Unilateral Geoengineering

A few basic ideas about the science to start our discussions

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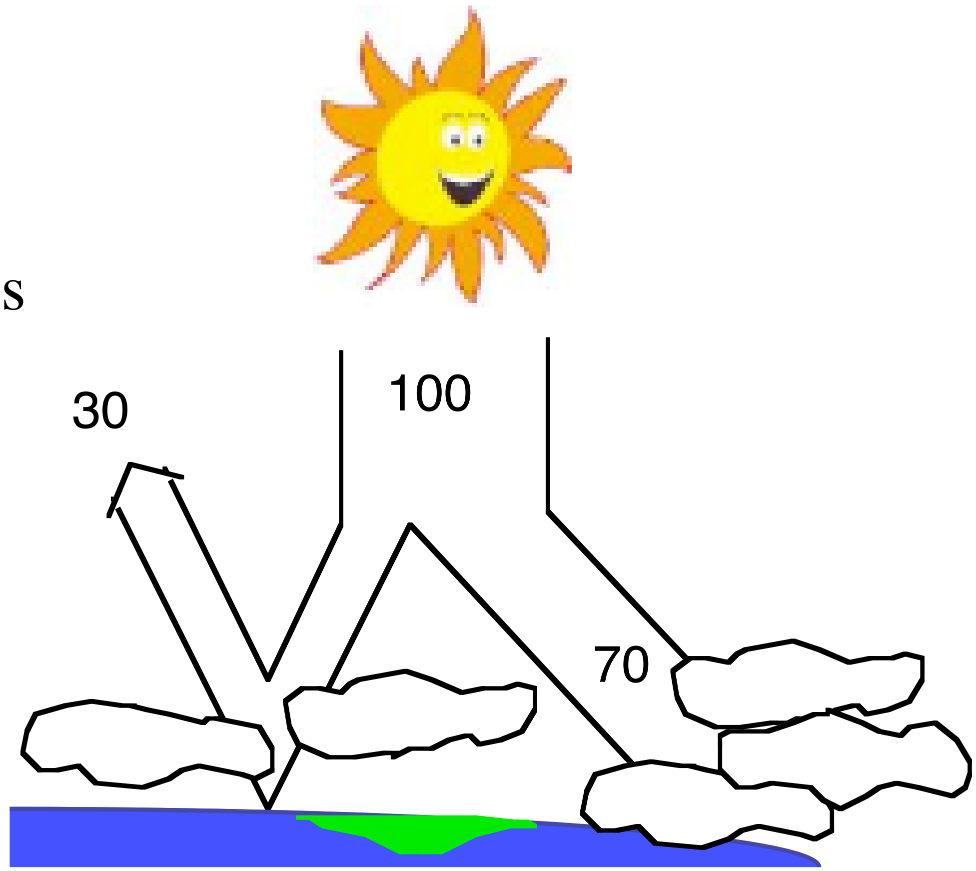
5. Explain why, if we are unlucky, the world may need to collectively engage in geoengineering.

Sun-earth system

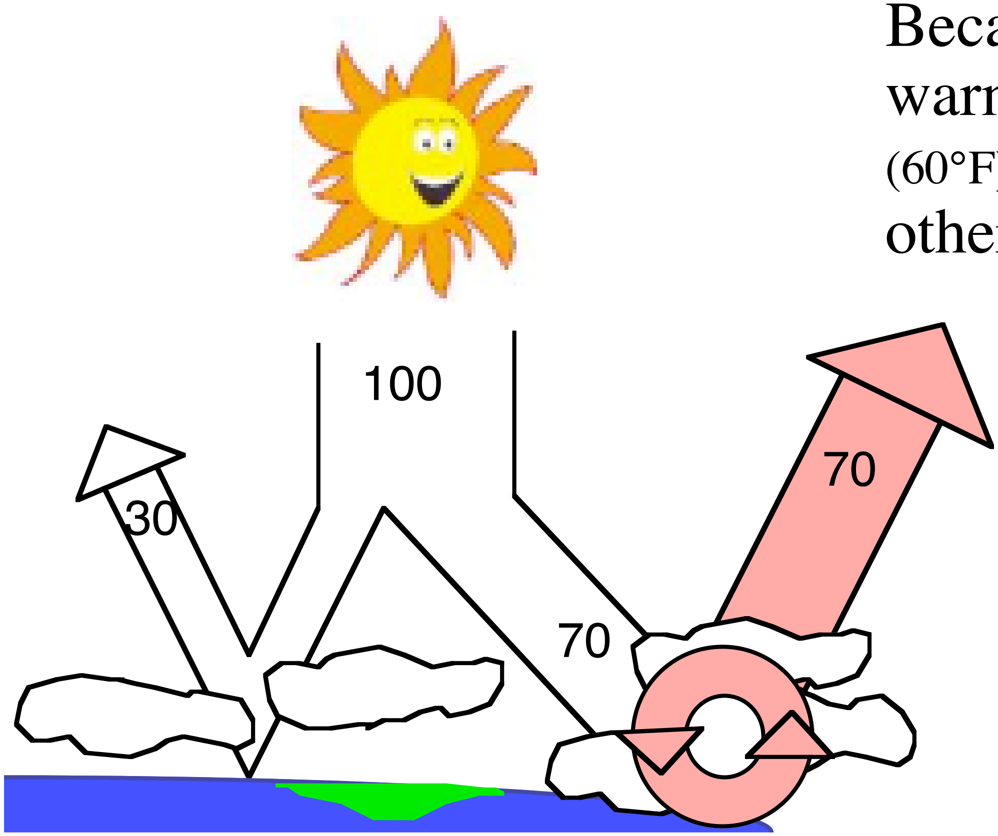
About 30% of the energy that comes to the earth from the sun is immediately reflected back into space…

…and about 70% is absorbed by the atmosphere and the ground where it becomes heat.
To stay in balance that heat energy has to get radiated back into space.



BUT, while the atmosphere is transparent to visible light, it is opaque to heat because infrared is absorbed by water vapor, carbon dioxide (CO_2) and other "greenhouse gases." So heat energy gets trapped and the planet warms. This is termed the "greenhouse effect."

Sun-earth system…(Cont.)



Because of this "greenhouse" warming the earth is 33°C (60°F) warmer* than it would otherwise be.

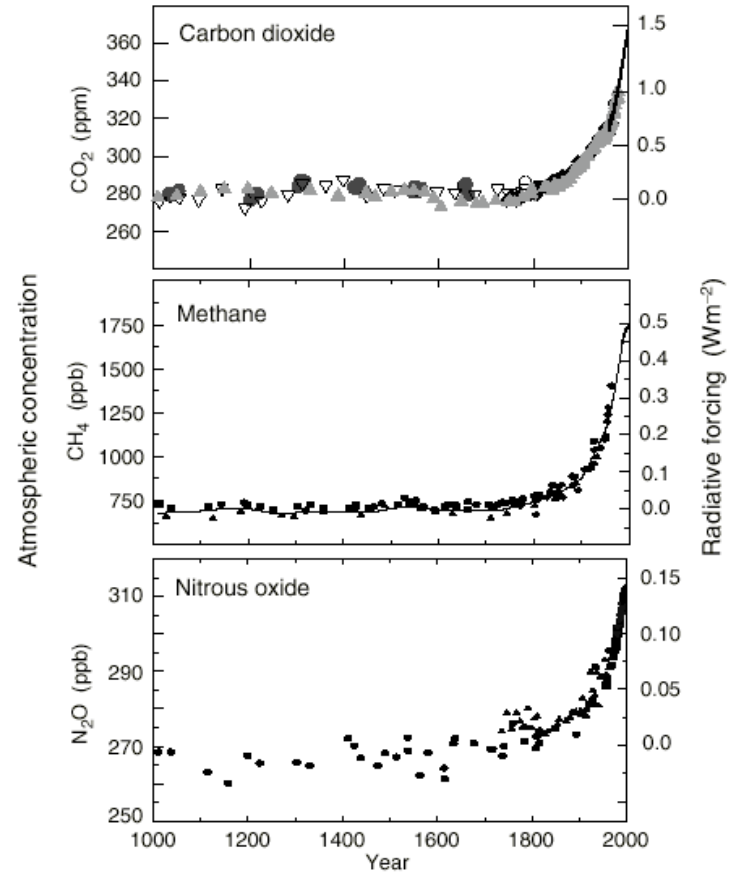
At that warmer temperature, an equilibrium is reached and the same amount of energy is radiated back to space from the top of the atmosphere.

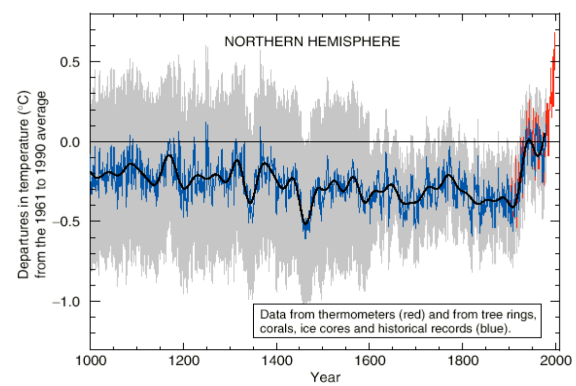
*About 32°C (57°F) of this warming is due to water vapor. The rest is due to ozone, carbon dioxide, and several other naturally occurring greenhouse gases.

As we humans…

…keep adding CO_2 and other "greenhouse gases" to the atmosphere, the average temperature of the earth has been going up.

You've probably have all seen the basic plots.





Source: IPCC WG1 2001.

But this is all rather abstract. Let me make it more concrete…

Just west…

… where I live in Pittsburgh is the 2360 Mw Bruce Mansfield power station.

A plant this size burns the equivalent of about 230 100T hopper cars of coal every day.

If coal were pure carbon, that would be the same as taking 130 such cars, converting them into invisible CO_2 gas, and releasing them into the atmosphere every day.

Hundreds of such plants are doing this all over the world.

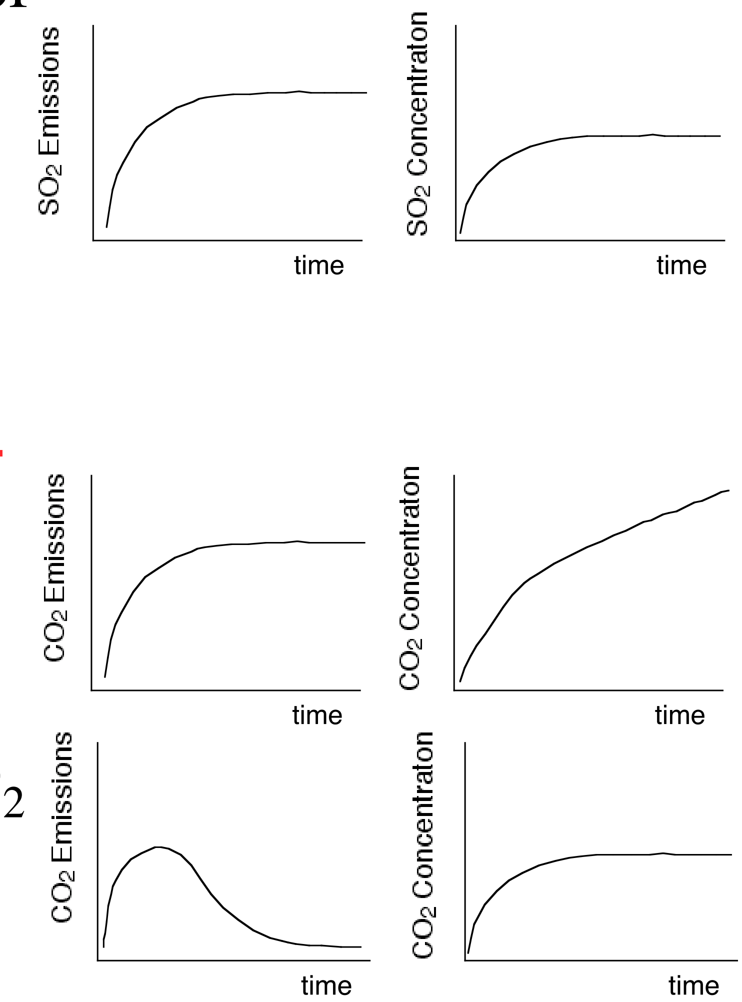
Sources: www.industcards.com/ st-coal-usa-pa.htm and www.battelle.org. Calculations by Jay Apt.

CO_2 is not like conventional air pollutants

Conventional pollutants like SO_2 or NO_x have a residence time in the atmosphere of just a few hours or days. Thus, stabilizing emissions of such pollutants results in stabilizing their concentration.

*This is **not** true of carbon dioxide.*

When CO_2 is emitted much of it lasts in the atmosphere for 100 years or more. Thus, stabilizing atmospheric *concentrations* of CO_2 will require the world to reduce emissions *by something like 80%*.



A useful analogy is…

…a bath tub with a very large faucet and a much smaller drain:

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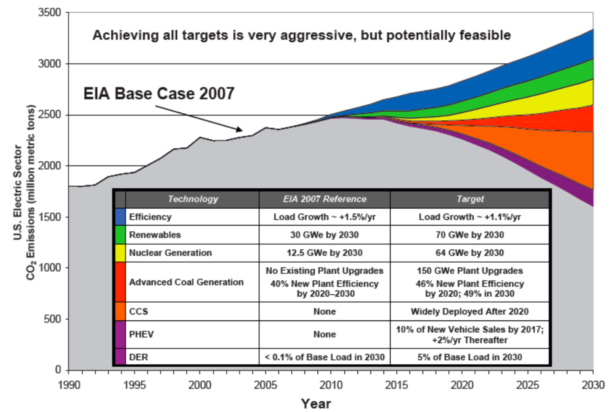
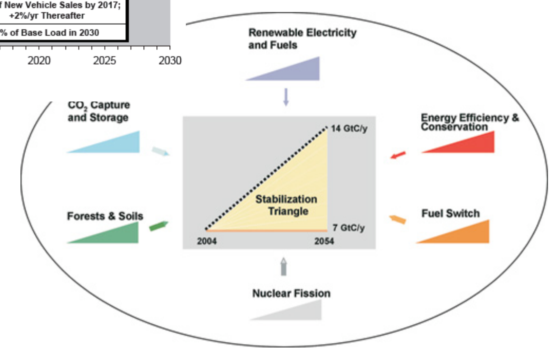
Reducing future climate change…

…basically means making major changes in the way in which human societies produce and uses energy.*

Achieving an 80% reduction in emissions will take everything we've got…

Conservation	Wind
Improved efficiency	Solar
Fuel switching	Geothermal
Electrification	Biomass
DG w/CHP	CCS
Nuclear	….etc.





Even if we manage to quickly reduce global emissions we'll <u>still</u> see significant warming and serious impacts in many regions over the next century.

*Changes in land use and agricultural practices are also contributors, but they are less important, especially in the long run, than emissions from the energy system.

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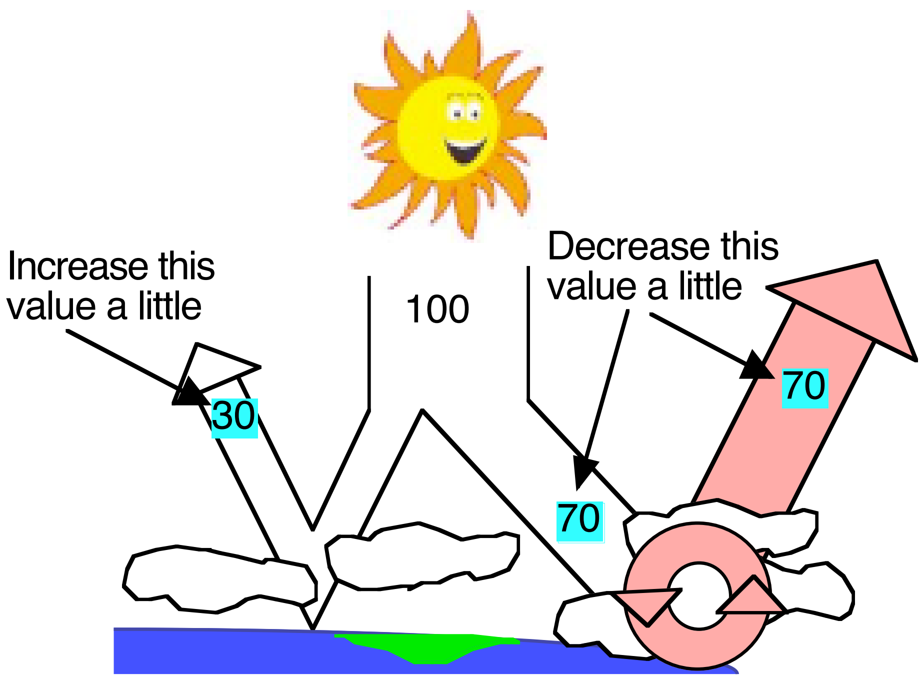
For many decades …

…within the scientific community there has been talk of the possibility that if climate change got serious enough, perhaps its effects could be slowed or reversed by taking steps to increase the amount of reflected sunlight (i.e. increase the earth's albedo).

A relatively modest change (~1%) is all that would be needed.



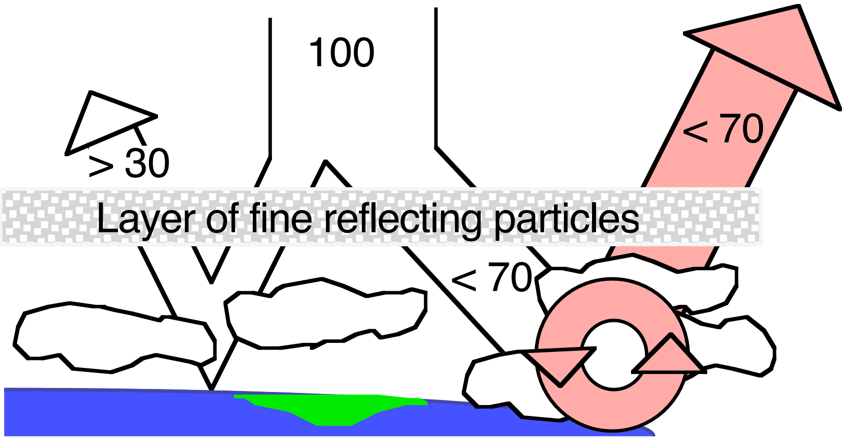
NOTE: some other activities, such as scrubbing CO_2 from the atmosphere may also be called geoengineering, but these are *not* the focus of this workshop.

Four examples of how the earth's albedo might be increased:

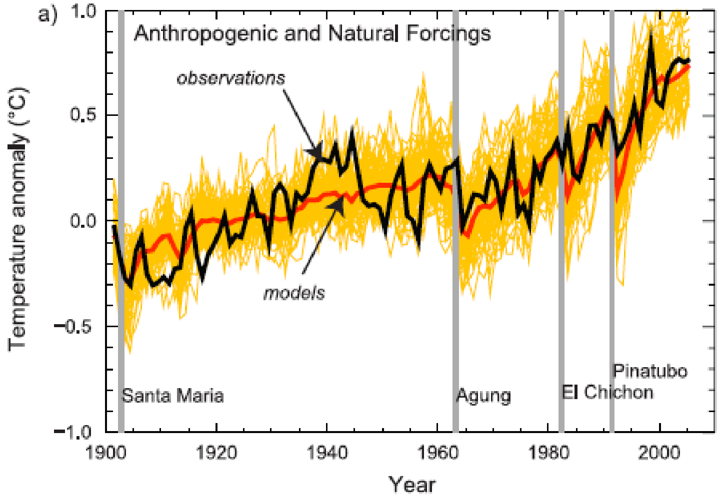
1. Add small reflecting particles in the stratosphere.
2. Add more clouds in the lower part of the atmosphere.
3. Place various kinds of reflecting objects or diffraction gratings in space either near the earth or at a stable location between the earth and the sun.
4. Change large portions of the planet's land cover from things that are dark and absorbing, such as trees, to things that are light and reflecting, such as open snow-cover or grasses.

Stratospheric aerosols

Adding more of the right kind of fine particles to the stratosphere can increase the amount of sunlight that is reflected back into space.

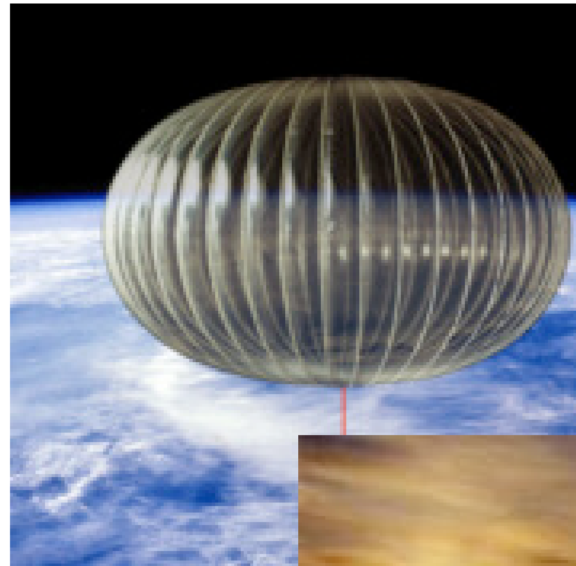


There is clear evidence from many large past volcanic eruptions that this mechanism can cool the planet (Mount Pinatubo produced global scale cooling of about 0.5°C).



Source: NASA and IPCC.

This is not hard to do, nor all that expensive.



David Keith has suggested that it should be possible to create microscopic reflecting composite particles that would be self-orienting and self-levitating, and thus might not have to be replaced very frequently.

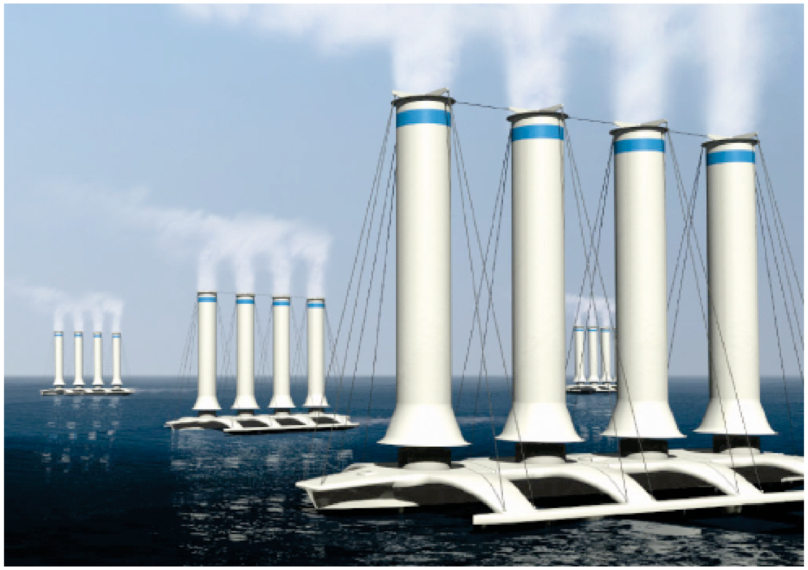
Sources: NASA; Boeing; www.carlstumpf.com

A single nation could do these within it's national boundaries

More clouds in the lower atmosphere

Early proposals suggested using sulfur. That would cause acid rain.

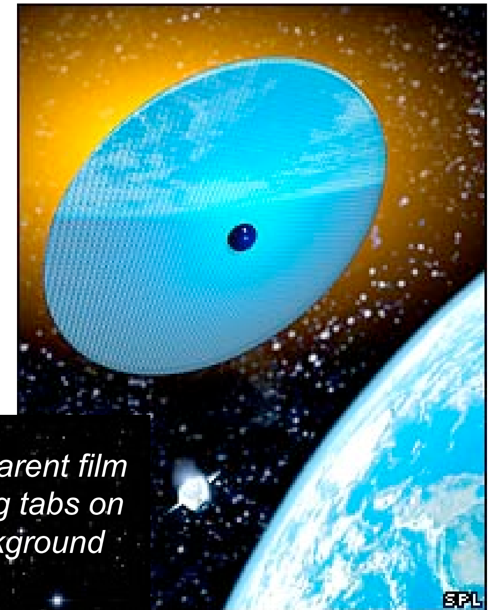
John Latham of the National Center for Atmospheric Research has proposed that salt from seawater could be effectively used as cloud condensation nuclei.

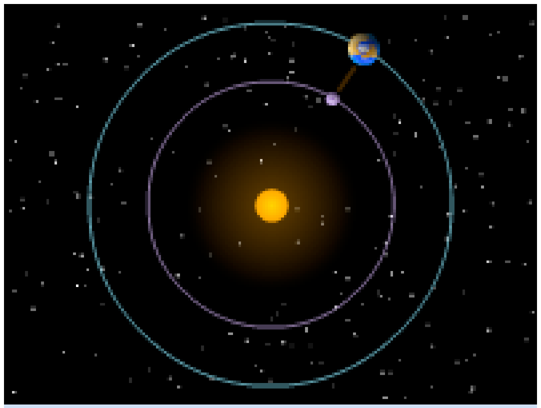


Stephen Salter of the University of Edinburgh has designed an "albedo spray vessel" which would put the Latham theory into practice.

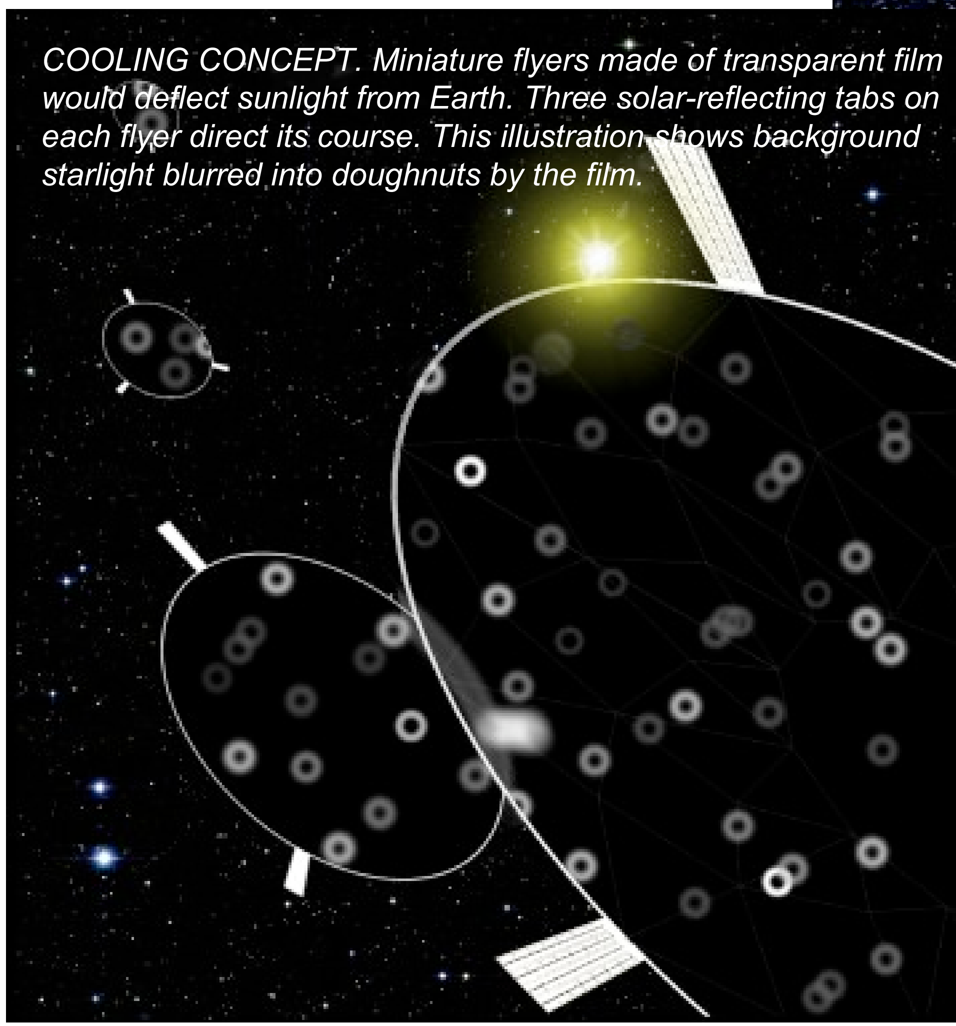
Source: S. Salter.

Reflectors or diffraction gratings in space





Lagrange point 1 is between the Earth and the sun. The solar wind reaches it about one hour before reaching Earth. In 1978, the International Sun-Earth Explorer-3 (ISEE-3) was launched towards L1, where it conducted solar observations for several years. Now the ESA/NASA SOHO solar watchdog is positioned there. *Credit:ESA*



COOLING CONCEPT. Miniature flyers made of transparent film would deflect sunlight from Earth. Three solar-reflecting tabs on each flyer direct its course. This illustration shows background starlight blurred into doughnuts by the film.

Source: Roger Angel, UA Steward Observatory, ESA, BBC.

Change land cover

For example, when the boreal forests were removed in the NCAR coupled ocean-atmosphere climate model, air temperature fell 12°C at 60°N in April and were still as much as 5°C colder in July.

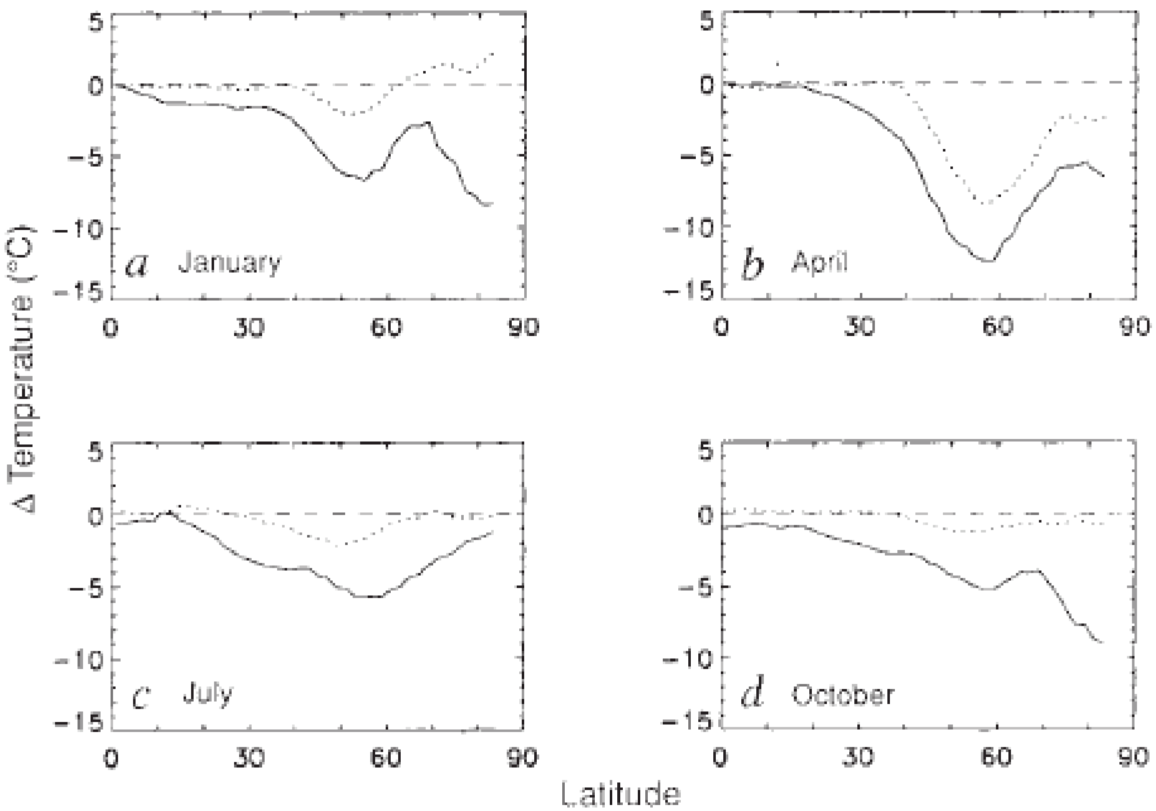


FIG. 2 Zonally averaged air temperature at a height of 2 m above land surfaces. See Fig. 1 for details.

Source: Gordon Bonan et al.,"Effects of borial forest vegetation on climate," *Nature*, *358*, pp. 716 - 718,1992.

Relative Costs

How does the cost of achieving ~80% reduction in the emissions of CO_2 and other GHGs compare the cost of geoengineering (which of course would have no impact on CO_2 level but could eliminate warming)?

The cost of GHG abatement

Today the world is emitting about 50×10^9 tonnes per year CO_2-eq

(of which about 30×10^9 is CO_2)

The IPCC 4th assessment says:

"Modelling studies show that global carbon prices rising to US$20-80/t$CO_2$-eq by 2030 are consistent with stabilisation at around 550ppm CO_2-eq by 2100. For the same stabilisation level, induced technological change may lower these price ranges to US$5-65/t$CO_2$-eq in 2030."

$$(50 \times 10^9 \text{ tCO}_2\text{-eq})(5 \text{ to } 65\$/\text{tCO}_2\text{-eq}) = 250 \text{ to } 3300 \times 10^9 \ \$/\text{year}$$

The size of the global economy is of the order of $\$60 \times 10^{12}$

$$\frac{0.25 \text{ to } 3.3 \times 10^{12} \ \$/\text{year}}{60 \times 10^{12} \ \$/\text{year}} \longrightarrow 0.4\% \text{ to } 5.5\% \text{ of world GDP/year}$$

Will this, as some have argued, wreck the economy?

Surely not.

For example: Jay Apt has estimated that if it were done in an orderly way over the next 50 years, the US electricity system could be decarbonized for a bit less than what it cost that industry to meet the requirements of the Clean Air Act.

However, while abatement done in an orderly way, is affordable, geoengineering is likely to be *much* cheaper.

The cost of geoengineering

As noted in the briefing paper:

A National Research Council 1992 report estimated the undiscounted annual costs for a 40-year project to be \$100 billion.

Teller, Wood and Hyde have suggested that well designed systems might reduce this cost to as little as a few hundred million dollars per year.

If we take cost to be between \$100 million and \$100 billion per year

$$\frac{1\text{-}100 \times 10^{9}\ \$/\text{year}}{50 \times 10^{12}\ \$/\text{year}} \longrightarrow 0.0002\% \text{ to } 0.2\% \text{ of world GDP/year}$$

Bottom line

It is probably safe to assume that the direct monetary cost of geoenginering would be *at least* 100 times less than the cost of a full program of GHG abatement…

…*and perhaps much cheaper than that*.

Because it is relatively cheap, a nation that had not done much abatement, but started experiencing serious climate impacts, might be tempted to unilaterally engage in albedo-modifying geoengineering.

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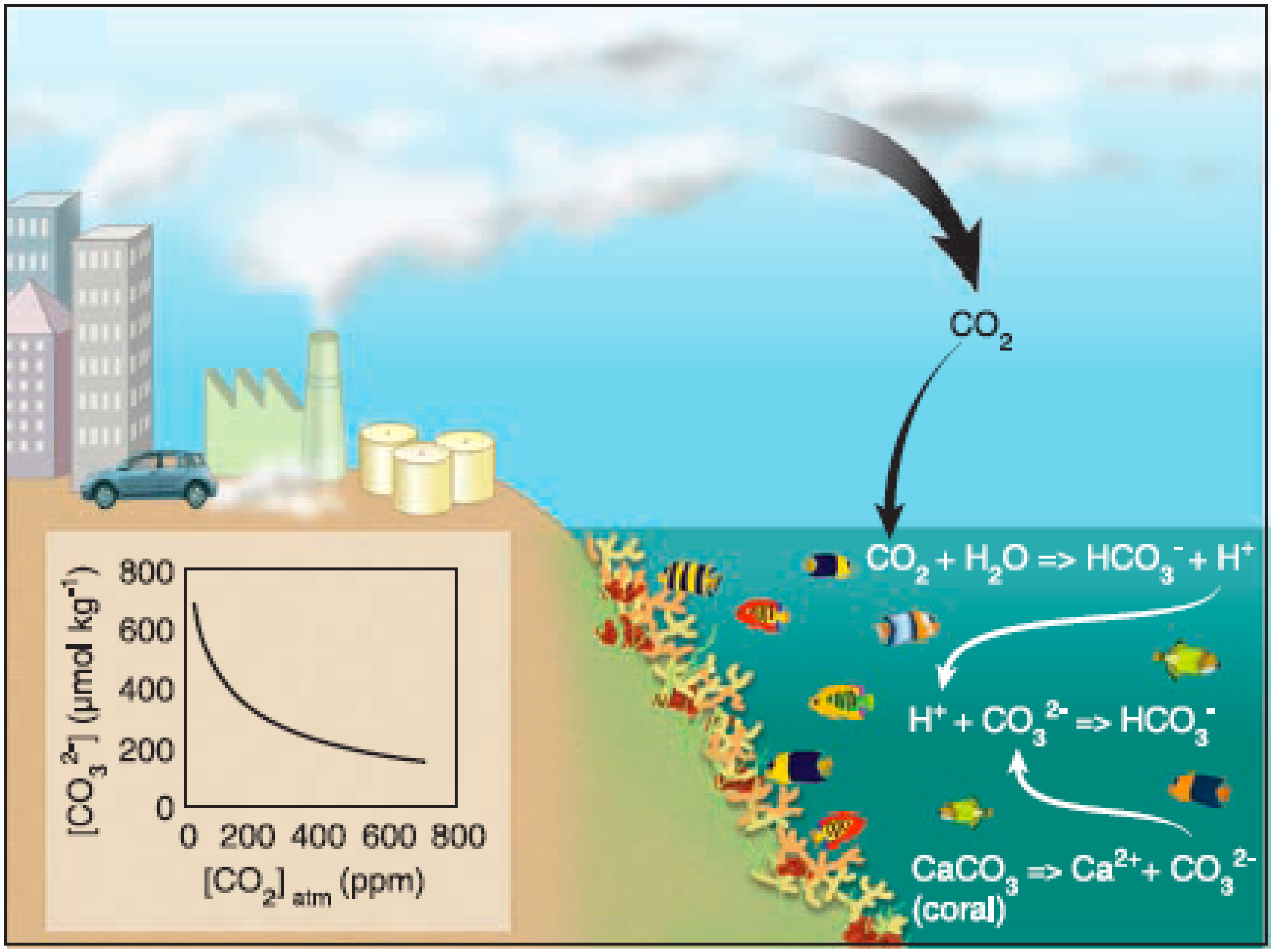
Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms

James C. Orr[1], Victoria J. Fabry[2], Olivier Aumont[3], Laurent Bopp[1], Scott C. Doney[4], Richard A. Feely[5], Anand Gnanadesikan[6], Nicolas Gruber[7], Akio Ishida[8], Fortunat Joos[9], Robert M. Key[10], Keith Lindsay[11], Ernst Maier-Reimer[12], Richard Matear[13], Patrick Monfray[1]†, Anne Mouchet[14], Raymond G. Najjar[15], Gian-Kasper Plattner[7,9], Keith B. Rodgers[1,16]†, Christopher L. Sabine[5], Jorge L. Sarmiento[10], Reiner Schlitzer[17], Richard D. Slater[10], Ian J. Totterdell[18]†, Marie-France Weirig[17], Yasuhiro Yamanaka[8] & Andrew Yool[18]

Today's surface ocean is saturated with respect to calcium carbonate, but increasing atmospheric carbon dioxide concentrations are reducing ocean pH and carbonate ion concentrations, and thus the level of calcium carbonate saturation. Experimental evidence suggests that if these trends continue, key marine organisms—such as corals and some plankton—will have difficulty maintaining their external calcium carbonate skeletons. Here we use 13 models of the ocean–carbon cycle to assess calcium carbonate saturation under the IS92a 'business-as-usual' scenario for future emissions of anthropogenic carbon dioxide. In our projections, Southern Ocean surface waters will begin to become undersaturated with respect to aragonite, a metastable form of calcium carbonate, by the year 2050. By 2100, this undersaturation could extend throughout the entire Southern Ocean and into the subarctic Pacific Ocean. When live pteropods were exposed to our predicted level of undersaturation during a two-day shipboard experiment, their aragonite shells showed notable dissolution. Our findings indicate that conditions detrimental to high-latitude ecosystems could develop within decades, not centuries as suggested previously.

The process of ocean acidification

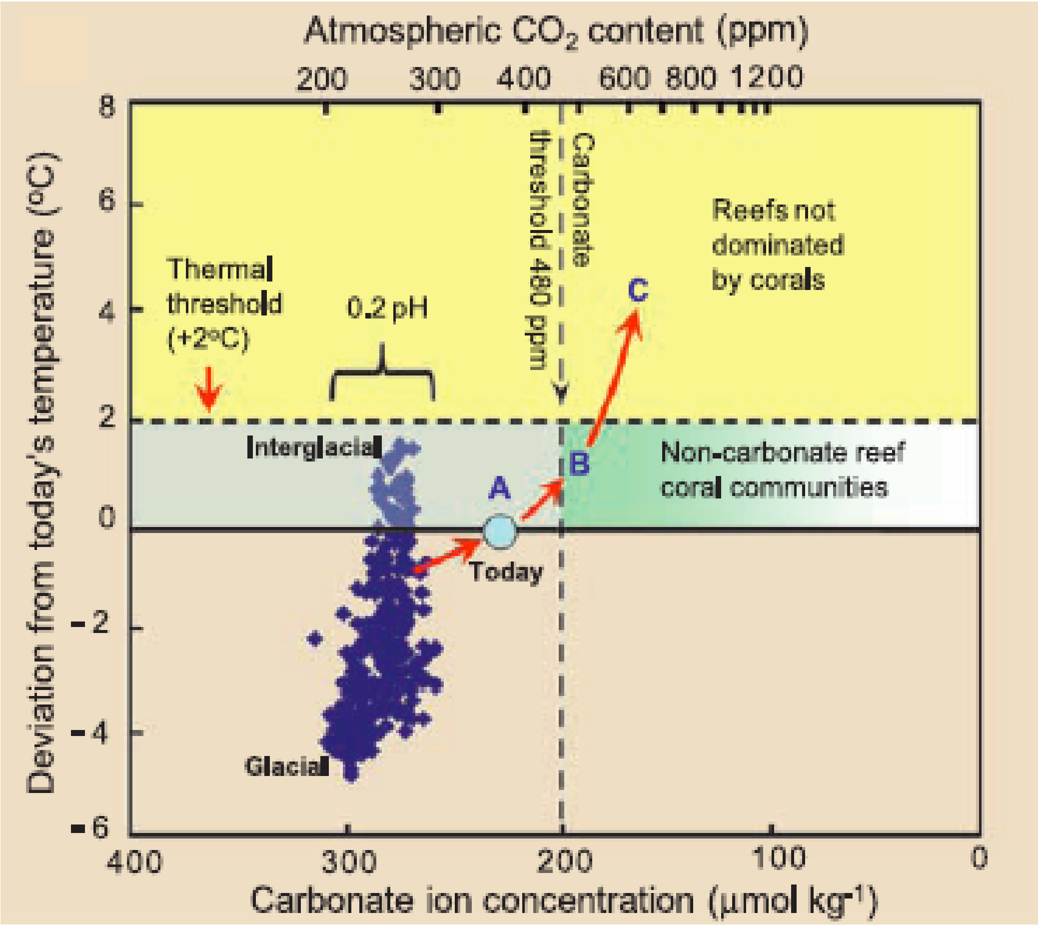


Source: O. Hoegh-Guldberg et al., "Coral reefs under rapid climate change and ocean acidification," *Science*, *318*, pp. 1737-1742, December 14, 2007.

Over the next few decades…

…as CO_2 rises and warming occurs, the ocean will acidify.

That will have profound implications for coral and much marine life that makes shells by extracting dissolved carbonate from the water.



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What does this mean for reefs?

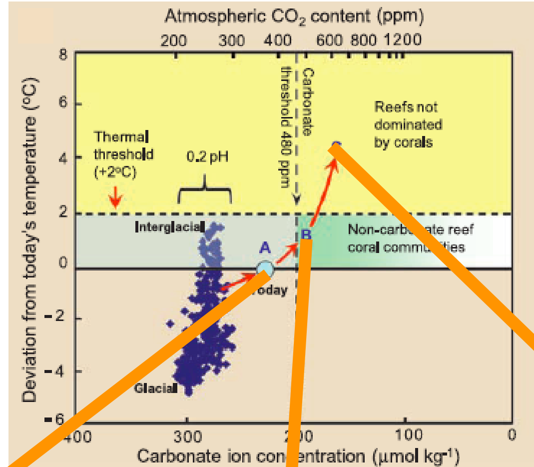

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Fig. 5. Extant examples of reefs from the Great Barrier Reef that are used as analogs for the ecological structures we anticipate for Coral Reef Scenarios CRS-A, CRS-B, and CRS-C (see text). The $[CO_2]_{atm}$ and temperature increases shown are those for the scenarios and do not refer to the locations photographed. **(A)** Reef slope communities at Heron Island. **(B)** Mixed algal and coral communities associated with inshore reefs around St. Bees Island near Mackay. **(C)** Inshore reef slope around the Low Isles near Port Douglas. [Photos by O. Hoegh-Guldberg]

Shell dissolution (e.g. pteropod or "sea butterfly")

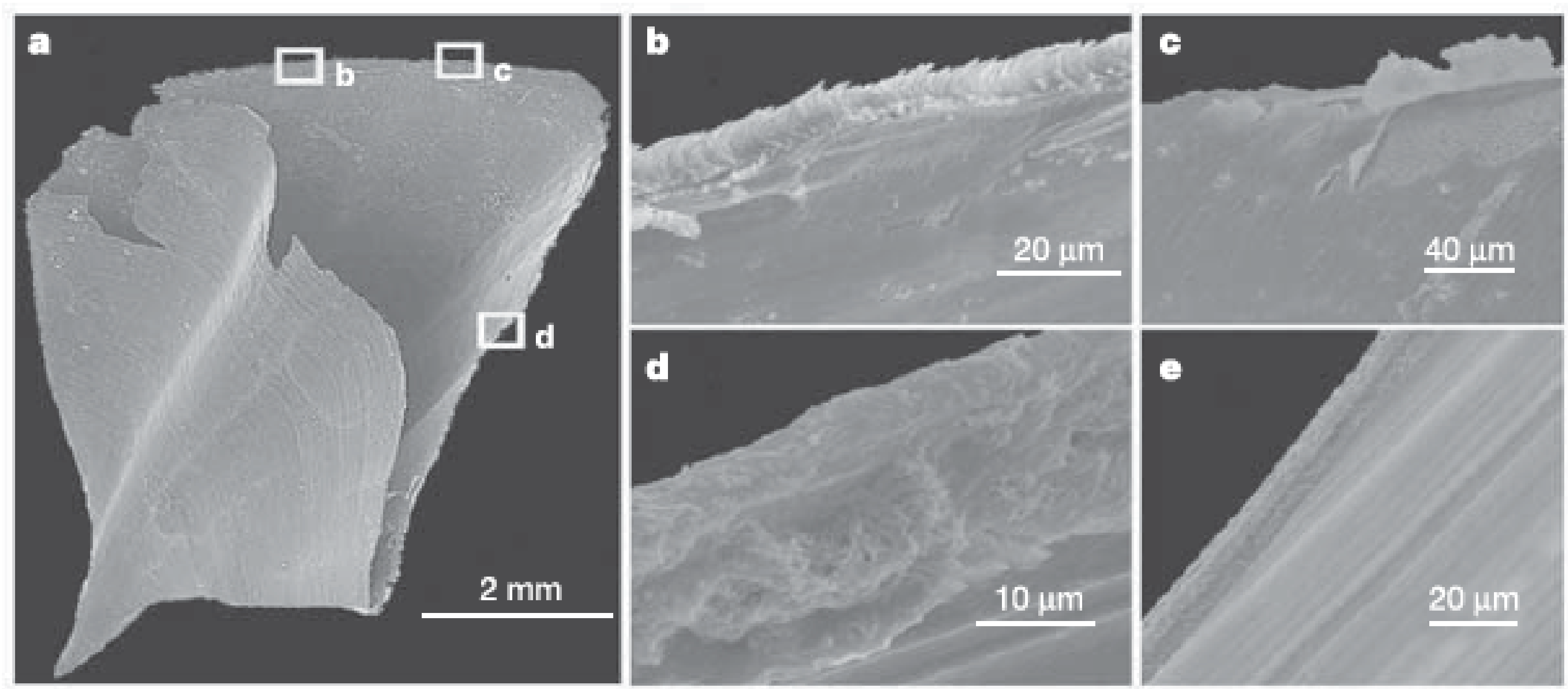
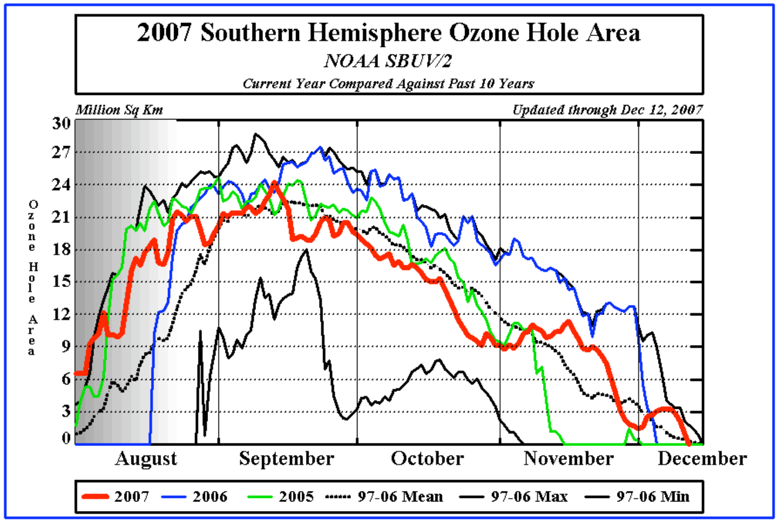
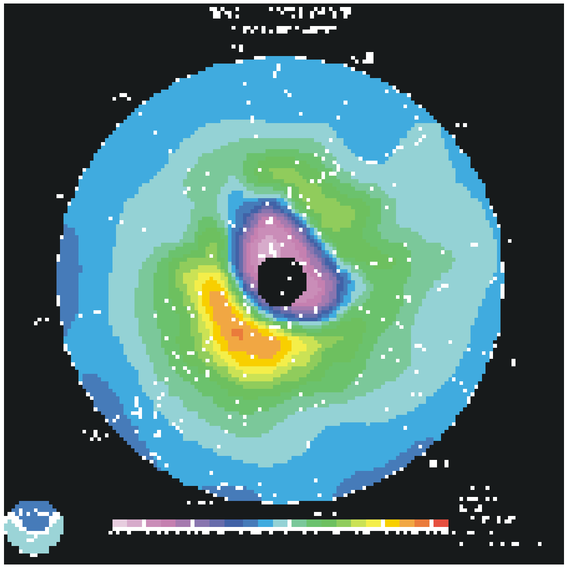


Figure 6 | Shell dissolution in a live pteropod. a–d, Shell from a live pteropod, *Clio pyramidata*, collected from the subarctic Pacific and kept in water undersaturated with respect to aragonite for 48 h. The whole shell (**a**) has superimposed white rectangles that indicate three magnified areas: the shell surface (**b**), which reveals etch pits from dissolution and resulting exposure of aragonitic rods; the prismatic layer (**c**), which has begun to peel back, increasing the surface area over which dissolution occurs; and the aperture region (**d**), which reveals advanced shell dissolution when compared to a typical *C. pyramidata* shell not exposed to undersaturated conditions (**e**).

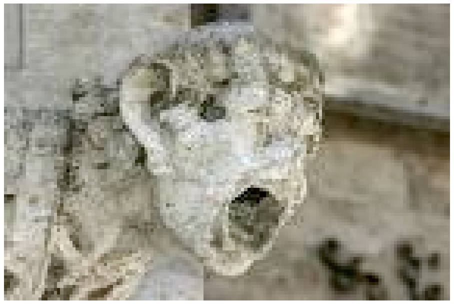
Source: Orr et al., *Nature*, 2005; Wikipedia.

More reactive surfaces in the stratosphere





If sulfur aerosol is used: more acid rain



Source: NOAA, commons.wikimedia.org

Cooling would almost certainly not be uniform.

If one stopped after doing it for a while, very rapid warming could occur.

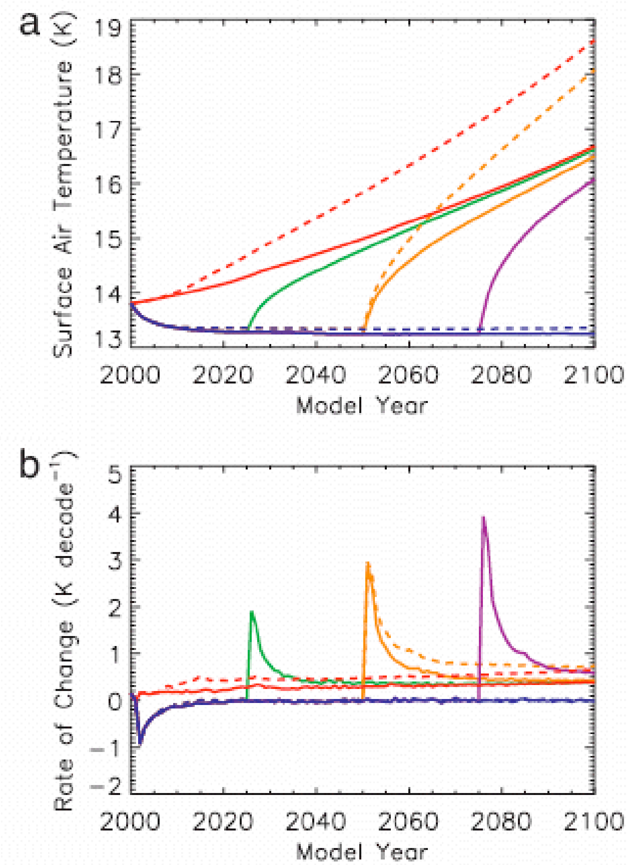


Fig. 3. Simulated surface air temperature (*a*) and annual rate of temperature change (*b*) for runs A2 (red), GEO (BLUE), OFF_2025 (green), OFF_2050 (orange), and OFF_2075 (purple). Runs with doubled climate sensitivity (A2+CS, GEO+CS, and OFF_2050+CS) are plotted as dashed lines.

Source: Matthews and Caldeira, PNAS, Jul 12, 2007,

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Most climate projections…

…assume that the climate system and the ecosystem will respond in smooth and continuous ways to increased GHG and warming.

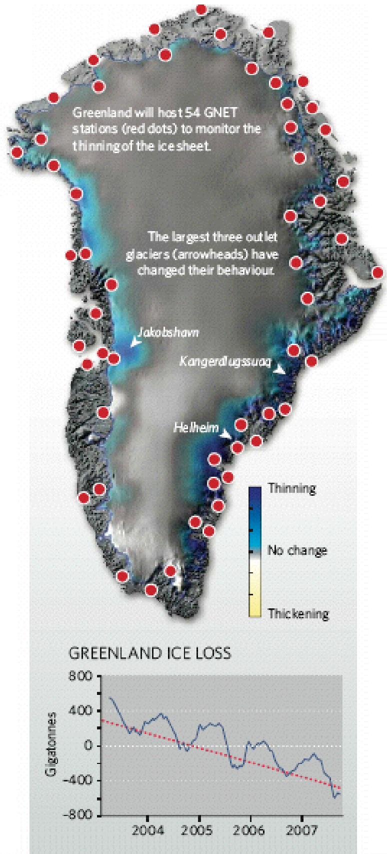
BUT…there are several things that could lead to much more abrupt changes. These could include:

Rapid release of large amounts of carbon stored in tundra, methane hydrates, etc.

Dramatic changes in ocean or atmospheric circulation patterns, precipitation, storm intensities and tracks, etc.

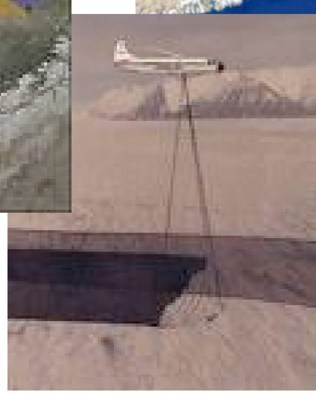
Rapid sea level rise.

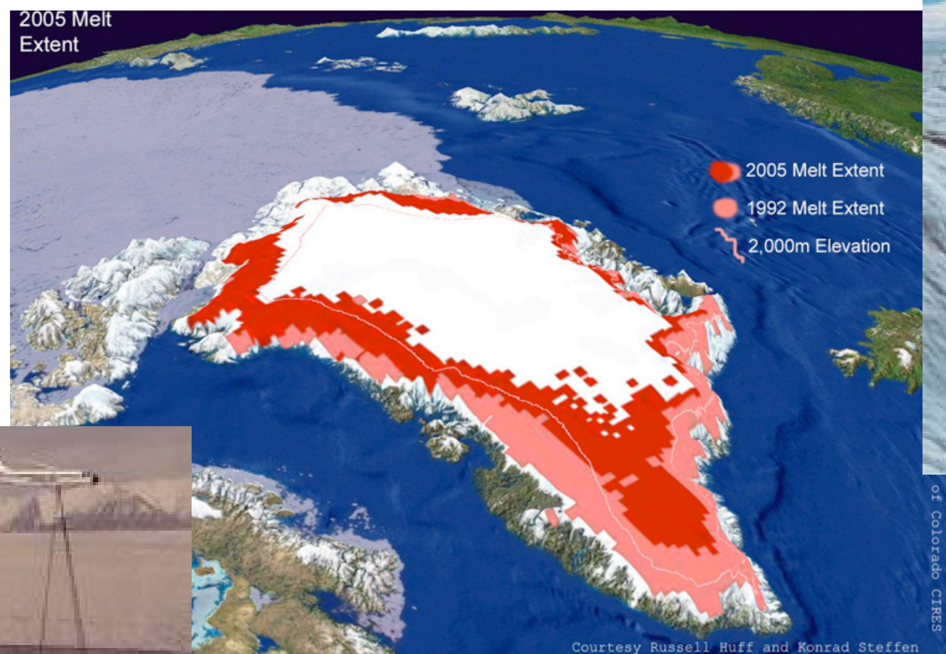
If some of these things were to happen, the world might collectively decided we need geoengineering



Recent IPCC estimates of sea level rise may be too small

For example, there is some evidence that suggests that Greenland is melting more quickly than previously thought.

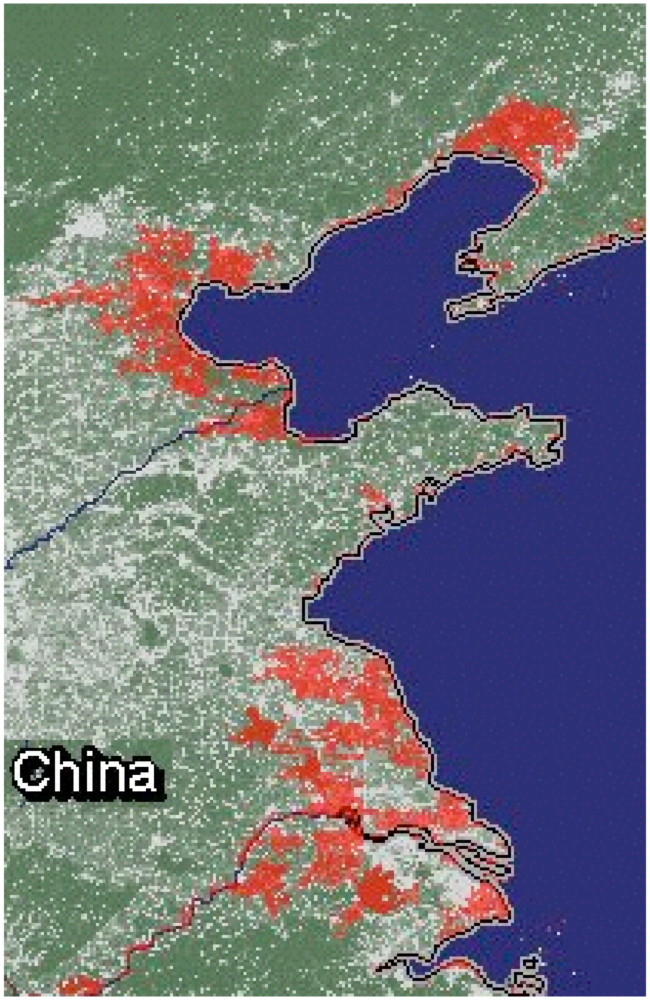


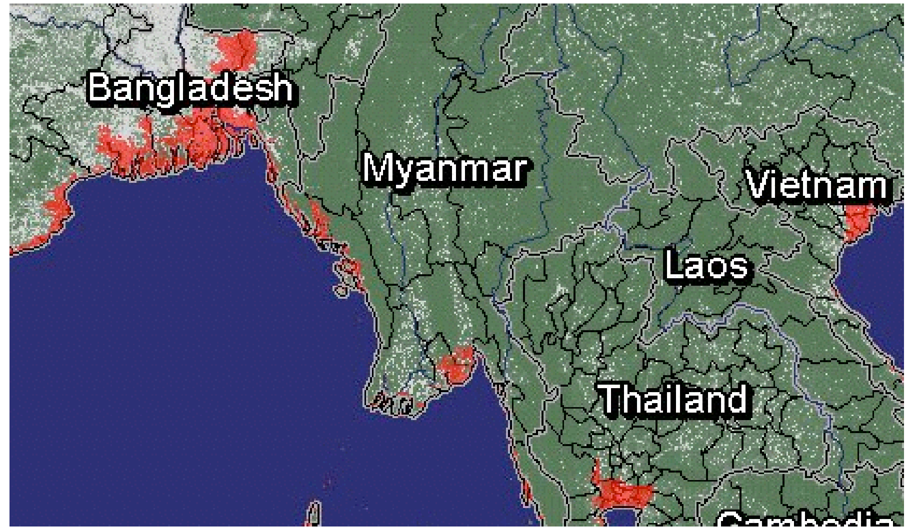


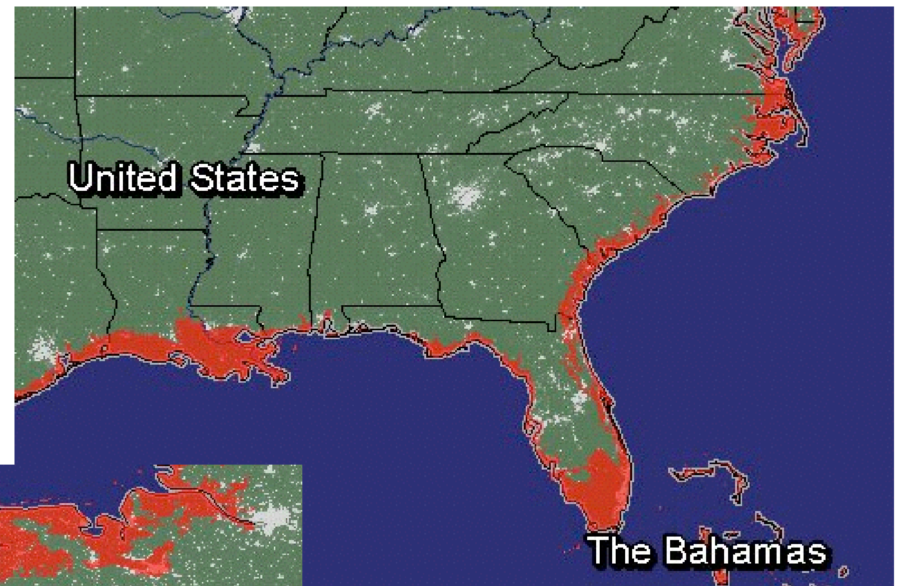
Loss of Greenland ~7m of sea level rise.

Sources: CIRES, NASA, *Nature*, ABC

6m of Sea Level Rise







Source: http://geongrid.geo.arizona.edu/arcims/website/slrworld/viewer.htm

I take this to mean…

…that while it would be a very bad idea to allow single nations or other entities to unilaterally engage in geoengineering by modifying the earth's albedo, we'd also would be unwise to take the option completely off the table.

If we get a large and very serious climate surprise, as a last resort the world might need to collectively engage in some albedo-modifying geoengineering.

Panel Discussion

Now, to provide additional commentary, and correct or offer alternative views to what I have just said, we will turn for comments from:

Ken Caldeira

Ralph Cicerone

David Keith

Steve Pacala