December 03, 2020	December 15, 2020	3 of 7

Which courses are evaluated?

Created by Michael Passarella-George, last modified on Apr 08, 2019

We aim to include as many courses as we can in course evaluations. All credit-bearing course sections that are not flagged in SIS as Individual Instruction courses (e.g. internships, student teaching) or cohort tracking courses (e.g. MSBA) are expected to be evaluated. A small number of classes that end very early during the semester or after it is over also will not be evaluated. ***Beginning Fall 2016, course sections with fewer than five enrolled students will be evaluated, but reports for these small sections will not be generated to protect student anonymity.***

Students enrolled in AOSC 633 are welcome to screen capture your evaluations, place into a single PDF file, and email to me, Genevieve Cooper gcooper@umd.edu, and Sumant Nigam nigam@umd.edu, with subject of "AOSC 633 Evaluation"

Announcements: Class

- Rather than have a final exam, ***every student*** must complete Learning Outcome quizzes for **Lectures 18, 19, 20, 21, 22, and 23** using your *real name*, with two attempts per student, and the percentage score of these grades will be averaged together and used instead of a final exam.
- Review of Problem Set 4 will occur Mon, Dec 14, at 6 pm
- Would appreciate a strong turnout for the review of Problem Set 4, especially because this will occur the evening before Reading Day and this will be our last opportunity to meet.

If you attend, please be prepared to discuss your answers to these questions:

c) Assume for the next 40 years that society decides to continue to rely on the combustion of fossil fuel to supply its energy needs.

iii) (5 points) In your opinion, is the use of this much land (i.e., your answer to ii) for carbon sequestration over a 40 year period of time "reasonable", from a pure land resource requirement? Please give your reply and support with a sentence or two.

Assume that a decision is made to place an 8 kilowatt solar PV array on the roof of each single-family home. ***8 kilowatt refers to the output of this system at noon (peak sun), for clear sky conditions.***

c) (10 points) If you were advising a U.S. Senator, would you recommend that the government invest in the installation of an 8 kilowatt solar PV system on the roof top of every single-family home?

Please support your reply with a few sentences.

Announcements: Outside of Class

AOSC Senior Research Prospectus Defense Schedule

Thursday Dec 10, 2020
Attend the Presentation: meet.google.com/dkd-wncs-hnx

Time Slot	**Presenter** ***Title*** **Advisor(s)**
3:30 - 3:45pm	Samantha Volz *Evapotranspiration, Primary Production, and Carbon Storage in Soils with Varying Land Use* Karen Prestegaard
3:45 - 4:00pm	Emma Bonanno *Climate Change in the Indian Ocean: A Comparison of Historic Cruise Data and Modern Argo Float Data* Jacob Wenegrat
4:00 - 4:15pm	Maggie Bridges *Change of pH and Aragonite Saturation State in the Great Barrier Reef* *Liqing Jiang*
4:15 - 4:30pm	Christopher Smith *The Statistical Analysis of Marine Surface Warnings* Joseph Sienkiewicz
4:30 - 4:45pm	Nicole Oehlmann *Developing a Definition for Dangerous Seas* Hillary Fort, Joseph Sienkiewicz

https://meet.google.com/dkd-wncs-hnx

Nuclear Power: Safety

- U.S.
  - 1979 : Three Mile Island (TMI) near Harrisburg, Pennsylvania
  - Loss of coolant and partial meltdown
  - Release of radioactive gases: no fatalities, normal cancer rates in area

    The accident began about 4:00 a.m. on March 28, 1979, when the plant experienced a failure in the secondary, non-nuclear section of the plant. The main feedwater pumps stopped running, caused by either a mechanical or electrical failure, which prevented the steam generators from removing heat. First the turbine, then the reactor automatically shut down. Immediately, the pressure in the primary system (the nuclear portion of the plant) began to increase. In order to prevent that pressure from becoming excessive, the pilot-operated relief valve (a valve located at the top of the pressurizer) opened. The valve should have closed when the pressure decreased by a certain amount, but it did not. Signals available to the operator failed to show that the valve was still open. As a result, cooling water poured out of the stuck-open valve and caused the core of the reactor to overheat.

    For more info, see http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

- Russia
  - 1986 : Chernobyl
  - During a test, operators interrupted flow of cooling water to core
  - Insufficient control rods were in reactor
  - Heat surge resulted, leading to ***chemical*** explosion
  - Water was sprayed; water reacted with graphite producing H_2 ($2H_2O + C \rightarrow 2H_2 + CO_2$), which caused additional ***chemical*** explosion
  - 31 firefighters and several people in plant died from acute radiation sickness; an estimated 250 million people were exposed to elevated radiation that may shorten their lives
  - Nuclear engineers state that no U.S. commercial reactors have Chernobyl design defects

Chemistry in Context, pages 299 to 302 & page 321

TMI 2 Timeframe Overview - 40 yrs ago

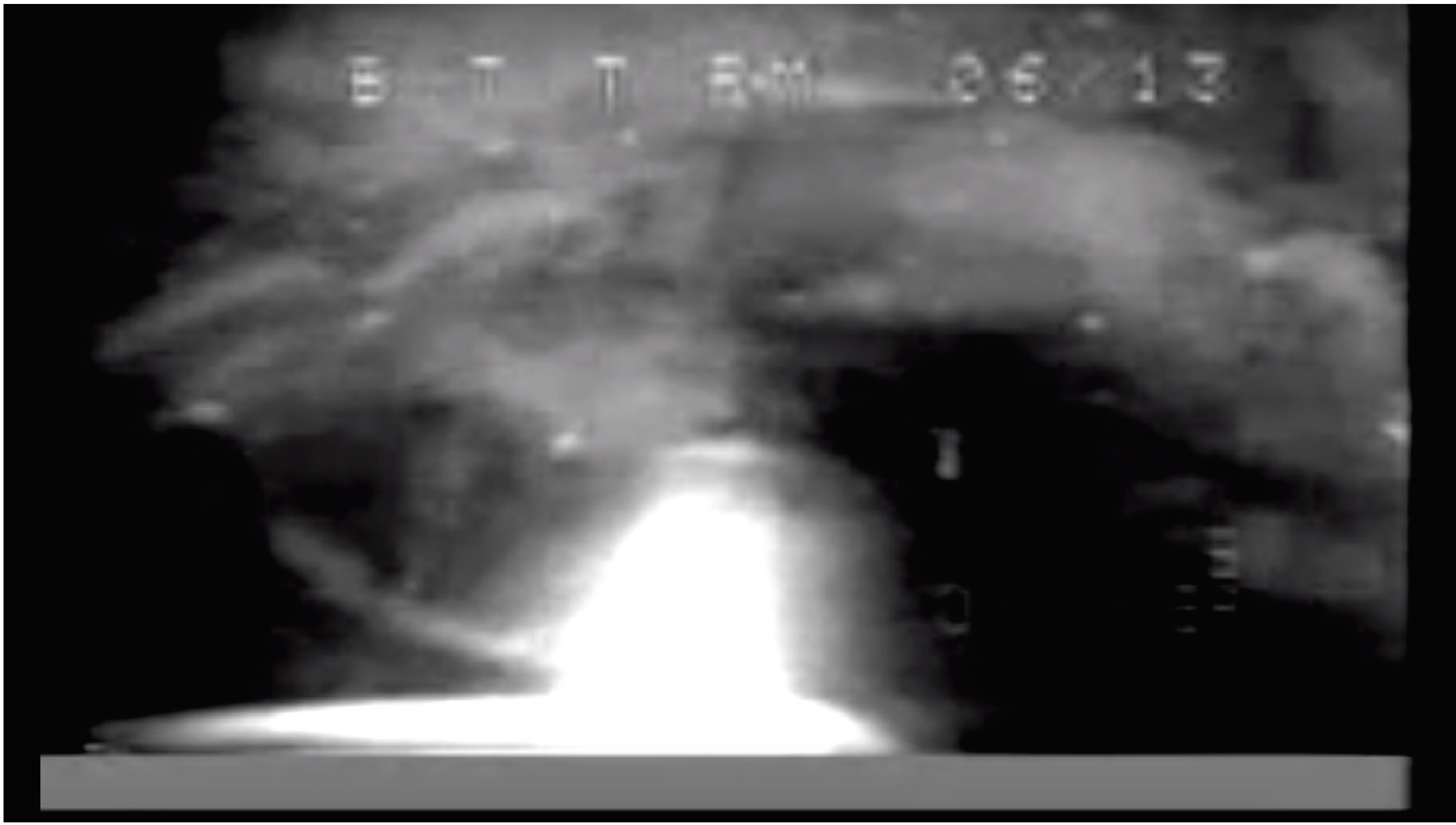
- March 1979 – Accident Day. Utility - "Reactor damaged - but <u>not a meltdown</u>." ☺
- June 1982 (+3 yrs) – Inserted probes into reactor & went in ok. Utility – "<u>Still not too bad</u>." ☺
- July 1982 - Inserted small TV camera into reactor – **<u>5' of nothing</u>** before spotting debris pile. Watched video next day in DC engineering offices. Looked like ice cube trays that had been through a blender. <u>**Dead silence** in room during video</u>. ☹

- *(July 1986 – Chernobyl w/ no containment bldg.!!!)*
- 1989 (+10 yrs!) – Found melted fuel in bottom of RV. ☹ ☹ **"**Partial?" meltdown - <u>really</u>??

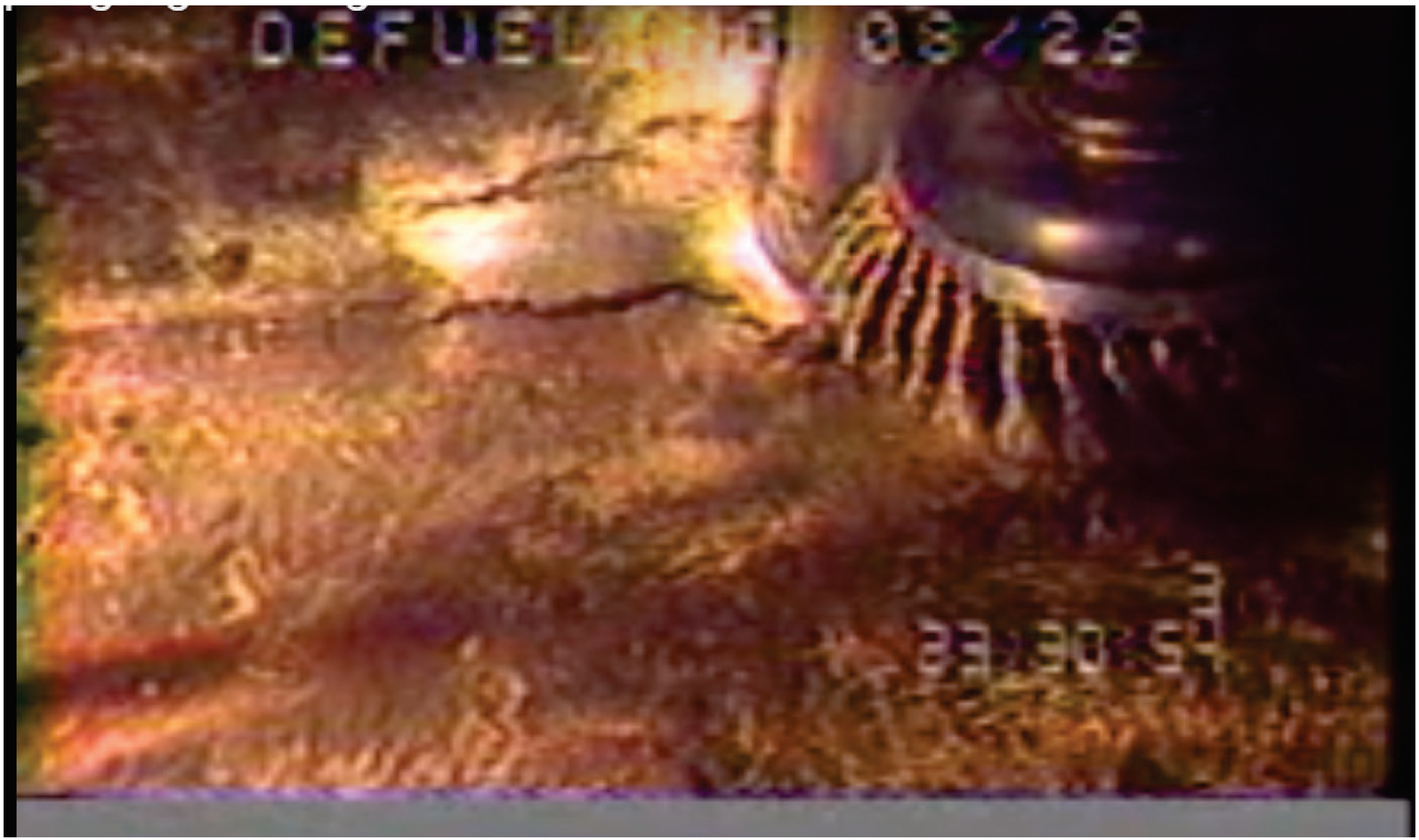
A disaster such as TMI was <u>inside</u> a reactor vessel that was <u>inside</u> a containment bldg and did <u>not</u> lead to a disaster offsite - like Chernobyl.

Underwater TV camera inside TMI reactor
~ 5 ft into area where core <u>should</u> have been.

Small white spots were “floating” in turbid water.
Very eerie video!



Special tool (wire brush) used under 40’ of radioactive water in bottom of TMI 2 RV – 1990ish



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/

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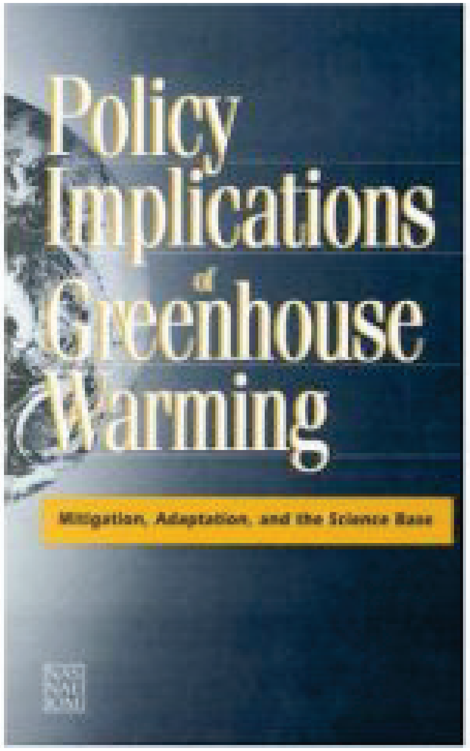

National Academy of Sciences, 1992

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**

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

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NOBEL PRIZE TO OZONE RESEARCHERS (1995)

Professor Paul Crutzen

Professor Mario Molina

Professor F. Sherwood Rowland

By Sean Henahan, Access Excellence

STOCKHOLM, Sweden- Three noted chemistry researchers have been awarded the Nobel Prize in Chemistry for atmospheric studies which led to an understanding of how the ozone layer forms and decomposes. The Royal Swedish Academy of Sciences praised the researchers' contribution "to our salvation from a global environmental problem that could have catastrophic consequences."

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)

NASA/CP–2007-214558 **April 2007**

Workshop Report on Managing Solar Radiation

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- **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

Henning Wagenbreth
NY Times, 24 Oct 2007

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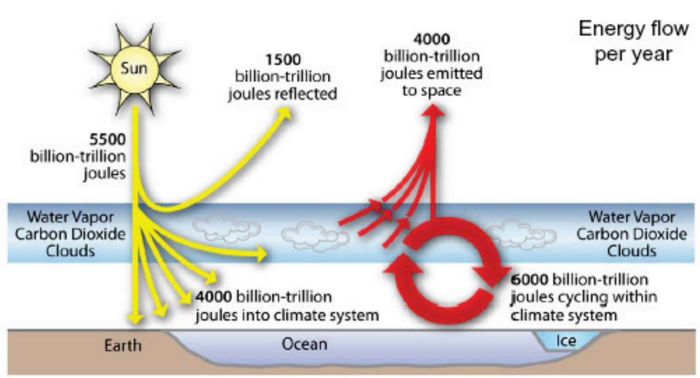
- **Nov 2007: Geo-engineering meeting, Harvard University**
  - covered by Science (**http://sciencenow.sciencemag.org/cgi/content/full/2007/1109/1**)

Harvard climate researcher James Anderson told the group that 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”

James G. Anderson
Harvard University

AMS Society Environmental Science Seminar Series
December 18, 2007



- To melt all of the Greenland Glacial System requires approx. 550 billion-trillion joules.
- If that is done in 100 years, that is approx. 5 billion-trillion joules per year.
- That is 5 out of the 5000 billion-trillion joules circulating in the climate system per year.

Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR

X. Fettweis[1], B. Franco[1], M. Tedesco[2], J. H. van Angelen[3], J. T. M. Lenaerts[3], M. R. van den Broeke[3], and H. Gallée[4]

[1]Department of Geography, University of Liege, Liege, Belgium
[2]The City College of New York, The City University of New York, New York, NY, USA
[3]Institute for Marine and Atmospheric research (IMAU), Utrecht University, the Netherlands
[4]Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE), Grenoble, France

To estimate the sea level rise (SLR) originating from changes in surface mass balance (SMB) of the Greenland ice sheet (GrIS), we present 21st century climate projections obtained with the regional climate model MAR, forced by output three CMIP5 general circulation models (GCMs). Our results indicate that in a warmer climate, mass gain from increased winter snowfall over the GrIS does not compensate mass loss through increased meltwater run-off in summer. Despite the large spread in the projected near-surface warming, all theMAR projections show similar non-linear increase of GrIS surface melt volume because no change is projected in the general atmospheric circulation over Greenland.

By coarsely estimating the GrIS SMB changes from GCM output, we show that the uncertainty from the GCM-based forcing represents about half of the projected SMB changes. In 2100, the CMIP5 ensemble mean projects a GrIS SMB decrease equivalent to a mean SLR of 4 ± 2 cm and 9 ± 4 cm for the RCP (Representative Concentration Pathways) 4.5 and 8.5 scenarios, respectively.

These estimates do not consider the positive melt–elevation feedback, although sensitivity experiments using perturbed ice sheet topographies consistent with the projected SMB changes demonstrate that this is a significant feedback, and highlight the importance of coupling regional climate models to an ice sheet model. Such a coupling will allow the assessment of future response of both surface processes and ice-dynamic changes to rising temperatures, as well as their mutual feedbacks.

https://www.the-cryosphere.net/7/469/2013/tc-7-469-2013.pdf

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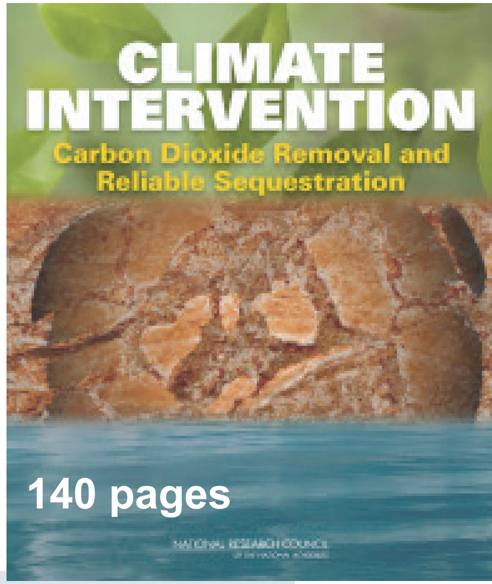
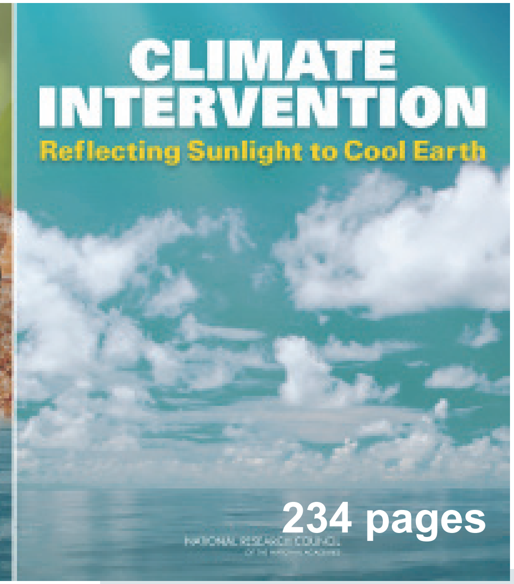
- **June 2009: National Academy of Sciences (NAS) Geo-engineering meeting**
  - Chapter 15, Solar Radiation Management (SRM) of NAS America Climate Choice's 2010 report:

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" & on governance systems that could facilitate whether, when, & 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

PDF files can be downloaded for free at:
https://www.nap.edu/catalog/18988/climate-intervention-reflecting-sunlight-to-cool-earth
https://www.nap.edu/catalog/18805/climate-intervention-carbon-dioxide-removal-and-reliable-sequestration

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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

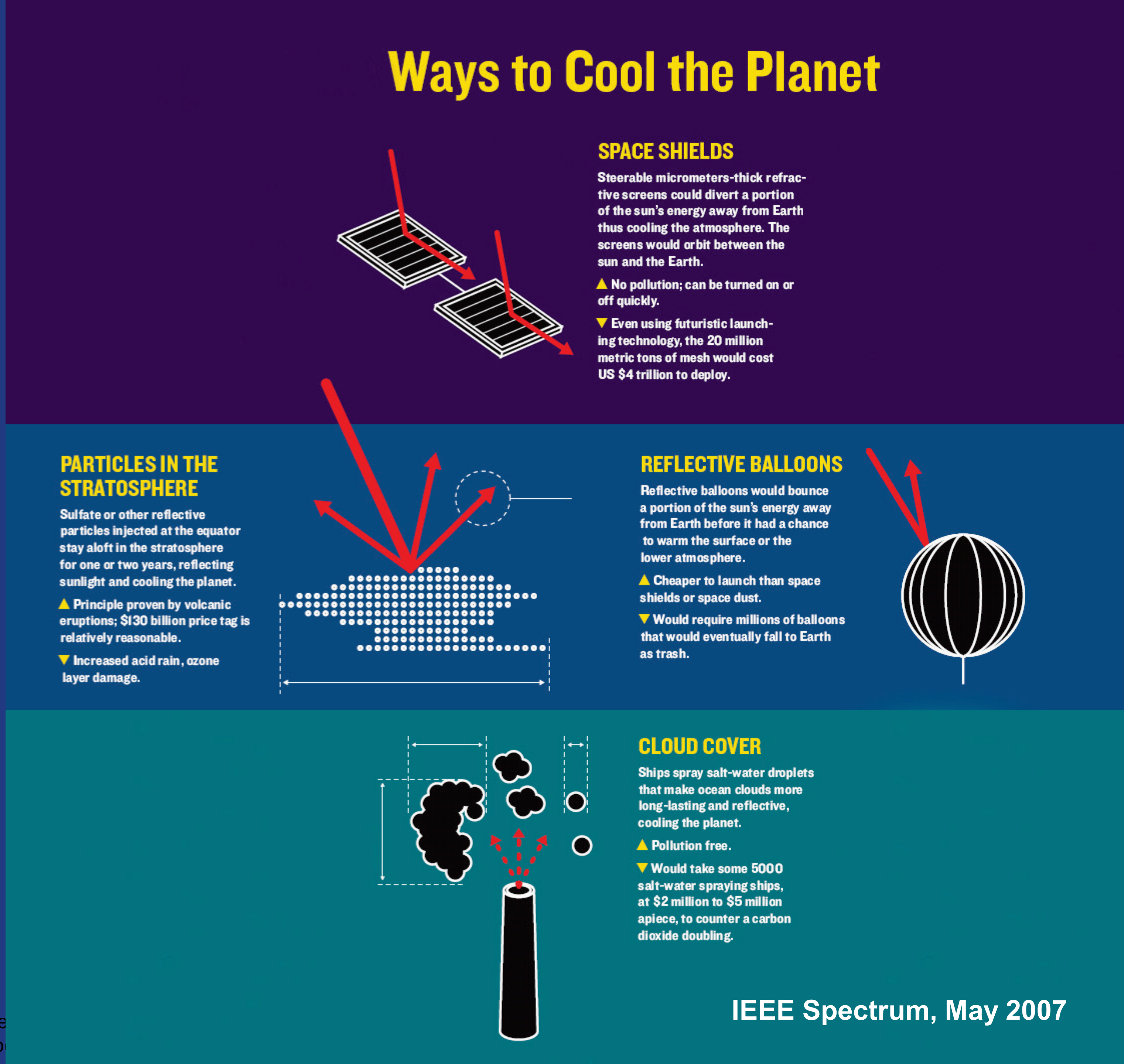
4. An albedo modification research program be developed and implemented that emphasizes multiple benefit research that also furthers both basic understanding of the climate system and its human dimensions

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:

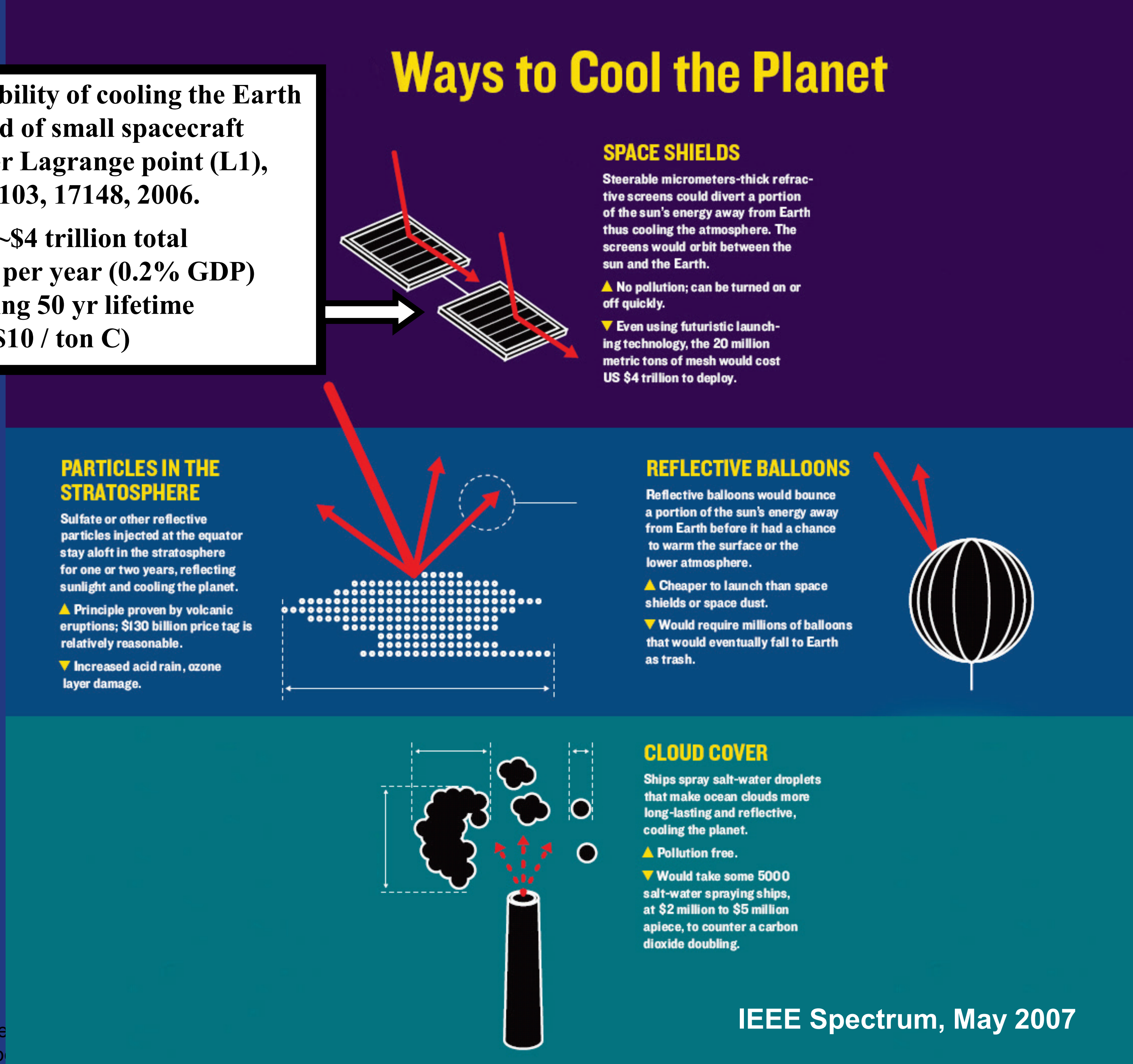
   (a) What types of research governance, beyond those that already exist, may be needed for albedo modification research;

   (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

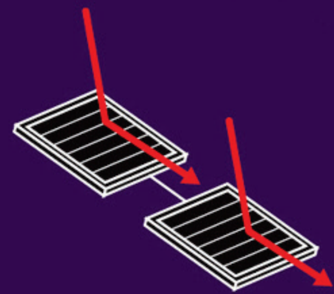
Angel, R., Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1), *PNAS*, 103, 17148, 2006.

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.

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Crutzen, P., Climatic Change, 2006

Cost: $70 to 140 billion per year

($7 to 14 / ton C)

PARTICLES IN THE STRATOSPHERE

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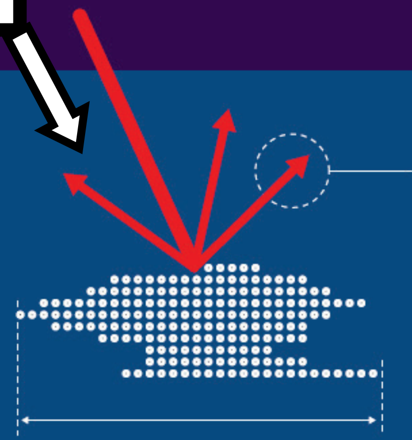

REFLECTIVE BALLOONS

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CLOUD COVER

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

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IEEE Spectrum, May 2007

Ways to Cool the Planet

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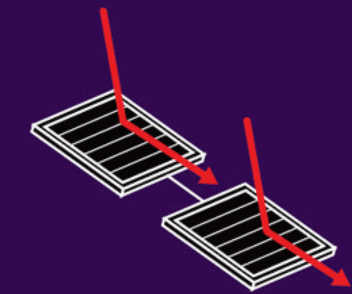

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Chapter 28 & Appendix Q, NAS 1992.

Cost: $80 billion total
$2 billion per year
assuming 40 yr lifetime
($0.25 / ton C)

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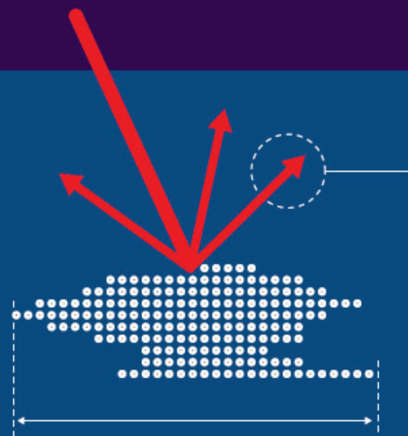

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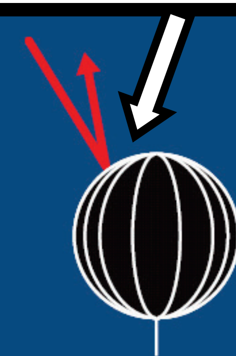

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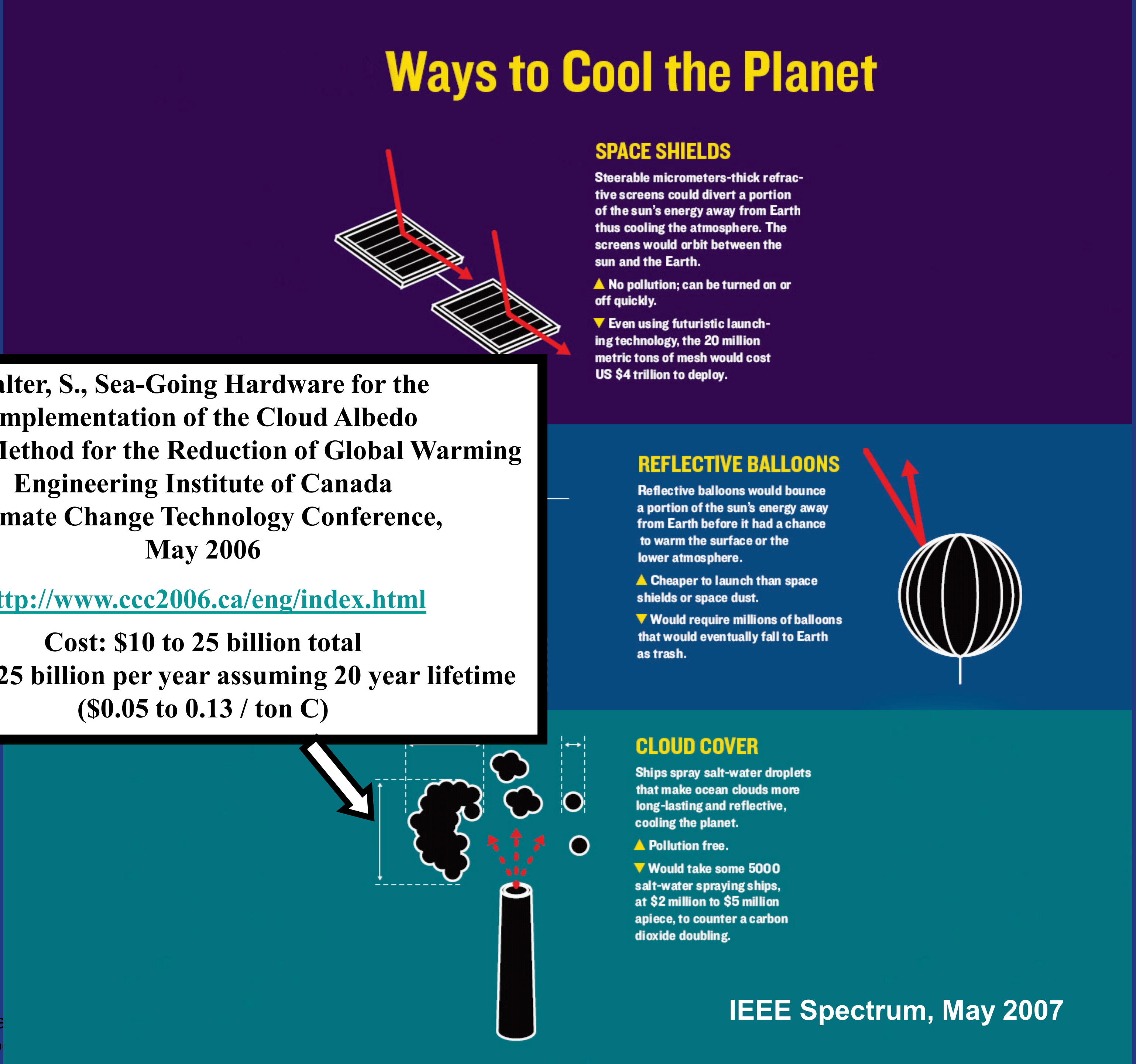
IEEE Spectrum, May 2007



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)

IEEE Spectrum, May 2007

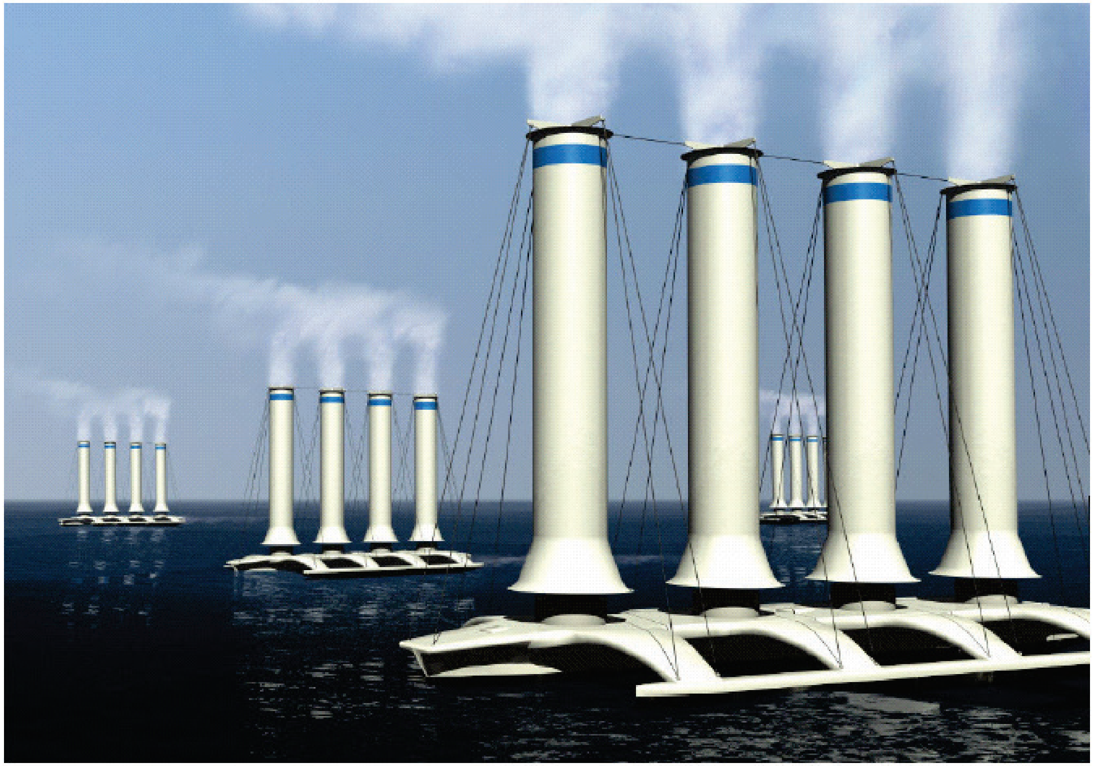


Figure 2. Albedo spray vessels. They would sail back and forth square to the local prevailing wind. The spinning cylinders are Flettner rotors which can give lift coefficients up to 9, much higher than cloth sails. Artwork courtesy of John MacNeill.

Salter, Stephen
Engineering Institute of Canada
Climate Change Technology Conference,
May 2006

http://www.hm-treasury.gov.uk/media/9/6/Ottawa_formatted.PDF

he Planet

IELDS

rometers-thick refrac-
uld divert a portion
ergy away from Earth
e atmosphere. The
orbit between the
rth.

can be turned on or

uturistic launch-
, the 20 million
mesh would cost
o deploy.

ECTIVE BALLOONS

ive balloons would bounce
n of the sun's energy away
arth before it had a chance
n the surface or the
tmosphere.

per to launch than space
or space dust.

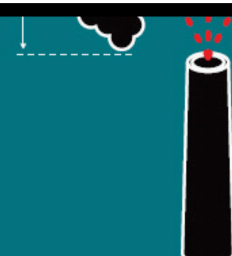
d require millions of balloons
uld eventually fall to Earth

D COVER

ray salt-water droplets
e ocean clouds more
ting and reflective,
he planet.

ion 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

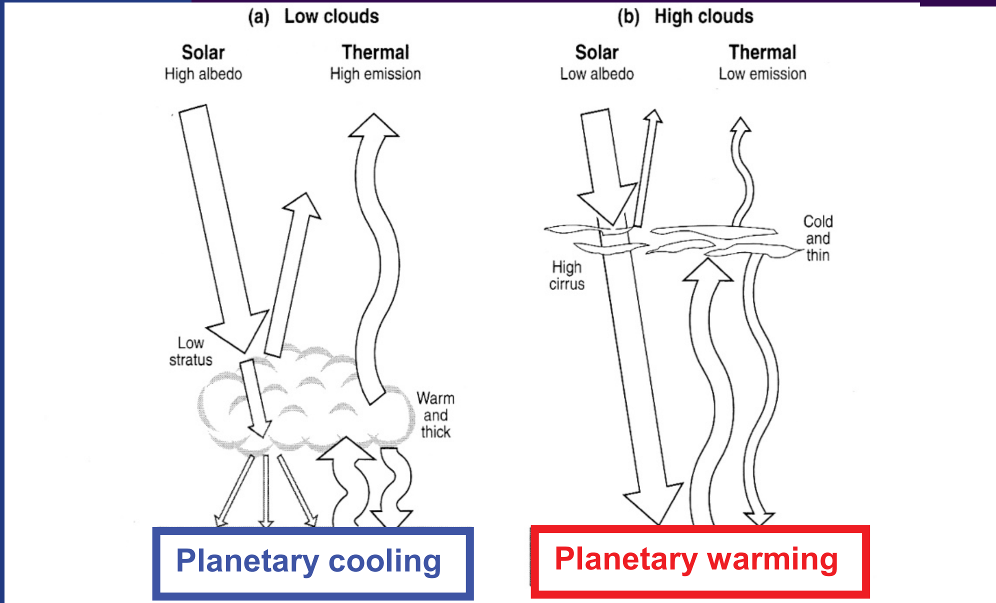
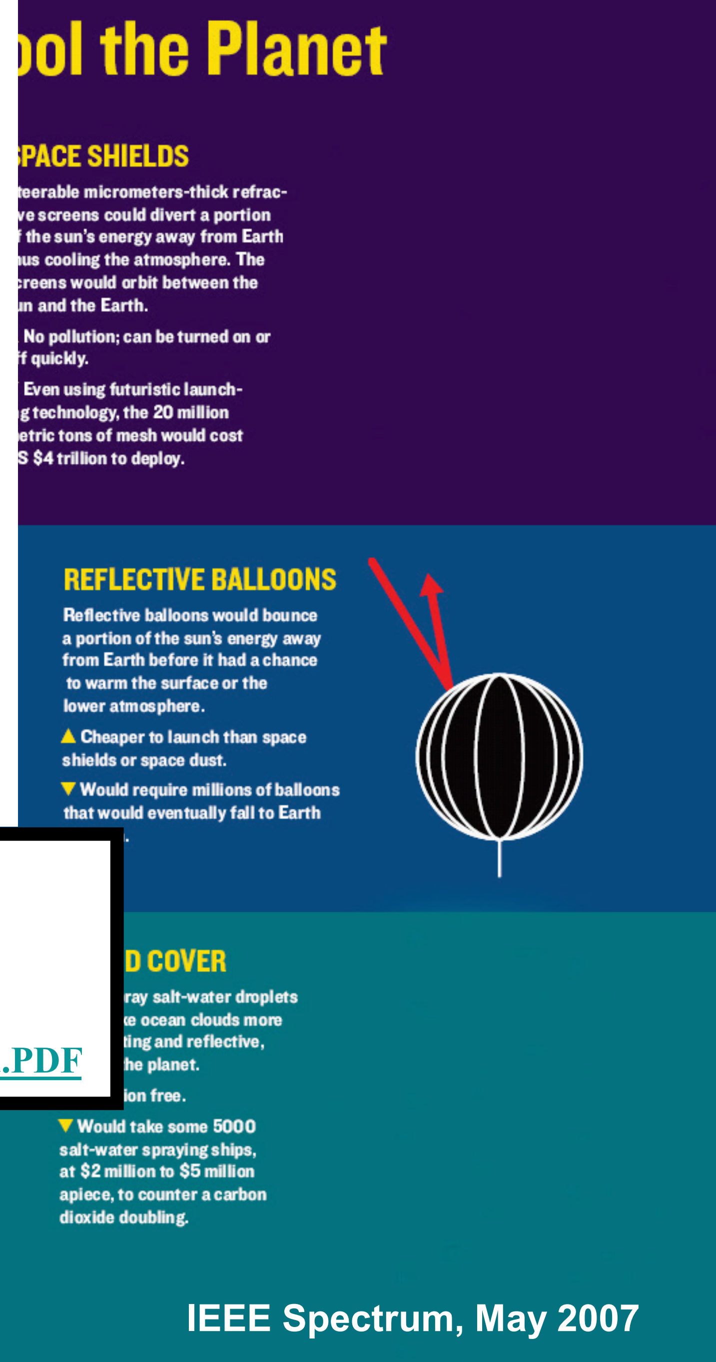


Figure 11.13 The effects of clouds on the flow of radiation and energy in the lower atmosphere and at the surface. Two cases are shown: (a) low clouds, with a high solar albedo and high thermal emission temperature; and (b) high clouds, with a low solar albedo and low thermal emission temperature. The solar components are shown as straight arrows, and the infrared components, as curved arrows. The relative thicknesses of the arrows indicate the relative radiation intensities. The expected impact on surface temperature in each situation is noted along the bottom strip.

Lecture 8



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According to model calculations … complete ***improvement in air quality*** could lead to a decadal global average surface air temperature increase by 0.8°C on most continents and 4°C 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 1.4–5.8°C

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

Lecture 8

RF of Climate due to GHGs and Aerosols

- 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)

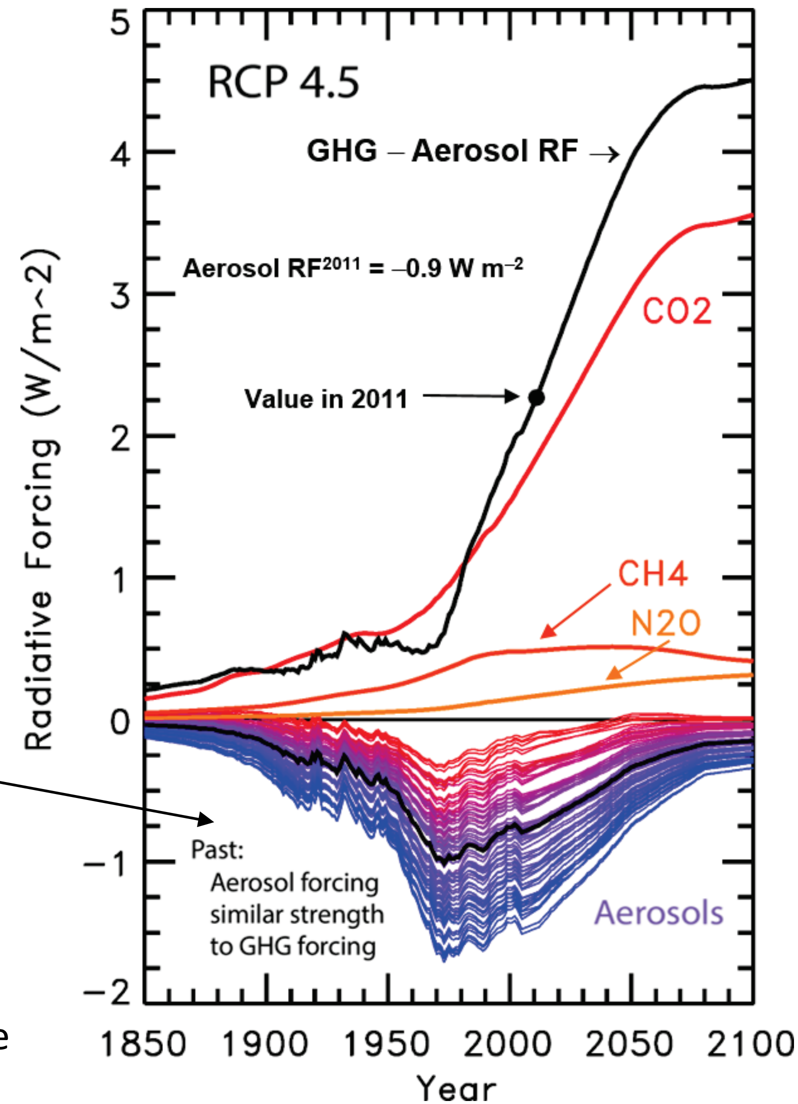

Figure 1-10, Paris Beacon of Hope

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

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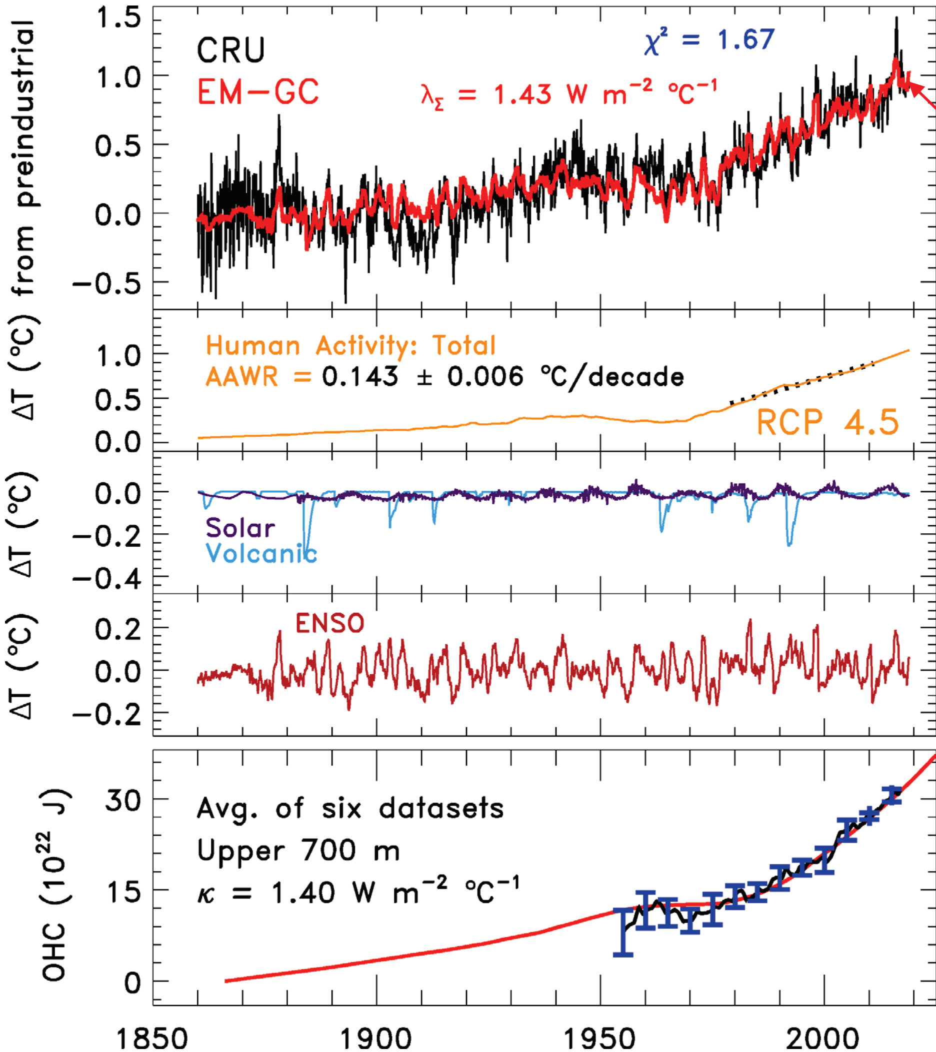
by Paul J. Crutzen : Climatic Change, 77, 211-219, 2006

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).



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

where:

i denotes month

$\lambda_p = 3.2$ 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

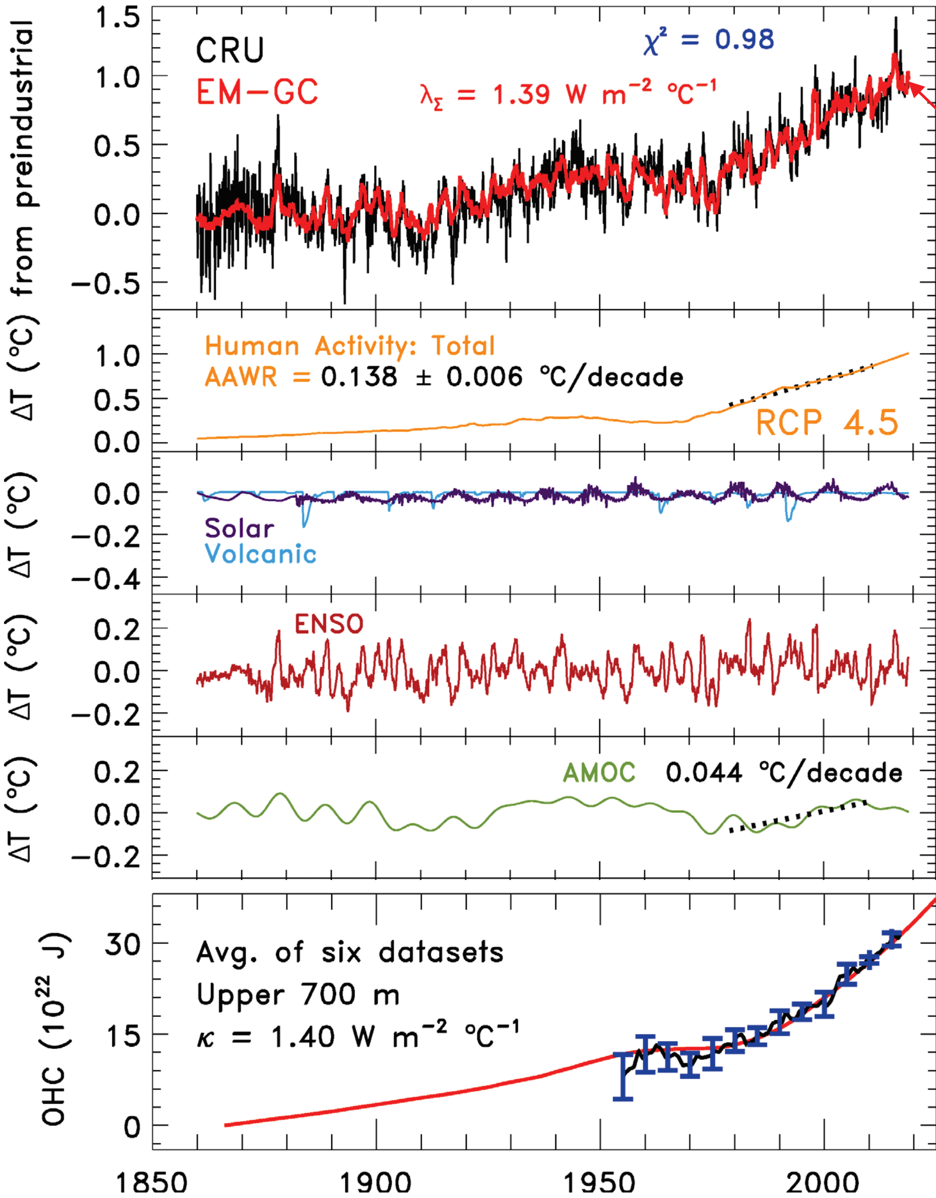
TSI = Total Solar Irradiance

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

Similar slide shown in Lecture 2. Also shown in Lectures 7 & 8.



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- AMOC = Atlantic Meridional Overturning Circulation
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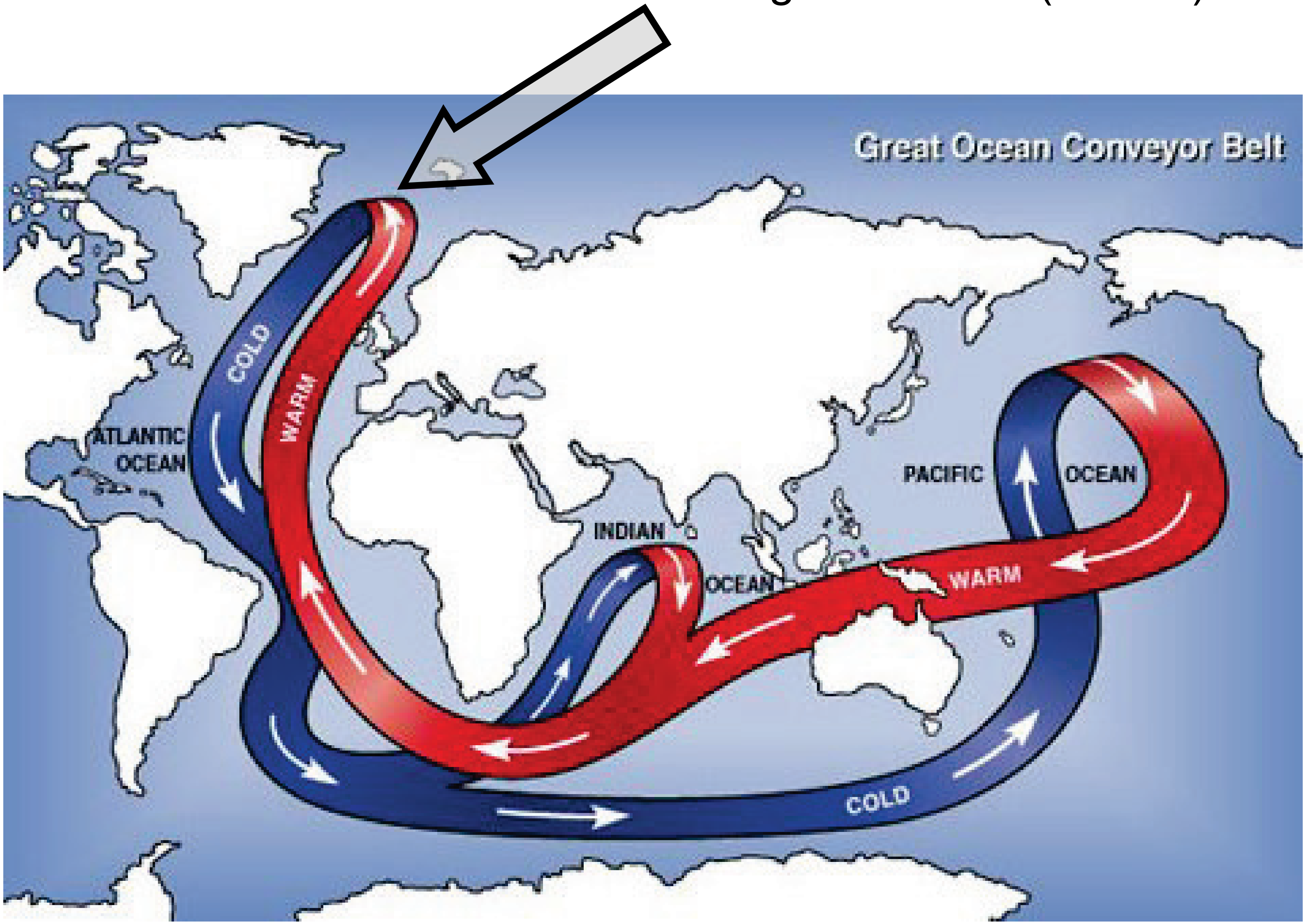
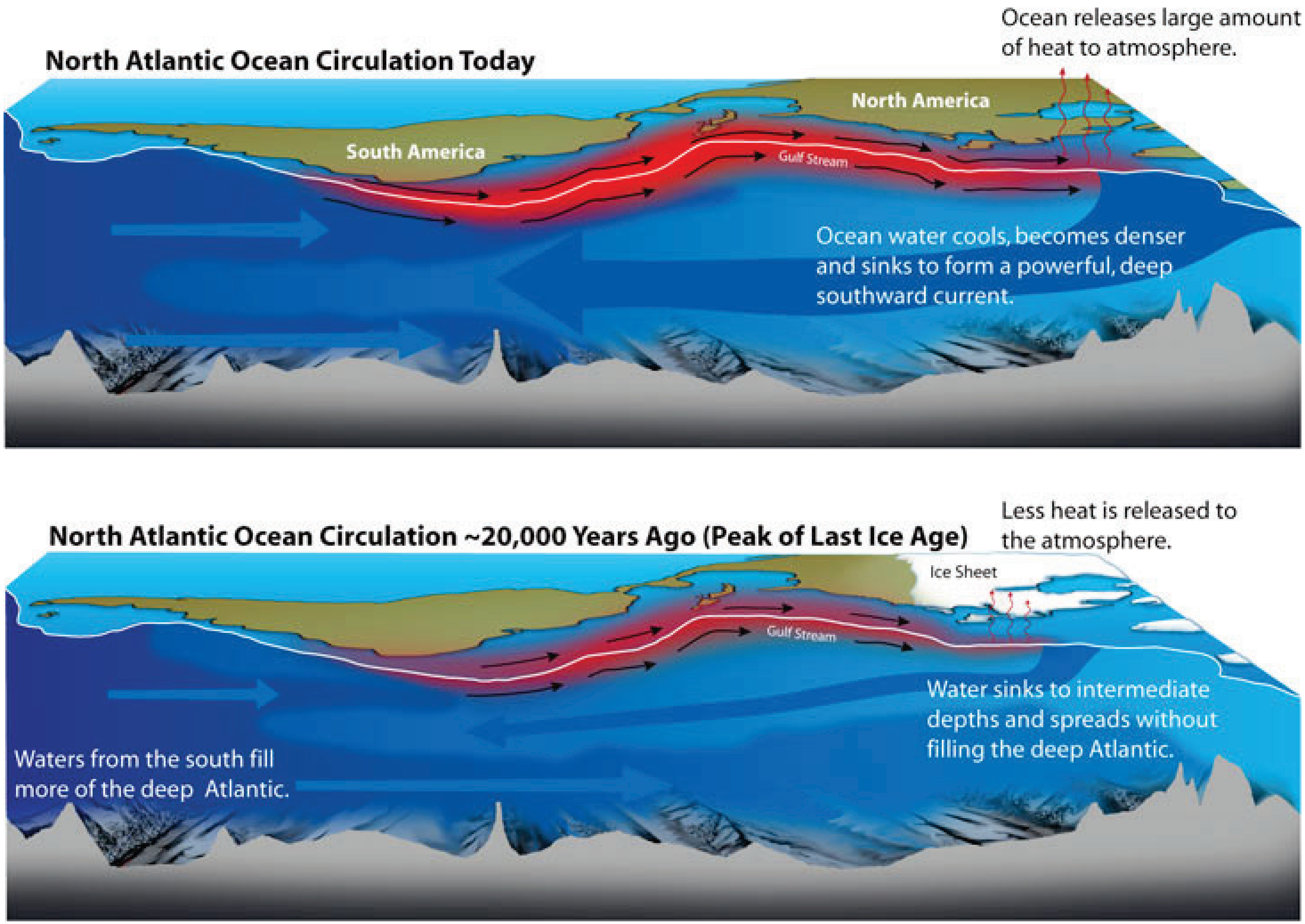
Atlantic Meridional Overturning Circulation (AMOC)



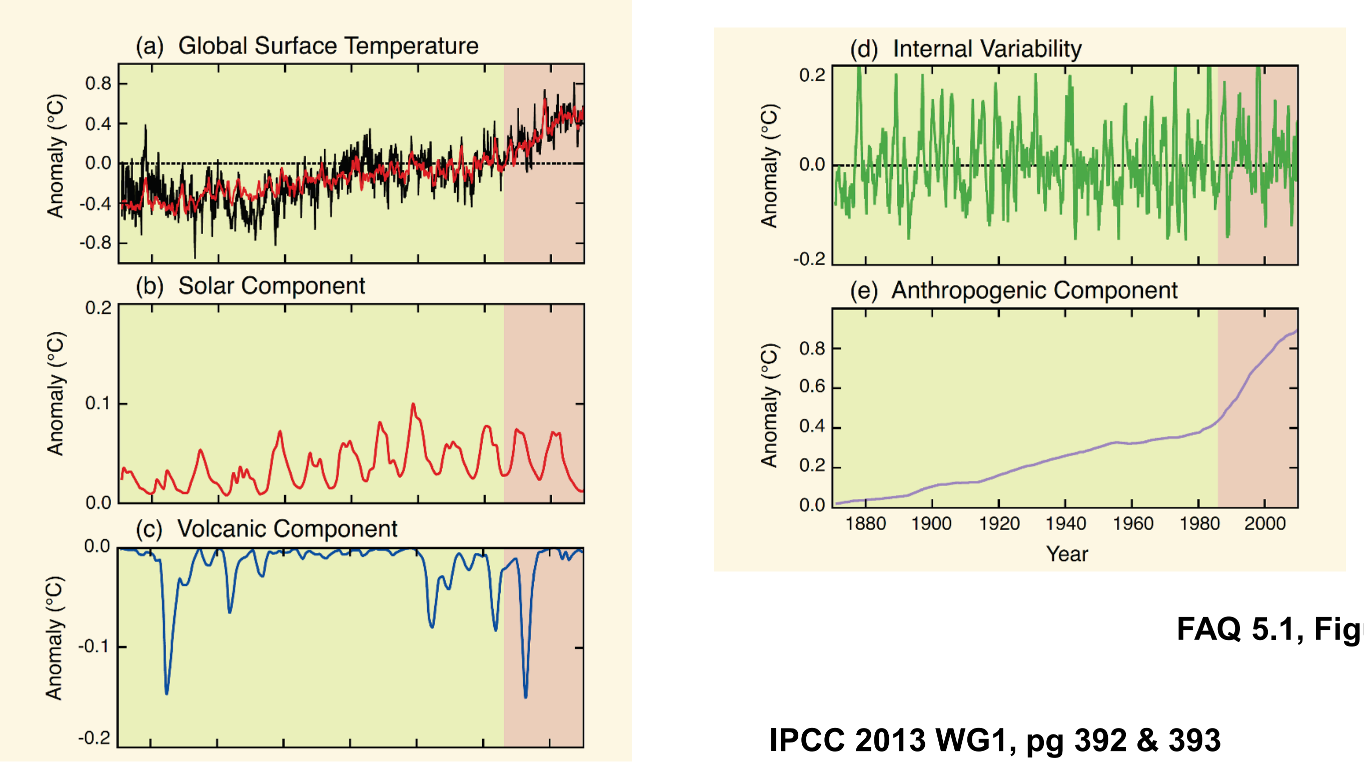
Atlantic Meridional Overturning Circulation (AMOC)



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)*

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  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

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$$\Delta F \approx 5.35 \text{ W m}^{-2} \ln\left(\frac{CO_2^{\;Final}}{CO_2^{\;Initial}}\right) = 5.35 \text{ W m}^{-2} \ln(2) = 3.7 \text{ W m}^{-2}$$

Lecture 4

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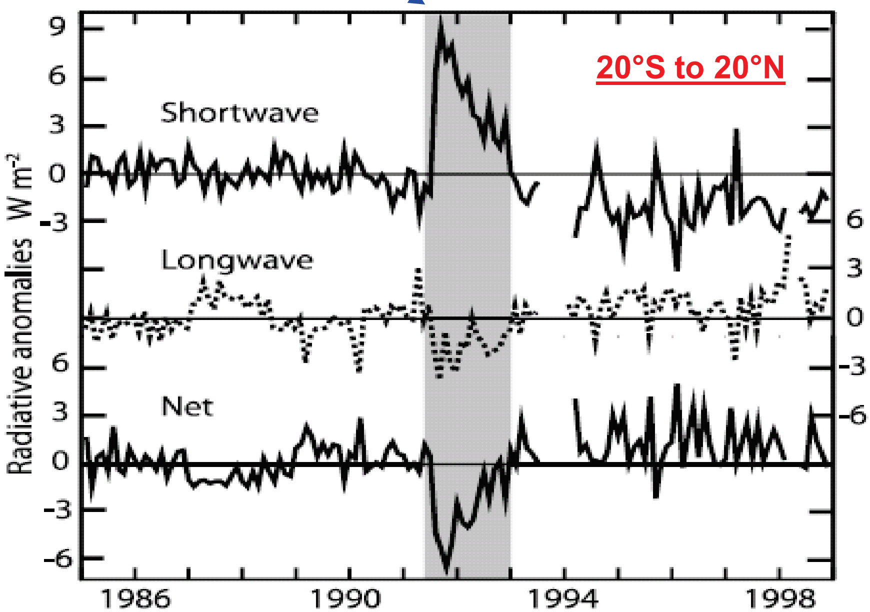
June 1991



Trenberth and Dai, *GRL*, 2007

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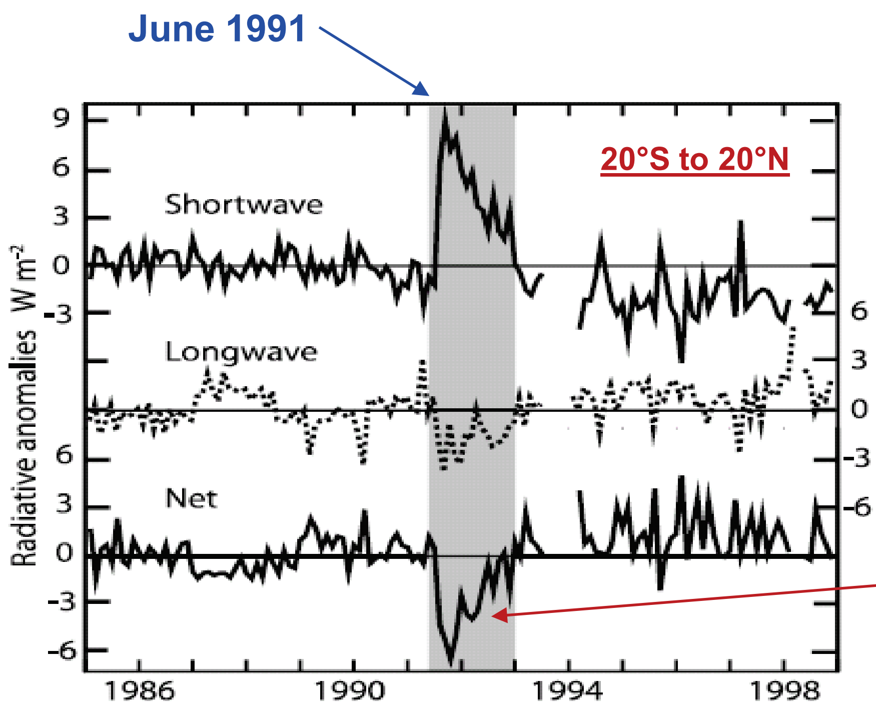
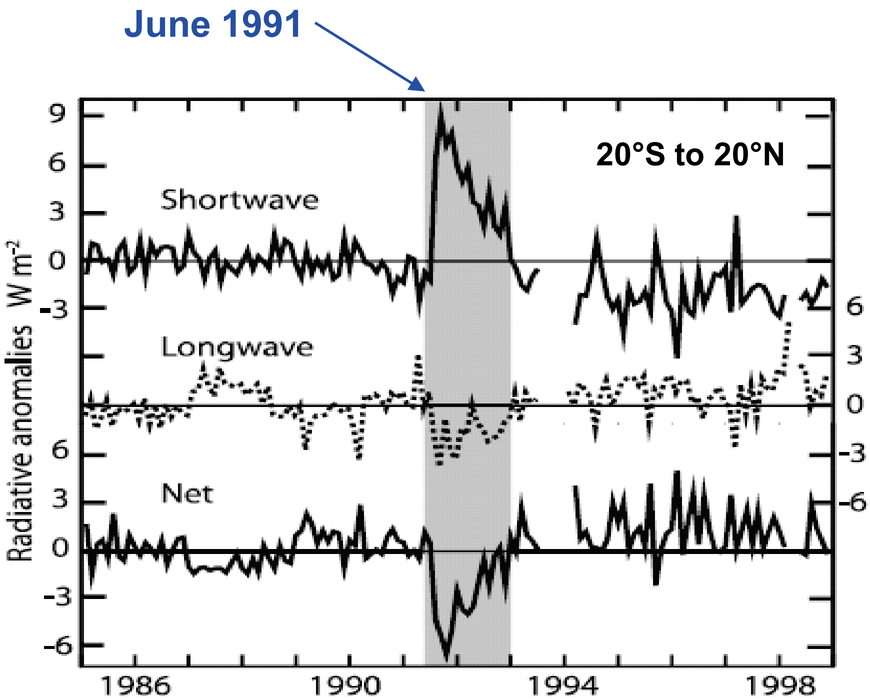


Radiative anomaly due to Pinatubo may have been ~ 4.5 W m^{-2} in the tropics

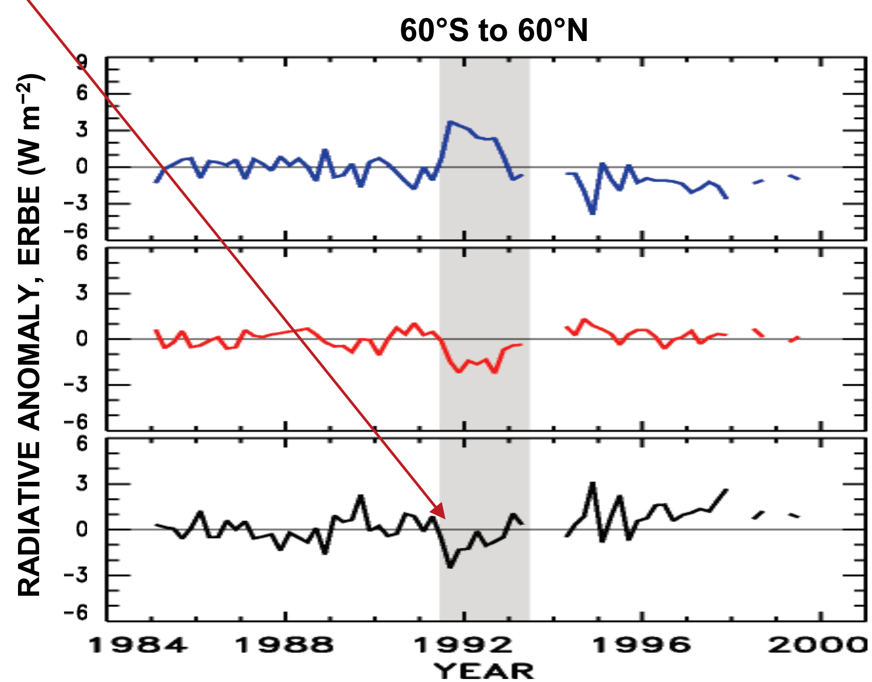
Trenberth and Dai, *GRL*, 2007

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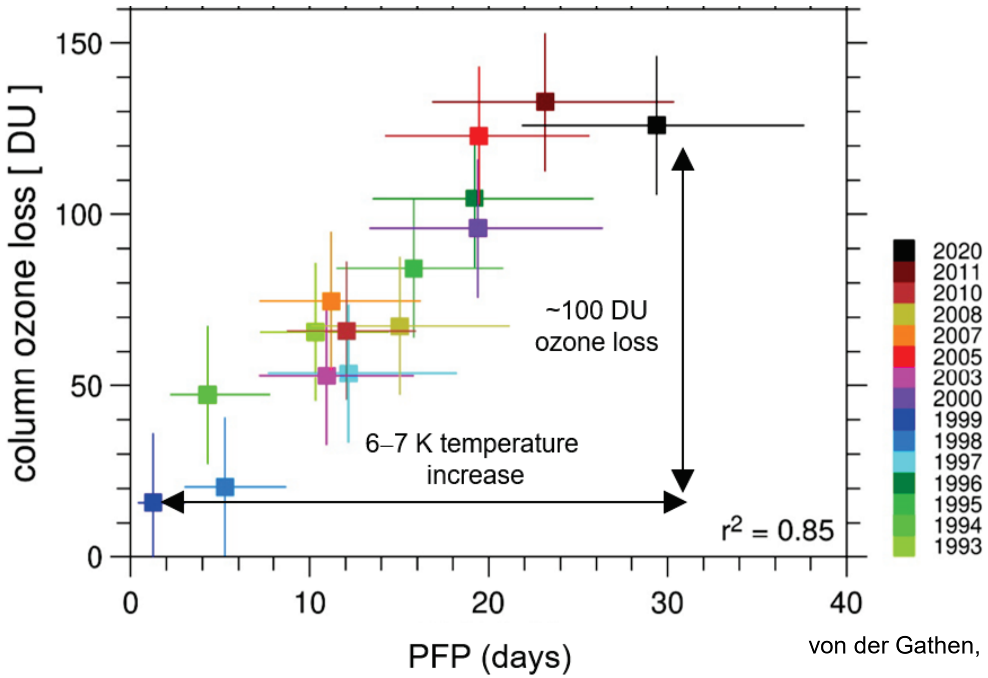
Will the response of *polar ozone* to stratospheric sulfur injection be as modest as suggested by the response of global ozone to Mt. Pinatubo aerosol?

Arctic Ozone Loss Varies as a function of PSC Formation Potential

Data:



von der Gathen, *Nature Communications*, submitted, 2020

- Surprisingly simple relationship between chemical loss of column ozone and volume of air exposed to PSC formation potential over winter, where

$$\mathrm{PFP} = \int_{16\ \mathrm{Nov}}^{17\ \mathrm{Apr}} \frac{V_{PSC}(t)}{V_{VORTEX}(t)}\,dt$$

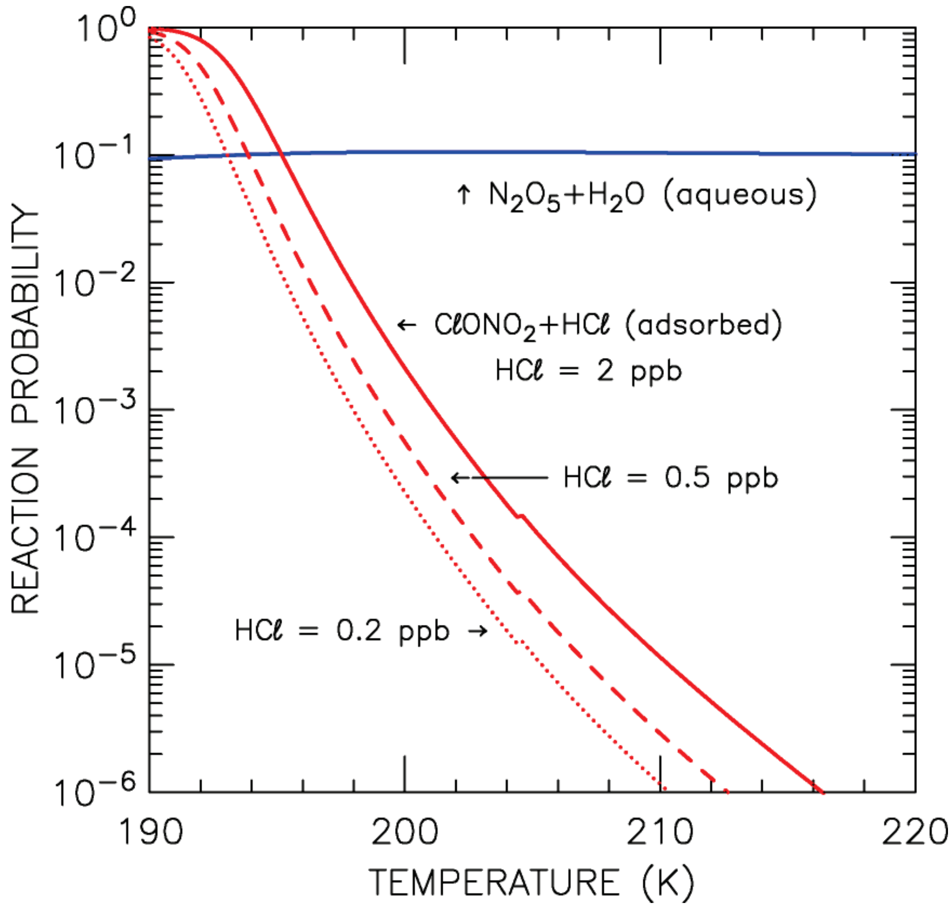
PFP is PSC Formation Potential

and V_{PSC} is the volume of the vortex where T is cold enough to allow for formation of PSCs, and V_{VORTEX} is the volume of the Arctic vortex

- Polar stratospheric clouds: provide ***surfaces*** for heterogeneous conversion of HCl and $ClNO_3$ to ClO
- Relation leads to estimate of ~15 DU additional loss of ozone per degree Kelvin cooling of *Arctic* stratosphere

Lecture 16

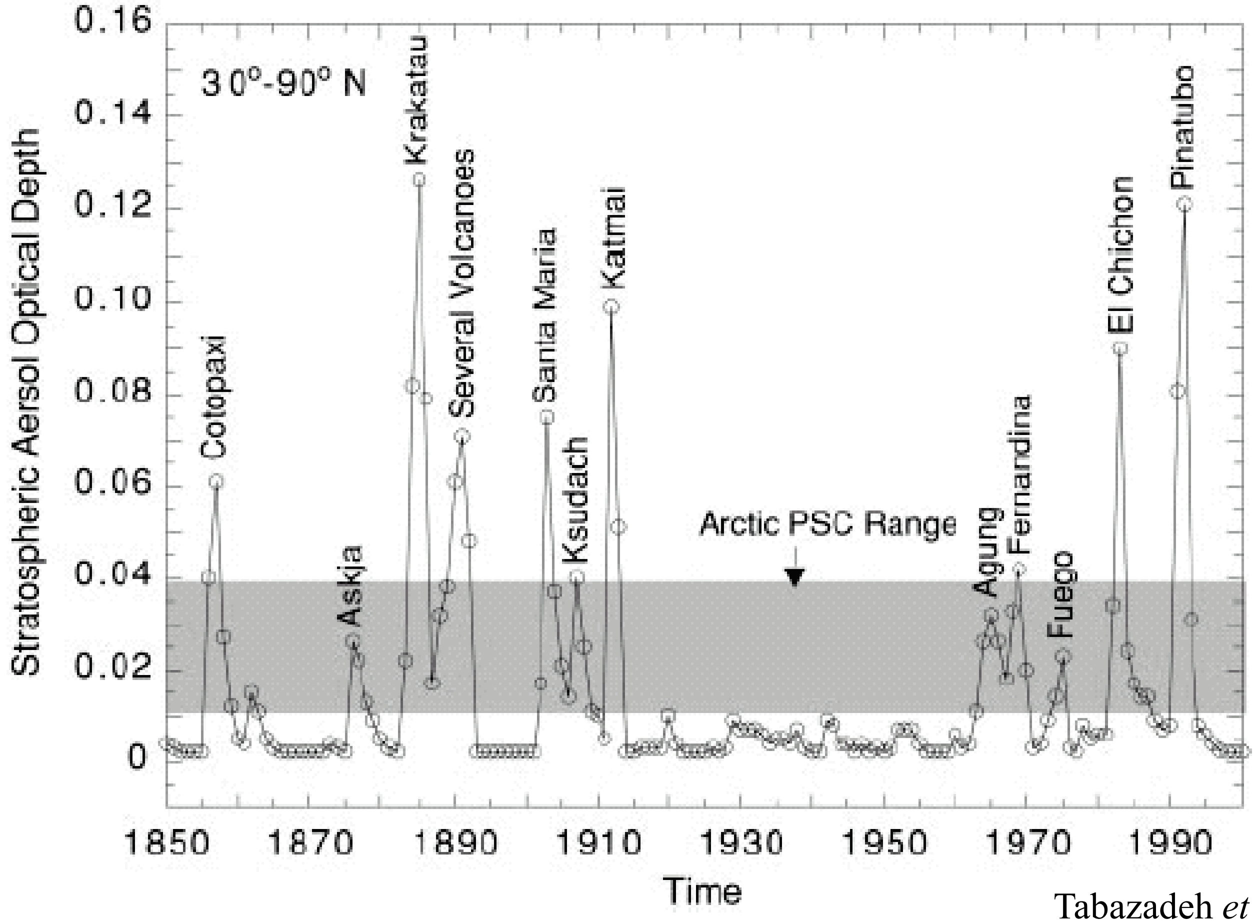
Chlorine Activation



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

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

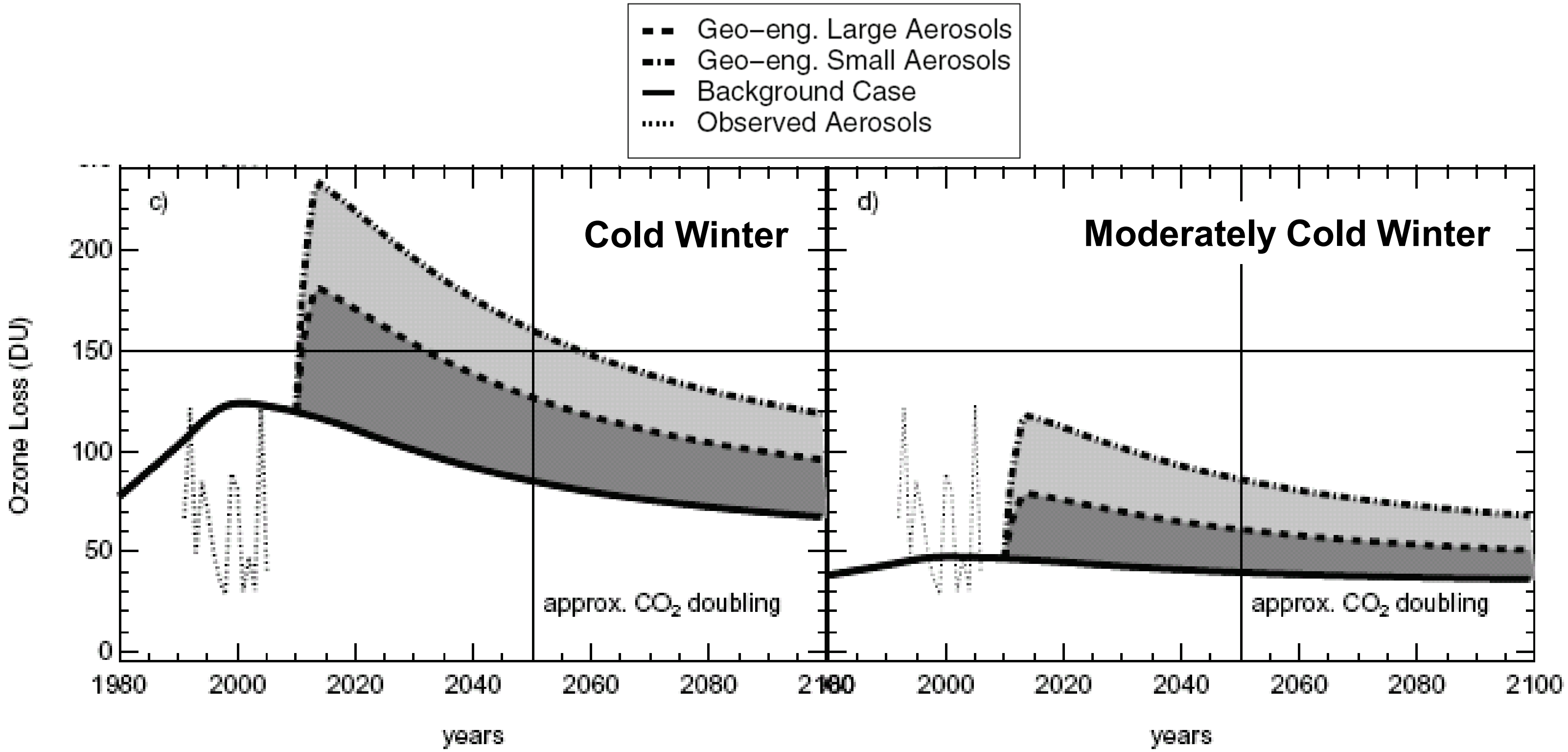
Lecture 12



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

290 citations, and counting ☺

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- National Academy of Sciences (2015):

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

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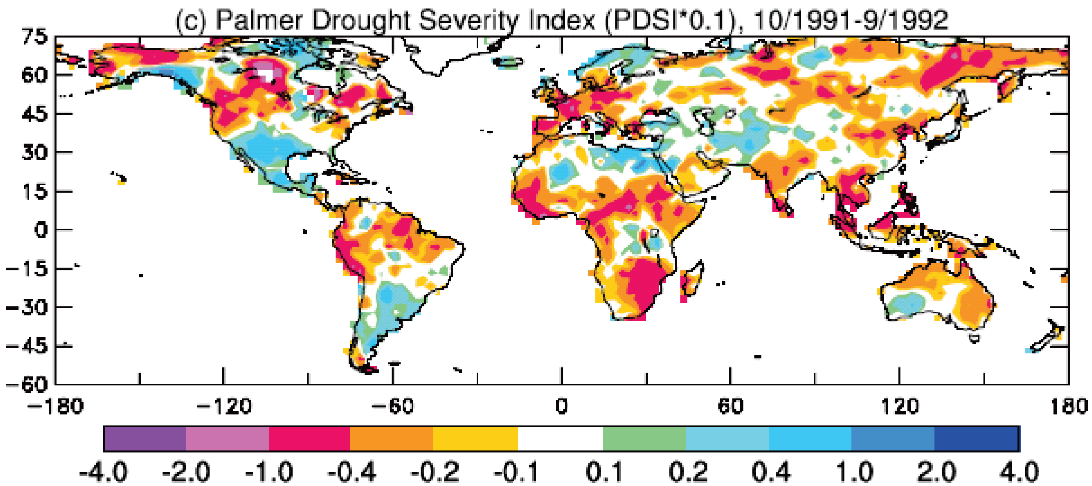
Quote from a geo-engineering email thread:

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**
- **If we ever do implement geo-engineering, rapid warming would likely ensue if the perturbation were to stop**

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

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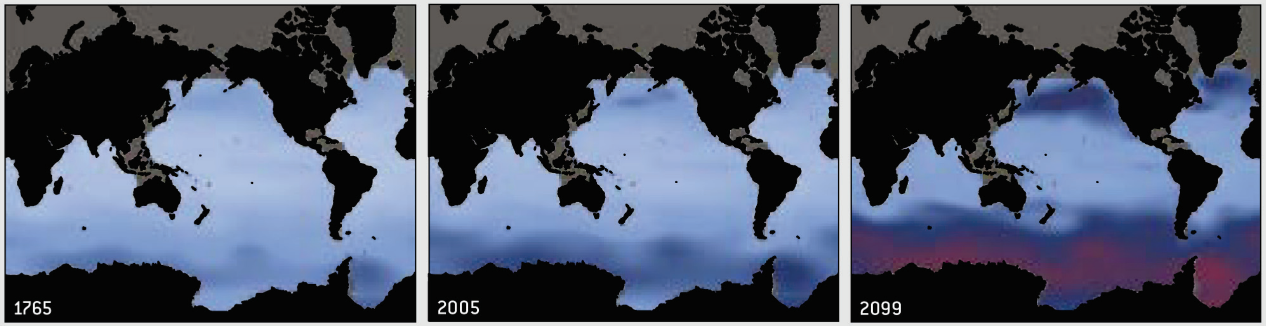
If society is able to successfully "manage solar radiation" reaching the surface, what ecological impact of rising CO_2 would still occur ?

Ocean acidification due to ↑ CO_2 would not have been addressed

Ocean Acidification

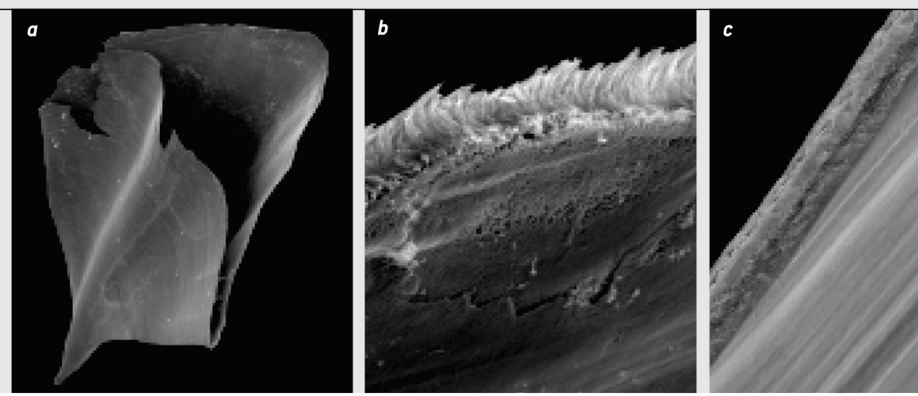
THE (RAGGED) FUTURE OF ARAGONITE

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*).

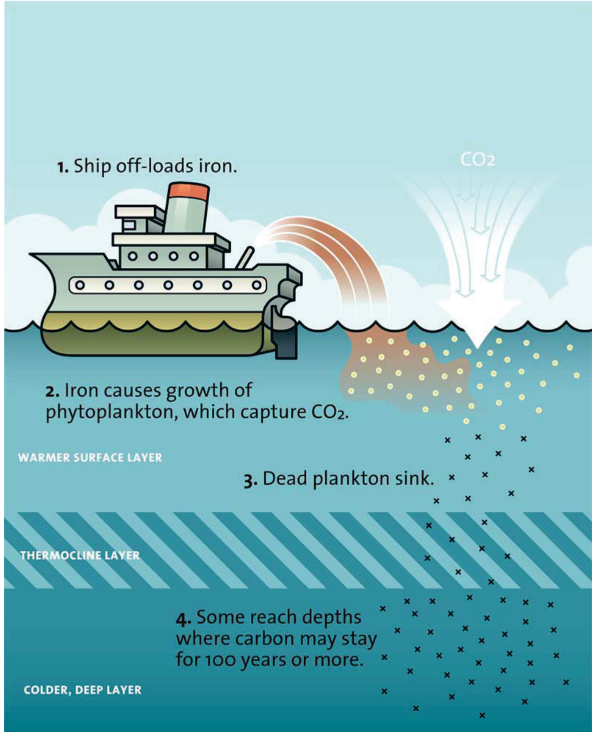


Doney, The Dangers of Ocean Acidification, *Scientific American*, March, 2006

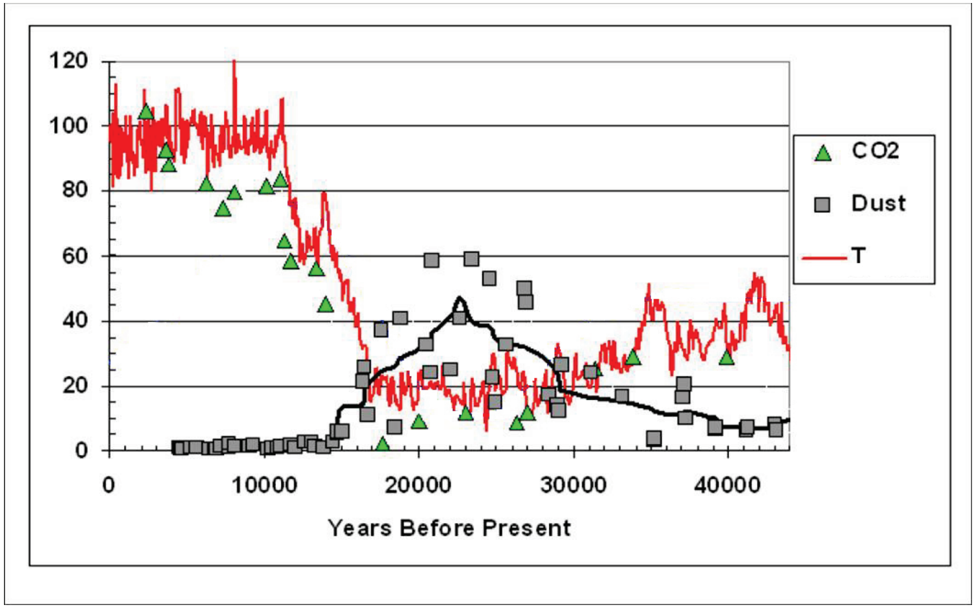
Lecture 5

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

Lecture 4, Slide 63

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.

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

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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 53 Parties to the Protocol.

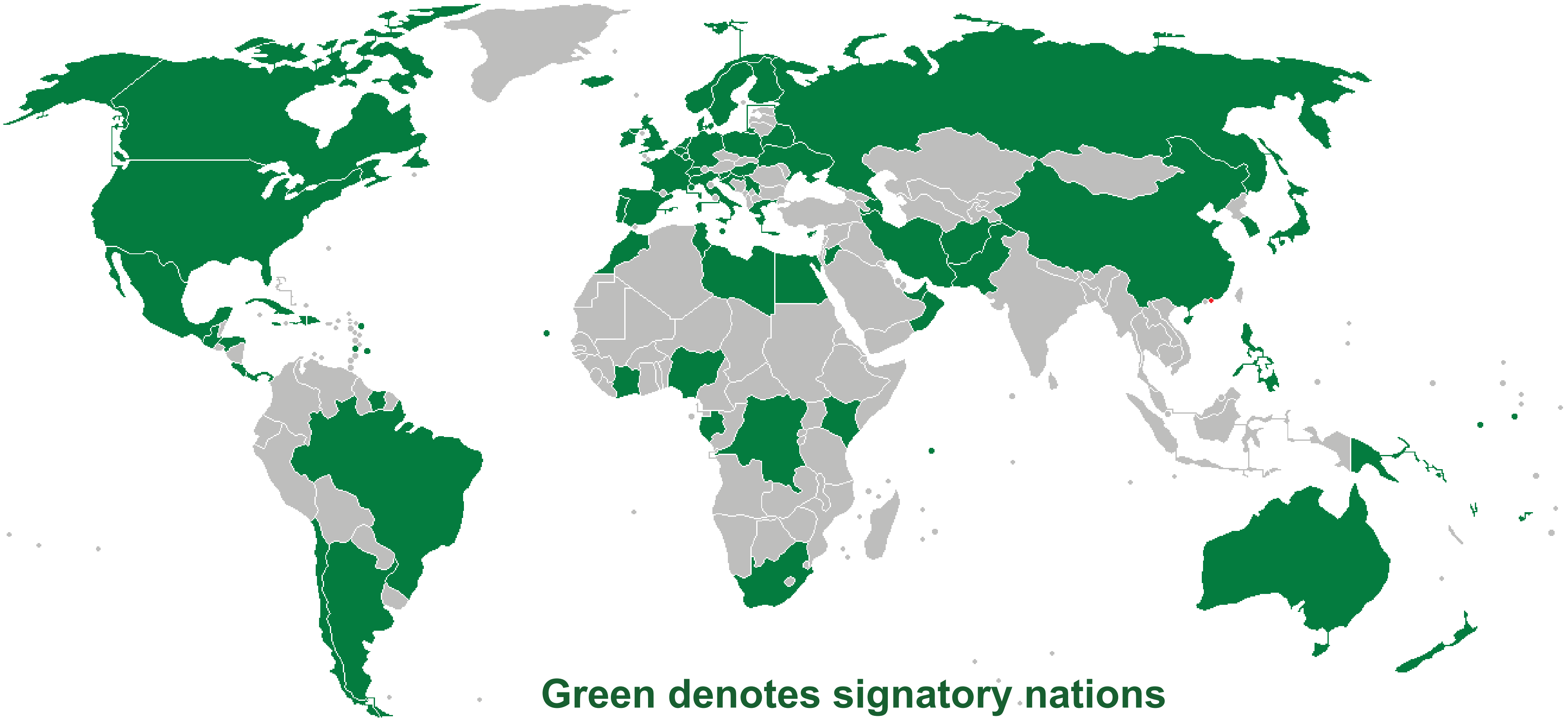
LC&P

LC&P
LONDON CONVENTION AND PROTOCOL

Related Documents

http://www.imo.org/OurWork/Environment/LCLP/Pages/default.aspx
https://web.archive.org/web/20190702064110/http://www.imo.org/en/OurWork/Environment/LCLP/Pages/default.aspx

Sequestration of CO_2 from the Atmosphere: Ocean Biology



Green denotes signatory nations

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

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 projected emissions, 2020 to 2060
- Land available ✓ Cost ✓

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

Afforestation

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- But:
  - forests are dark … as albedo declines, T rises, particularly in winter
  - once trees are fully grown, sequestration stops (yikes)
  - offset is modest 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

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.

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 also 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

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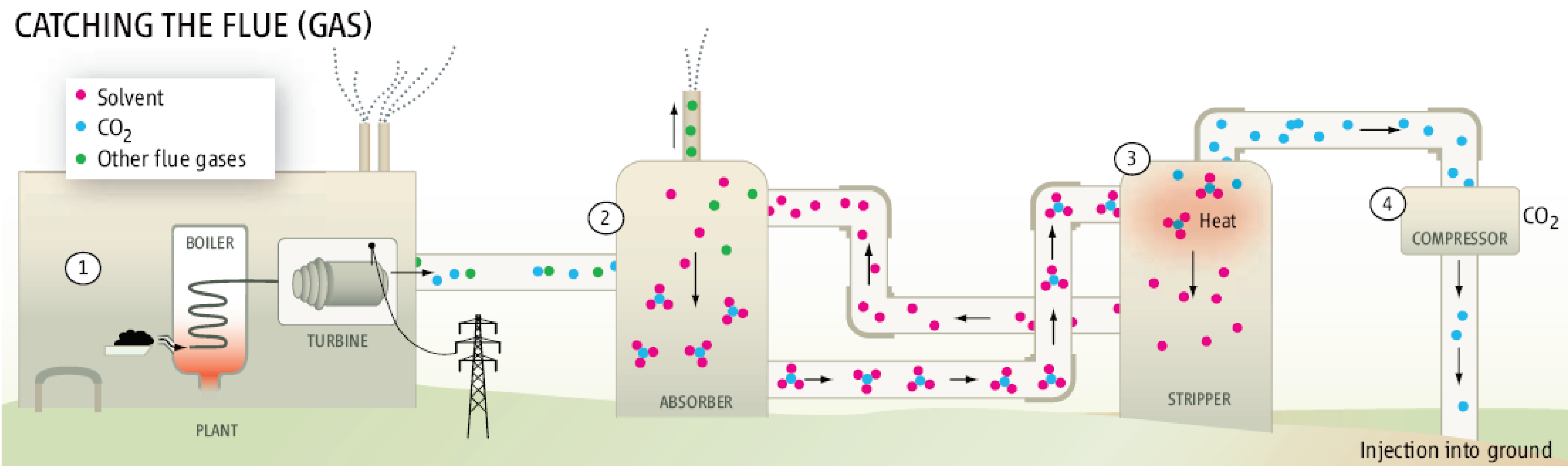
Why might these words be a concern ?!?

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.)

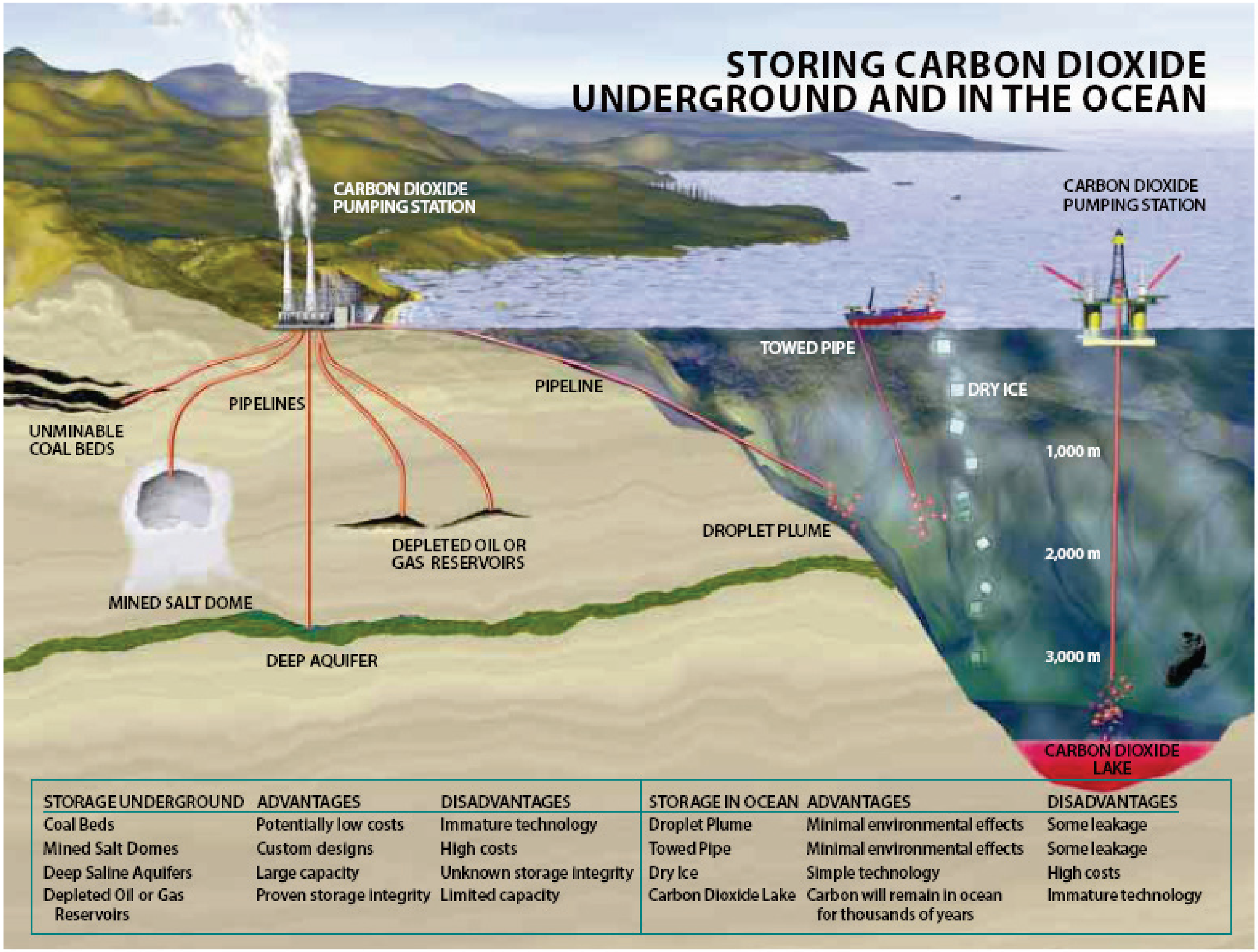
MEA-monoethanolamine $(CH_2CH_2OH)NH_2$ in an aqueous solution will absorb CO_2 to form ethanolammonium carbamate.

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

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

Kintisch, *Science*, 2007
https://science.sciencemag.org/content/317/5835/184

Sequestration of CO_2 from Power Plants



STORAGE UNDERGROUND	ADVANTAGES	DISADVANTAGES
Coal Beds	Potentially low costs	Immature technology
Mined Salt Domes	Custom designs	High costs
Deep Saline Aquifers	Large capacity	Unknown storage integrity
Depleted Oil or Gas Reservoirs	Proven storage integrity	Limited capacity

STORAGE IN OCEAN	ADVANTAGES	DISADVANTAGES
Droplet Plume	Minimal environmental effects	Some leakage
Towed Pipe	Minimal environmental effects	Some leakage
Dry Ice	Simple technology	High costs
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** $CO_2 \times 11 \times 10^9$ tonne C / yr $\times (44/12) \times 0.5$ = **$ 1.1 trillion**

Global GDP, 2019: **$ 86.6 trillion** CO_2 capture = **1.3 % of world GDP**

Back of the envelope analysis

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC)

WMO UNEP

Carbon Dioxide Capture and Storage

http://www.ipcc.ch/pdf/presentations/briefing-montreal-2005-11/presentation-special-report-co2.ppt

Sequestration of CO_2 from Power Plants: Cost

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Tra	m
Geo	
Oce	
Min	

Revised estimate is ~$80 per ton of CO_2 (median) for capture, transport, and storage, based on work of group of Professor Edward Rubin at Carnegie Mellon University

https://www.cmu.edu/epp/people/faculty/edward-s-rubin.html

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Global GDP, 2019: **$ 86.6 trillion** CO_2 capture = **1.8 % of world GDP**

WMO

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http://www.ipcc.ch/pdf/presentations/briefing-montreal-2005-11/presentation-special-report-co2.ppt

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
- **10 States are now part of RGGI**
  - Each state has an emissions cap
  - Regional market for CO_2 emission allowances
- Maryland joined on 20 April 2007
  - Bill passed in Annapolis
  - Participation governed by Md Dept of the Environment (MDE)
- **NJ, under the leadership of Gov Murphy, re-joined on 17 June 2019**

2020

State	Emissions Cap (Tons CO_2)
CT	3,642,677
DE	2,521,222
MA	8,904,648
ME	2,027,048
NH	2,937,362
NJ	18,000,000
NY	21,913,642
RI	1,602,826
VT	400,510
MD	*12,513,684*
TOTAL	**74,463,439**

https://www.rggi.org/sites/default/files/Uploads/Allowance-Tracking/2020_Allowance-Distribution.pdf

Cost of Fossil Fuels

- Current Regional Greenhouse Gas Initiative (RGGI) auction price: **$7.41 per ton of CO_2**

Allowance Prices and Volumes

Auction	Date	Quantity Offered	CCR Sold	Quantity Sold	Clearing Price	Total Proceeds
Auction 50	2020-12-02	16,237,495	0	16,237,495	$7.41	$120,319,837.95
Auction 49	2020-09-02	16,192,785	0	16,192,785	$6.82	$110,434,793.70
Auction 48	2020-06-03	16,336,298	0	16,336,298	$5.75	$93,933,713.50
Auction 47	2020-03-11	16,208,347	0	16,208,347	$5.65	$91,577,160.55
Auction 46	2019-12-04	13,116,444	0	13,116,444	$5.61	$73,583,250.84
Auction 45	2019-09-04	13,116,447	0	13,116,447	$5.20	$68,205,524.40

https://www.rggi.org/auctions/auction-results

- Fuel cost per ton of CO_2 released to the atmosphere (U.S., December 2020):
  - Coal:
  - Natural Gas:
  - Gasoline:

Cost of Fossil Fuels

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Cost of Fossil Fuels

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https://www.rggi.org/auctions/auction-results

- Fuel cost per ton of CO_2 released to the atmosphere (U.S., December 2020):
  - Coal: ~ $14
  - Natural Gas: ~ $57
  - Gasoline:

Cost of Fossil Fuels

- Current Regional Greenhouse Gas Initiative (RGGI) auction price: **$7.41 per ton of CO_2**

Allowance Prices and Volumes

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https://www.rggi.org/auctions/auction-results

- Fuel cost per ton of CO_2 released to the atmosphere (U.S., December 2020):
  - Coal: ~ $14
  - Natural Gas: ~ $57
  - Gasoline: ~$244