Solar-Band Climate Engineering:
Technologies, Risks and Unknowns

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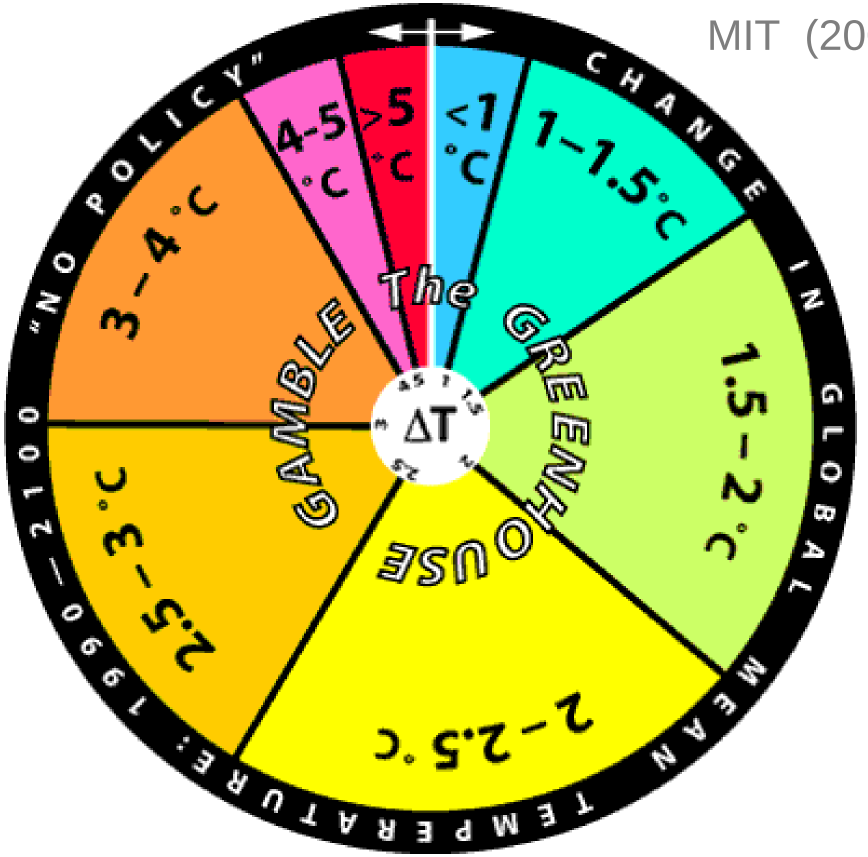
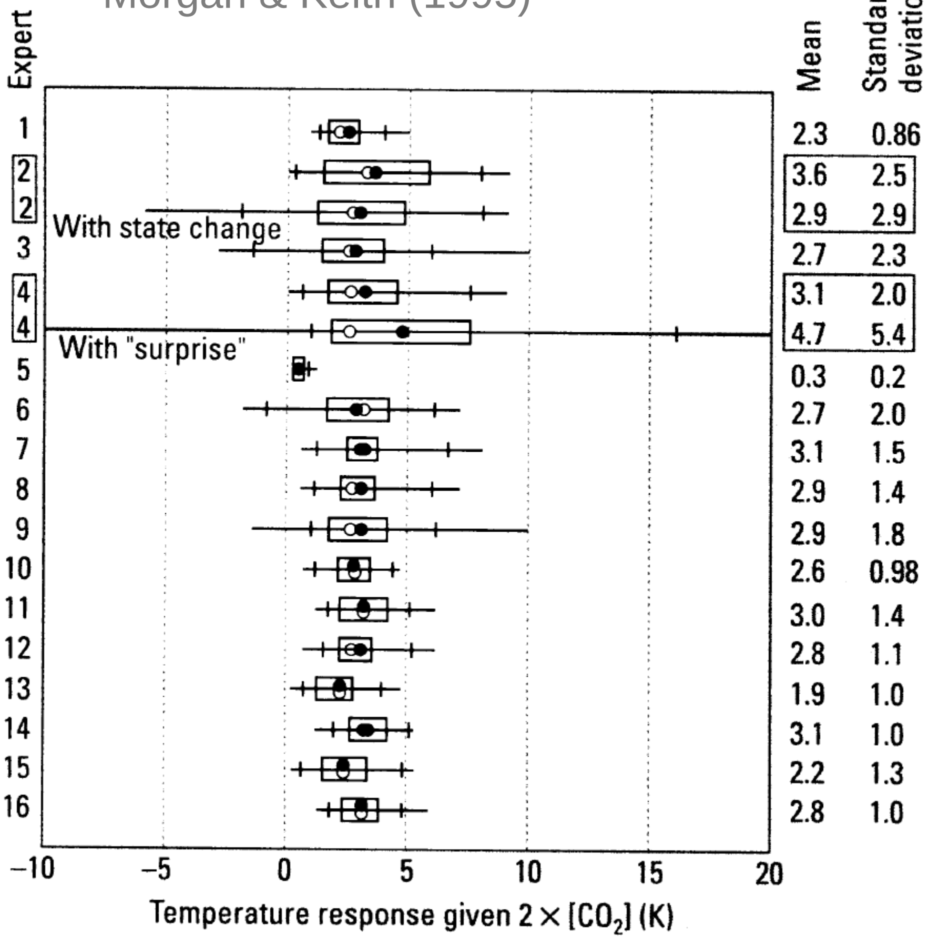
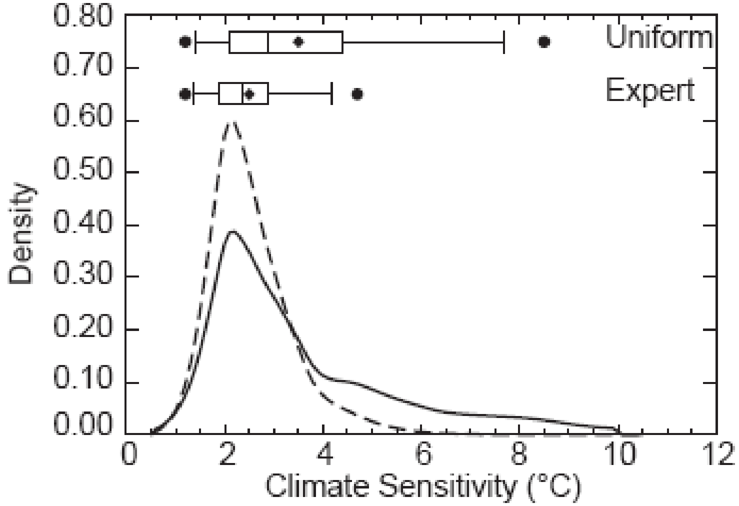


MIT (2007)

Morgan & Keith (1995)



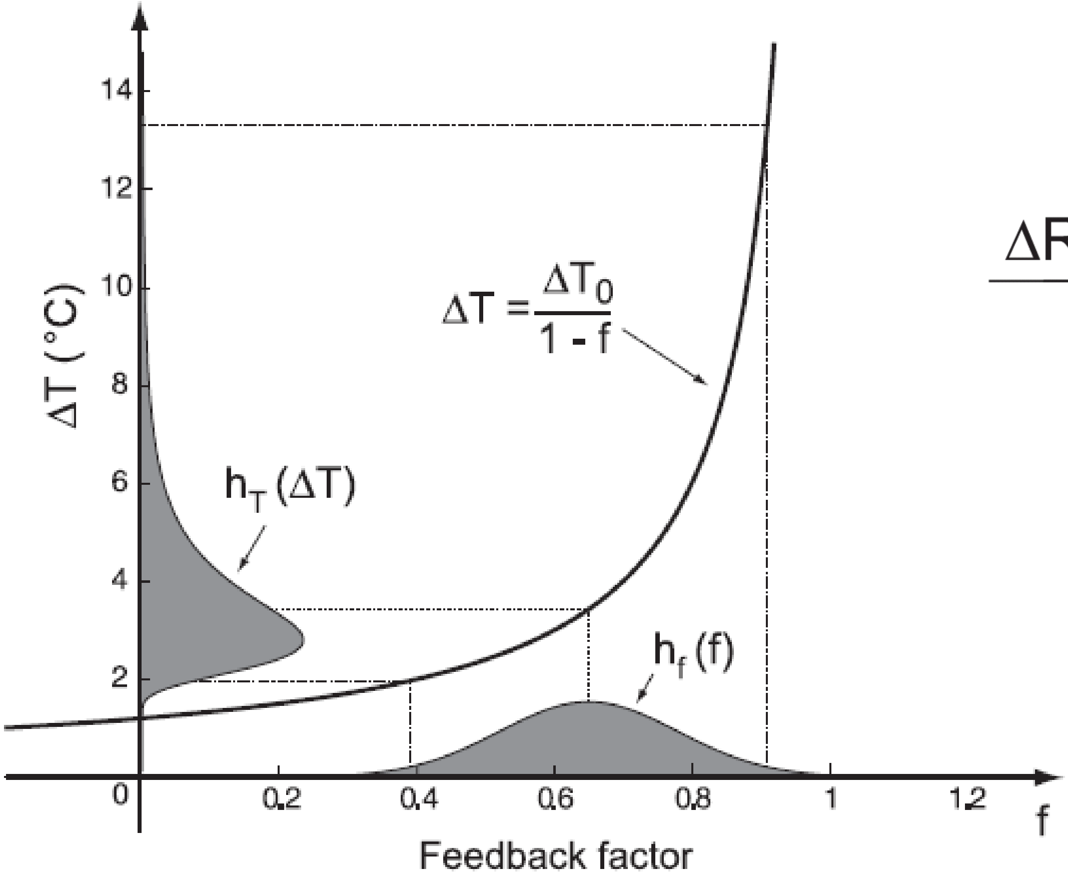


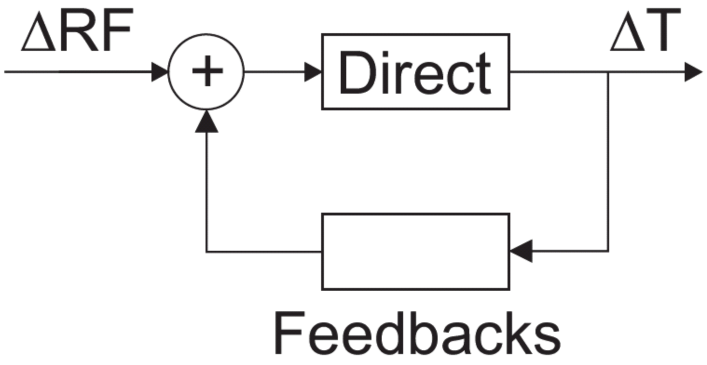
Forest et al (2002)

Why Is Climate Sensitivity So Unpredictable?

SCIENCE
26 OCTOBER 2007

Gerard H. Roe* and Marcia B. Baker





Inertia

Turn wheel (e.g., enact policy)

Low emissions **infrastructure** is built at some **rate** after a **time delay**

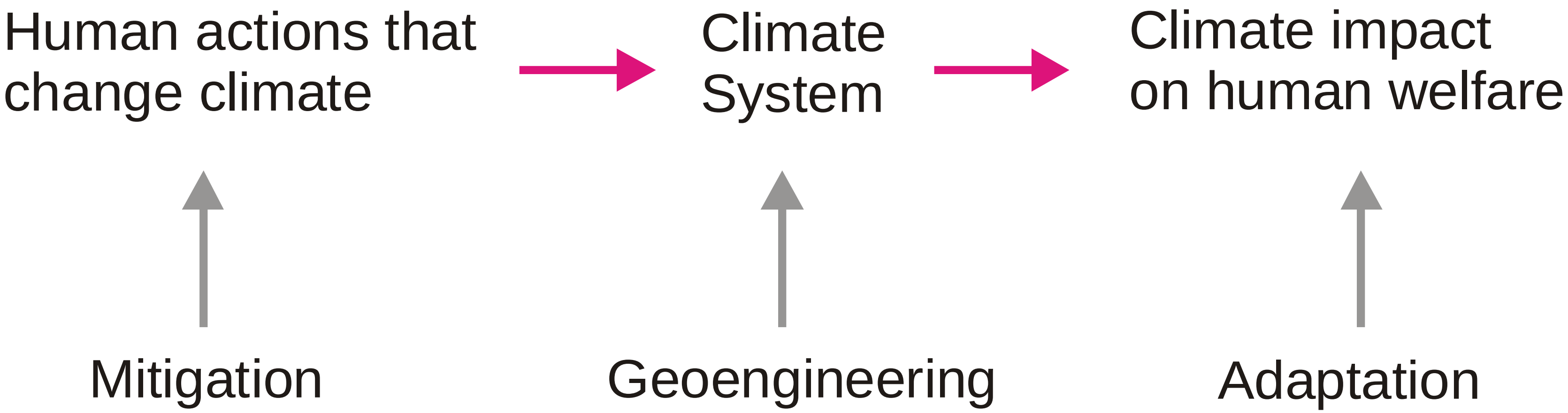
Emission reductions grow as the integral of the **infrastructure build rate**.

Concentration reductions grow as the integral of **emissions** reductions.

Reduction in temperature (from BAU) responds more slowly that reduction in concentrations due to **ocean thermal inertia**

Climate reacts

Uncertainty + Inertia = Danger



Human actions that change climate

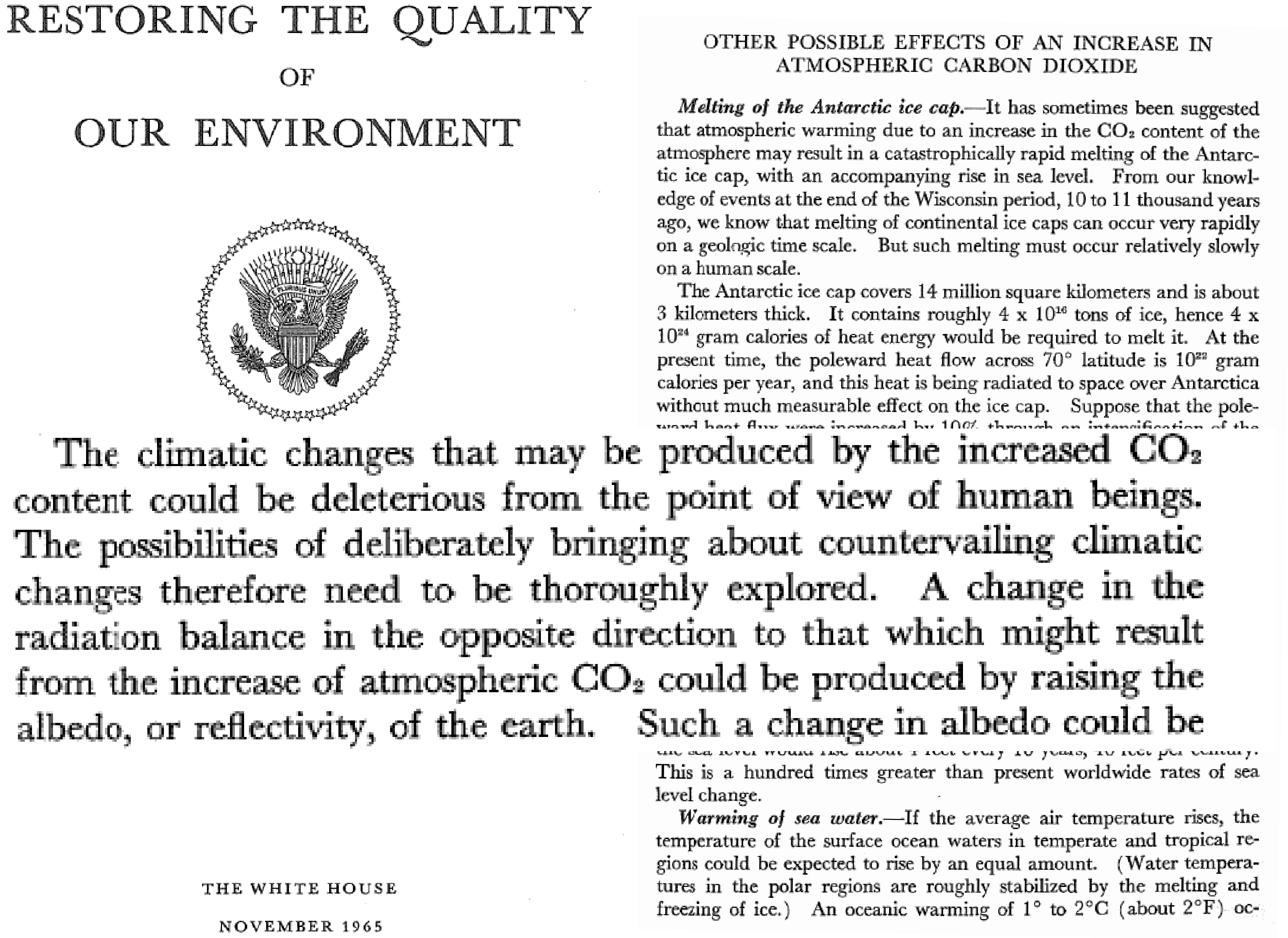
Climate System

Climate impact on human welfare

Mitigation

Geoengineering

Adaptation



RESTORING THE QUALITY
OF
OUR ENVIRONMENT

THE WHITE HOUSE

NOVEMBER 1965

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 CO_2 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 10^{16} tons of ice, hence 4 x 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 pole-

The climatic changes that may be produced by the increased CO_2 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 CO_2 could be produced by raising the albedo, or reflectivity, of the earth. Such a change in albedo could be

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-

Albedo Geoengineering ≠ carbon engineering

Albedo engineering

- Sulfates in the stratosphere
- Sea salt aerosols in low clouds
- Altering plant albedo
- Engineered particles in mesosphere

Carbon cycle engineering

- Biomass + CCS
- Direct capture of CO_2 from air
- Adding Fe to oceans
- Adding macro-nutrients to oceans
- Adding alkalinity (Mg) to oceans
- Bio-char
- Adding alkalinity to soils

Carbon

$$\$ \rightarrow \text{Carbon removing hardware} \rightarrow \text{50 years} \rightarrow \Delta\text{RF}$$

$$100\,\$\text{B/yr} \rightarrow 100\,\$\text{B/yr} \times \left(300\frac{\$}{\text{tC}}\right)^{-1} = 0.33\ \text{GtC/yr} \rightarrow \frac{50\times 0.33\,\text{GtC}}{2.1\text{GtC/PPM}} = 8\,\text{PPM} \rightarrow 0.12\,\text{Wm}^{-2}$$

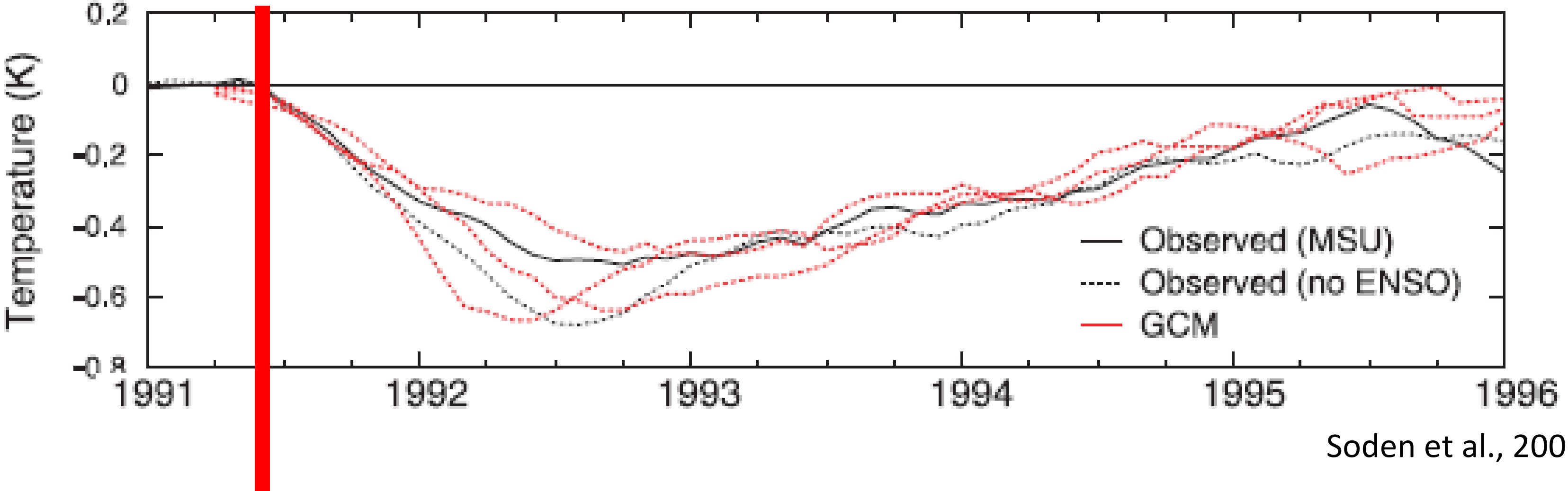
Albedo

$$\$ \rightarrow \text{Albedo modification hardware} \rightarrow \Delta\text{RF}$$

$$100\,\$\text{B/yr} \rightarrow 100\,\$\text{B/yr} \times \left(25\frac{\$\text{B}}{\text{Wm}^{-2}\ \text{yr}}\right)^{-1} = 4\text{Wm}^{-2} \rightarrow 4\,\text{Wm}^{-2}$$

Shielding some sunlight

Temperatures after Mt. Pinatubo



Soden et al., 2002

USGS

Thermal inertia of ocean mediates response:

If the radiative forcing from Mt Pinatubo were sustained, temperature changes would have been nearly an order of magnitude larger.

Experiments by Phil Rasch, Paul Crutzen, Danielle Coleman

NCAR Community Atmosphere Model

Middle atmosphere configuration

- Model top at about 80km
- 52 layers
- 2x2.5 Degree resolution
- Finite Volume dynamics

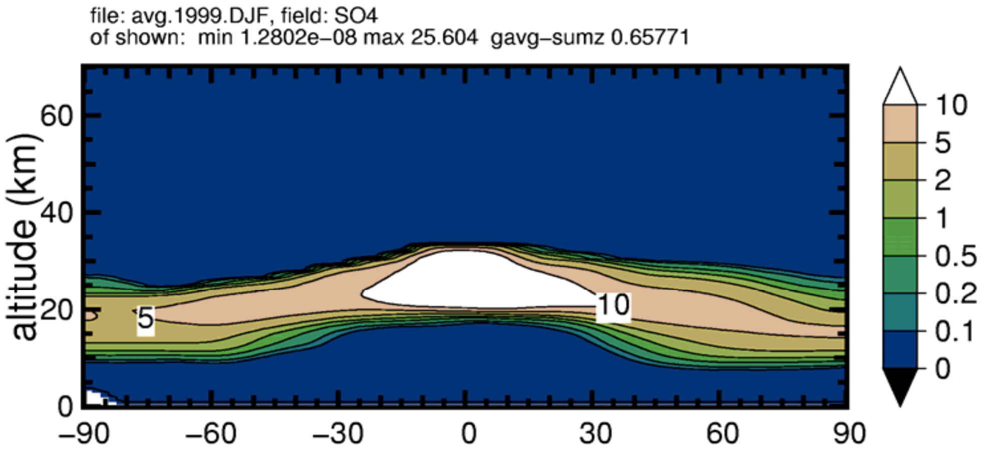
Photochemistry includes only that relevant to oxidation of DMS and $SO_2 \rightarrow SO_4$

Injection of SO_2

- at 25km
- from 10N - 10S
- 1 Tg S/yr assuming a small (or background) aerosol size distribution

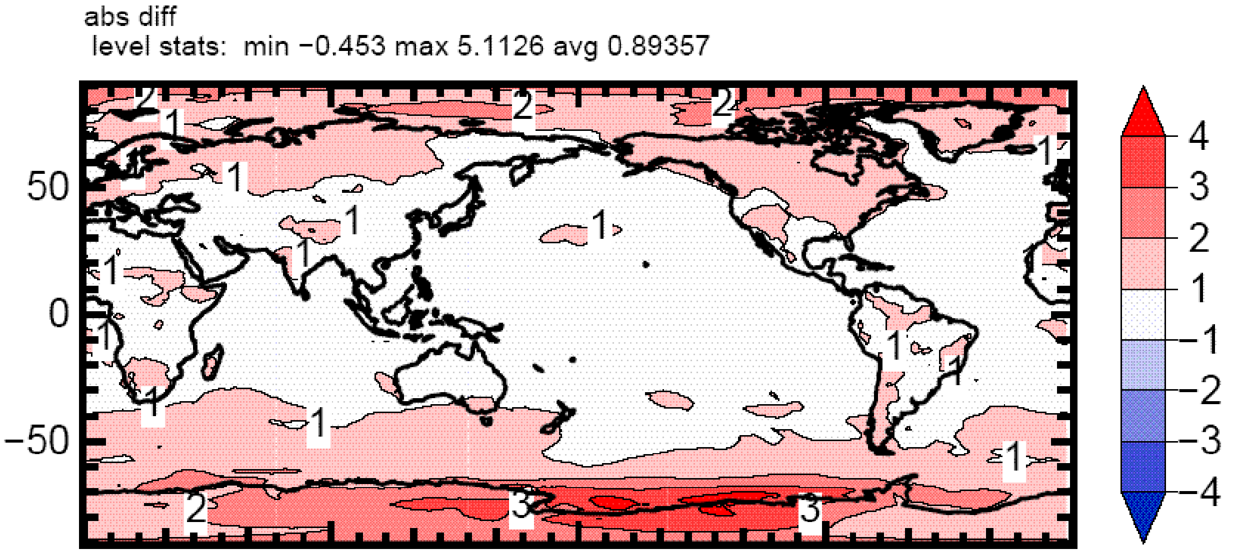
Pinatubo ≈10-15 Tg S

SO4 (ppbv) zonal avg

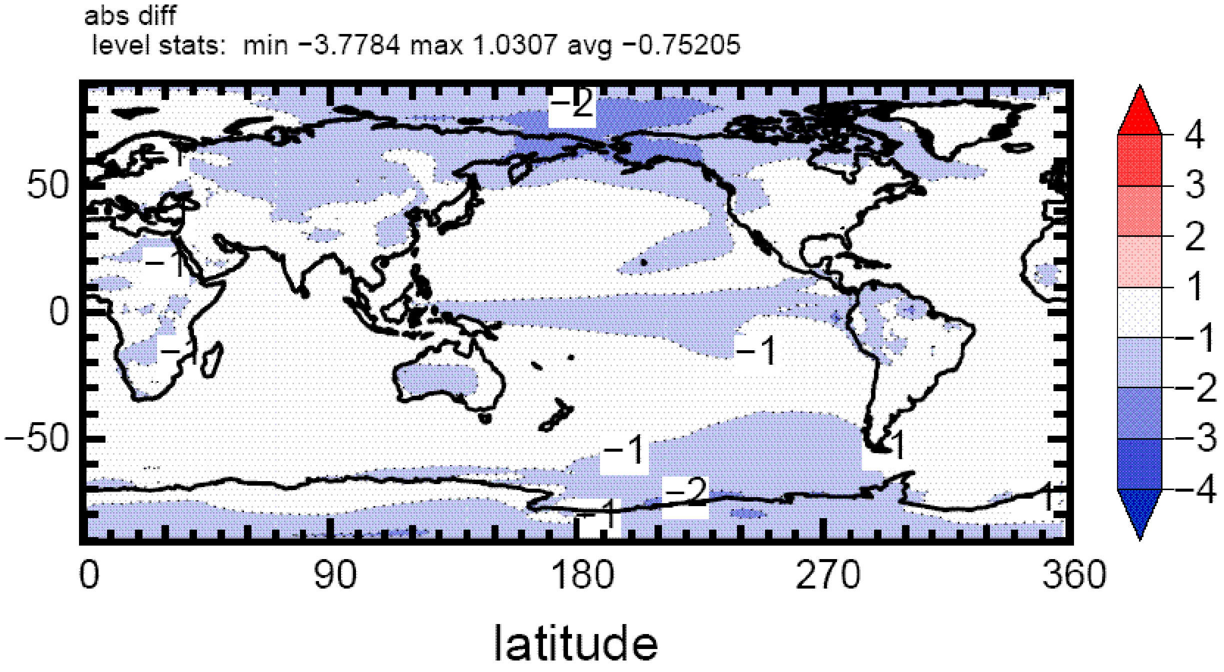


Rasch et al: Annual Average Surface Temperature

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



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



Research: Stratospheric scatterers

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)

10 \$/kg → 10's of \$bn per year ≈ 0 ➔ Cost not the deciding issue.

Lofting methods:

- Aircraft
- Naval guns
- Tethered balloon with a hose

Scattering design goals:

- Lower mass
- Spectral selectivity
- Altitude selectivity
- Direct: diffuse selectivity
- Latitude selectivity

Alternative scattering systems

Oxides

- H_2SO_4 or Al_2O_3

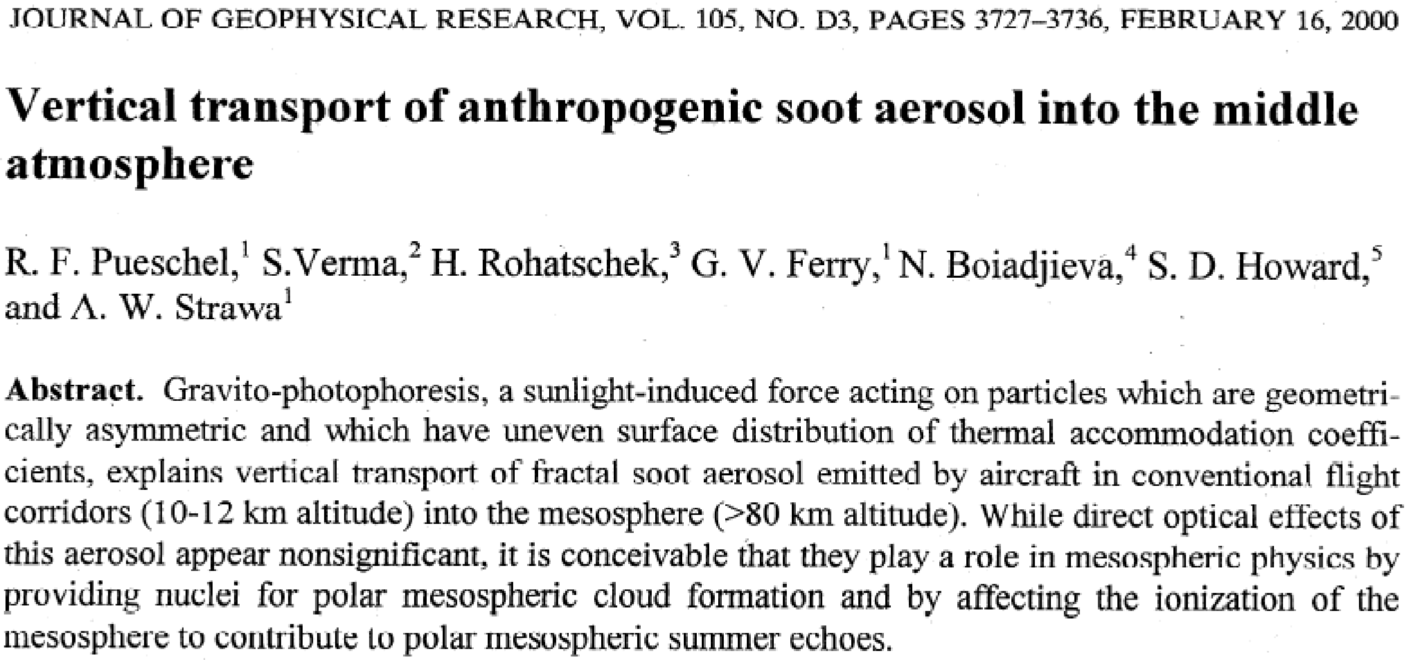
Metallic particles ($10\text{-}10^3 \times$ lower mass)

- Disks, micro-balloons or gratings

Resonant ($10^4\text{-}10^6 \times$ lower mass ??)

- Encapsulated organic dyes

Self-lofting particles



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. D3, PAGES 3727–3736, FEBRUARY 16, 2000

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. Strawa[1]

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

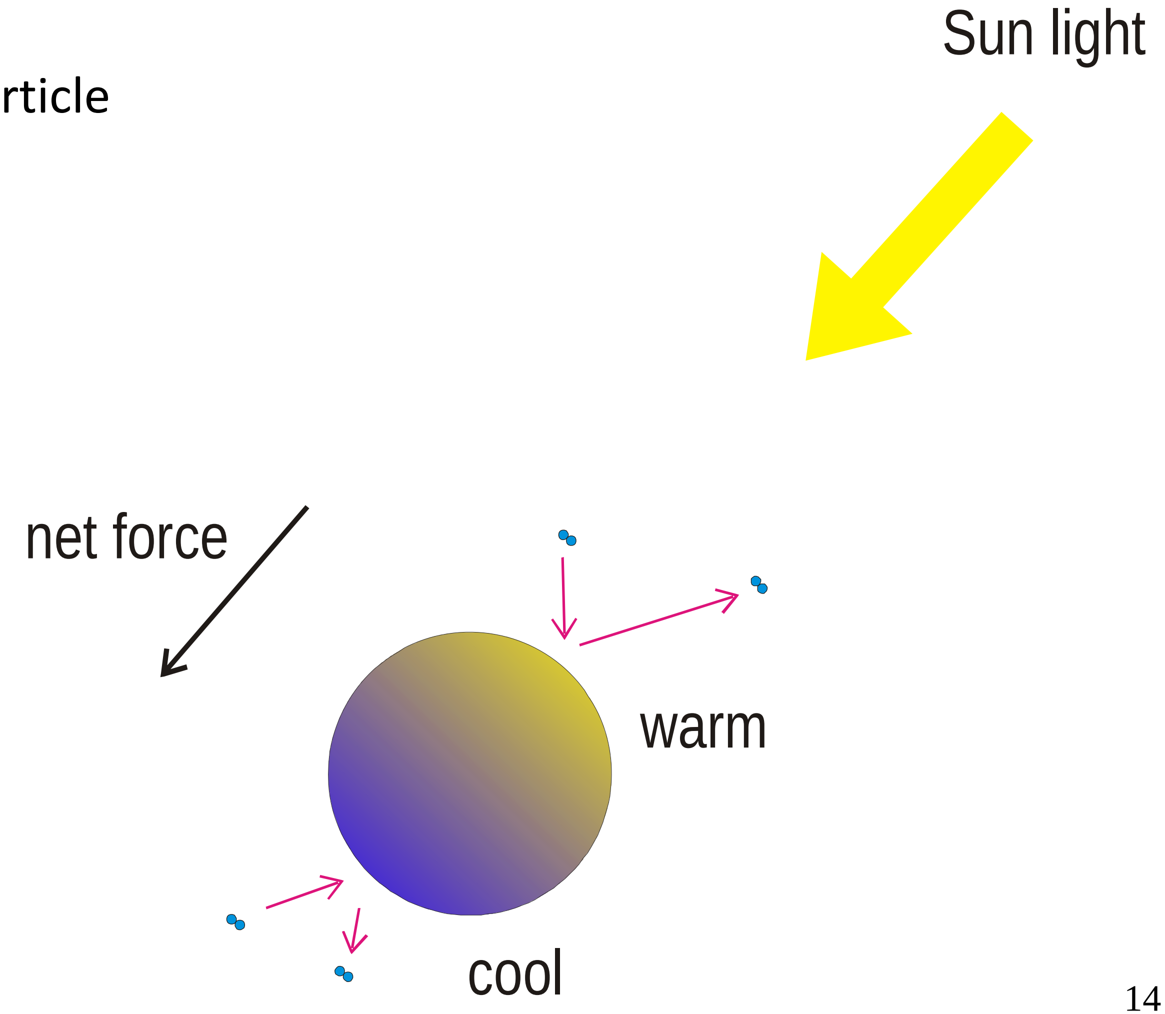
Uneven illumination

↓

Temperature gradient across particle

↓

Net force toward cool side



Gravito-Photophoresis

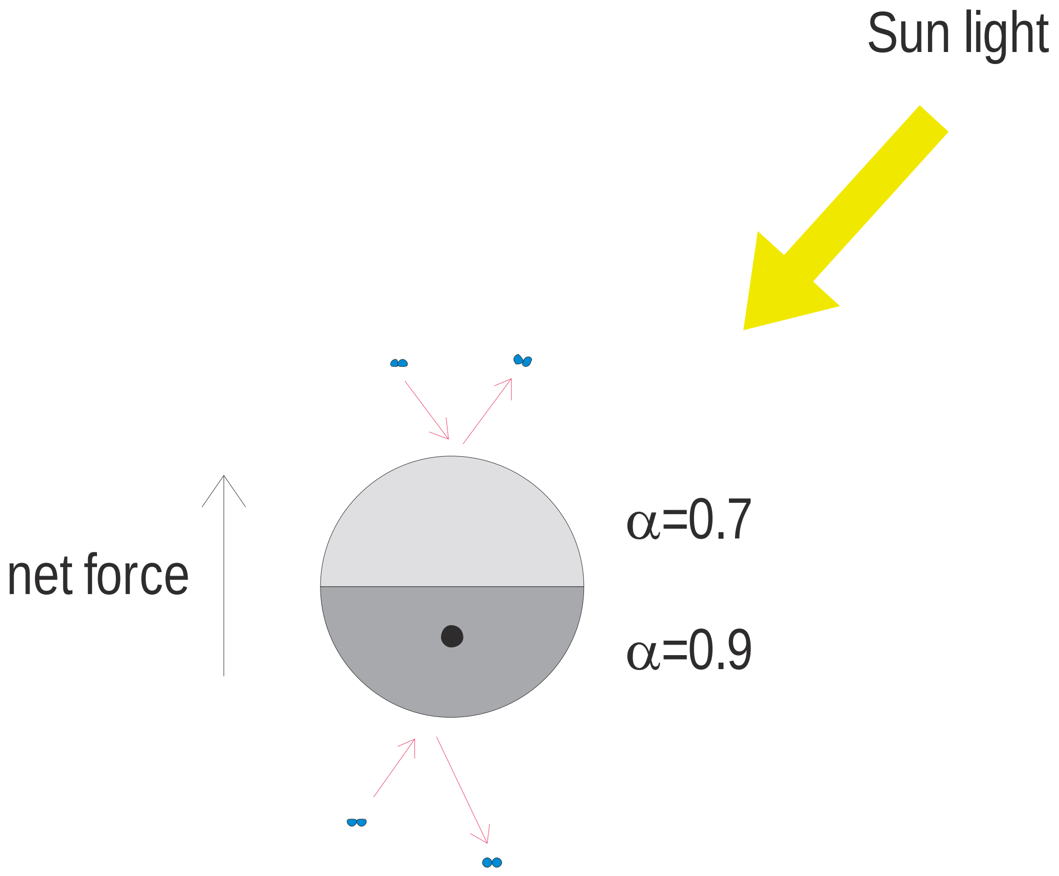
Radiative heating (or cooling)

↓

Accommodation coefficient asymmetry

↓

Body-fixed force



Force independent of pressure ~10 to 100 km

Force depends on $\delta T\, p$

$$F = \frac{1}{4}\Delta\alpha \frac{\Delta T}{T} p$$

…but δT depends $1/p$

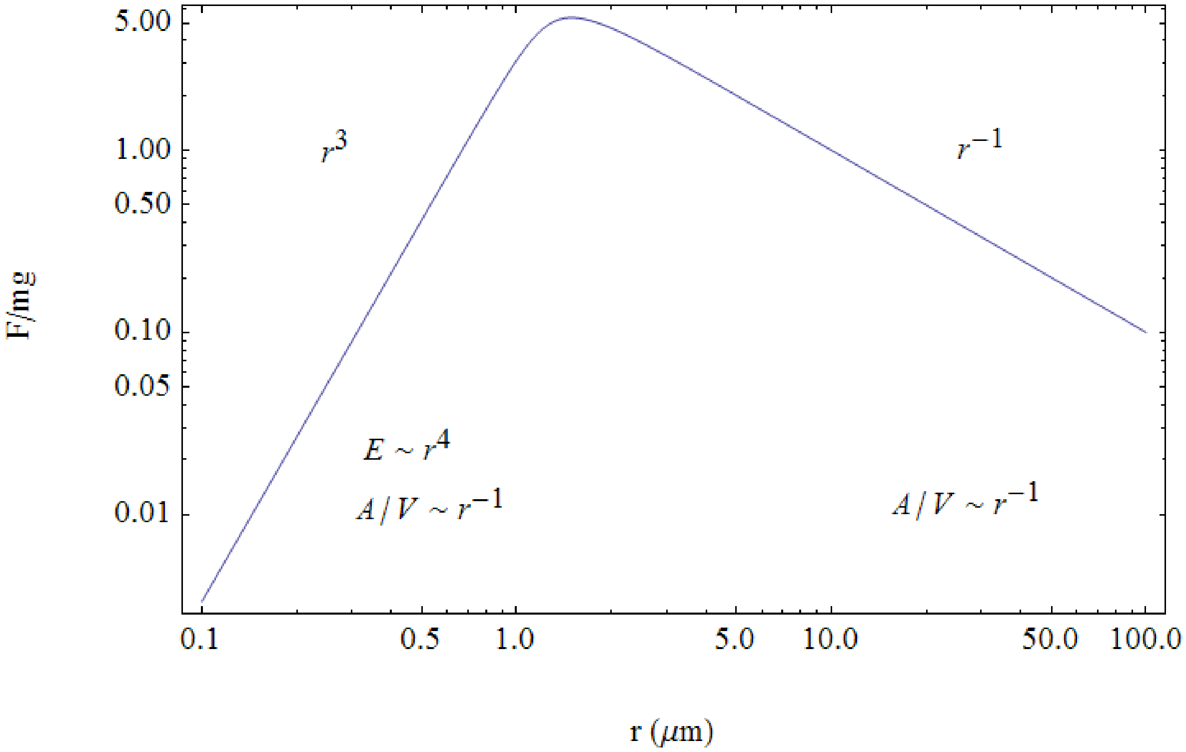
$$\underbrace{\frac{S\,\varepsilon_{\mathrm{S}}}{4}}_{\text{Solar input}} + \underbrace{\sigma\,\varepsilon_{\mathrm{T}} T_{\mathrm{E}}^{4}}_{\text{Outgoing longwave input from earth}} - \underbrace{\sigma\,\varepsilon_{\mathrm{T}}(T+\Delta T)^{4}}_{\text{Radiative cooling}} = \underbrace{\frac{3}{2} V \bar{\alpha} \frac{\Delta T}{T} p}_{\text{Conduction}}$$

➔ force approximately altitude independent until radiative heat loss dominates above about 100 km.

What limits the size of particles that can be levitated?

The mass-specific force instantaneous force proportional to r^{-1} (volume/area)

Net gravito-photophoretic force declines as r^{3} for particle radii below ~1 μm as the orienting torque overwhelmed by Brownian motion as $r \rightarrow 0$.



Gravity is not the only way to break symmetry

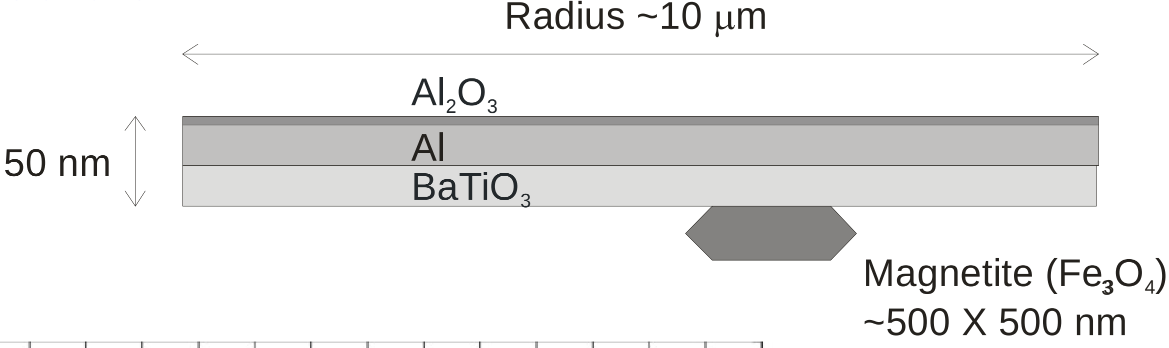
Magnetic or electrostatic torques can greatly exceed gravitational torques for small particles in the upper atmosphere.

Consider the 1 μm radius sphere in which the center of mass is displaced 0.1 μm from the geometric center (Rohatschek example).

A similar magnetite sphere with magnetization of 10^5 J T^{-1} m^{-3} would feel magnetic torques that exceeded gravitational torque by a factor of ~10^4 at the typical terrestrial magnetic field strength of 0.5×10^{-4} T

Similarly, a sphere of barium titanate, a common ferroelectric, with residual charge of 2×10^{-3} C m^{-2} would experience a torque 10^3 times the gravitational torque in the typical atmospheric electric field of 100 V/m.

Conceptual design: A levitated disk



Radius ~10 µm

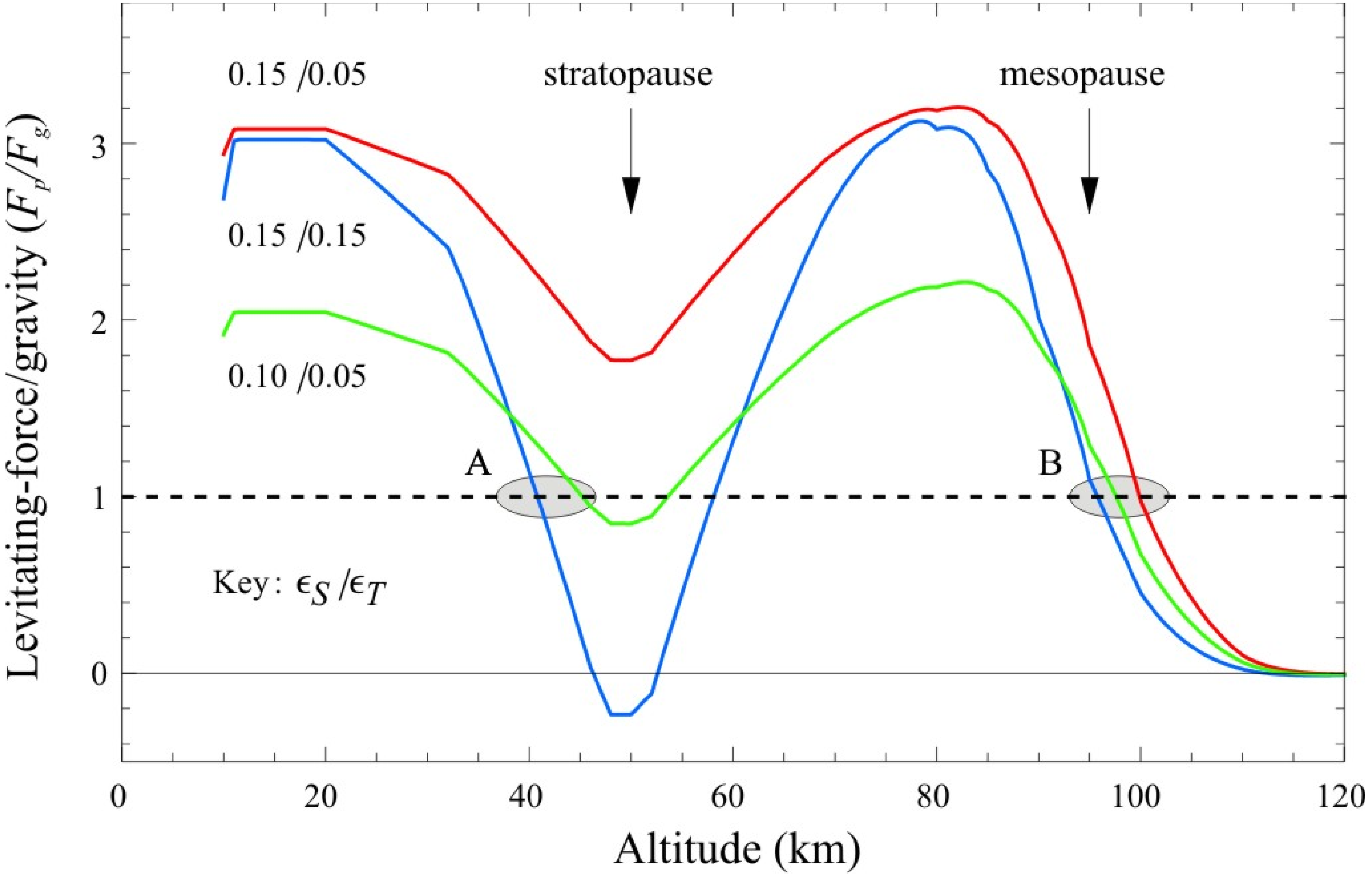
Al_2O_3

50 nm

Al

$BaTiO_3$

Magnetite (Fe_3O_4)
~500 X 500 nm



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.

3. The ability to concentrate scattering particles near the poles
    - ➔ Concentrate climate engineering where it’s needed most.

4. Non-spherical scattering particle designs
    - ➔ Minimal forward scattering.
    - ➔ Advanced designs that are spectrally selective.

Could you make engineered particles at an interesting cost?

Approximately 10^9 kg of engineered particles to offset radiative effect $2\times CO_2$

- Assuming 50 nm thickness

A lifetime of 10 years ➔ 10^8 kg/yr.

Suppose cost of manufacture must be < 1% of cost of emissions control which is ≈2% of GDP ➔ cost < 100 $/kg.

Many nano-scale particles now made at costs far less than 100 $/kg

- E.g., Silica-Alumina ceramic hollow 1 µm diameter microspheres (3M Zeeospheres) costs less than 0.3 $/kg.
- Bulk vapor phase deposition methods exist to produce mono-layer coatings on fine particles.
- Self-assembly of nano-structures that might be applicable to bulk production of engineered aerosols.

Is climate or weather control impossible?

Chaos = extreme sensitivity to initial conditions

One might assume: Weather is chaotic ~~→~~ control is impossible

Not so!

Control of chaotic systems requires four things

1. A model (initial conditions → future state).
2. Observations.
3. An appropriate lever.
4. Feedback.

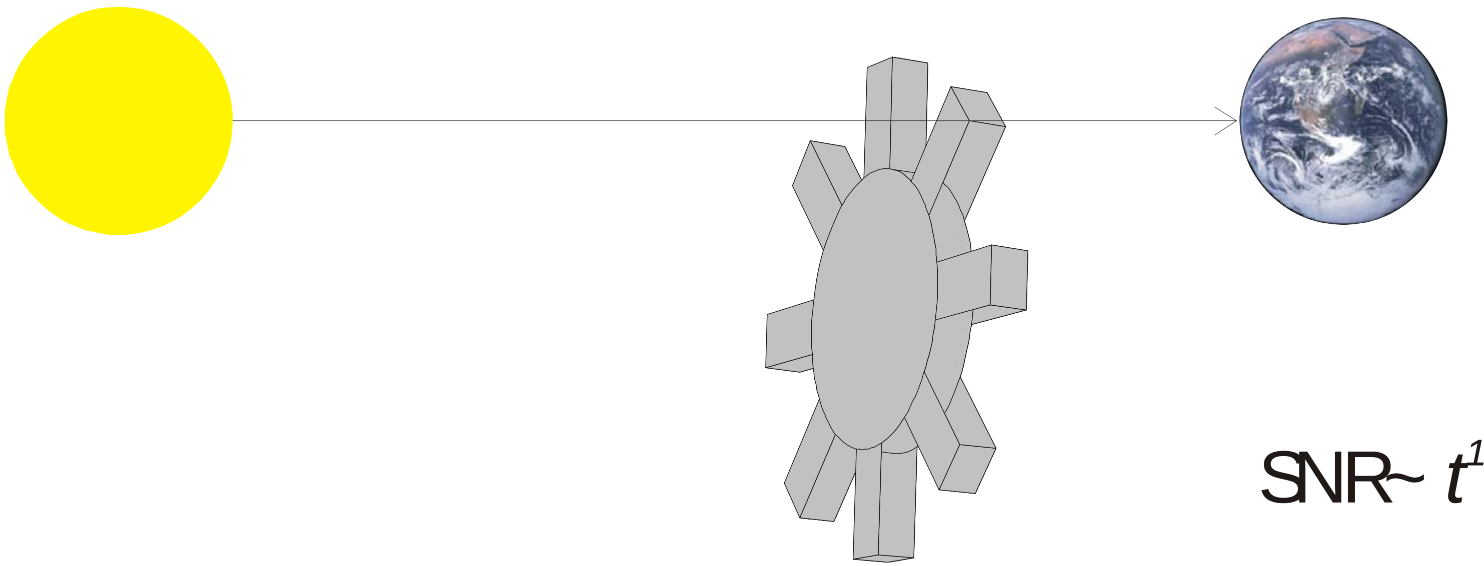
X-29 NASA-DFRC

Improved observations
Improved models
Improved analysis/forecast systems

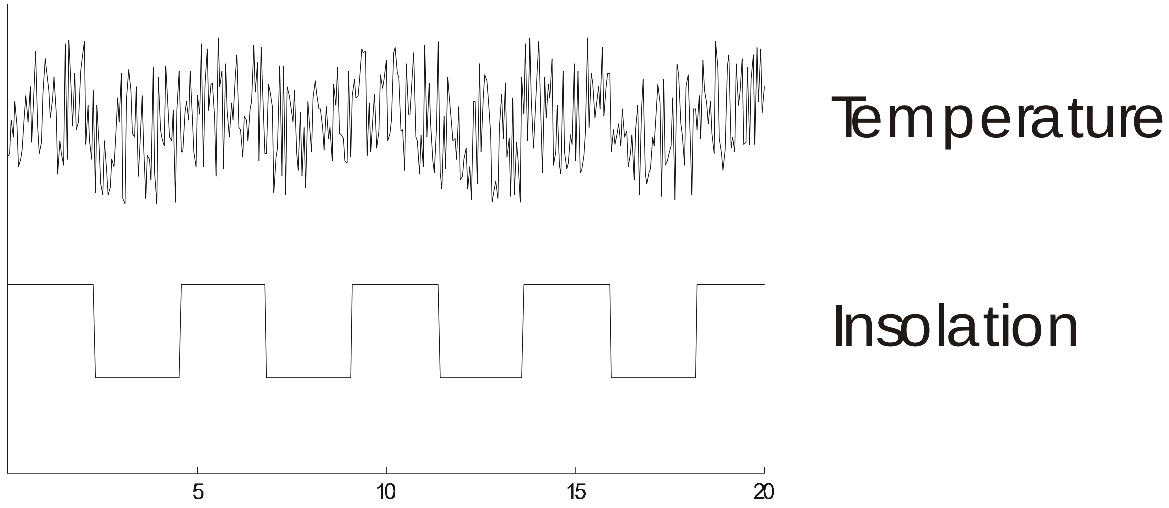
A bigger lever → Smaller perturbations needed to achieve a given degree of weather control

See Ross Hoffman, "Controlling the global weather",
Bulletin of the American Metrological Society February 2002 : 241-248

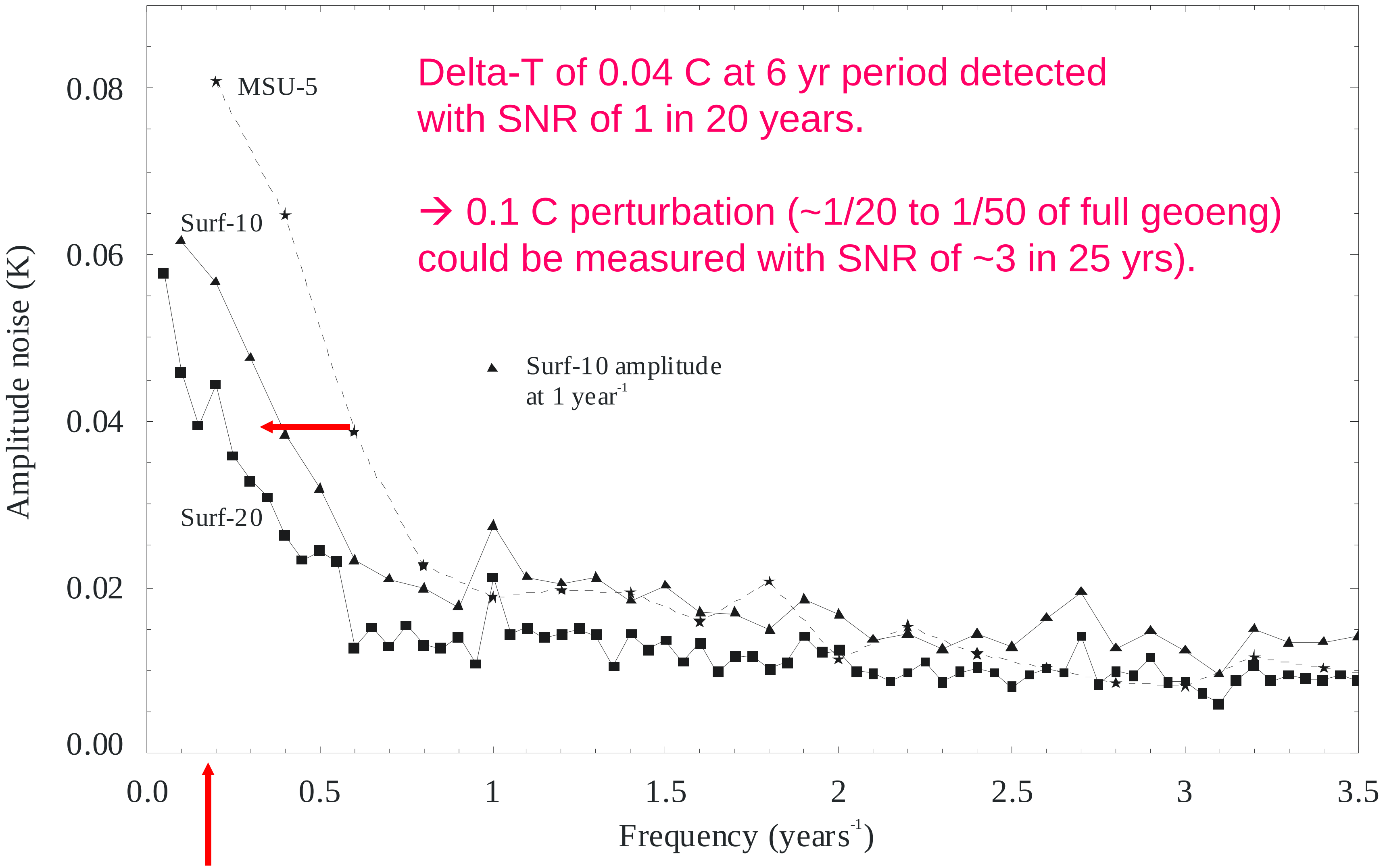
“Lock-in” or phase-sensitive detection at a planetary scale



$\text{SNR} \sim t^{1/2}$

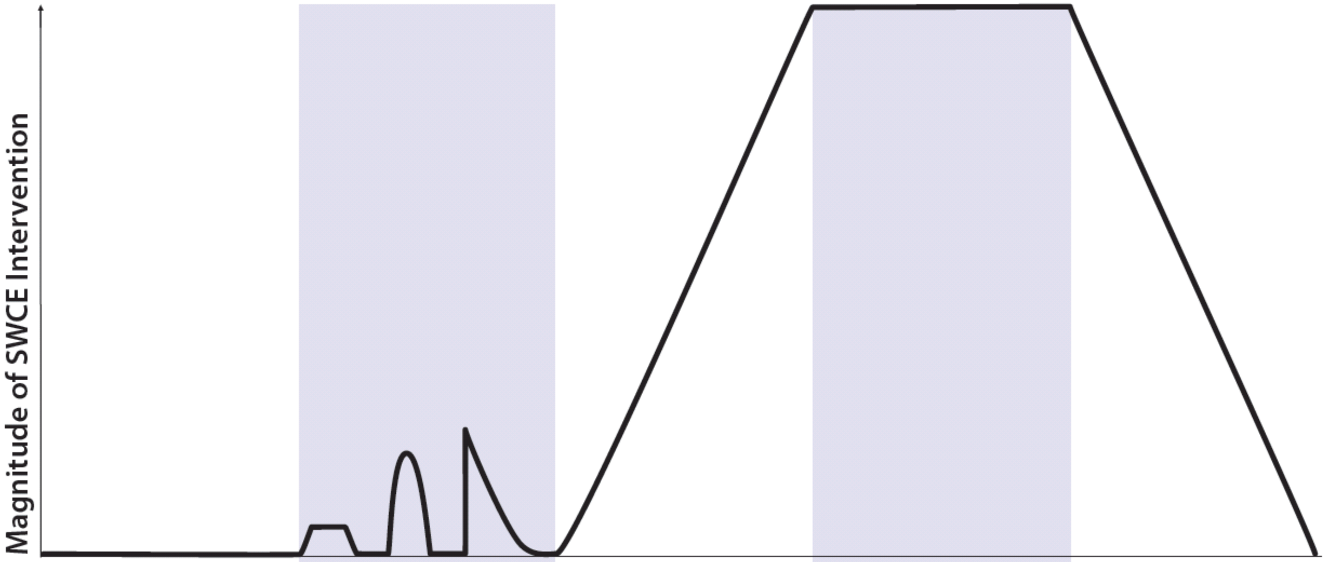


Amplitude spectrum of the incoherent variability in global surface temperature



Delta-T of 0.04 C at 6 yr period detected with SNR of 1 in 20 years.

→ 0.1 C perturbation (~1/20 to 1/50 of full geoeng) could be measured with SNR of ~3 in 25 yrs).



Phase I
Non-Invasive Research

Objective Utilize existing understanding of climate system to evaluate SWCE concepts

Components

- Laboratory experiments
- Computer modeling
- Analogue case studies

Important Characteristics

- No direct climatic impacts or associated risks
- Limited learning potential without some iterative empirical testing (Phase II research)
- Existing evaluations of SWCE concepts are Phase I research (*see Boxes 2.1.1.2 and 2.1.1.3*)

Phase II
Field Experiments

Objective Develop understanding of potential SWCE concepts through limited scale intervention experiments

Components

- SWCE interventions limited in duration, magnitude and/or spatial range
- Climatic impact monitoring

Associated Issues

- Climatic impacts and associated risks increase with scale of field test (though not necessarily increasing proportionally)
- Signal-to-noise limits associated with natural variability and temporal/-spatial delays in climatic responses constrain potential learning from field-tests (*see Section 3.2 for discussion*)
- Empirical data from tests could iteratively improve Phase I research

Phase III
Monitored Deployment

Objective Achieve a desired state of the climate system

Components

- Deployment of a full-scale SWCE intervention (possible ramp-up timescale between gradual and immediate)
- Climatic impact monitoring
- Development of a control-system for the SWCE intervention system (based on monitored climate parameters)

Associated Issues

- Increasing climatic impacts and risks with increasing SWCE intervention scale (though not necessarily increasing proportionally)
- Gradual deployment could be similar to Phase II research, allowing time for testing iterative improvement of Phase I research

Phase IV
Steady-State Intervention

Objective Maintenance of a desired state of the climate system

Components

- Maintenance and improvement a full-scale SWCE intervention
- Climatic impact monitoring
- Improvement of the SWCE intervention control-system

Associated Issues

- Long-term SWCE could generate cumulative climate impacts and risks unobserved in field-tests (Phase II) or initial deployment (Phase III)
- Increasing atmospheric GHG concentrations will have a separate impact on the climate system that must be incorporated into any intervention control-system

Phase V
Disengagement

Motivations for Intentional Disengagement

- Reduction in need due to successful achievement of intervention target (e.g. mitigation reduces GHG levels and SWCE to prevent warming no longer required)
- Discovery of harmful side effects of the intervention

Possible Causes of Unintentional Disengagement

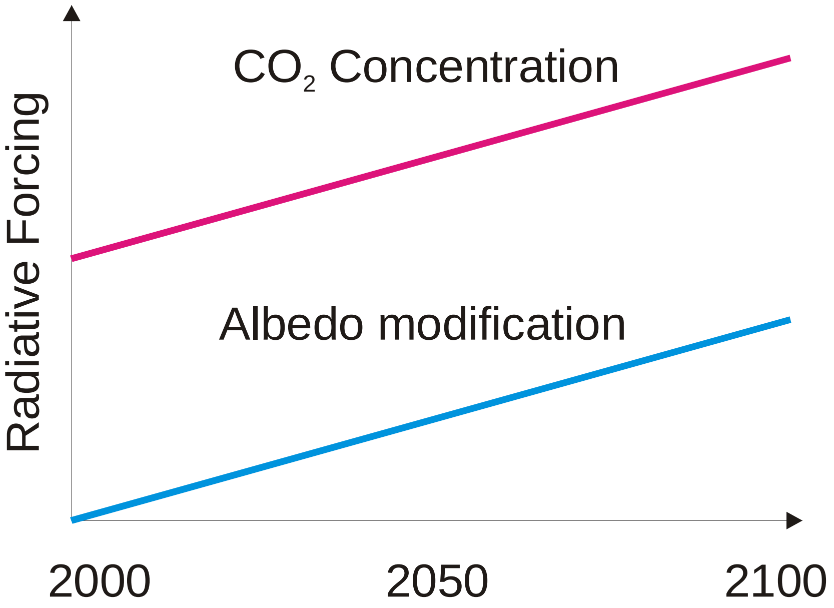
- Technical or socio-political system failure
- Counter-climate engineering or countermeasures

Associated Issues

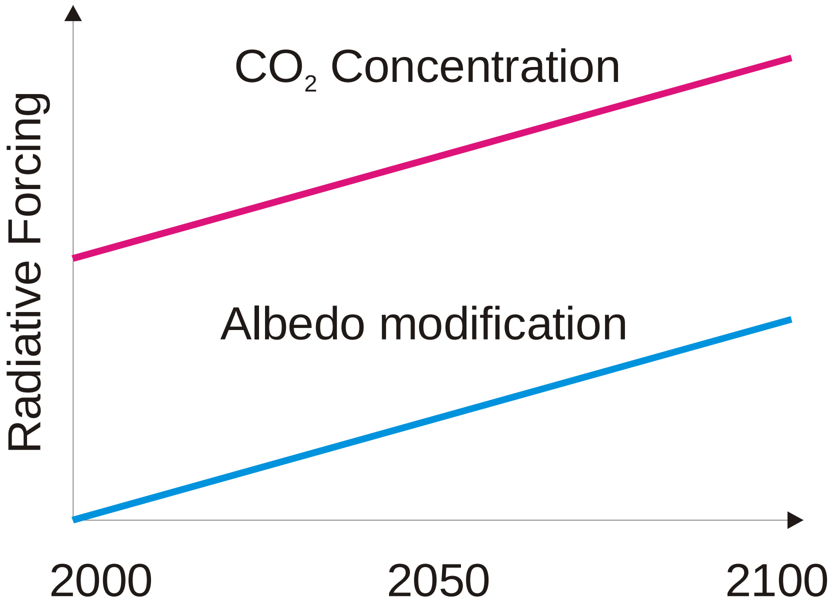
- Potential for climatic parameter rebound effects
- Severity of climate parameter rebound will increase with intervention scale and disengagement rate

Credit: Novim

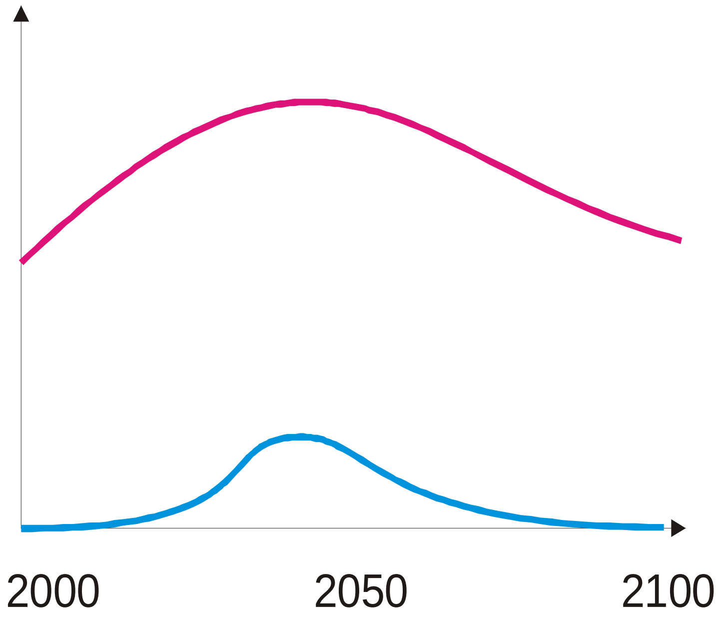
Geoengineering instead of mitigation



Geoengineering instead of mitigation



Geoengineering to take the edge of the heat



Warning: Moral Hazard

Knowledge that geoengineering is possible

↓

Climate impacts look less fearsome

↓

A weaker commitment to cutting emissions now

Questions & Opinions

Opinions

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

2. Current understanding of climate systems suggests that intelligently executed climate engineering would reduce climate risks.

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

4. 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? Norms? An alternate mechanism?