Technologies for Climate Engineering

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Emissions are rising faster than expected

Skeptics argued that this “unrealistic” scenario was included only to make the problem look worse.

This is where we need to be heading.
How Industry May Change Climate

The amount of carbon dioxide in the air will double by the year 2080 and raise the temperature an average of at least 4 per cent. The burning of about two billion tons of coal and oil a year keeps the average ground temperature somewhat higher than it would otherwise be. If industrial growth extended over several thousand years instead of over a century only, the oceans would have absorbed most of the excess carbon dioxide. Seas circulate so slowly that they have had little effect in reducing the amount of the gas as man's smoke-making abilities multiplied during a hundred years.

All this and more came out in the course of a paper that Dr. Gilbert N. Plass of Johns Hopkins presented before the American Geophysical Union. He found that man's industries add six billion tons of carbon dioxide to the atmosphere.

Theory Applied to Glaciers

All this reinforces a theory advanced in 1861 that decreases in carbon dioxide explain the growth and advance of glaciers at various intervals in the past. In 1941 Dr. Plass finds the
Forest et al. (2002) and Morgan & Keith (1995) have contributed to understanding the climate sensitivity and temperature response to doubled CO₂ levels. The diagrams illustrate the distribution of expert estimates for the temperature response given a doubling of CO₂, with and without state change and surprise.
Why Is Climate Sensitivity So Unpredictable?

Gerard H. Roe* and Marcia B. Baker
Forest et al, expert prior (Morgan & Keith)  \( P > 8 = 3\% \)

Sanderson et al (2007)  \( P > 8 = 7\% \)

Forest et al, uniform  \( P > 8 = 15\% \)
Human actions that change climate → Climate System → Climate impact on human welfare
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Mitigation → Geoengineering → Adaptation
Putting sulfur in the stratosphere

*Of order* 1-2 Mt-S per year offsets the radiative forcing of $2 \times CO_2$ (~2-4% of current global S emissions)

~3 gram sulfur in the stratosphere *roughly* offsets 1 ton carbon in the atmosphere (S:C ~ 1:300,000)

Assuming the NAS 1992 number of 20 $/kg \rightarrow 30$ billion per year.

Methods:
1. Naval guns
2. Aircraft
3. Tethered balloon with a hose
Models suggest the compensation is quite good

\[2 \times \text{CO}_2\]

and

\[1.8\% \text{ reduction in solar intensity}\]

Caldeira et al., in prep, 2007
NCAR Community Atmosphere Model

Middle atmosphere configuration
- Model top at about 80km
- 52 layers
- 2x2.5 Degree Horizontal resolution
- Finite Volume solution for dynamics with desirable properties for transport

Photochemistry includes only that relevant to oxidation of DMS and $\text{SO}_2 \rightarrow \text{SO}_4$

Injection of $\text{SO}_2$
- at 25km
- from 10N - 10S
- 1 Tg S/yr assuming a small (or background) aerosol size distribution

Pinatubo $\approx$ 10-30 Tg S
Rasch et al: Annual Average Surface Temperature

Geo-SO4/2xCO2
(1Tg Bkg)- Control

Geo-SO4/2xCO2
(2Tg Bkg)- Control
Engineered scattering systems

Alternative scattering systems

- Oxides
  - H$_2$SO$_4$ or Al$_2$O$_3$
- Metallic particles ($10^{-3} \times$ lower mass)
  - Disks, micro-balloons or gratings
- Resonant ($10^4$-$10^6 \times$ lower mass ??)
  - Encapsulated organic dyes

What you might get:

- Much lower mass
- Spectral selectivity
Vertical transport of anthropogenic soot aerosol into the middle atmosphere

R. F. Pueschel, S. Verma, H. Rohatschek, G. V. Ferry, N. Boiaidjeva, S. D. Howard, and A. W. Strawa

Abstract. Gravito-photophoresis, a sunlight-induced force acting on particles which are geometrically asymmetric and which have uneven surface distribution of thermal accommodation coefficients, explains vertical transport of fractal soot aerosol emitted by aircraft in conventional flight corridors (10-12 km altitude) into the mesosphere (>80 km altitude). While direct optical effects of this aerosol appear nonsignificant, it is conceivable that they play a role in mesospheric physics by providing nuclei for polar mesospheric cloud formation and by affecting the ionization of the mesosphere to contribute to polar mesospheric summer echoes.
Photophoresis

Uneven illumination

Temperature gradient across particle

Net force toward cool side

Sunlight

Net force
Gravito-Photophoresis

Sunlight warms particle evenly

Particles more likely to rebound hot from bottom of particle

Net upward force
Conceptual design: A levitated disk

Radius ~10 μm

50 nm

Al₂O₃

Al

BaTiO₃

Magnetite (Fe₃O₄)  
~500 X 500 nm

Electric field  
100-200 V/m

Magnetic field  
10⁻⁴ T

Lifting force

Poleward force
Photophoretic levitation of nano-engineered scatterers for climate engineering

1. Long atmospheric lifetimes
   - Lower cost and impact of replenishment
   - Can afford more elaborately engineered scatters

2. Particles above the stratosphere
   - less ozone impact.

2. The ability to concentrate scattering particles near the poles
   - Concentrate climate engineering where it’s needed most.
RESTORING THE QUALITY
OF
OUR ENVIRONMENT

OTHER POSSIBLE EFFECTS OF AN INCREASE IN ATMOSPHERIC CARBON DIOXIDE

Melting of the Antarctic ice cap.—It has sometimes been suggested that atmospheric warming due to an increase in the CO₂ content of the atmosphere may result in a catastrophically rapid melting of the Antarctic ice cap, with an accompanying rise in sea level. From our knowledge of events at the end of the Wisconsin period, 10 to 11 thousand years ago, we know that melting of continental ice caps can occur very rapidly on a geologic time scale. But such melting must occur relatively slowly on a human scale.

The Antarctic ice cap covers 14 million square kilometers and is about 3 kilometers thick. It contains roughly $4 \times 10^{26}$ tons of ice, hence $4 \times 10^{24}$ gram calories of heat energy would be required to melt it. At the present time, the poleward heat flow across 70° latitude is $10^{22}$ gram calories per year, and this heat is being radiated to space over Antarctica without much measurable effect on the ice cap. Suppose that the poleward heat flow could be increased by 10%. How long would it take for all of this heat to melt the ice cap?

The climatic changes that may be produced by the increased CO₂ content could be deleterious from the point of view of human beings. The possibilities of deliberately bringing about countervailing climatic changes therefore need to be thoroughly explored. A change in the radiation balance in the opposite direction to that which might result from the increase of atmospheric CO₂ could be produced by raising the albedo, or reflectivity, of the earth. Such a change in albedo could be

THE WHITE HOUSE
NOVEMBER 1965

This is a hundred times greater than present worldwide rates of sea level change.

Warming of sea water.—If the average air temperature rises, the temperature of the surface ocean waters in temperate and tropical regions could be expected to rise by an equal amount. (Water temperatures in the polar regions are roughly stabilized by the melting and freezing of ice.) An oceanic warming of 1° to 2°C (about 2°F) oc-
Geoengineering instead of mitigation

- CO$_2$ Concentration
- Albedo modification

Radiative Forcing

2000  2050  2100
Geoengineering instead of mitigation

Geoengineering to take the edge of the heat

Radiative Forcing

CO₂ Concentration

Albedo modification

2000 2050 2100

2000 2050 2100
Warning: Moral Hazard

Knowledge that geoengineering is possible

Climate impacts look less fearsome

A weaker commitment to cutting emissions now
“Interest in CO$_2$ may generate or reinforce a lasting interest in national or international means of climate and weather modification; once generated, that interest may flourish independent of whatever is done about CO$_2$. ”

1982 US National Academy study, Changing Climate.
Current discussions of geoengineering are unsystematic and take insufficient account of prior results. The possibility of unpleasant surprises in the climate system justifies a more coherent (though not large) research program in order to define fallback options needed to make reasonable policy choices. A rational allocation of research priorities dictates that some resources be spent to study geoengineering unless nasty surprises are assigned a zero probability.

The existence of a fallback is critically contingent on unlimited energy at fixed (usually high) marginal cost. The perception of direct ocean disposal and afforestation, these schemes have the theoretical potential to mitigate the full effect of anthropogenic climate change.
Questions & Opinions

Opinions
1. We need a serious research program
   – Impacts & methods and implications
   – International
   – Need not be large $$ to make enormous progress.

2. Geoengineering should be treated as a means of managing the worst impacts of climate change, not as a substitute for emissions controls.

3. The science community should expect to lose control.

Questions
1. How can we best avoid the geoengineering $\leftrightarrow$ mitigation trade off?

2. Should we work toward a treaty? An alternate mechanism?
www.ucalgary.ca/~keith/Bibliography.html

Username: carbon
Password: graphite
Is climate control impossible?

Chaos = extreme sensitivity to initial conditions

One might assume: Weather is chaotic \(\rightarrow\) control is impossible

**Not so!**

Control of chaotic systems requires four things
1. A model (initial conditions \(\rightarrow\) future state).
2. Observations.
3. An appropriate lever.

Improved observations
Improved models
Improved analysis/forecast systems

A bigger lever \(\rightarrow\) Smaller perturbations needed to achieve a given degree of weather control

See Ross Hoffman, “Controlling the global weather”,