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


Debra Weisenstein, AER, Inc.

Along with

Patricia Heckendorn[1], Thomas Peter[1], Eugene Rozanov[1,2]

David Keith[3], Jeffrey Pierce[4]

[1] Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland

[2] PMOD-WRC, Davos, Switzerland

[3] Univeristy of Calgary, Calgary, AB, Canada

[4] Dalhousie University, Halifax, NS, Canada

# 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.

Funding for this project provided to AER from NASA/ACMAP

# Geoengineering

Paul Crutzen's reconsideration:

**1 Tg S** stratospheric burden

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

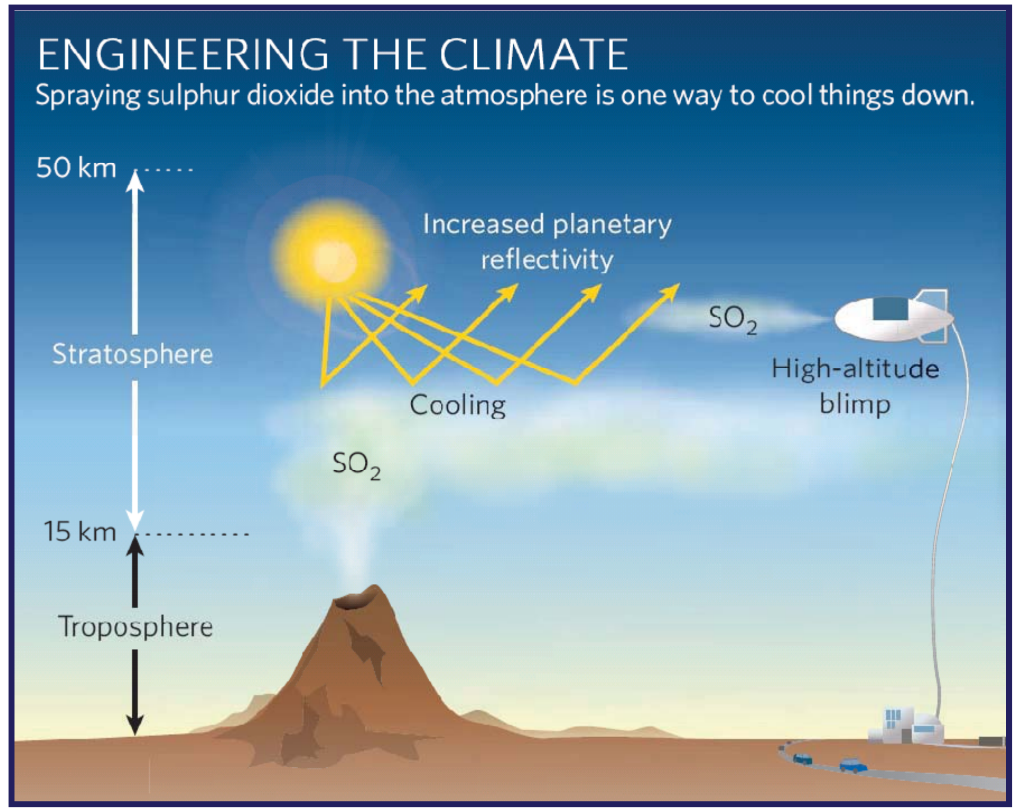
downscaling Pinatubo:

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

EXCELLENCE IN SCIENCE

**The ROYAL SOCIETY**
**1st September 2009**

**Stop emitting $CO_2$ or geoengineering could be our only hope**

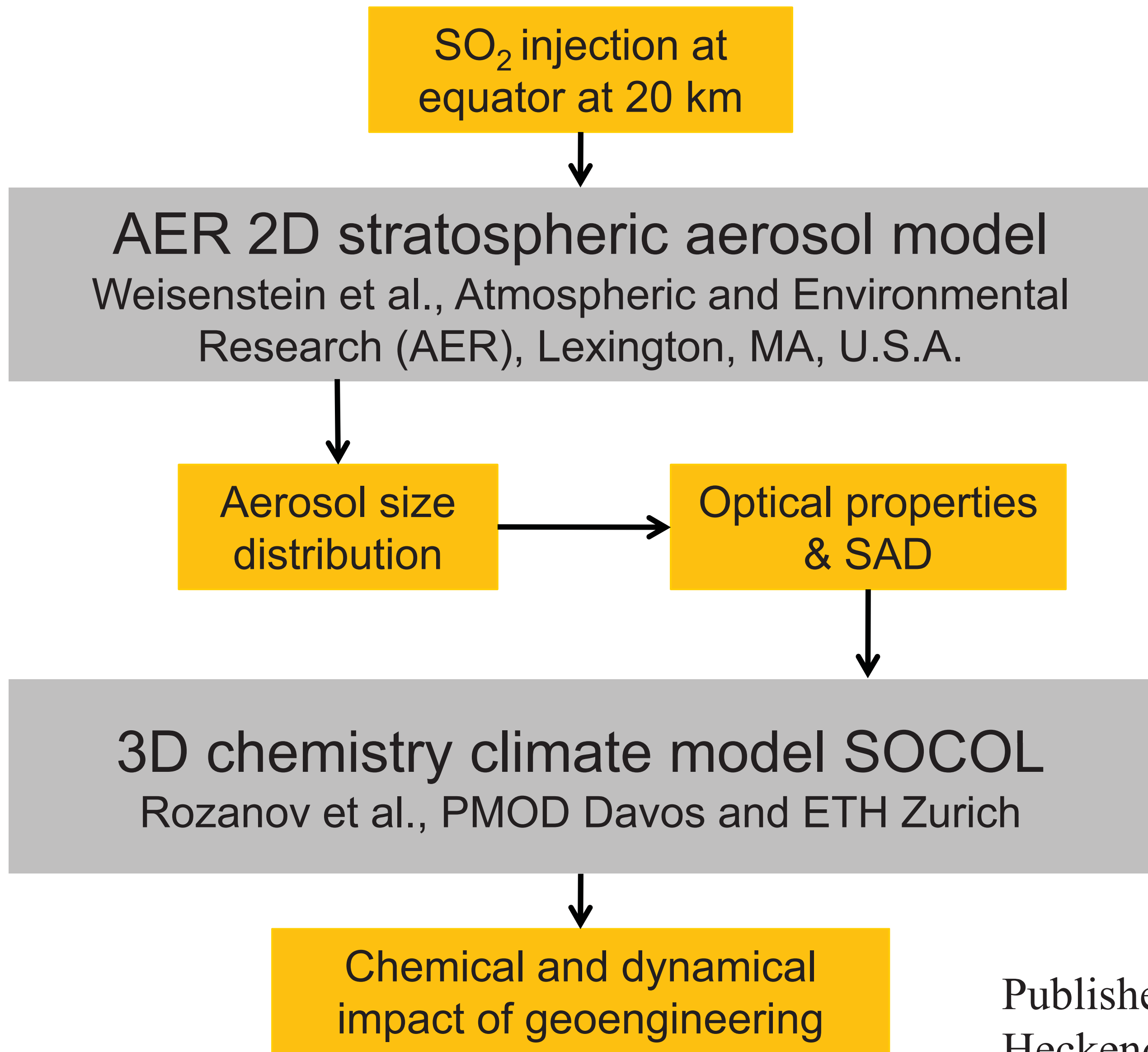
The future of the Earth could rest on potentially dangerous and unproven geoengineering technologies unless emissions of carbon dioxide can be greatly reduced…

(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

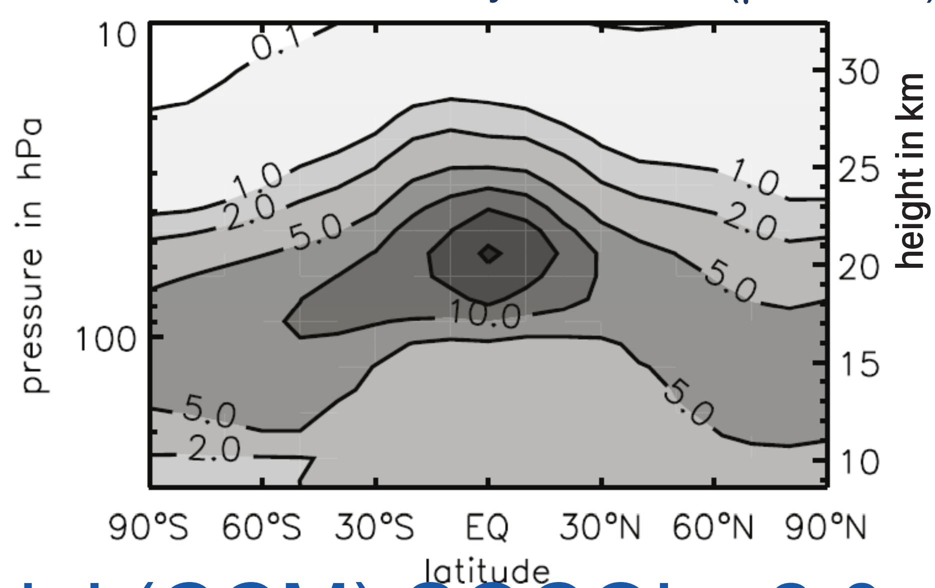
# AER 2D aerosol model□

- 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 |

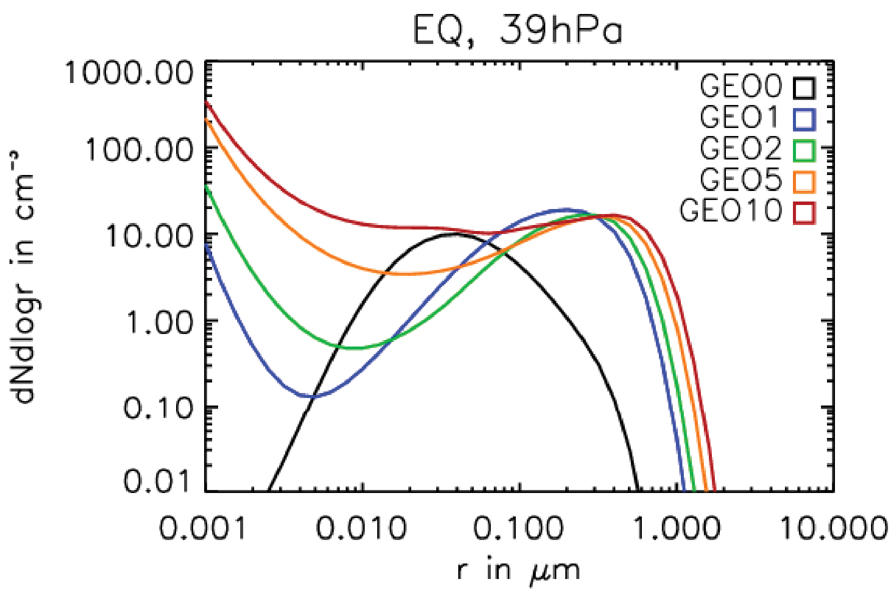
Surface area density of GEO5 ($\mu m^2/cm^3$)



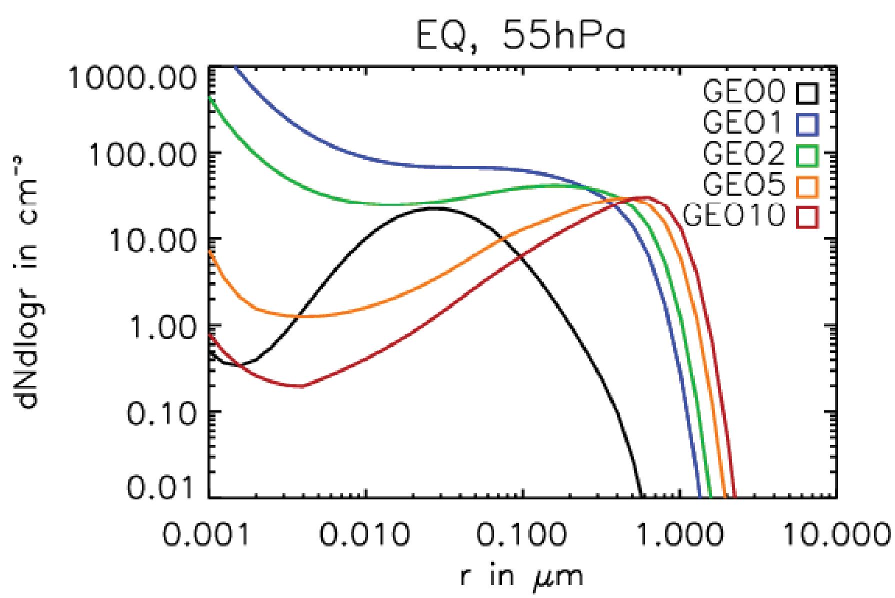

# Chemistry climate model (CCM) SOCOL v2.0

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

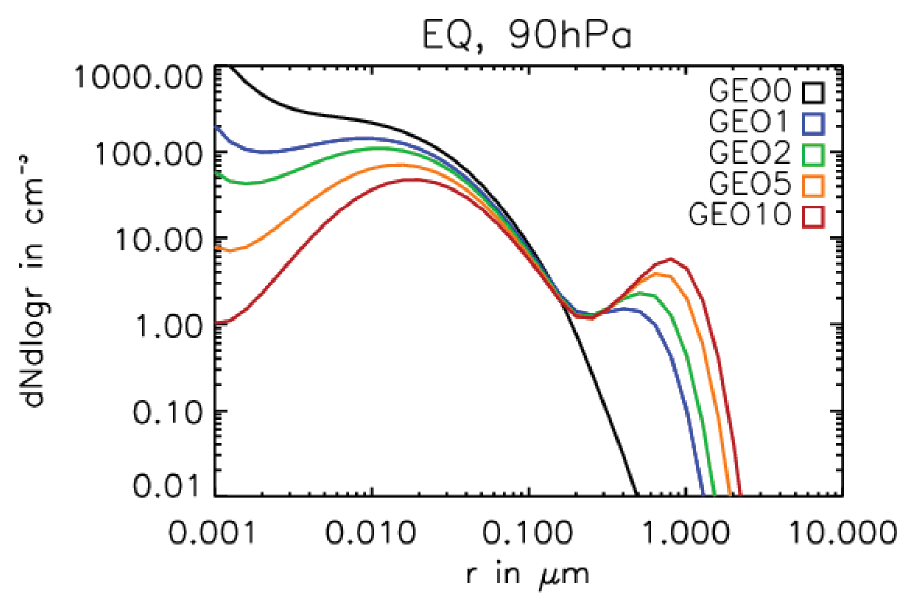
# Aerosol Size Distributions at Equator and 39, 55, 90 hPa with continuous sulfur input




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

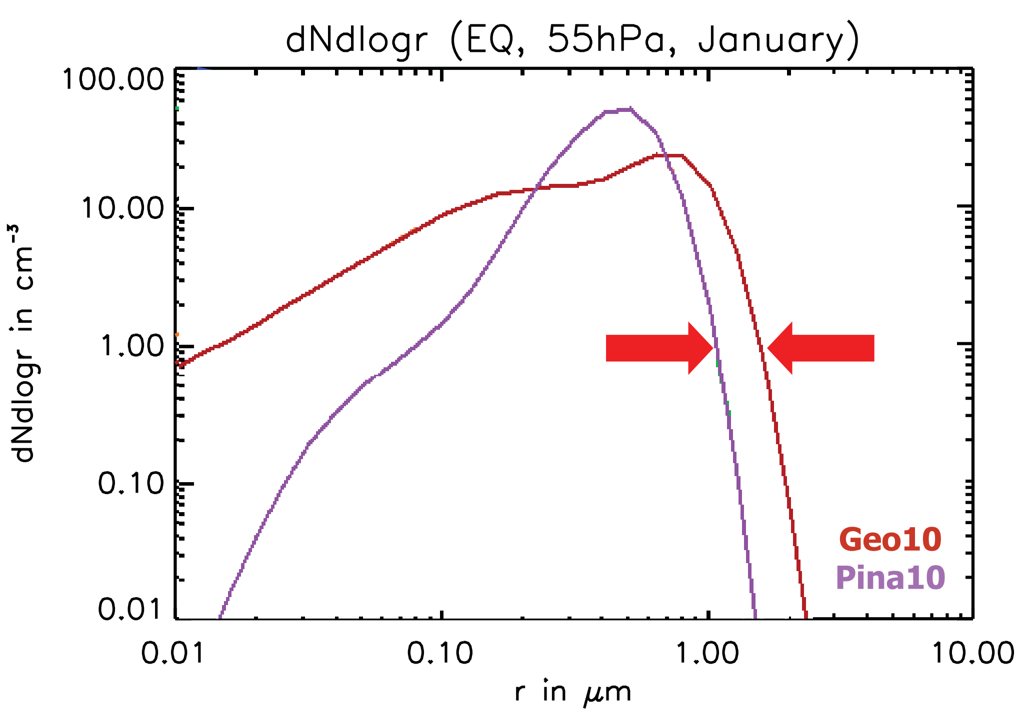
Volcanic eruption:
1 single $SO_2$ injection

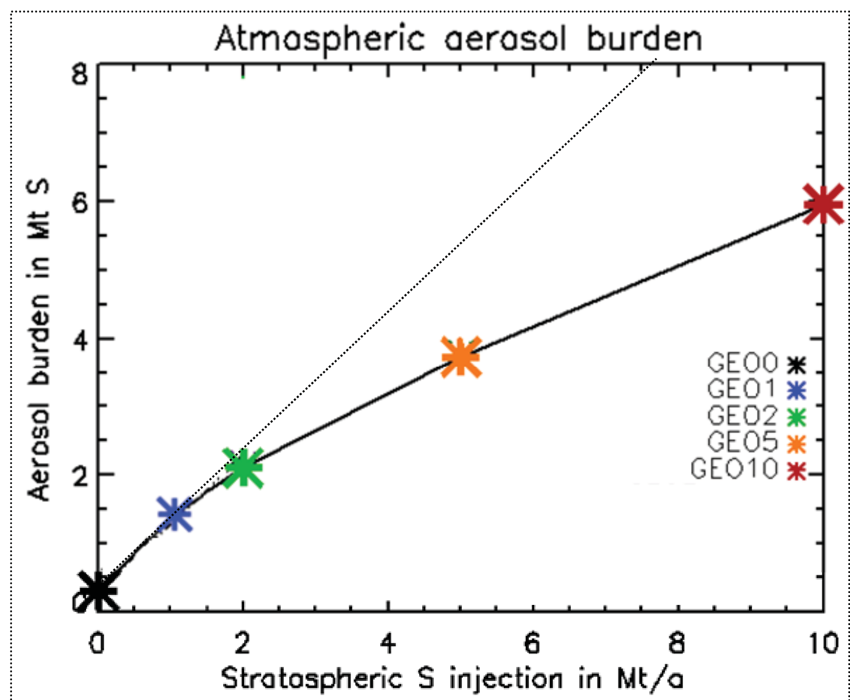
Geoengineering:
continuous $SO_2$ emissions

→ Formation of larger aerosol particles

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

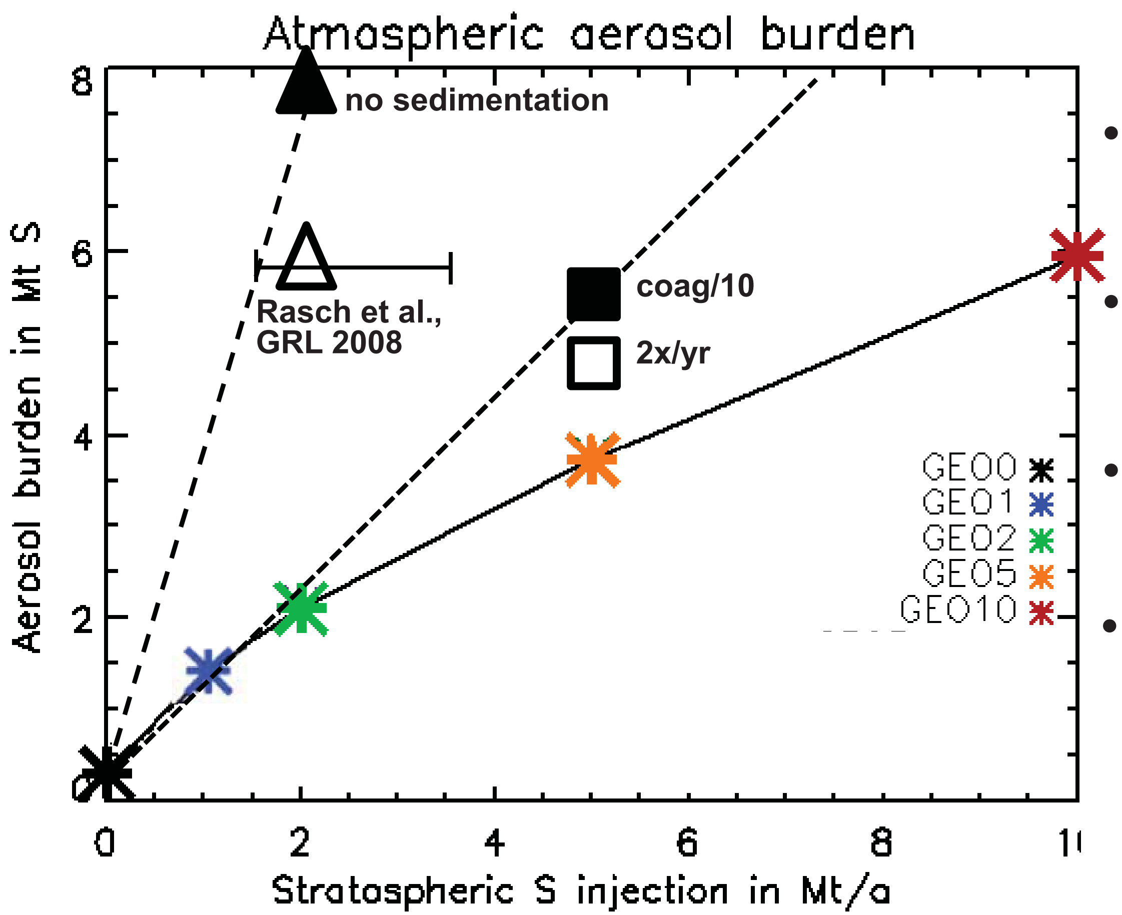
Geo0, Geo1, Geo2, Geo5, Geo10
1 Mt, 2Mt, 5Mt, 10Mt S/a



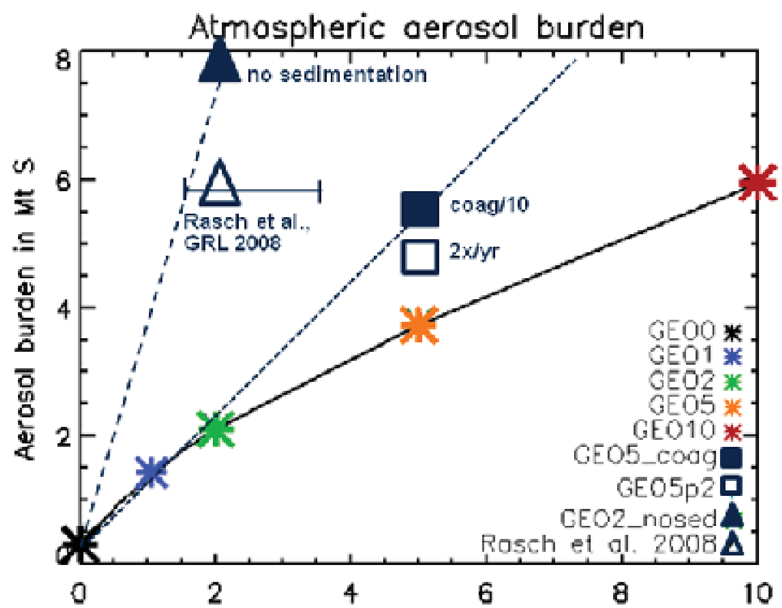
# Nonlinear injection-burden relationship

Total amount of S in the condensed phase:

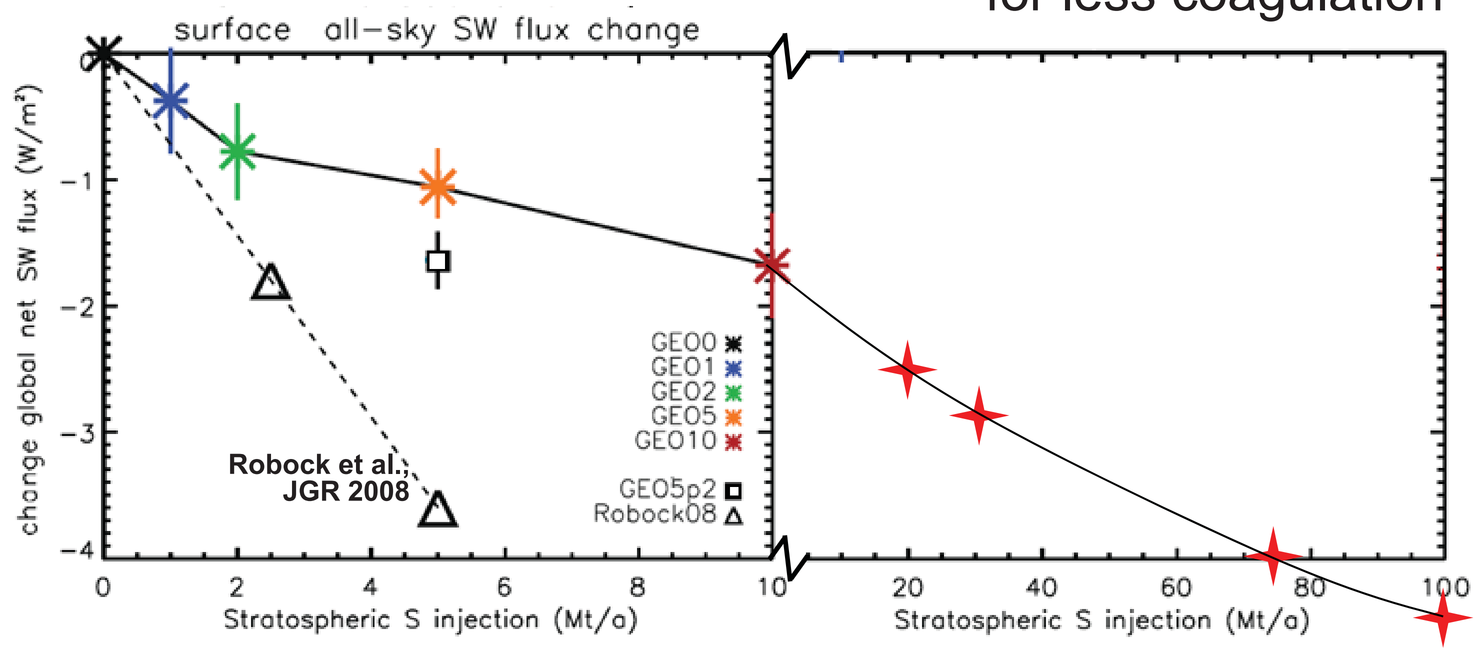



- Nonlinear dependence on annual sulfur injections
- Larger injections lead to more efficient coagulation
- Partial compensation by less frequent injections
- Sedimentation lowers loading by ~3/4
- Rasch et al.: “About 1.5 Tg S/yr are found to balance $CO_2$ x 2 if particles are small, while perhaps 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

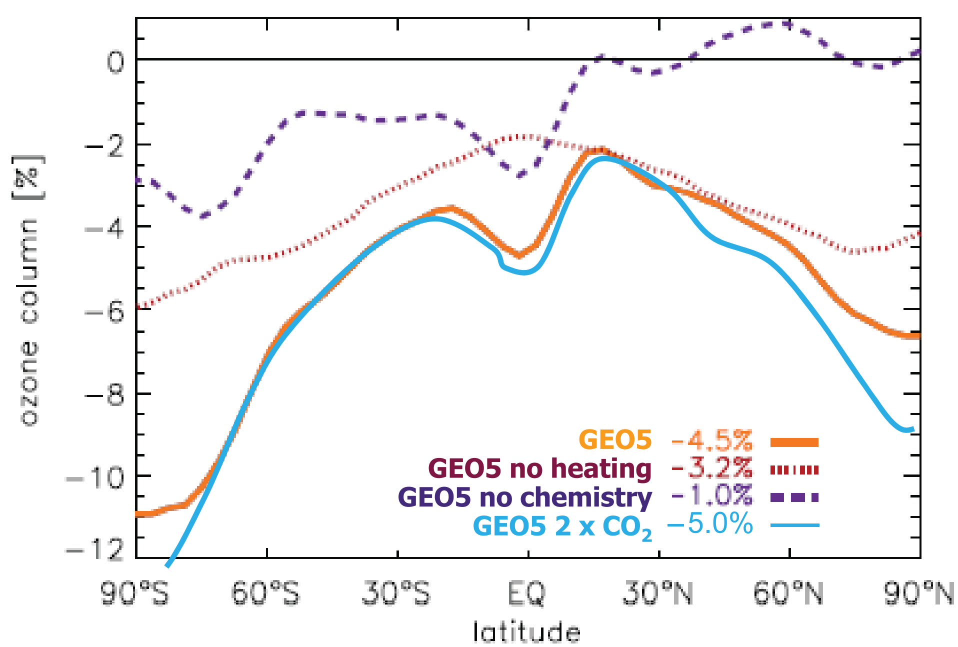


# Impact on ozone layer

**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 |

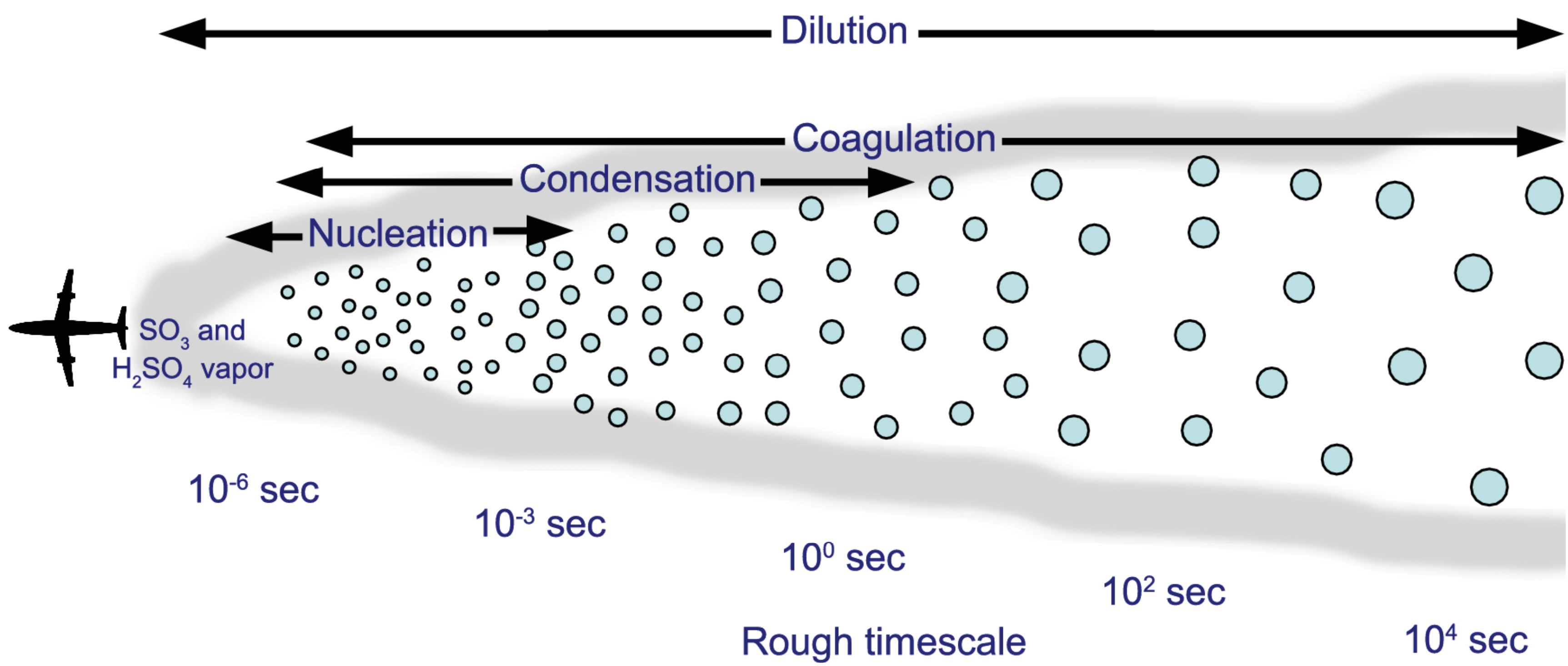
# Improve Efficiency of Geoengineering by controlling particle size

- 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 $\Rightarrow$ 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

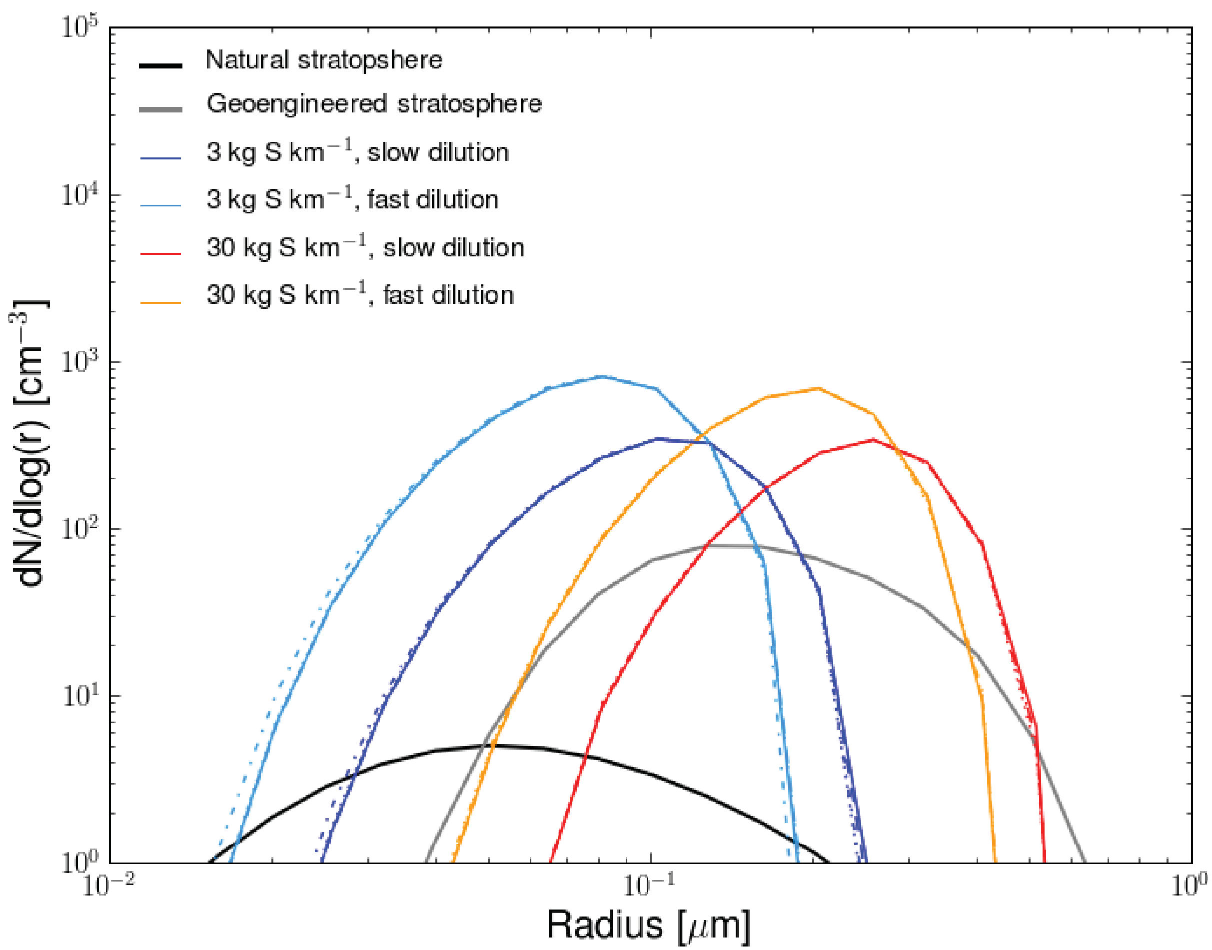


# Lagrangian Model of Expanding Aircraft Plume

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

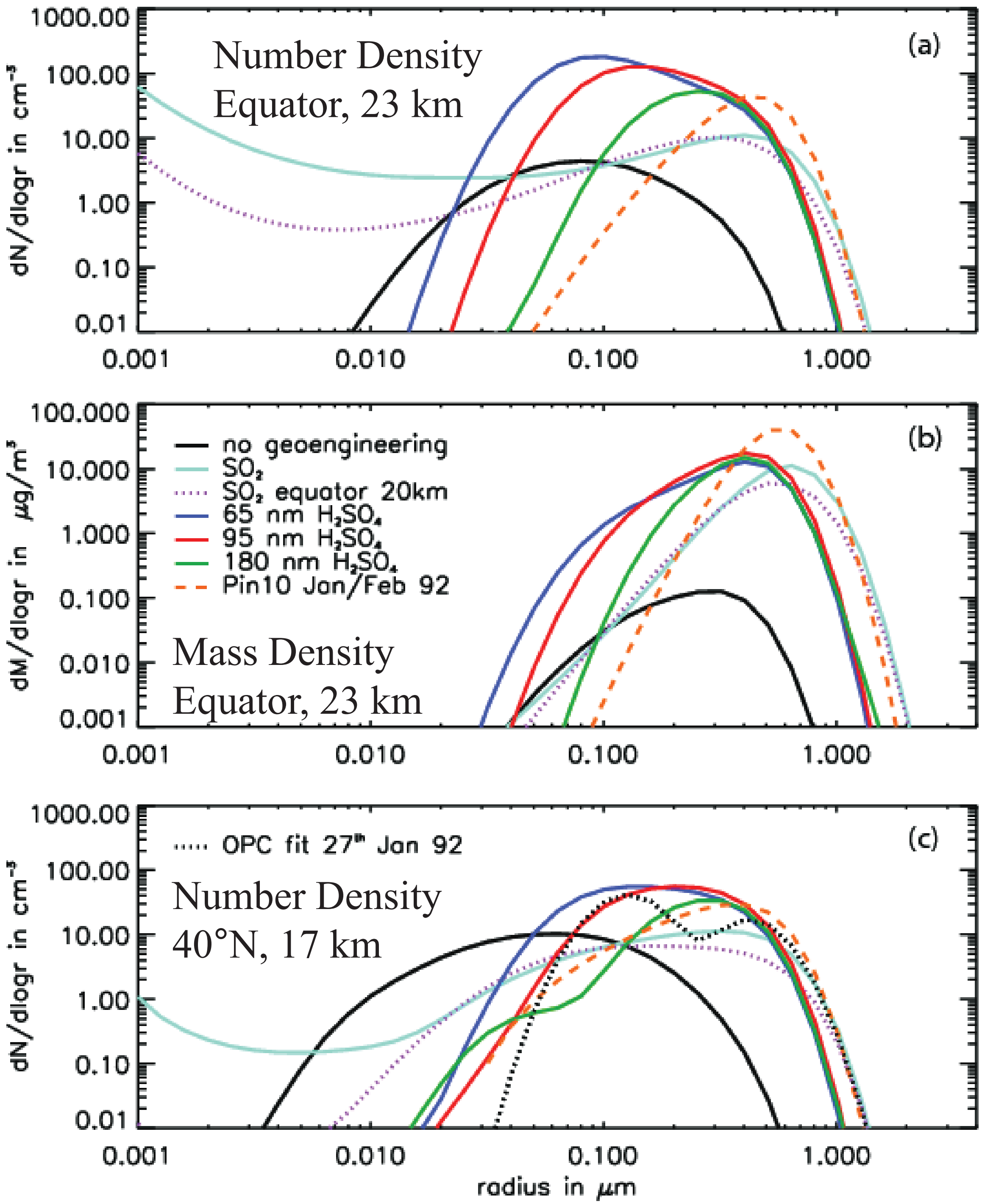



Particle size controlled by injection rate, dilution rate, coagulation rate

Insensitive to nucleation rate, condensation rate

r = 0.065-0.2 μm,
$\sigma = 1.5$
used as input to 2D

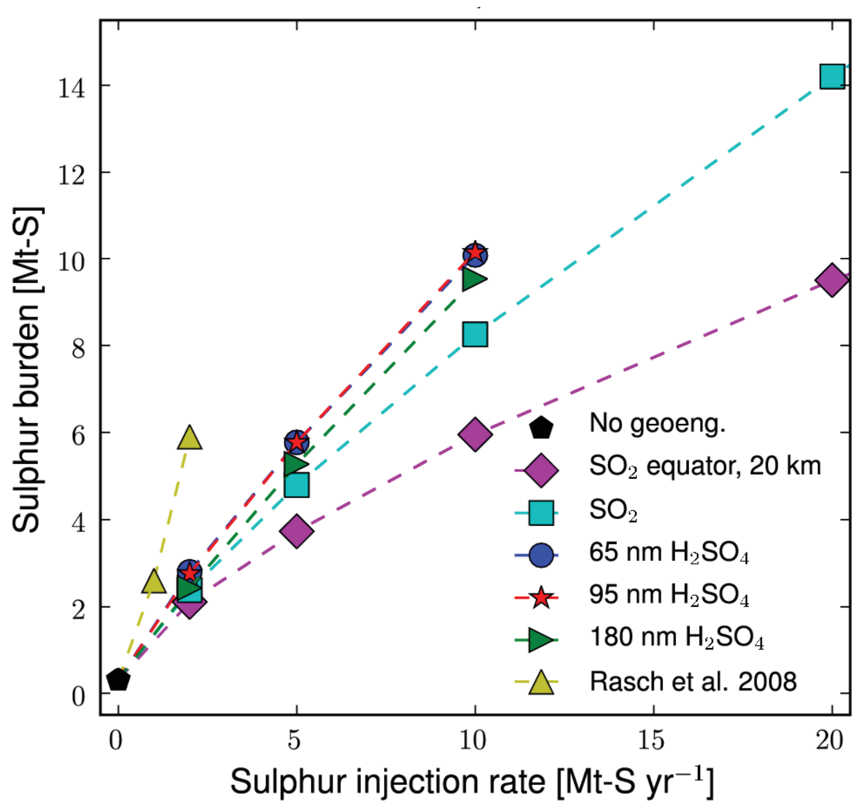
# Steady State Size Distributions
## with 5 MT-S/yr continuous emission



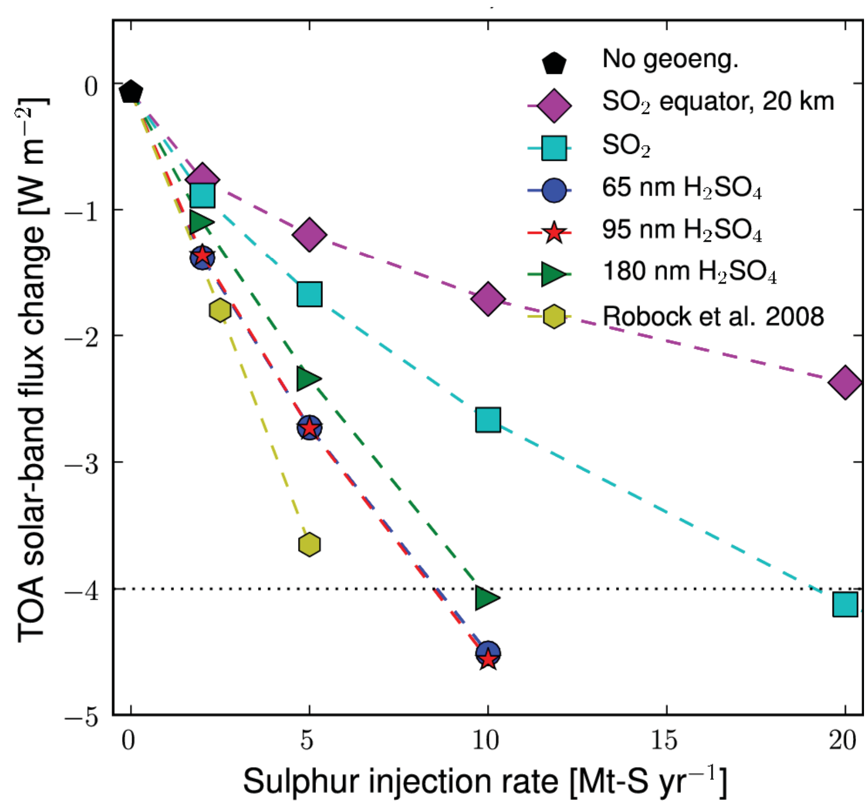

$SO_2$ emission cases: nucleation mode, more large particles

$H_2SO_4$ 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 2x$CO_2$ 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?