Stratospheric sulfate geoengineering has limited efficacy and increases tropospheric burdens

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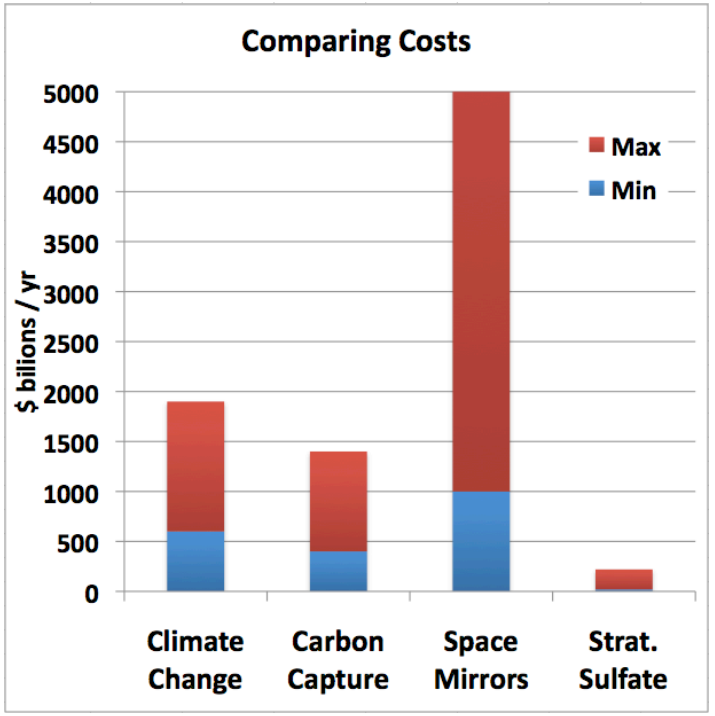
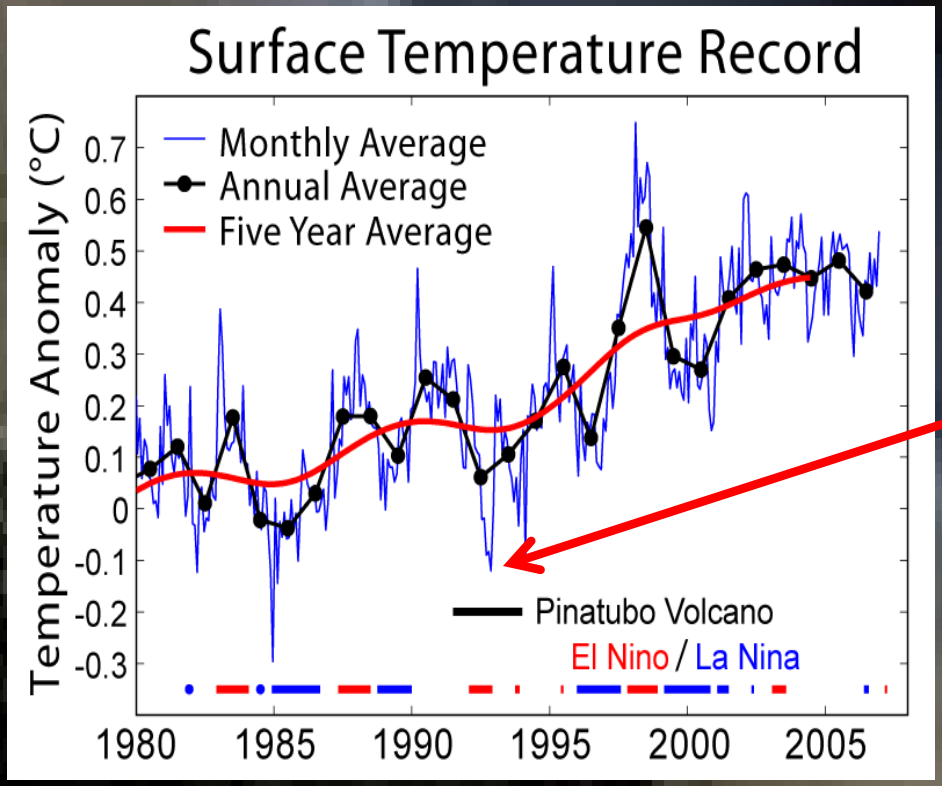
The stratospheric sulfate geoeng. approach

Drawing by Brian West. Robock et al., 2009

- Why the stratosphere?
  - Aerosols stay aloft 100x longer
- Inject ~5 to 20 Tg SO_2/yr
- Balloons, tall pipes, aircraft, artillery
- Cost: <$2 to 200 billion/yr
- This may be economical…

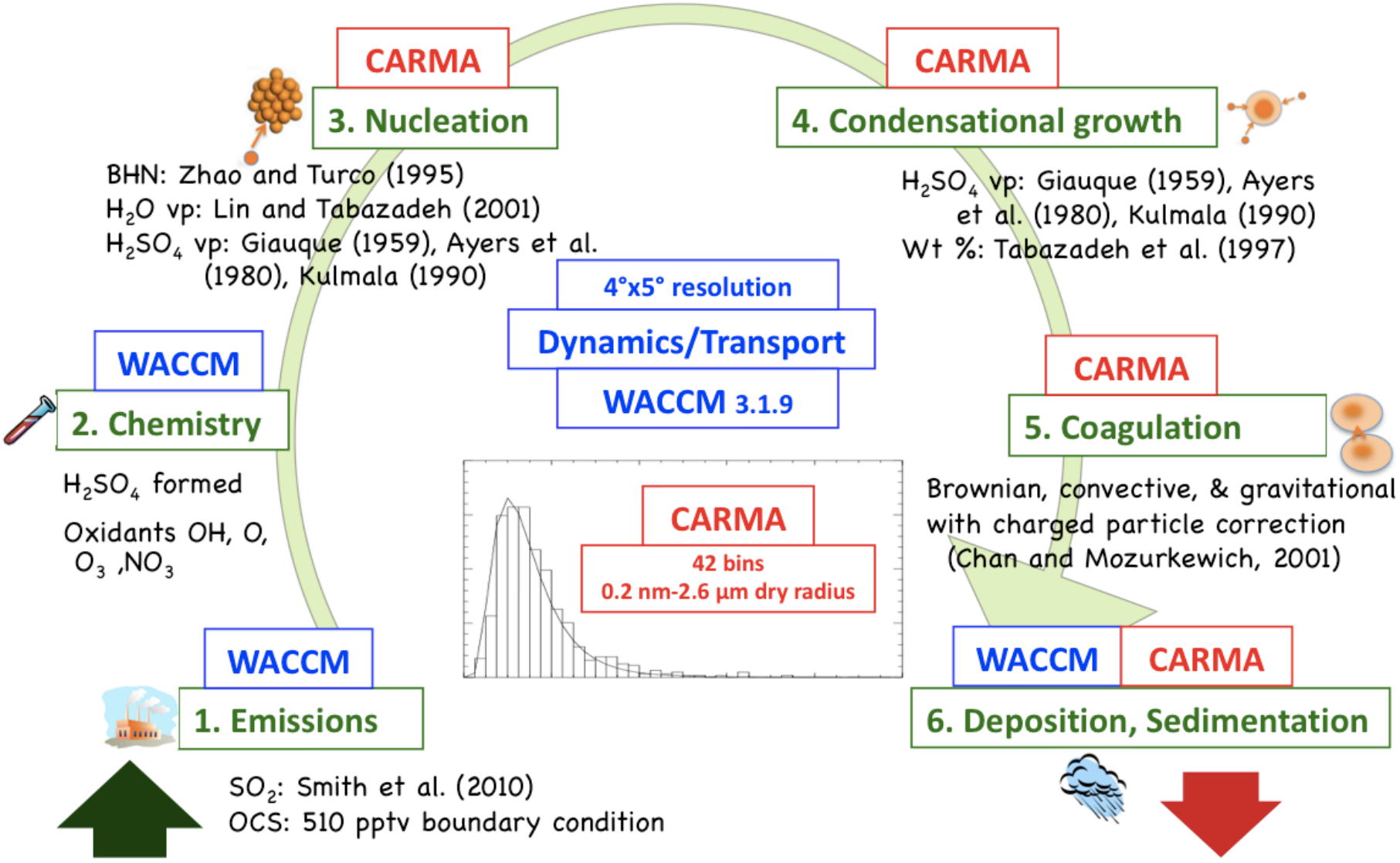


Mt. Pinatubo (1991) demonstrated cooling



- 1992: Temperature dropped 0.5°C; coolest year in the past 25 years
- We also saw ozone loss, hydrological changes

WACCM/CARMA Coupled Model (English *et al.*, *ACPD*, 2011)



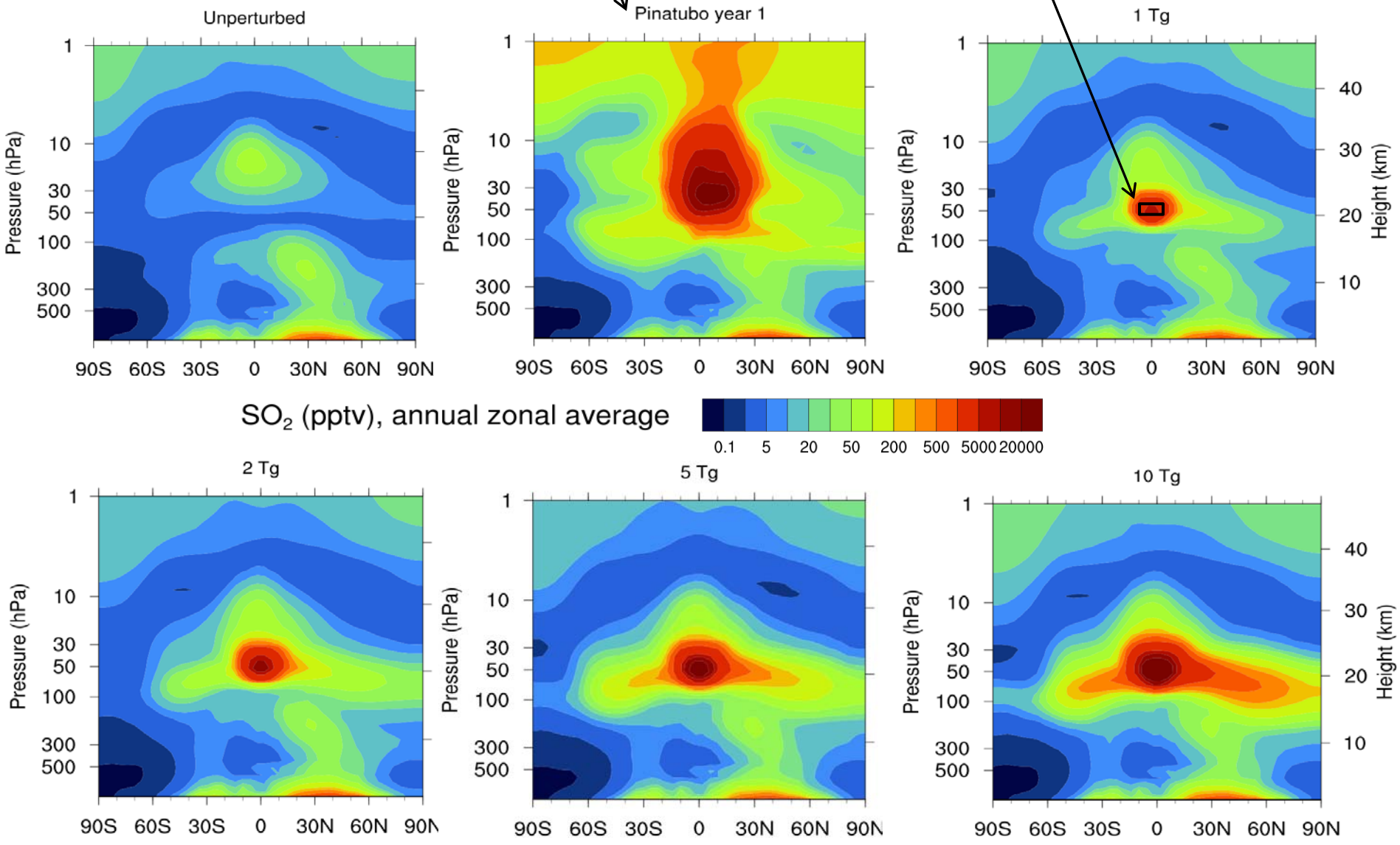
Aerosol radiative effects not coupled, but het chem is

5 year simulations; 5th year analyzed

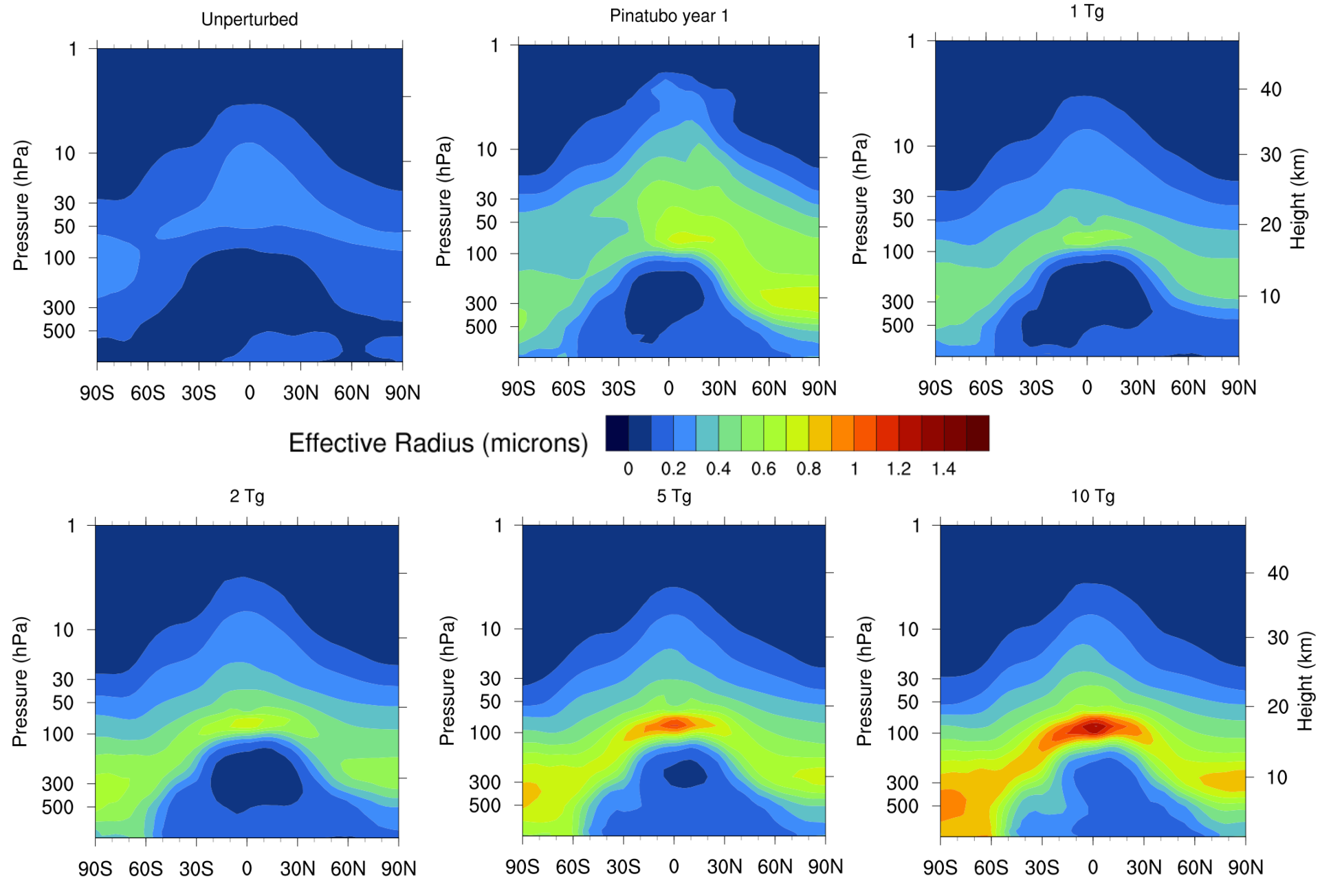
6 runs: Unperturbed, Pinatubo, and 4 Geoeng Injections

10 Tg 1-day, 13-100 mb, 2S-16N, 97-117E

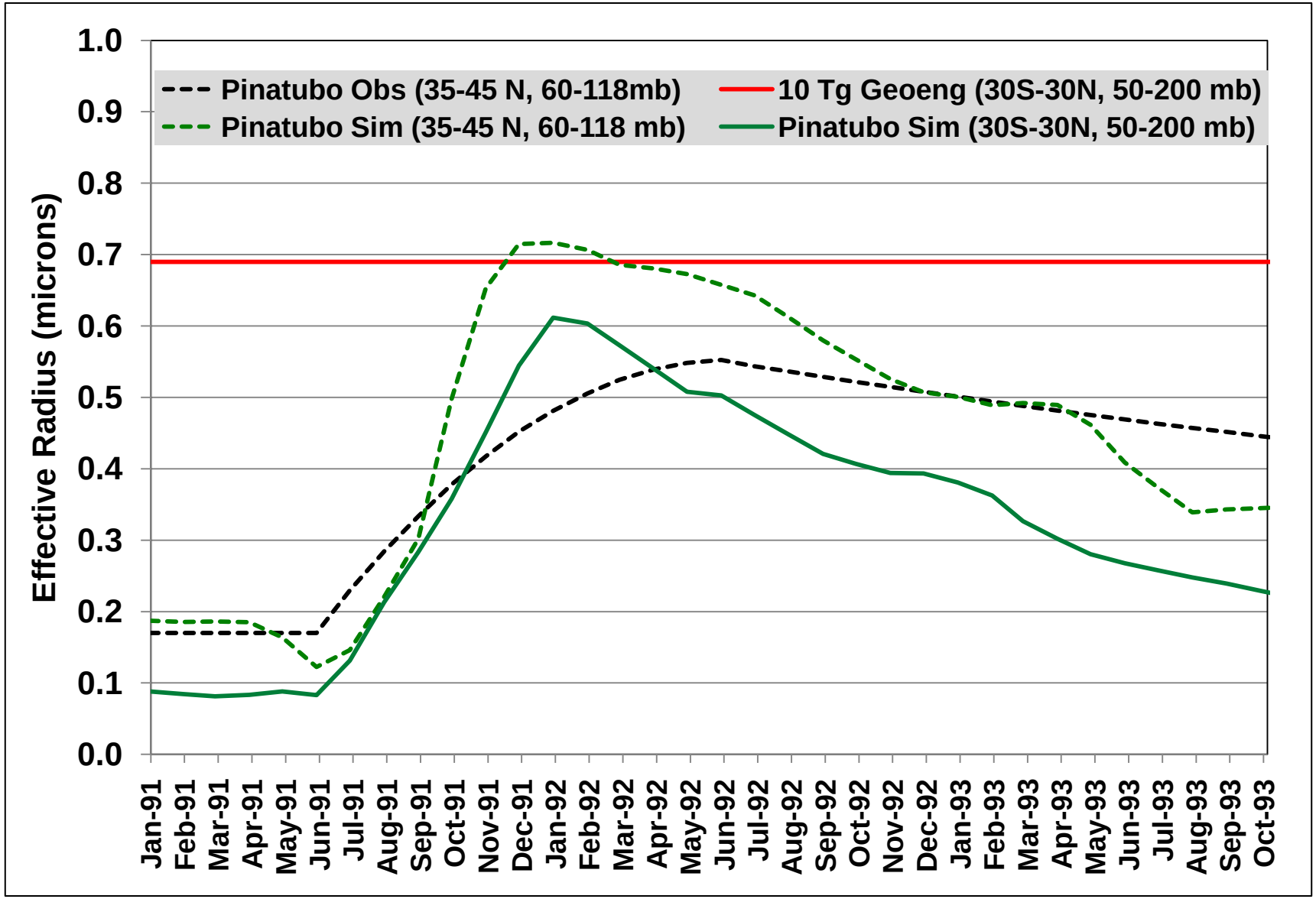
Continuous, 50 mb, 4N-4S, all lon



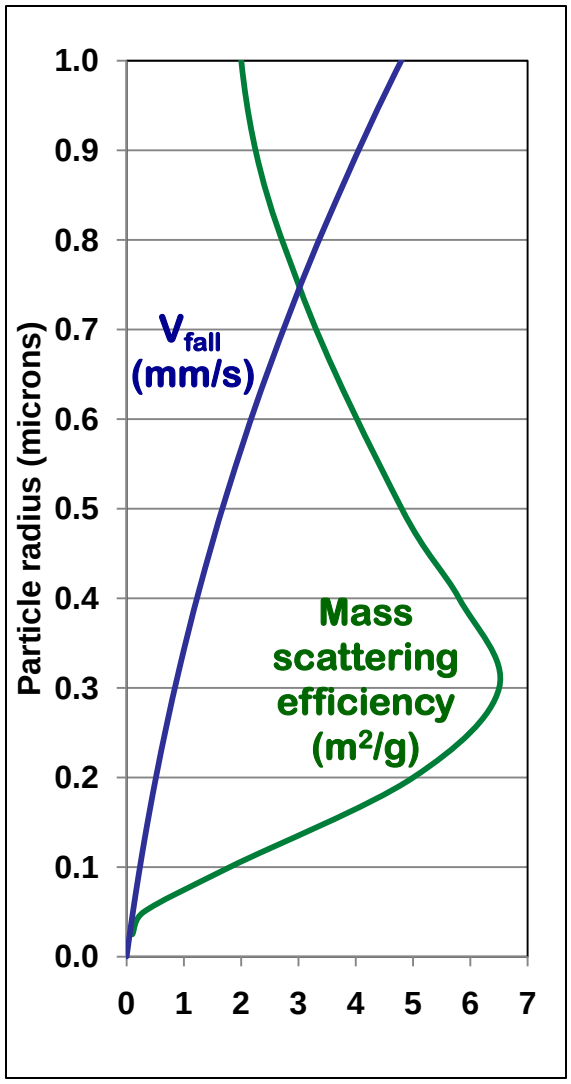
Geoengineered effective radius is larger

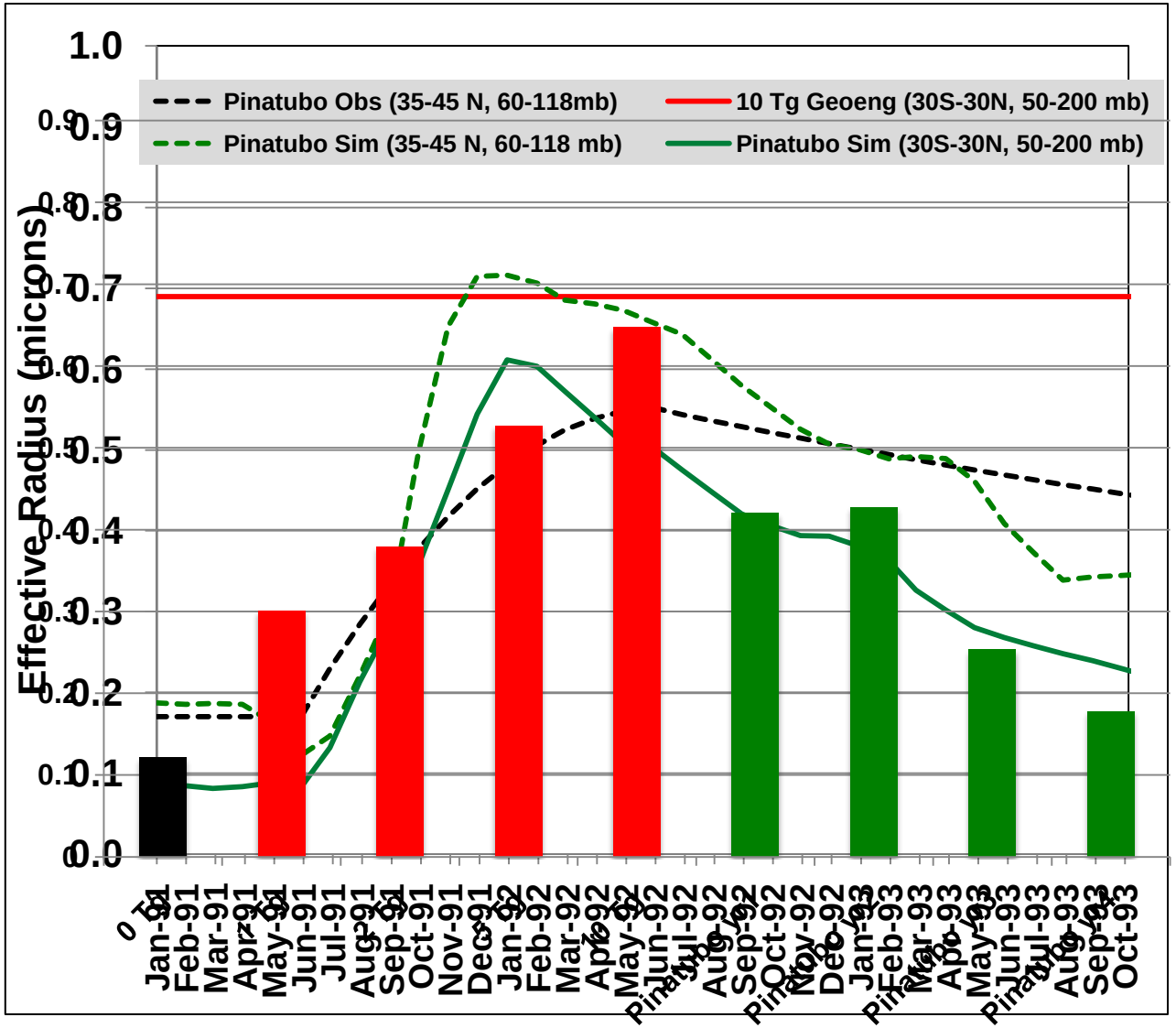


Simulated Pinatubo R_{eff} reaches peak sooner than obs; Simulated Geoeng R_{eff} larger than Pinatubo

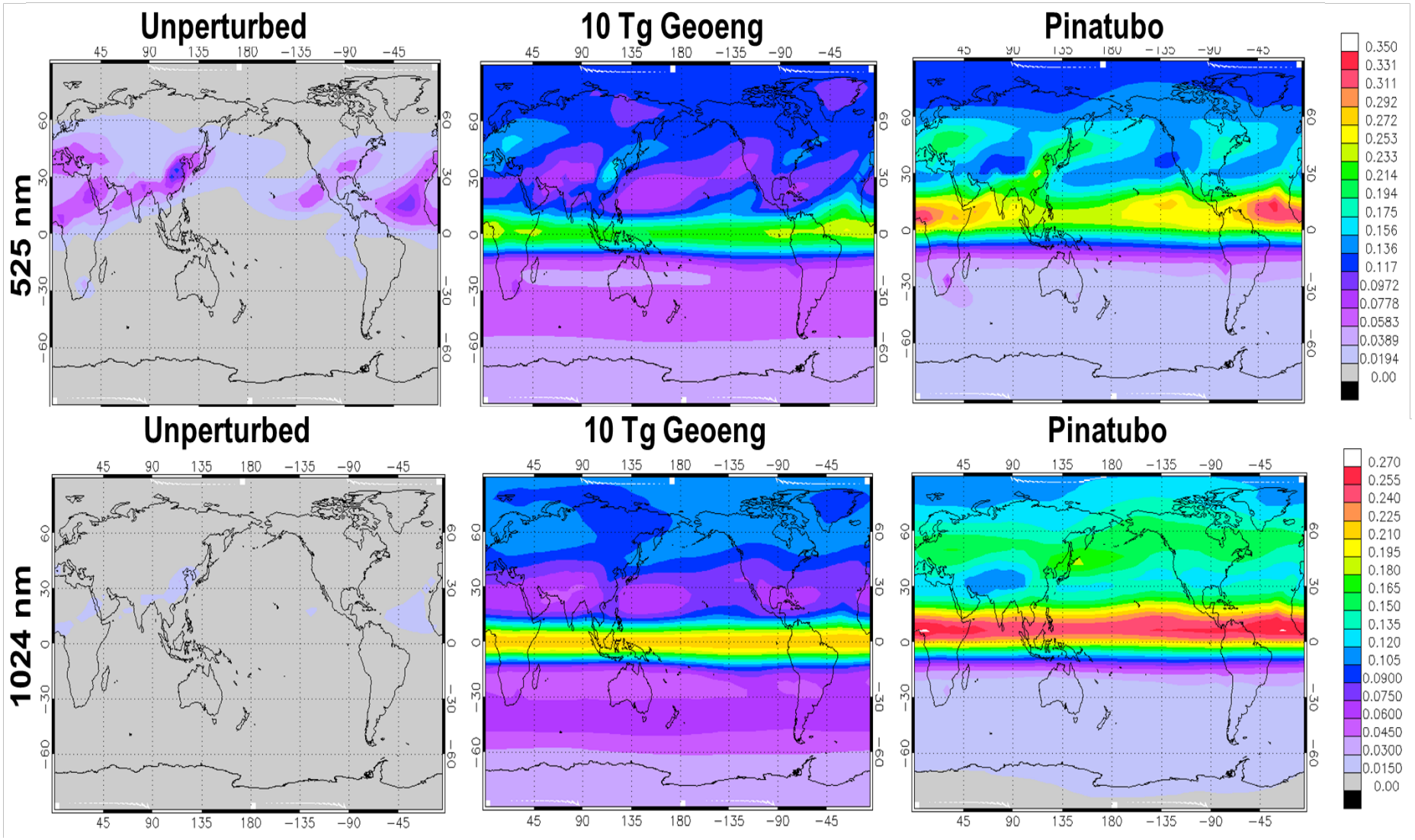


Larger particles fall faster and RF less effective

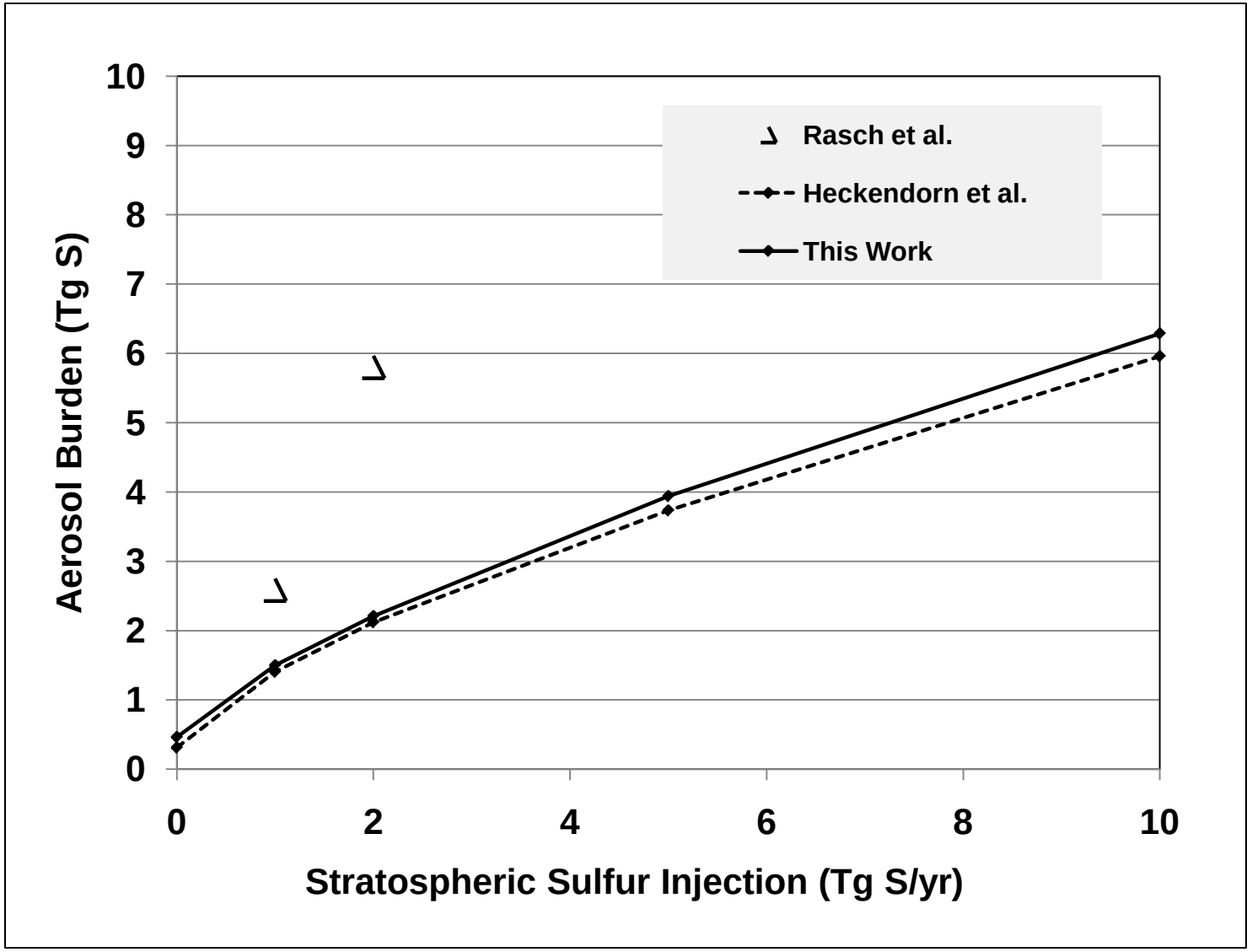




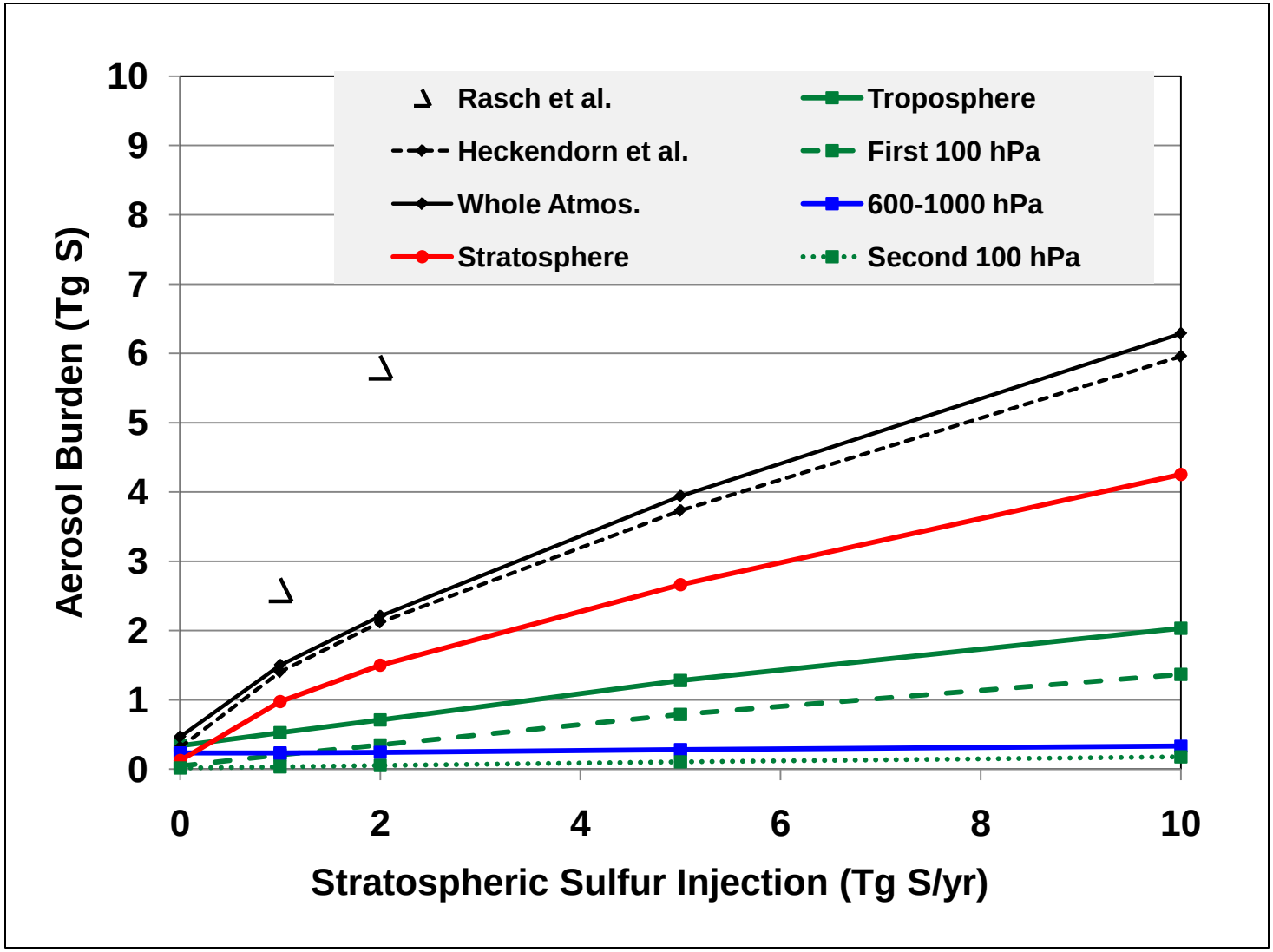
Continuous injection has lower AOD than a Volcano



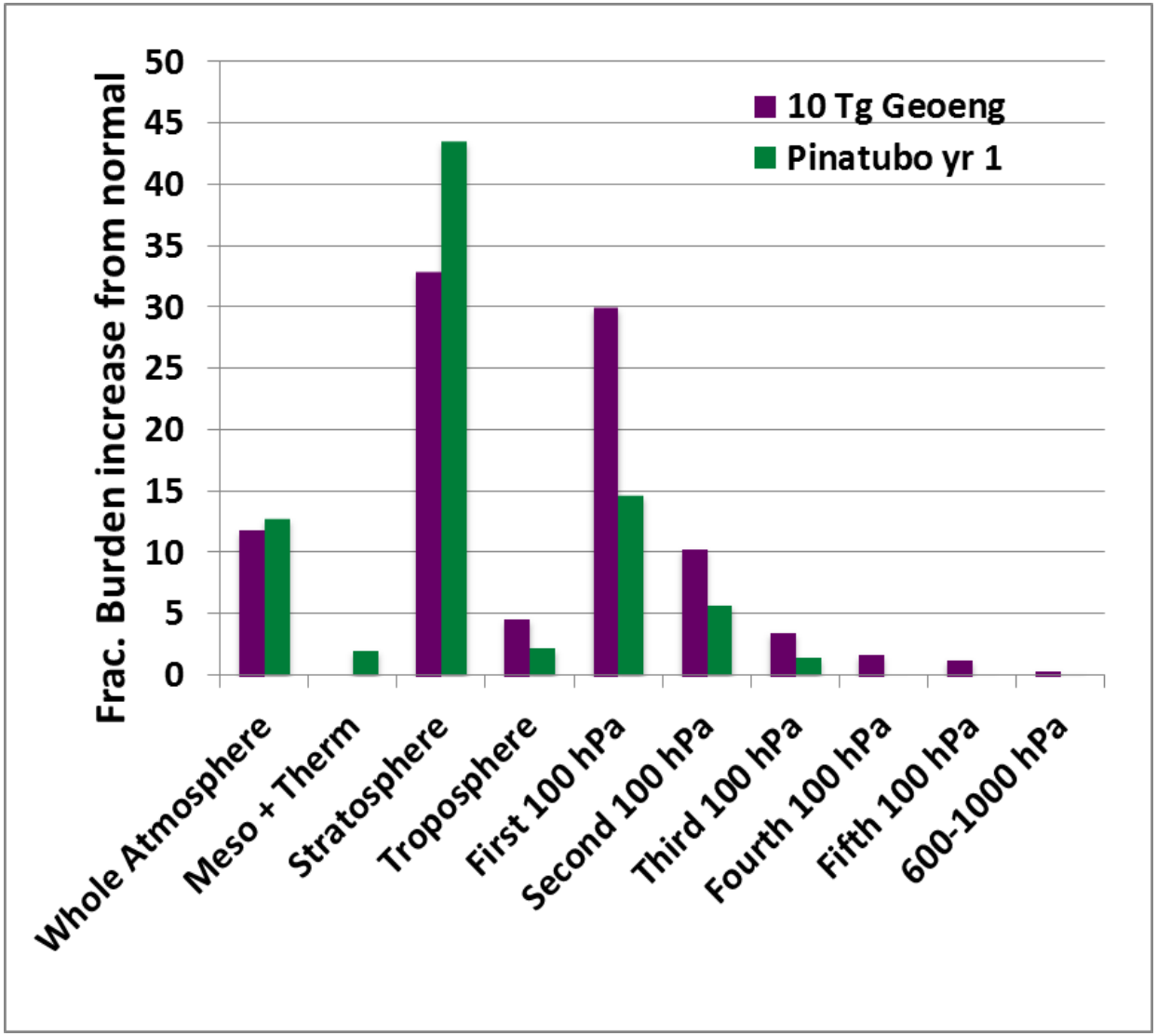
Two microphysical studies compare well, and differ significantly from GCM-only simulations

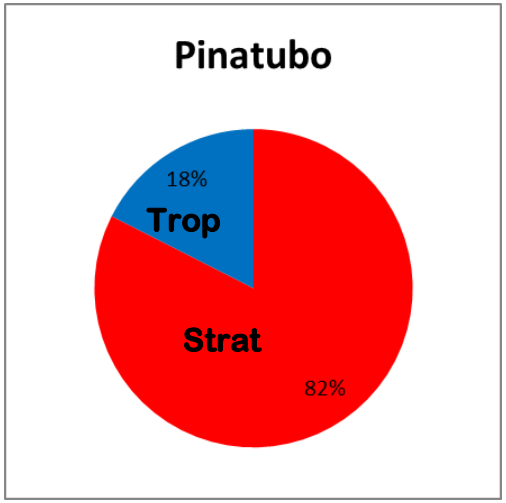


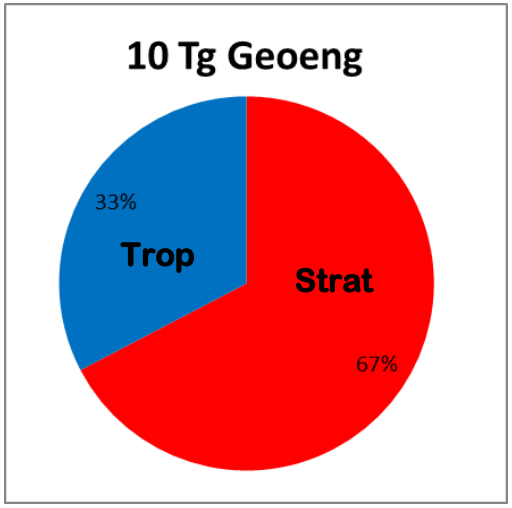
1/3 of total burden is in the troposphere; 1/3 of that is in the first 100 hPa below the tropopause



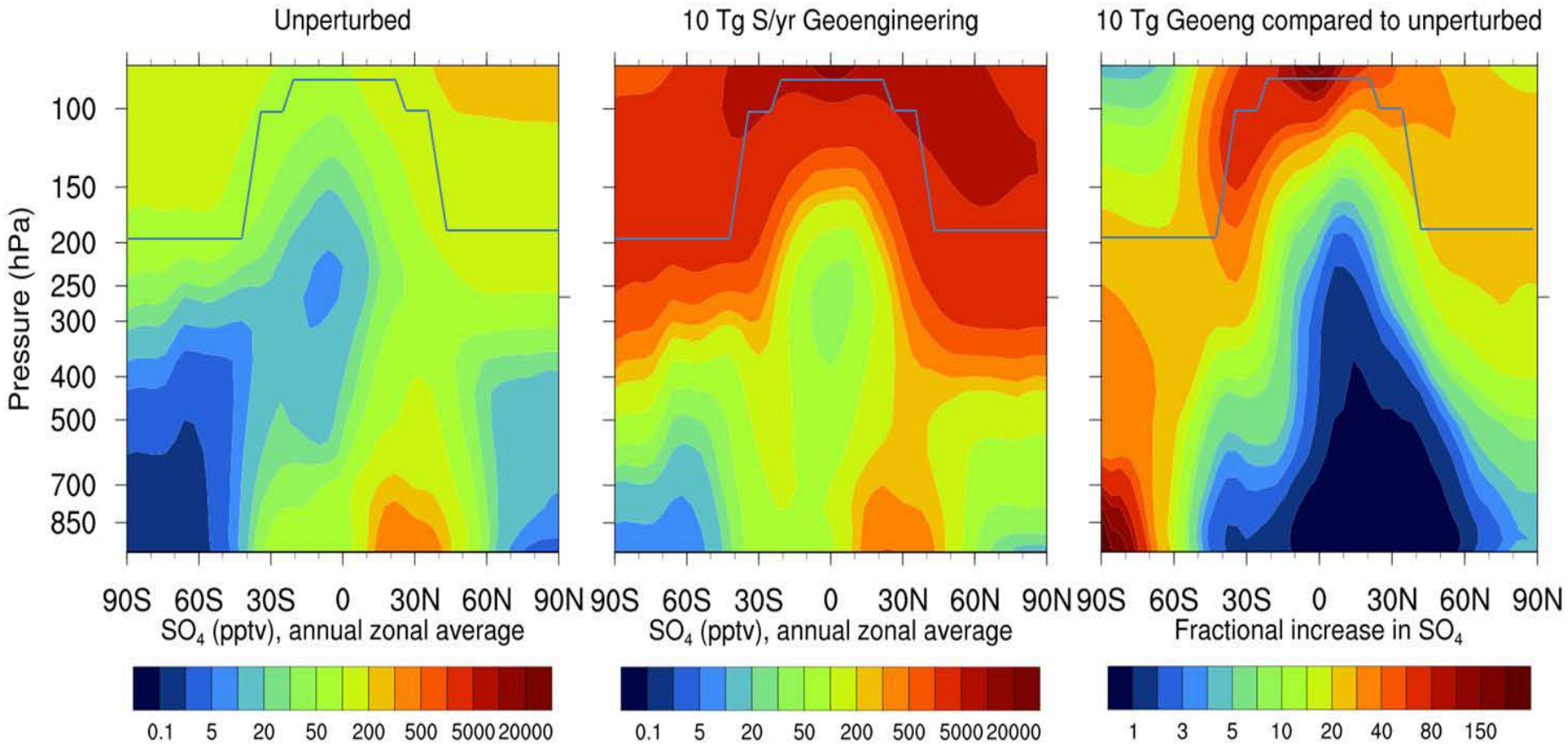
Continuous injection adds more burden to troposphere



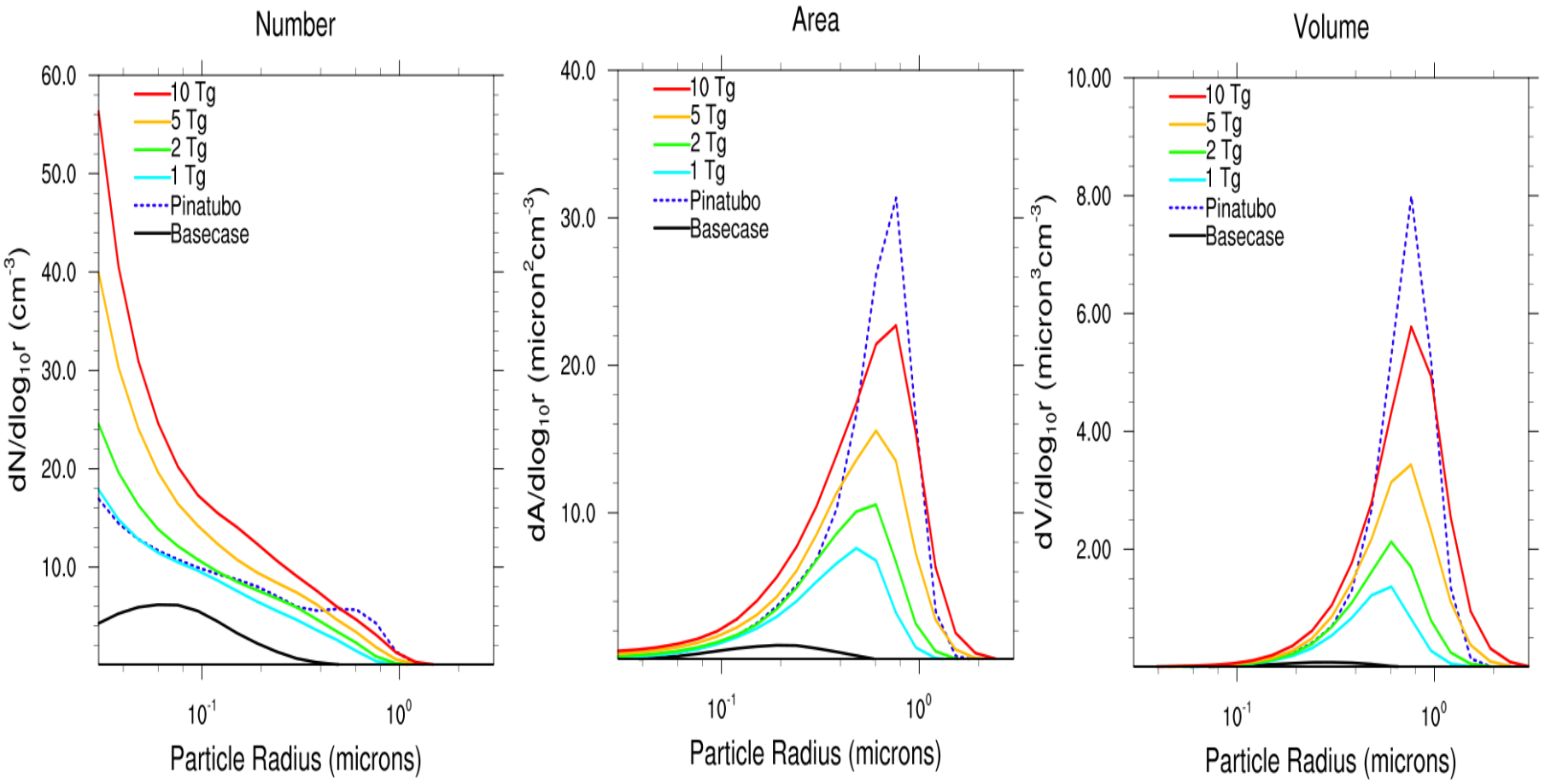




Geoeng increases tropospheric burden in the upper troposphere and high latitudes up to 100x



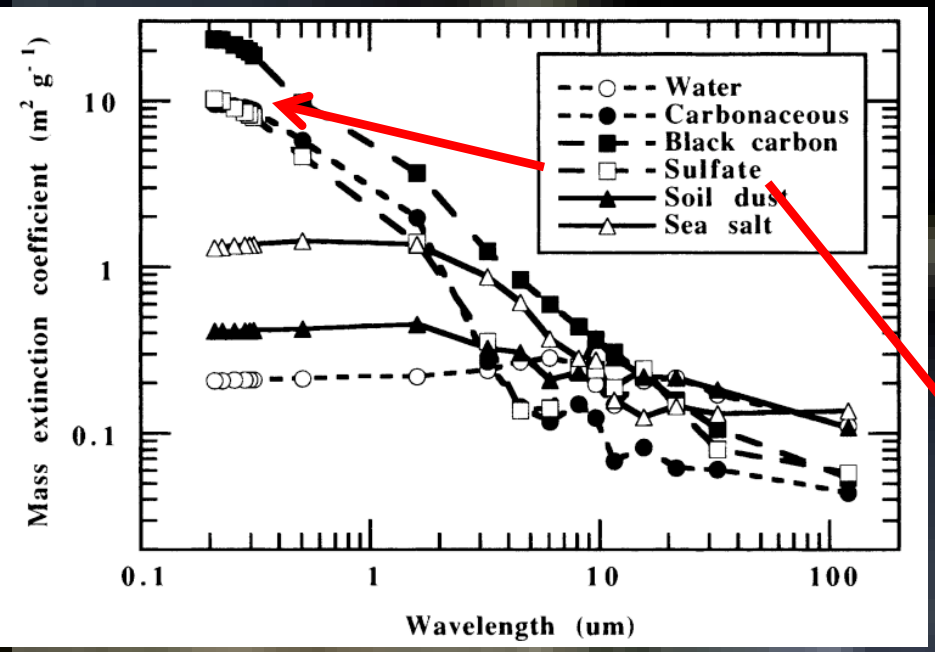
Geoeng increases aerosol number, area, and volume in the upper troposphere



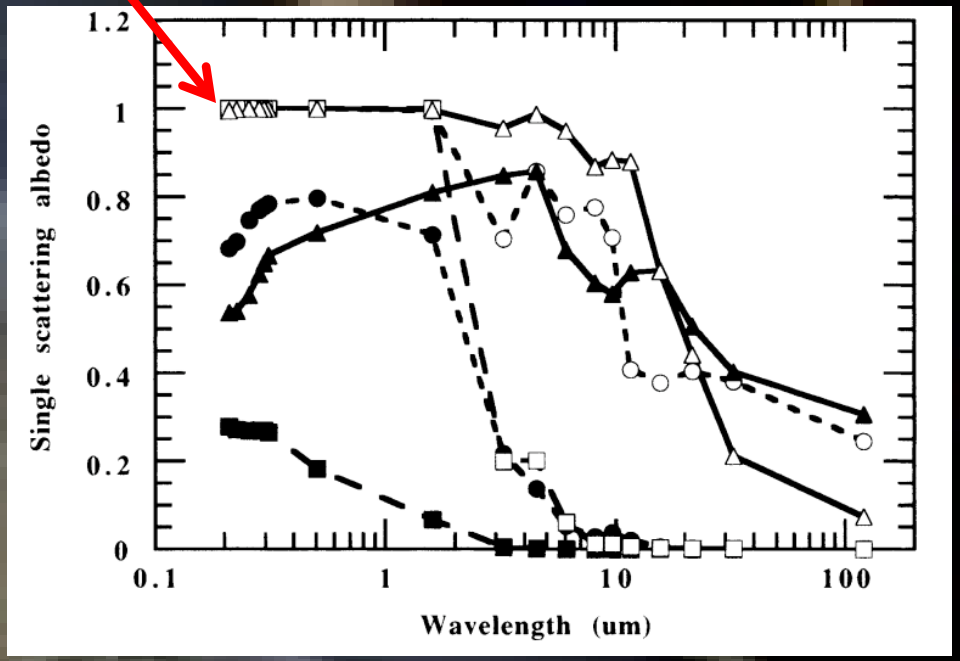
Our 3D microphysical simulations of stratospheric SO_2 injection suggest…

- Geoengineered effective radius is larger than Pinatubo; shorter lifetime limits aerosol burden to ~6 Tg burden (~2 W m^{-2})
  - Results compare favorably to Heckendorn et al.
- Geoeng increases tropospheric aerosol burden, especially high altitude and latitude
  - Troposphere increases 5x; upper troposphere by 30x; high latitudes by 30x
  - Could impact tropospheric clouds, radiative forcing, and chemistry
- Other consequences previously identified:
  - Ozone destruction / stratospheric chemistry changes
  - Acid deposition in mid/high latitudes
  - Hydrological changes/reduced precipitation
- Stratospheric lifetime may be increased by
  - Sulfur sources with slower conversion to aerosol
  - Other aerosol types
  - Higher injection / more spread out

Why are sulfate aerosols so special?



Sulfates have high extinction (ability to reflect and absorb radiation)

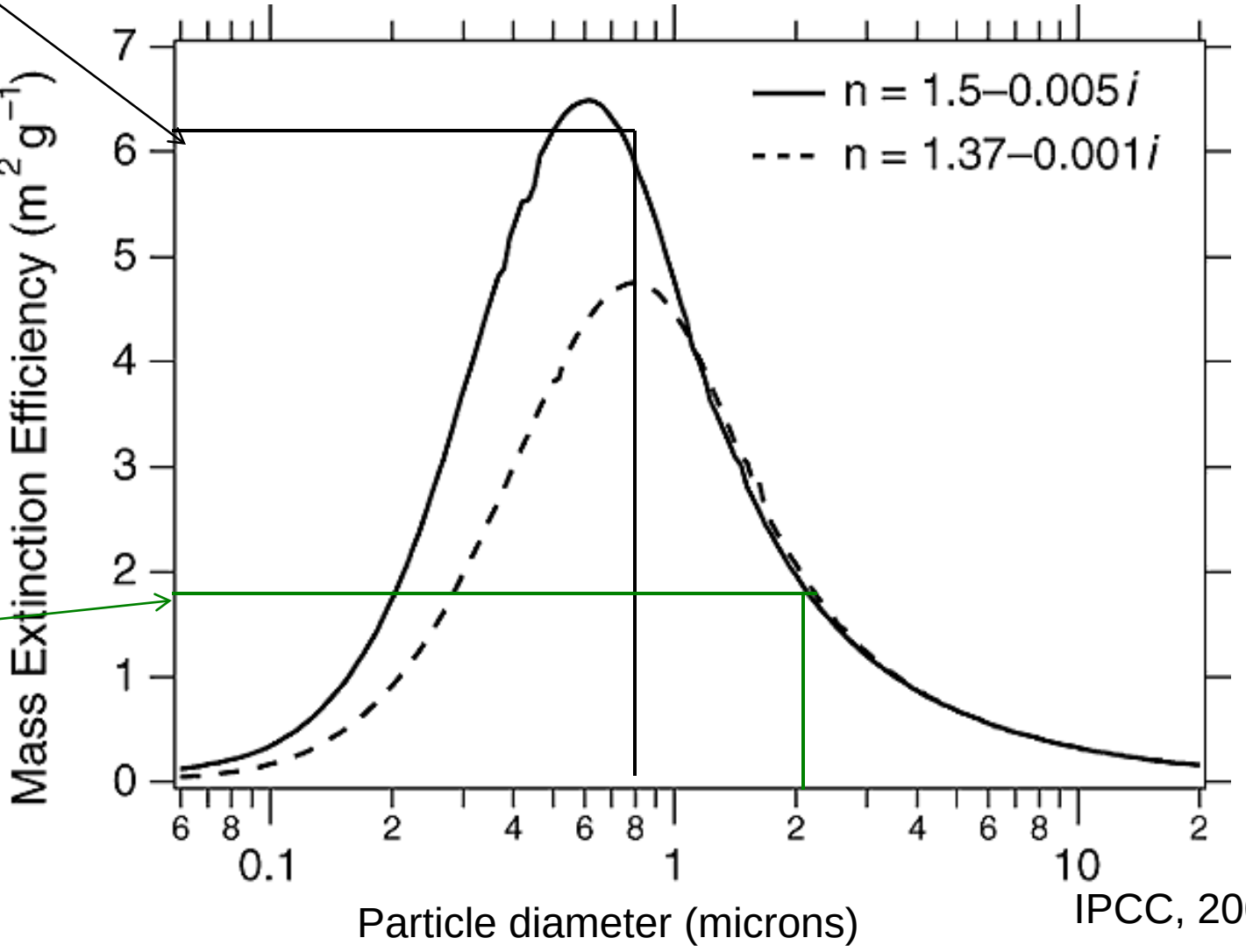


Sulfates have high Single Scattering Albedo (they prefer to reflect radiation rather than absorb it)

What does SO_2 have to do with sulfate aerosols?

…And the particles that are there, aren't as effective at scattering radiation

Pinatubo:
6 m^2/g

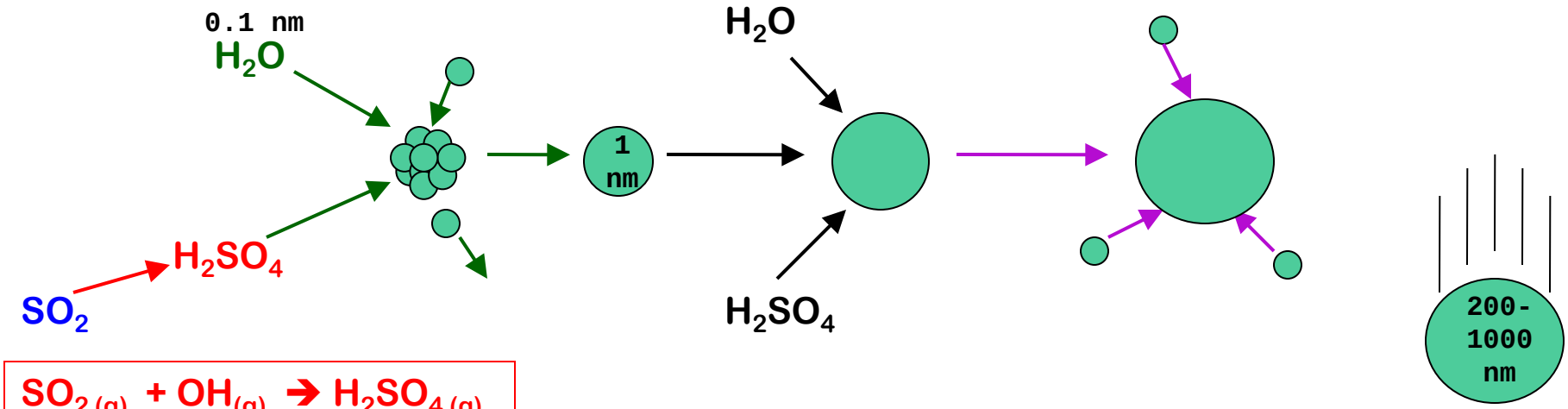


13 Tg geoeng:
2 m^2/g

IPCC, 2001

The sulfate aerosol life cycle

1. emissions	2. chemistry	3. nucleation	4. growth	5. coagulation	6. deposition
Mt. Pinatubo (20 Tg SO_2), geoengineering (? Tg SO_2)	Sulfuric acid is made	an aerosol is born	evaporation, condensation	particles collide and combine	particles fall to the earth



$SO_{2\,(g)} + OH_{(g)} \rightarrow H_2SO_{4\,(g)}$

Most climate models parameterize some of these processes (esp. nucleation, growth, coagulation)