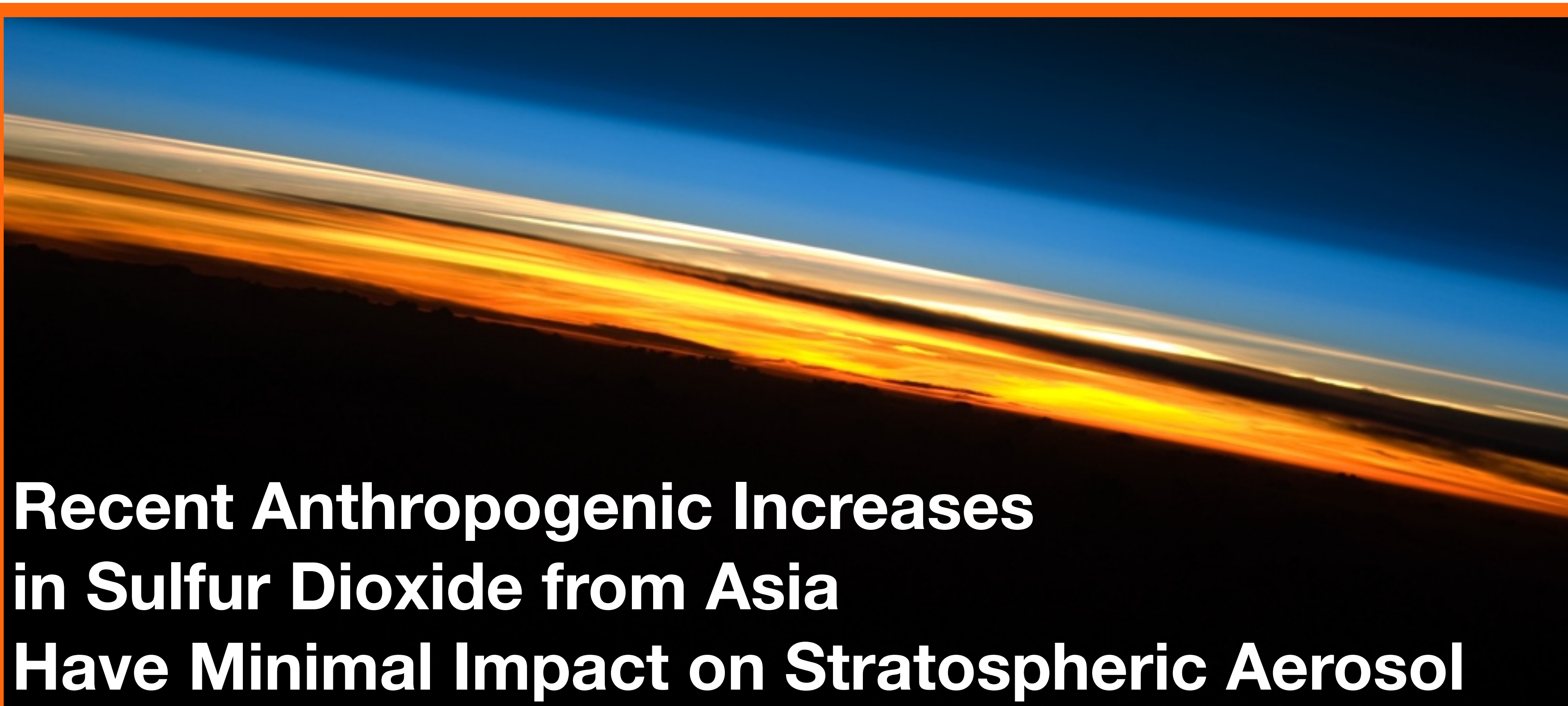


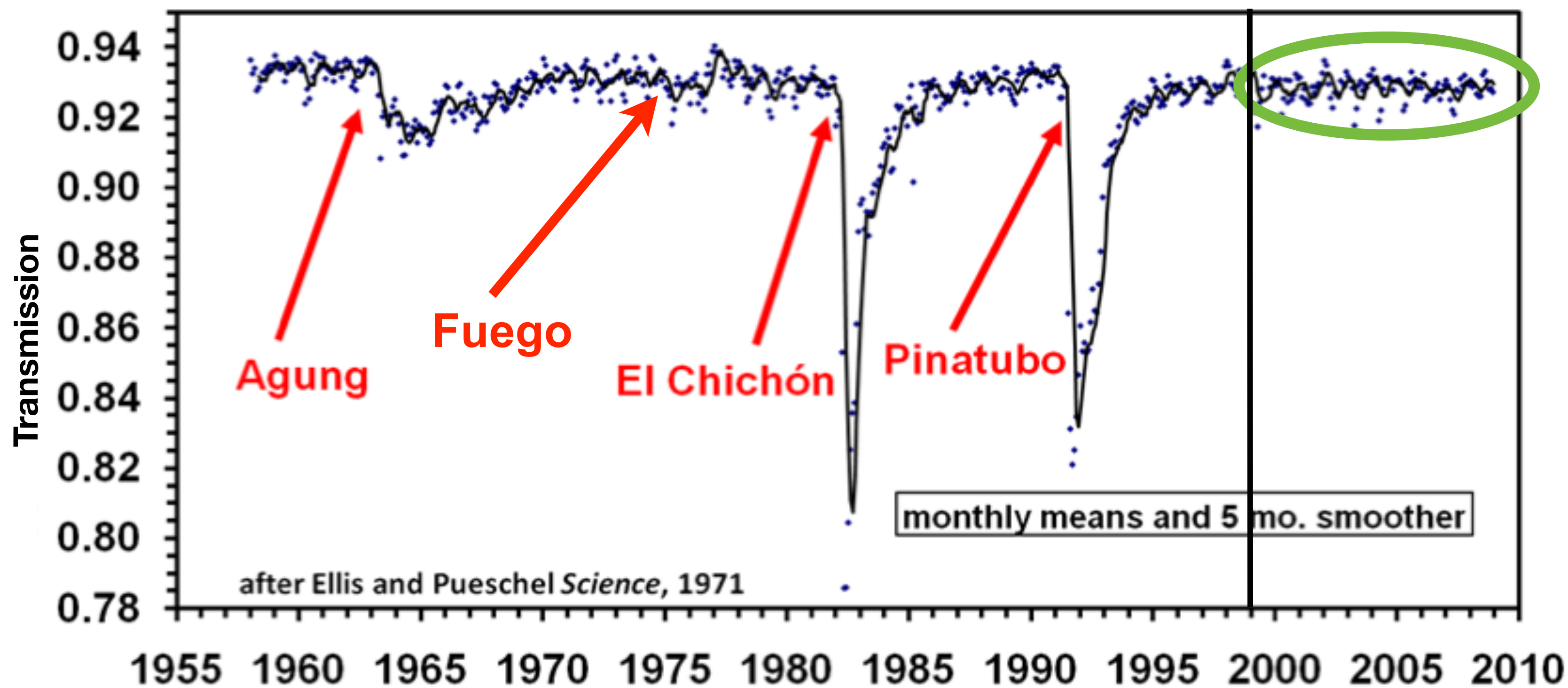
Recent Anthropogenic Increases in Sulfur Dioxide from Asia Have Minimal Impact on Stratospheric Aerosol

Ryan R. Neely III, O. Brian Toon, Susan Solomon, J. P. Vernier, C. Alvarez, J. M. English, K. H. Rosenlof, M. J. Mills,C. G. Bardeen, John S. Daniel, Jeffrey P. Thayer

Acknowledgments: P. Yu, H. L. Miller, J. E. Barnes

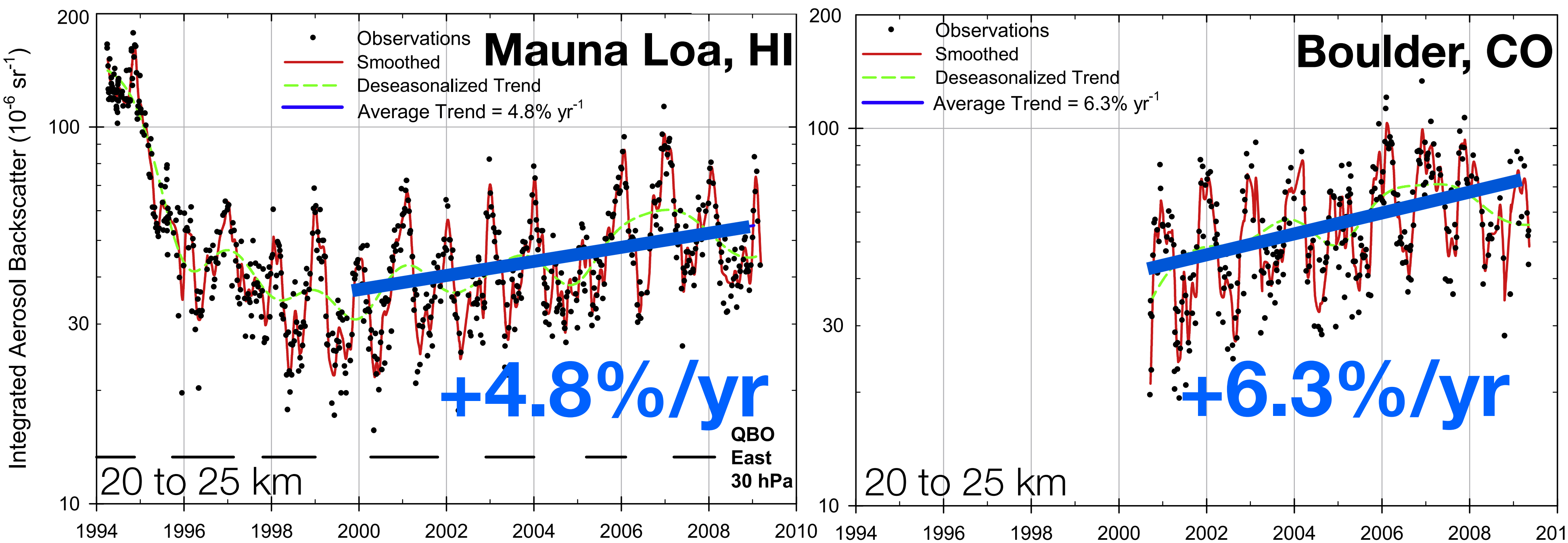
Neely et al. (2013), Recent anthropogenic increases in SO_2 from Asia have minimal impact on stratospheric aerosol, GRL, 40, doi:10.1002/grl.50263.

2000 to 2010 is an unprecedented “background” period



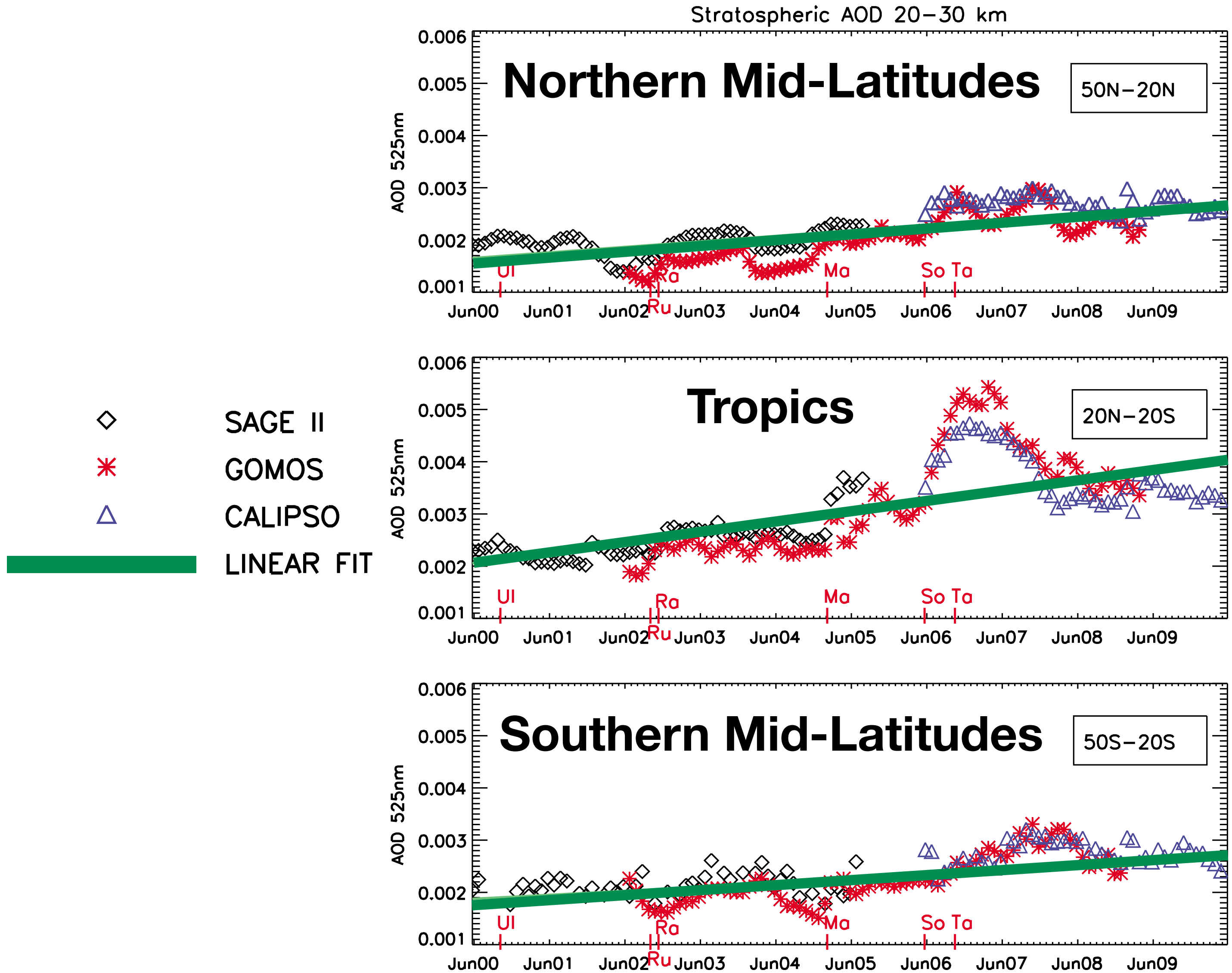
Clear Sky Transmission At Mauna Loa, HI indicates “background” stratospheric aerosol conditions since 1998.

GMD Lidar observations reveal variability in “background” stratospheric aerosol



Adapted from Hofmann at al. (2009)

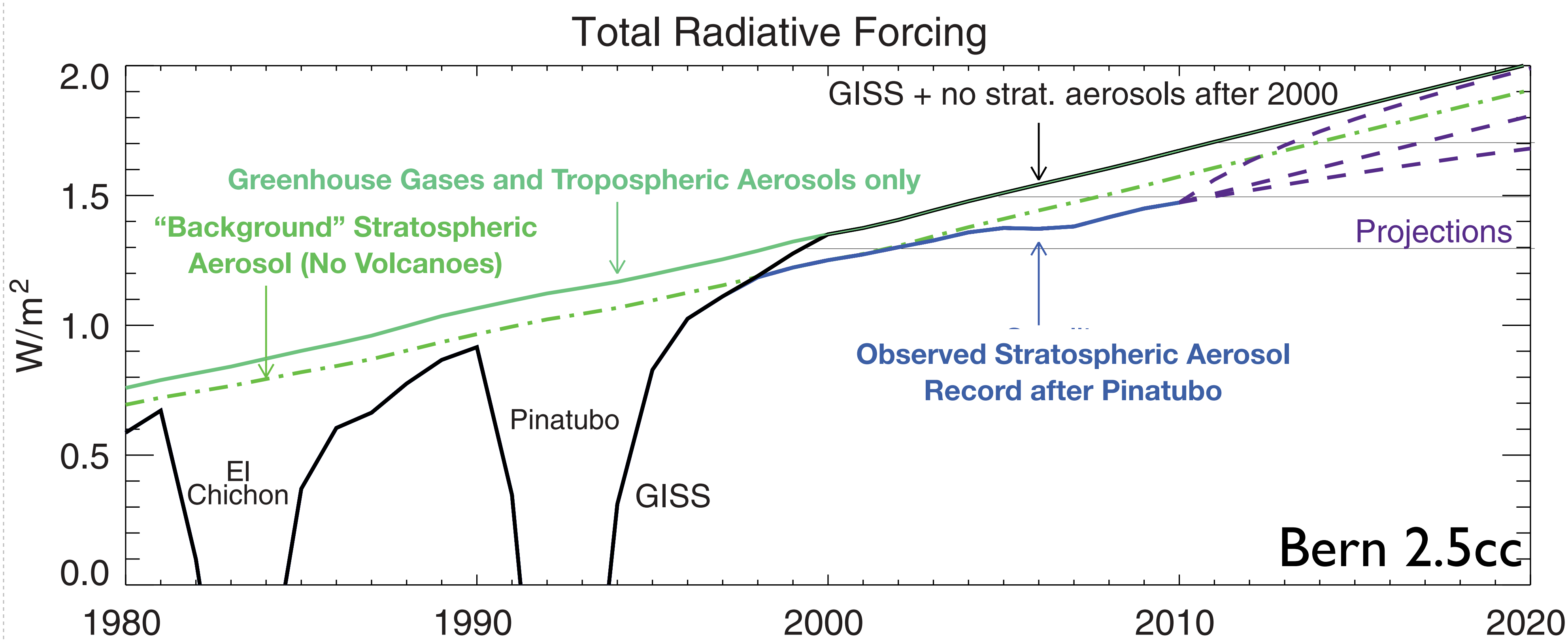
A “Trend” In Global Stratospheric Aerosol?



Trends 4-7%/yr

Adapted from Vernier, J. P. et al. Major influence of tropical volcanic eruptions on the stratospheric aerosol layer during the last decade. Geophys. Res. Lett 38, L12807– (2011).

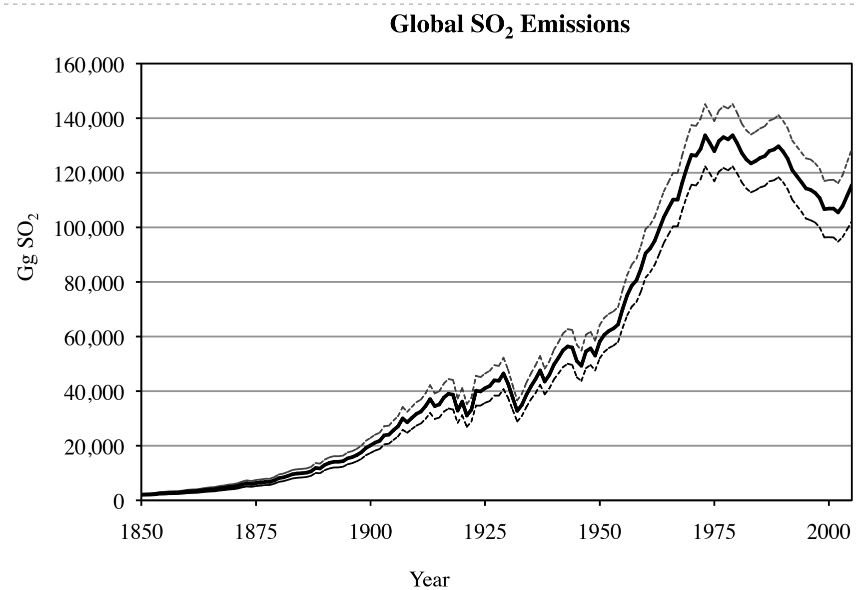
Variability in stratospheric aerosol impacts global radiative forcing

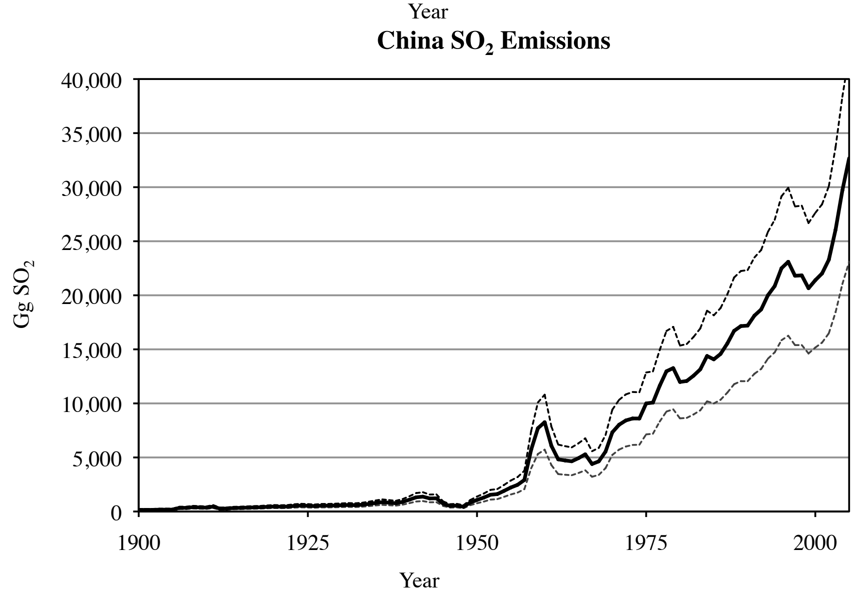


Greenhouse gas forcing increased continuously throughout period. Stratospheric aerosol only slowed increase by ~0.2W/m²

Possible Theories for "Trends": Asian Emissions?

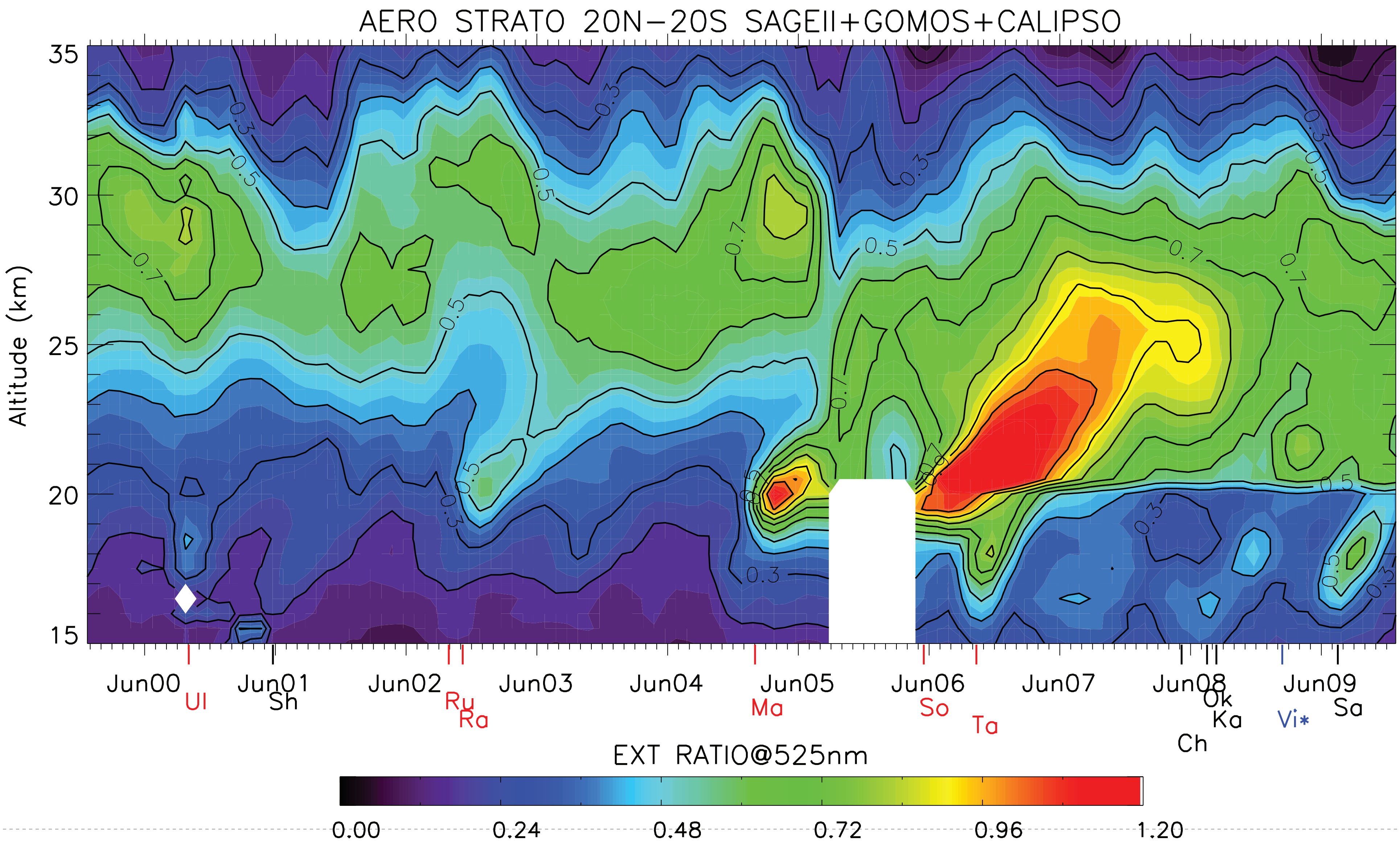
0.6% of Global Emissions must make it to stratosphere to maintain sulfur burden (Hofmann et al. 2009)





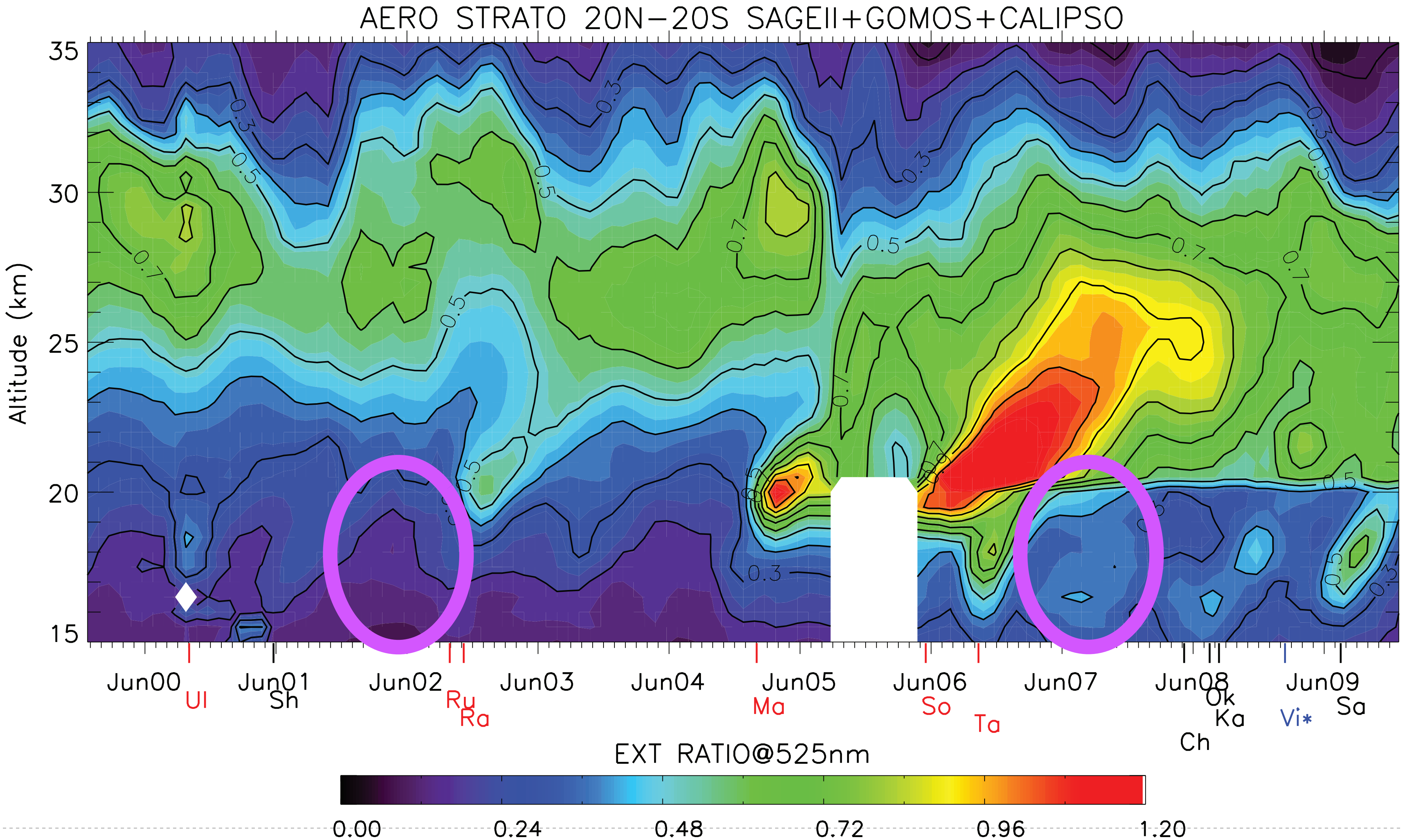
Adapted from Smith, S. J., J. van Aardenne, Z. Klimont, R. J. Andres, A. Volke, and S. Delgado Arias (2011), Anthropogenic sulfur dioxide emissions: 1850–2005, Atmos. Chem. Phys, 11(3), 1101–1116, doi:10.5194/acp-11-1101-2011.

Possible Theories for “Trends”: Moderate Volcanoes?

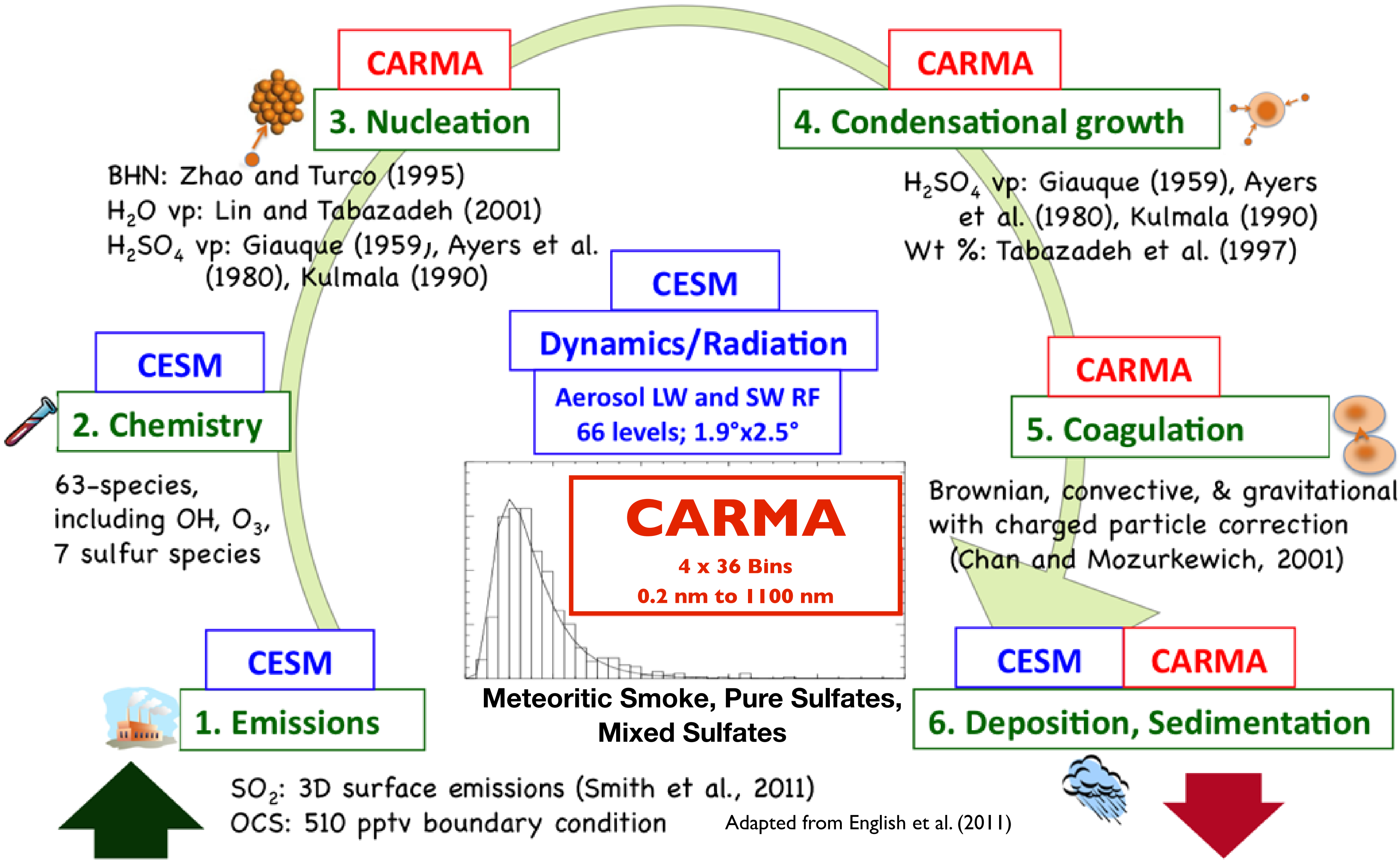


Adapted from Vernier, J. P. et al. Major influence of tropical volcanic eruptions on the stratospheric aerosol layer during the last decade. GRL 38, L12807– (2011).

Current observations cannot partition the observed variability to sources

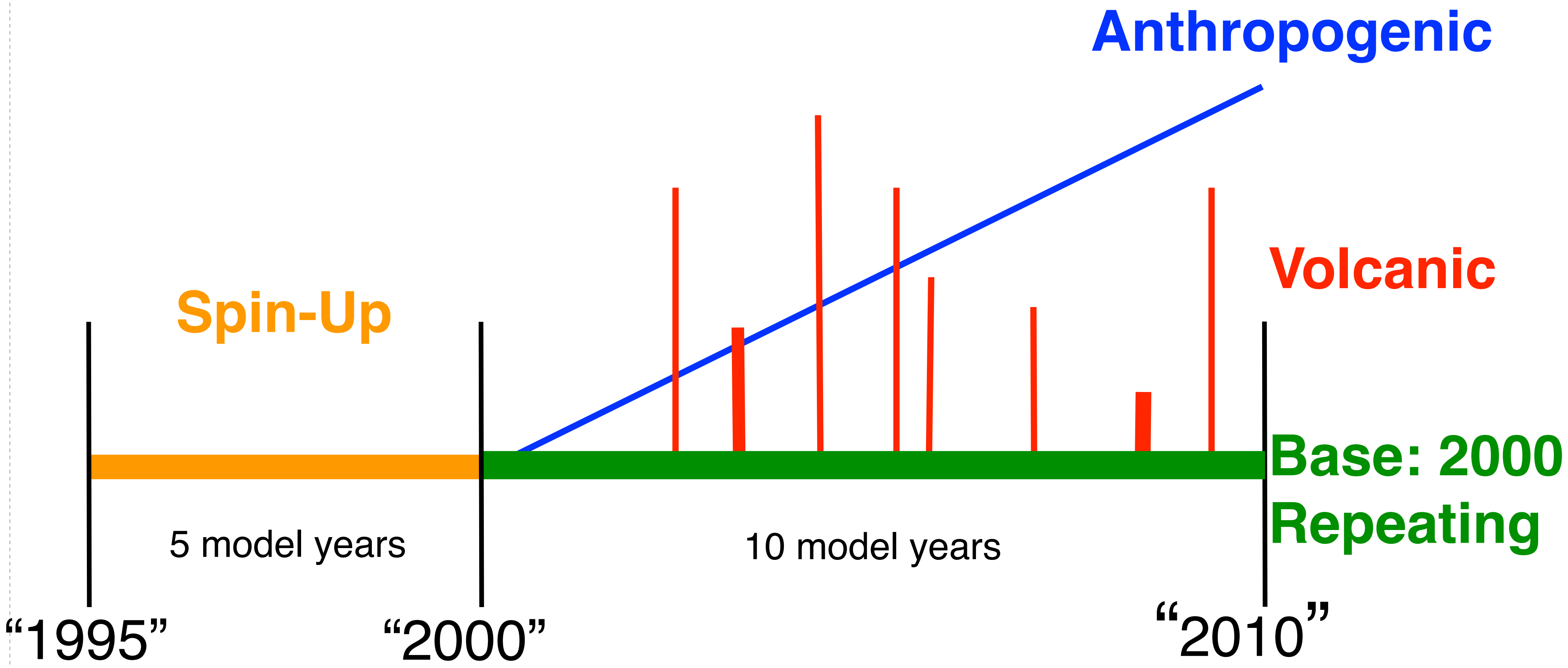


The Model

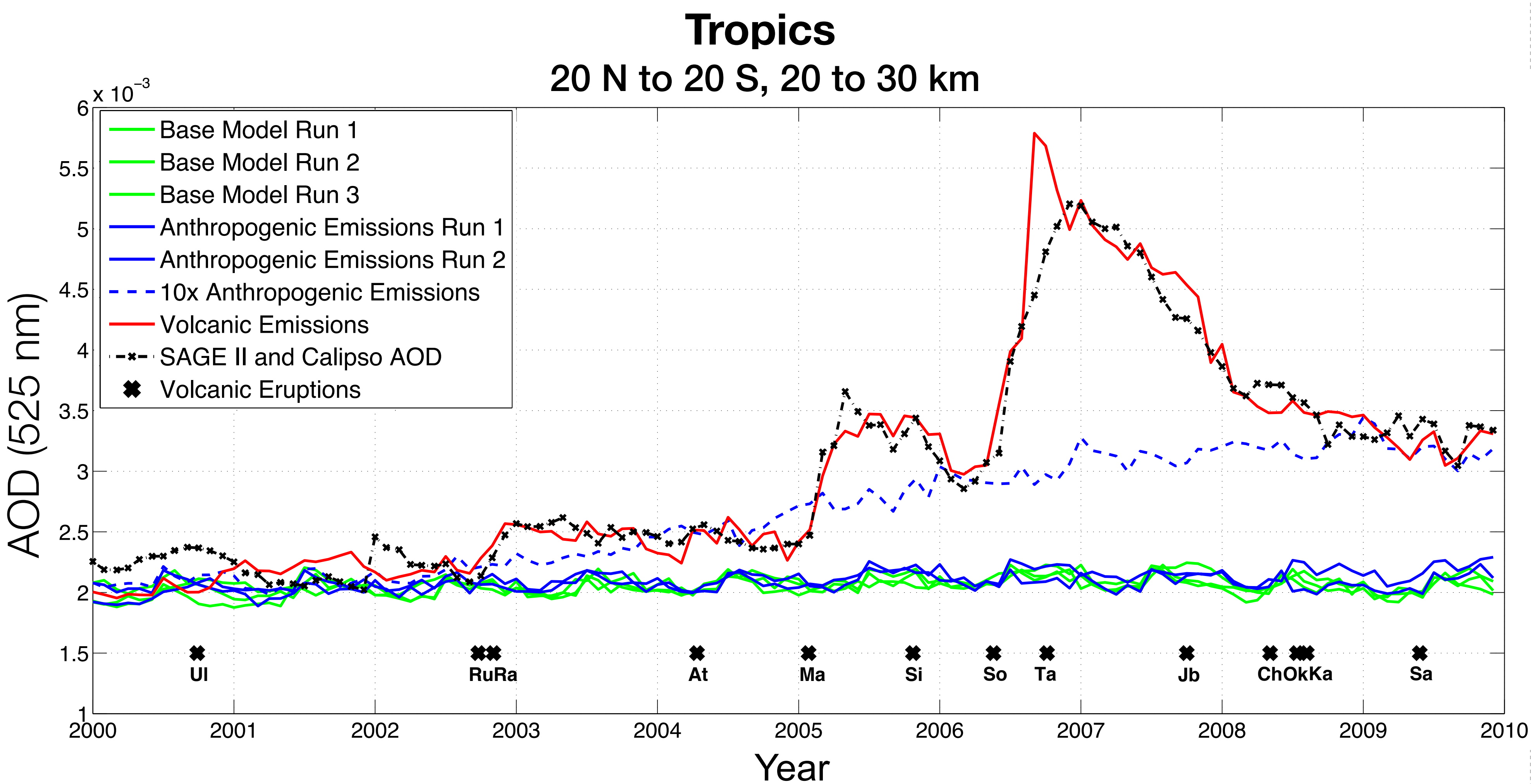


Neely, R. R., III, J. M. English, O. B. Toon, S. Solomon, M. Mills, and J. P. Thayer (2011), Implications of extinction due to meteoritic smoke in the upper stratosphere, Geophys. Res. Lett, 38(24), doi:10.1029/2011GL049865.

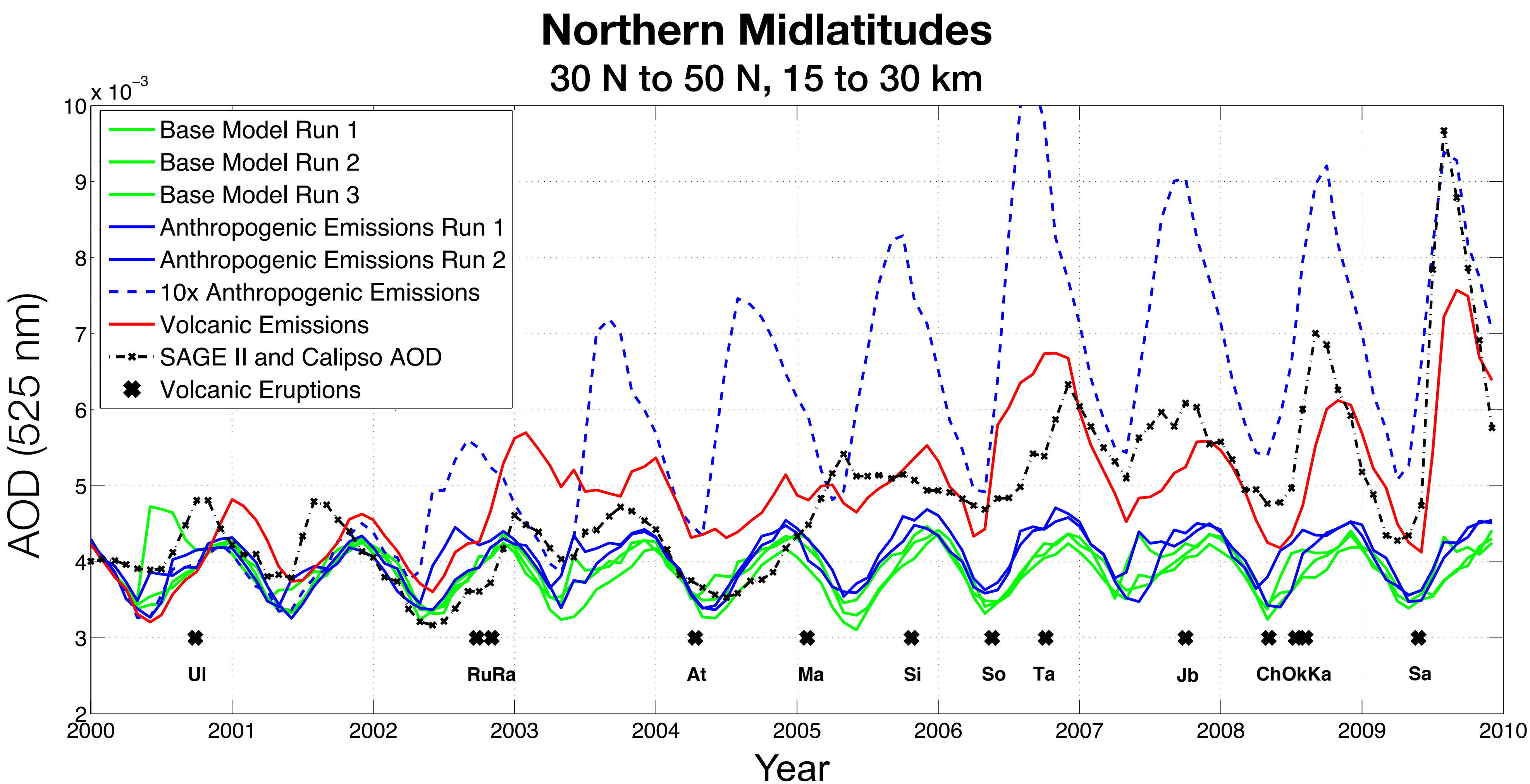
Model Experiment Setup: SO_2 Schemes



Volcanoes drive stratospheric aerosol variability

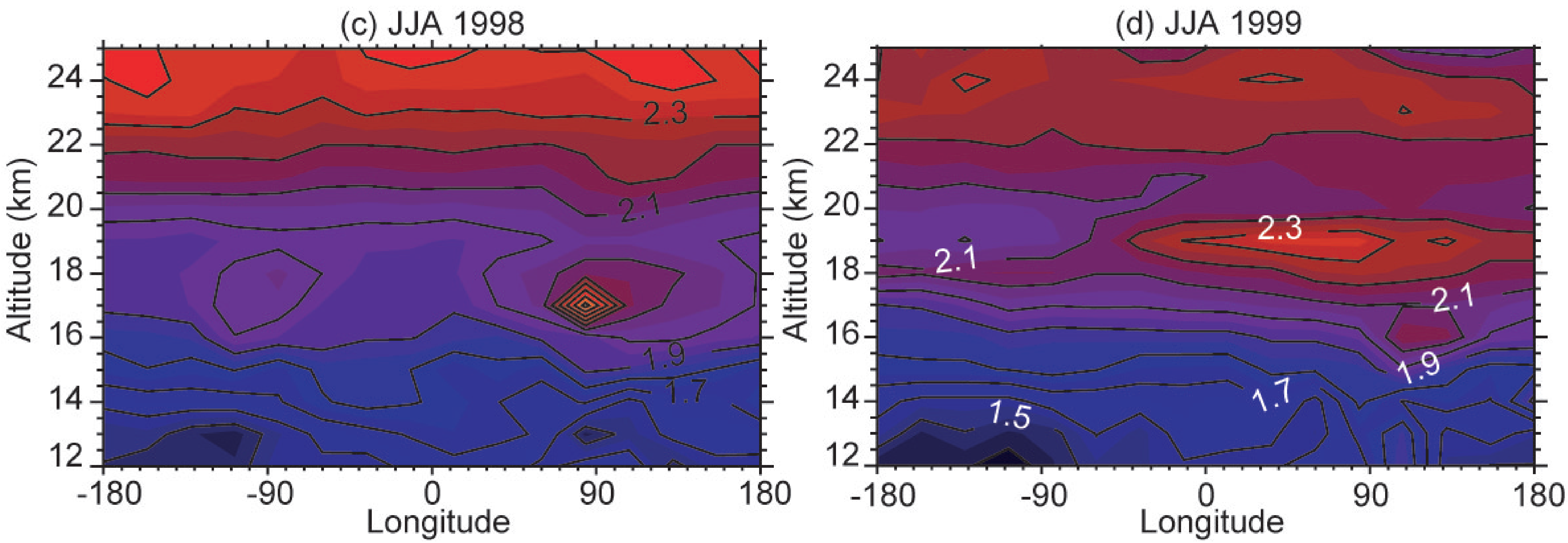


Anthropogenic emissions may have some influence



Anthropogenic Influence: The Asian Tropical Aerosol Layer (ATAL)

Median 1020 nm Extinction Ratio Observed by SAGE II from 15N to 45N, June thru August



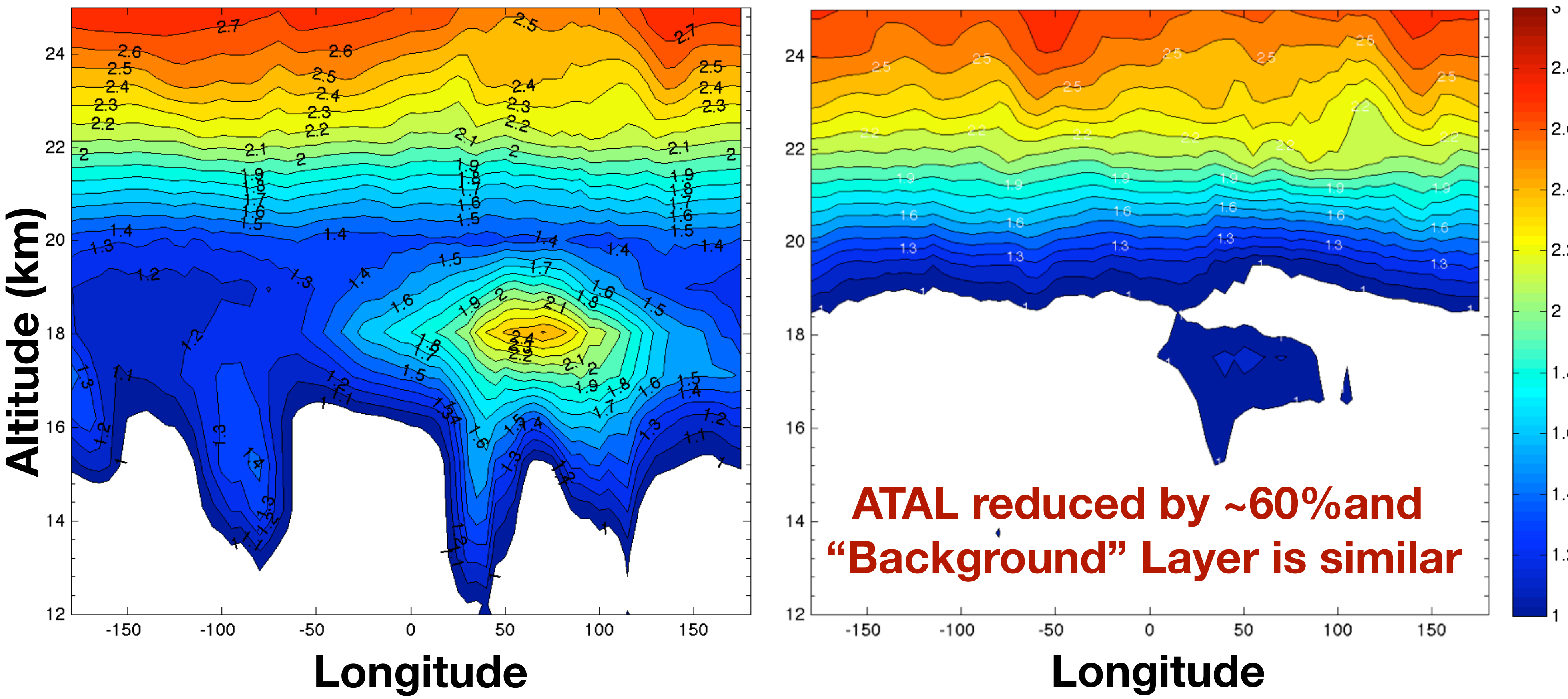
Plot adapted from Thomason, L. W. and Vernier, J.-P.: Improved SAGE II cloud/aerosol categorization and observations of the asian tropopause aerosol layer: 1989–2005, Atmos. Chem. Phys. Discuss., 12, 27521-27554, doi:10.5194/acpd-12-27521-2012, 2012.

Anthropogenic Influence: The ATAL

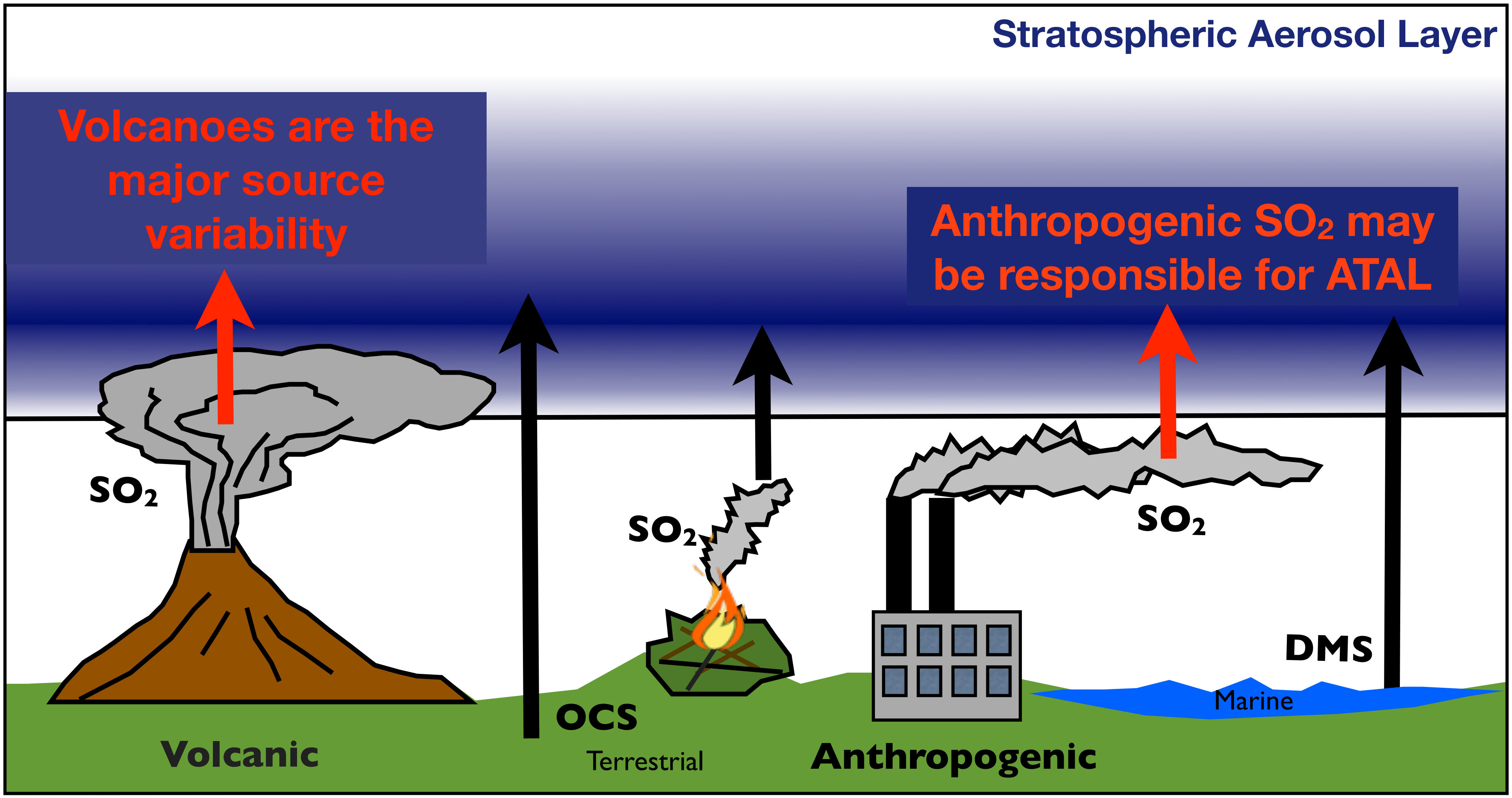
Modeled Mean 1020 nm Extinction Ratio from 14N to 46N, June thru August

With Global Anthropogenic Sulfur Emissions

Without Chinese and Indian Anthropogenic Sulfur Emissions



Conclusions



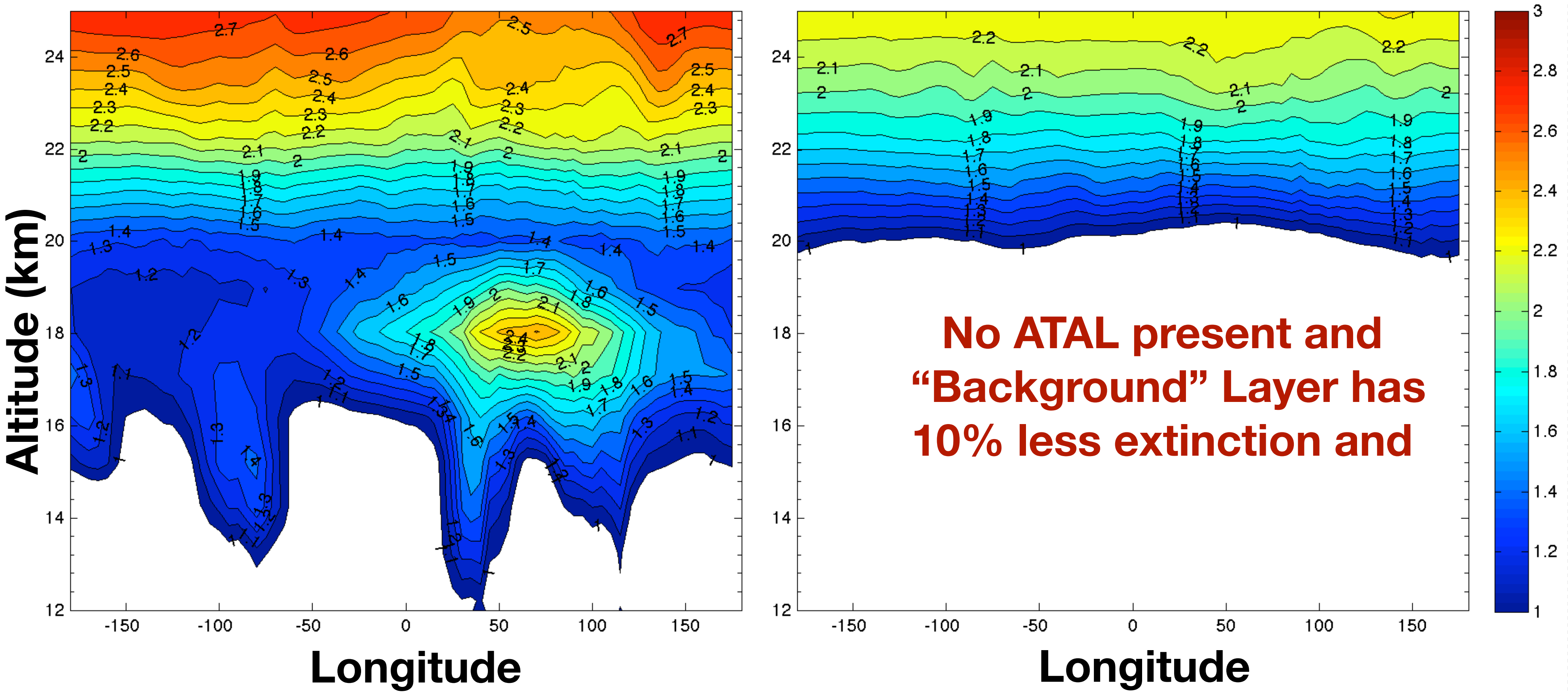
Back Up Slides

Anthropogenic Influence: The ATAL

Modeled Mean 1020 nm Extinction Ratio from 14N to 46N, June thru August

With Global Anthropogenic Sulfur Emissions

Without Global Anthropogenic Sulfur Emissions

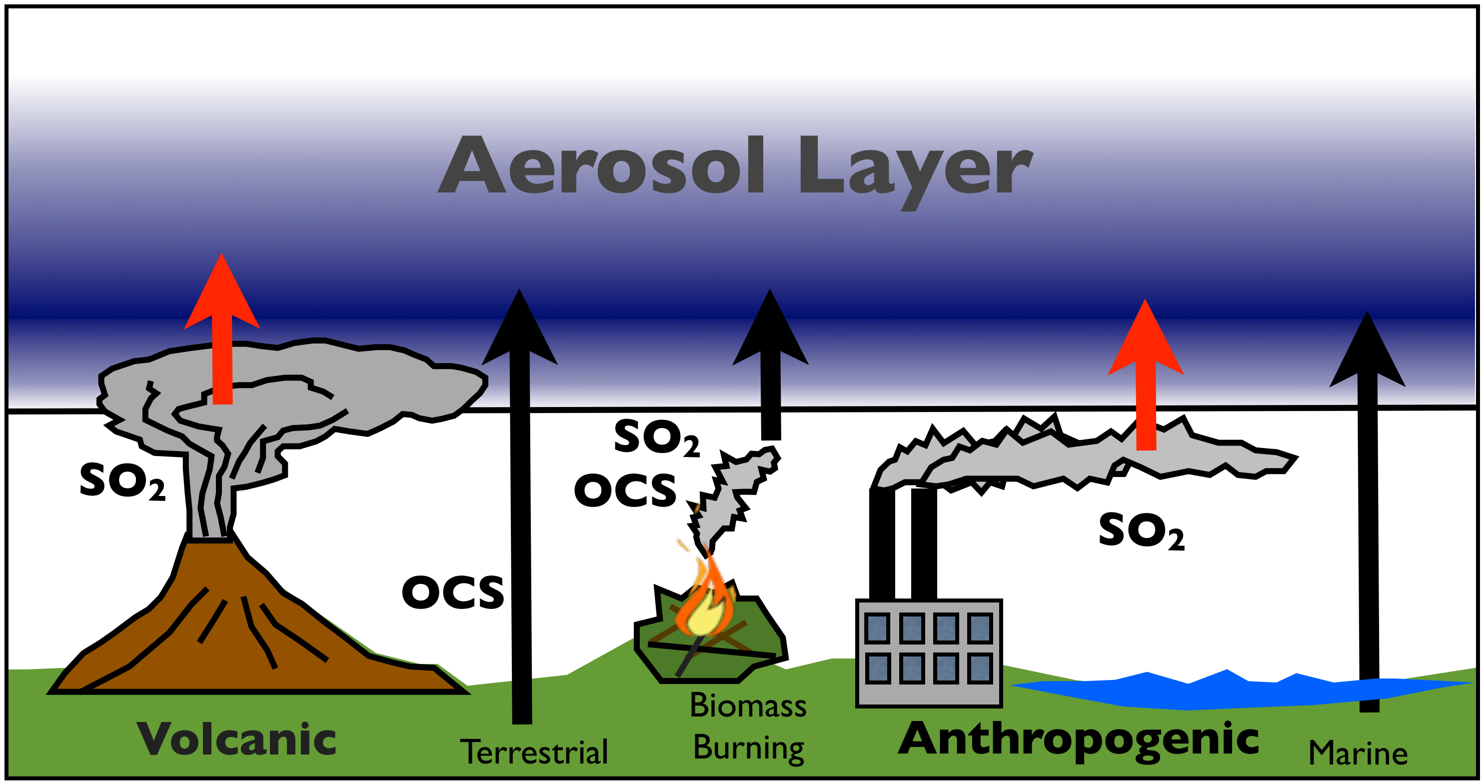


"Trends": Volcanic or Anthropogenic?

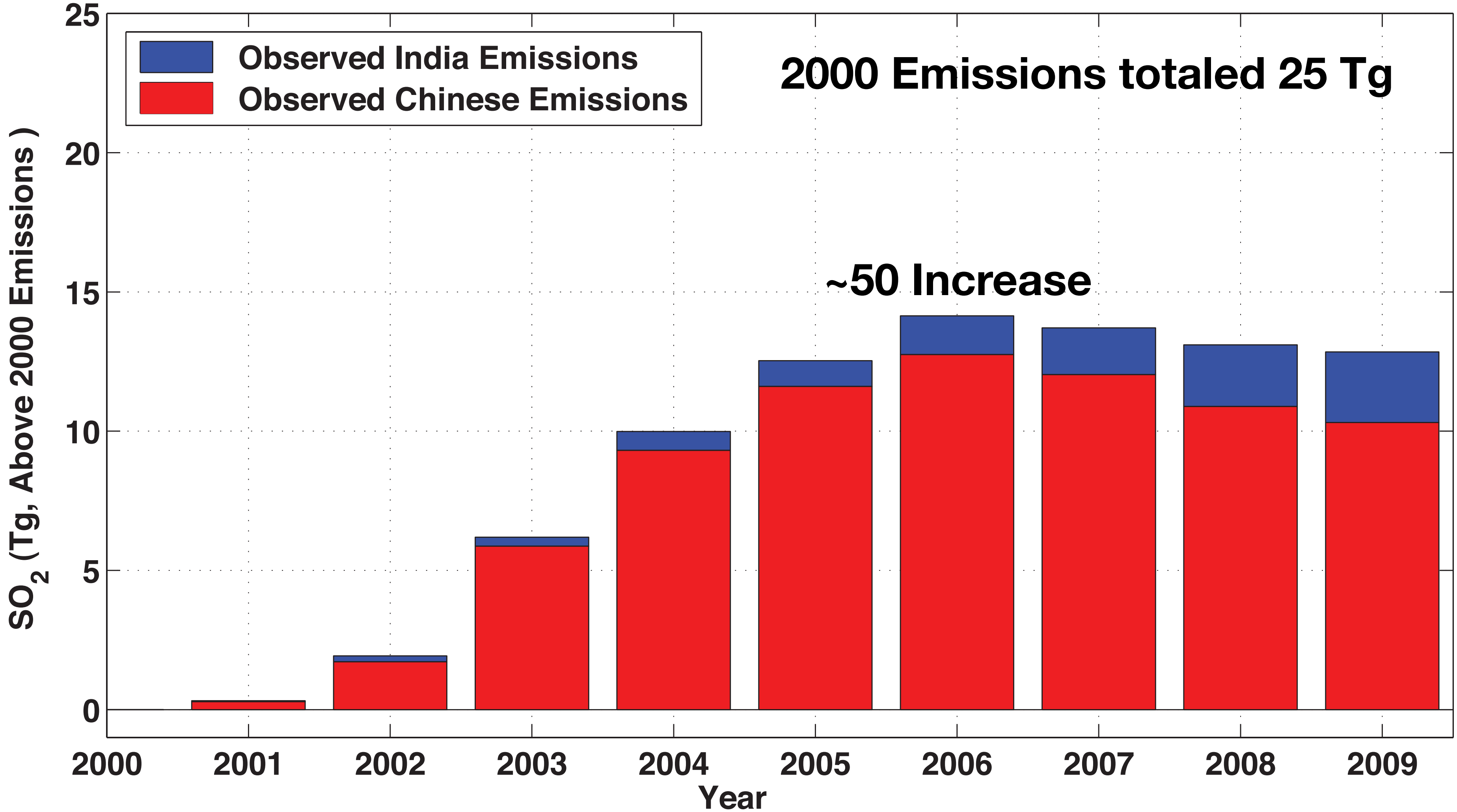
Stratosphere

Troposphere

Surface



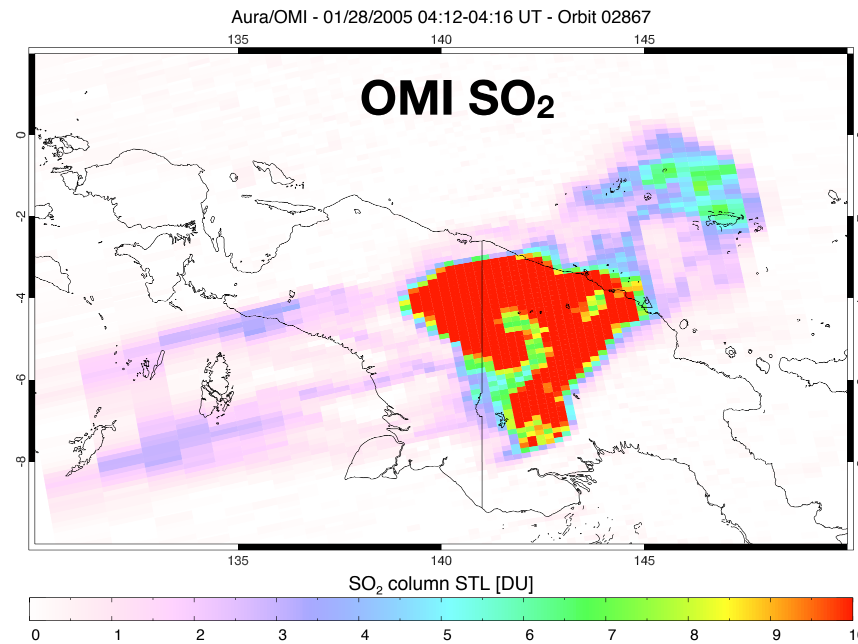
Increases in Asian Anthropogenic Emissions since 2000



Data source: Lu, Z., Zhang, Q. & Streets, D. G. Sulfur dioxide and primary carbonaceous aerosol emissions in China and India. 1996–2010, Atmospheric Chemistry and Physics 11, 9839–9864 (2011).

Modeling volcanic emissions as plumes of SO_2

Manam (Ma) shown as an example



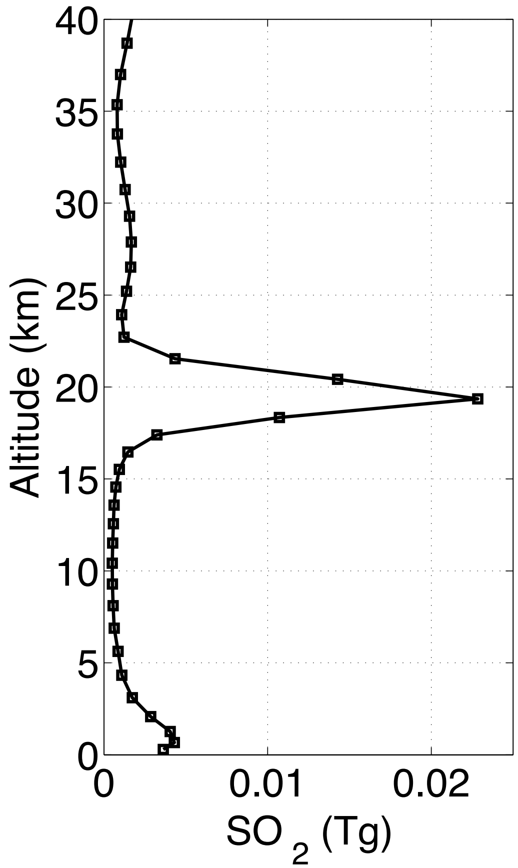
"The eruption...clearly penetrated into the stratosphere...based on the warmth of the central umbrella cloud, and the subsequent dispersion of the ice-cloud..."

Andrew Tupper at the Darwin Volcanic Ash Advisory Centre

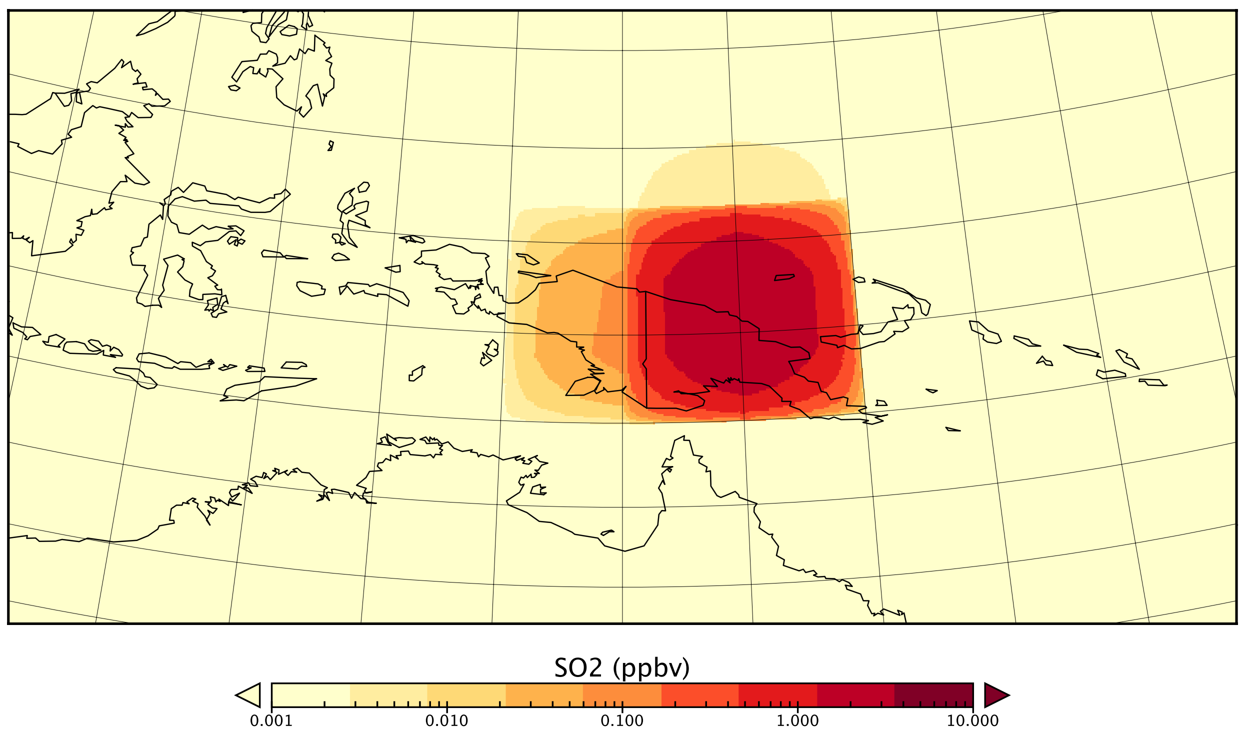
Modeling volcanic emissions as plumes of SO_2

Manam (Ma) shown as an example

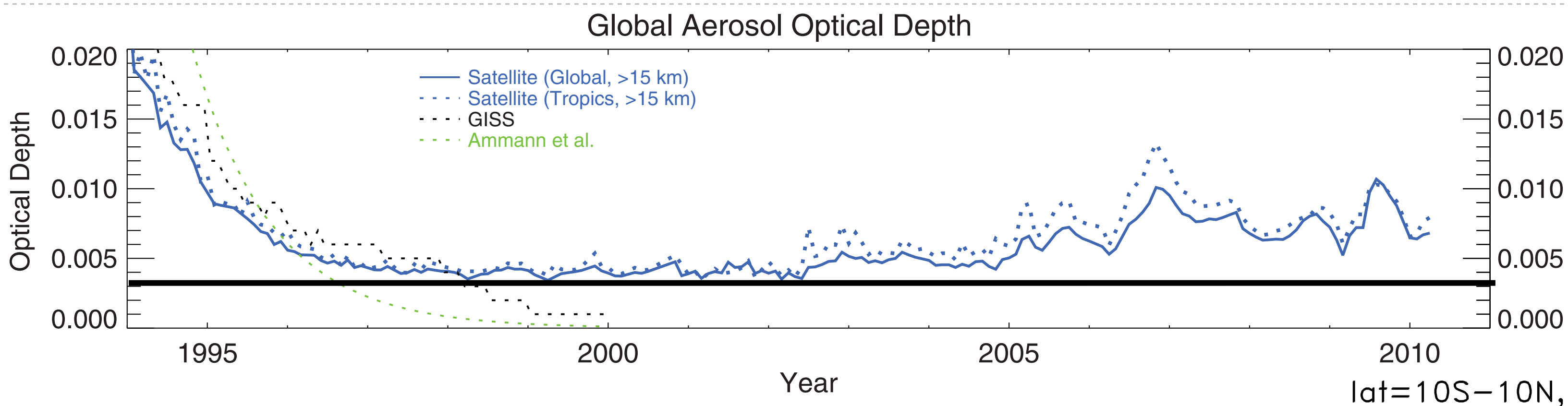
WACCM SO_2 Profile



WACCM SO_2 Mixing Ratio at 19 km

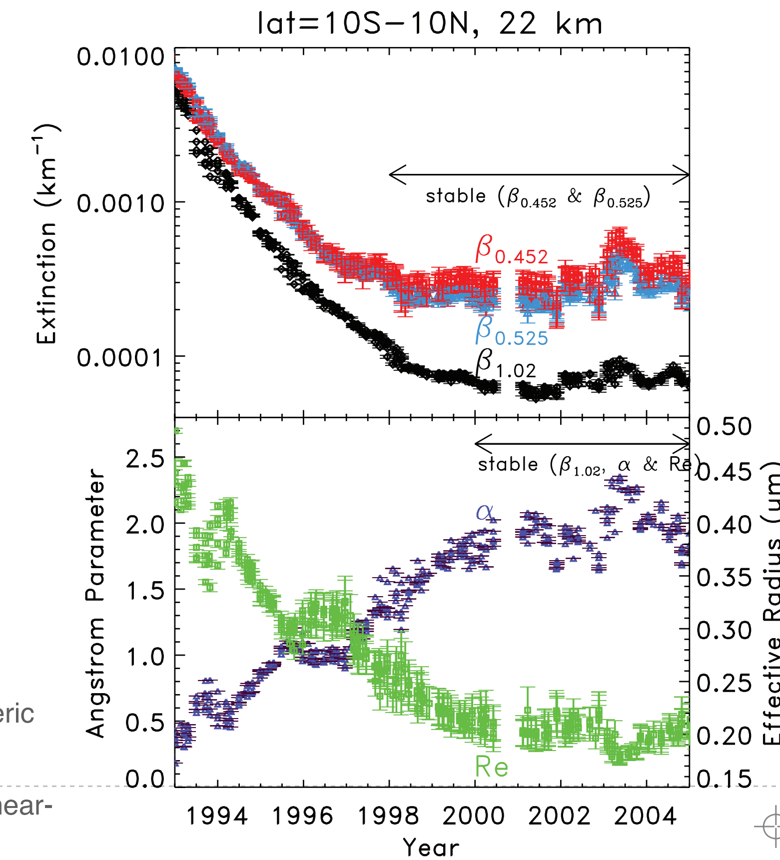


2000 to 2010 is an unprecedented "background" period



Layer became stable only in 2000.

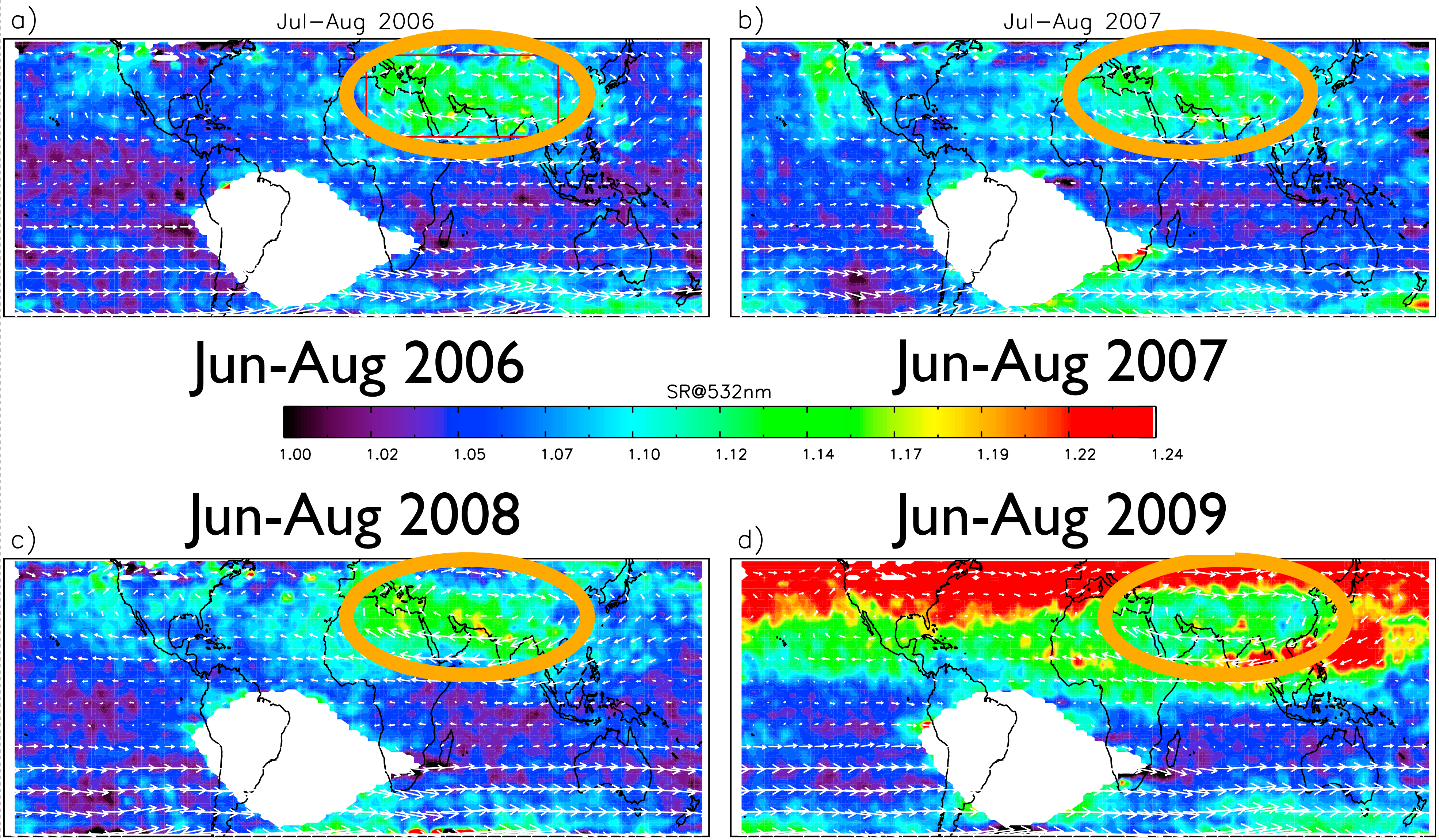
Previous observations will be influenced by 1991 Pinatubo eruption.



Adapted from Solomon et al. (2011), The Persistently Variable "Background" Stratospheric Aerosol Layer and Global Climate Change, *Science*

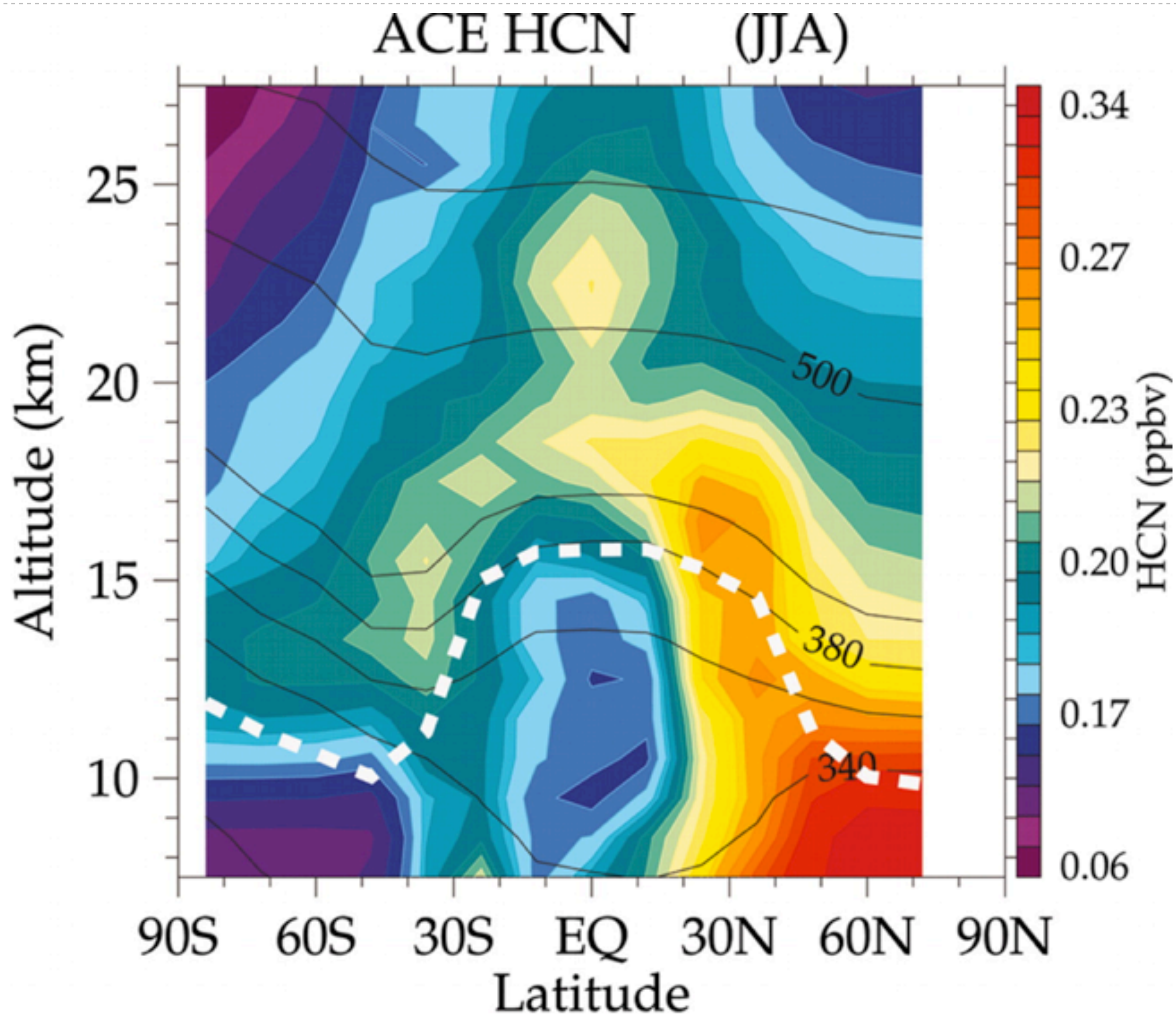
Niwano et al. (2009), Seasonal cycles of Stratospheric Aerosol and Gas Experiment II near-background aerosol in the lower stratosphere, J. Geophys. Res, 114(D14), D14306.

Anthropogenic Influence: The Asian Tropical Aerosol Layer (ATAL) Mean Scattering Ratio (SR) from CALIPSO at 532 nm between 15–17 km



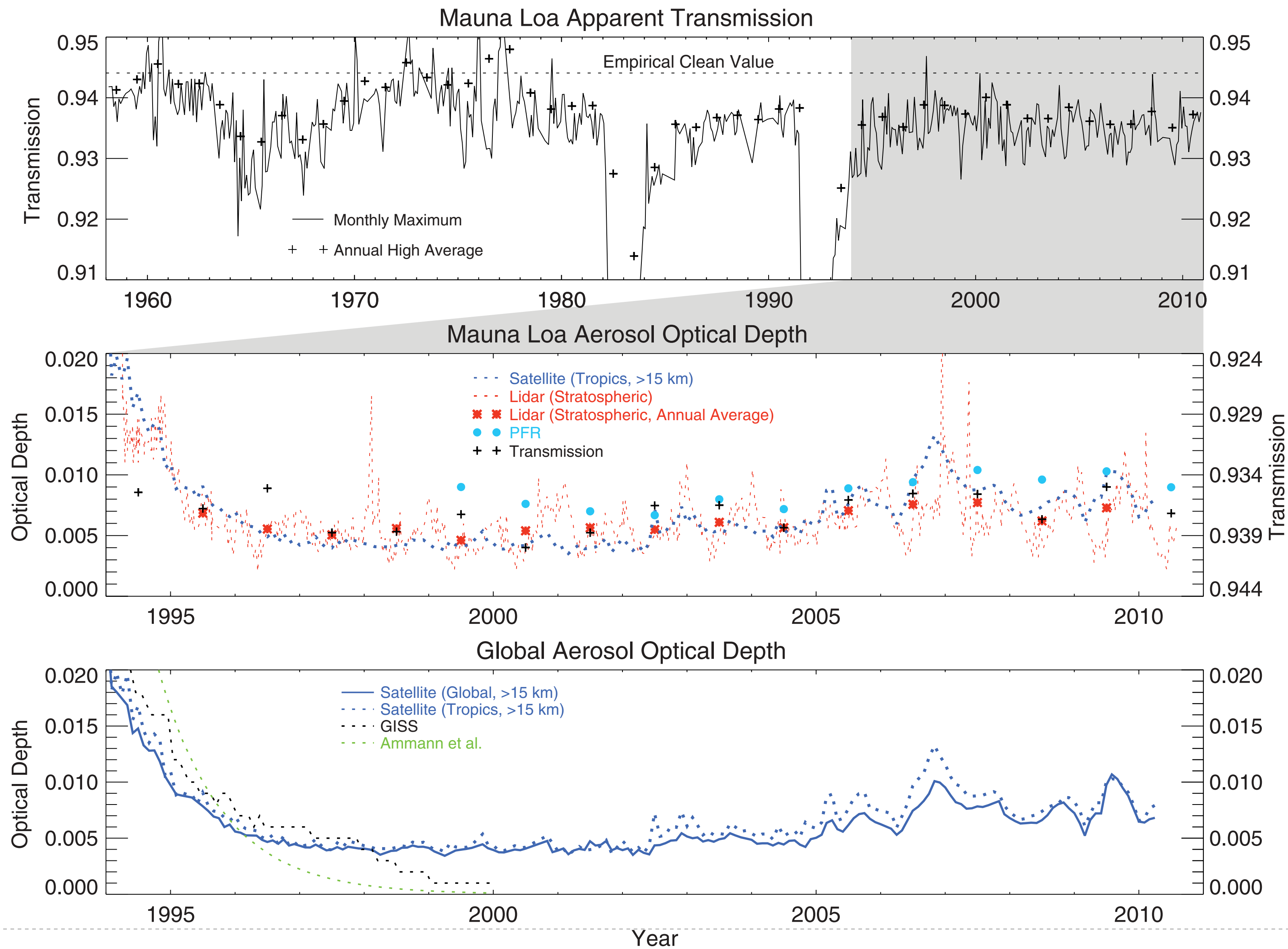
Adapted from: Vernier, J. P., L. W. Thomason, and J. Kar (2011), CALIPSO detection of an Asian tropopause aerosol layer, Geophys. Res. Lett, 38(7), doi:10.1029/2010GL046614.

Anthropogenic emissions transported to the stratosphere via the Asian Monsoon

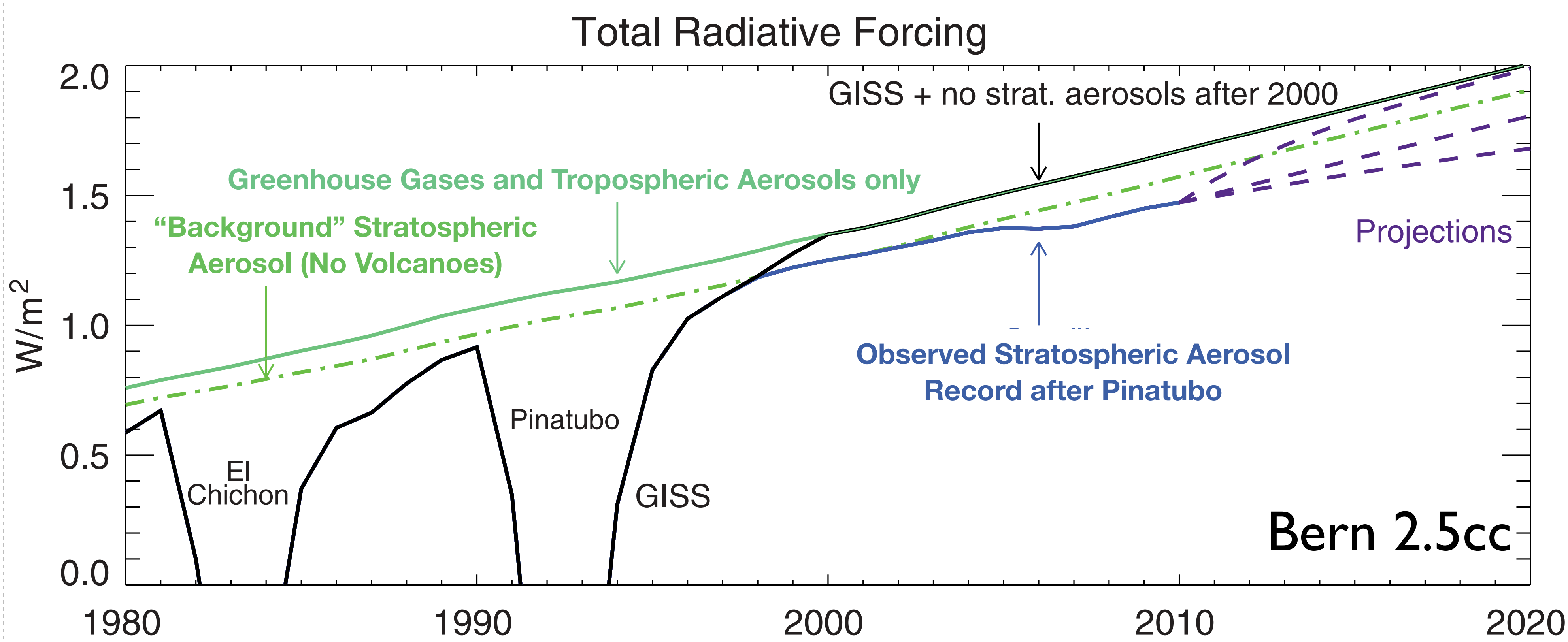


Plot from Randel et al. (2010), Asian Monsoon Transport of Pollution to the Stratosphere, *Science*.

2000 to 2010 is an unprecedented “background” period

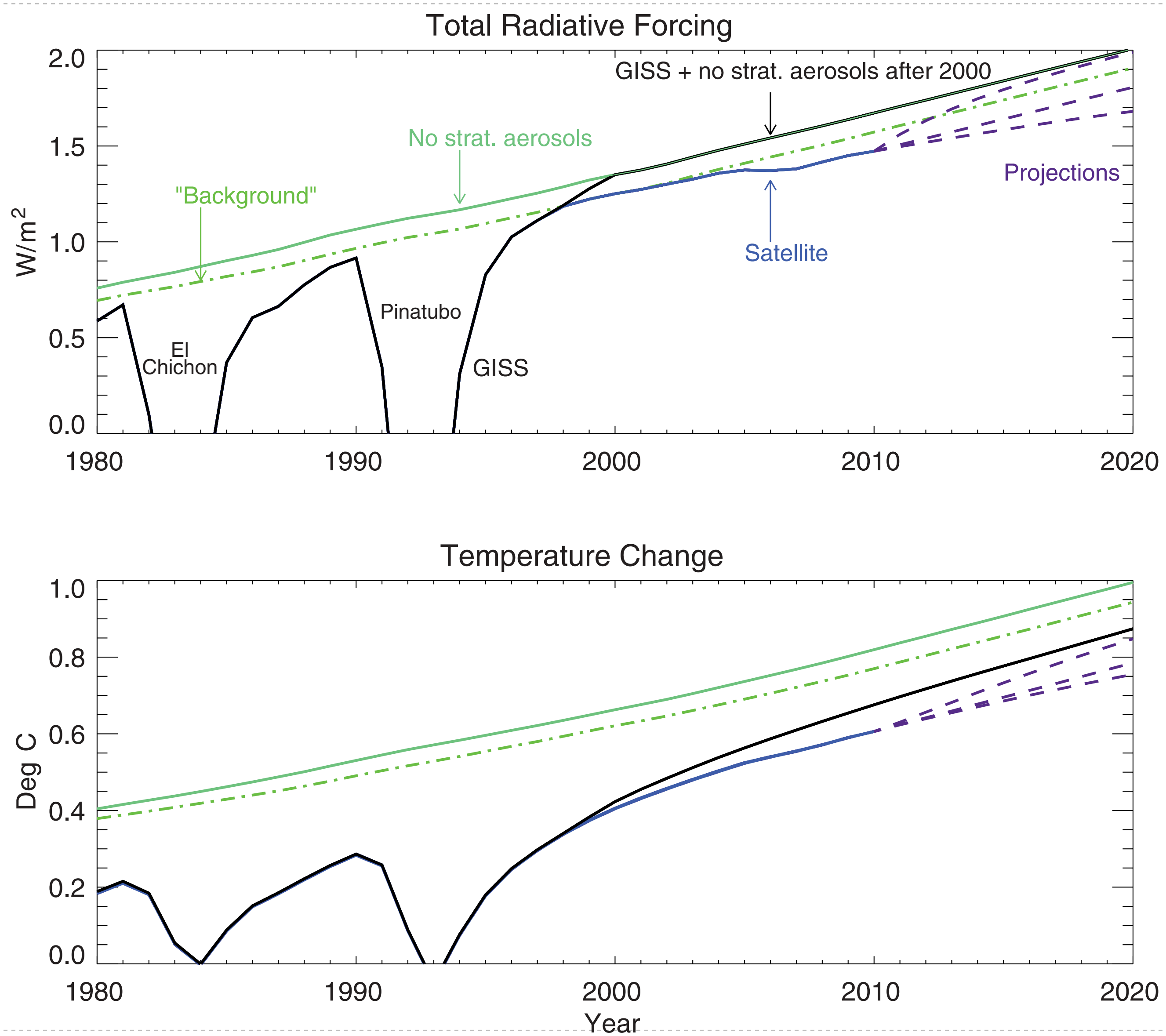


Variability in stratospheric aerosol impacts global radiative forcing



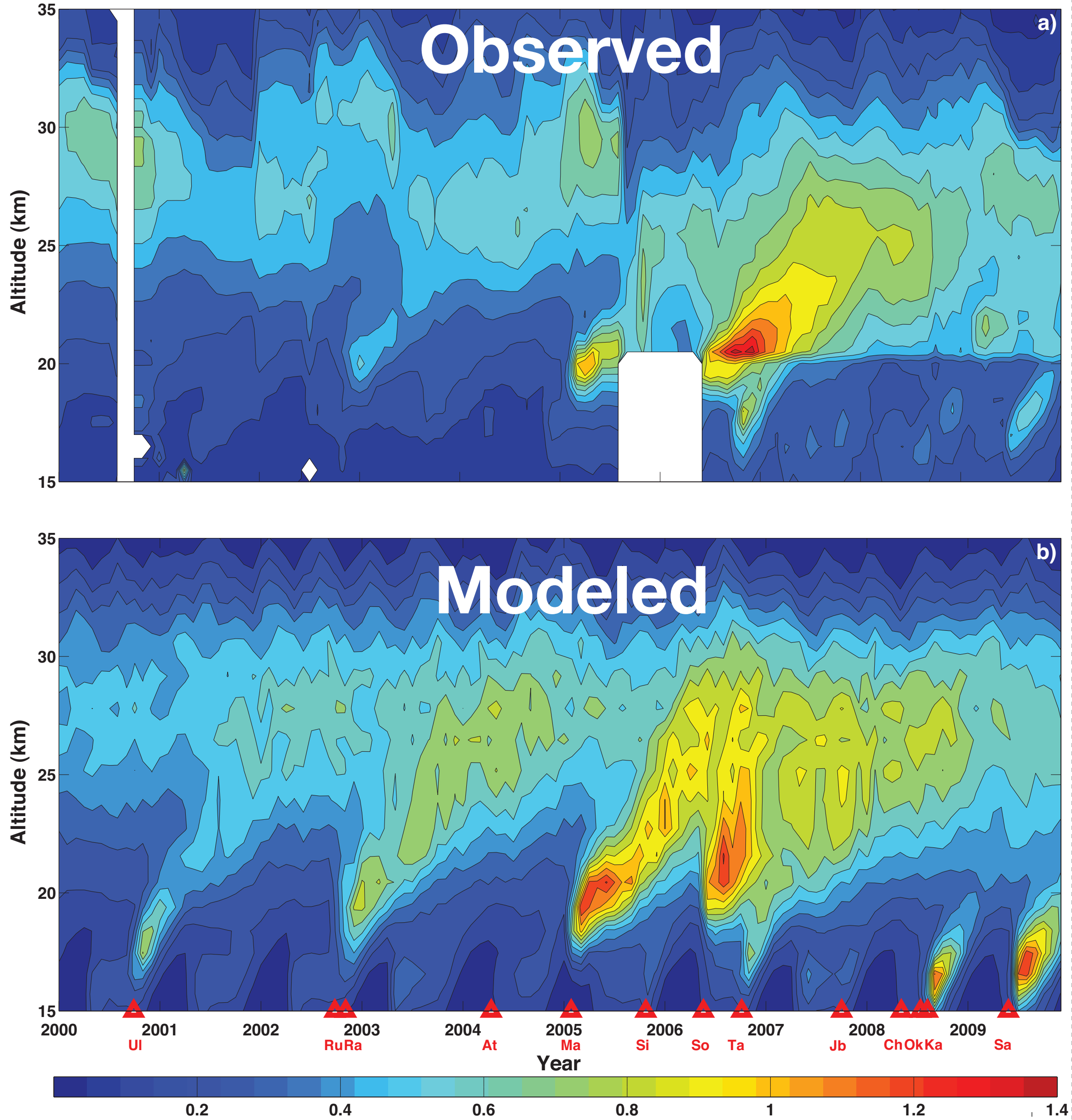
Radiative forcing is a measure of the imbalance in the radiative budget caused by an external factor on the Earth-atmosphere system

Impacts on global temperature

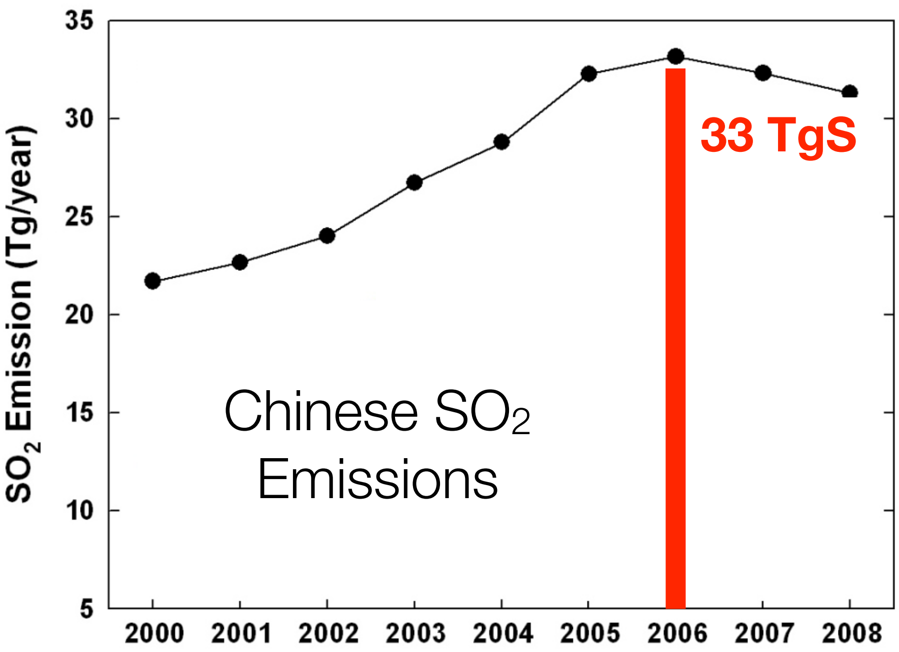


Trends are largely due to episodic injections from volcanic eruptions

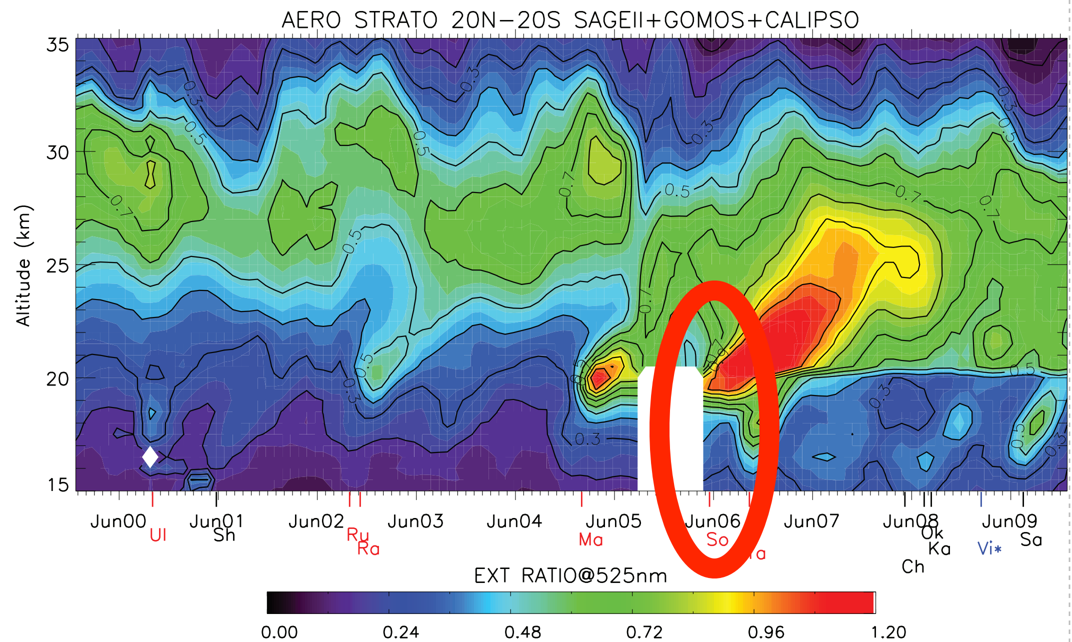
Extinction Ratio (Aerosol over Molecular) from 15 to 35 km, 20 S to 20 N



Anthropogenic vs Volcanic emissions



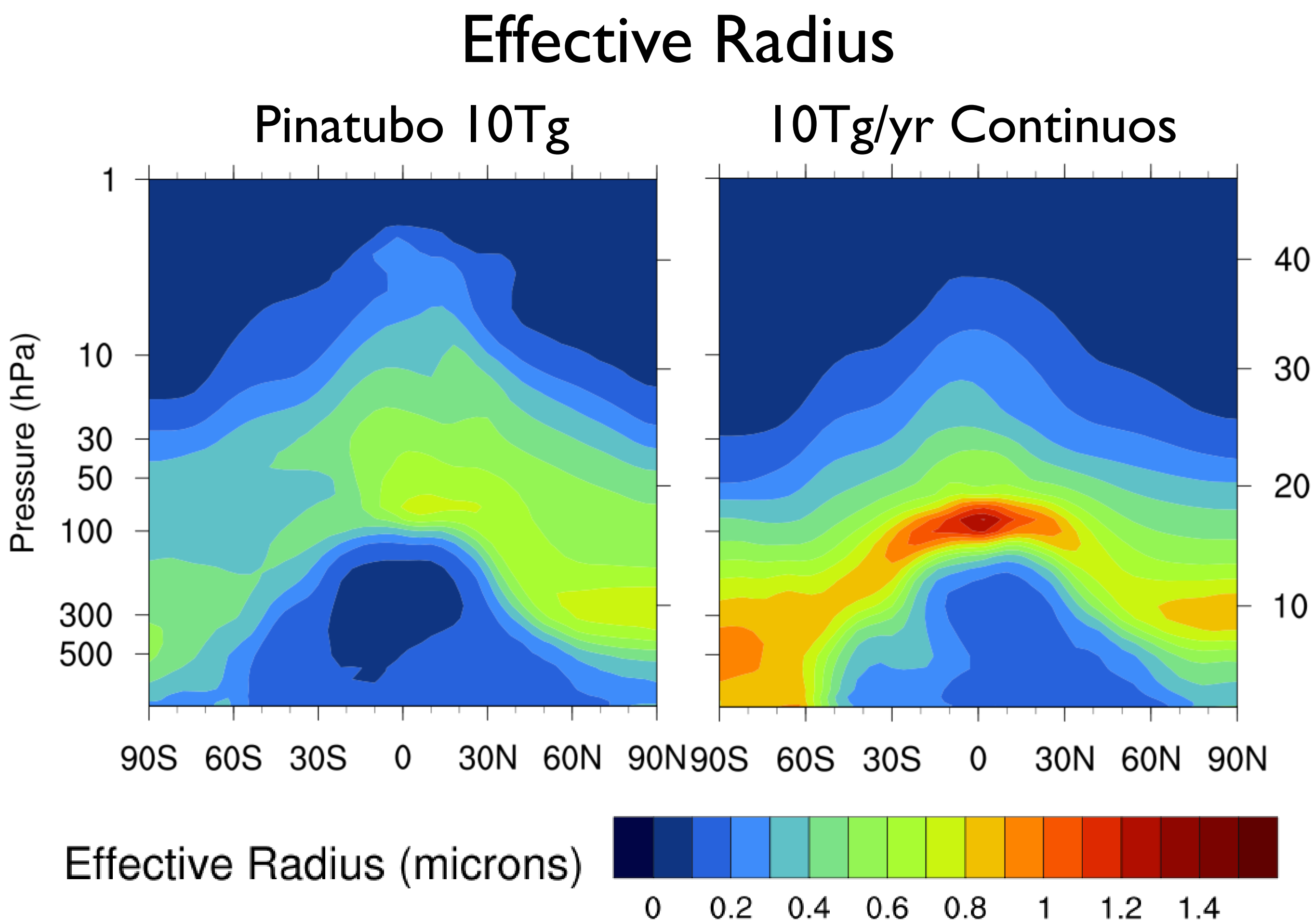
Lu et al. (2010), Sulfur dioxide emissions in China and sulfur trends in East Asia since 2000, *Atmos. Chem. Phys*, *10*(13)

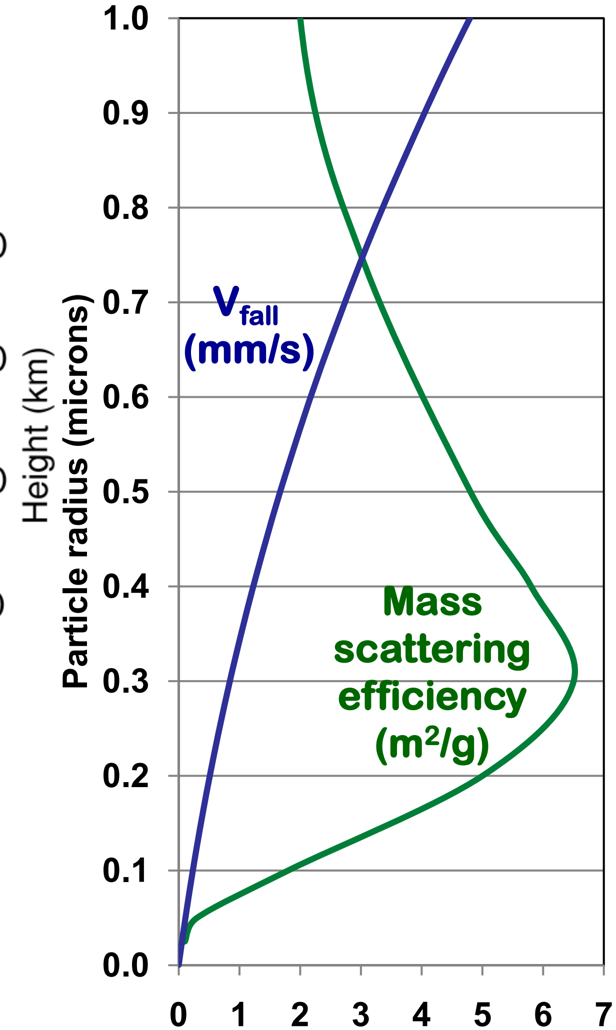


Estimated Emission to Stratosphere
(0.6% of Global Emissions must make it to stratosphere to maintain sulfur burden (Hofmann et al. 2009))

Year	China	Volcano
2006	0.2 TgS	Soufrière Hills 0.17 TgS

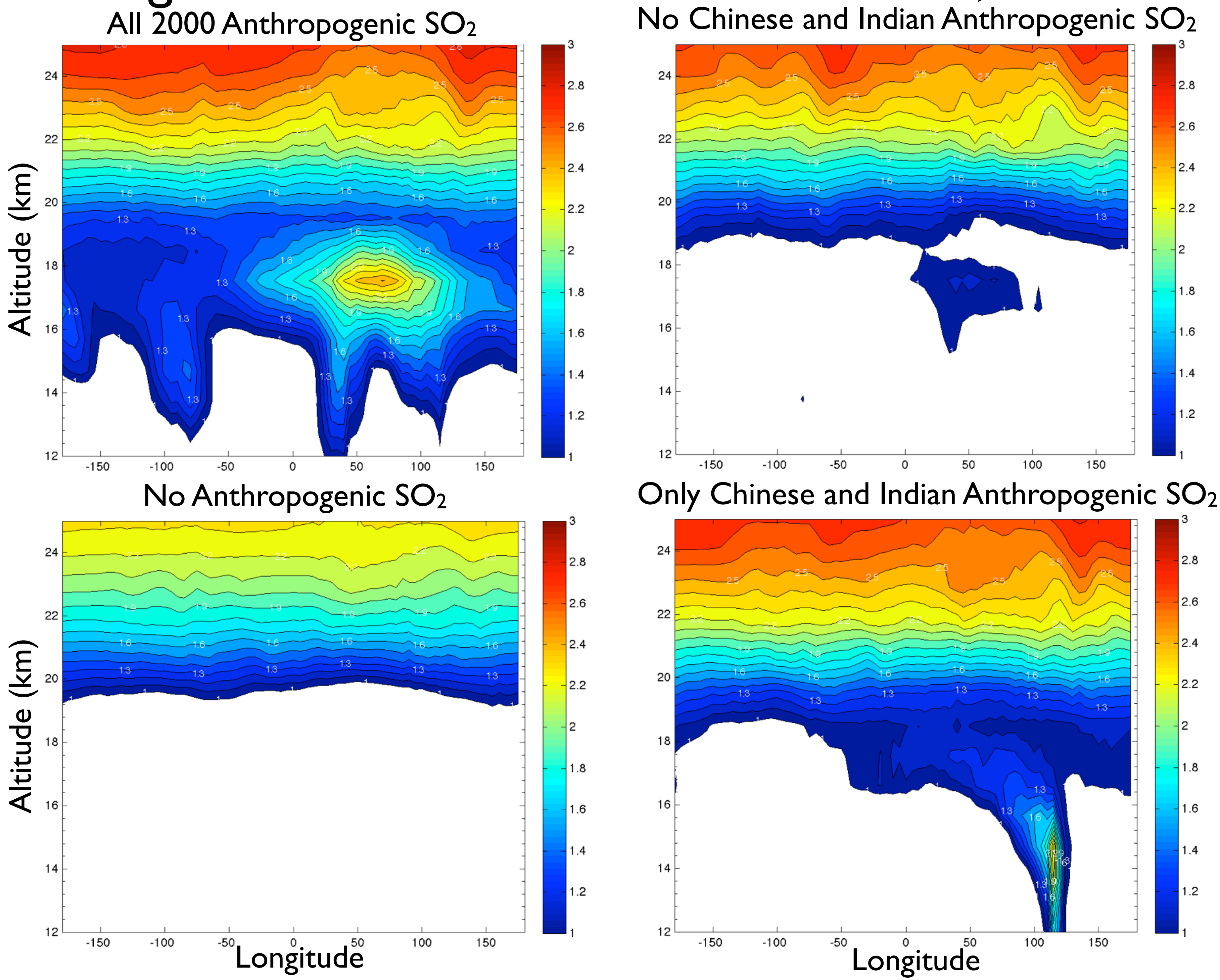
Why Are Volcanoes More Efficient at Making Aerosol?



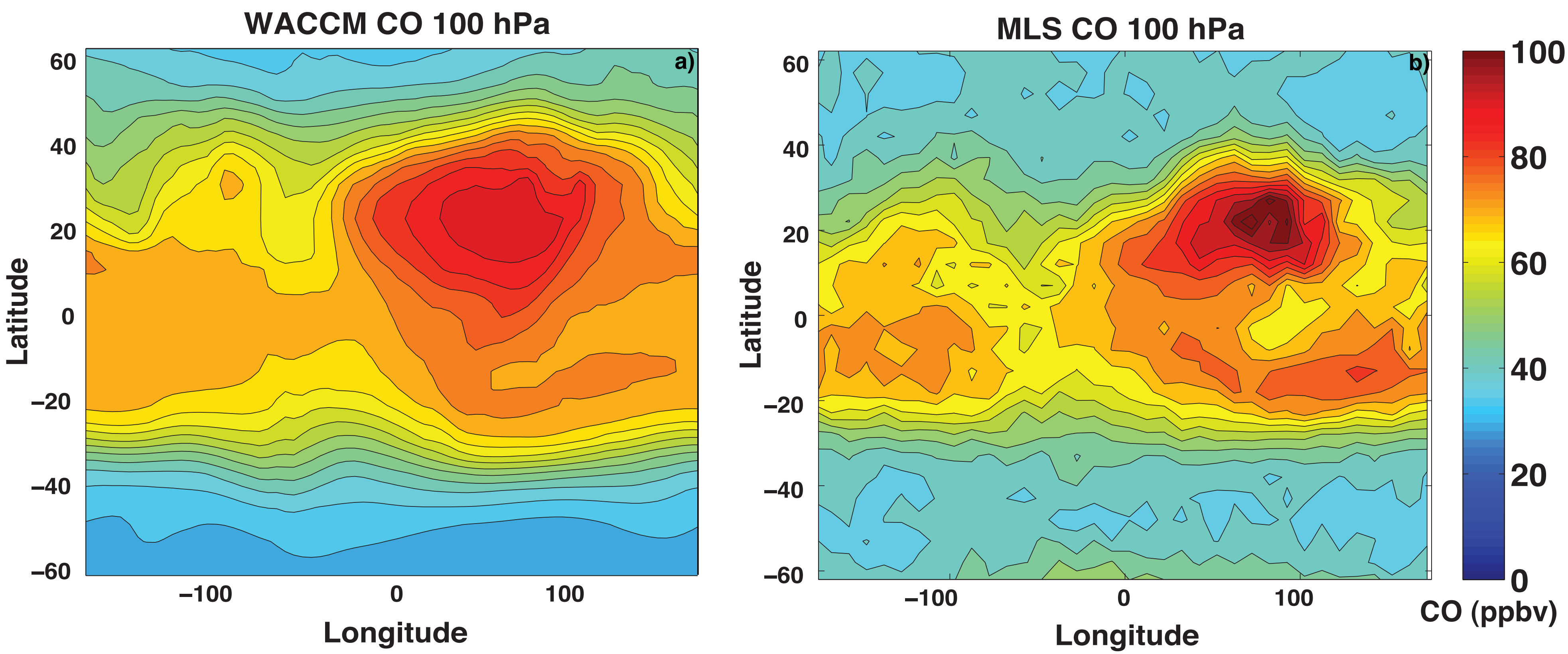


Plots adapted from English, J. M., O. B. Toon, and M. J. Mills (2011), Microphysical simulations of stratospheric sulfur geoengineering, *J. Geophys. Res.*, under review.

June-Aug. Mean Extinction Ratio at 1020 nm, 14N to 46N



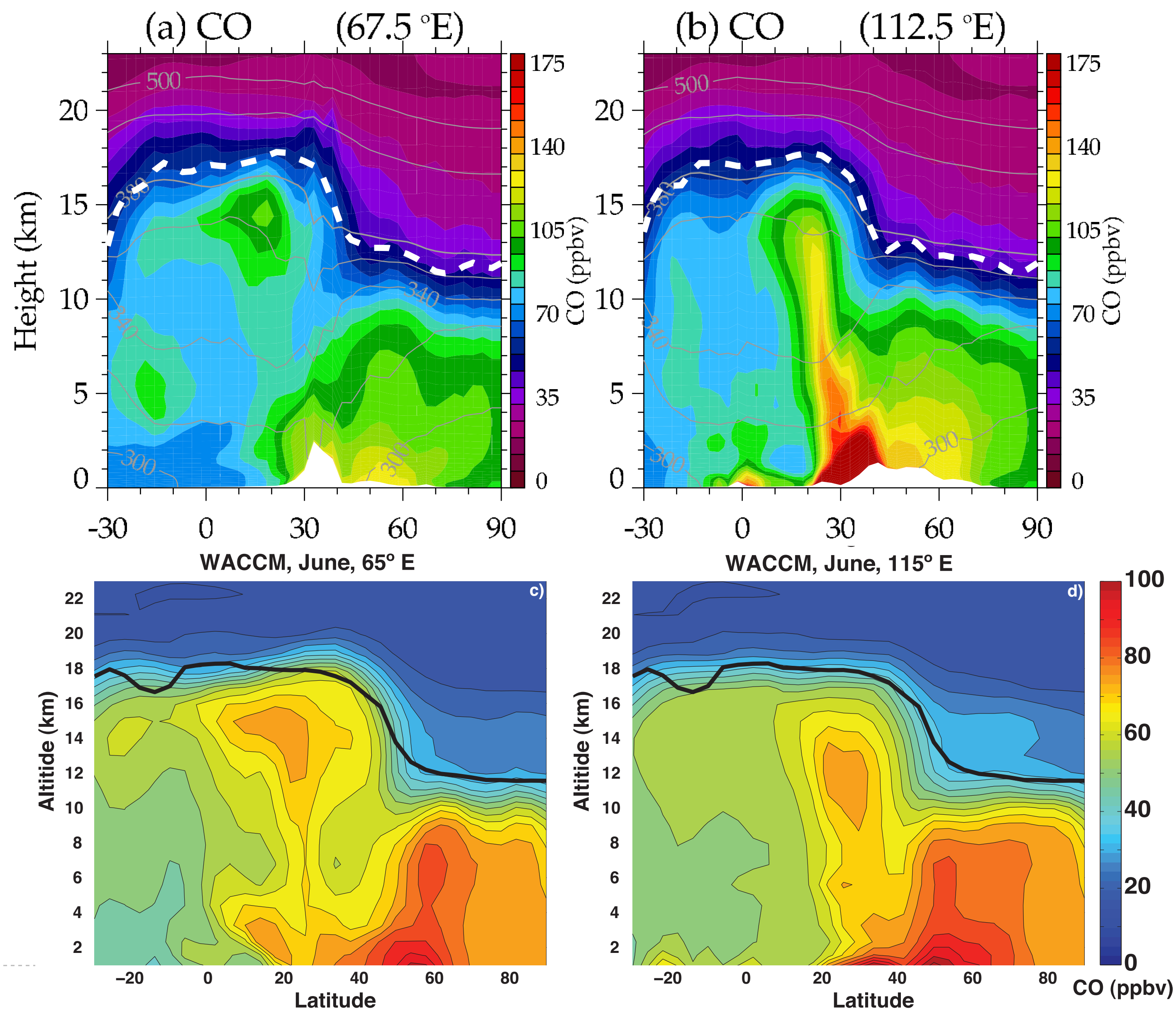
Transport in WACCM



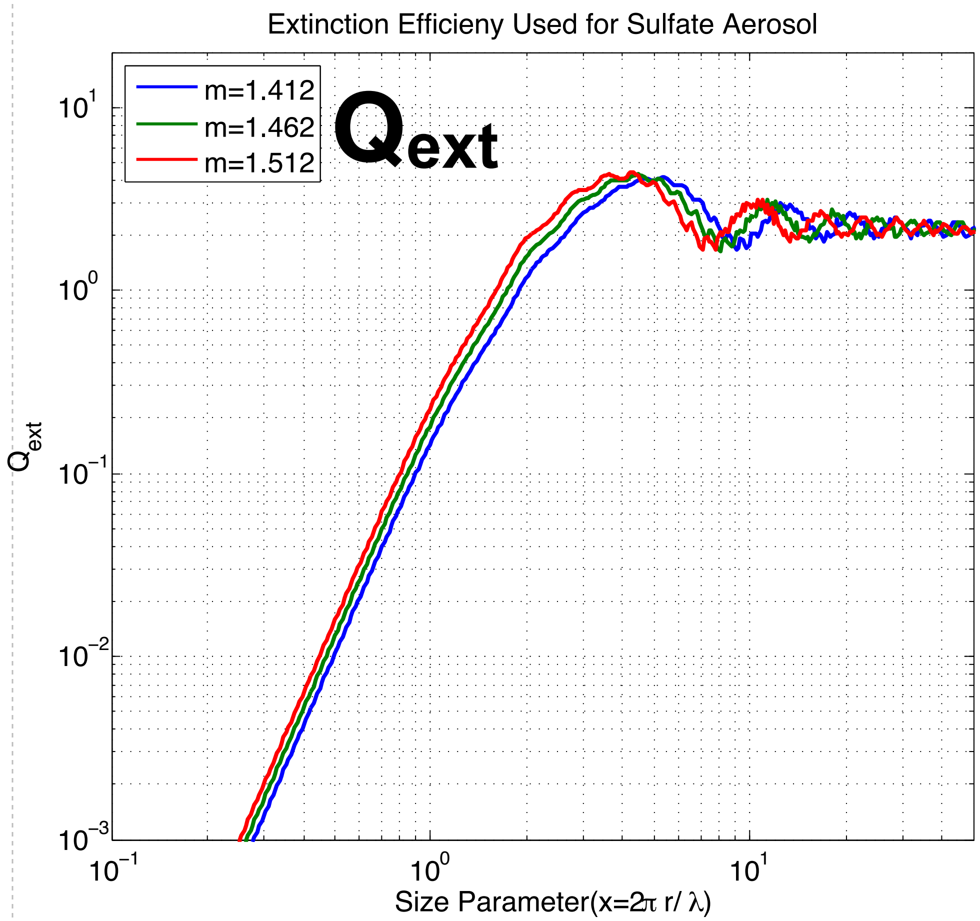
Transport pathways of carbon monoxide in the Asian summer monsoon diagnosed from Model of Ozone and Related Tracers (MOZART)

Mijeong Park,[1] William J. Randel,[1] Louisa K. Emmons,[1] and Nathaniel J. Livesey[2]

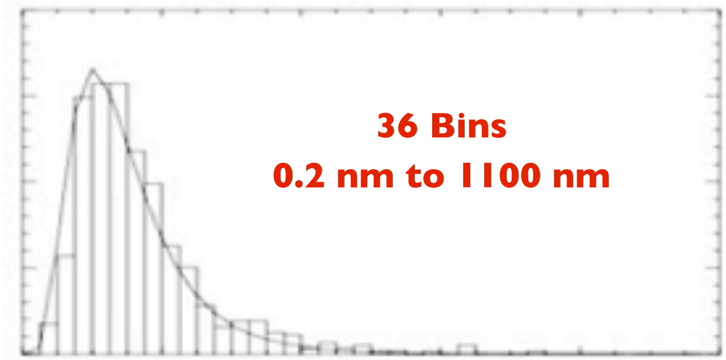
Figure 7. Latitude-altitude cross-sections of monthly mean MOZART-4 CO at the (a) western (67.5°E) and (b) eastern (112.5°E) sides of the monsoon maximum in June 2005. Thermal tropopause derived from the model temperature profile is denoted as thick dashed lines. Thin solid lines are isentropes (320, 340, 360, 380, 450, and 500 K).



Scattering Calculations



$n(r,z) =$



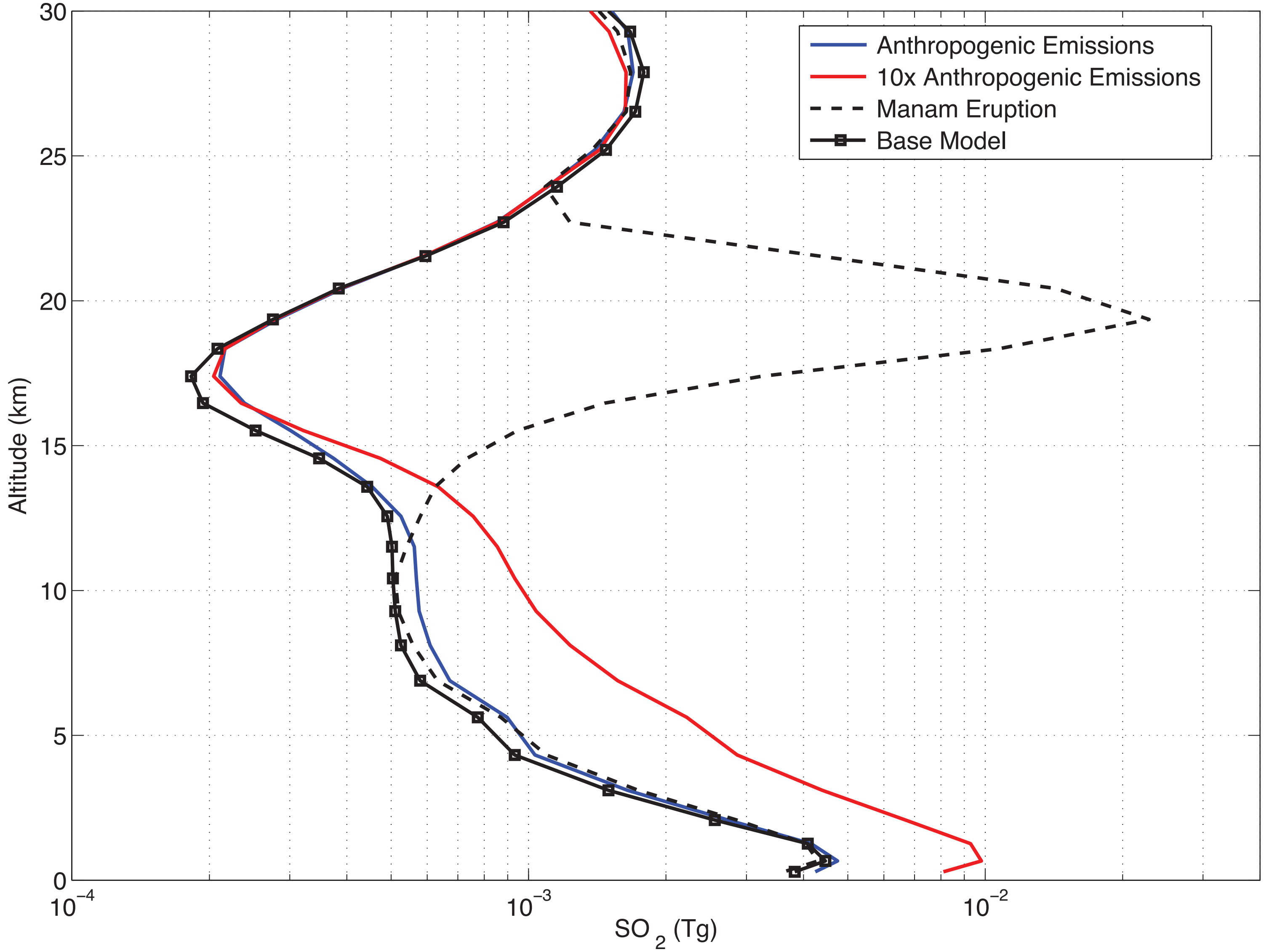
$$\beta_a(z,t) = \pi \int_0^\infty r^2 Q_\pi(\tilde{m}, x) n(r,z)\,dr$$

Bohren and Huffman (1983)

Volcanoes

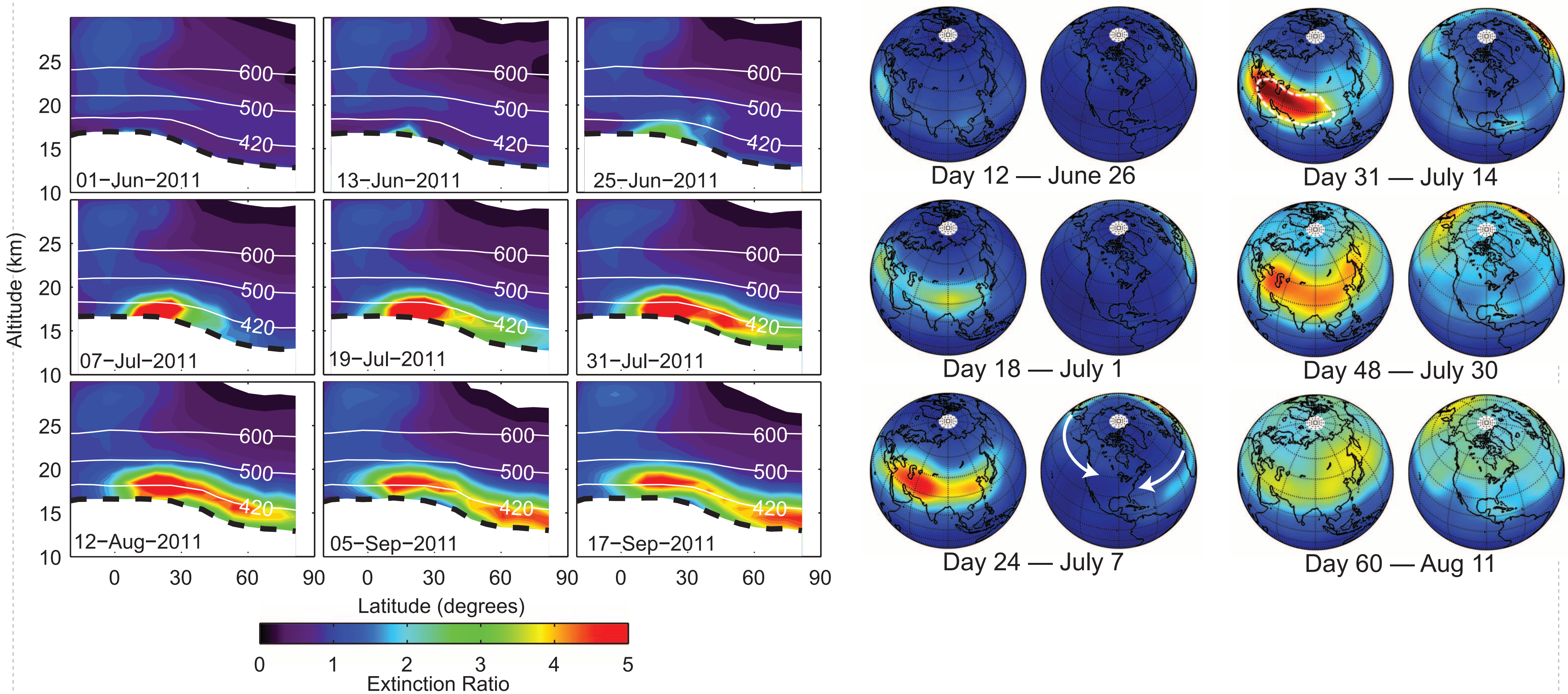
Volcano	Eruption Date	Lat.	Long.	SO_2 Injected (Tg)	Max. Injection Height (km)	VEI
Ulawun (Ul)	2000.74	-5	151	0.05[29]	15	4
Ruang (Ru)	2002.73	2	125	0.055[30]	20[30] 16*[31]	4
Reventador (Ra)	2002.83	0	-78	0.096[32]	17	4
Anatahan (At)	2004.28	16	146	0.065[30]	15[30]	3
Manam (Ma)	2005.07	-4	145	0.18[30]	19[33]	4
Sierra Negra (Si)	2005.81	1	91	0.36[34]	15[34,35]	3
Soufrière Hills (So)	2006.38	16	-62	0.2[30]	20[30]	3
Tavurvur (Ta)	2006.76	-4	152	0.125[30]	17[30]	4
Jebel at Tair (Jb)	2007.75	16	42	0.08[32]	16[32]	3
Chaiten (Ch)	2008.34	-43	-73	0.01[32]	19*[32]	4
Okmok (Ok)	2008.53	53	-168	0.122[36]	16[37]	4
Kasatochi (Ka)	2008.60	52	-176	1.7[38]	14-18[39] 18*[40]	4
Sarychev (Sa)	2009.44	48	153	1.4[41]	17[41]	4

SO_2 Profiles



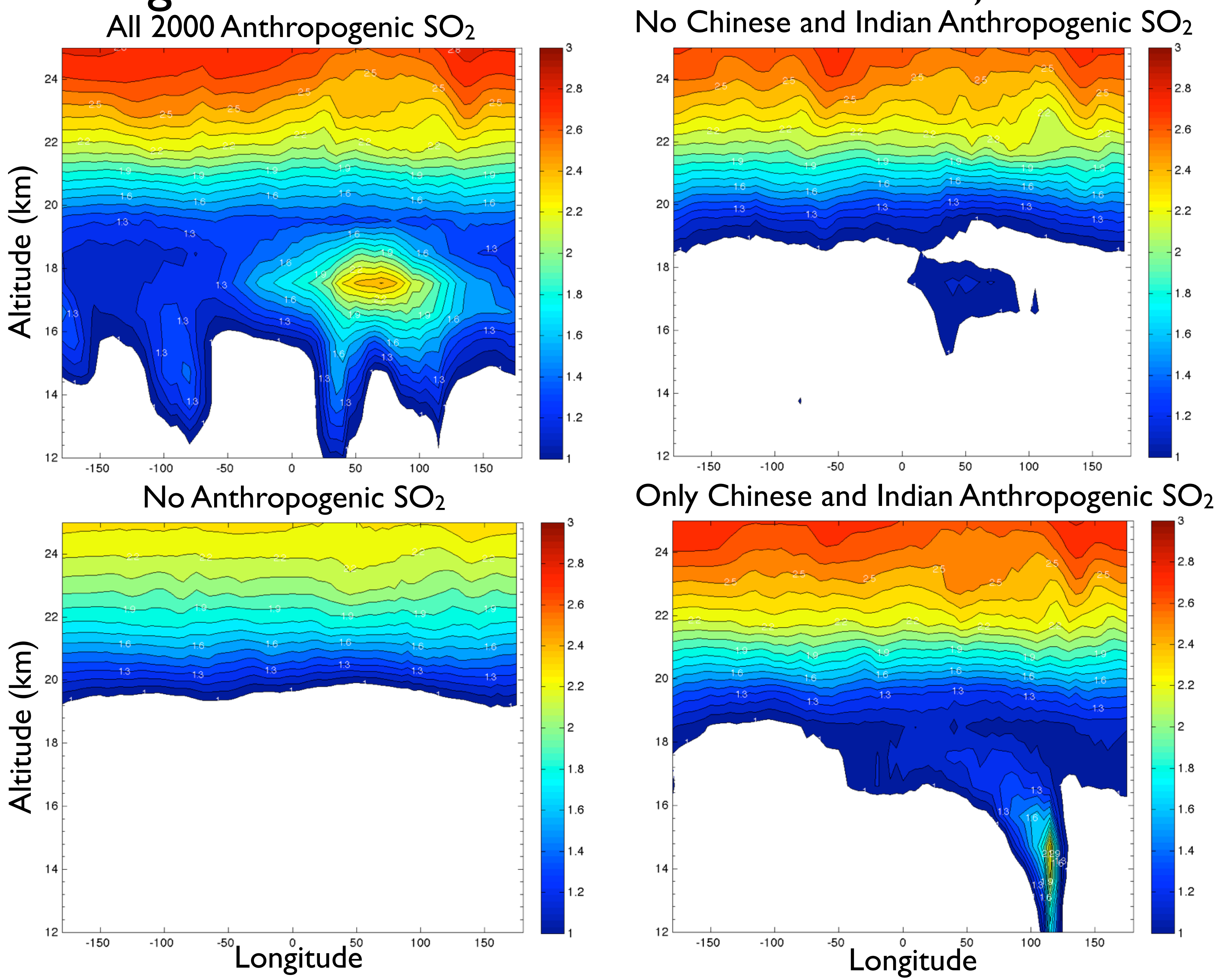
Volcanic aerosol is also transported to the stratosphere via the Asian monsoon

Nabro erupted on 13 June, 2011 in NE Africa injecting 1.3 Tg of SO_2 to 9 to 14 km (below tropopause).



Bourassa, A., A. Robock, W. Randel, and T. Deshler (2012), Large Volcanic Aerosol Load in the Stratosphere Linked to Asian Monsoon Transport, Science.

June-Aug. Mean Extinction Ratio at 1020 nm, 14N to 46N



New Experiment:
Modulate Global Anthropogenic Emissions

Global July Model Surface SO_2 Emissions