Geoengineering by stratospheric sulfur injection and volcanic analogs: Applications for a 3-D chemistry-climate model with aerosol microphysics

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Along with
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Purpose: show a potential use for GMI with stratospheric aerosols coupled to a chemistry-climate model

Publications:

Heckendorn, P., D. Weisenstein, S. Fueglistaler, B. P. Luo, E. Rozanov, M. Schraner, L. W. Thomason, and T. Peter, Impact of geoengineering aerosols on stratospheric temperature and ozone, *Environ. Res. Lett.*, *4*, 045108, doi:10.1088/1748-9326/4/4/045108, 2009.

Pierce, J. R., D. K. Weisenstein, P. Heckendorn, T. Peter, and D. W. Keith, Efficient formation of stratospheric aerosol for climate engineering by emission of condensible vapor from aircraft, *Geophys. Res. Lett.*, 37, doi:10.1029/2010GL043975, 2010.

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Geoengineering

Paul Crutzen's reconsideration:

1 Tg S stratospheric burden

- **0.007** average optical depth
- **1 ppbV** sulfur (6 × natural)
- **-0.75 W / m²**

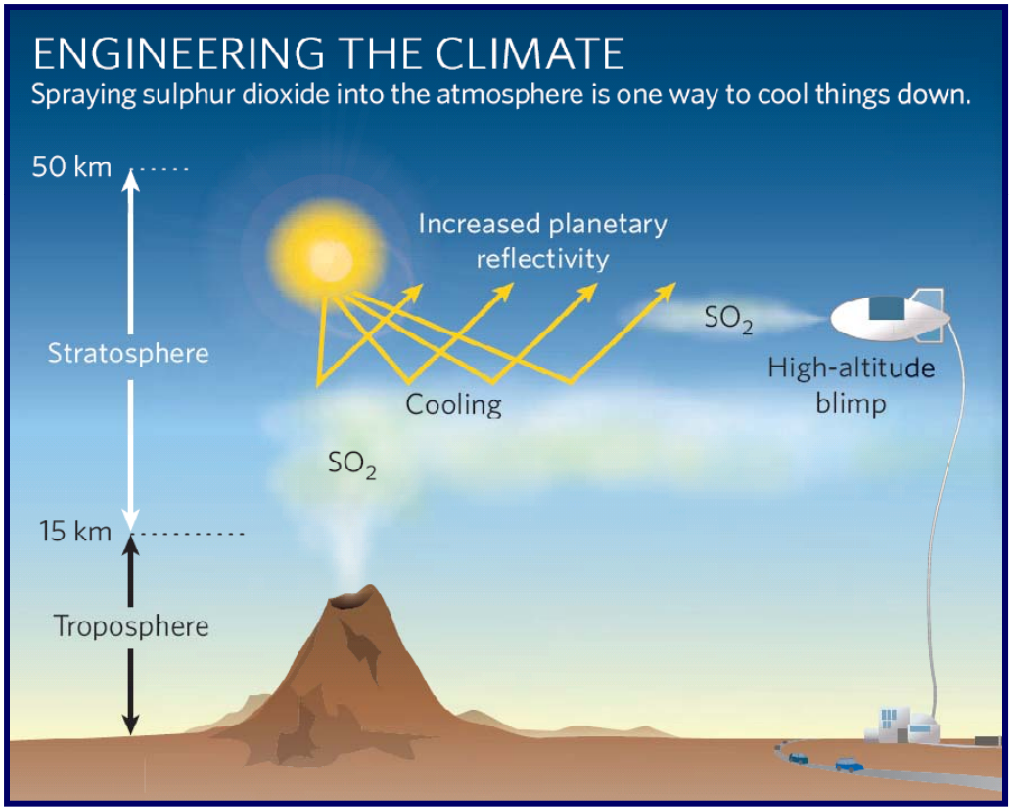
  downscaling Pinatubo:

  10 TgS injected into stratosphere,

  6 month after eruption remaining 6 TgS still caused -4.5 W/m² radiative cooling

Estimate:

- **5-6 Tg S** stratospheric burden would compensate 4 W/m² RF expected from CO_2 doubling



The Geoengineering Dilemma

The ROYAL SOCIETY
1st September 2009

Stop emitting CO_2 or geoengineering could be our only hope

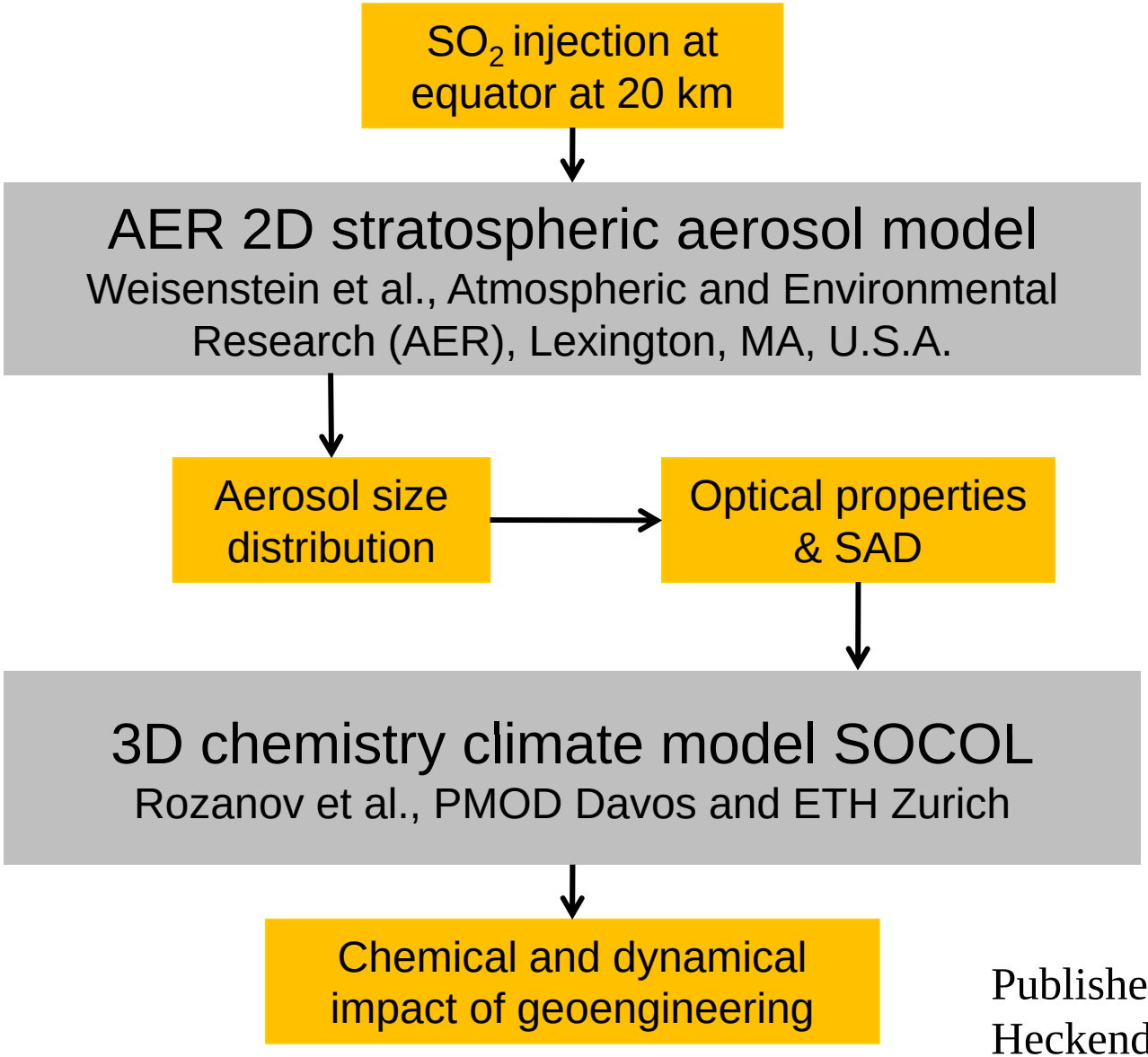
The future of the Earth could rest on potentially dangerous and unproven geoengineering technologies unless emissions of carbon dioxide can be greatly reduced…

(1) Mitigation/adaptation: Parties to the UNFCCC should agree to global emissions reductions of at least 50% by 2050

(2) Governance: To ensure that geoengineering methods can be adequately evaluated, and applied responsibly and effectively

(3) High Commission: The governance challenges should be explored in more detail by an international body such as the UN Commission for Sustainable Development

Geoengineering model experiments



Published in
Heckendorn et al., 2009

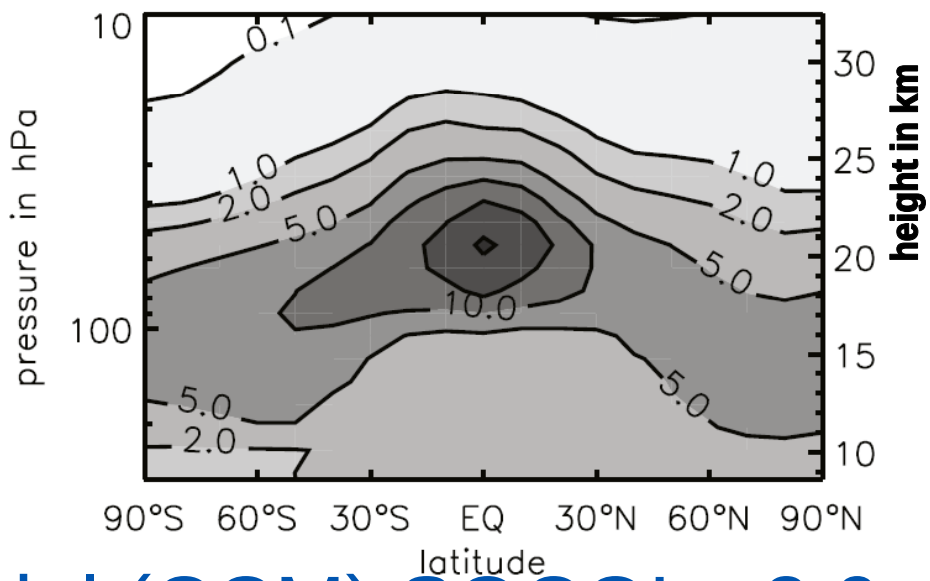
AER 2D aerosol model

- 40 bin sectional model with nucleation, condensation/evaporation, coagulation, sedimentation
- SPARC Stratospheric Aerosol Assessment (2006) showed AER model to be one of the better models for volcanic eruptions

Geoengineering scenarios

Scenario name	Continuous sulfur input
GEO0	0 Mt S/a
GEO1	1 Mt S/a
GEO2	2 Mt S/a
GEO5	5 Mt S/a
GEO10	10 Mt S/a

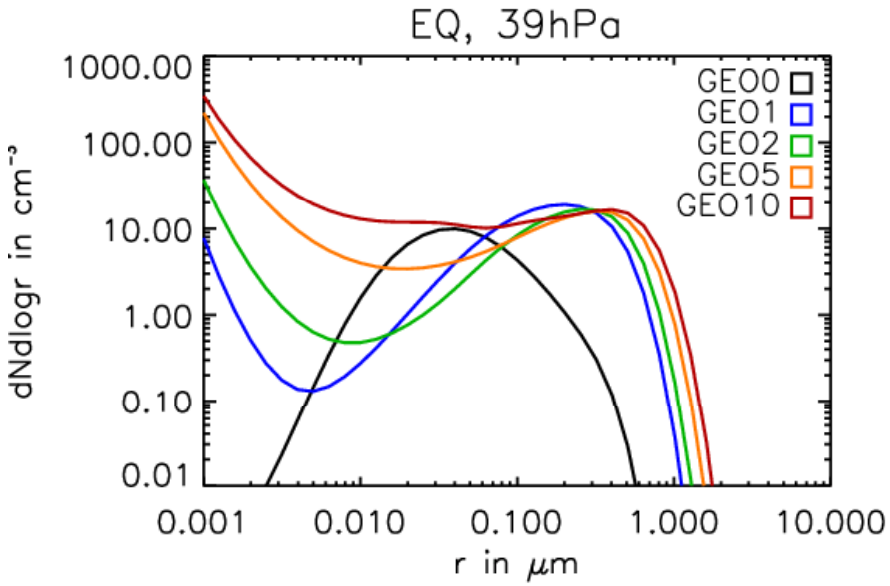
Surface area density of GEO5 ($\mu m^2/cm^3$)



Chemistry climate model (CCM) SOCOL v2.0

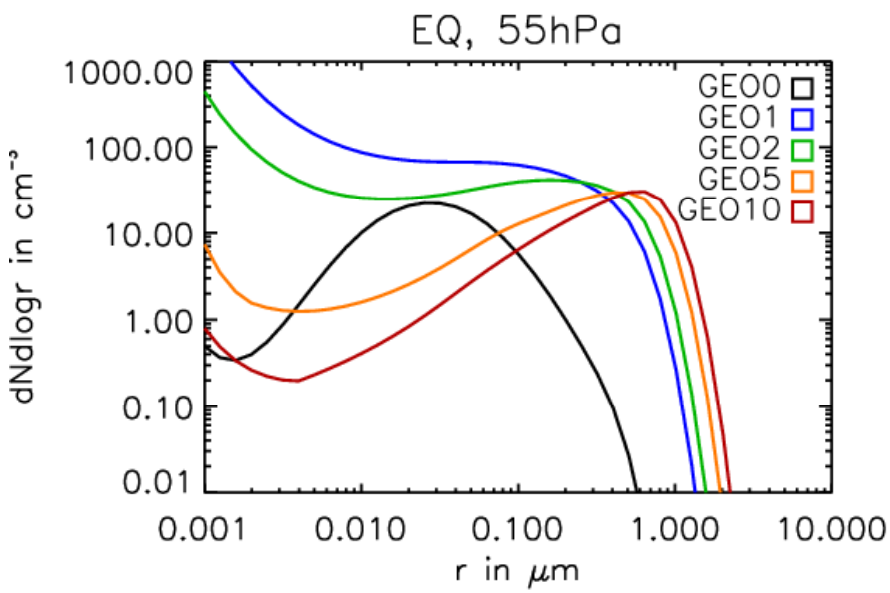
- GCM: Middle Atmosphere version of ECHAM-4
- CTM: Sophisticated stratospheric / mesospheric chemistry
- Prescribed SSTs, no coupled ocean

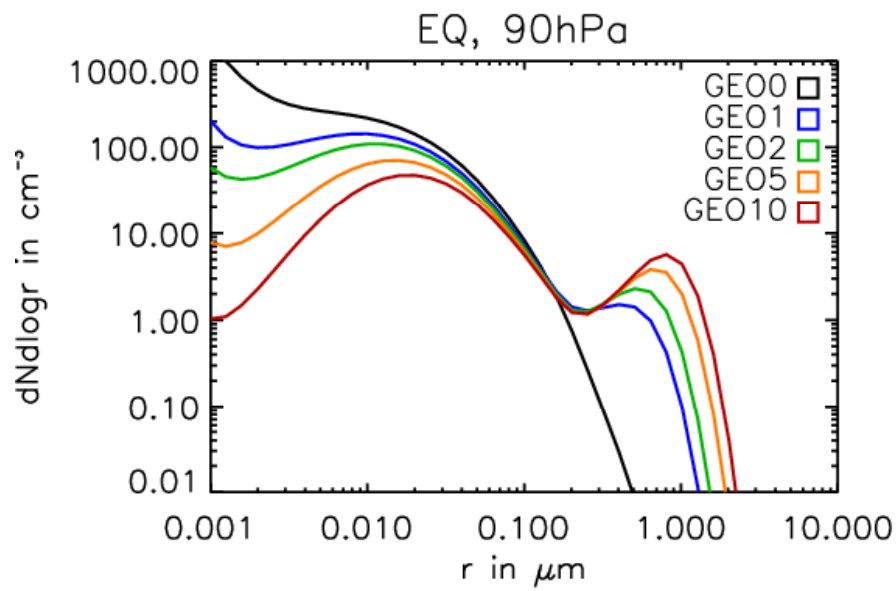
Aerosol Size Distributions at Equator and 39, 55, 90 hPa with continuous sulfur input



Greater S input ⇒ more nucleation, more large particles, faster sedimentation

Most efficient SW scattering ~0.1 μm radius





Large particles at 90 hPa cause LW heating of tropopause, ↑ strat H_2O

Compare volcanic eruption and geoengineering

AER 2D aerosol model results

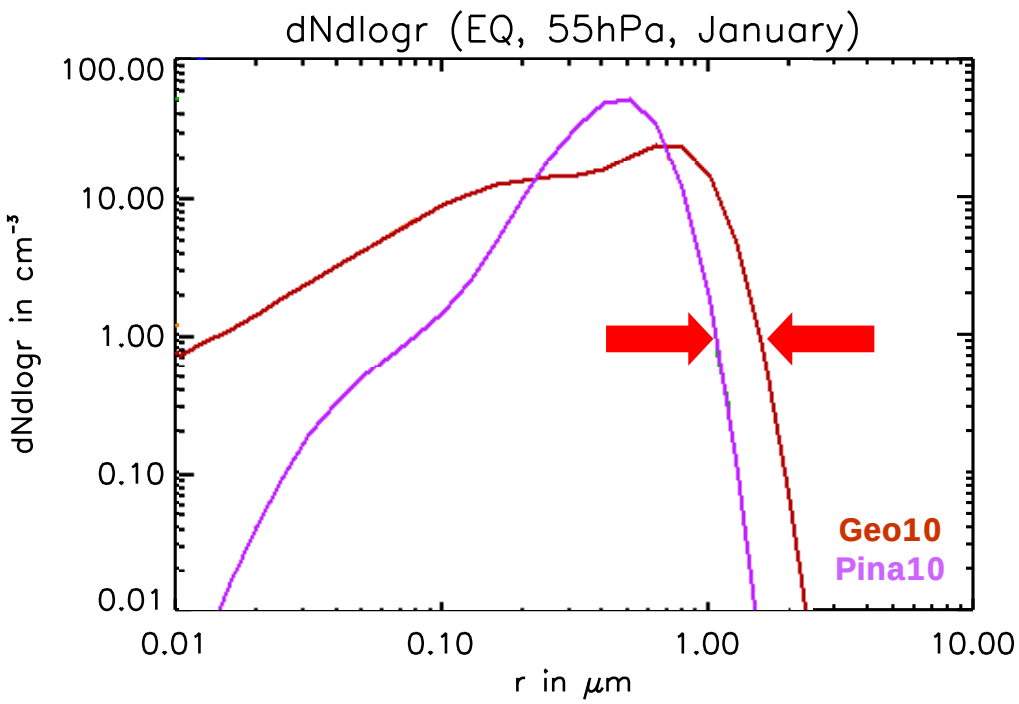
Volcanic eruption:
1 single SO_2 injection

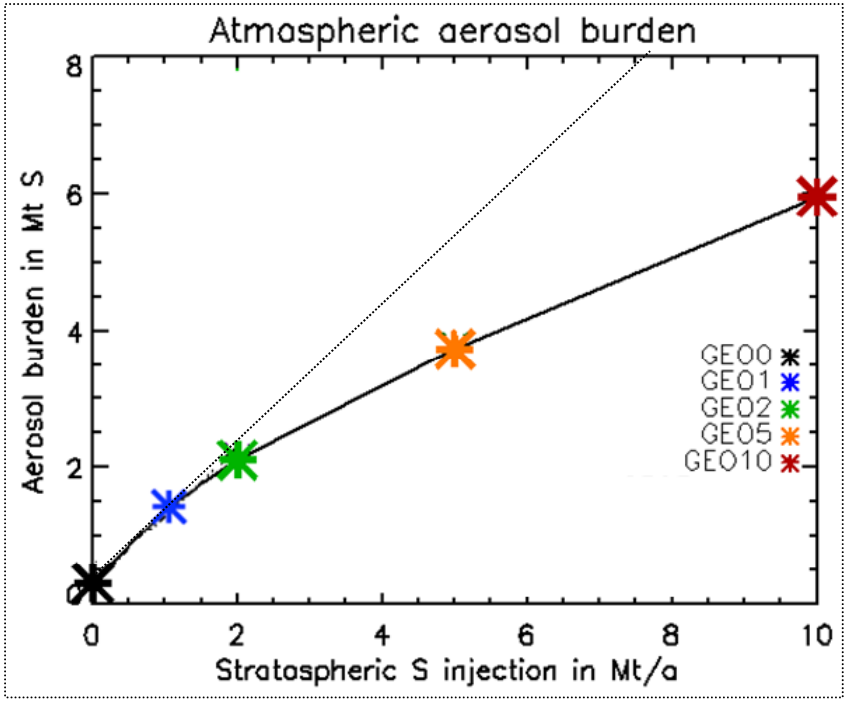
Geoengineering:
continuous SO_2 emissions

→ Formation of larger aerosol particles

Pina10: 10 Mt S in June 1991
7 Mt S in January 1992

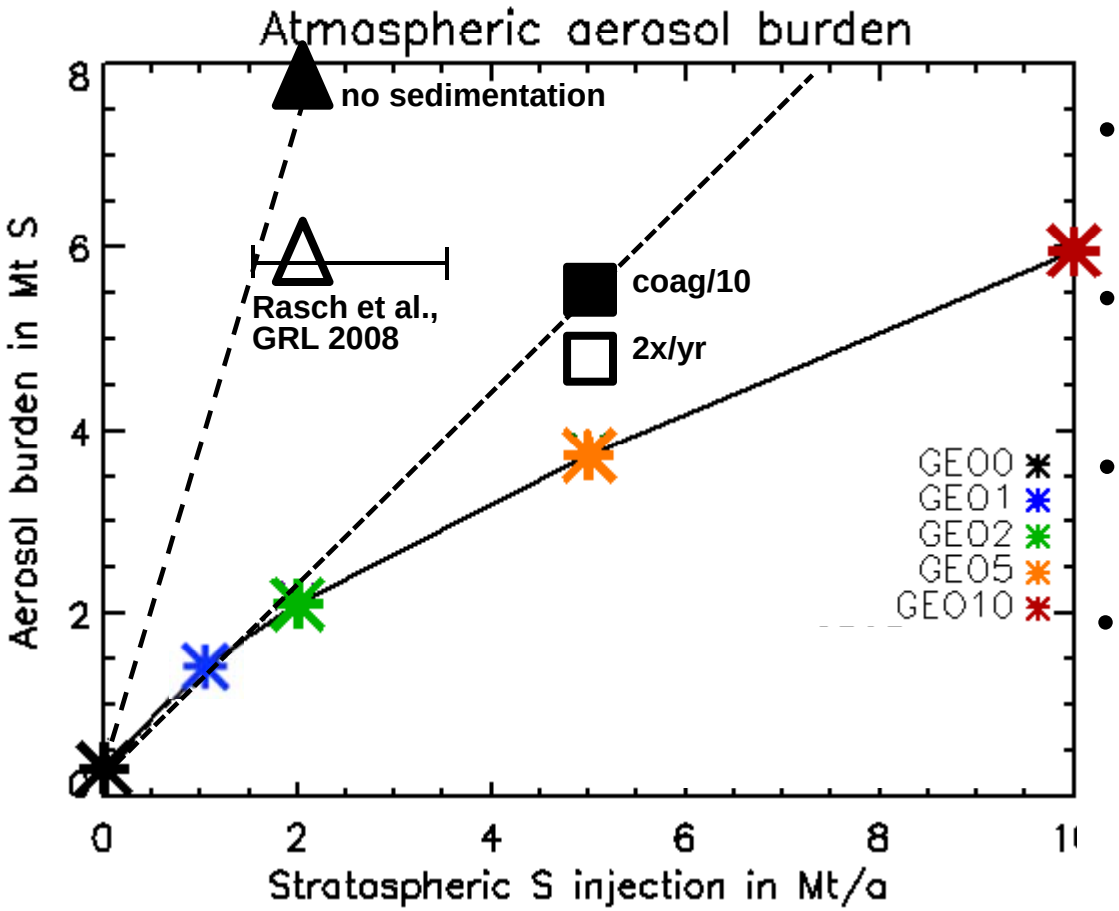
Geo0, Geo1, Geo2, Geo5, Geo10
1 Mt 2Mt 5Mt 10Mt S/a





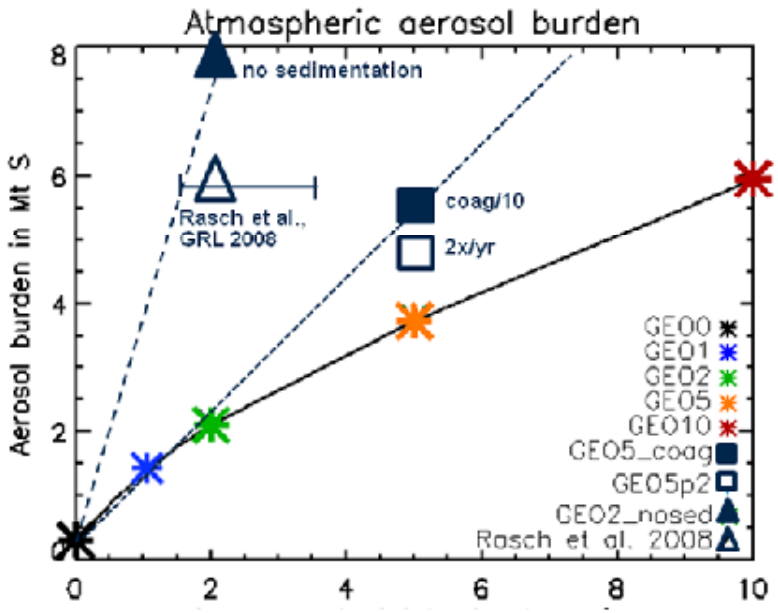
Nonlinear injection-burden relationship

Total amount of S in the condensed phase:

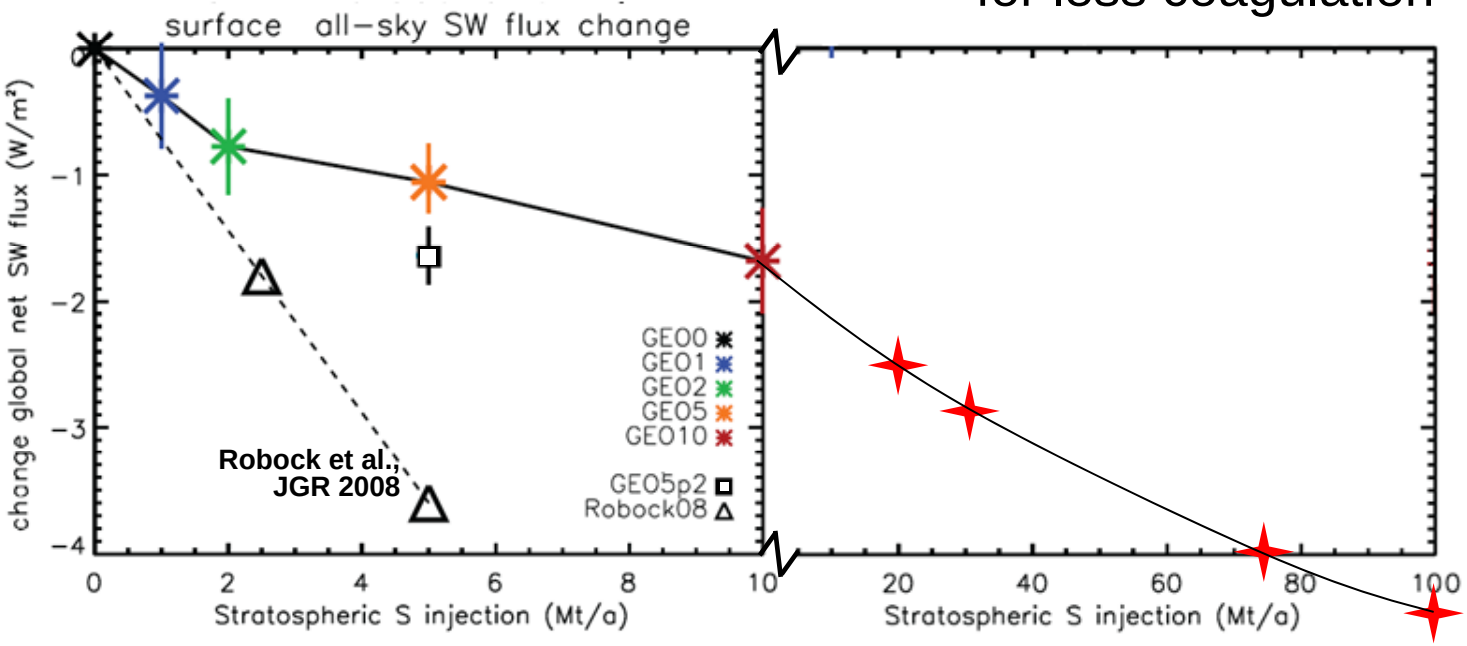


- Nonlinear dependence on annual sulfur injections
- Larger injections lead to more efficient coagulation
- Partial compensation by less frequent injections
- Sedimentation lowers loading by ~3/4
- Rasch et al.: “About 1.5 Tg S/yr are found to balance CO_2 x 2 if particles are small, while perhaps double that may be needed if they reach sizes seen following eruptions”.

Nonlinear injection-burden-radiation relationship



- SO_2 emission over the equator is a very inefficient geoengineering method
- Hard to achieve -4 W/m^2 to counteract CO_2 doubling
- Try larger injection region for less coagulation

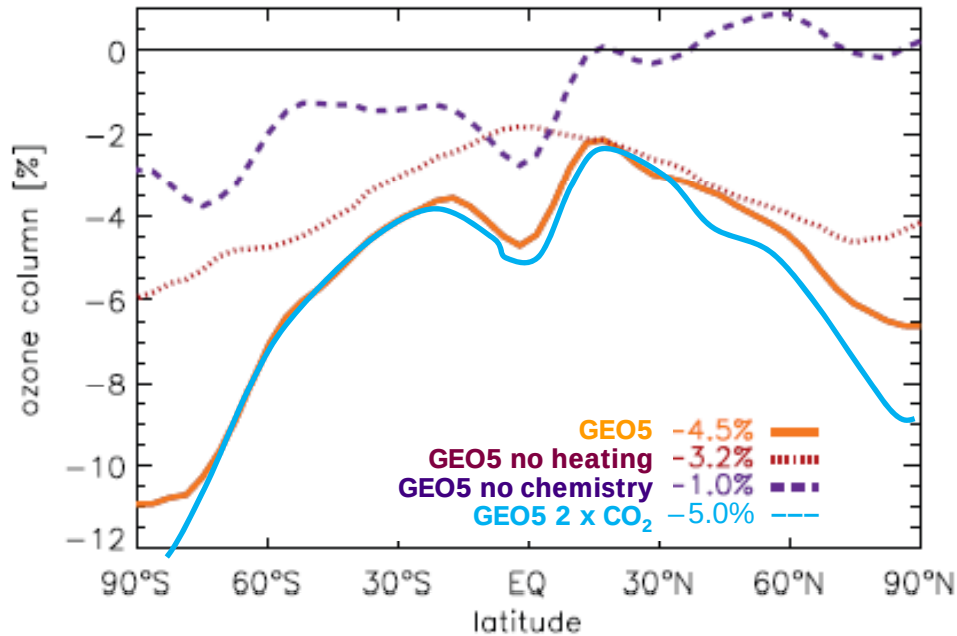


Impact on ozone layer

Potential repercussions of geoengineering:

- Warmer tropopause
- Moister stratosphere
- Changed dynamics
- More ozone loss
  - 1/3 of ozone loss caused by radiative effects ($T \uparrow \rightarrow$ faster chemistry, more HO_x)
  - 2/3 of ozone loss caused by enhanced heterogeneous chemistry on aerosol surface
  - Ozone loss due to geo-engineering could be of same magnitude as CFC-induced loss
  - Especially in the tropical aerosol reservoir and in the polar region strong ozone loss to be anticipated

Change in total ozone column



Scenario	Ozone change	
GEO1 = 1 Mt S/a	-2.3 %	-6.9 DU
GEO2 = 2 Mt S/a	-3.1 %	-9.4 DU
GEO5 = 5 Mt S/a	-4.5 %	-13.5 DU
GEO10 = 10 Mt S/a	-5.3 %	-15.9 DU
GEO5 no heating	-3.2 %	-9.7 DU
GEO5 no chemistry	-1.0 %	-2.9 DU
GEO5 2 x CO_2	-5.0 %	-15.0 DU

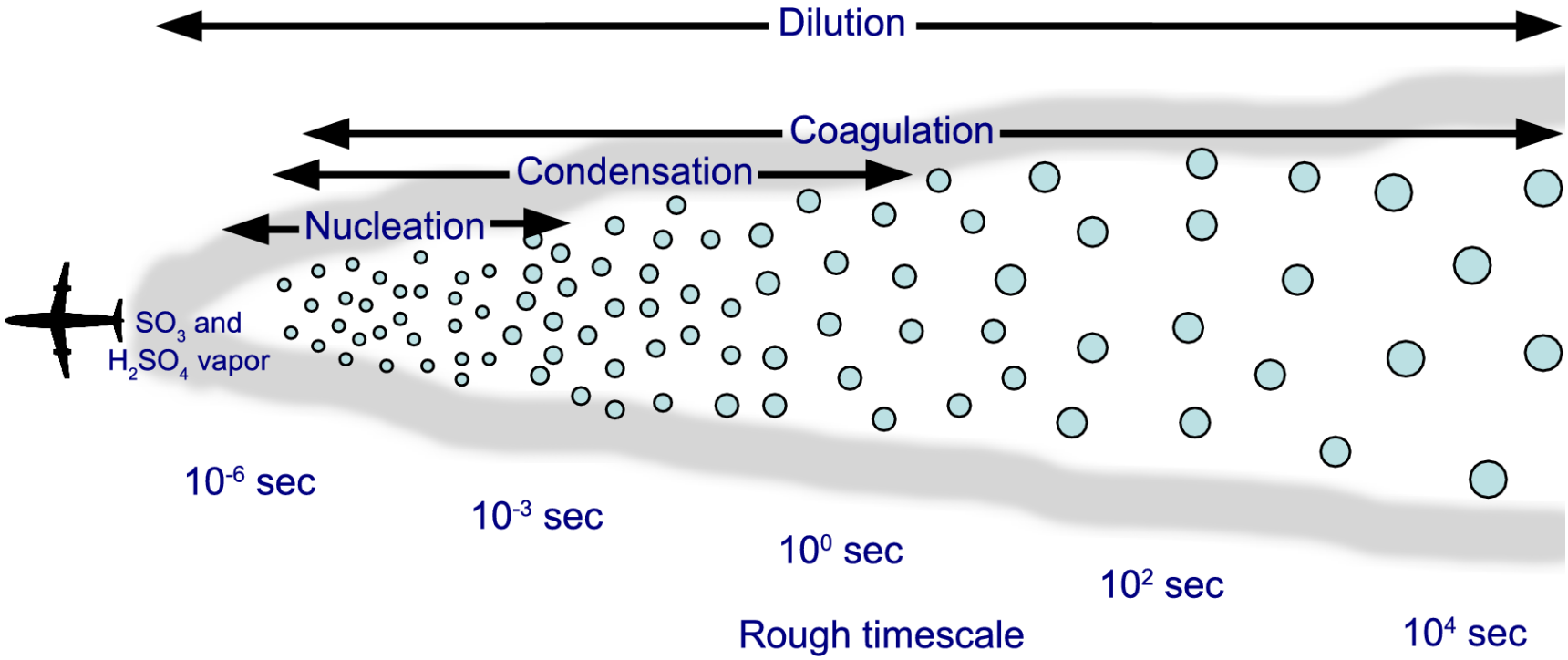
Improve Efficiency of Geoengineering by controlling particle size

- Spread sulfur injection spatially: 30°S-30°N, 20-25 km
- Emit a condensable sulfur gas (eg. H_2SO_4) from an aircraft nozzle
- Less mass to lift to the stratosphere
- Less sedimentation to tropical tropopause ⇒ less heating, smaller H_2O perturbation
- Ozone perturbations not improved (large SAD)

Original ideas by David Keith, UCalgary

Published in Pierce et al., 2010

Modeling of H_2SO_4 in aircraft plume

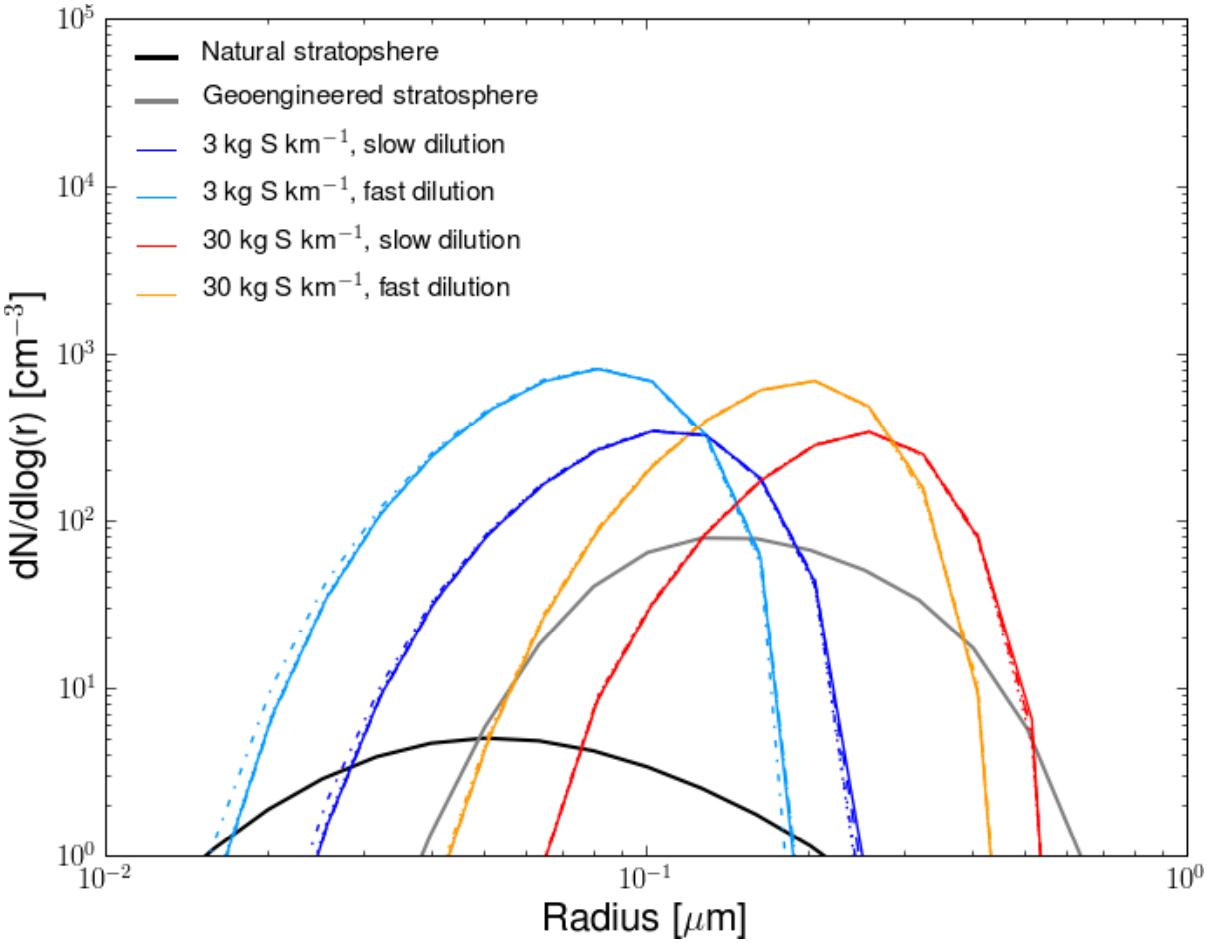


Lagrangian Model of Expanding Aircraft Plume

Jeff Pierce, Dalhouse U.

- TOMAS (Two Moment Aerosol Sectional) microphysics w/ 43 size bins: nucleation, condensation, coagulation
- Plume dilution rate [Yu and Turco, 1998]:
  - Fast $10+10^{\log(t[s])+3}$ for 16 minutes, then follow slow
  - Slow $6+10^{\log(t[s])+2}$
- Background aerosol 50 cm^{-3} from geoengineered global 2-D model result
- Sulfur injection rate: 3 or 30 kg/(km flight path)
- Integration continued until coagulation with background exceeds self-coagulation in plume, about 2 days

Plume model size distributions after 2 days



Particle size controlled by injection rate, dilution rate, coagulation rate

Insensitive to nucleation rate, condensation rate

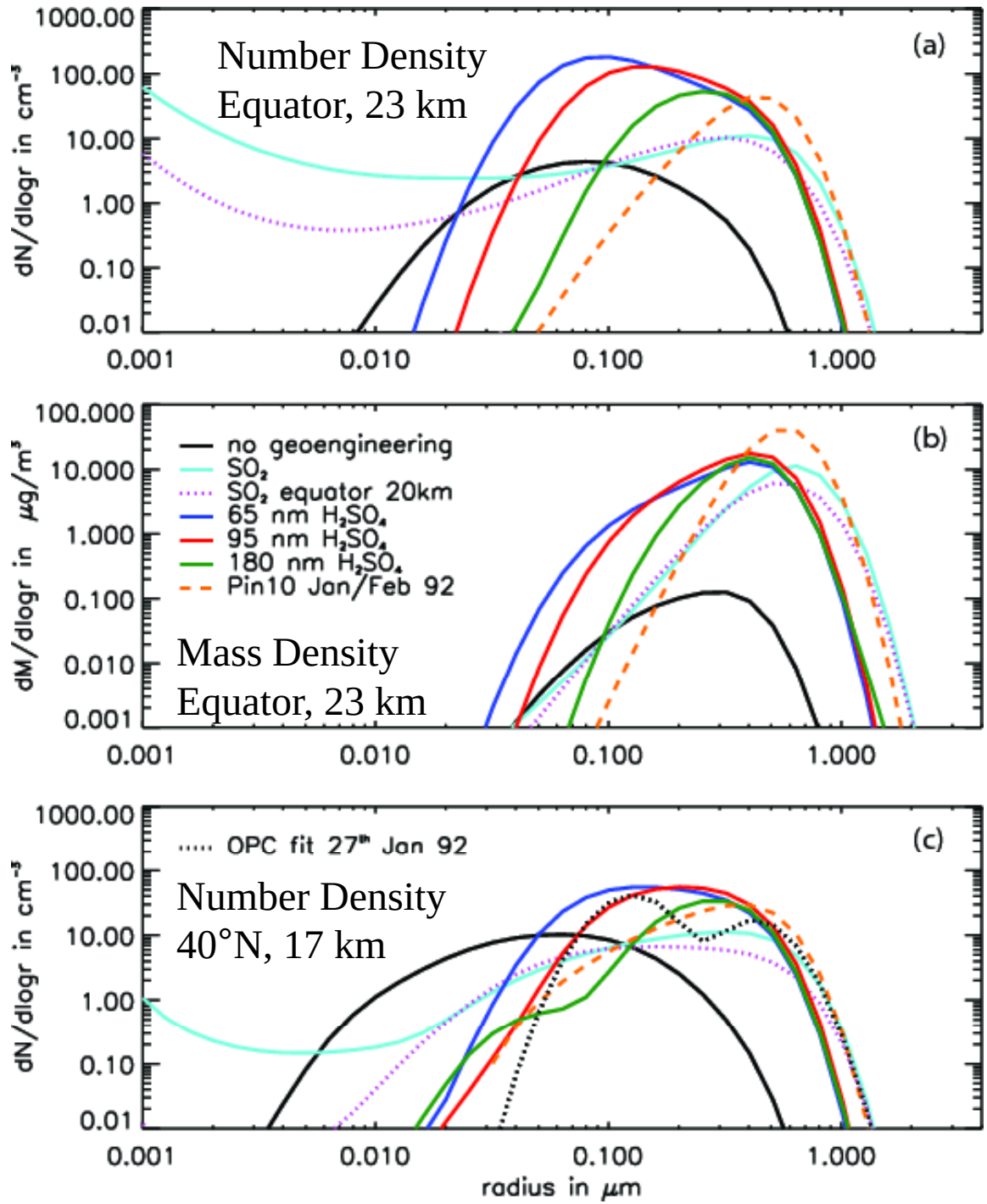
r = 0.065-0.2 μm,
σ = 1.5
used as input to 2D

Steady State Size Distributions

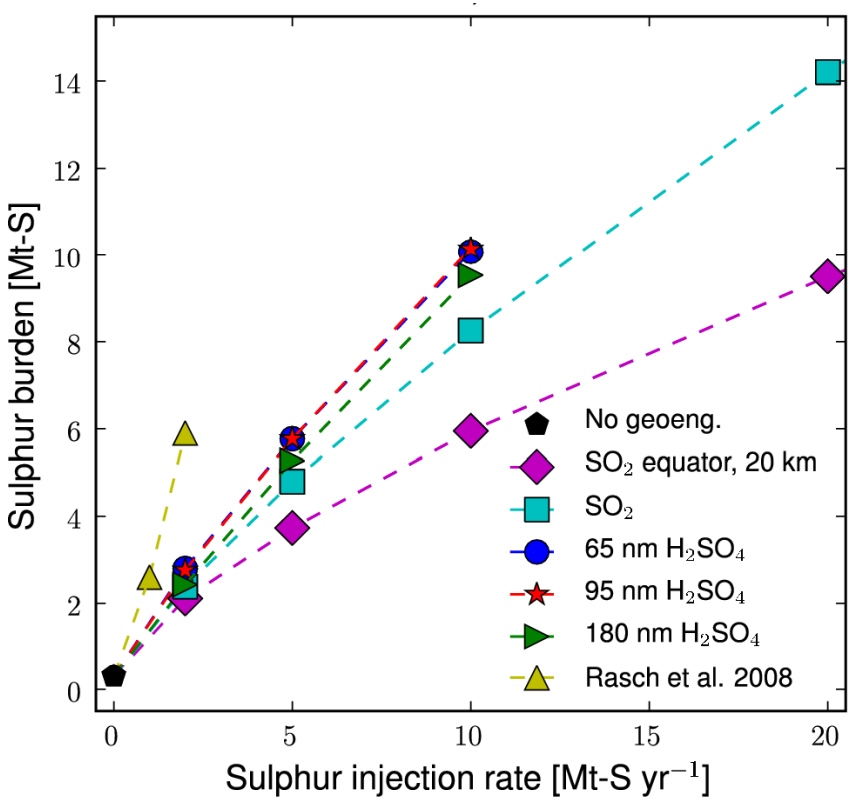
with 5 MT-S/yr continuous emission

SO_2 emission cases: nucleation mode, more large particles

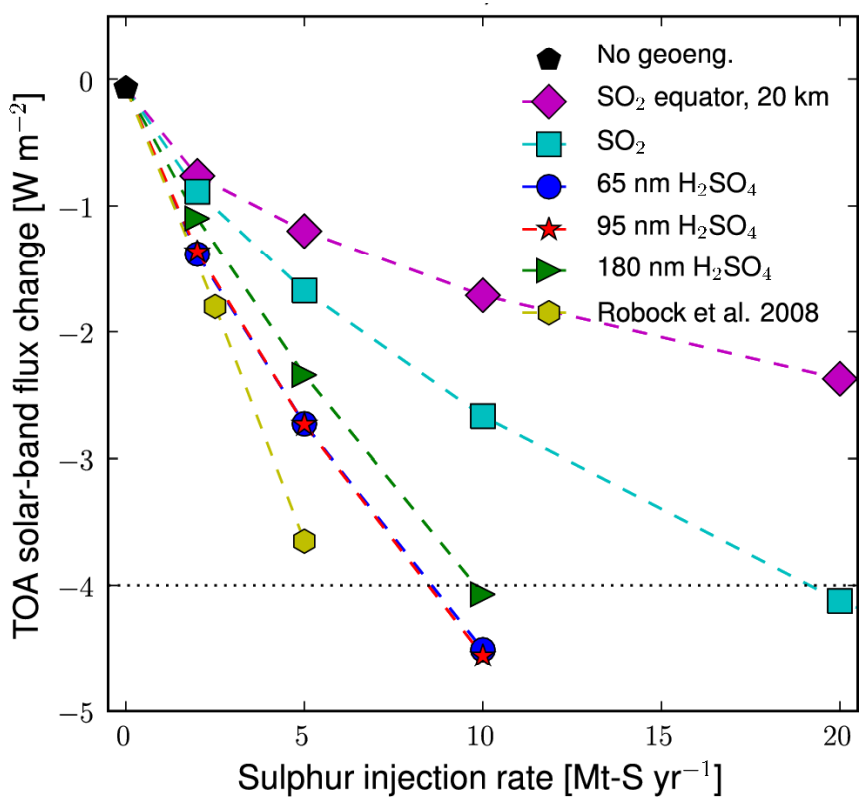
H_2SO_4 cases: radiatively effective particle sizes, fewer large particles than Pinatubo



Global Sulfur Burden



TOA SW Radiative Forcing



SO_2 injection location: Eq, 20 km vs 30°S-30°N, 20-25 km

H_2SO_4 vs SO_2: small burden increase, large radiative increase

Match 2xCO_2 or -4 W m^{-2} with:

- 8-10 MT-S/yr as H_2SO_4
- 20 MT-S/yr as SO_2
- 75 MT-S/yr as SO_2 at Eq, 20 km

Conclusions

- Is geoengineering by stratospheric sulfur injection feasible? Probably
- Is it moral? Will it distract from GHG reduction?
- Risk of geoengineering (precip, strat O_3, H_2O, T)
  vs Risk of doing nothing (surf T, sea level)
- Regional changes, Winners and Losers, international governance needed
- Should geoengineering research continue?
- An application for GMI?