Geoengineering

50th Anniversary of the Global CO₂ Record Symposium and Celebration, 30 November 2007, Kona, Hawaii

David Keith
(keith@ucalgary.ca; www.ucalgary.ca/~keith)
Director, Energy and Environmental Systems Group
Institute for Sustainable Energy, Environment and Economy
University of Calgary
Human actions that change climate → Climate System → Climate impact on human welfare
Human actions that change climate

Climate System

Climate impact on human welfare

mitigation

geoengineering

adaptation
Putting sulfur in the stratosphere

Of order 1-2 Mt-S per year offsets the globally-averaged radiative forcing from $2\times\text{CO}_2$ 
(~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

$2 \times \text{CO}_2$

and

1.8% 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 SO$_2$ $\rightarrow$ SO$_4$

Injection of 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

SO$_4$ (ppbv) zonal avg
Rasch et al: Annual Average Surface Temperature

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

**Geo-SO4/2xCO2**
(2Tg Bkg) - Control
global averaged surface temperature (K)

year of simulation

- control: 200.31 K
- geo-sulfate: 285.39 K (average over last 20 yrs)
- 2xCO2: 290.38 K (average over last 20 yrs)
- geo-sulfate + 2xCO2: 288.58 K (average over last 20 yrs)
- geo-sulfate source off
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 x 10⁸ tons of ice, hence 4 x 10³⁹ gram calories of heat energy would be required to melt it. At the present time, the poleward heat flow across 70° latitude is 10⁵⁰ 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 flux were increased by 10% through an intensification of the prevailing winds...
ALBEDO ENHANCEMENT BY STRATOSPHERIC SULFUR INJECTIONS: A CONTRIBUTION TO RESOLVE A POLICY DILEMMA?

Dr Strangelove saves the earth

Jan 15th 2007
From Economist.com

How big science might fix climate change

"massive and drastic" operations, as the chief U.I. describes them.

The Nobel Prize-winning scientist who first made it himself "not enthusiastic about it." heat-trapping greenhouse gases.

Their proposals were relegated to the fringes of climate

Few journals would publish them. Few government agencies, Environmentalists and mainstream scientists said they were extreme.

Cool Geo-Whiz Warming Ideas

More scientists are thinking outside the box on global warming—way outside

By Bret Schulte
Posted 10/15/06

A number of scientists are practically knocking down the door with geoengineering solutions. Advancing an idea once worked on by the father of the hydrogen bomb, Edward Teller, atmospheric scientist and Nobel Prize-winner Paul Crutzen believes Earth's temperature could be quickly brought down by spraying pollution into the atmosphere on a global scale. He issued a paper earlier this year pointing out that heavy artillery could fire rockets into the stratosphere. Once there, emissions from a special fuel would convert into sunlight-reflecting sulfate particles.
Engineered scattering systems

Alternative scattering systems

- Oxides
  - $\text{H}_2\text{SO}_4$ or $\text{Al}_2\text{O}_3$
- 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,¹ S. Verma,² H. Rohatschek,³ G. V. Ferry,¹ N. Boiadjieva,⁴ S. D. Howard,⁵ and A. W. Strawa¹

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
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.
Geoengineering instead of mitigation

CO₂ Concentration

Albedo modification

Radiative Forcing

2000  2050  2100
Geoengineering instead of mitigation

Geoengineering to take the edge of the heat

- **CO₂ Concentration**
- **Albedo modification**

Radiative Forcing

- 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
Warning: Slippery Slope

“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$_2$."

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 loose control.

Questions
1. How can we best avoid the geoengineering ↔ mitigation trade off?

2. Should we work toward a treaty? An alternate mechanism?
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 dependent on the prospect of unlimited energy at fixed (usually high) marginal cost. The exception of direct ocean disposal and afforestation, these schemes have the theoretical potential to mitigate the full effect of anthrop-