

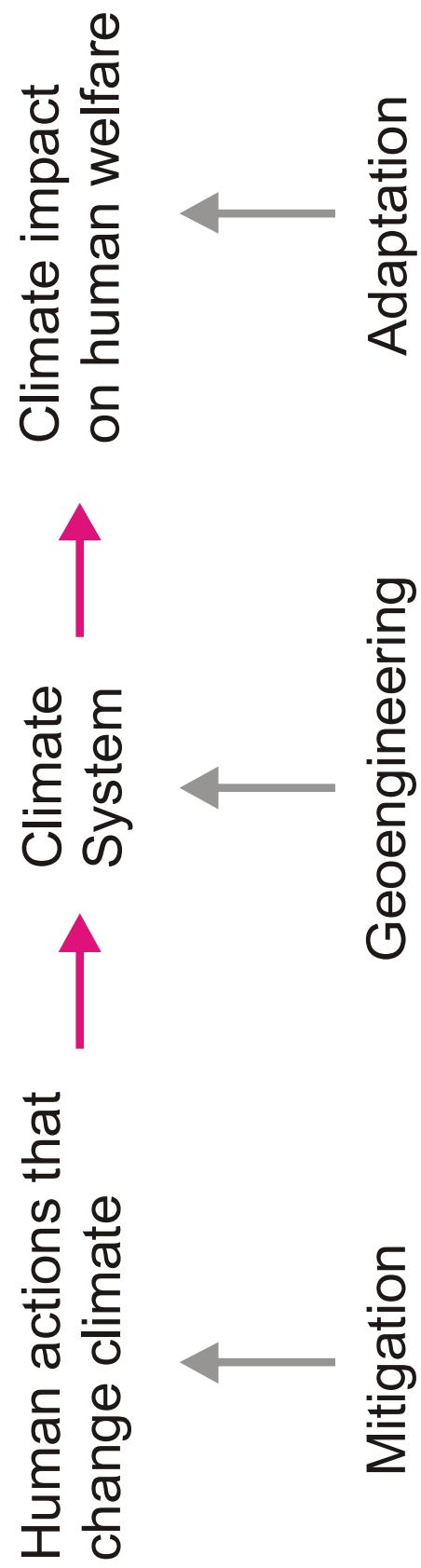
Solar geoengineering as a tool to manage climate risks

31 January 2011
Energy Seminar
Stanford University

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Year 2060: The search for a breakthrough technology to solve climate change continues.

IT'S A TIME MACHINE
WE HOPE WILL TAKE US
BACK 50 YEARS WHEN
WE SHOULD HAVE PUT
A PRICE ON CARBON.

NO! THAT'S THE
GREAT THING ABOUT
THIS TECHNOLOGY!
WE BETTER
HURRY!

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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 4×10^{18} tons of ice, hence 4×10^{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 increased by 100% through some mechanism.

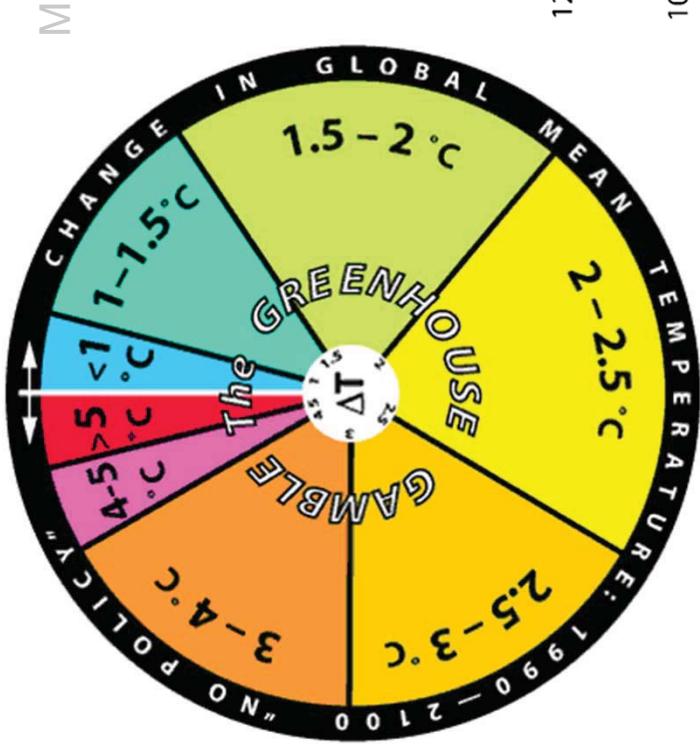
The climatic changes that may be produced by the increased CO₂ content could be deleterious from the point of view of human beings. The possibilities of deliberately bringing about countervailing climatic changes therefore need to be thoroughly explored. A change in the radiation balance in the opposite 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

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

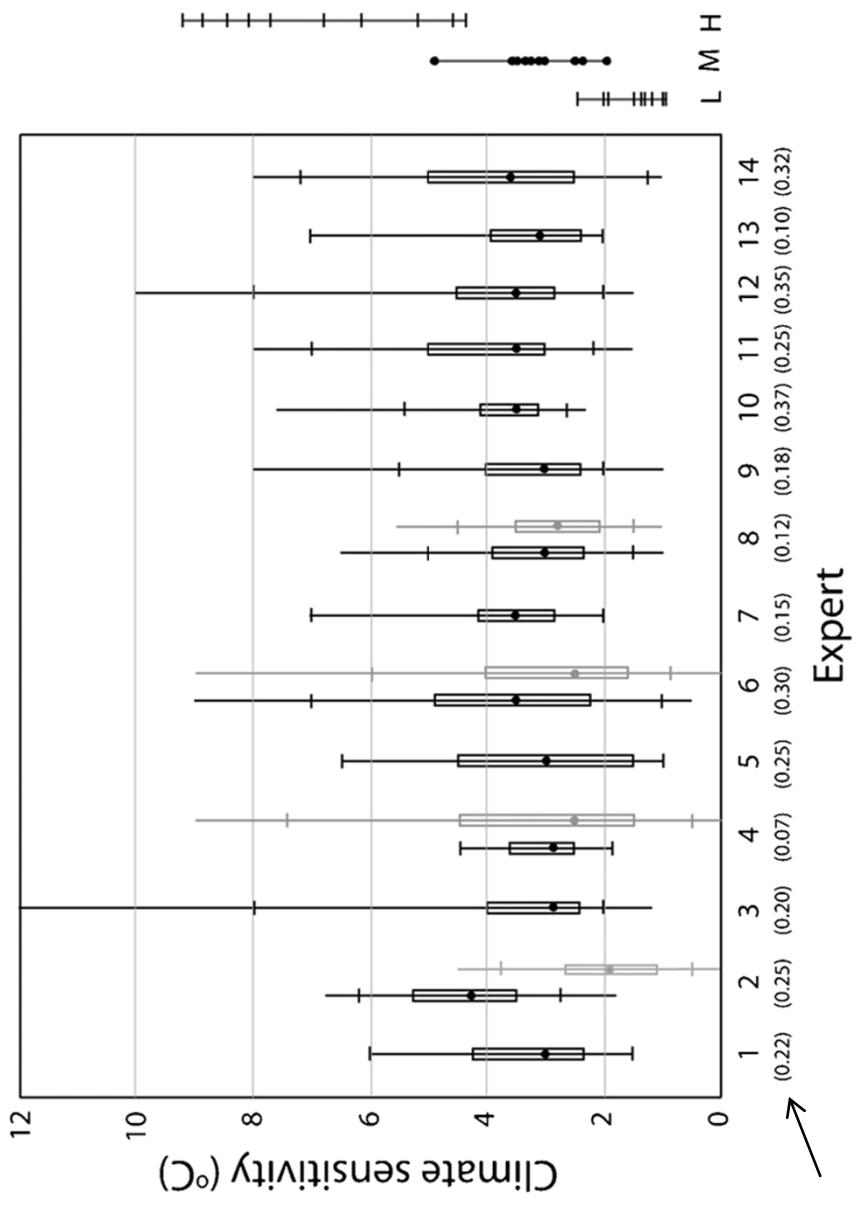
Warming of sea water.—If the average air temperature rises, the temperature of the surface ocean waters in temperate and tropical regions could be expected to rise by an equal amount. (Water temperatures in the polar regions are roughly stabilized by the melting and freezing of ice.) An oceanic warming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

THE WHITE HOUSE
NOVEMBER 1965

Uncertainty



Uncertainty in climate response to forcing over century-long timescales has not decreased in last few decades.



Zickfeld, Morgan, Frame &
Keith, PNAS (2010)

Data in gray from Morgan &
Keith, ES&T (1995)

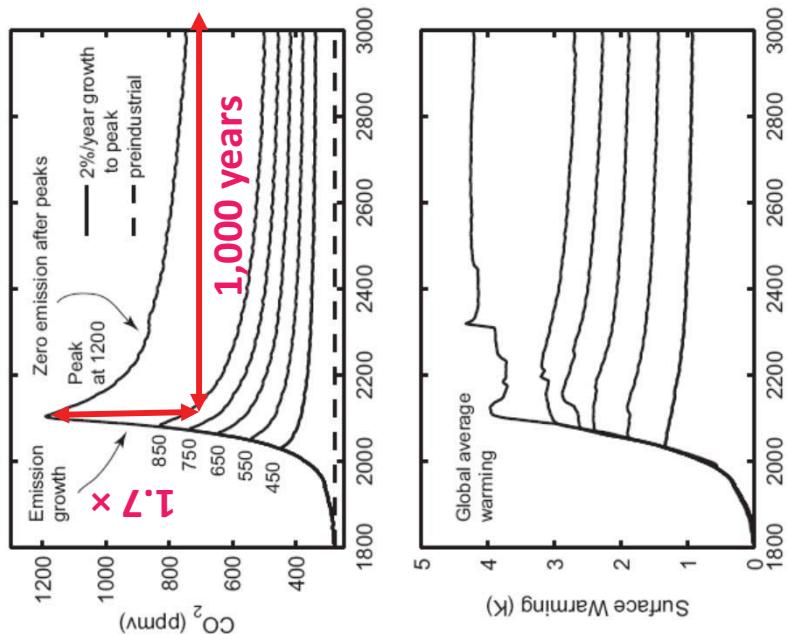
IPCC FAR can reasonably be
interpreted as saying
 $P_{>4.5C} = .17$

$$P_{>4.5C} = .17$$

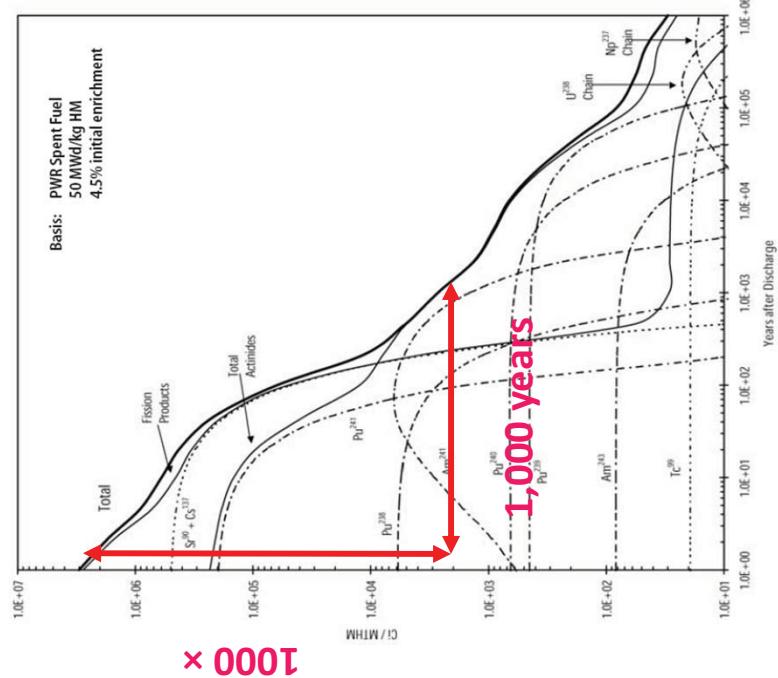
Inertia: CO_2 lasts longer than nuclear waste

- If we instantly stop emissions temperatures remain high for millennia
 - 1,000 years after emissions stop, CO_2 concentrations are ~60% of their peak.
 - 1,000 years after discharge nuclear waste is **1000 times** less radioactive than it was one year after discharge.
 - 10,000 later warming will be of order **1/3** the level it was the day the coal plants shut down.

Solomon et al (2009) Irreversible climate change due to carbon dioxide emissions, PNAS, **106**, 1704–1709. 6



MIT Study on the Future of Nuclear Power (2003)



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 than reduction in concentrations due to **ocean thermal inertia**

Climate reacts



Uncertainty + Inertia = Danger

Solar radiation management \neq Carbon cycle engineering

Solar radiation management (SRM)

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

Carbon cycle engineering (CDR)

- Biomass + CCS
- Direct capture of CO₂ from air
- Adding Fe to oceans
- Adding macro-nutrients to oceans
- Adding alkalinity (Mg) to oceans
- Bio-char
- Adding alkalinity to soils

Fast, cheap, imperfect and uncertain; and it does very little to manage the carbon in the air

Slow and expensive, but it gets the carbon out

Solar radiation management \neq Carbon cycle engineering

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Carbon

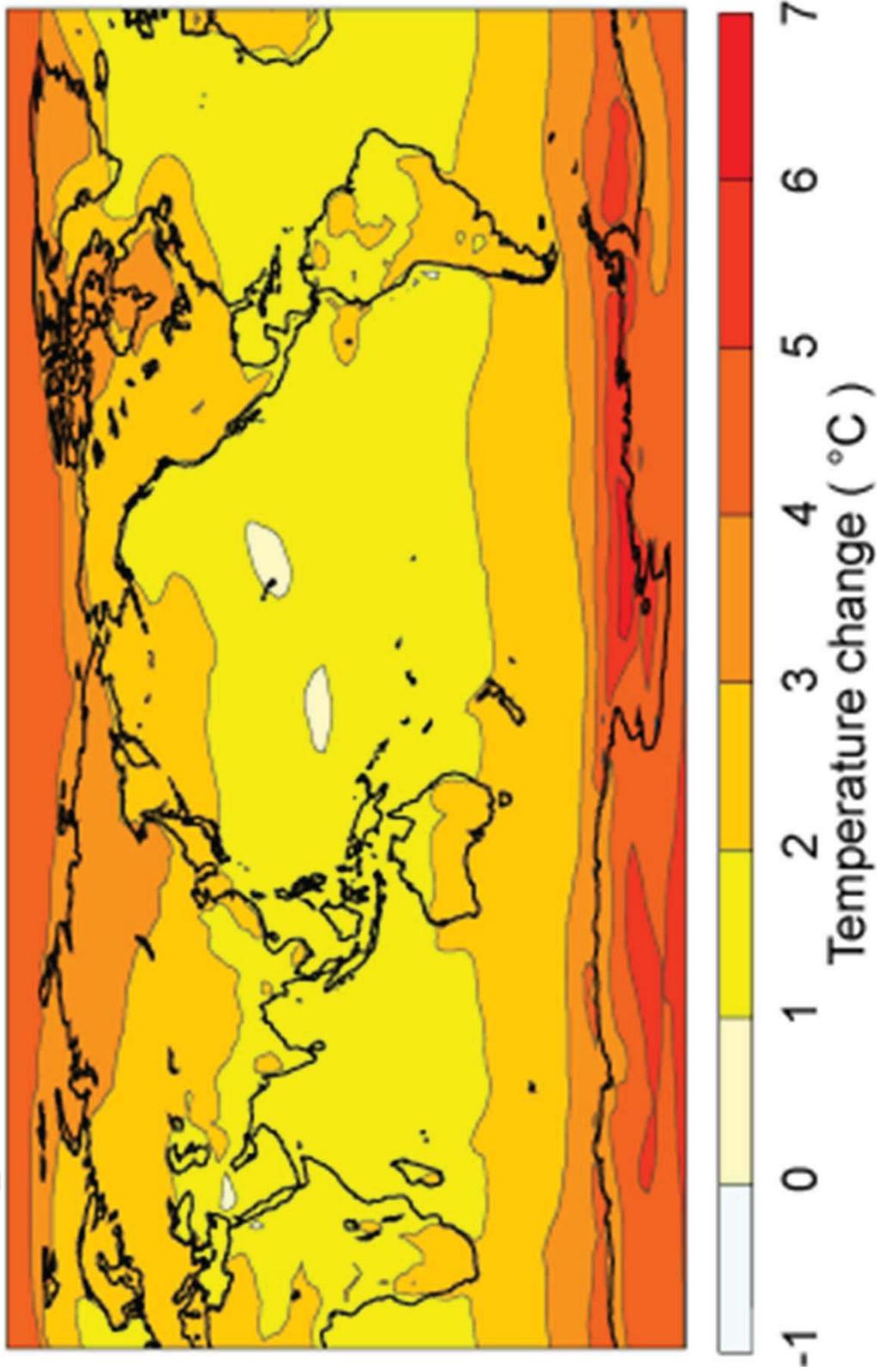
$$100\text{\$B/yr} \rightarrow 100\text{\$B/yr} \times \left(300 \frac{\$}{tC}\right)^{-1} = 0.33 \text{ GtC/yr} \rightarrow \frac{50 \times 0.33 \text{ GtC}}{2.1 \text{ GtC/PPM}} = 8 \text{ PPM} \rightarrow 0.12 \text{ Wm}^{-2}$$

Albedo

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

Temperature effects of doubled CO_2

$2\times\text{CO}_2$

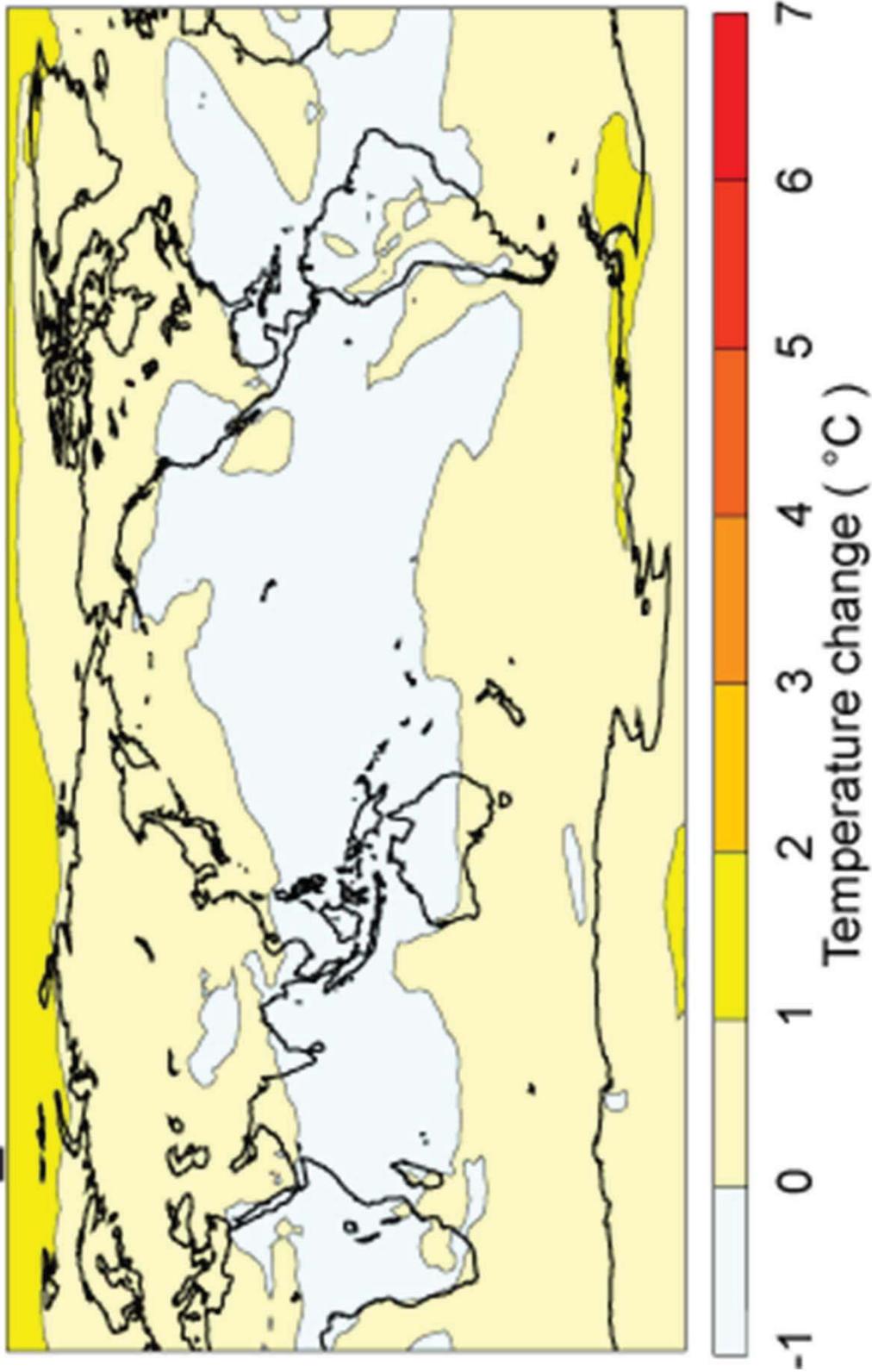


Caldeira and Wood, 2008

Temperature effects of doubled CO₂

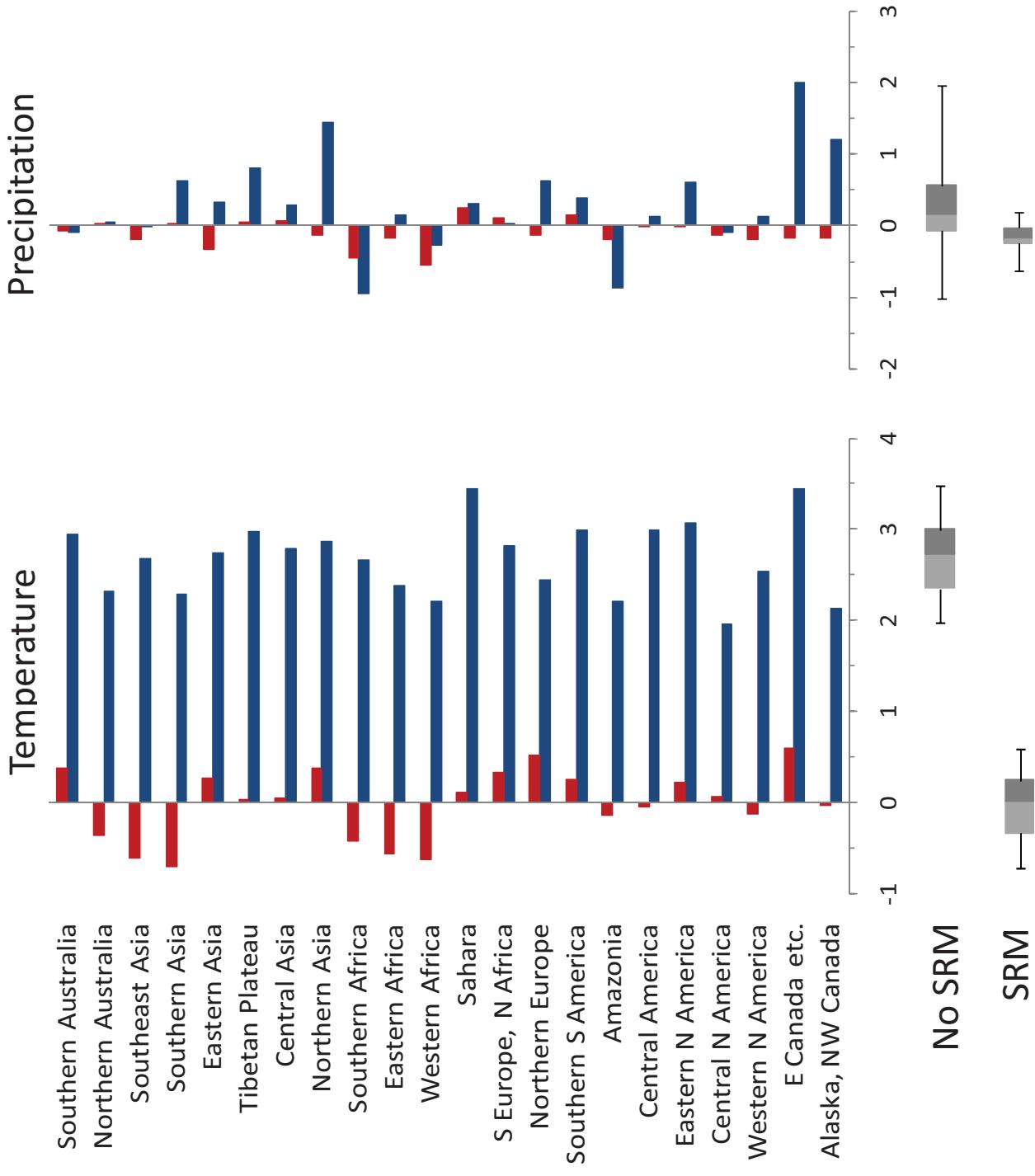
with a uniform deflection of 1.84% of sunlight

Global 1.84



Caldeira and Wood, 2008

Imperfect



Engineering interlude

Stratospheric scatterers

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

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

Lofting methods:

- Aircraft
- Naval guns
- Tethered balloon with a hose

Alternative scattering systems

- Oxides
 - H_2SO_4 or Al_2O_3
- Metallic particles ($10-10^3 \times$ lower mass)
 - Disks, micro-balloons or gratings
- Resonant ($10^4-10^6 \times$ lower mass ??)
 - Encapsulated organic dyes
- Self-lofting particles

Scattering design goals:

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

Efficient formation of stratospheric aerosol for climate engineering by emission of condensable vapor from aircraft

Jeffrey R. Pierce,¹ Debra K. Weisenstein,² Patricia Heckendorn,³ Thomas Peter,³ and David W. Keith⁴

GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L18805, doi:10.1029/2010GL043975, 2010

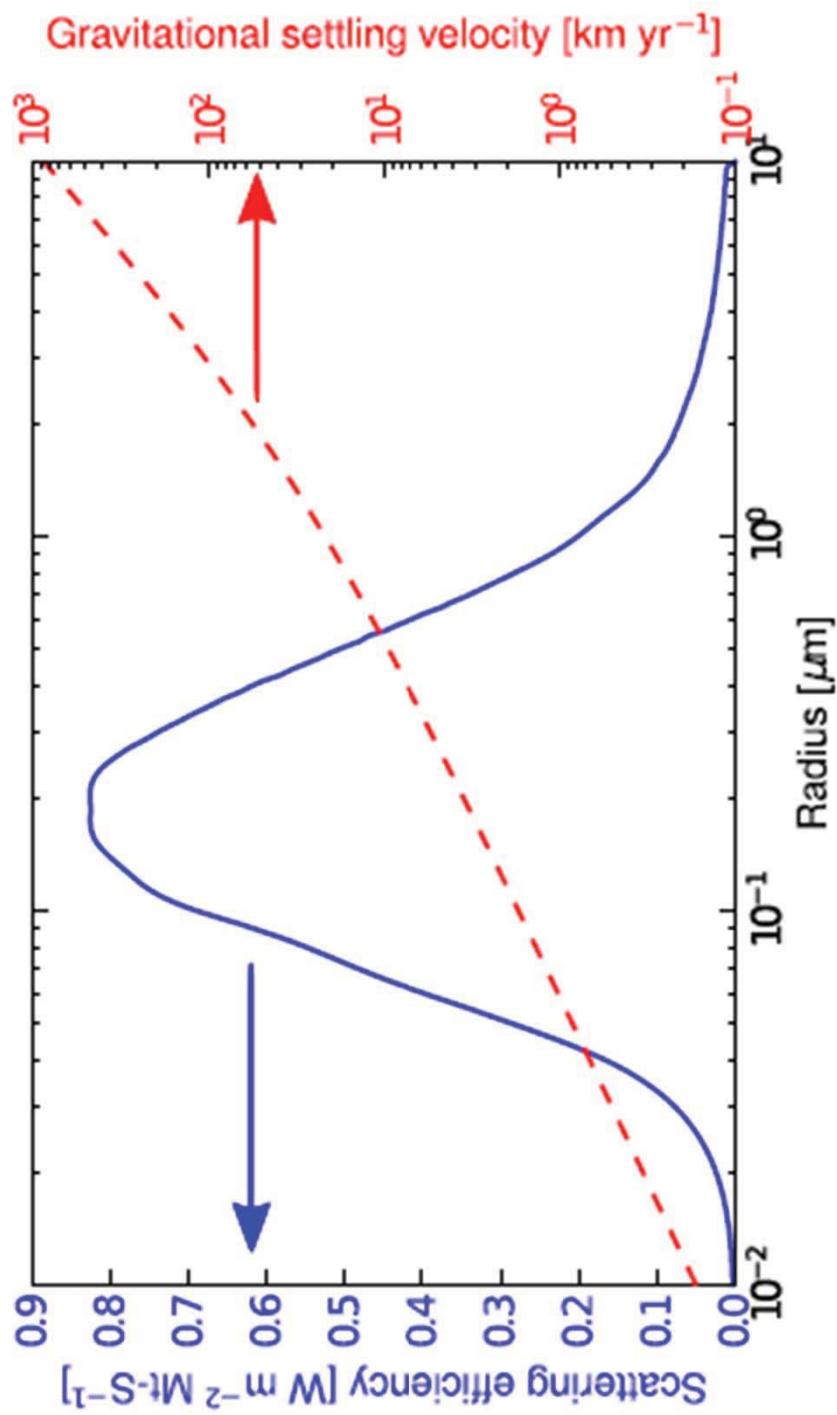
¹Department of Physics and Atmospheric Science, Dalhousie University, Halifax, Nova Scotia, Canada.

²Atmospheric and Environmental Research, Inc., Lexington, Massachusetts, USA.

³Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland.

⁴Energy and Environmental Systems Group, University of Calgary, Calgary, Alberta, Canada.

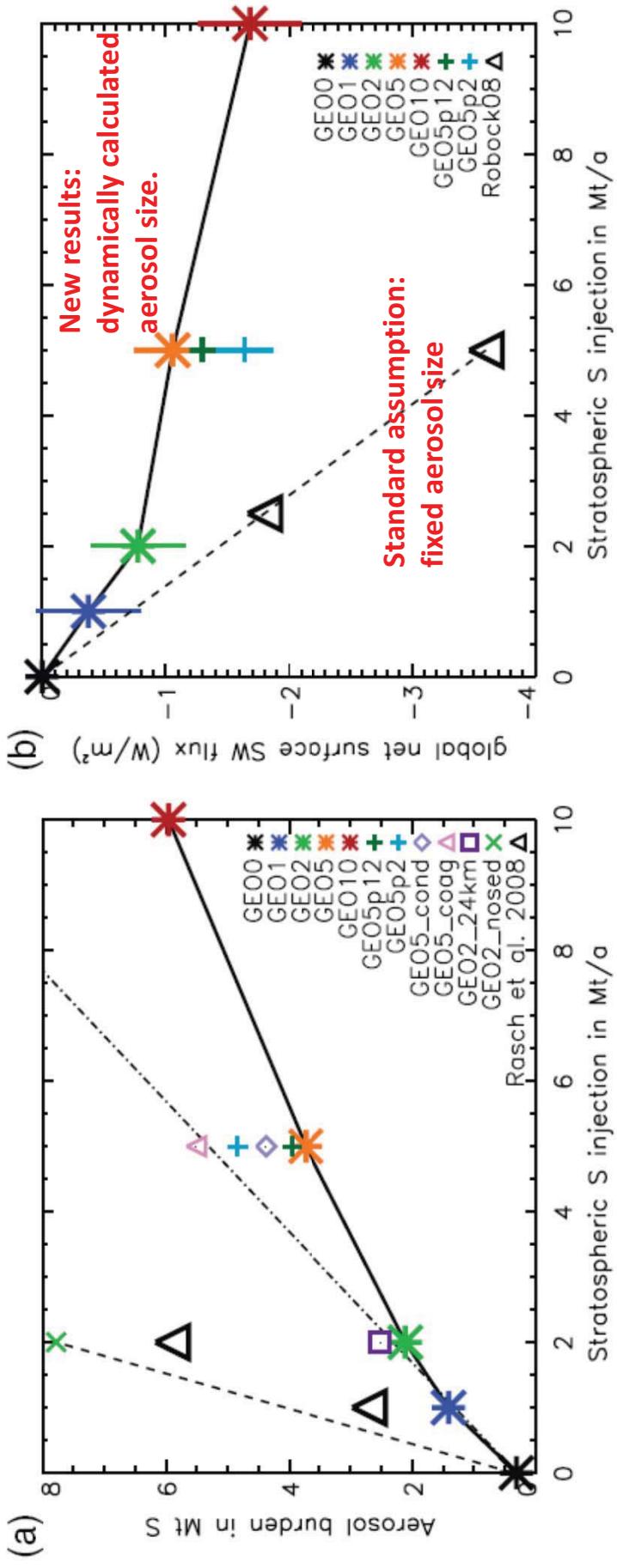
Scattering efficiency and settling rate vs size



Problems with the 'standard' SO_2 injection scheme

A first look at sulfate geoengineering with a model that includes microphysics of aerosol condensation, coagulation and nucleation suggests that SO_2 injection is far less effective than commonly assumed.

Even 10 Mt-S/year produces only 1.7 Wm^{-2} of radiative forcing!



Hekendorf et al, The impact of geoengineering aerosols on stratospheric temperature and ozone, *Environmental Research Letters*, **4** 2009.

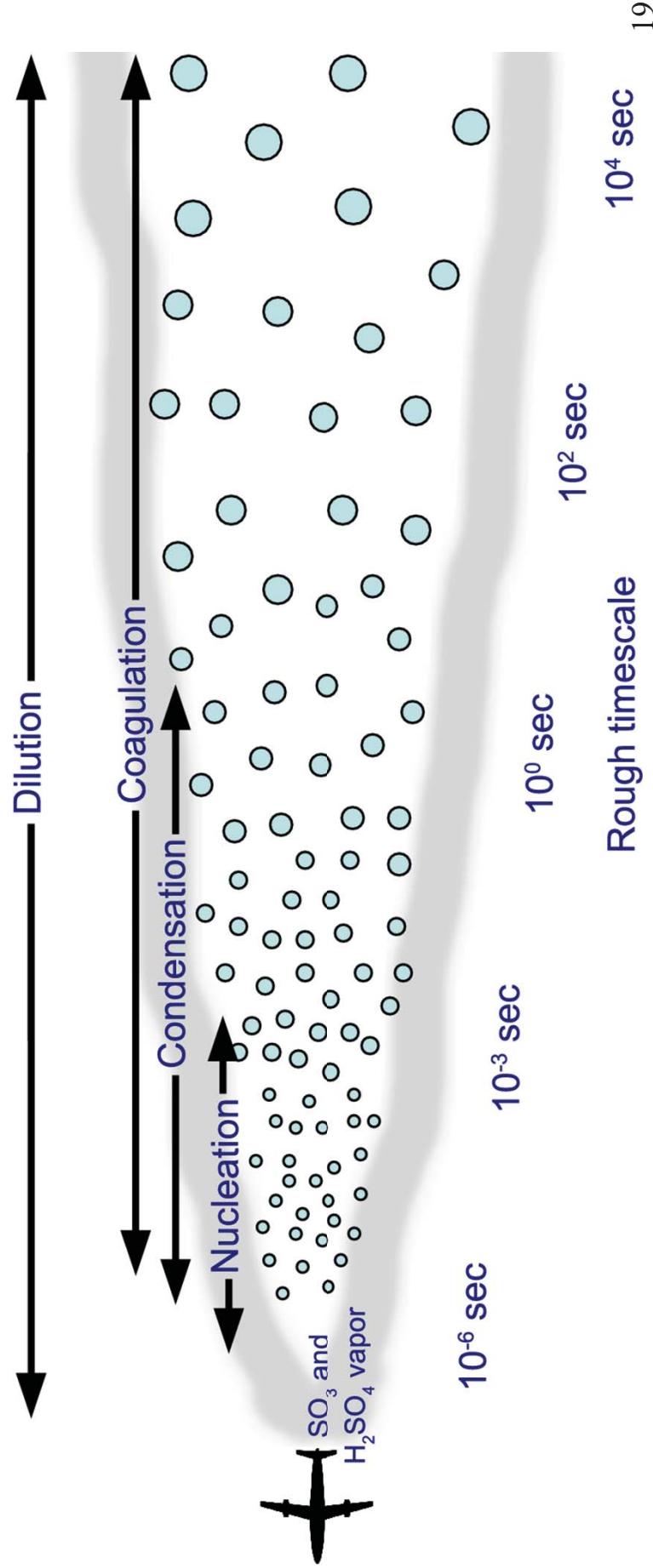
Four methods to disperse particles in the stratosphere

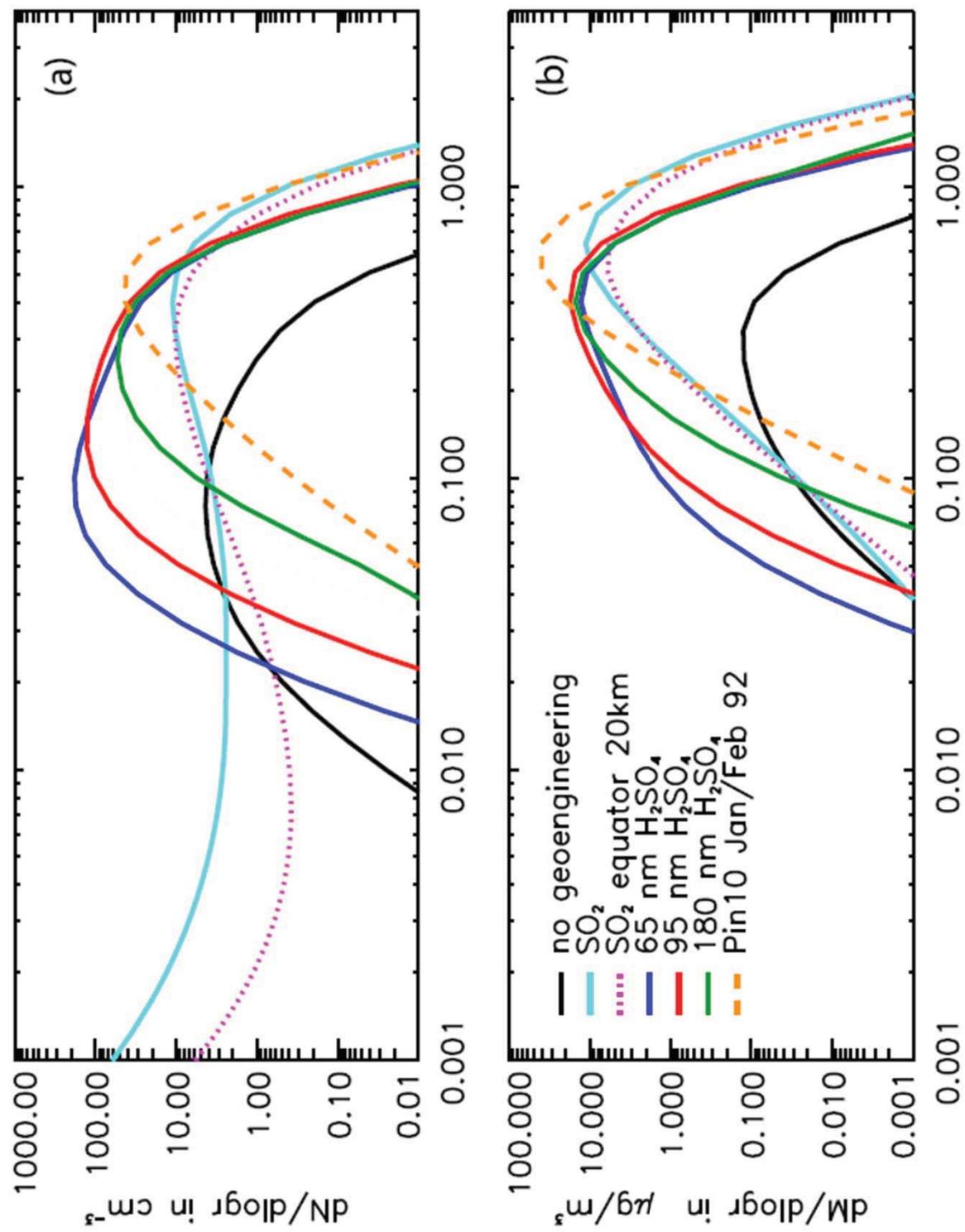
1. High vapor-pressure gas
 - **Process:** In situ conversion to a low vapor pressure gas followed by homogeneous nucleation and/or deposition on existing particles.
 - Almost all geoengineering studies to date have used this method where the injected gas is either SO₂ or H₂S.
2. Low vapor-pressure gas
 - **Process:** Release a low vapor pressure gas that rapidly condenses in aircraft plume.
 - Many kinds of nano-particles can be formed this way.
3. Liquid droplets by spraying
 - **Process:** disperse a liquid with an atomizing nozzle.
4. Solid particles
 - **Process:** disperse particles that are carried to the stratosphere as a solid powder

A possible solution

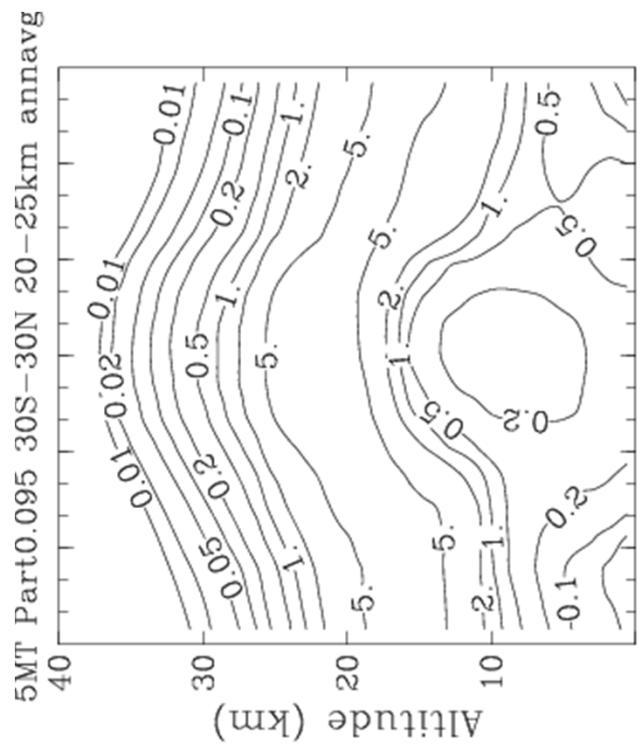
Release a condensable gas (H_2SO_4) directly into an aircraft plume produces high local vapor concentrations so homogeneous nucleation and rapid coagulation dominate and almost all mass goes to produce new particles.

By varying the spray rate expansion we can control the size distribution of the resulting particles.

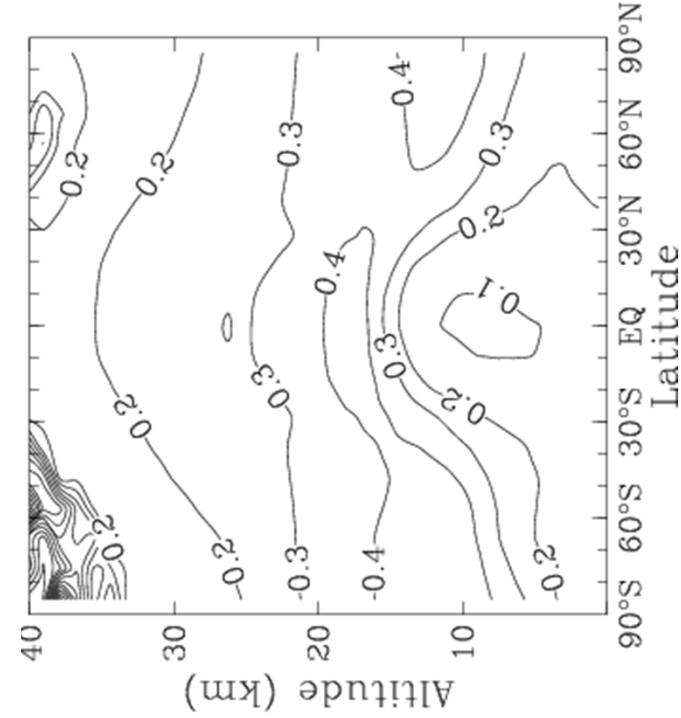
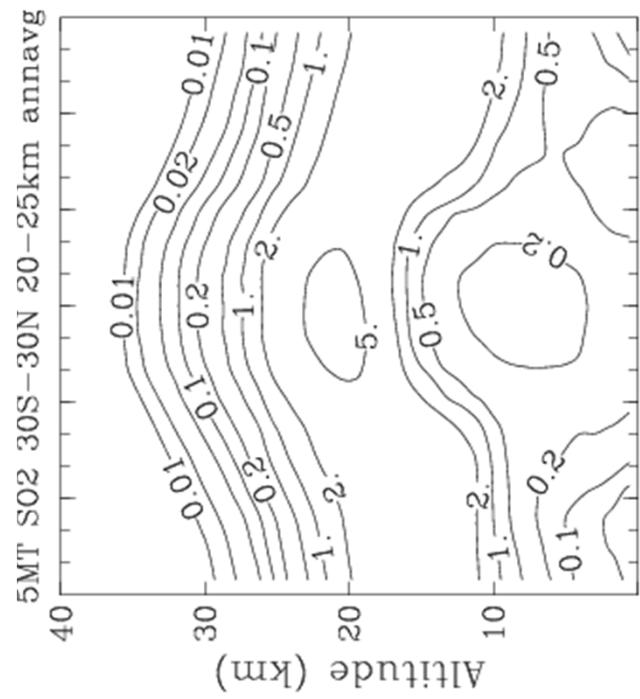




H_2SO_4 in plume



SO_2



Particle radius

Mass loading

90°S 60°S 30°S EQ 30°N 60°N 90°N
Latitude

90°S 60°S 30°S EQ 30°N 60°N 90°N
Latitude

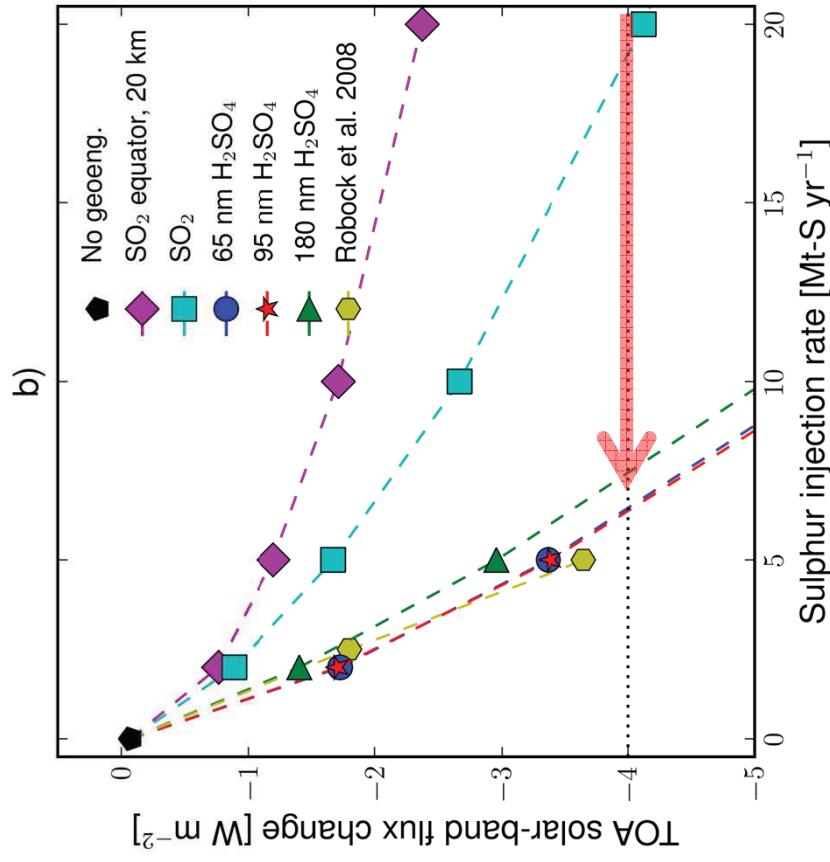
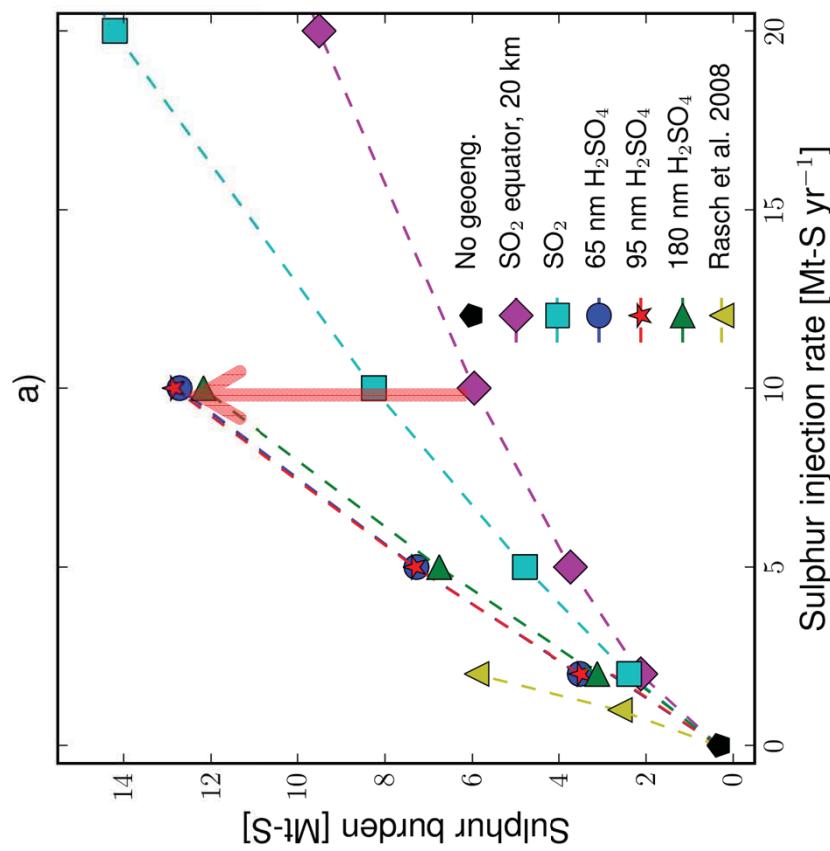
90°S 60°S 30°S EQ 30°N 60°N 90°N
Latitude

21

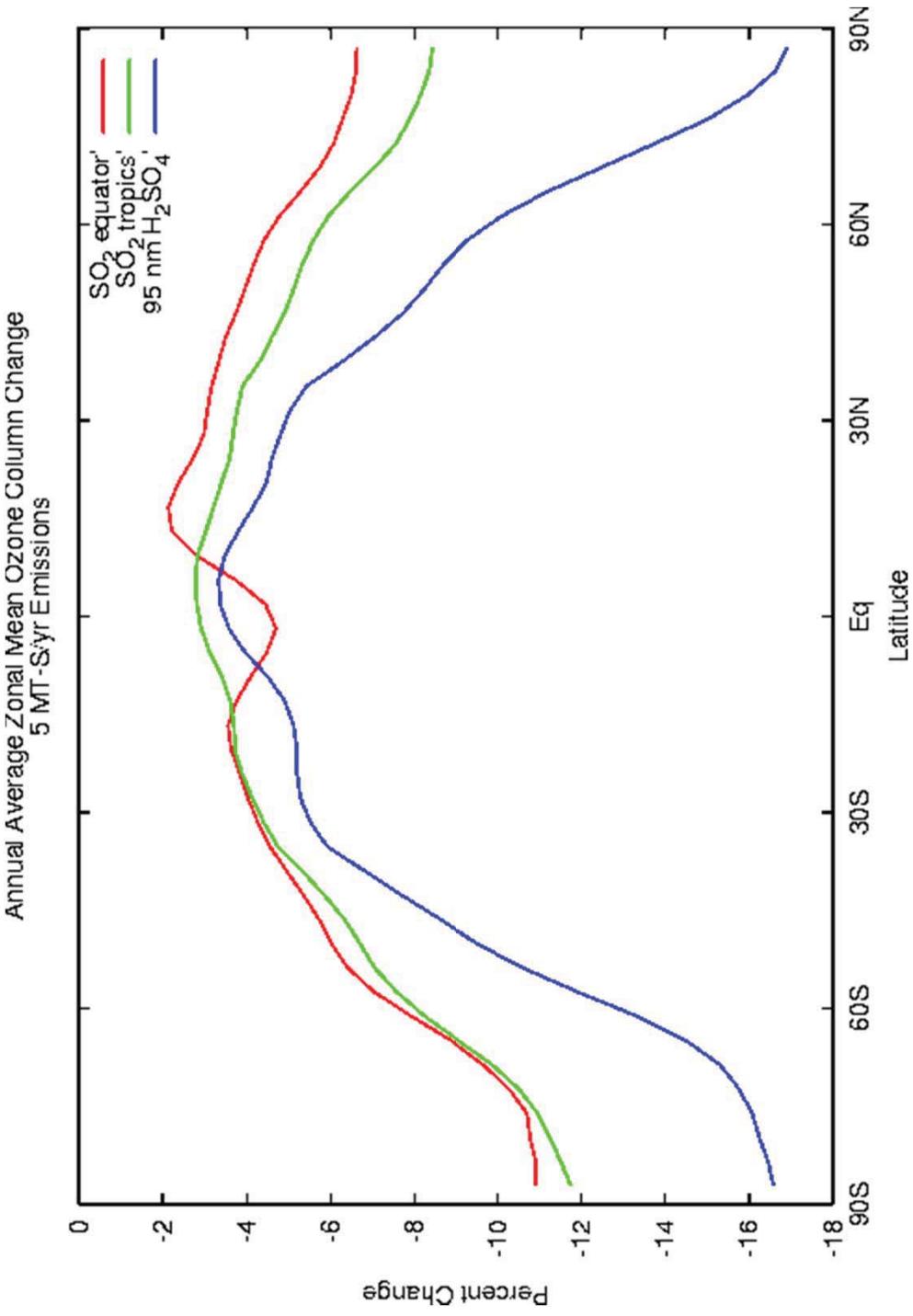
Results

Particles are smaller and mass loading higher for direct H₂SO₄ injection.

One can get to 4 W/m⁻² with 7 Mt-S per year using the direct H₂SO₄ method vs or 20 or more with the standard SO₂ method.



Smaller size → more surface area → less ozone



75% of this ozone loss is due to intensified heterogeneous chemistry caused by the increased aerosol surface area density.

Alumina

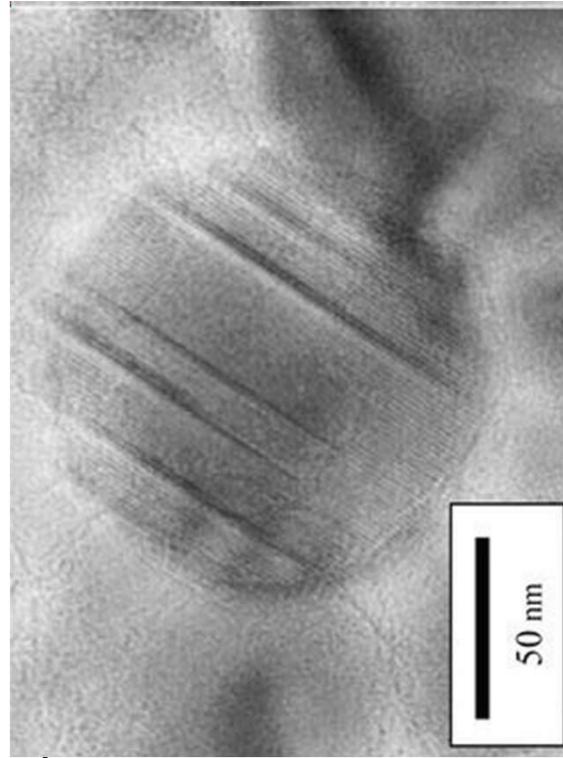
Volumetric scattering coefficient is roughly 4 X that of sulfate at 0.2 μm radius.

So an equivalent radiative forcing implies:

- Surface area 4 X smaller
 - Coagulation rate 16 X smaller
- ? ➔ very large decrease in coagulation-driven loss

Also

- There are a number of studies of impact of alumina aerosol on stratospheric chemistry and radiation
- Assume 1 Mt/year of Al, a few % of global production
- CO₂ emissions from aluminum production would be ~0.3% of global emissions



J Haidar (2008) Synthesis of Al Nanopowders in an Anodic Arc, *Plasma Chem Plasma Process* **29**:307–319

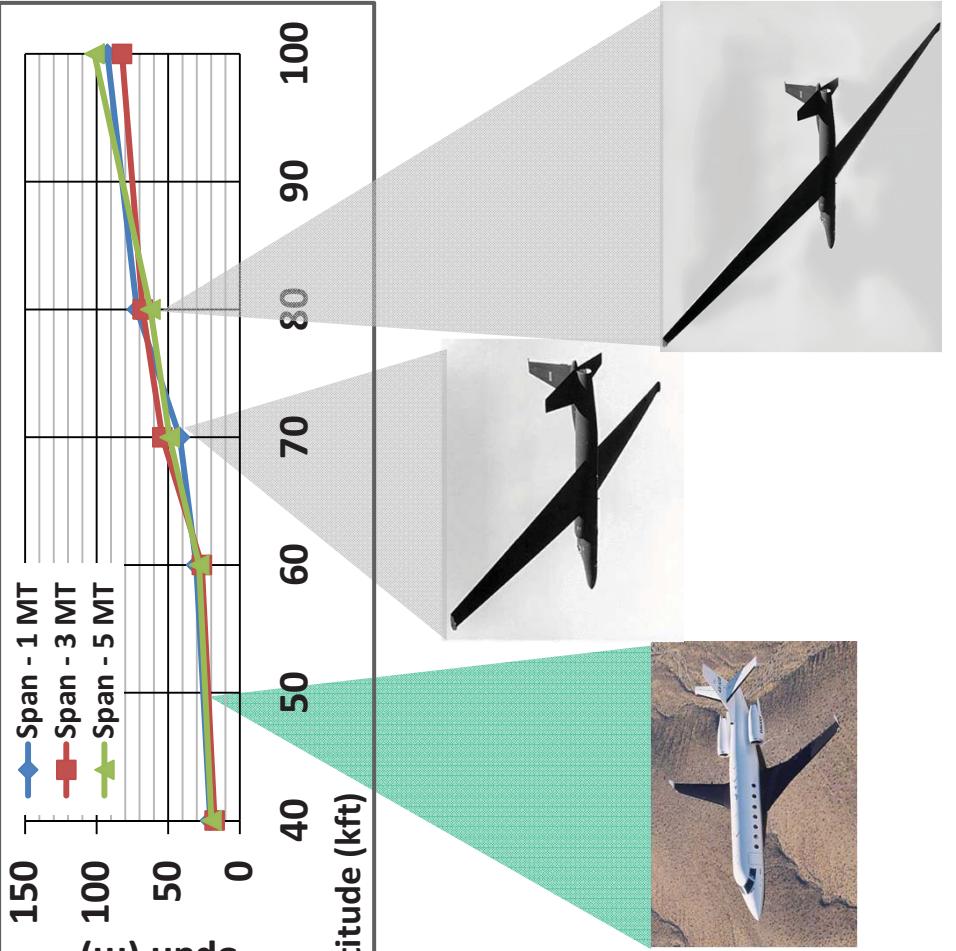
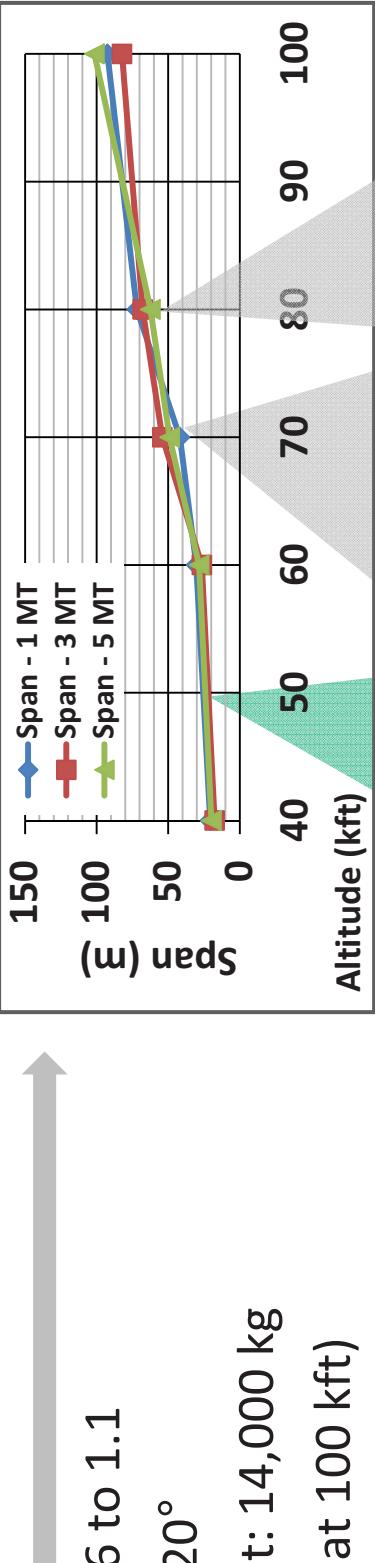
Closing thoughts on direct aerosol method

1. It much easier to think of a new method than it is to understand its effectiveness and environmental risks
2. There is a huge scope for new methods
3. The environmental hazards of SRM cannot be assessed without knowing the specific techniques that might be used.
4. It is impossible to identify and develop techniques without field testing; such process/micophysical tests can be done at the ton scale
5. These tests would say nothing (directly) about large-scale atmospheric response

The Optimized Aircraft

Payload: 10,000 kg for almost all cases

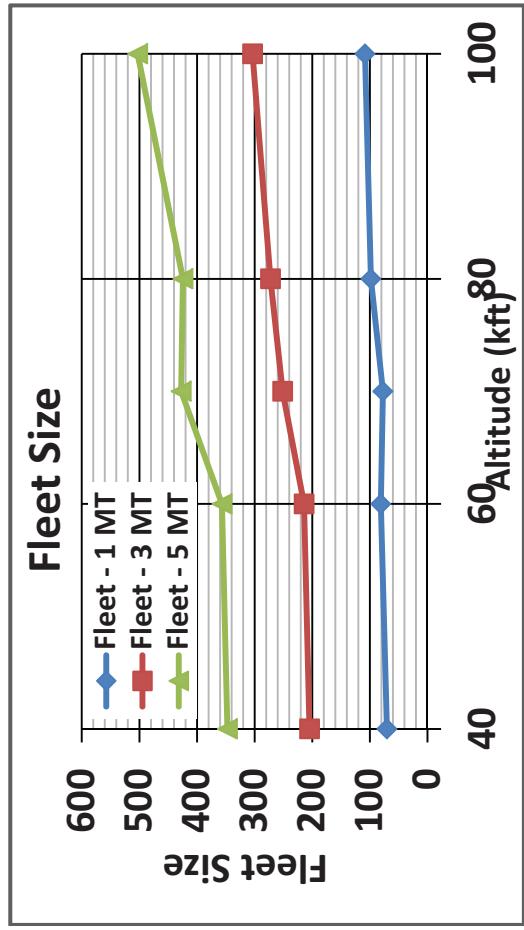
- For 5 MT per year, 40,000 kg payload is competitive at 60,70kft



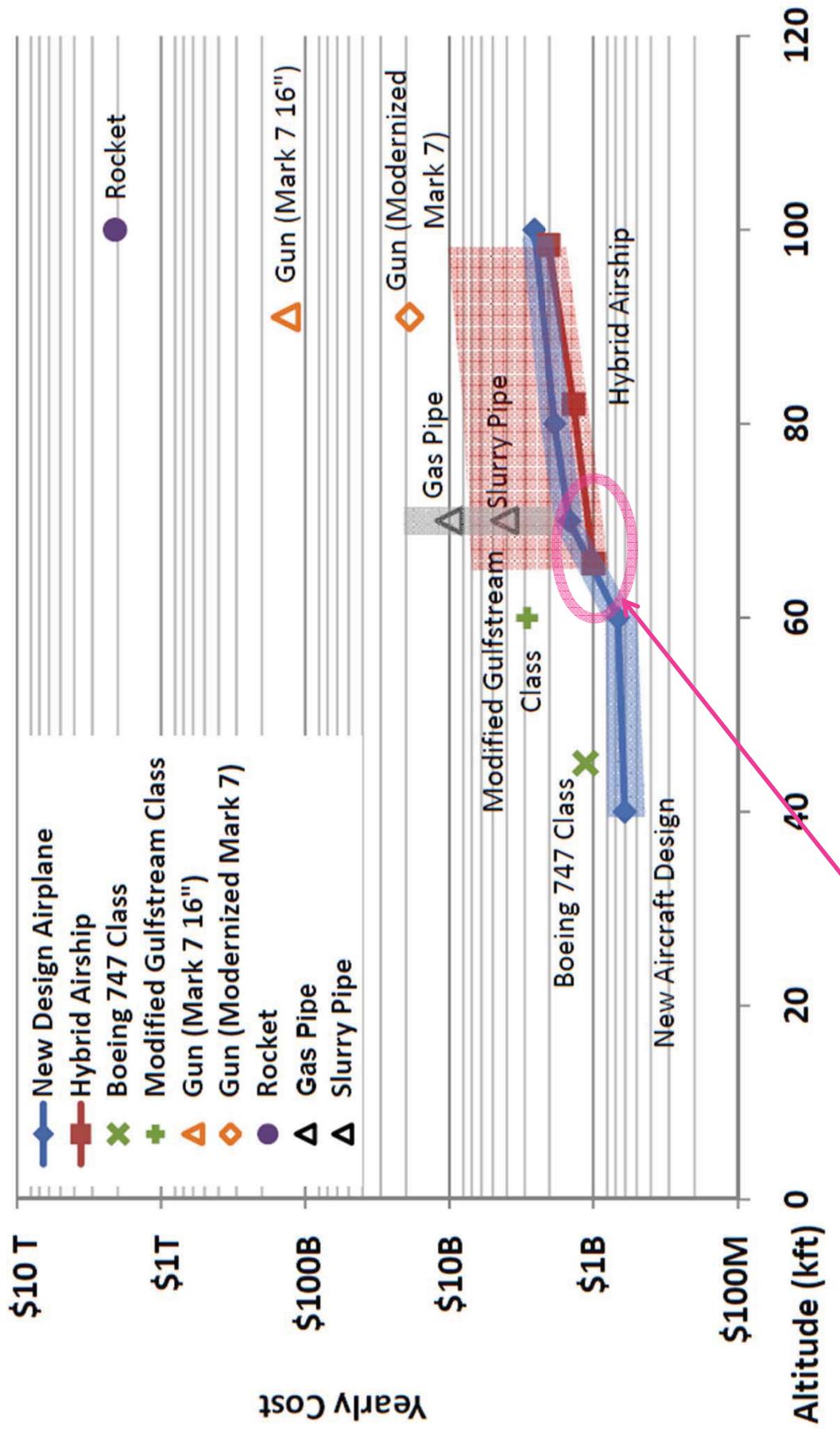
Cruise CL: 0.6 to 1.1

Sweep: 10° - 20°

Gross Weight: 14,000 kg
2 engines (4 at 100 kft)



Yearly Total Cost Comparison (1M tonnes / year)



About 1 \$/kg to the lower or middle stratosphere by several methods

Kilometers:	12.2	18.2	21.3	24.4	30.5
Thousands of Feet (kft):	40	60	70	80	100
Feet (kft):					

Photophoretic Levitation



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. 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

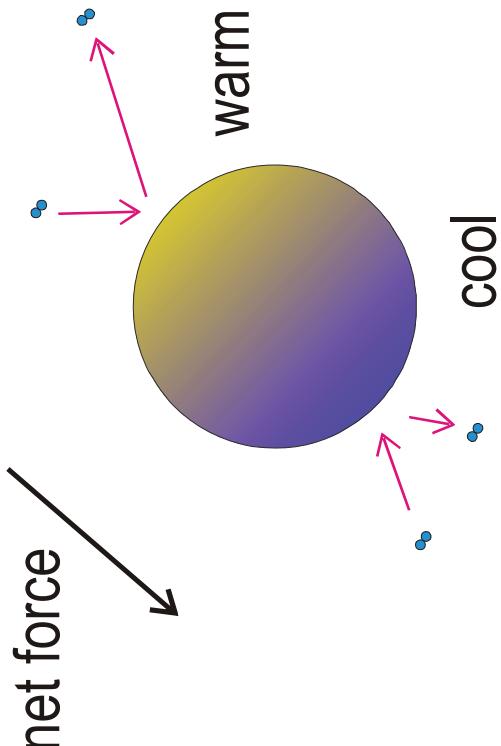
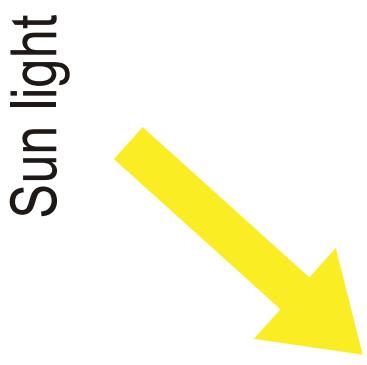
Uneven illumination



Temperature gradient across particle



Net force toward cool side



Gravito-Photophoresis

Radiative heating (or cooling)

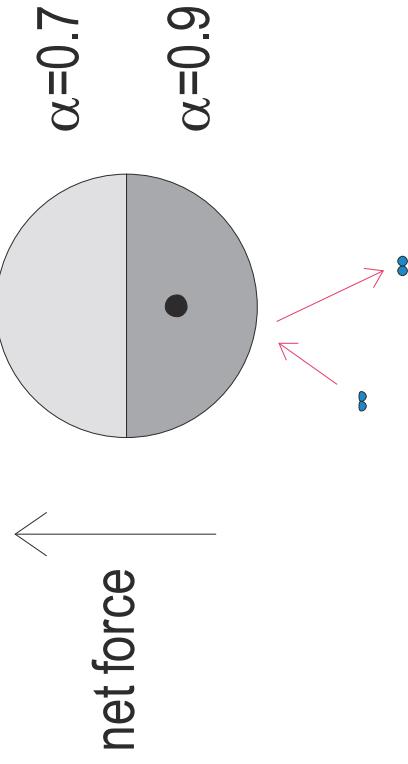


Accommodation coefficient
asymmetry



Body-fixed force

Sun light

A large yellow arrow pointing downwards, representing sunlight.

Force independent of pressure ~10 to 100 km

Force depends on $\delta T \rho$

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

...but δT depends $1/\rho$

$$\underbrace{\frac{S \varepsilon_S}{4}}_{\text{Solar input}} + \underbrace{\sigma \varepsilon_T T_E^4}_{\text{Outgoing longwave input from earth}} - \underbrace{\sigma \varepsilon_T (T + \Delta T)^4}_{\text{Radiative cooling}} = \underbrace{\frac{3}{2} V \alpha \frac{\Delta T}{T} \rho}_{\text{Conduction}}$$

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

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.

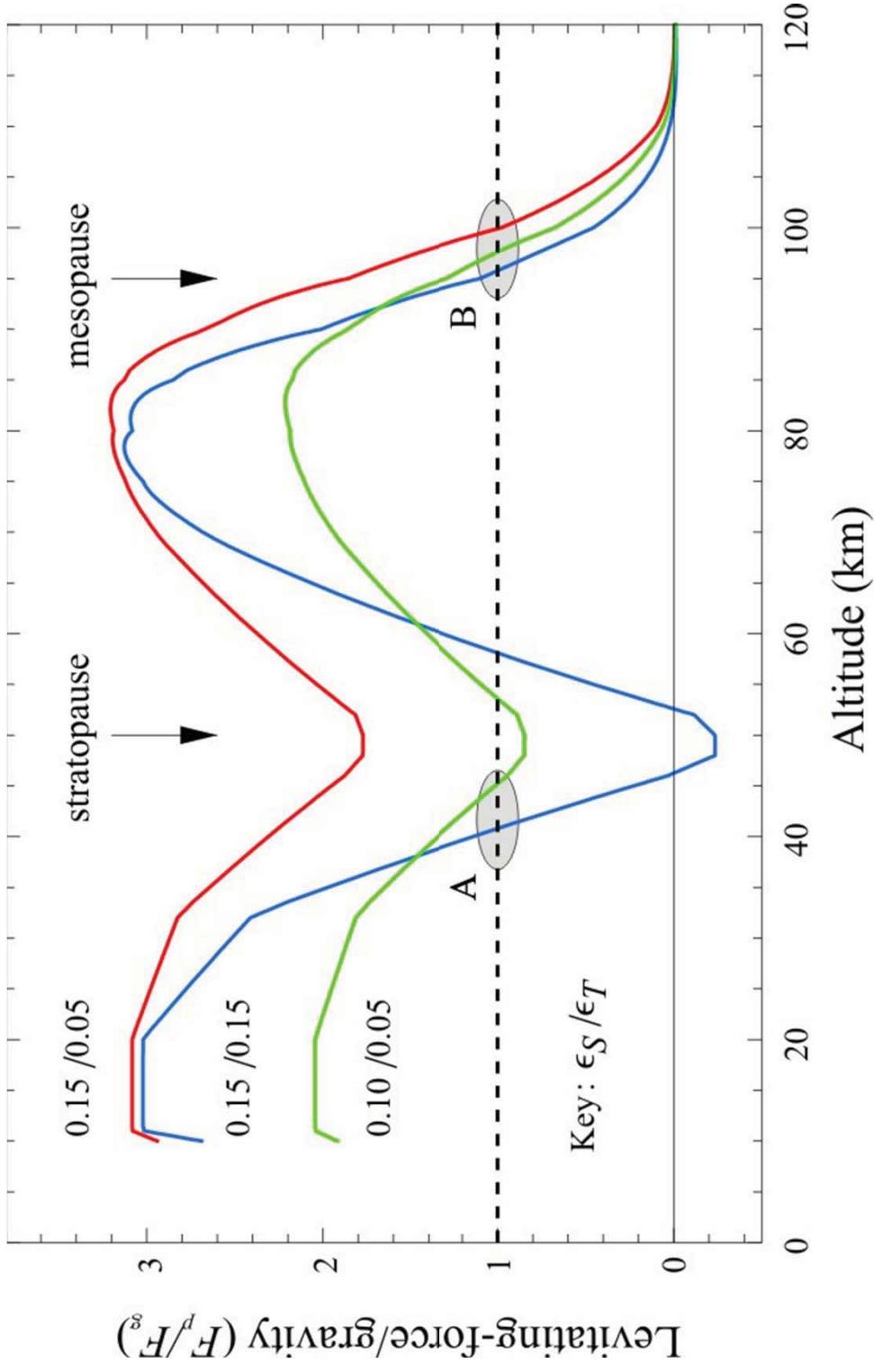
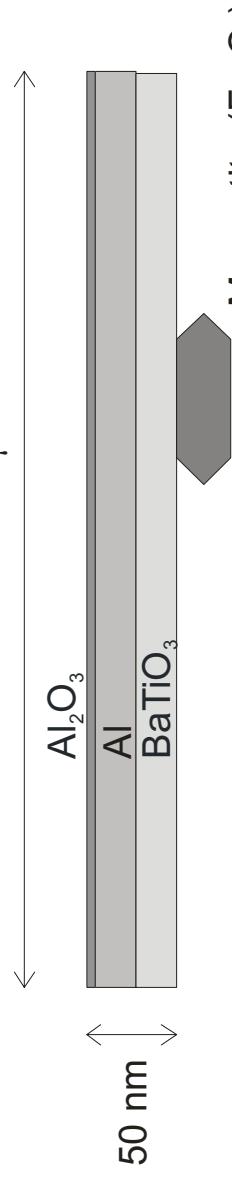
Consider the 1 μm radius sphere in which the center of mass is displaced 0.1 μm from the geometric center (Rohatschek example).

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

Similarly, a sphere of barium titanate, a common ferroelectric, with residual charge of $2 \times 10^{-3} \text{ C m}^{-2}$ 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 $\sim 10 \mu\text{m}$



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 might be most effective.
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 $2 \times \text{CO}_2$

- Assume a 50 nm thickness (e.g., metal plates or spheres)
- Assume lifetime of 10 years
→ 10^8 kg/yr for 4 W m^{-2}

Suppose cost of manufacture must be < 1% of cost of emissions control which is
 $\approx 2\%$ 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.

Detection and Attribution

What could be learned from sub-scale deployment?

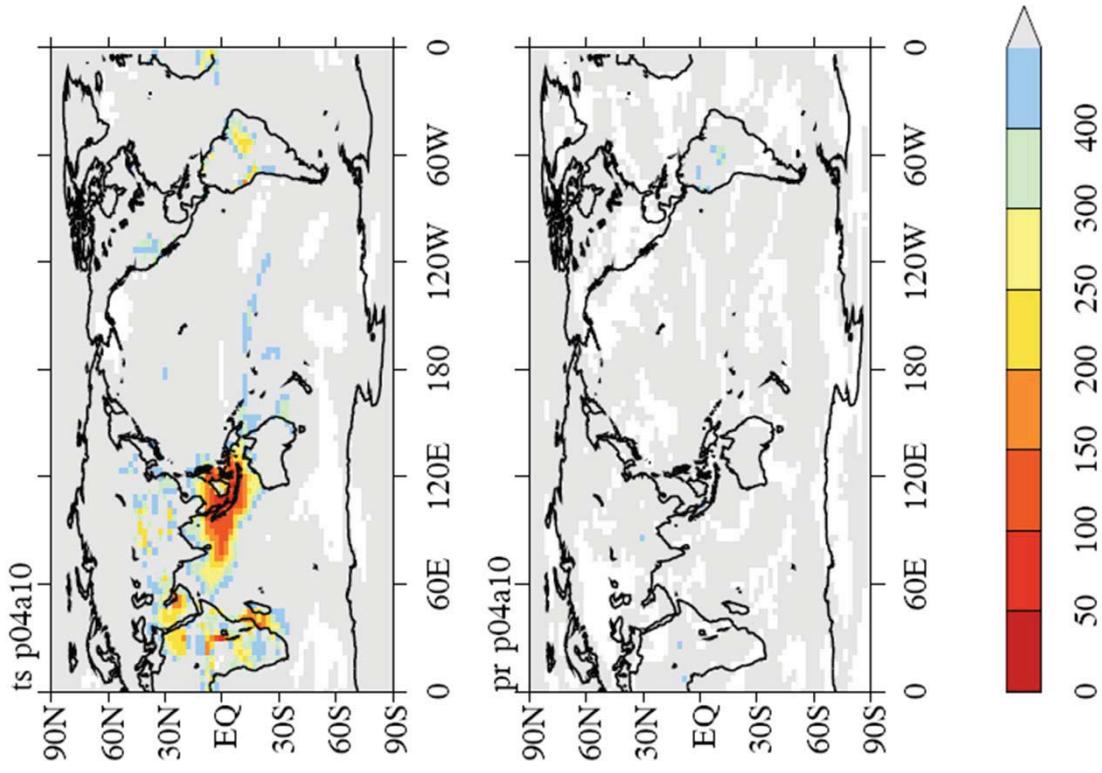
Stratospheric geoengineering cannot be tested in the atmosphere without full-scale implementation

Robock et al, A Test for Geoengineering, *Science* 327:530-531 (2010)

Detecting response at local-scale is very hard

Color scale on plot shows years required to estimate sensitivity to 25% at each 3.7×2.5 degree grid box give a 1 Wm^{-2} forcing.

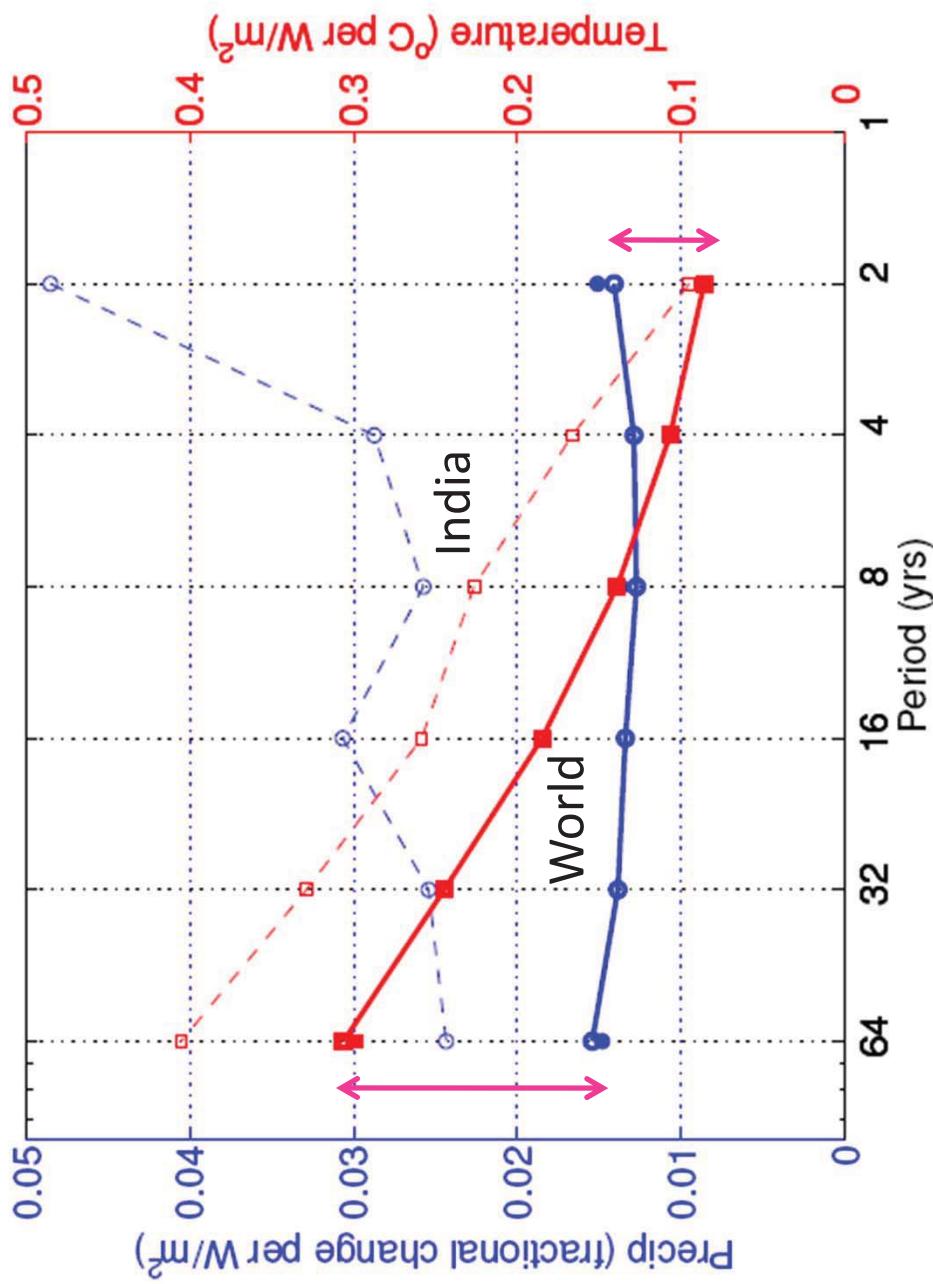
Conclusion: estimating regional responses is hard even with full ($\sim 4 \text{ Wm}^{-2}$) deployment.



Collaborators: Douglas MacMynowski, Ho-Jeong Shin, Ken Caldeira and David Keith

Frequency response of Temperature and Precipitation

Conclusion: short-period forcing greatly exaggerates the ratio of precipitation to temperature response



What could be learned from sub-scale deployment?

Stratospheric geoengineering cannot be tested in the atmosphere without full-scale implementation

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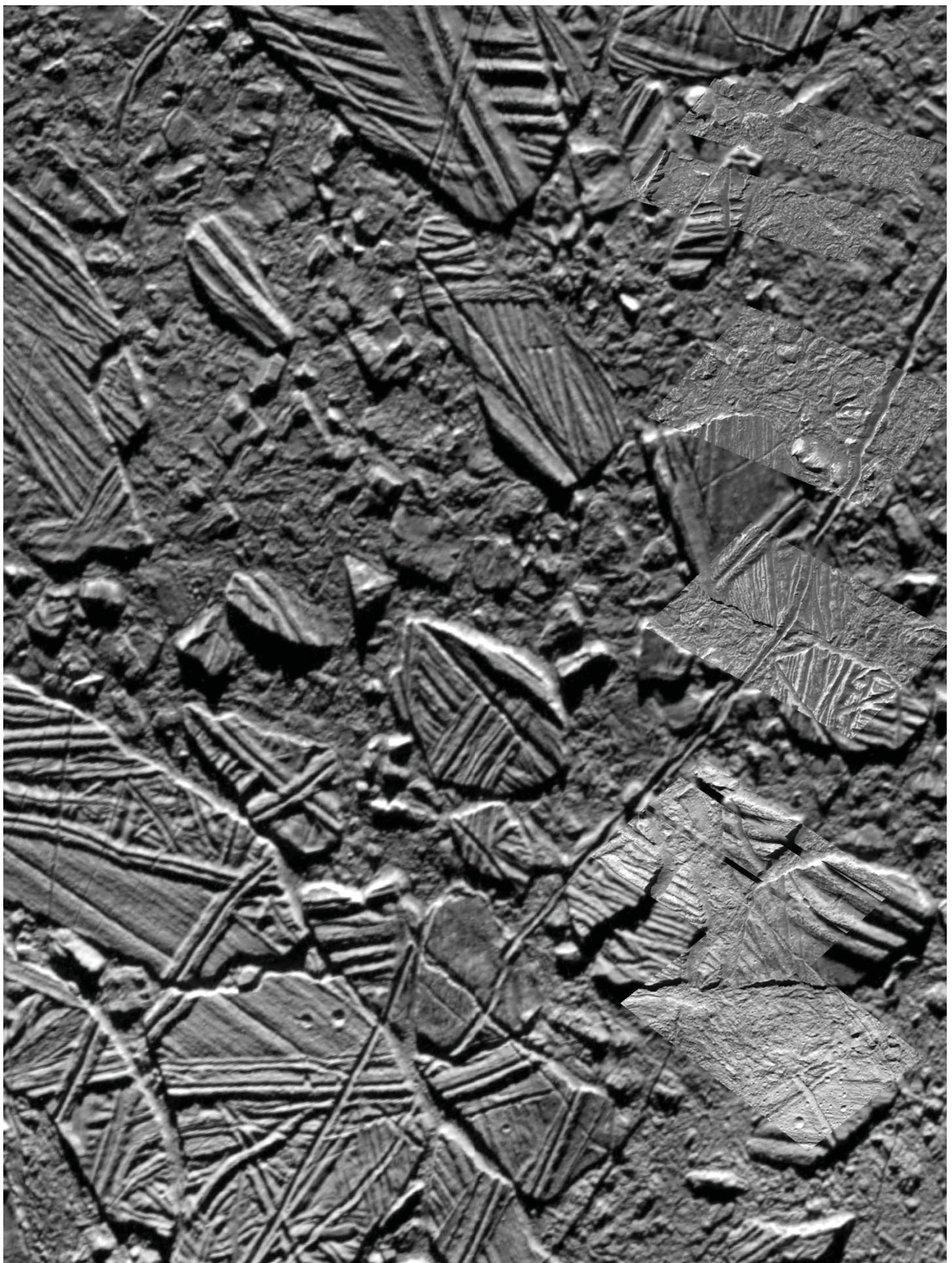
This is a signal detection problem in the presence of noise.

- ➔ There is nothing magic about full scale implementation
- ➔ We could learn a lot about extreme responses from sub-scale deployment.

E.g., Can detect response 1 to 0.5 sigma larger than expected in 25 years at 1/10 of full scale (0.4 Wm^{-2})

Suggestion: disagreement on this point arises in part from differing assumptions not from disagreement about the science

- ➔ We need a testable hypothesis

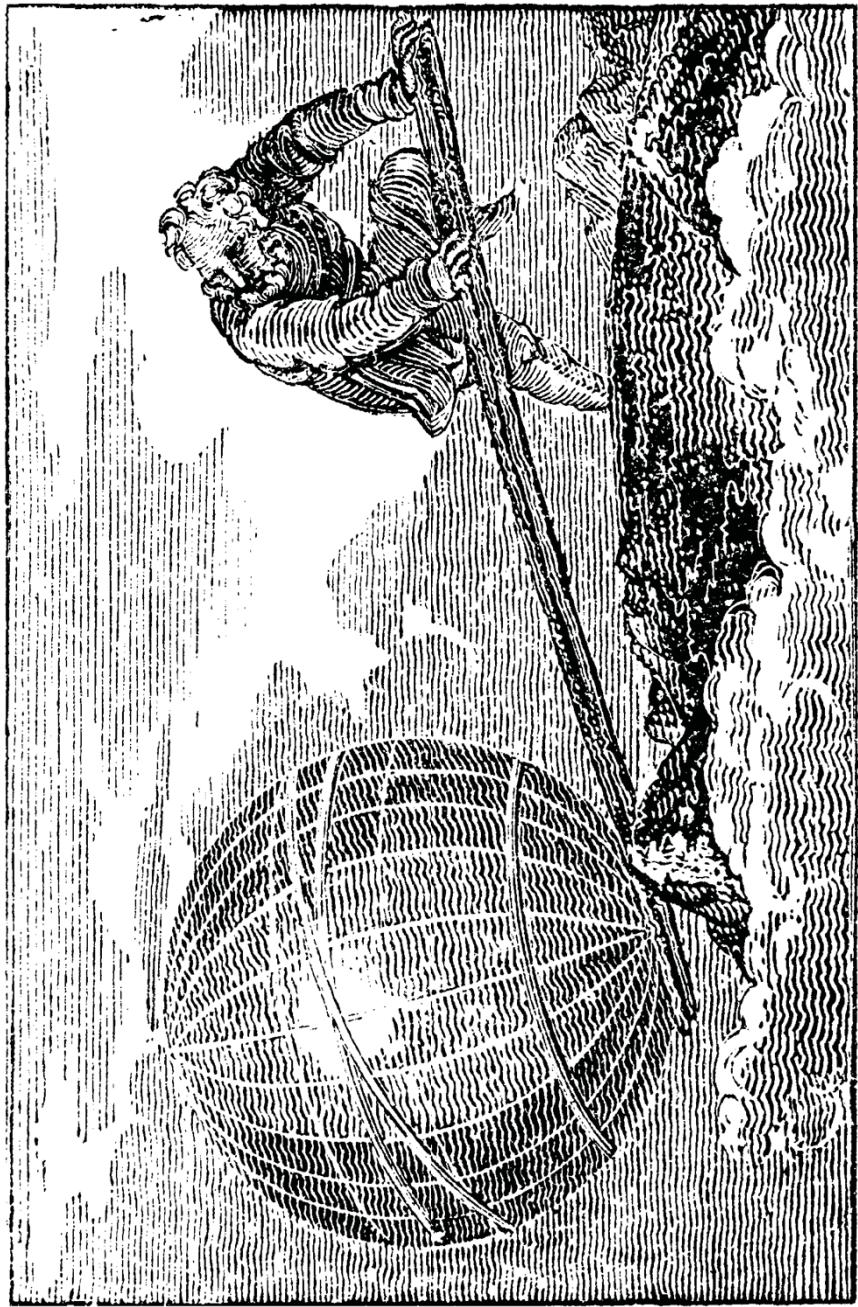


Cheap: Leverage

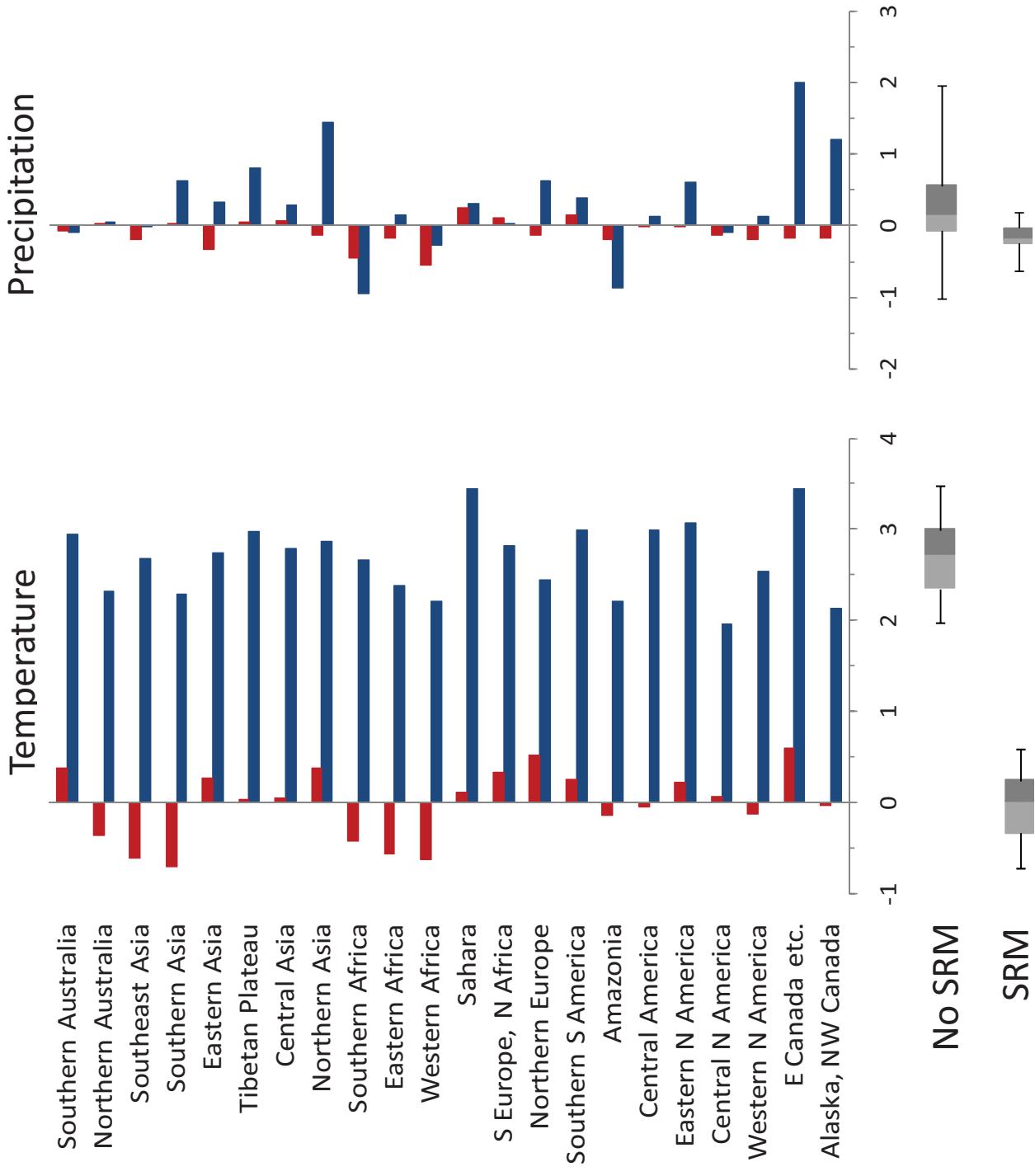
About 5 grams sulfur in the stratosphere *roughly* offsets the *climate forcing* of 1 ton carbon in the atmosphere

Example: 1 \$/kg → less than 10 \$bn per year → 0 \$/ton-CO₂

Conclusion: Cost will not drive decisions about implementation



Imperfect



SRM: Cheap, Fast and Imperfect

Cheap = high-leverage

- ➔ Decisions about implementation will be risk-risk not benefit-cost
 - *Abatement challenge is to get (almost) all to comply; while,*
 - *SRM challenge may be to constrain the actions of rogues*
- ➔ Policy challenge is control
 - *Need to build capacity for governance from the beginning*

Fast

- ➔ Given inertia + climate uncertainty SRM may be the **only** way to ensure global climate changes stay below some threshold
- ➔ Decisions about implementation can be delayed

Imperfect

- ➔ SRM cannot obviate the need to cutting emissions
 - *Although it will substitute at the margin*
- ➔ Distribution of winners and losers under SRM not the same as distribution from CO₂-driven climate change

Simple Research Taxonomy

Lab

- Climate modeling
- Engineering design studies of deployment hardware
- Lab measurement of relevant quantities (e.g., chlorine activation chemistry)
- Lab tests of technologies (e.g., sea spray hardware or, $S \rightarrow SO_3$ conversion)

Process experiments

- Outdoor test of technologies (e.g., sea spray hardware or hydrosol dispersal)
- Field experiments to understand micro-physics
 - Release vapor from ER-2 at 20 km on a 10 km track to test aerosol dynamics
 - Release sea-salt droplets from a ship or fixed source and measure cloud optical response.

Sub-scale deployment

- Ramp up to 0.25 Wm^{-2} of NH radiative forcing over a few decades as sulfur burden in troposphere is reduced
- Modulate global radiative forcing (e.g. 5 year period and 0.25 Wm^{-2} amplitude)

What we expect

Works Does not work

work

What we get

Works	Does not work
Missed chance to limit damages	Better knowledge of risks
Some protection	Dangerous overconfidence

Warning: Moral Hazard†

Knowledge that geoengineering is possible



Climate impacts look less fearsome



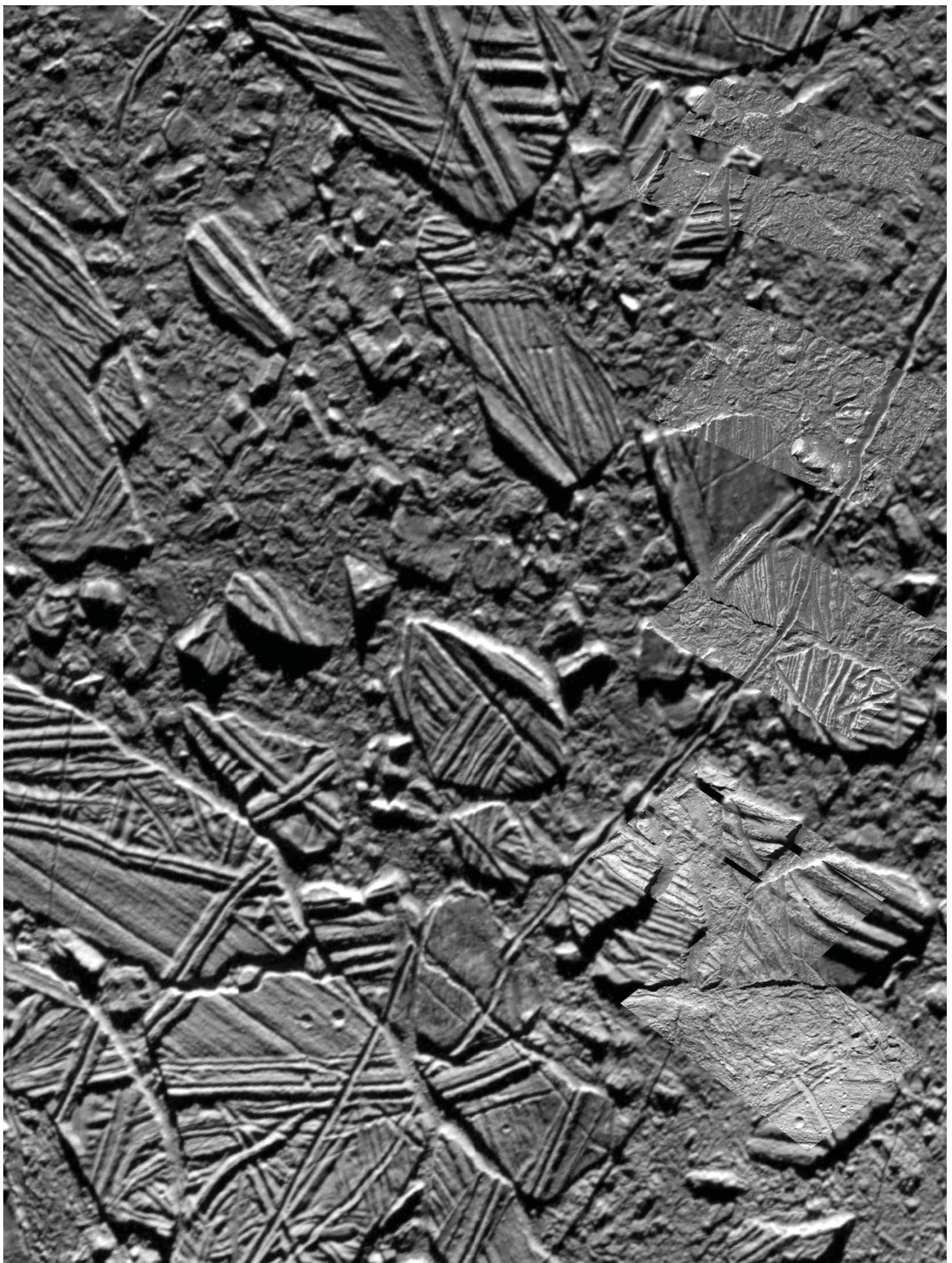
A weaker commitment to cutting emissions now

Opposite reaction possible:

**“if the pointy-heads think we need to shoot nano dust into the stratosphere
then we should get worried & get serious about cutting emissions”**

Whatever the reaction: it seems reckless and un-precautionary to avoid looking at something that might help limit the damage of the CO₂ already in the air.

+ ***Free-riding on our grandkids***



www.ucalgary.ca/~keith

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