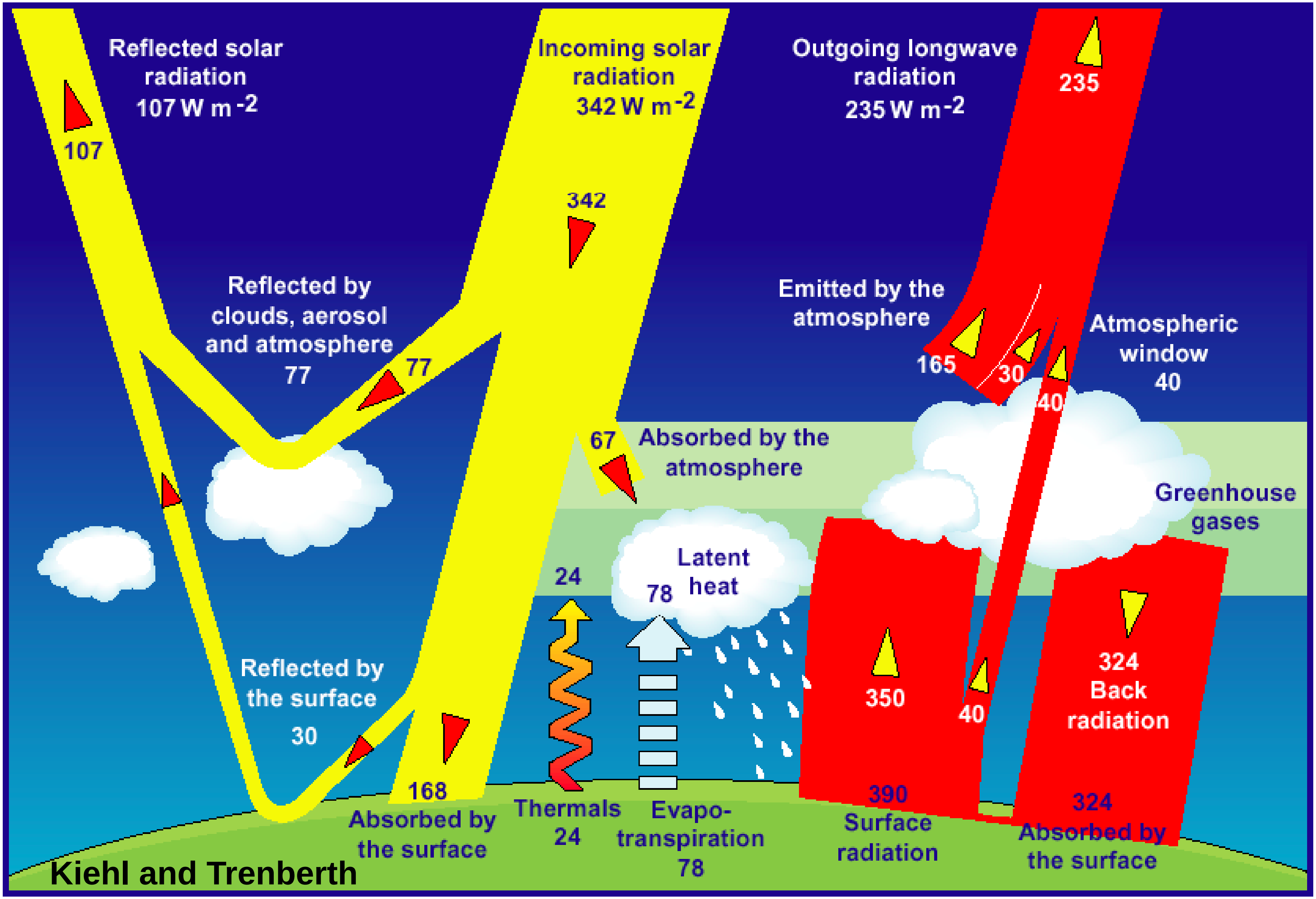
Modeling Climate Physics: Challenges and Climate Sensitivity Studies

Philip Rasch, Pacific Northwest National Laboratory

with thanks to
Cecelia Bitz, Dave Battisti, Jack Chen, Paul Crutzen, Dick Easter, Jerome Fast, Graham Feingold, John Latham, Po-Lun Ma, Kelly McCusker, Alan Robock, Vinoj Velu, Hailong Wang, Rob Wood, Jin-ho Yoon**.**

Climate System Energy Balance



Classes of Geoengineering

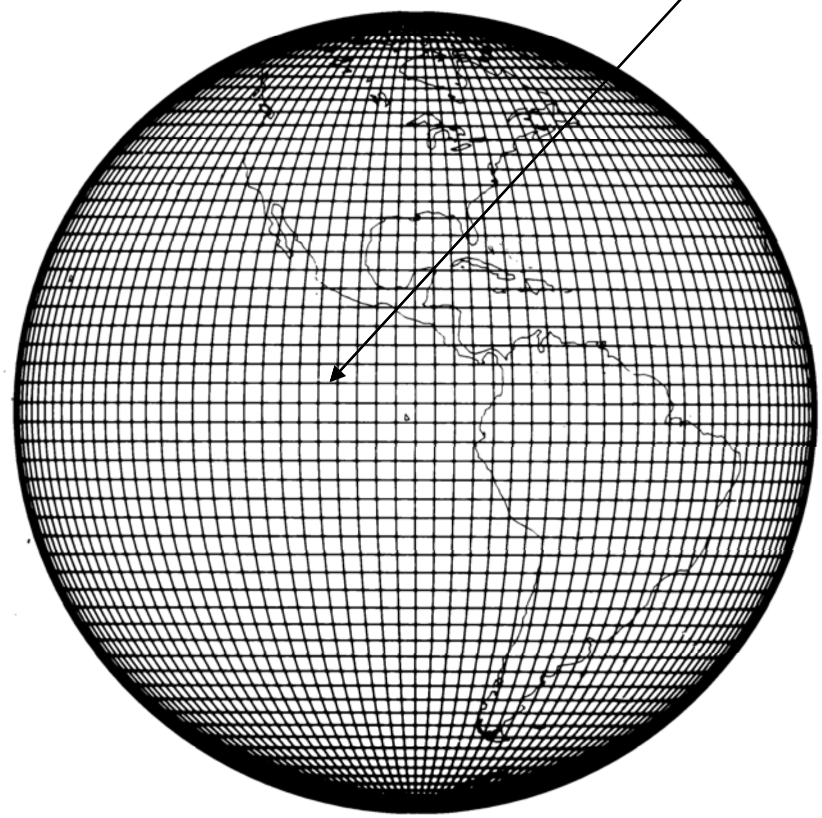
- "Carbon Dioxide Removal"
  - Capture at stack or remote from source sequester
  - Biochar
- "Solar Radiation Management"
  - Mirrors in Space
  - Stratospheric Aerosols
  - "Whitening clouds"
  - Painting rooftops white
  - Plant selection or genetic engineering to make "whiter plants"
- Increase Outgoing Longwave Emission
  - Make cirrus more transparent

Possible long term solution, slow and expensive

Probably not a long term solution, cheap, quick & maybe other good reasons to consider it.

Global Climate Model Simulations

100km horizontal resolution



Typical Climate Model Horizontal Resolution

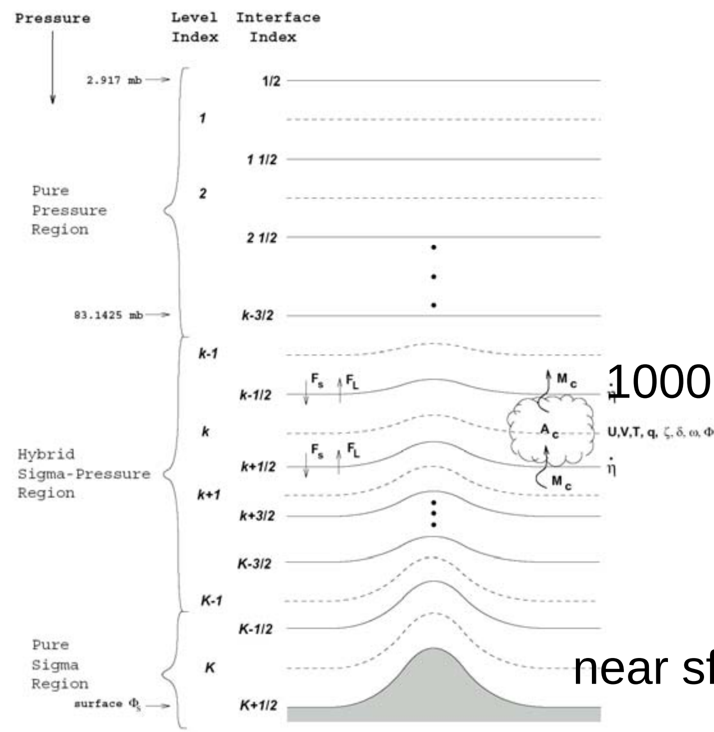
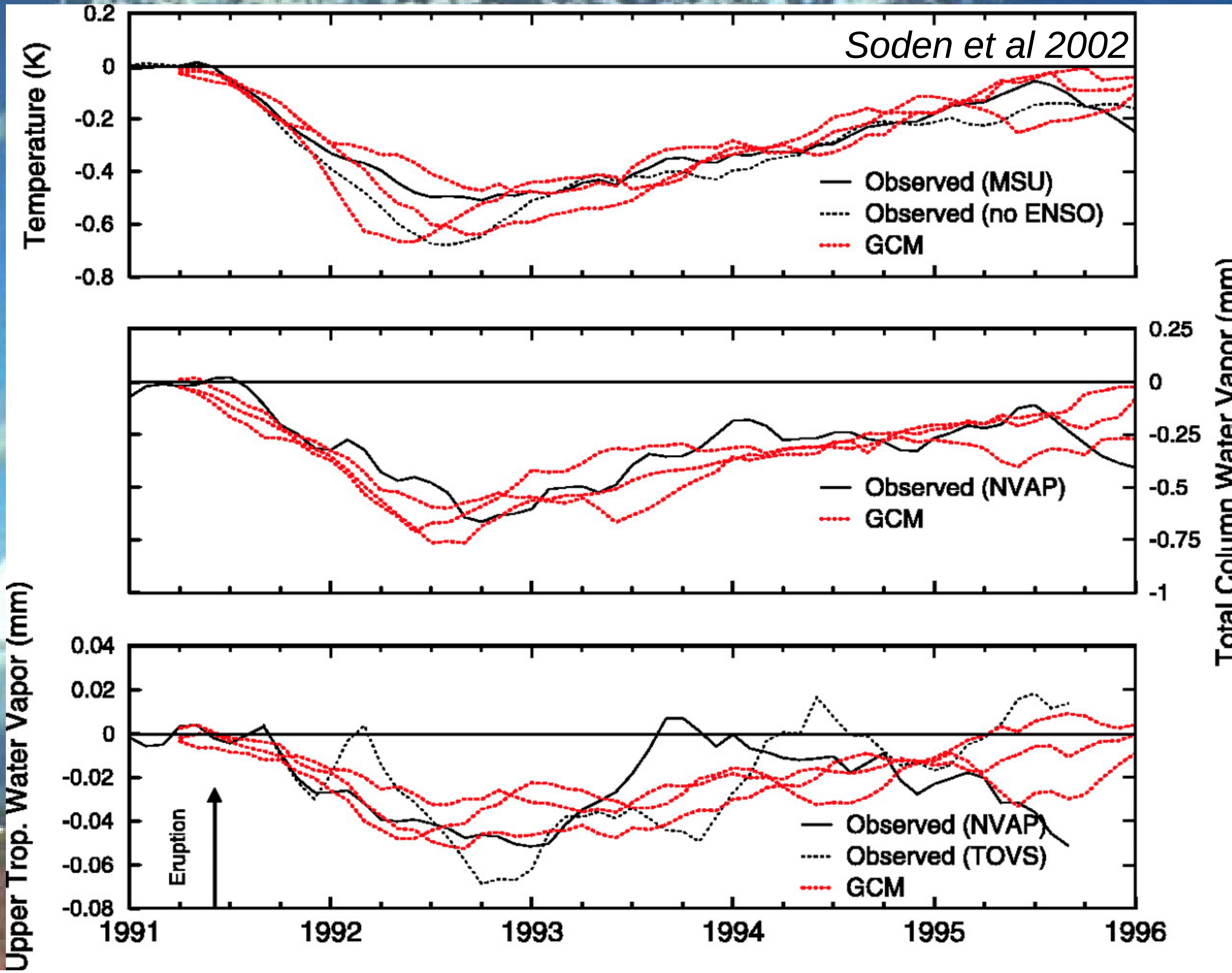


Figure 1. Vertical level structure of CCM

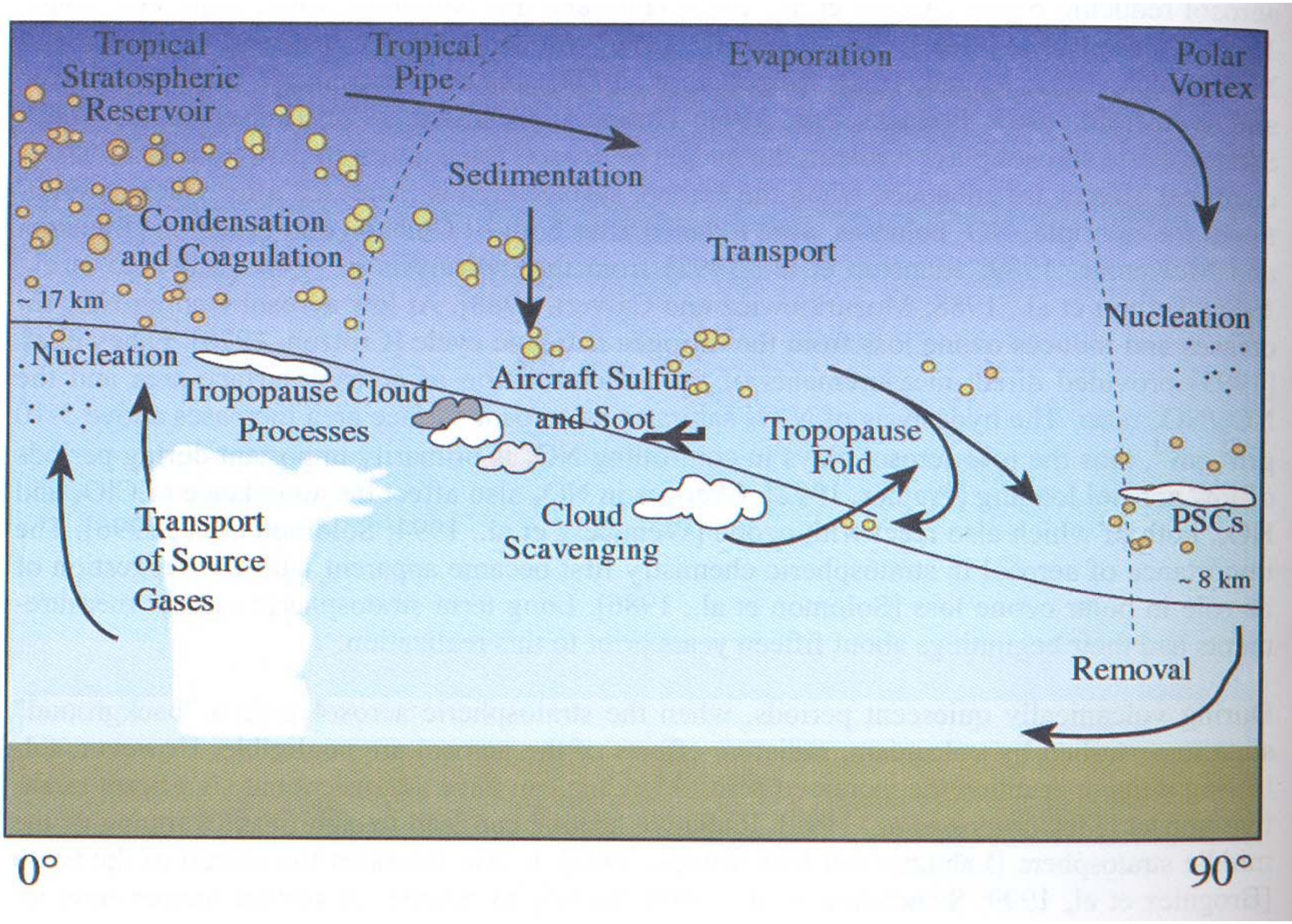
Vertical Resolution

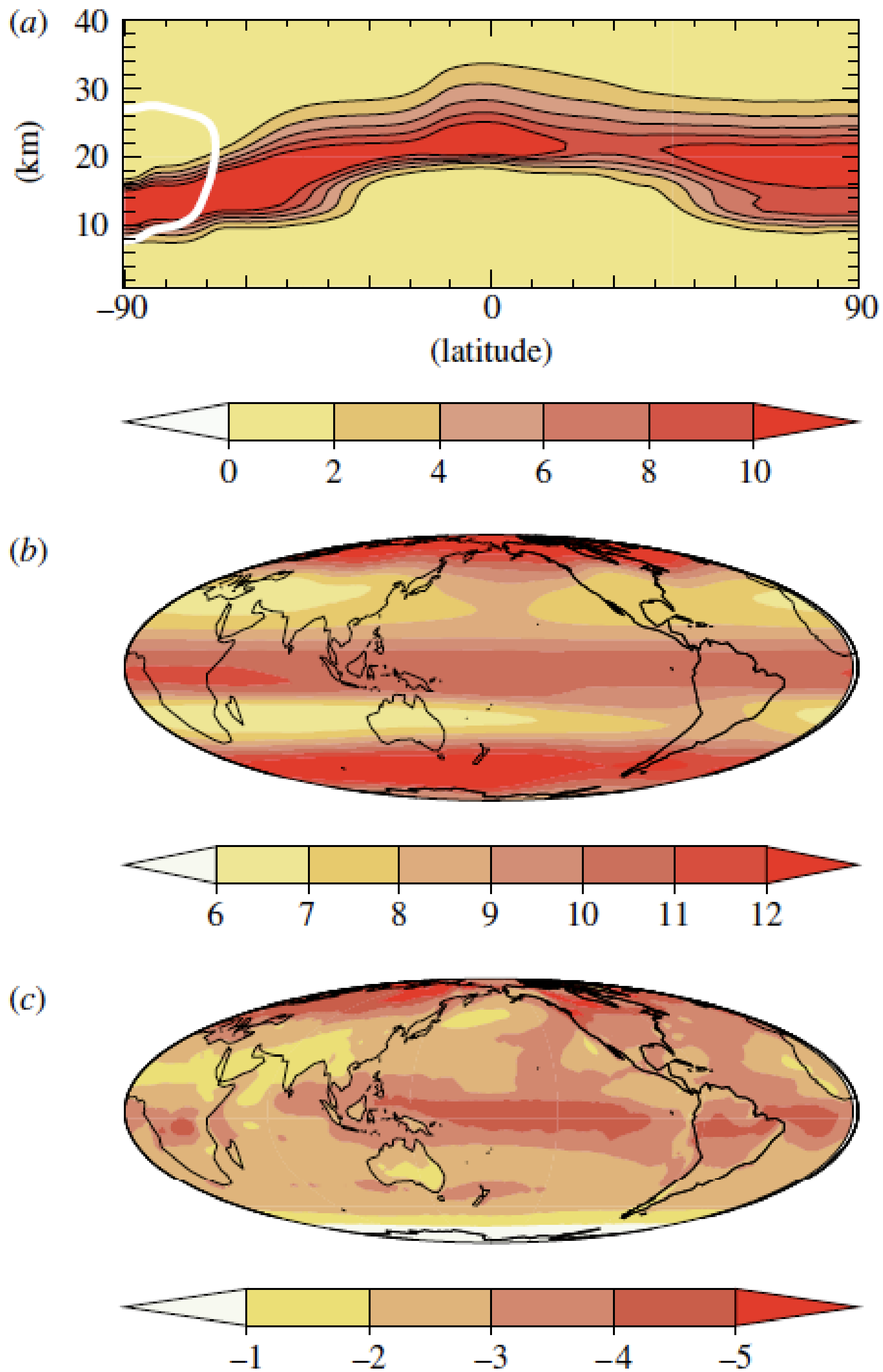
Cooling after Pinatubo



Important processes for stratospheric aerosols

(from SPARC Assessment of Stratospheric Aerosols, 2006





Lat-Height Section of Aerosol Surface area Density

Aerosol Burdens

Rasch et al (2008), June, July August Distributions

Radiative Forcing

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Impact on Surface Temperature (JJA)

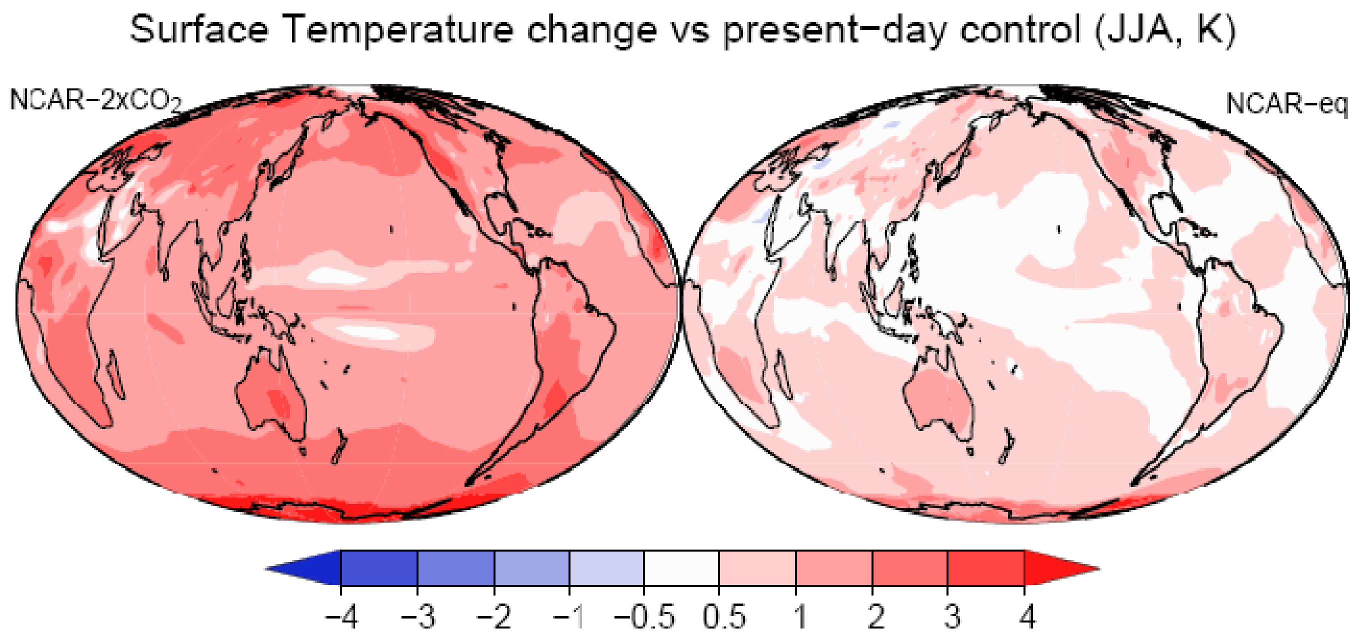
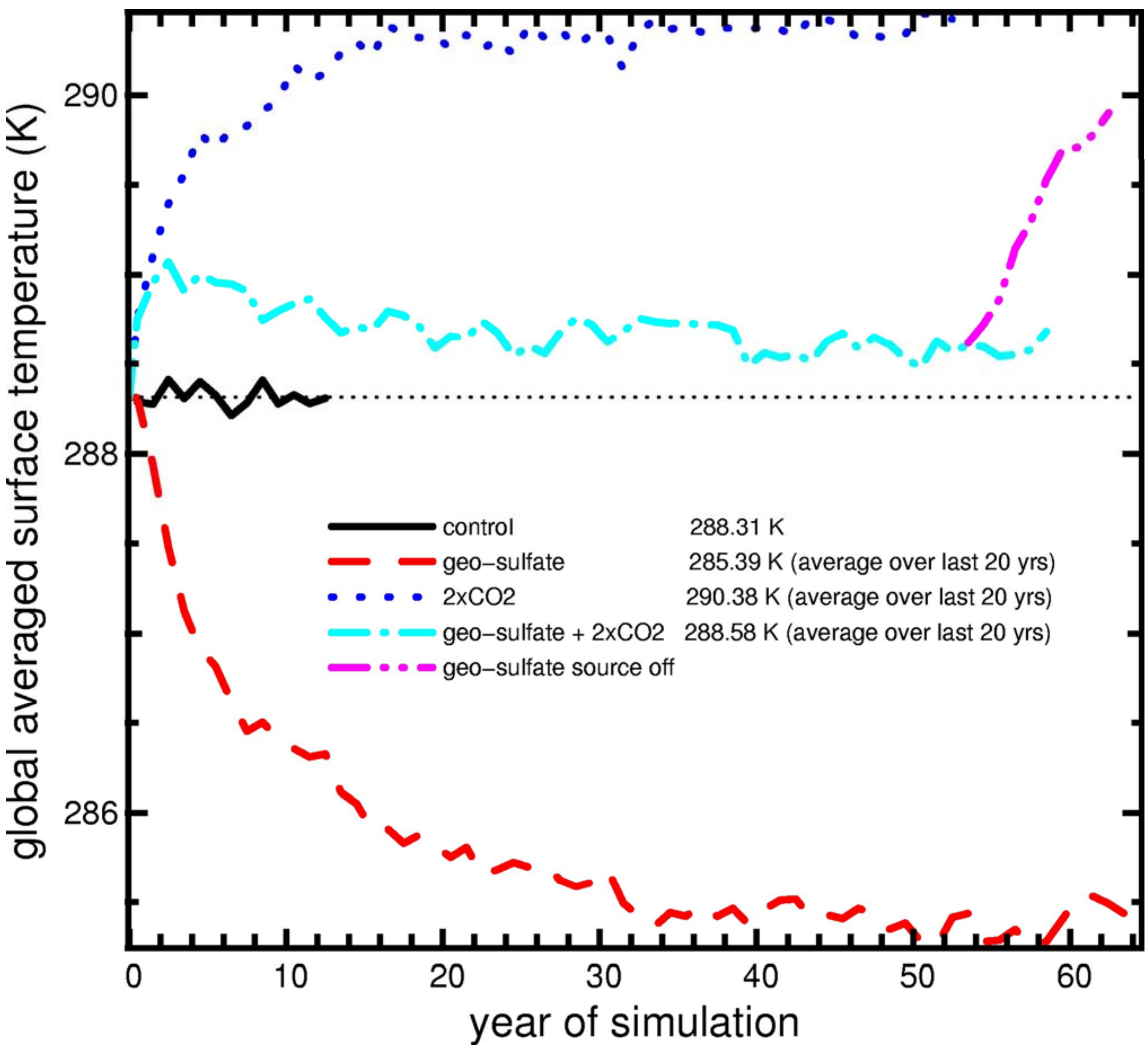


Figure 5: The surface temperature difference from present day during June, July, August the $2xCO_2$ simulation and the geoengineering simulation using 2 Tg S/yr emission (which is not sufficient to entirely balance the greenhouse warming).

Global Averaged Annual Averaged Surface Temperature change (flawed representation for evap and sedimentation)



Precipitation after Pinatubo

Trenberth and Dai, GRL, 2007

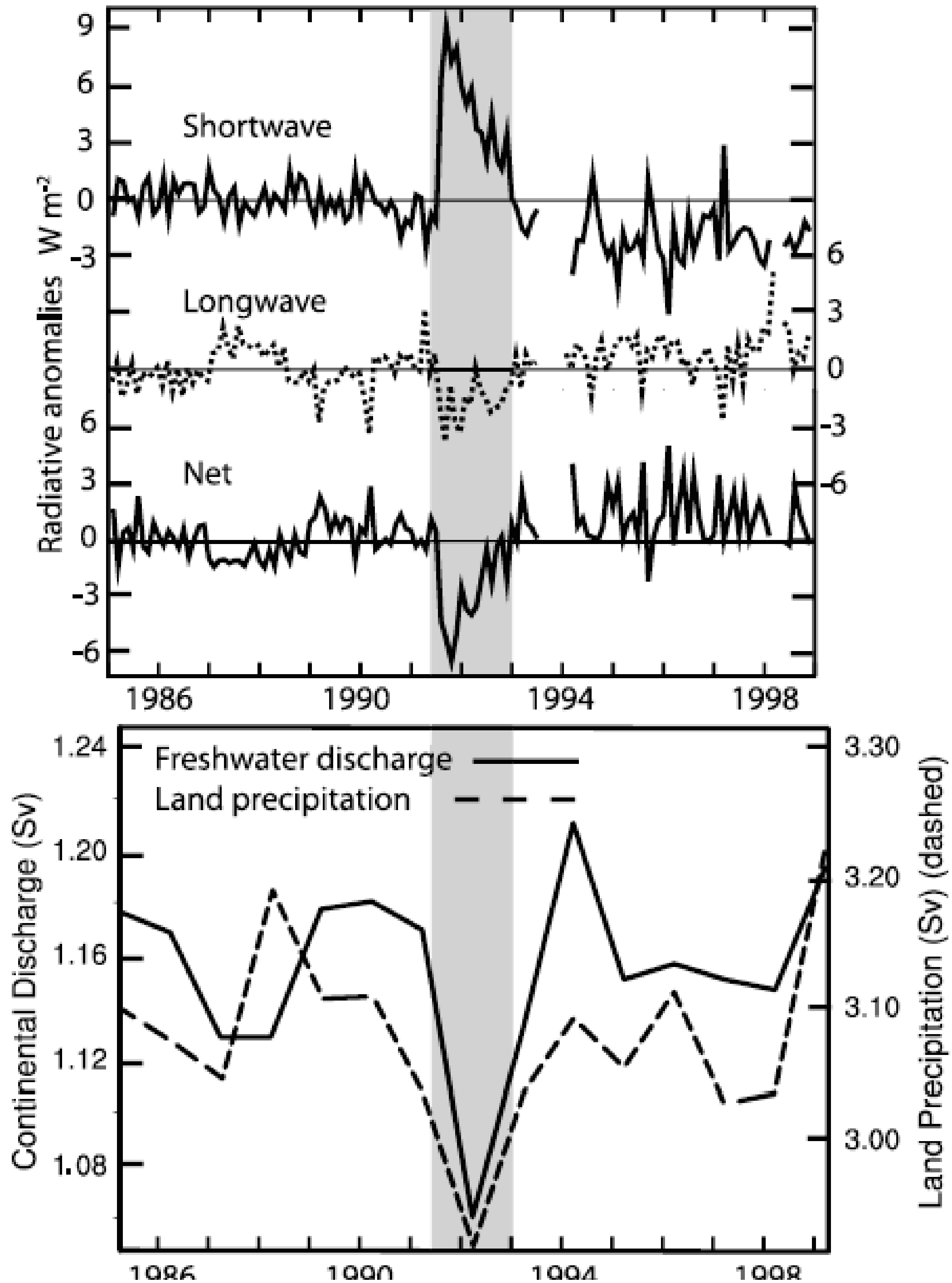


Figure 2. (top) Adapted time series of 20°N to 20°S ERBS non-scanner wide-field-of-view broadband shortwave, longwave, and net radiation anomalies from 1985 to 1999 [*Wielicki et al.*, 2002a, 2002b] where the anomalies are defined with respect to the 1985 to 1989 period with Edition 3_Rev 1 data [*Wong et al.*, 2006]. (bottom) Time series of the annual water year (Oct. to Sep.); note slight offset of points plotted vs. tick marks indicating January continental freshwater discharge and land precipitation (from Figure 1) for the 1985 to 1999 period. The period clearly influenced by the Mount Pinatubo eruption is indicated by grey shading.

Uncertainties in Precipitation Projections

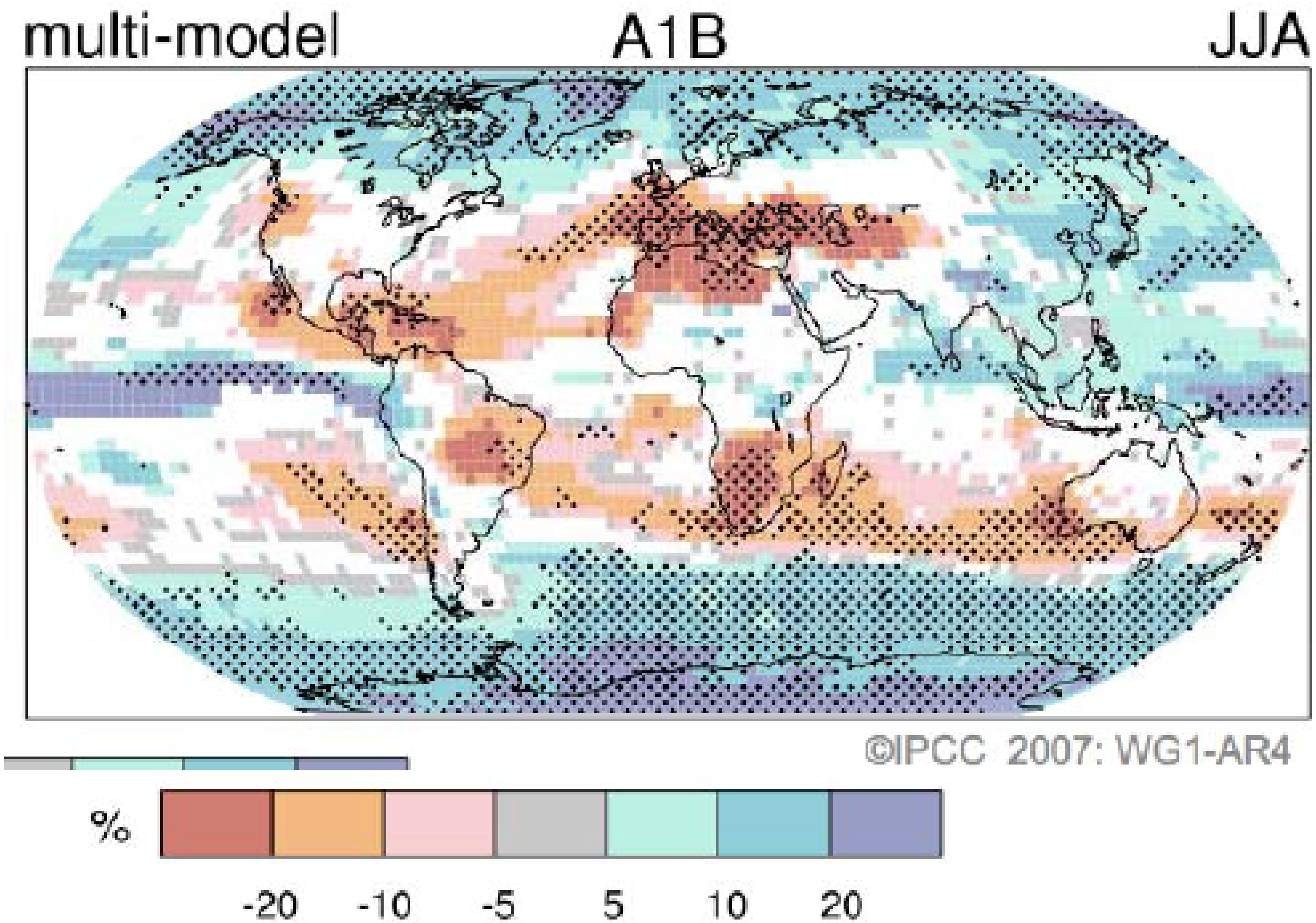
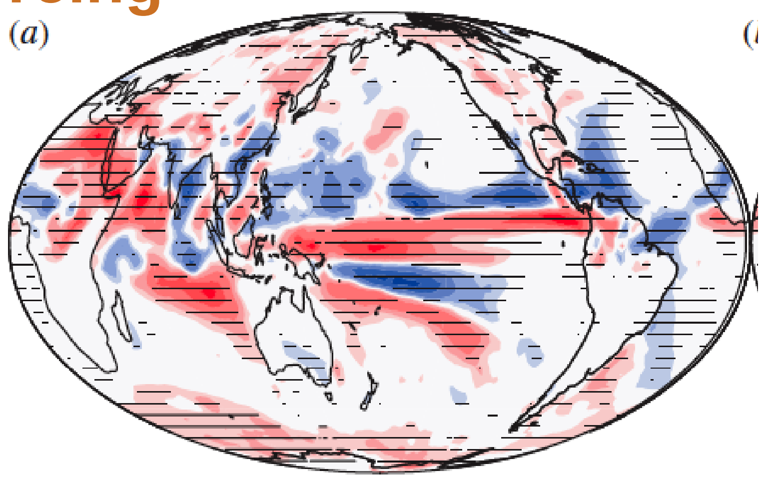


FIGURE SPM-7. Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. {Figure 10.9}

Rasch et al. (2008)

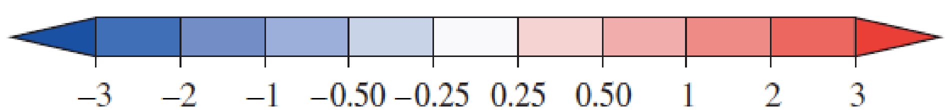
Precipitation Response to forcing from CO2 and Stratospheric aerosols

CO2 Forcing



- Amplification of Hydrologic cycle
- Narrowing of ITCZ
- *Stippling indicate statistical significance*

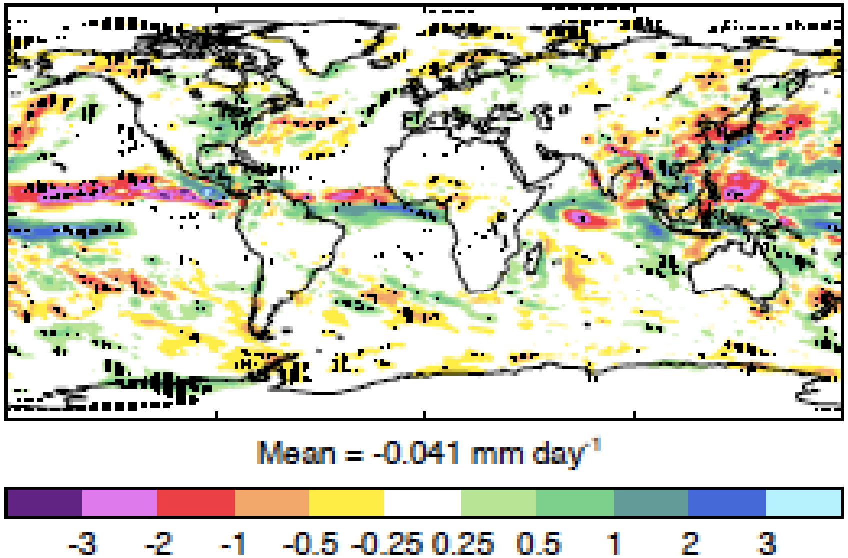
- Other consequences for
  - Temperature
  - Winds
  - Sea Ice
  - Chemistry



Jones et al (2010),

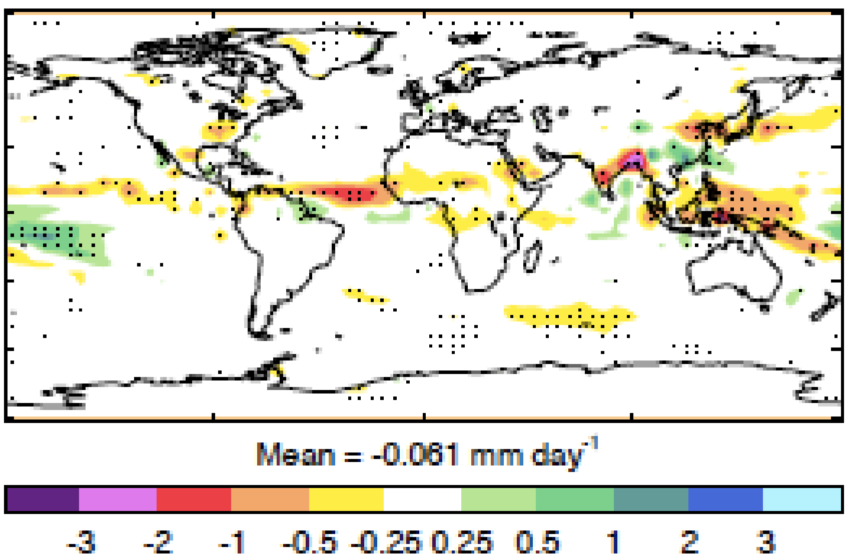
JJA precipitation response to stratospheric aerosol forcing (No CO_2 Forcing)

(d)



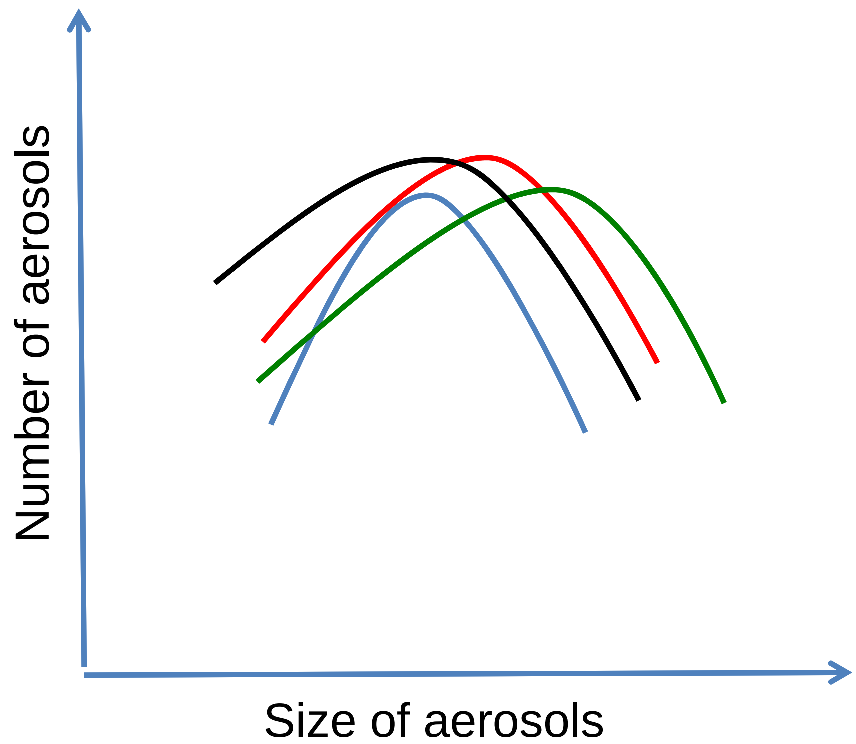
GISS, Robock

(e)



UKMO, Jones

Complexities of “making” stratospheric aerosols



Background

Volcanic

Geoengineering aerosol Produced from SO_2

Geoengineering aerosols produced from H_2SO_4

- Smaller aerosols are “brighter”, and produce more ozone loss
- Larger aerosols fall out faster

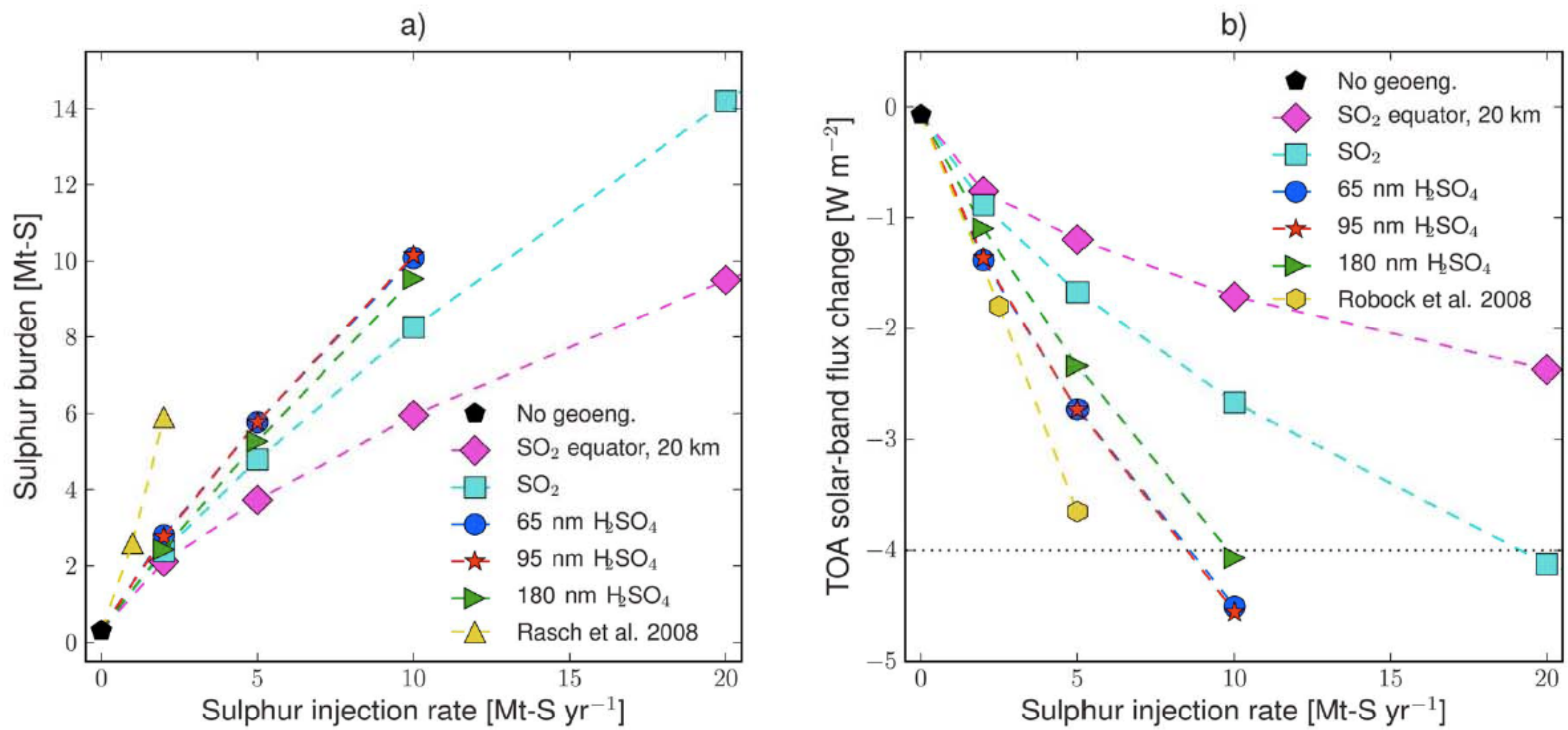
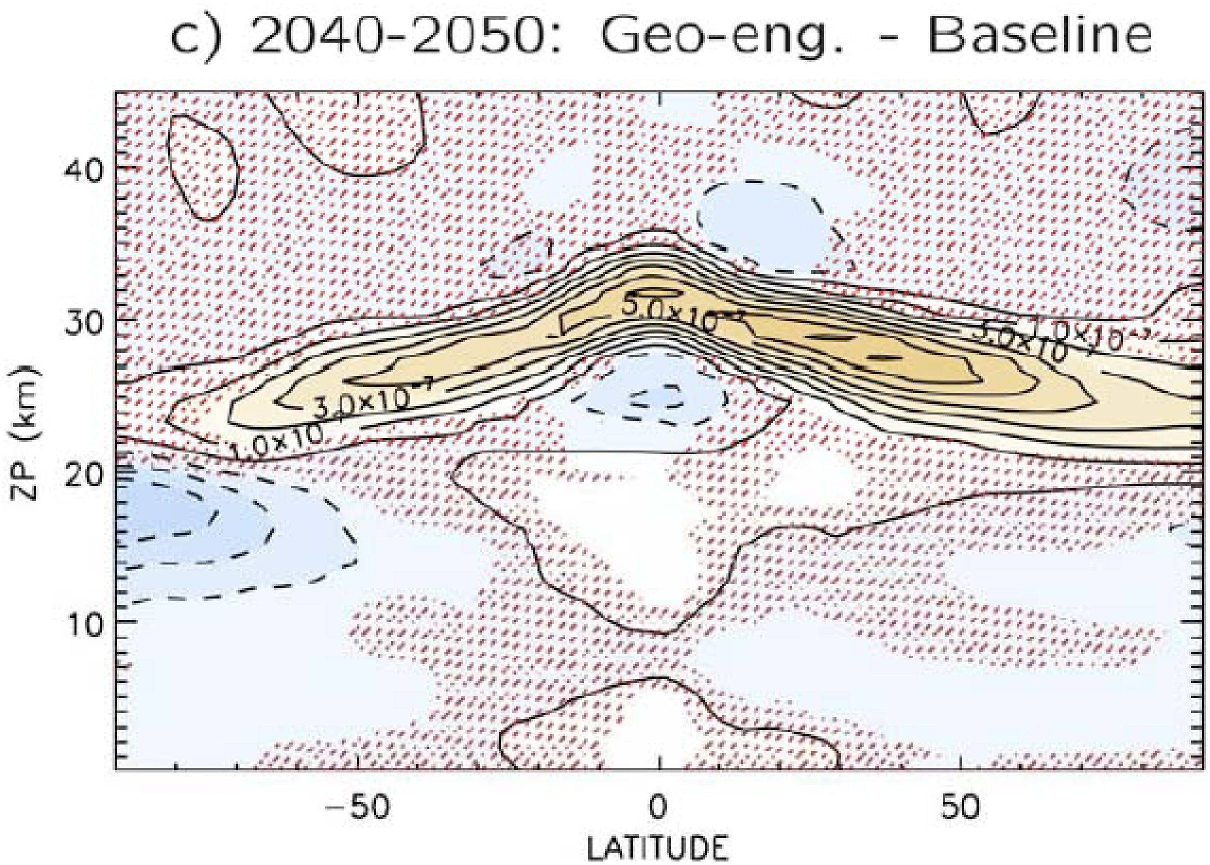


Figure 4. Steady-state (a) stratospheric sulfur burden and (b) top-of-atmospheric solar-band (shortwave) radiative flux change from the stratospheric aerosols as a function of sulfur injection rate. All simulations have emissions evenly distributed between 30°S–30°N and 20–25 km, except results for SO_2 emitted only above the equator (5°S–5°N) at 20 km (19.5–20.5 km). Also included for comparison are the stratospheric sulfur burdens computed by *Rasch et al.* [2008a] (with fixed effective radius of 0.43 μm) and the solar flux changes by *Robock et al.* [2008], both without aerosol microphysics. Black horizontal dotted line in Figure 4b represents the approximate cooling necessary to offset a doubling of CO_2 in the global-mean energy budget.

Pierce et al, 2010, GRL

Ozone change due to geoengineering

with – without geo-engineering (Tilmes et al, 2009)



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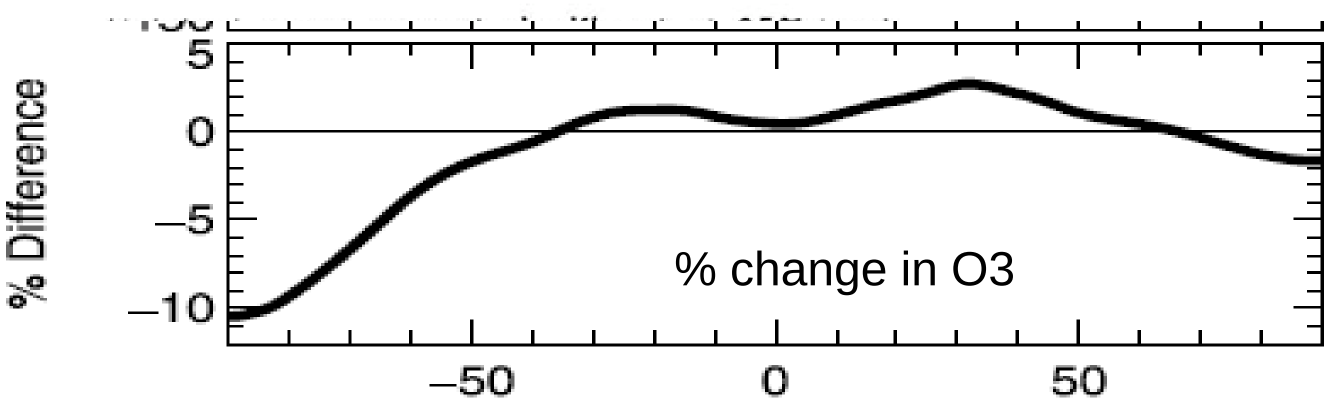

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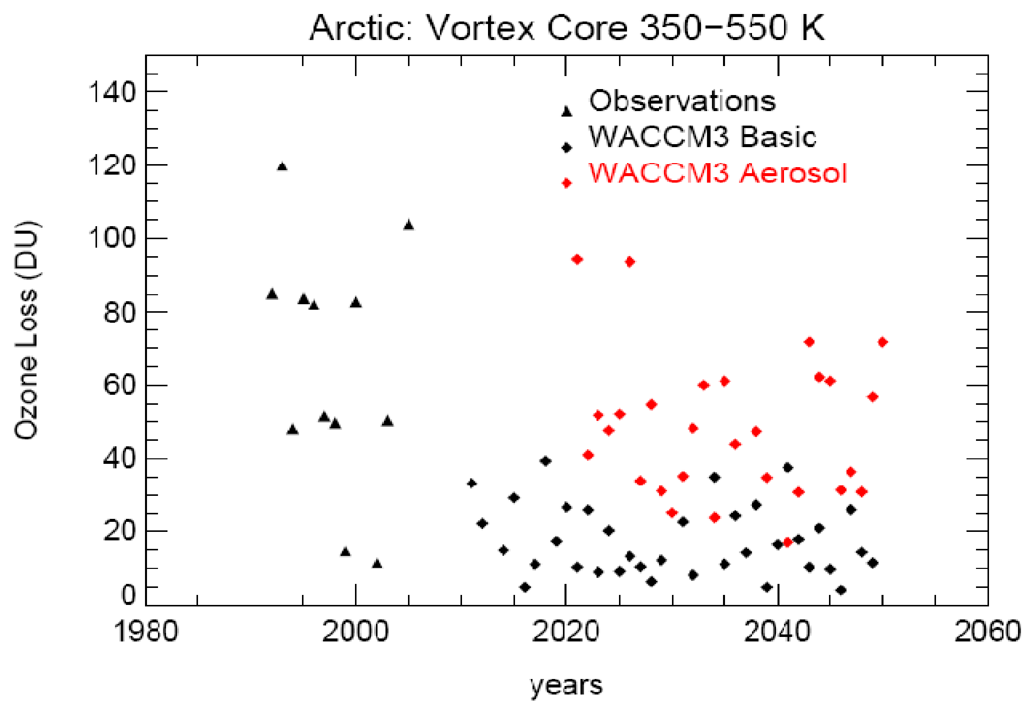
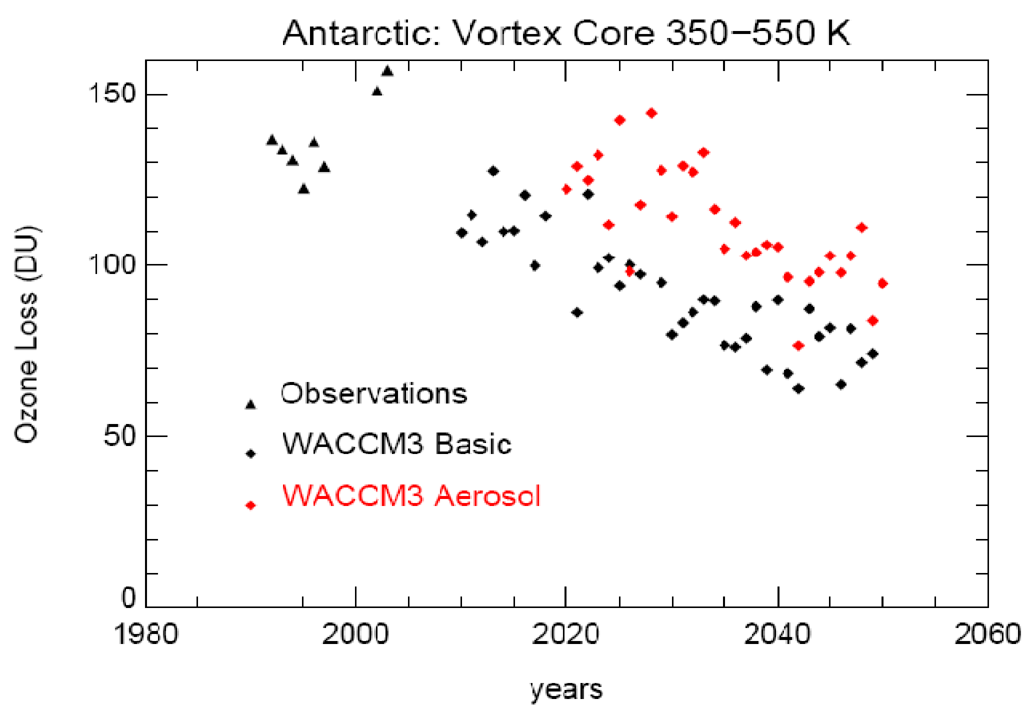
Springtime Ozone loss from geoengineering

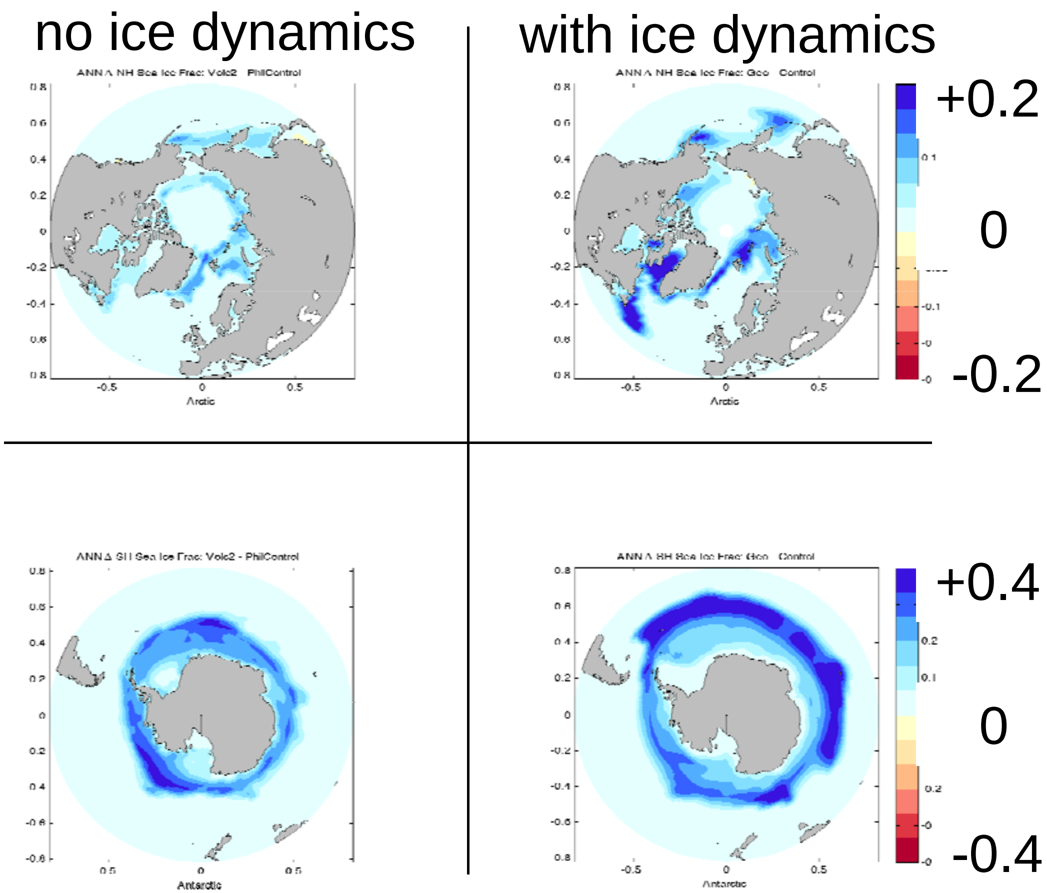
(2 Tg S/yr, volcanic sized)





The impact of sea ice dynamics

Change in Annual Average Sea Ice Concentration
"2 Tg of S" minus "control (350ppm)"



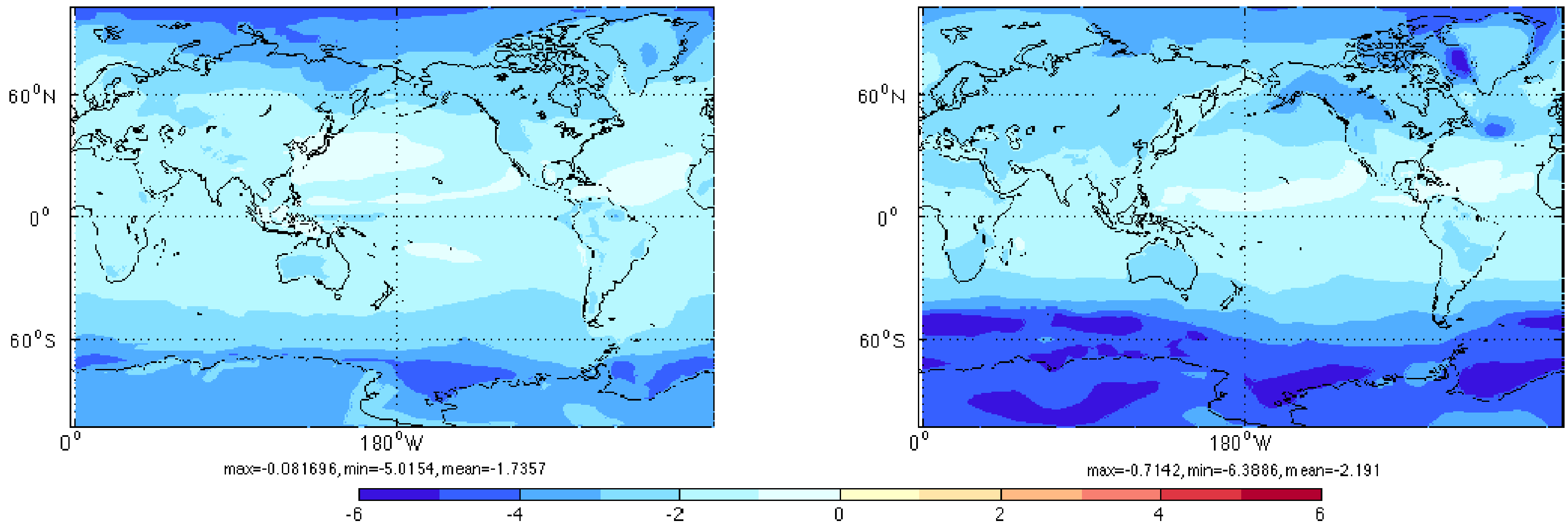
Sea Ice extent and concentration is enhanced by the inclusion of sea ice dynamics (SH: moves farther into westerlies)

The impact of sea ice dynamics

Change in Annual Average Surface Temperature

"2 Tg of S" minus "control (350ppm)"

no ice dynamics | with ice dynamics



-6° 0 +6° °C

Sea Ice dynamics amplifies the cooling that is induced by the injection of aerosols but warms the central arctic (~2°C changes)

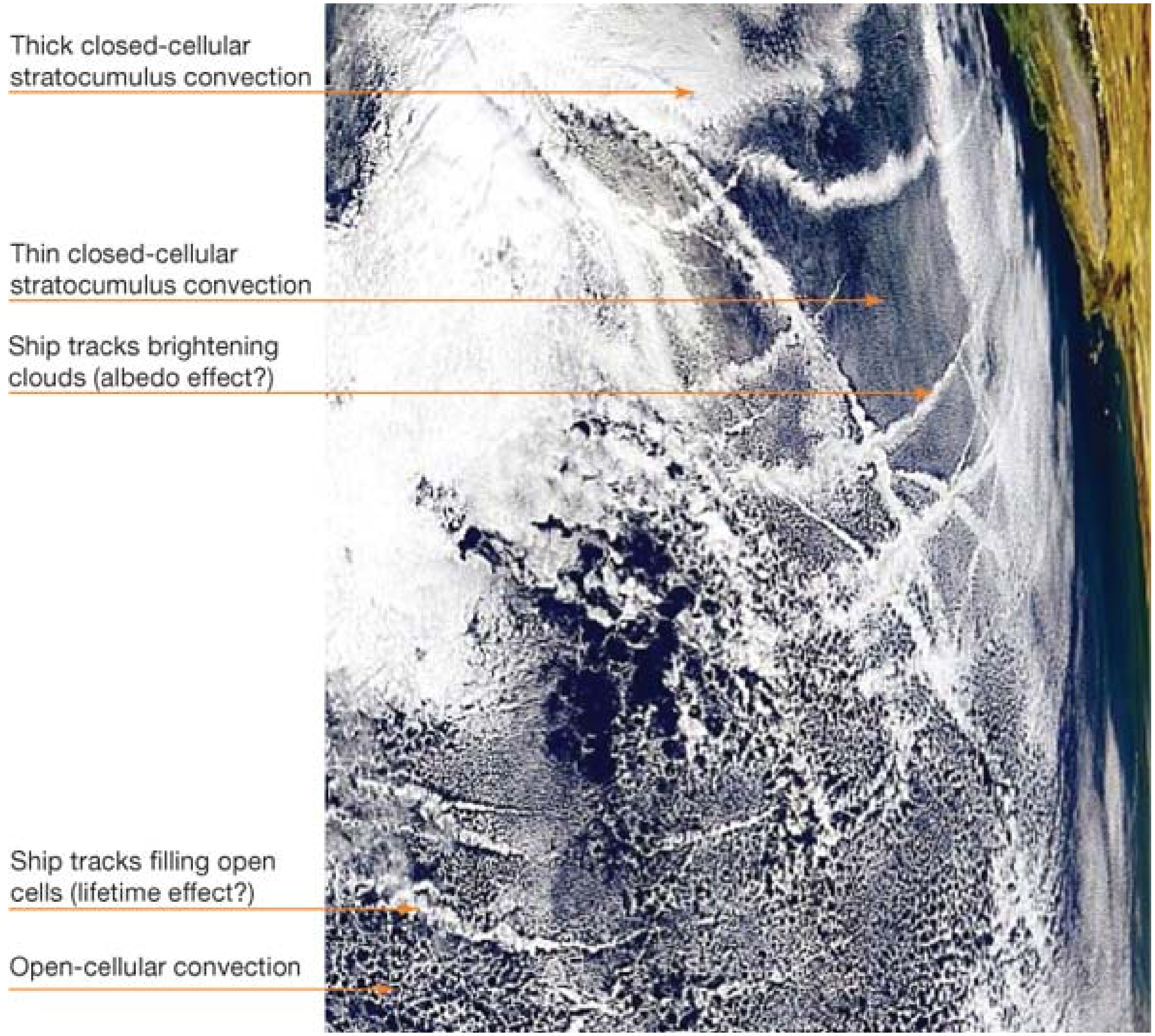
Stratospheric Aerosol summary

- Modeling suggests the earth will cool, with many components returning to a state more like the unperturbed earth, but
  - More cooling over land than ocean
  - Arctic winter cools less than equatorial regions
- Delivery of aerosol (or precursor) a formidable task but seems possible/viable
- Unlikely that all aspects of climate will match present day. Stratospheric Aerosols influence precipitation patterns with consequences to the Earth system
  - Models have difficulty in predicting a consistent spatial pattern
  - Will not be able to return planet to same global precipitation and temperature amounts simultaneously
- Increase in aerosols will deplete more ozone (until chlorine is lower). The increase in UV from ozone depletion balanced to some degree by aerosol attenuation & extinction
- Change in direct/diffuse radiation with impact on photosynthesis (-> ecosystem, carbon cycle, and solar energy production)
- Some consequences (e.g. Ocean Acidification) are not dealt with at all by this strategy

Humans do affect clouds

Simple theory suggests

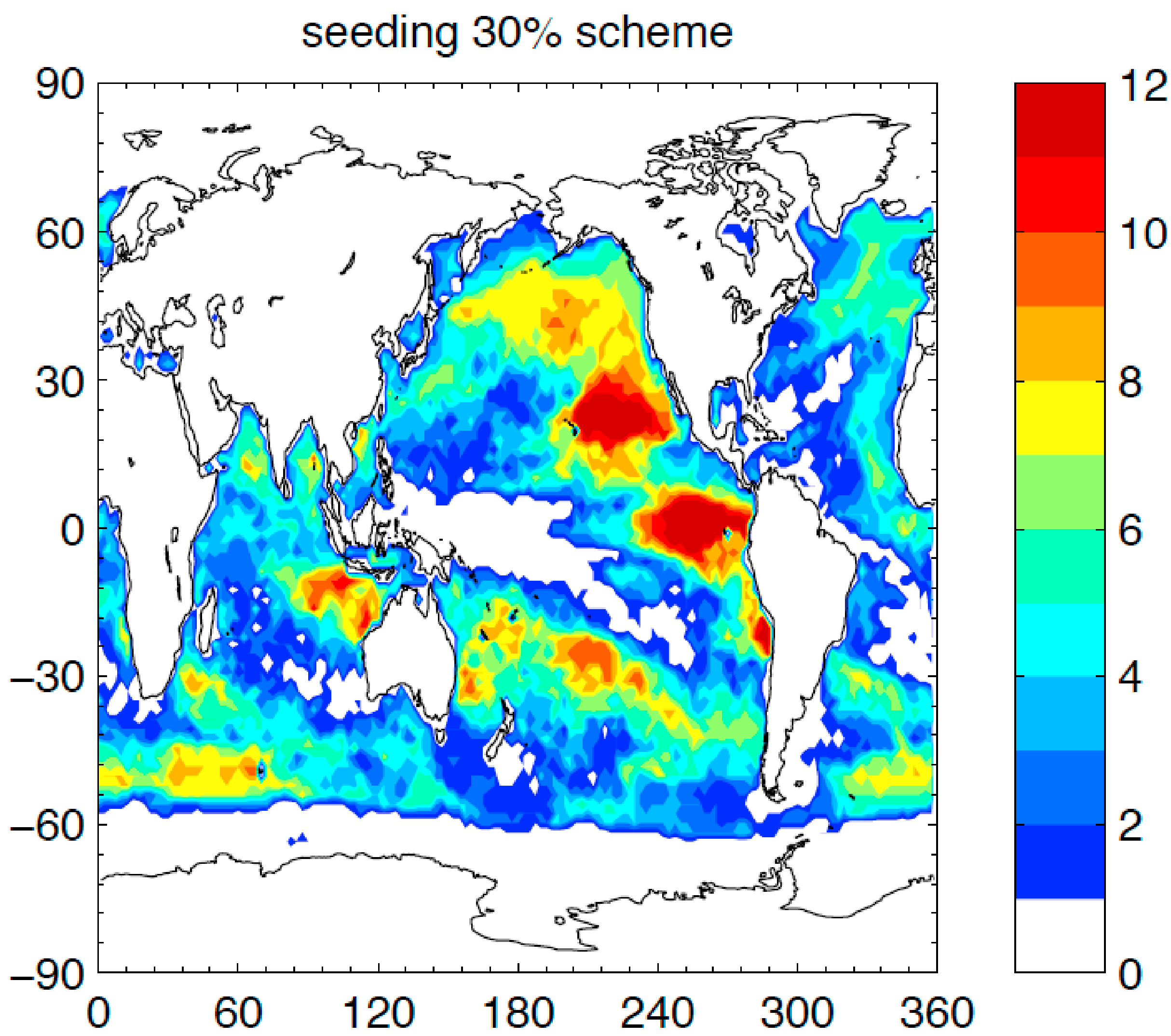
More aerosol
→ more drops
→ smaller drops
→ more reflective clouds



- CO_2 doubling compensated by (Slingo, 1990):
  - **120%** increase in droplet concentrations
  - **40%** decrease in cloud drop size
  - **12%** increase in oceanic cloud cover

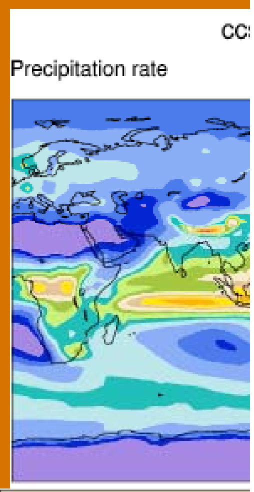
If we decided to seed 30% of the globe, where might we seed? (number of months we seed at each location)

Latham, Rasch et al, 2008



Precipitation Change (compared to today)

Precipitation Today



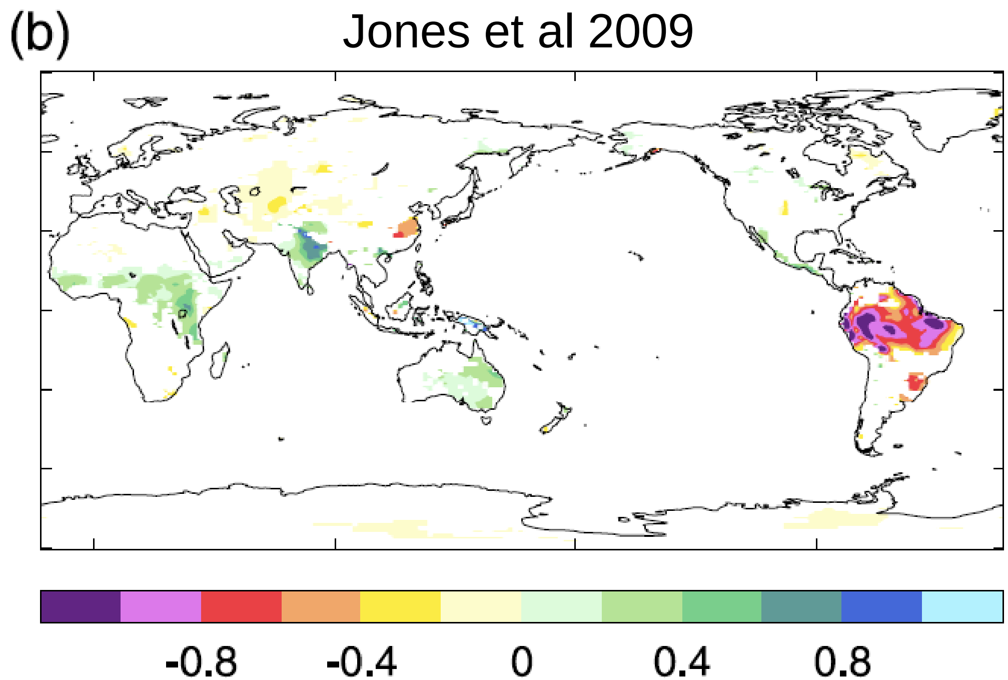
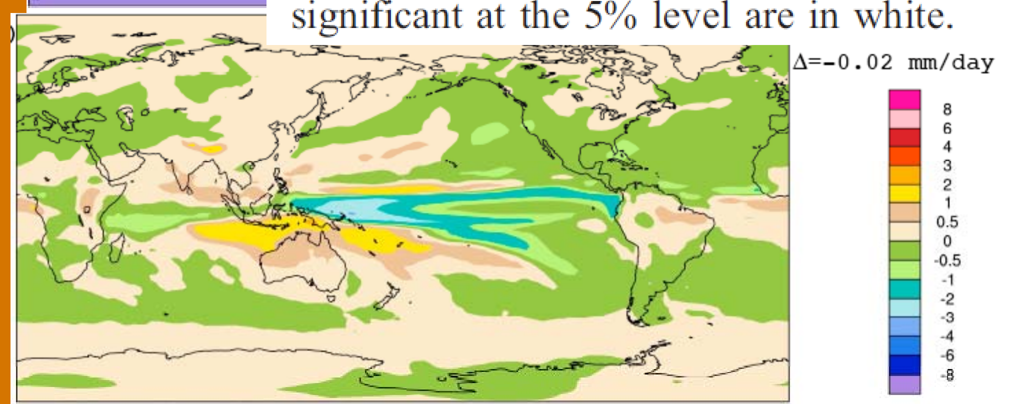


Figure 4. Mean 2030–2059 land precipitation (mm day^{-1}): (a) distribution in A1B; (b) ALL – A1B. Land areas in Figure 4b where the change is not statistically significant at the 5% level are in white.

Change from geoengineering by seeding 20% of the ocean



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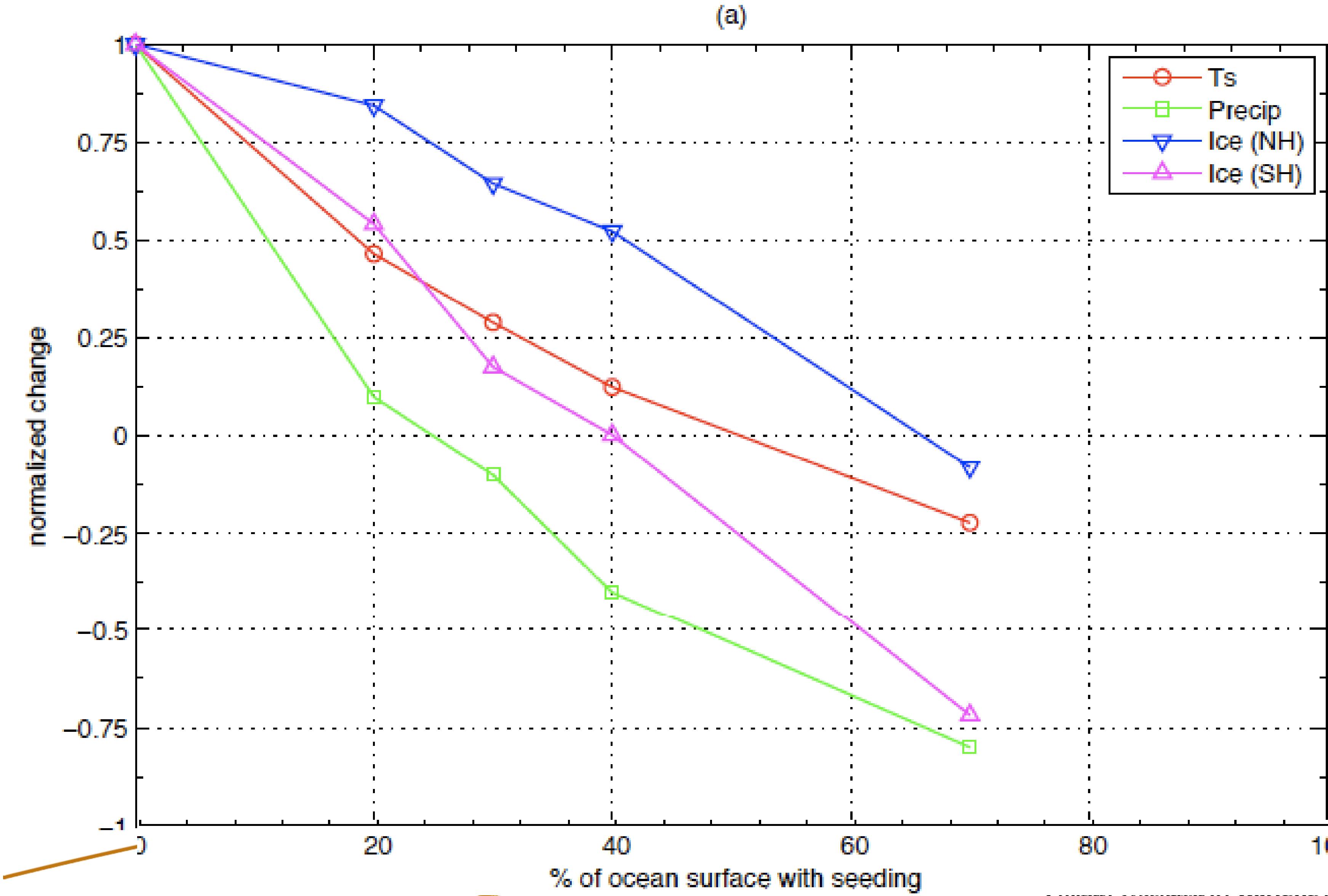
Two science questions can be considered

- If we could increase the reflectivity of clouds, what might be the consequence to the planet?
(with many others)
- Is it possible to increase the reflectivity of clouds deliberately? (How? Where? What works, what doesn't?)
(with Hailong Wang and Graham Feingold)

Return to "present day" global average (0 -> complete)



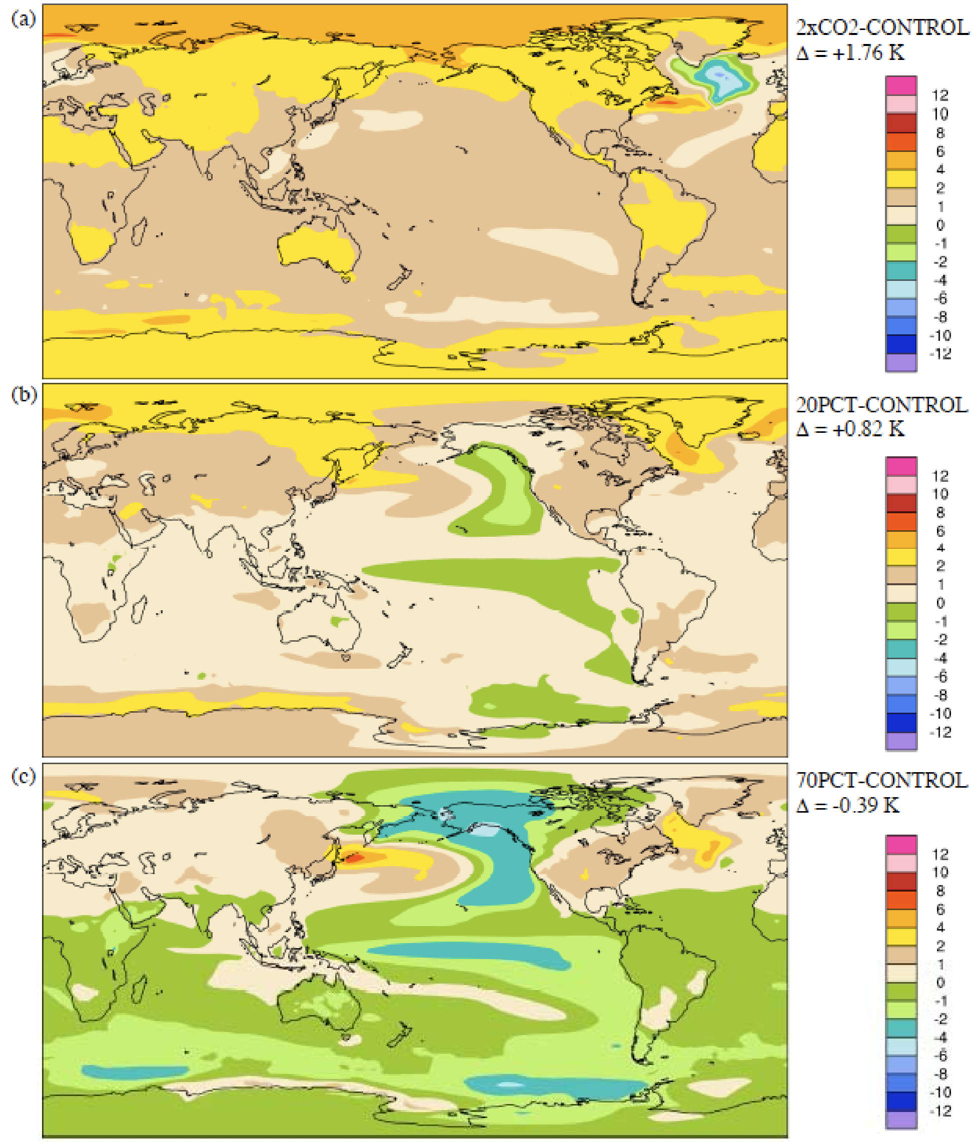
Exploring Impacts on climate

Surface Temperature Change (compared to control)

2xCO2

+ seeding 20% of the ocean

+ seeding 70% of the ocean



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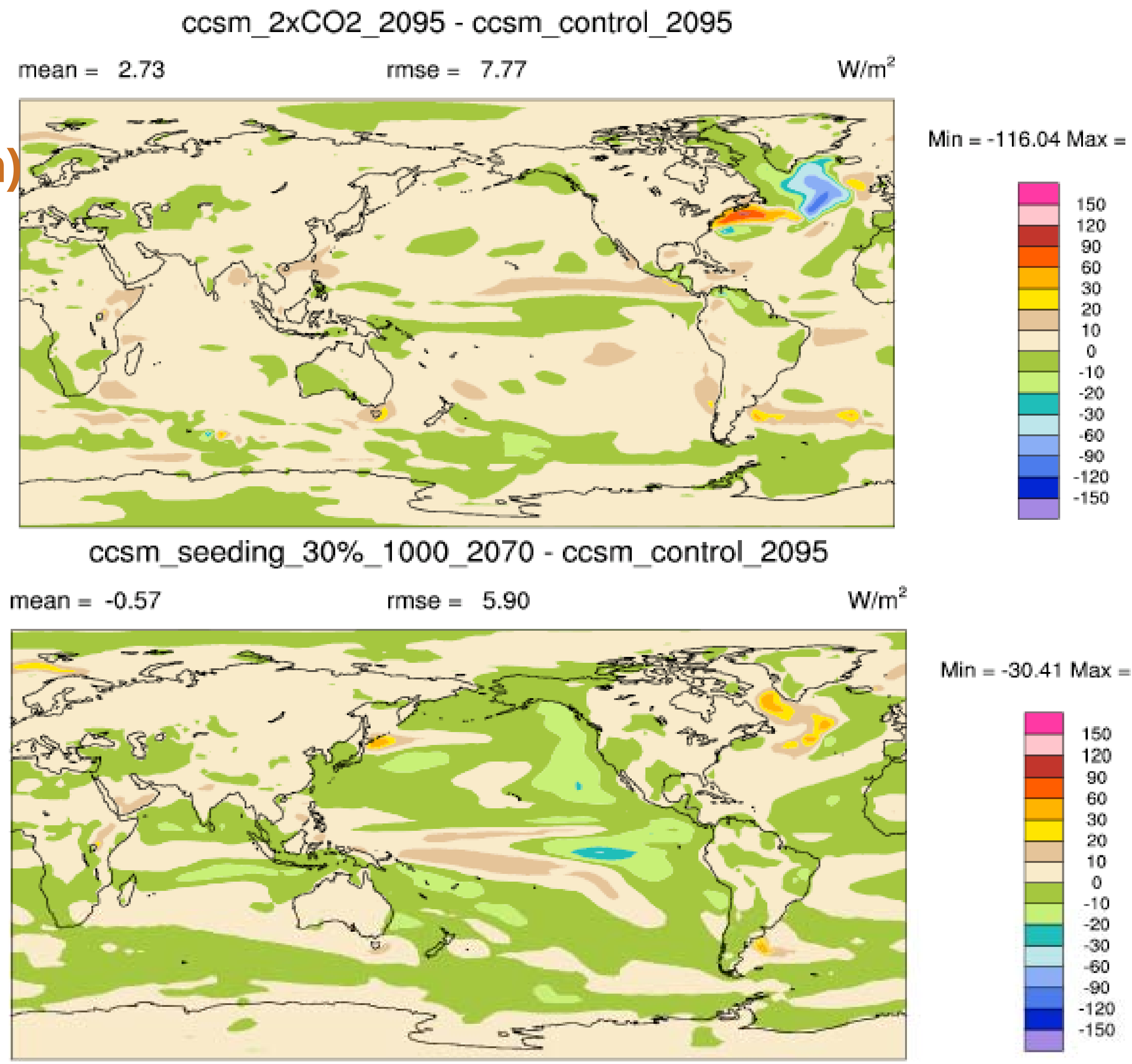
Change in Latent Heat Flux (evaporation)

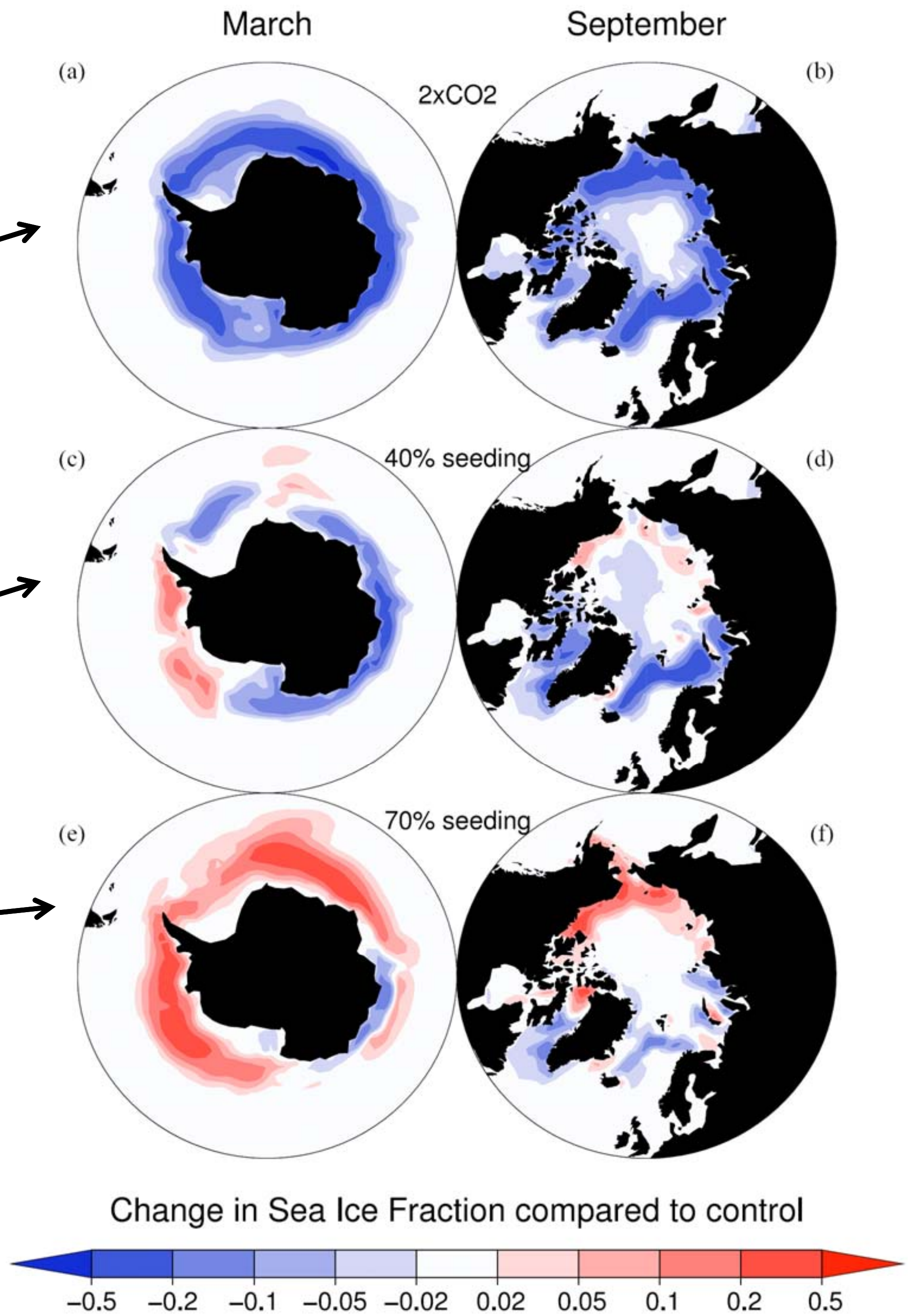


Sea Ice is affected by global warming and geoengineering

Summer sea ice goes away with a doubling of CO2

Ice returns with geoengineering

It is possible to overdo the effect



Precipitation Chang
(compared to today)

(b) Jones et al 2009

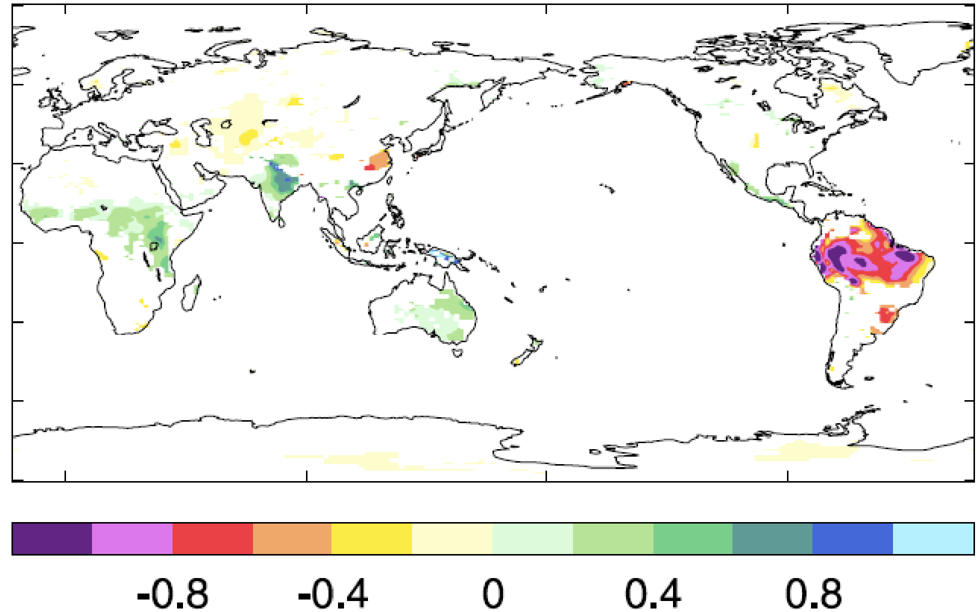
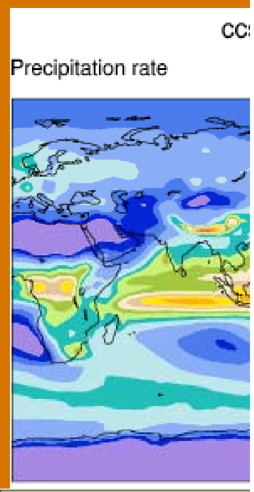
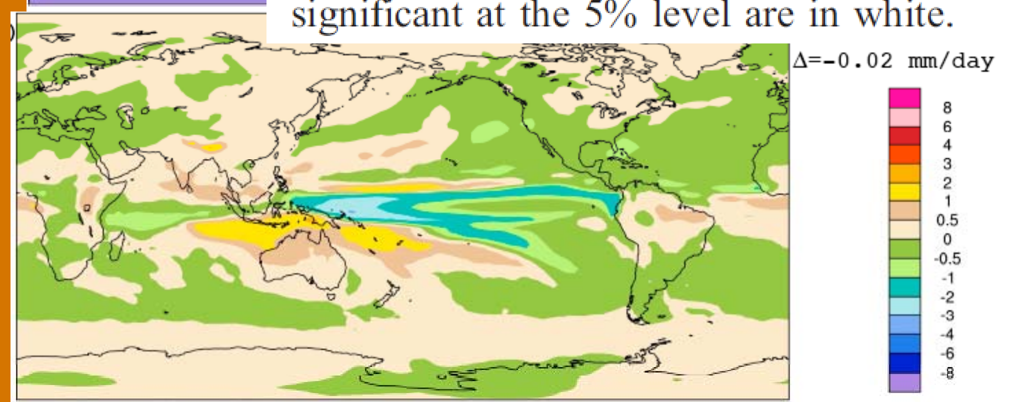


Figure 4. Mean 2030–2059 land precipitation (mm day^{-1}): (a) distribution in A1B; (b) ALL – A1B. Land areas in Figure 4b where the change is not statistically significant at the 5% level are in white.

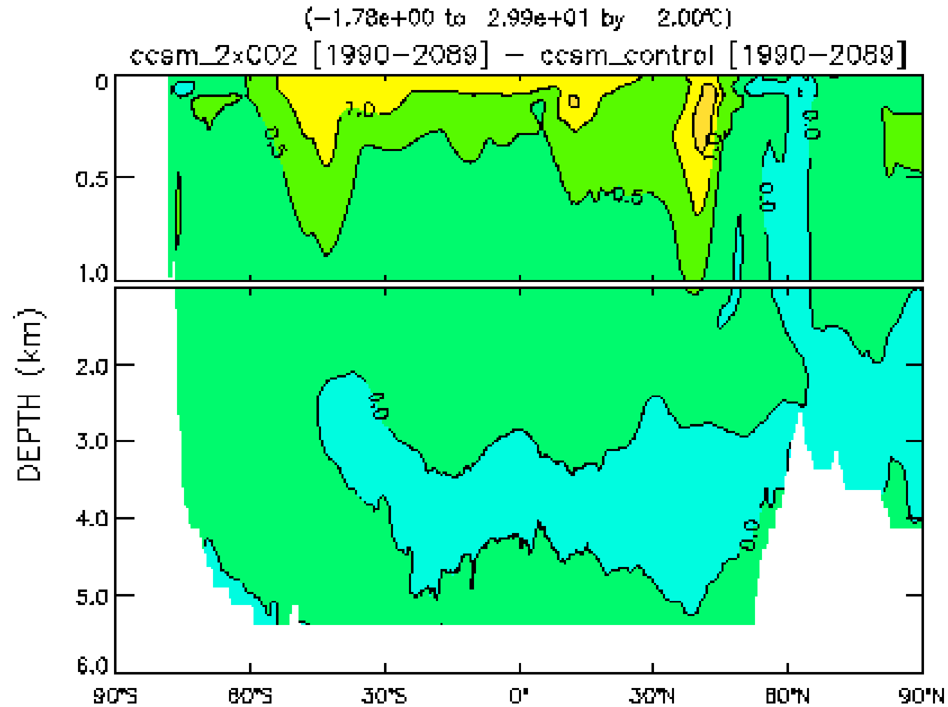
Precipitation Today

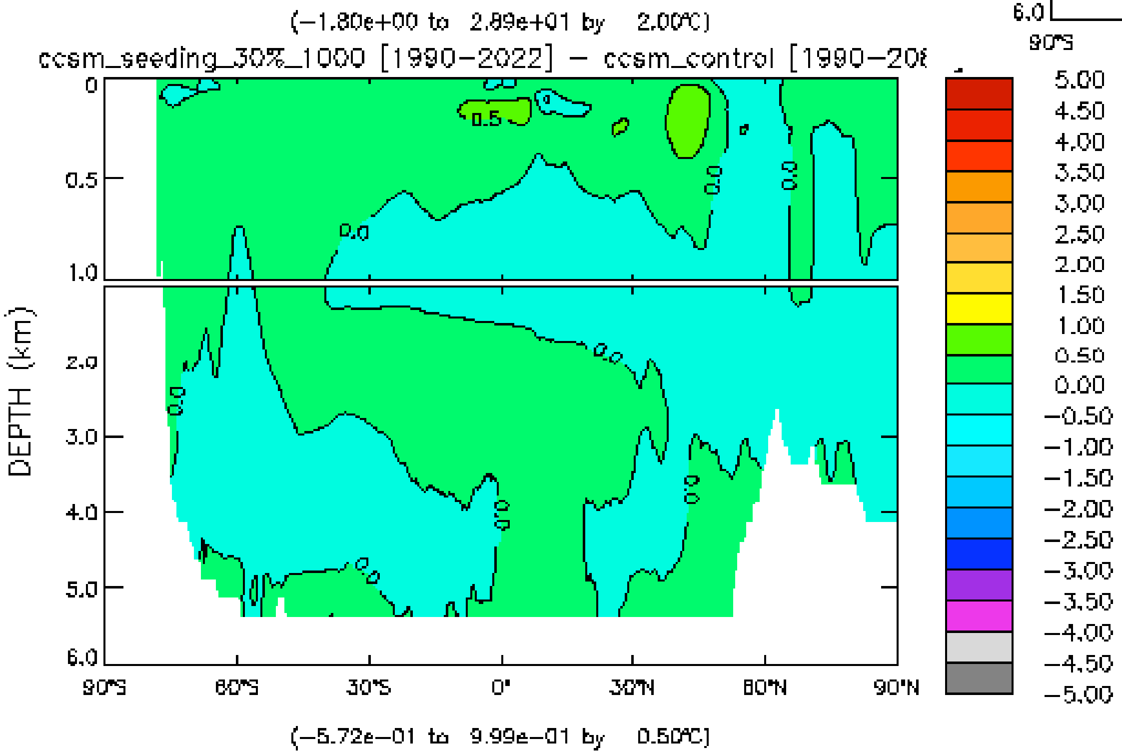


Change from geoengineering by seeding 20% of the ocean

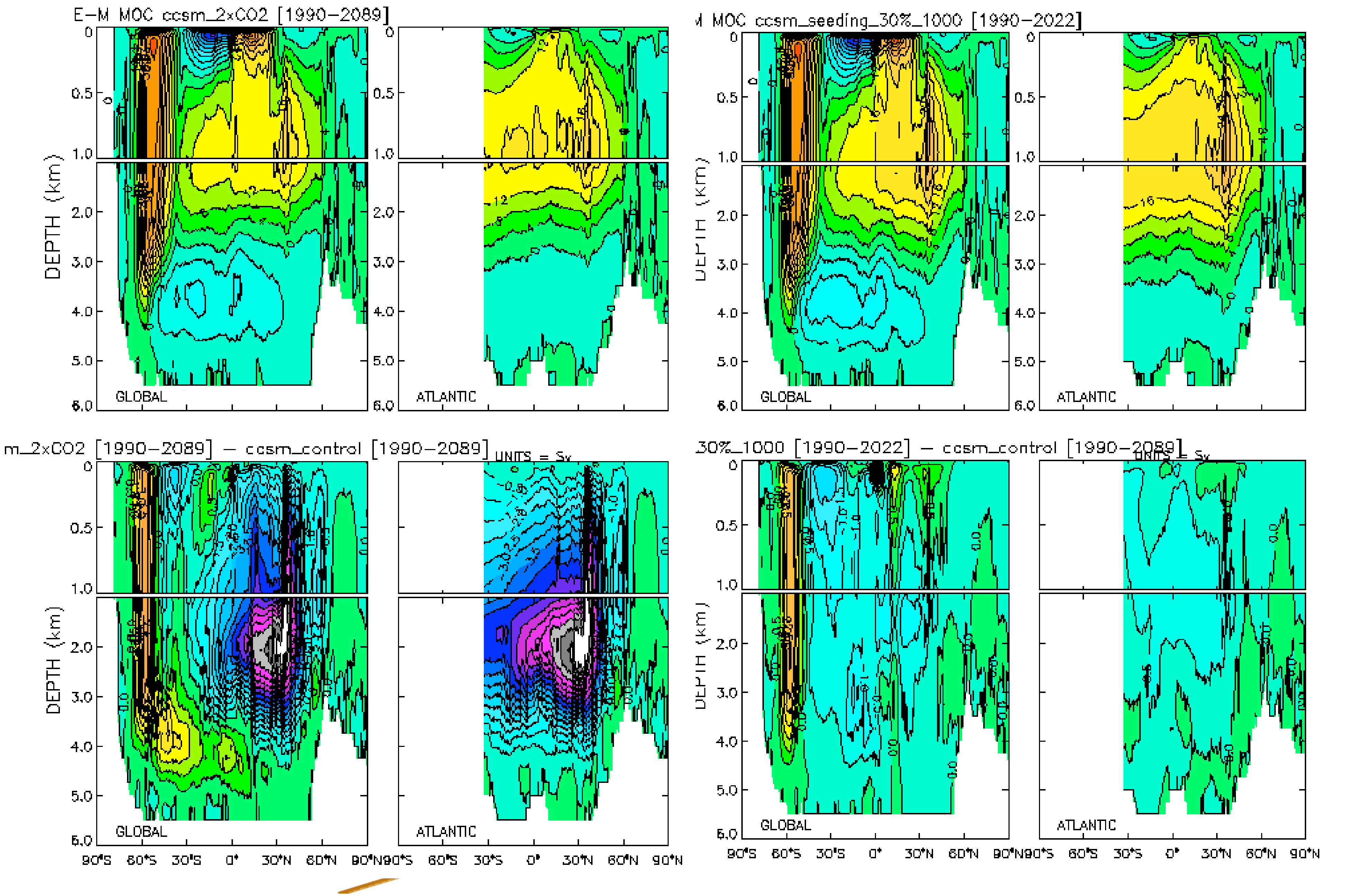


Upper Ocean Temperature Change





Meridional Overturning Circulation Changes



Volcanic signals in oceans

Georgiy Stenchikov,[1,2] Thomas L. Delworth,[3] V. Ramaswamy,[3] Ronald J. Stouffer,[3] Andrew Wittenberg,[3] and Fanrong Zeng[3]

largest in the 20th and 19th centuries, respectively. The simulated climate perturbations compare well with available observations for the Pinatubo period. The stronger Tambora forcing produces responses with higher signal-to-noise ratio. Volcanic cooling tends to strengthen the Atlantic meridional overturning circulation. Sea ice extent appears to be sensitive to volcanic forcing, especially during the warm season. Because of the extremely long relaxation time of ocean subsurface temperature and sea level, the perturbations caused by the Tambora eruption could have lasted well into the 20th century.

We have assumed to this point that it is possible to change the reflectivity of clouds deliberately

- Is it so easy to do? Does it occur by
  - “Twomey effect”?
  - “Albrecht effect”?
  - Which is more important? Drop Size? Lifetime? LWP? Cloud Fraction? Cloud Morphology?
  - Do we seed in pristine regions?
  - Do we seed before a cloud forms? (nighttime?)
  - Avoid Precipitation?
  - Questions go on and on and on……

Size distribution of emitted natural aerosol matters

- There is “competition for water vapor during aerosol growth.
- Increasing Sea Salt Fluxes:
  - *Increases Activation*
    - in pristine conditions and strong updrafts
    - (due to activation of accumulation mode sea salt particles)
  - *Decreases Activation*
    - in polluted conditions with weak updrafts
    - (due to competition with coarse mode sea salt particles)

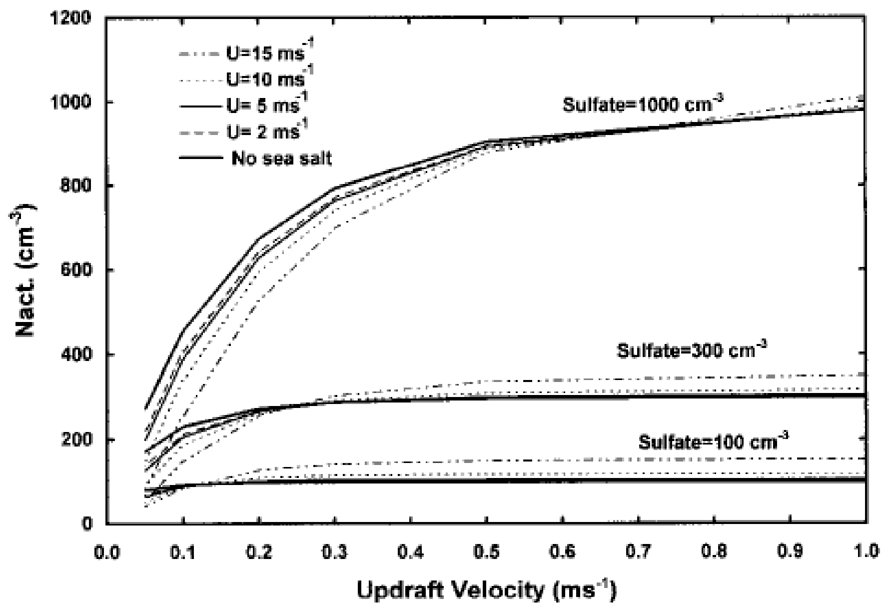


FIG. 1. Number concentration of particles activated as a function of updraft velocity for sulfate number concentrations of 100, 300, and 1000 cm^{-3} without competition with sea salt and with competition for wind speeds of 2, 5, 10, and 15 m s^{-1}. The sulfate size distribution is lognormal with a number mode radius of 0.08 μm and a geometric standard deviation of 1.4.

Ghan et al, JAS 1998

Sea Salt aerosols may decrease natural aerosol activation (Korhonen, 2010)

H. Korhonen et al.: Enhancement of marine cloud albedo via controlled sea spray injections 4139

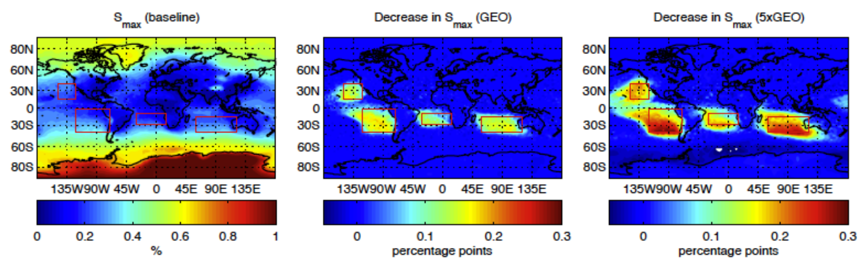


Fig. 5. Maximum supersaturation reached during cloud droplet activation at 1 km altitude in the baseline run (left panel) and the decrease in supersaturation caused by sea spray injections (GEO middle panel; 5×GEO right panel). All values are for updraft velocity 0.1 m/s.

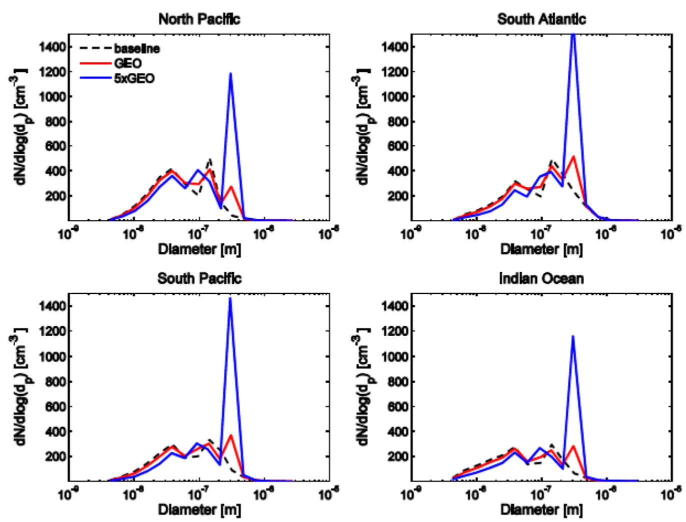


Fig. 6. Annual mean size distributions in the four geoengineered regions at 1 km altitude.

- Additional CCN may grow more readily than natural aerosol
- Supersaturation is lowered by extra aerosols at a fixed updraft rate
- Therefore natural aerosols may not activate

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Korhonen (2010), mechanism 2

4140 H. Korhonen et al.: Enhancement of marine cloud albedo via controlled sea spray injections

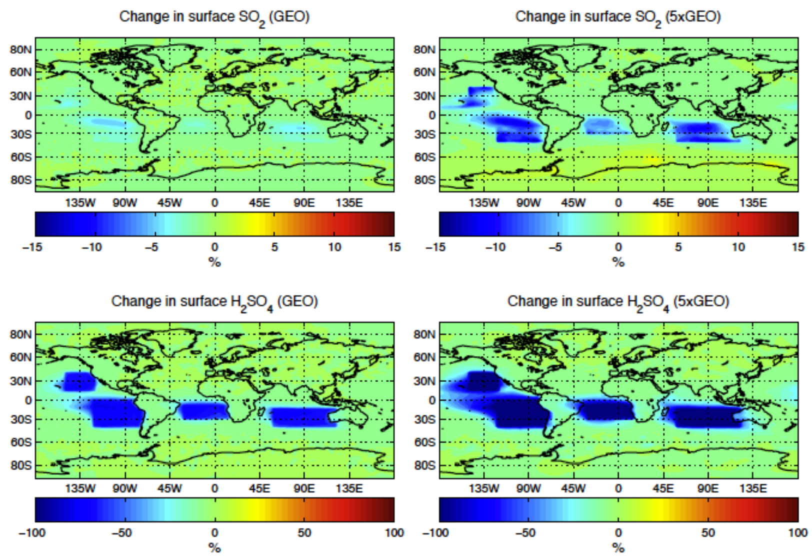

Fig. 7. Effect of cloud seeding on the annual mean surface level concentrations of SO_2 (top panels) and H_2SO_4 (bottom panels).

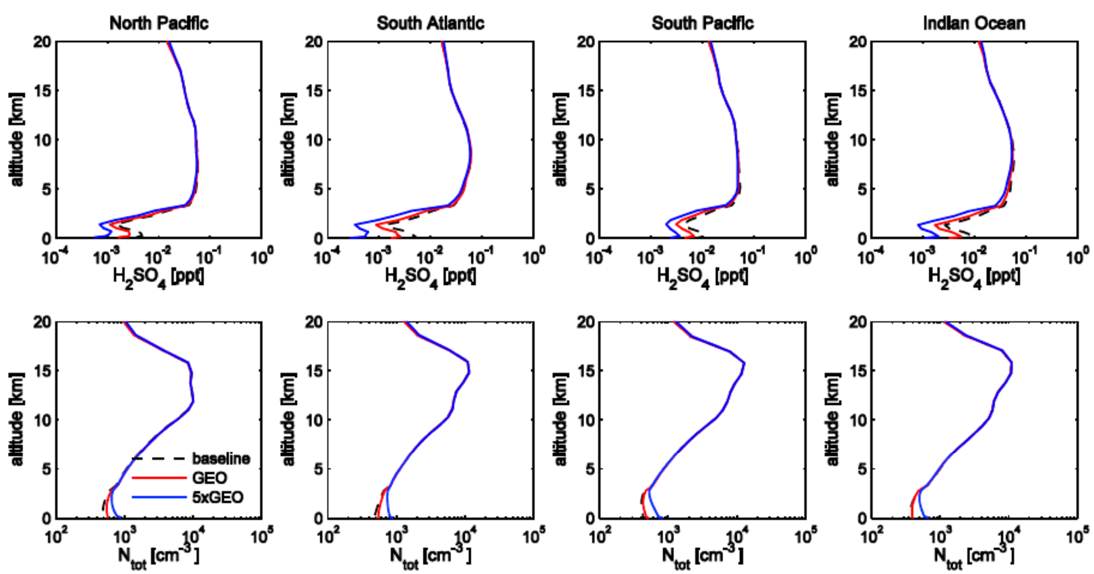

Fig. 8. Effect of cloud seeding on the annual mean vertical profiles of H_2SO_4 (top panels) and total particle number concentration (N_{tot}) in the four geoengineered regions.

- Increasing sea salt makes clouds more alkaline
- pH changes affect rate of aqueous oxidation of SO_2
- This in turn changes gaseous phase oxidation of SO_2
- This changes new particle formation rate

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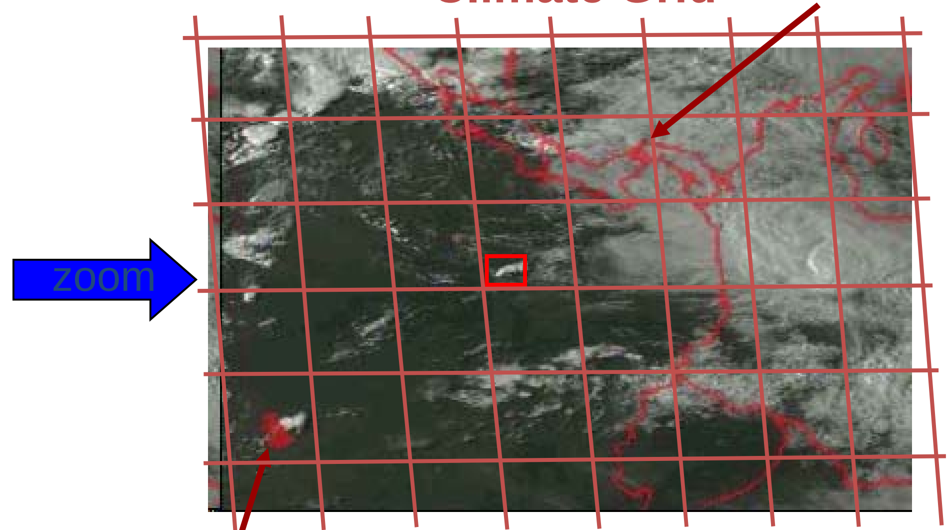
The need for high resolution modeling



~ 130 km

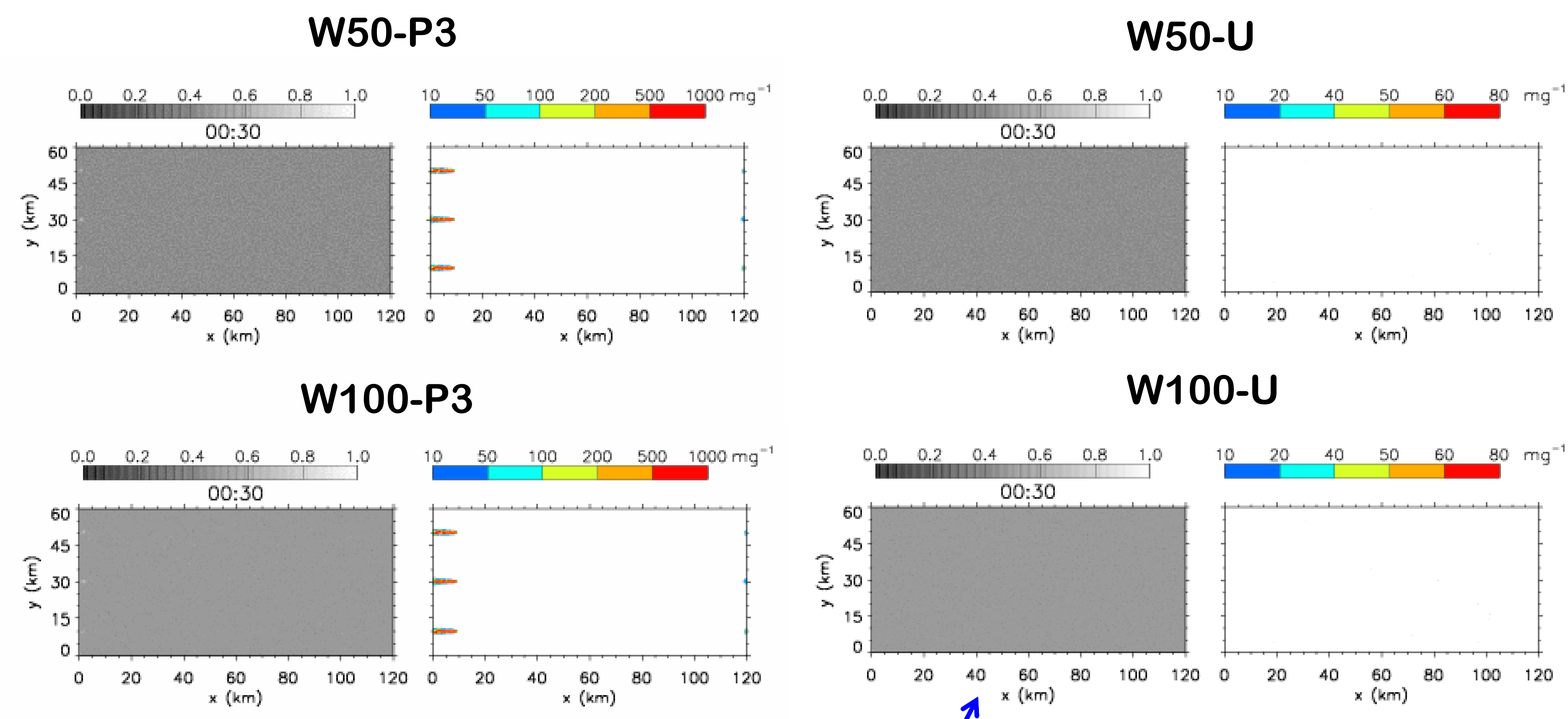
300km grid

Clouds are not "resolved" by climate models

Courtesy, NASA Goddard Space Flight Center Scientific Visualization Studio

Impact of CCN injection on cloud albedo

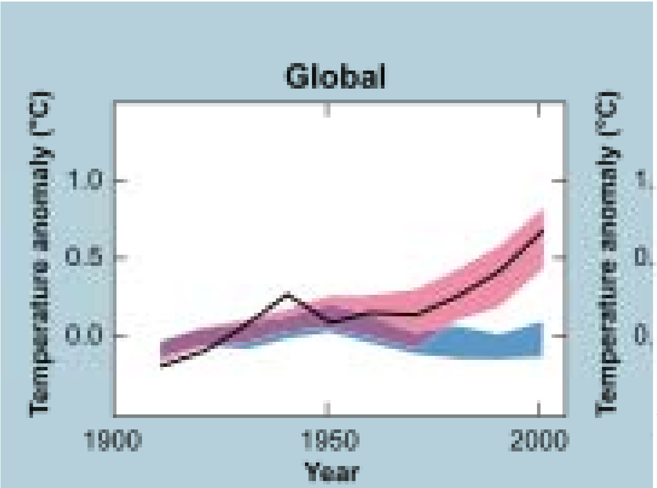
Wang, Rasch & Feingold, 2011, ACP



More effective in the weakly precipitating case (areal coverage of CCN is more important than # concentration)

Why do we care?

- Many models reproduce the historical trend in T_S when "total" anthropogenic forcings were included
- Some models didn't include aerosol cloud interactions (the "indirect effect")
- Models "forcings" differ by > a factor of 2
- Models "climate sensitivities" differ by > a factor of 2



IPCC, AR4

Kiehl, GRL, 2007

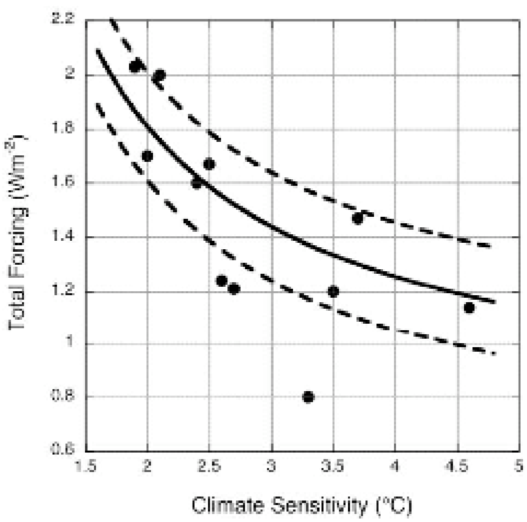


Figure 1. Total Anthropogenic Forcing (Wm^{-2}) versus equilibrium climate sensitivity (°C) from nine coupled climate models and two energy balance models that were used to simulate the climate of the 20th century. Solid line is theoretical relationship from equation (4). Dashed lines arise from assuming a ±0.2 Wm^{-2} uncertainty in ocean energy storage in equation (4).

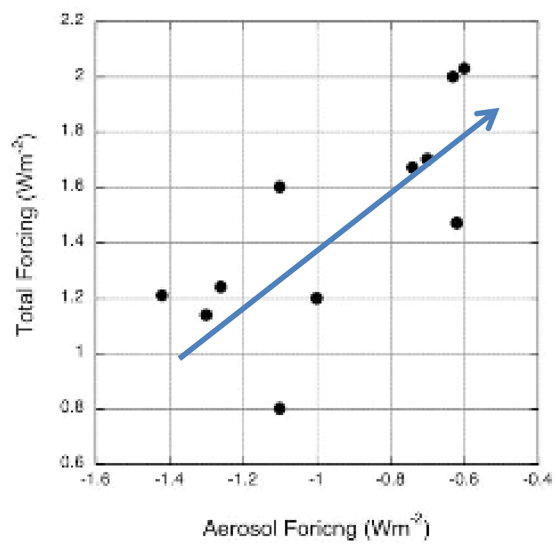
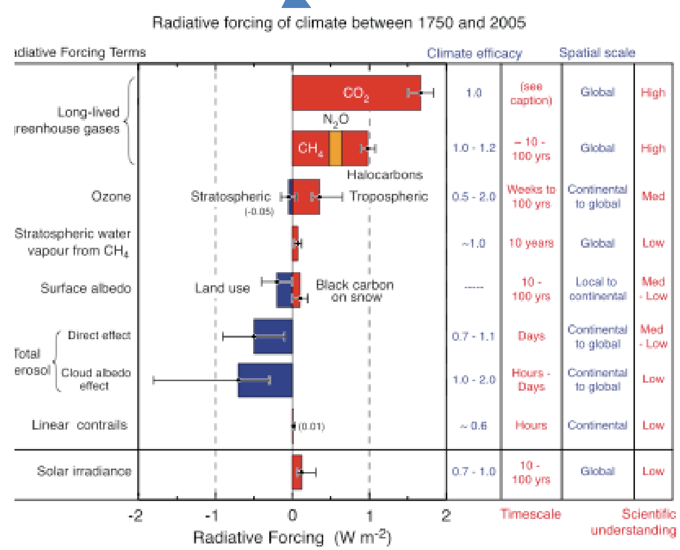


Figure 2. Total anthropogenic forcing (Wm^{-2}) versus aerosol forcing (Wm^{-2}) from nine fully coupled climate models and two energy balance models used to simulate the 20th century.



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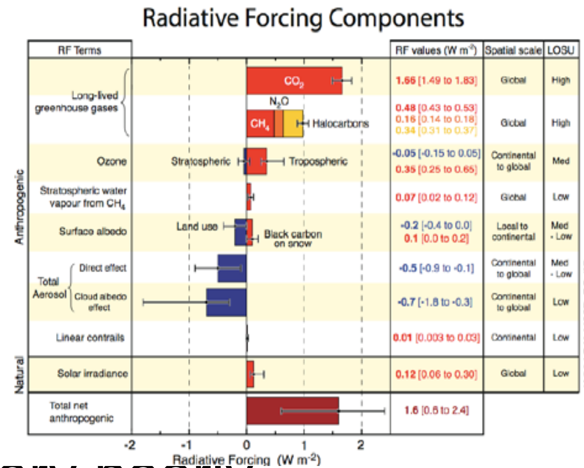
Why it might make sense to consider field experiments related to geoengineering



1. Aerosol-Cloud interactions are a critical and very poorly understood component of the climate system
2. We are currently stuck with "studies of opportunity"
3. We have little opportunity to systematically and thoroughly explore the response of clouds to aerosols, particularly on scales larger than a single cloud
4. We know that our lack of knowledge about aerosol cloud interactions
   - A. Has hindered our ability to explain the change in climate over the last century + and isolate climate sensitivity to CO2 forcing & cloud feedbacks.
   - B. It thus also confounds our ability to predict future climate change
5. Field Experiments may contribute to Fundamental Understanding of the Climate System & Geoengineering

LIMITED AREA FIELD EXPERIMENT: EXPERIMENTAL DESIGN

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