Volcanic eruptions, global cooling and ozone loss: we need to measure after the next eruption

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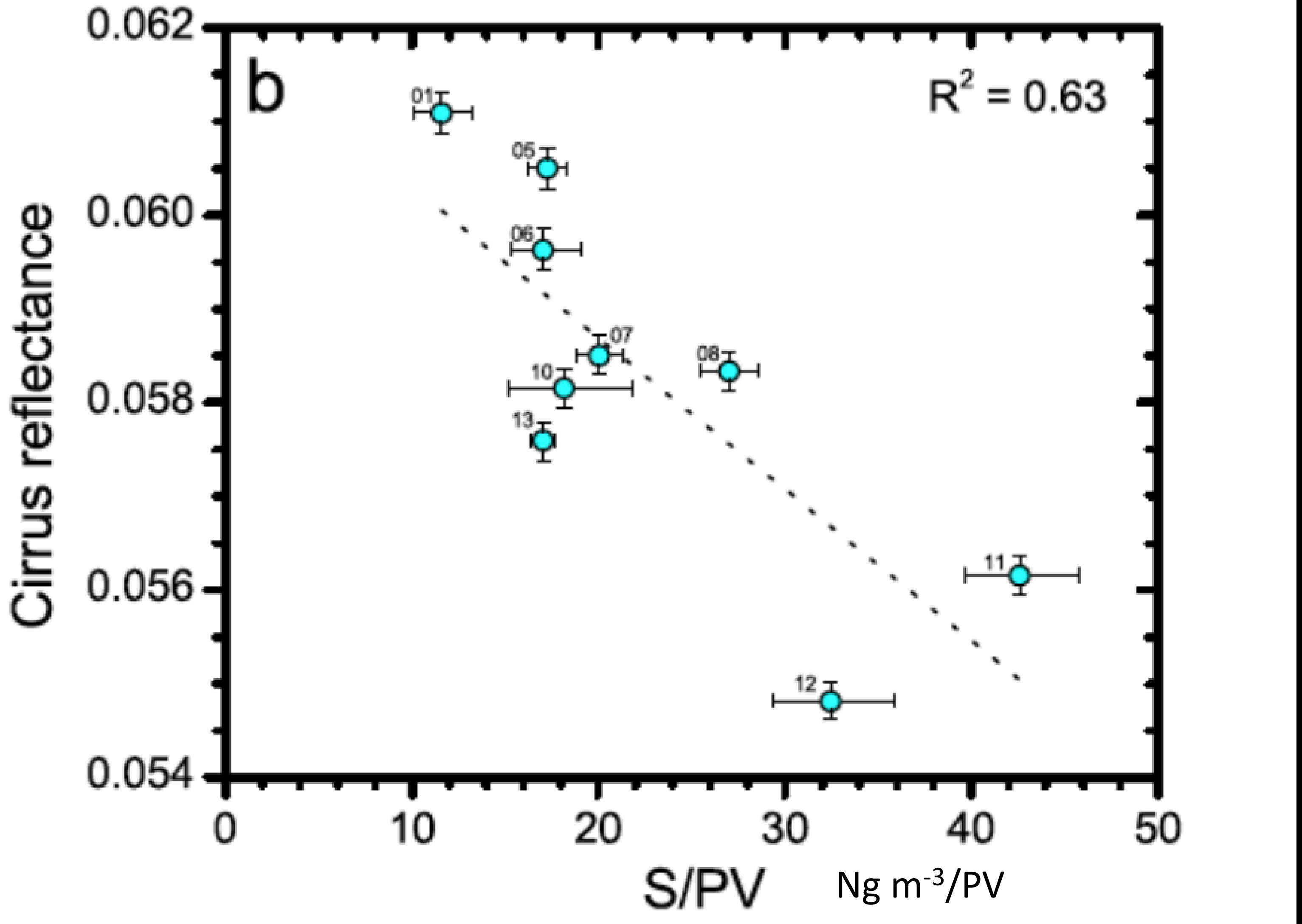
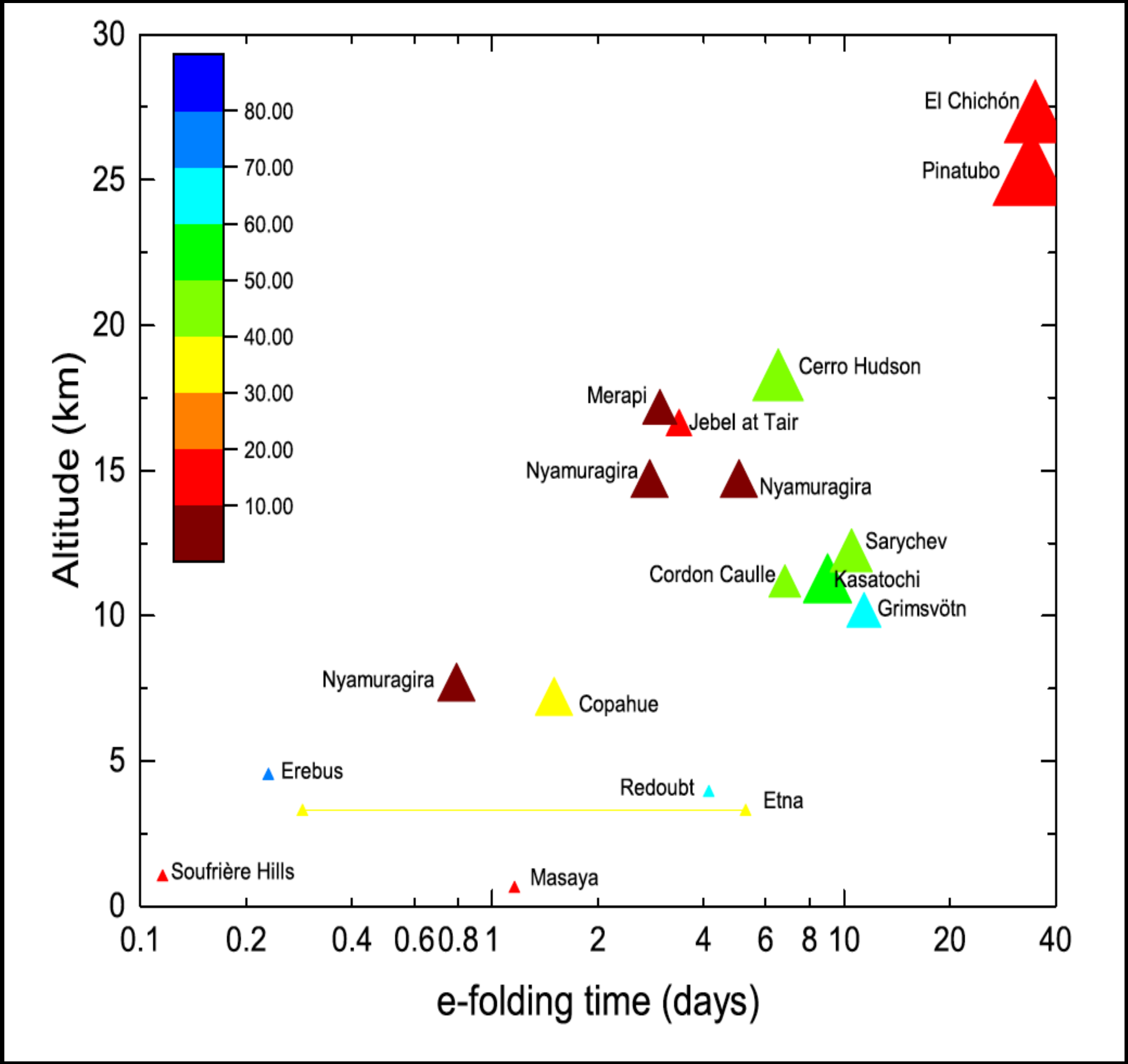
Cirrus reflectivity decreases as sulfur in lower stratosphere goes up



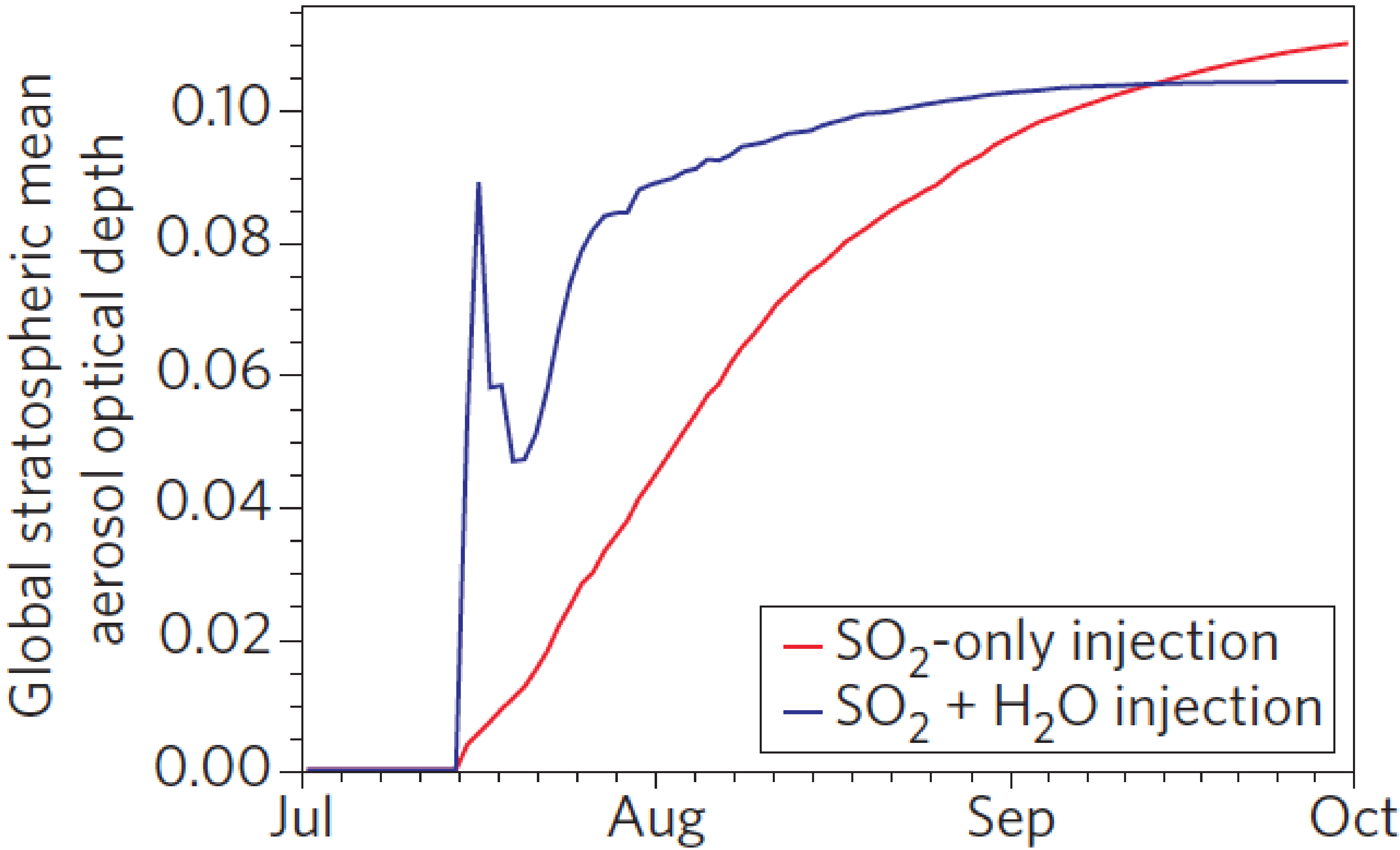
Friberg et al., 2015

Oxidation lifetime of SO_2 depends on cloud altitude



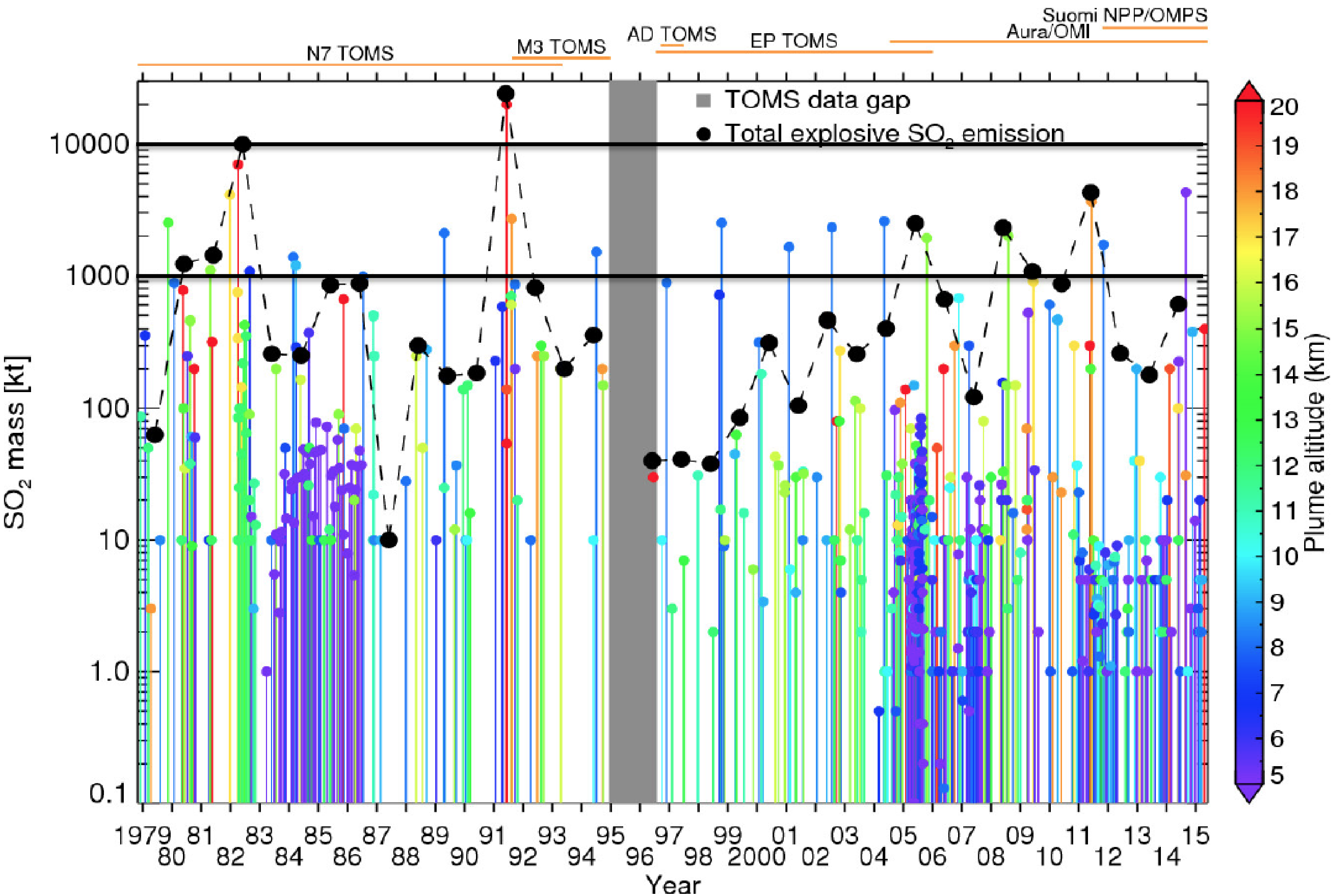
Carn et al. 2016

GISS model suggest H_2O injections needed to explain Pinatubo

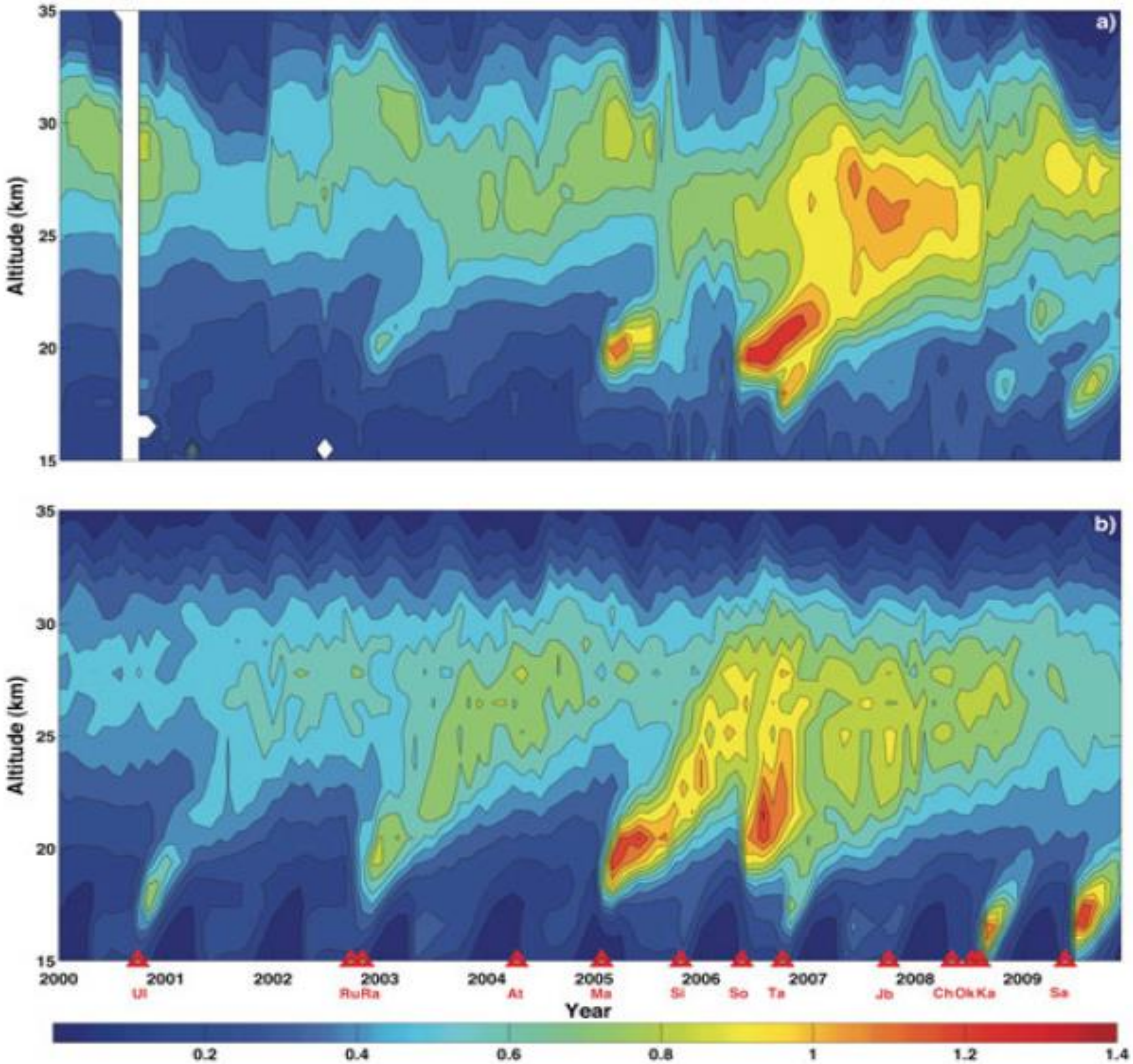


Legrande et al.Nature, 2016

SO_2 is key to volcano climate effects



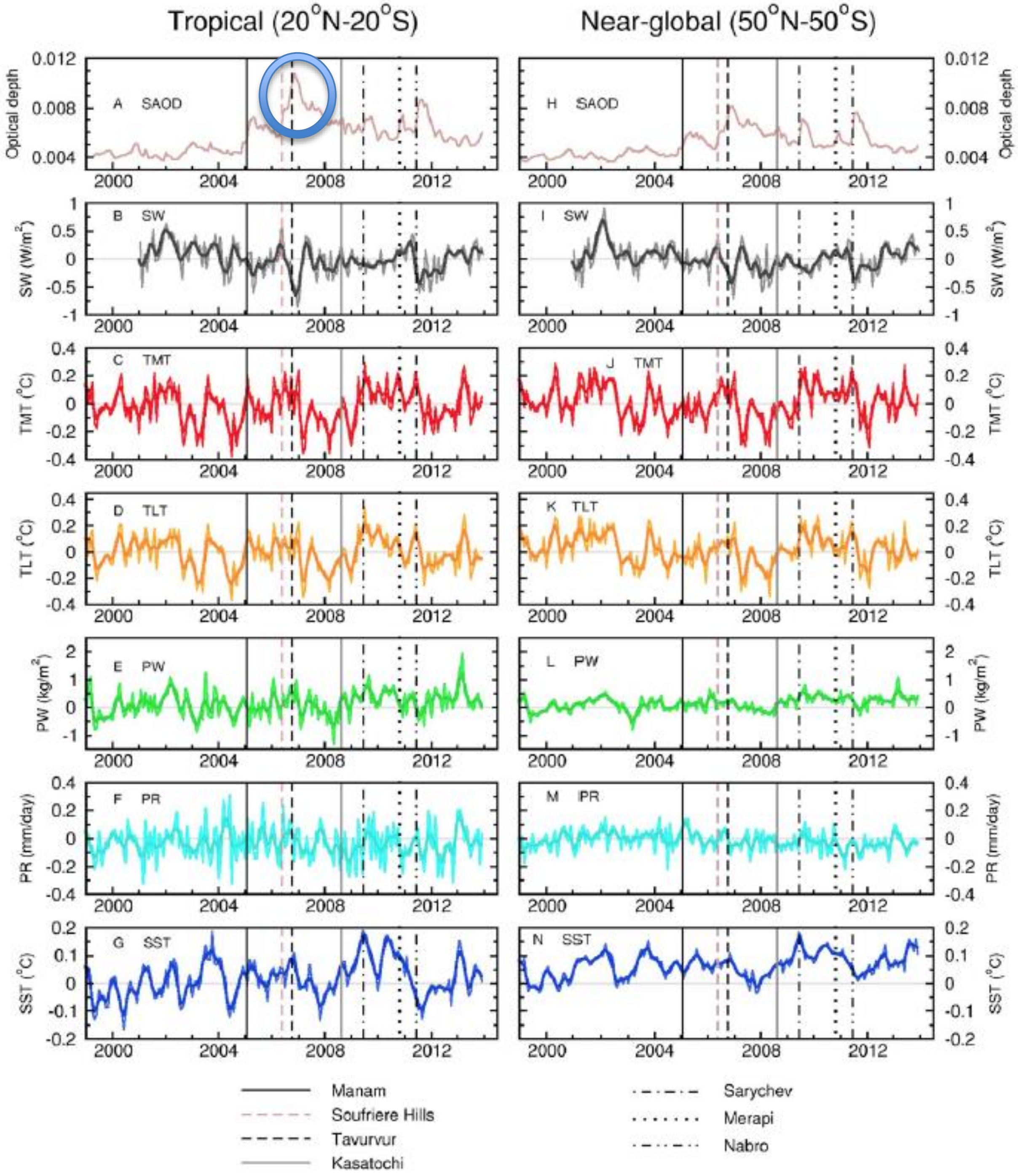
Satellites detect and models can simulate extinction ratio for small volcanic clouds



Data
Vernier et al., 2011

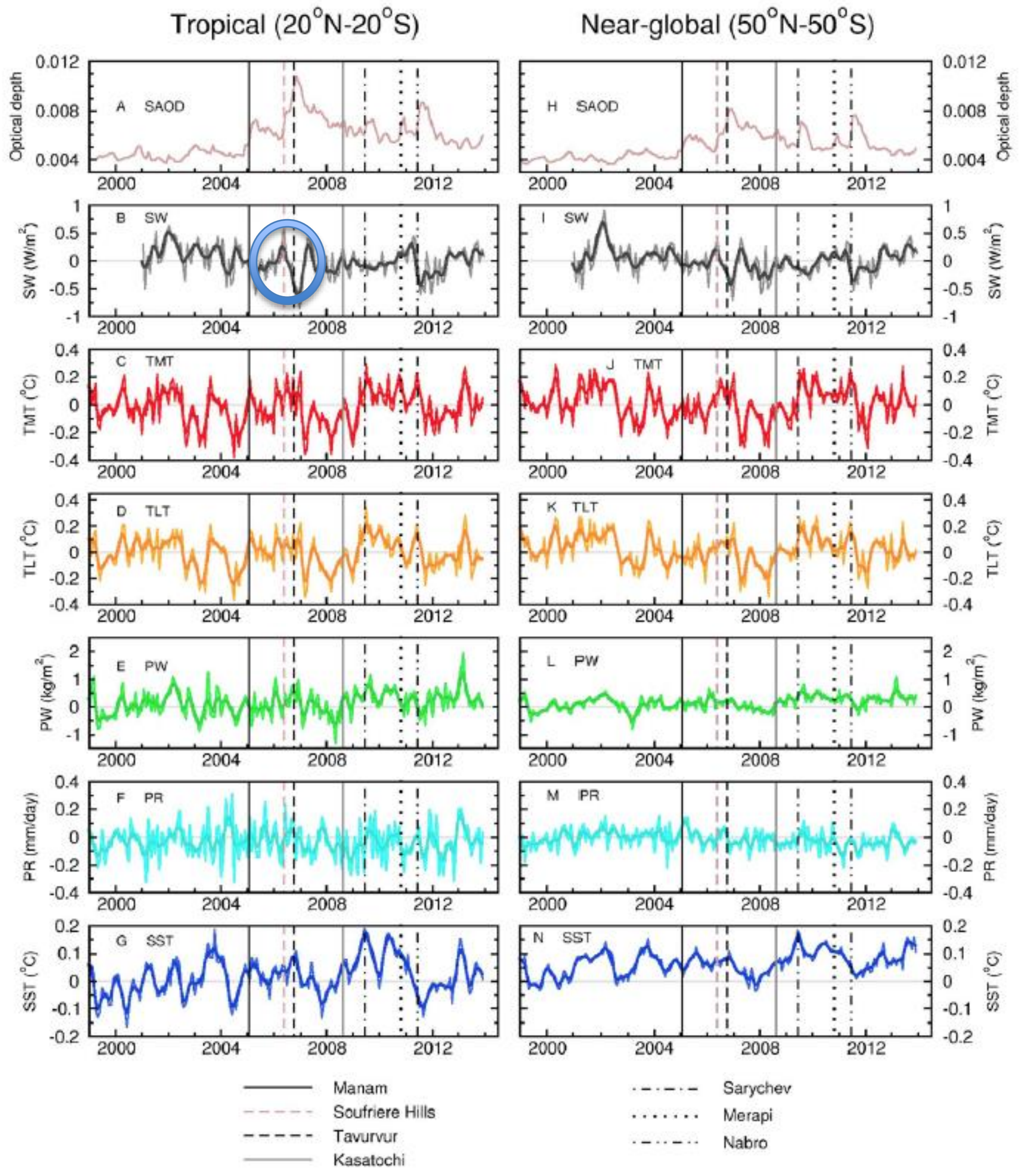
Model
Neely III et al., 2013

Extinction ratio



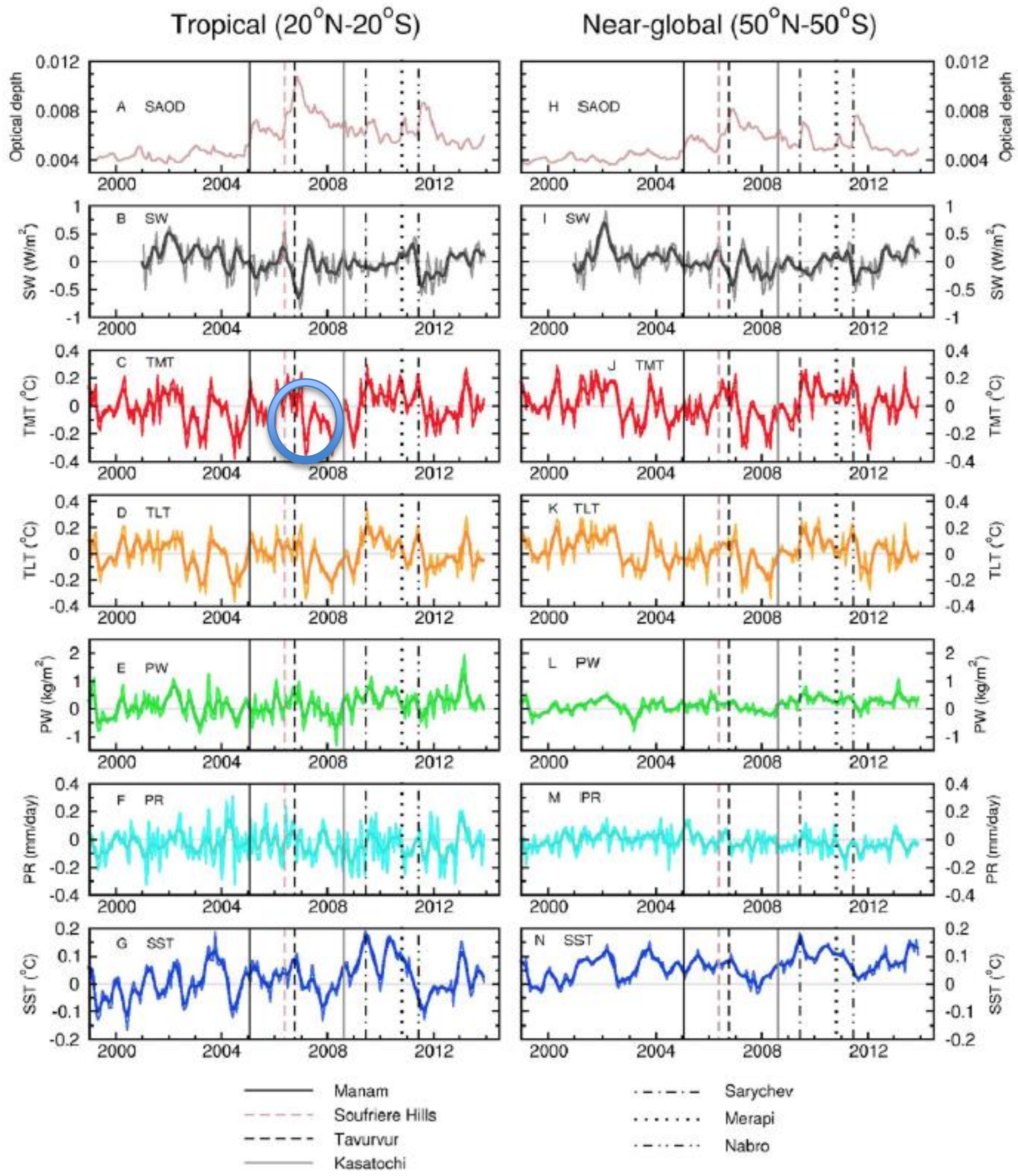
Small, common, eruptions have detectable signals in aerosol optical depth

Santer et al. 2015



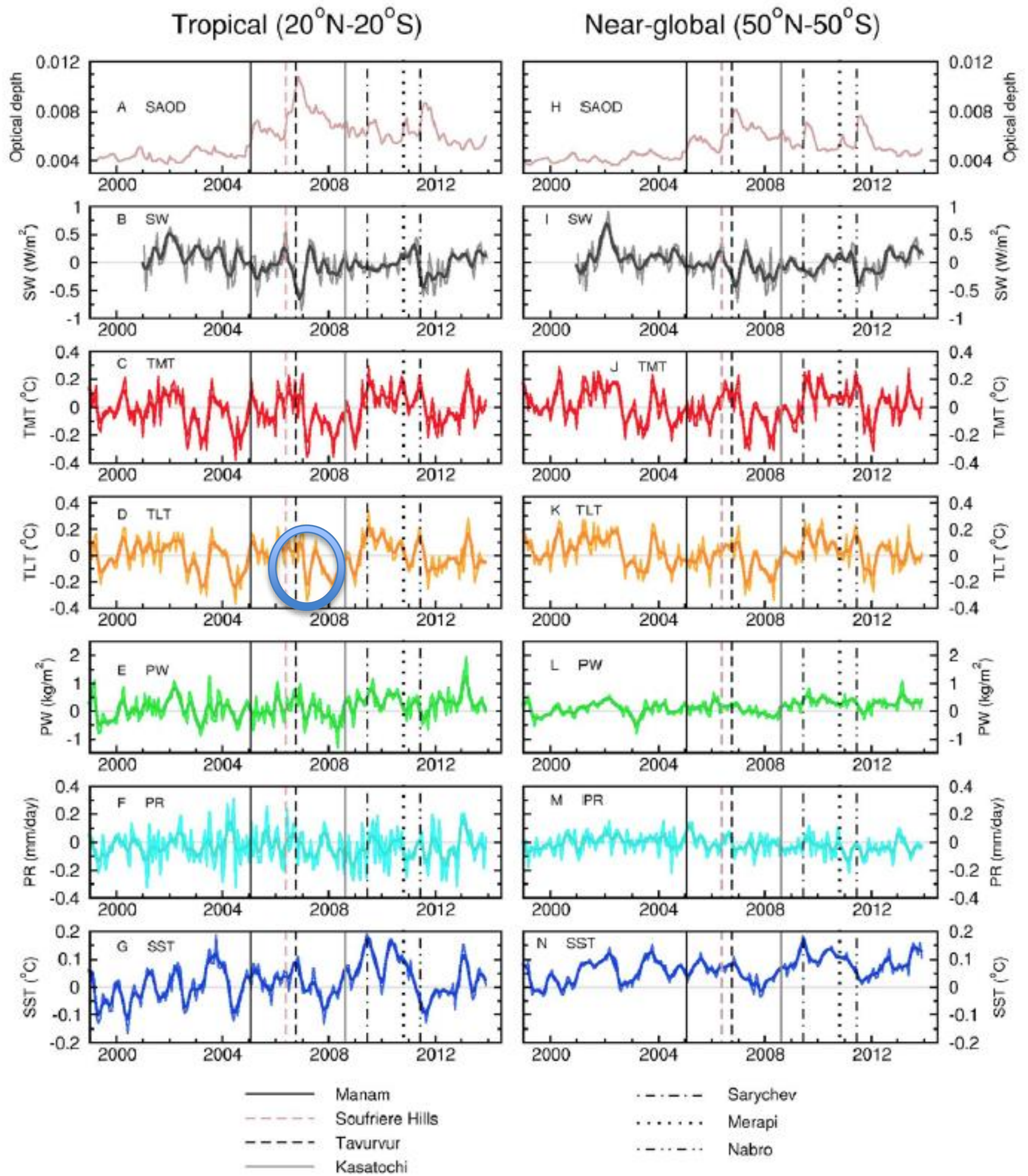
Small, common, eruptions have detectable signals in short wave flux

Santer et al. 2015



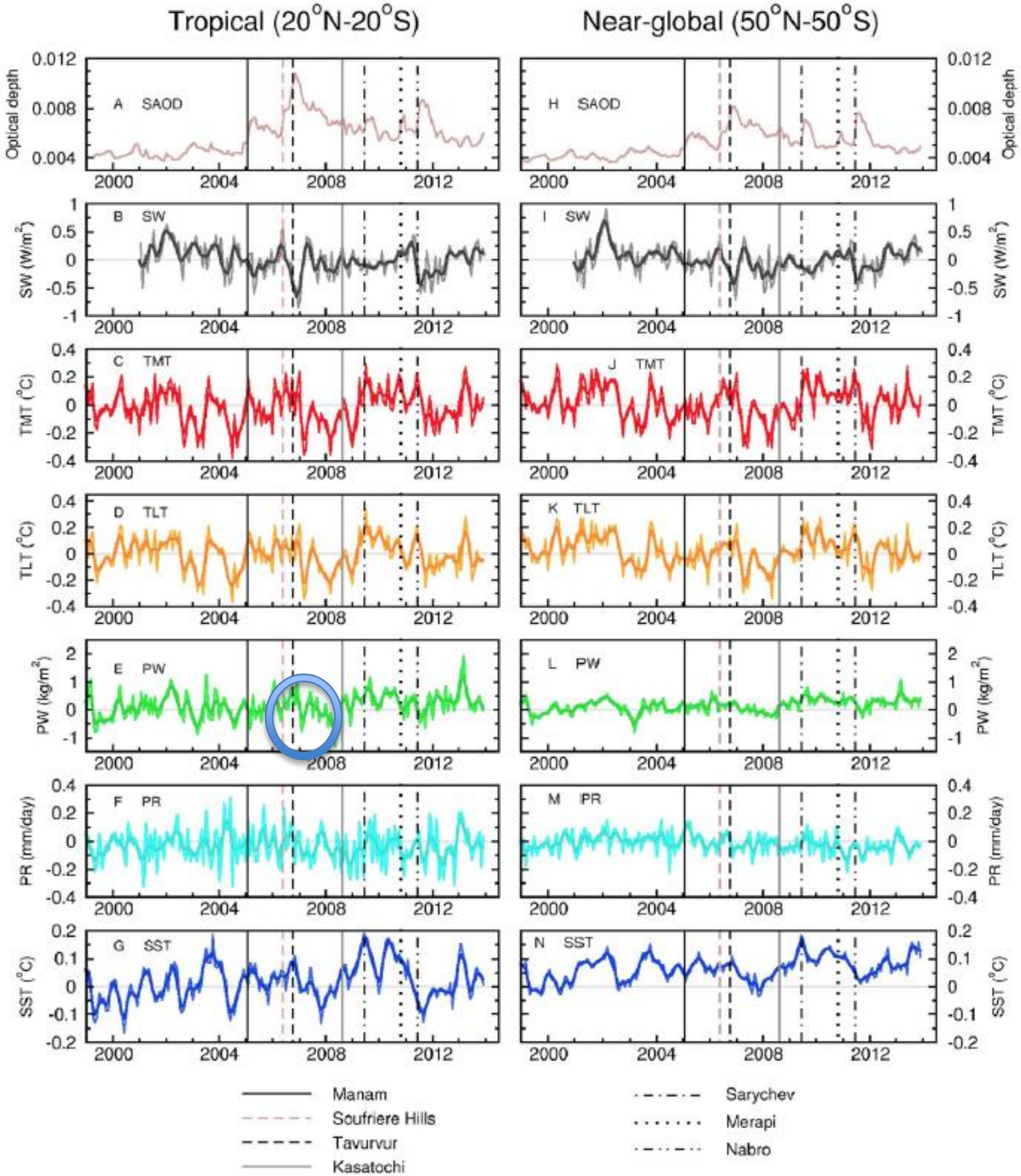
Small, common, eruptions have detectable signals in temperature of middle and upper troposphere

Santer et al. 2015



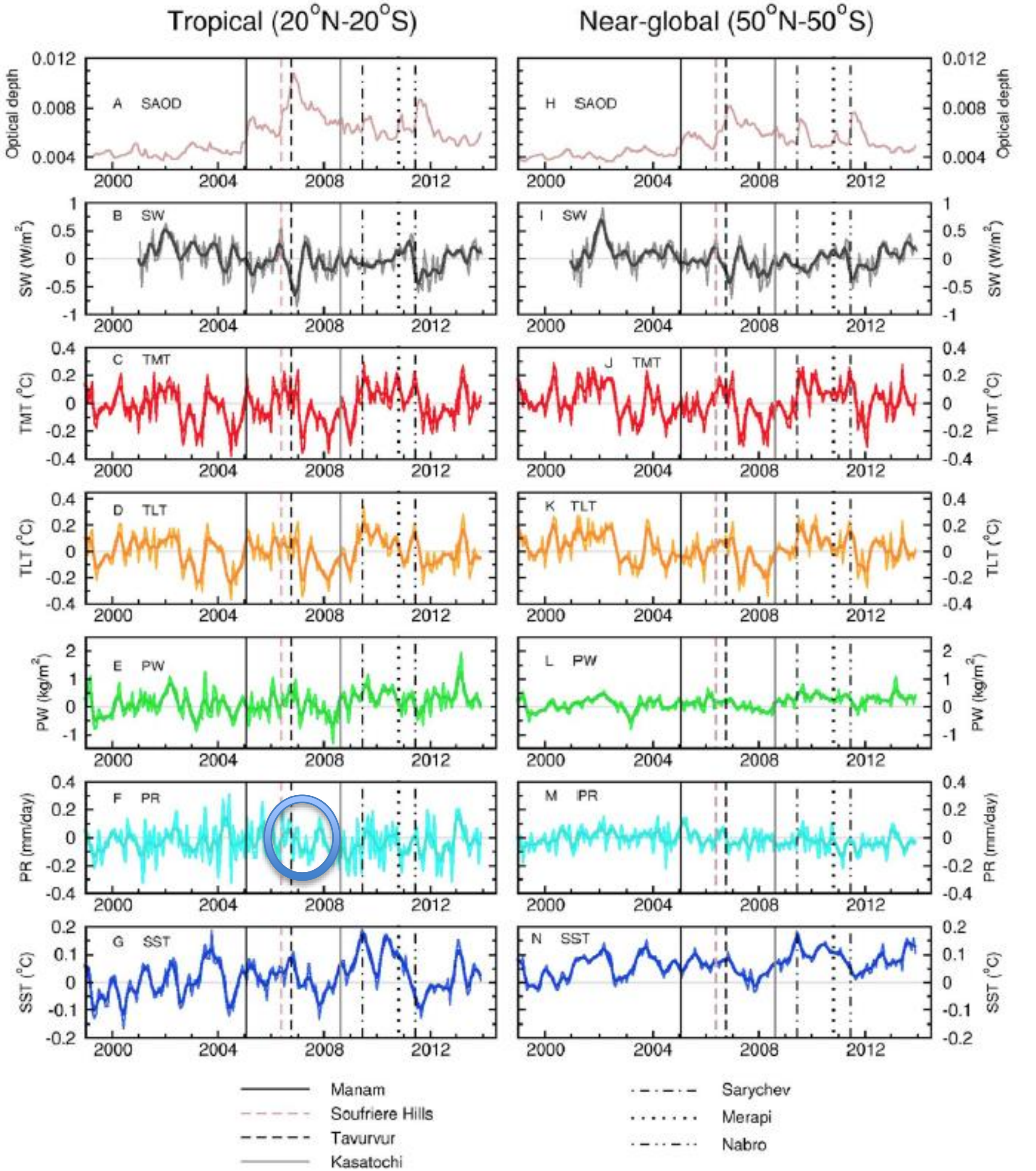
Small, common, eruptions have detectable signals in temperature of lower troposphere

Santer et al. 2015



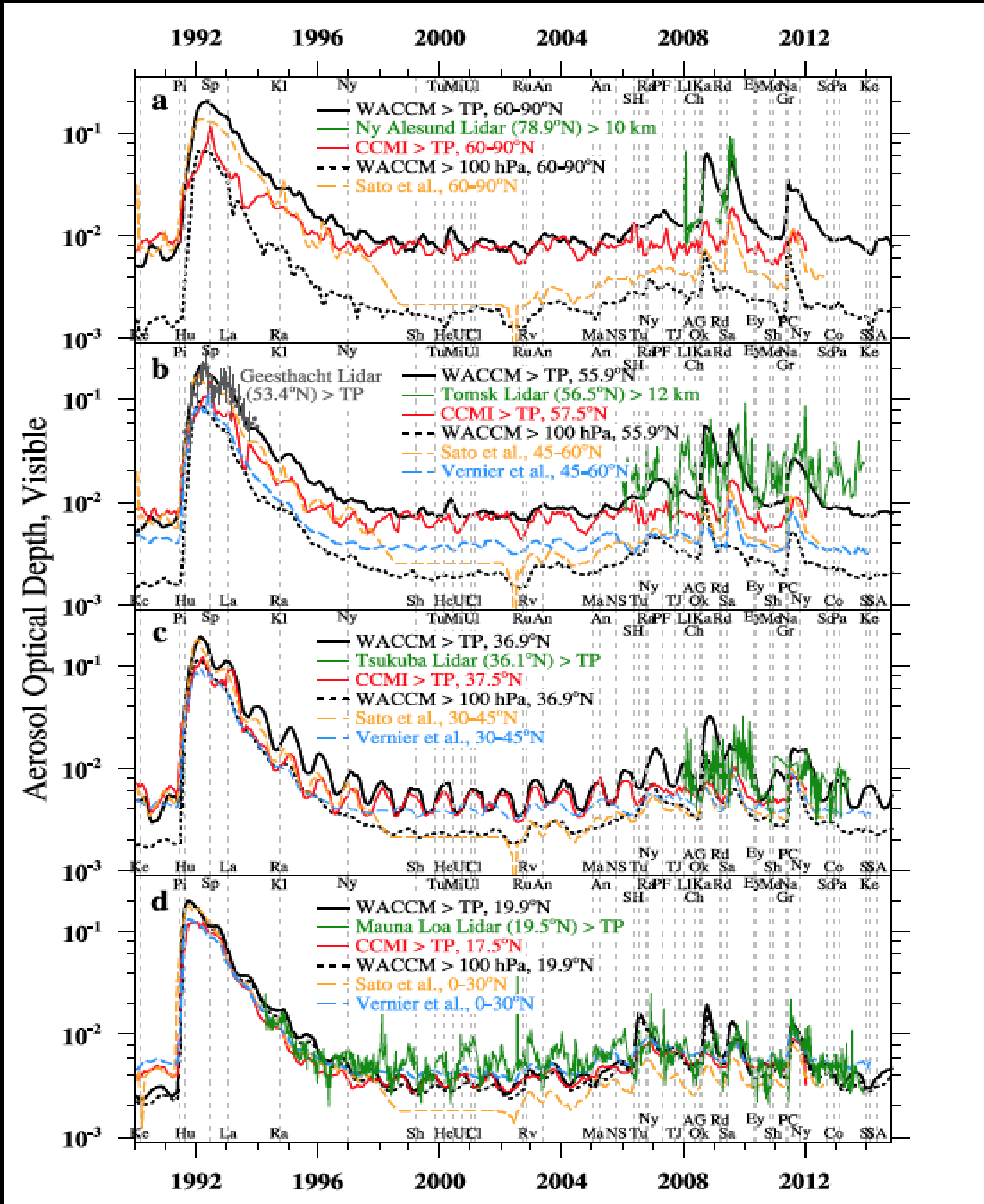
Small, common, eruptions have detectable signals in temperature of column water vapor

Santer et al. 2015



Small, common, eruptions have detectable signals in precipitation

Santer et al. 2015



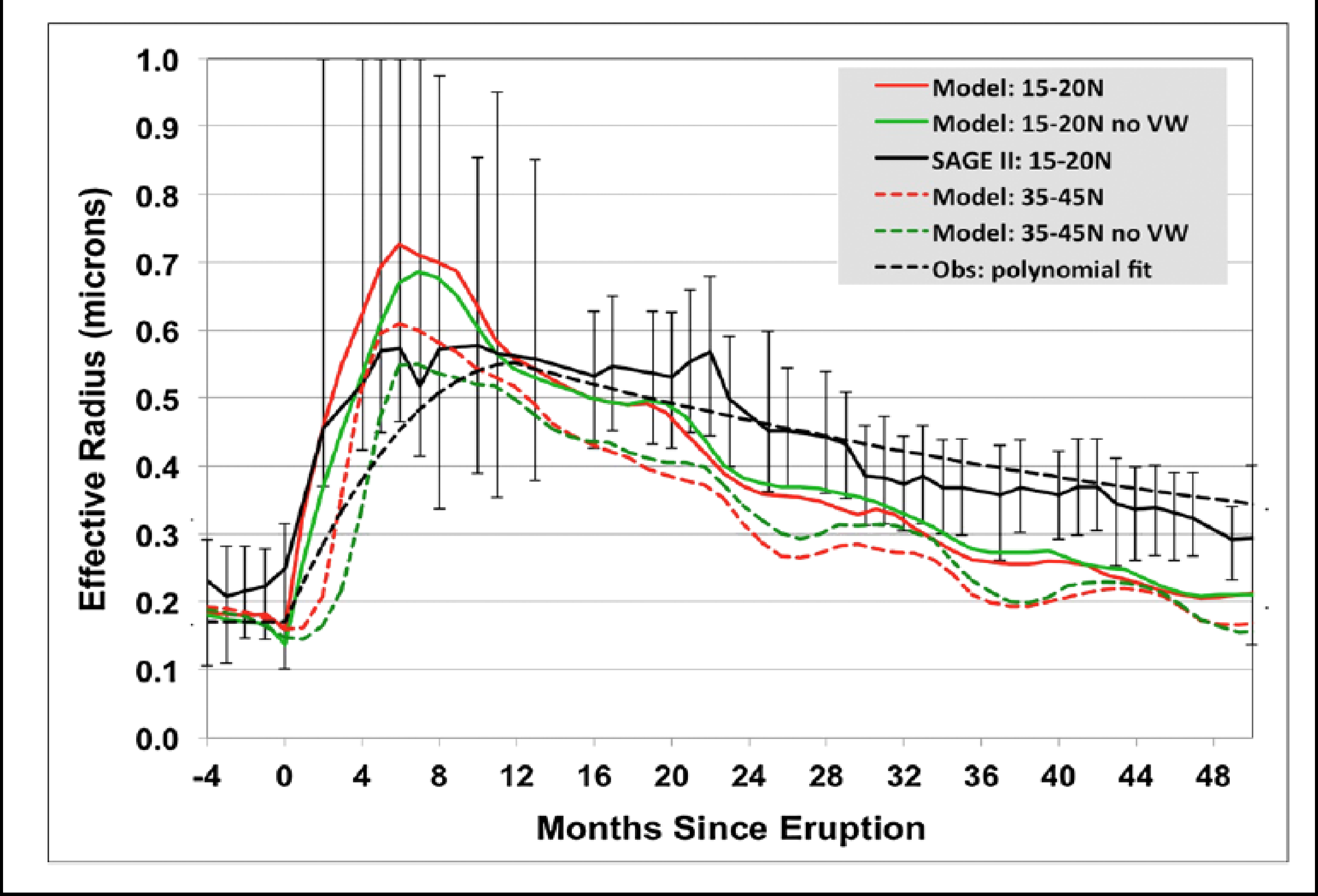
Models can reproduce the optical depth given SO_2 from observations, but data needed from tropopause up at mid-latitudes

Mills et al., 2016

Effective radius is a measure of the particle size that impacts radiation

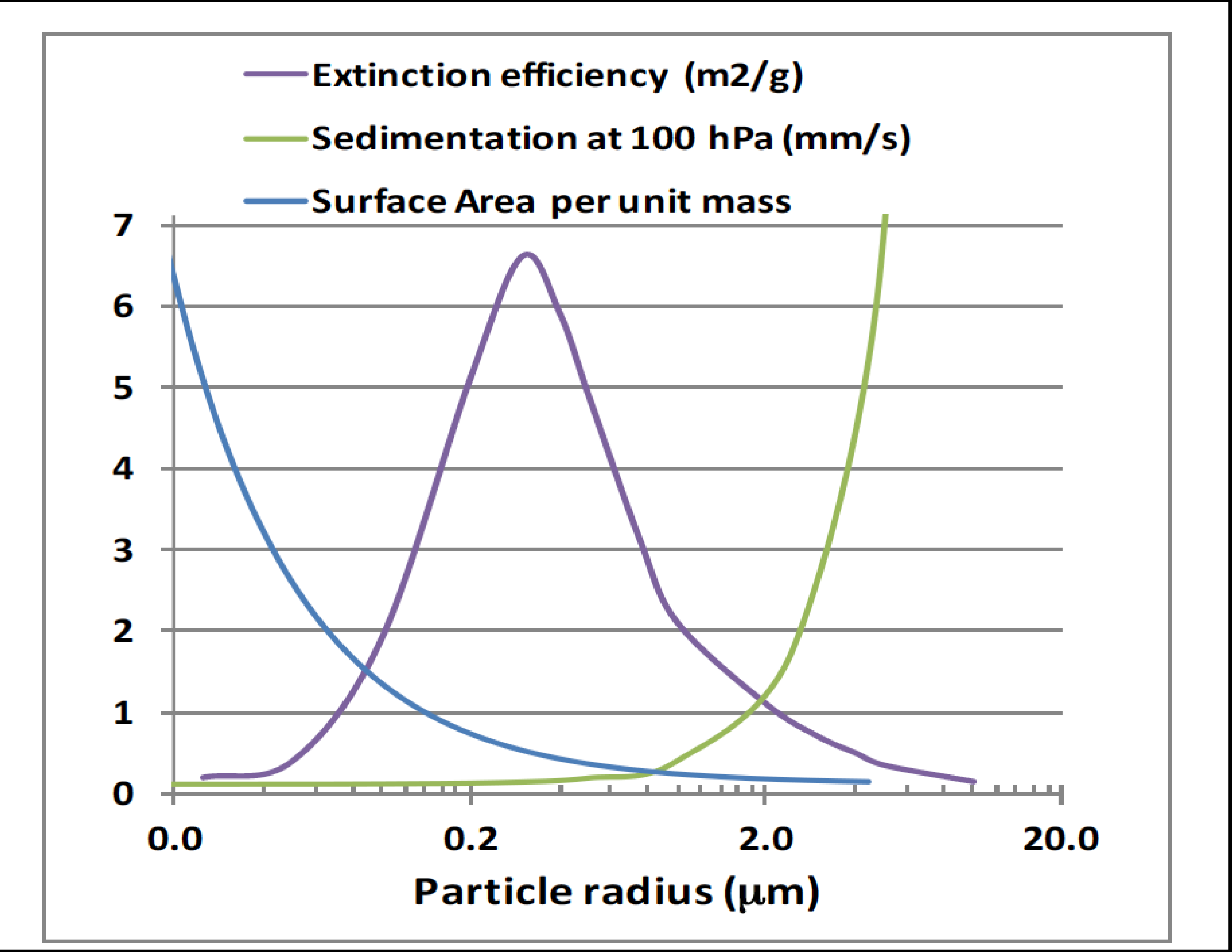
$$r_{eff} = \frac{\int r\left(\pi r^2 n(r) q_{ext}(m, \lambda / r)\right) dr}{\int \pi r^2 n(r) q_{ext}(m, \lambda / r) dr} \approx \frac{3}{4}\frac{V}{A_c}$$

The effective radius after Pinatubo was not constant in time



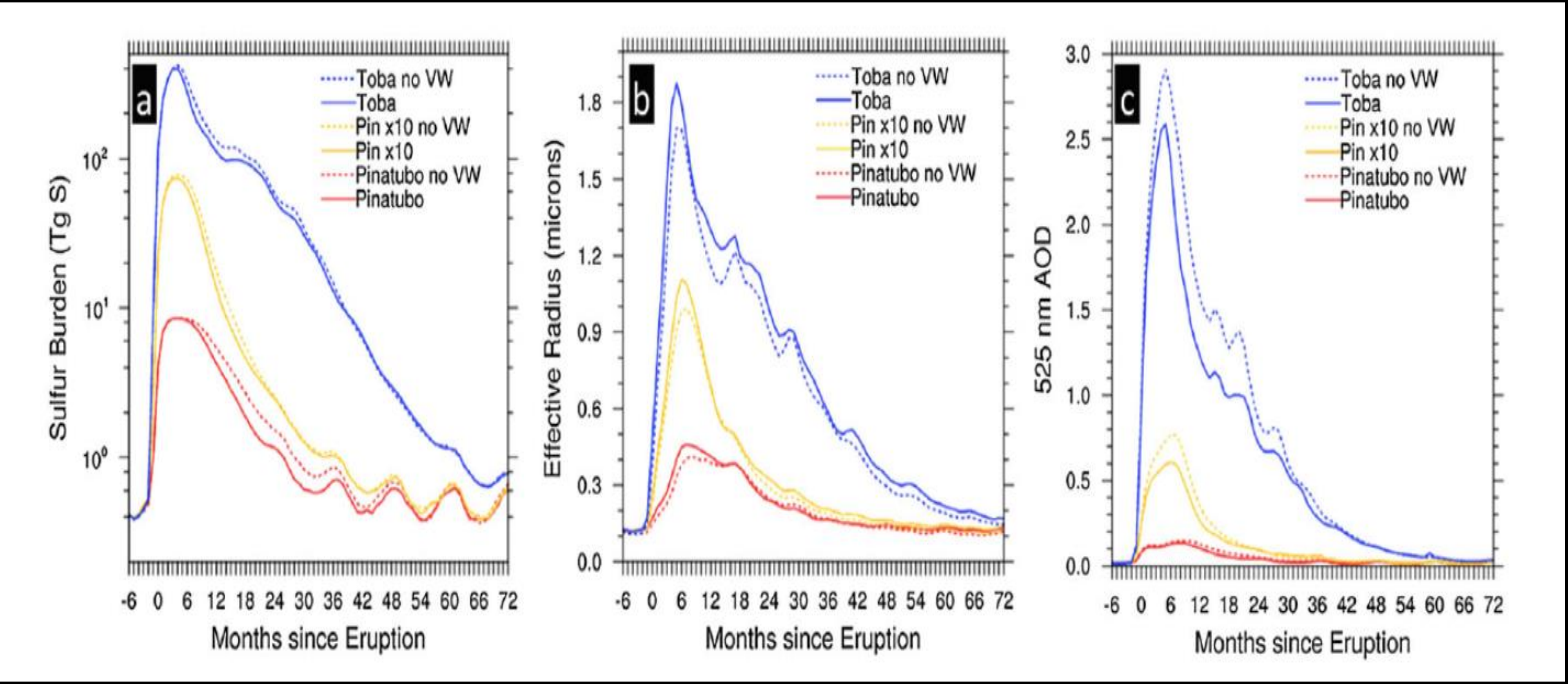
English et al., J. Geophys. Res., 2013

Reff is not enough to compute physics



Courtesy of Jason English

Models show optical depth not linear in SO_2 emission or sulfate burden



S in sulfate 37% of S in SO_2
Pinatubo to 100x Pinatubo

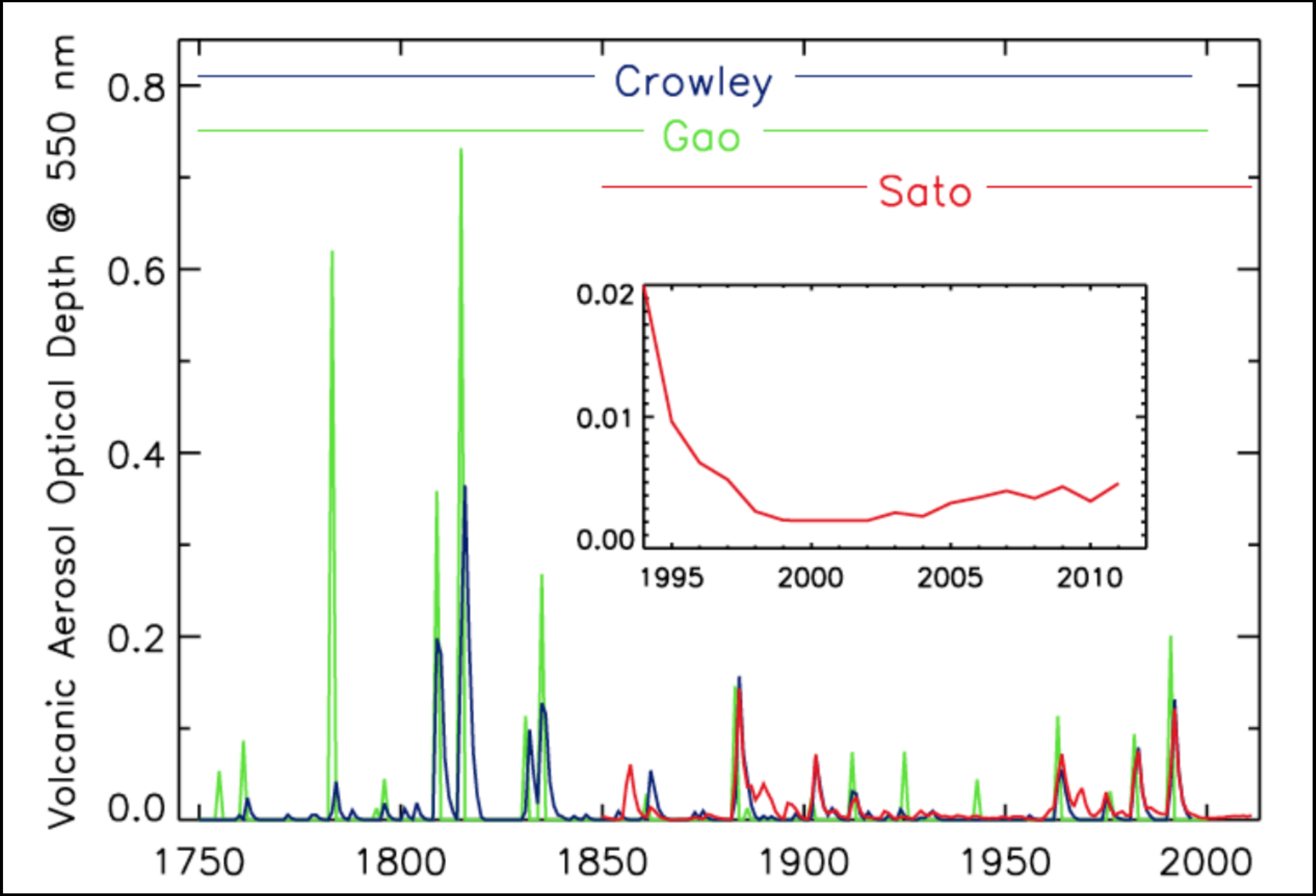
Reff ~ $M_{SO2}^{1/3}$

AOD~M/Reff

Peak AOD~20% of increase in S Pinatubo to 100x Pinatubo

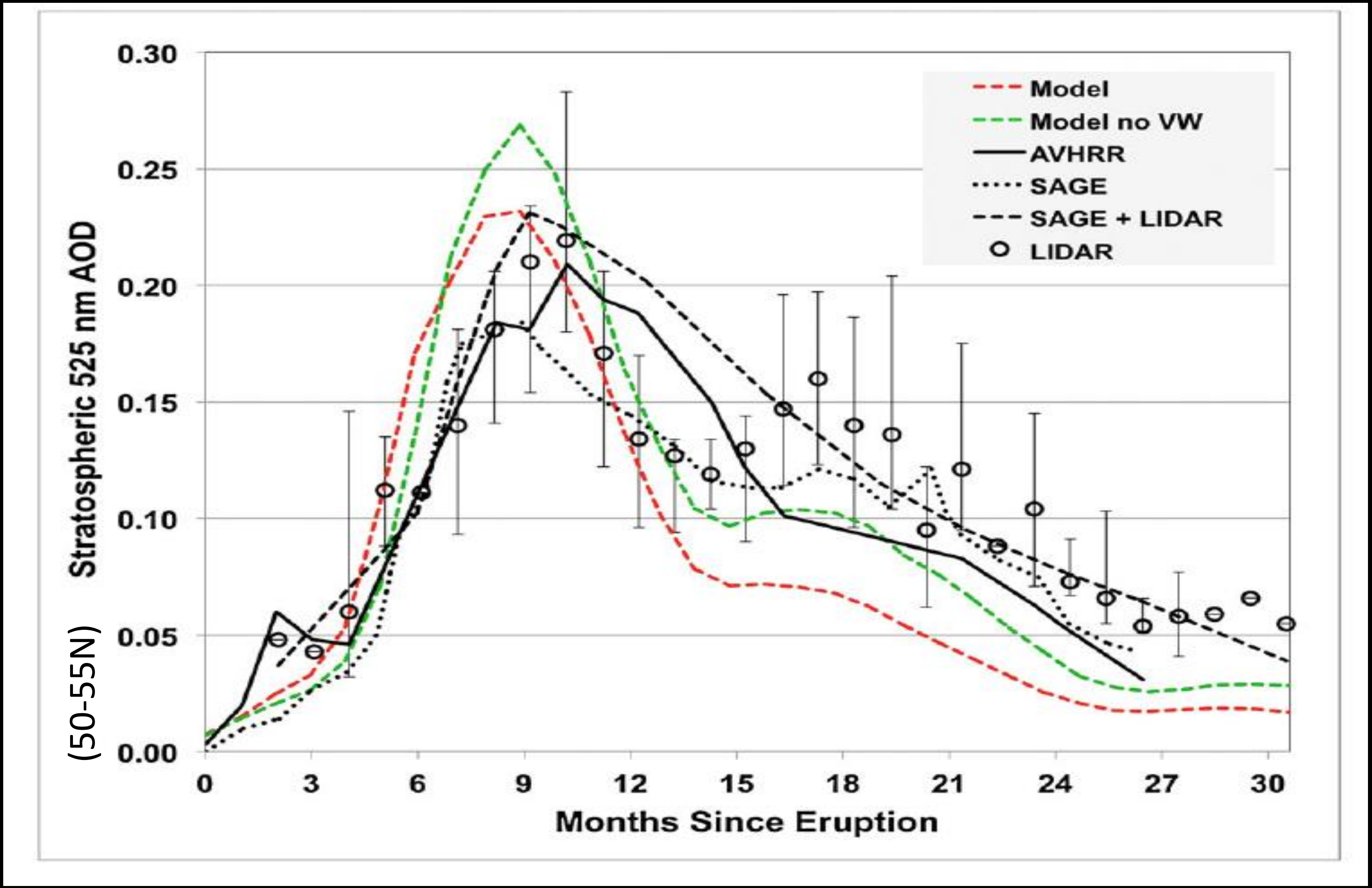
English et al., J. Geophys. Res., 2013

Is a global average optical depth good enough?



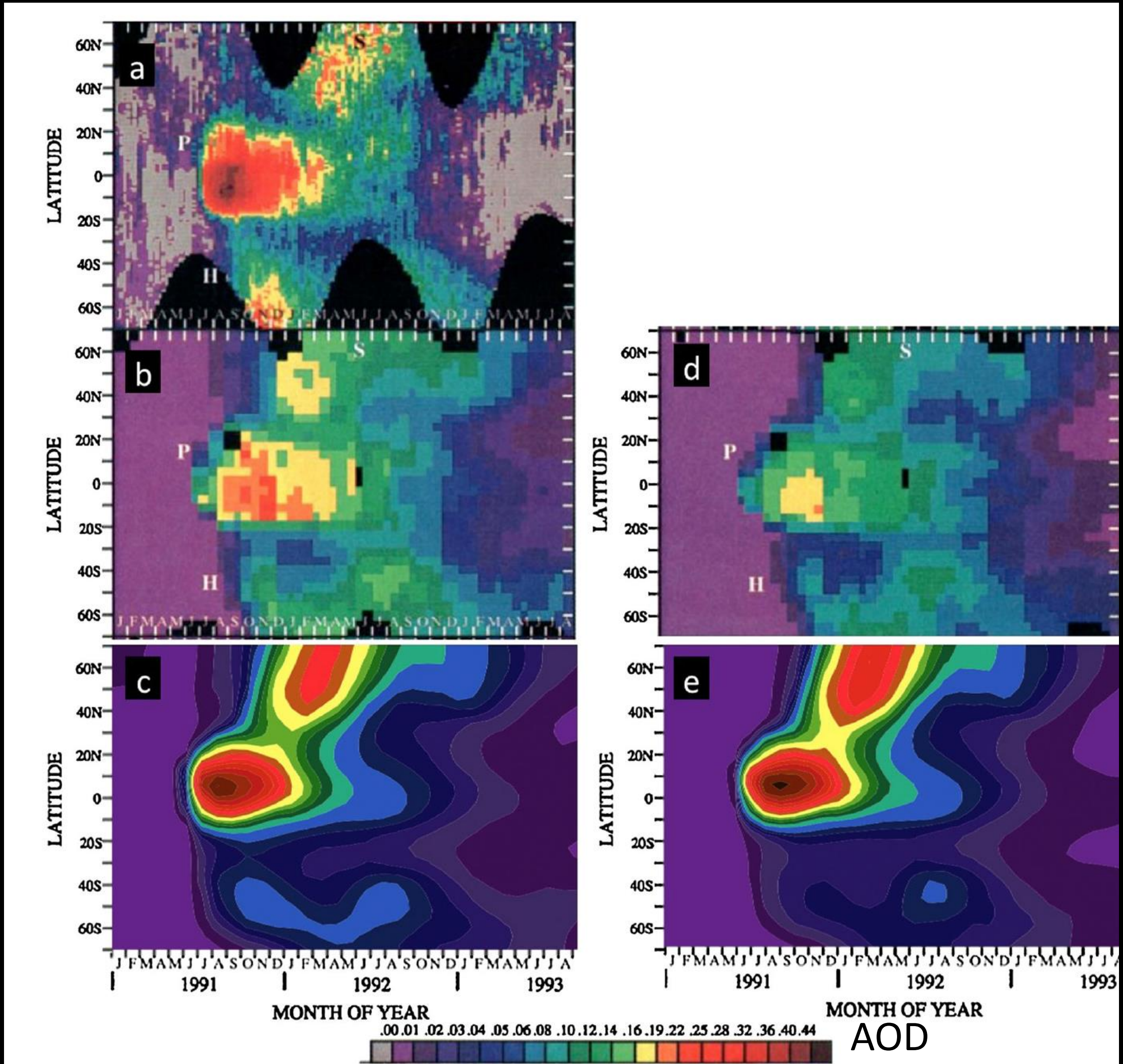
Myhre et al., 2013

Optical depth difficult to predict at fixed location, data have errors, but models have some skill.



English et al., J. Geophys. Res, 2013

The optical depth varies in space and time. A global average makes no sense.

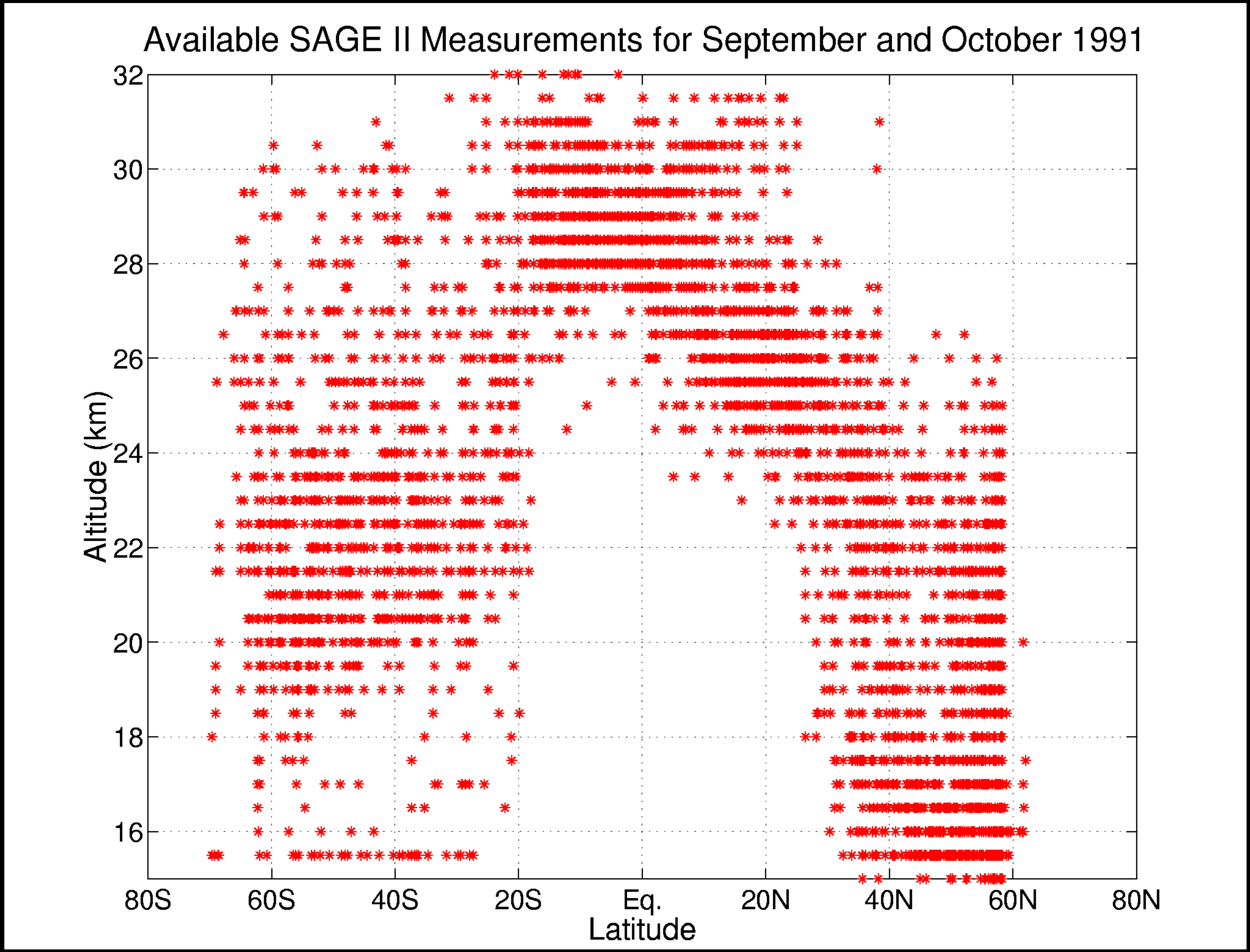


AVHRR, 500nm

SAGE II

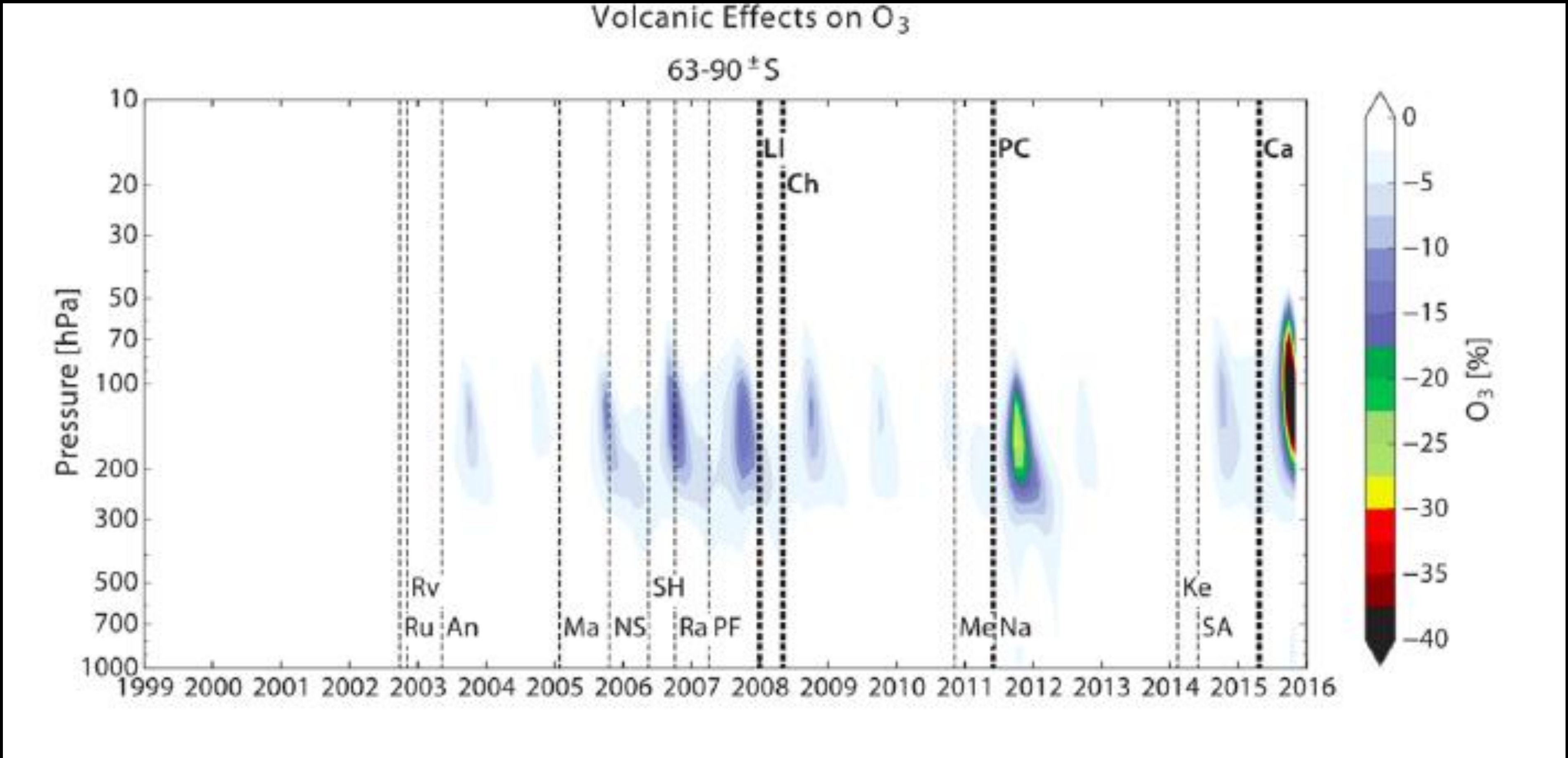
Model 525,1024nm
English et al., 2013

Limb sounders are blocked by Pinatubo sized events



Plot by Juan Carlos Antuña
Courtesy Alan Robock

Small eruptions may cause polar ozone loss

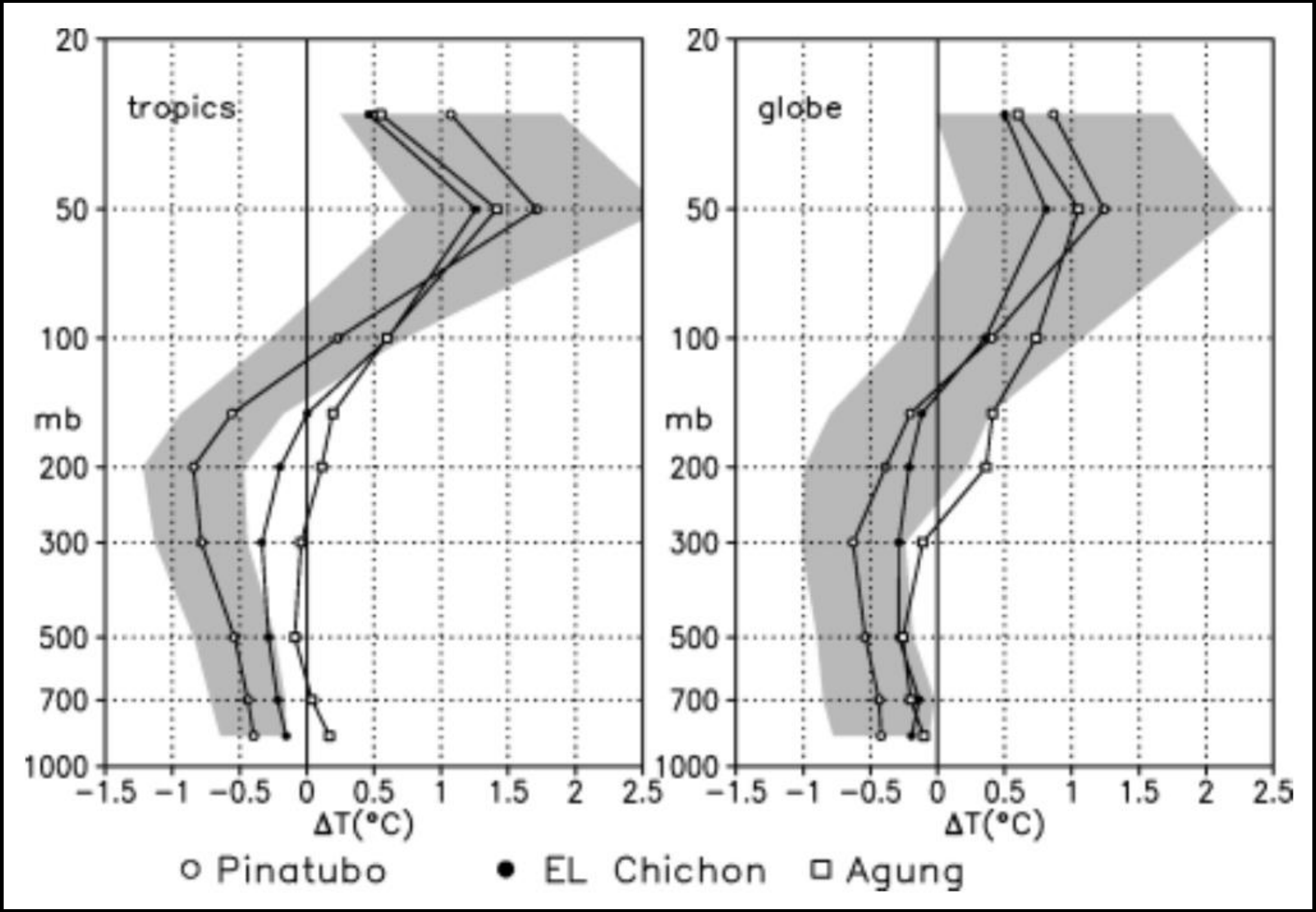


Solomon et al., Science 2016

What could we do?

- Need detailed size measurements from nm to microns so that we can check growth rates, nucleation rates, resolve remote sensing issues.
- Need AOD data, or ways to compute it following large eruptions, because limb scanners will be blocked, scatters will have retrieval problems.
- Make improved models/ observations of volcanic effects on ozone, cirrus.
- Understand relation between injection height, SO2 lifetime, water injections
- Quantify relation of reff, AOD to SO_2 mass injected

Most focus has been on temperature



Free and Angell, 2002

Summary

- Global average optical depths don’t correspond to reality.
- The optical depth depends on SO_2 injected not explosivity.
- Optical depth is less than linear with SO_2 mass injected.
- Recovery of the ozone layer retarded by small eruptions
- Large error bars on observed properties of historical volcanic clouds.
- We need more data and we need to be prepared to get it. Small eruptions are important to study. Better models are needed.

Tambora and the Year Without Summer-1816

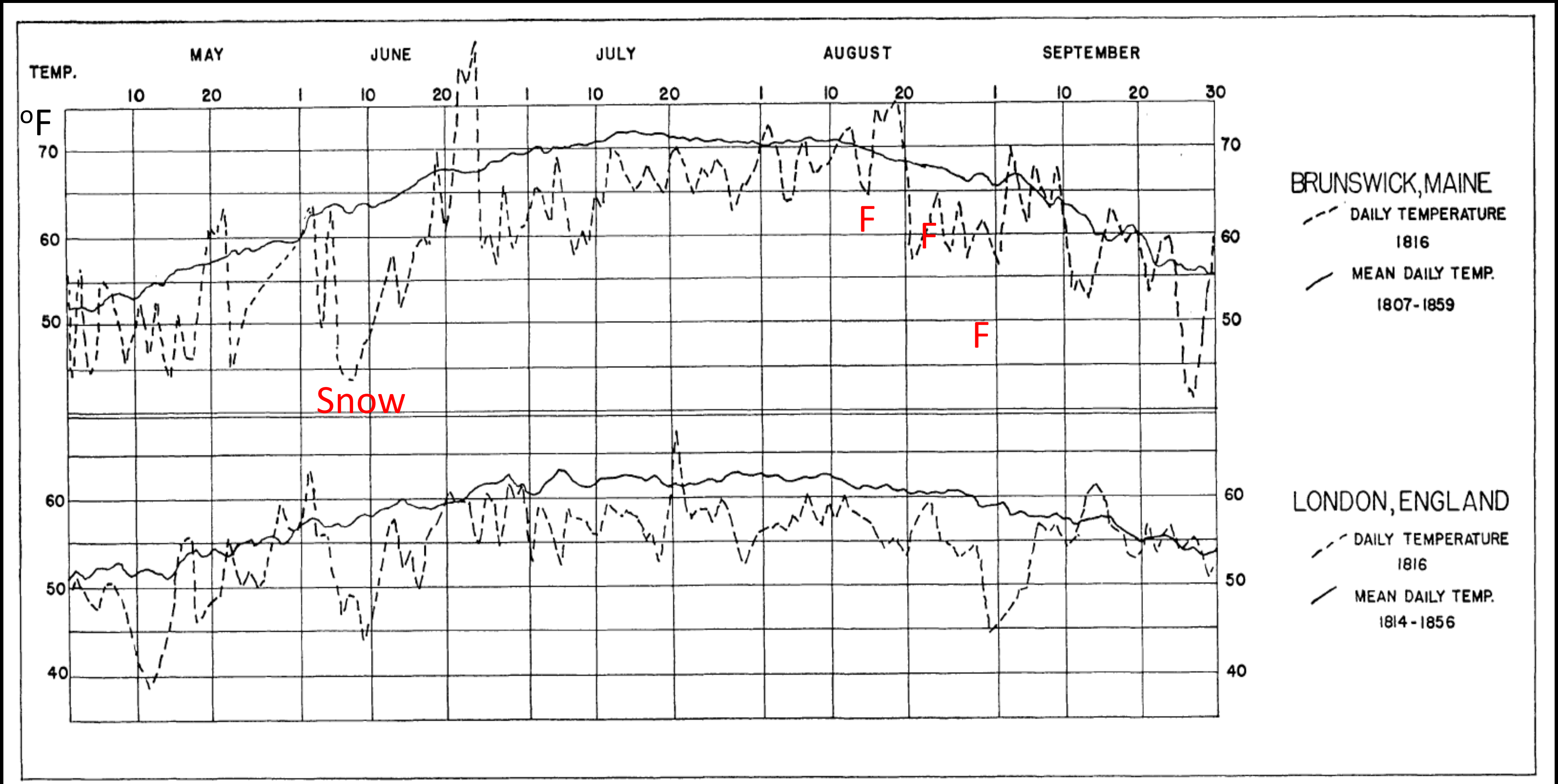
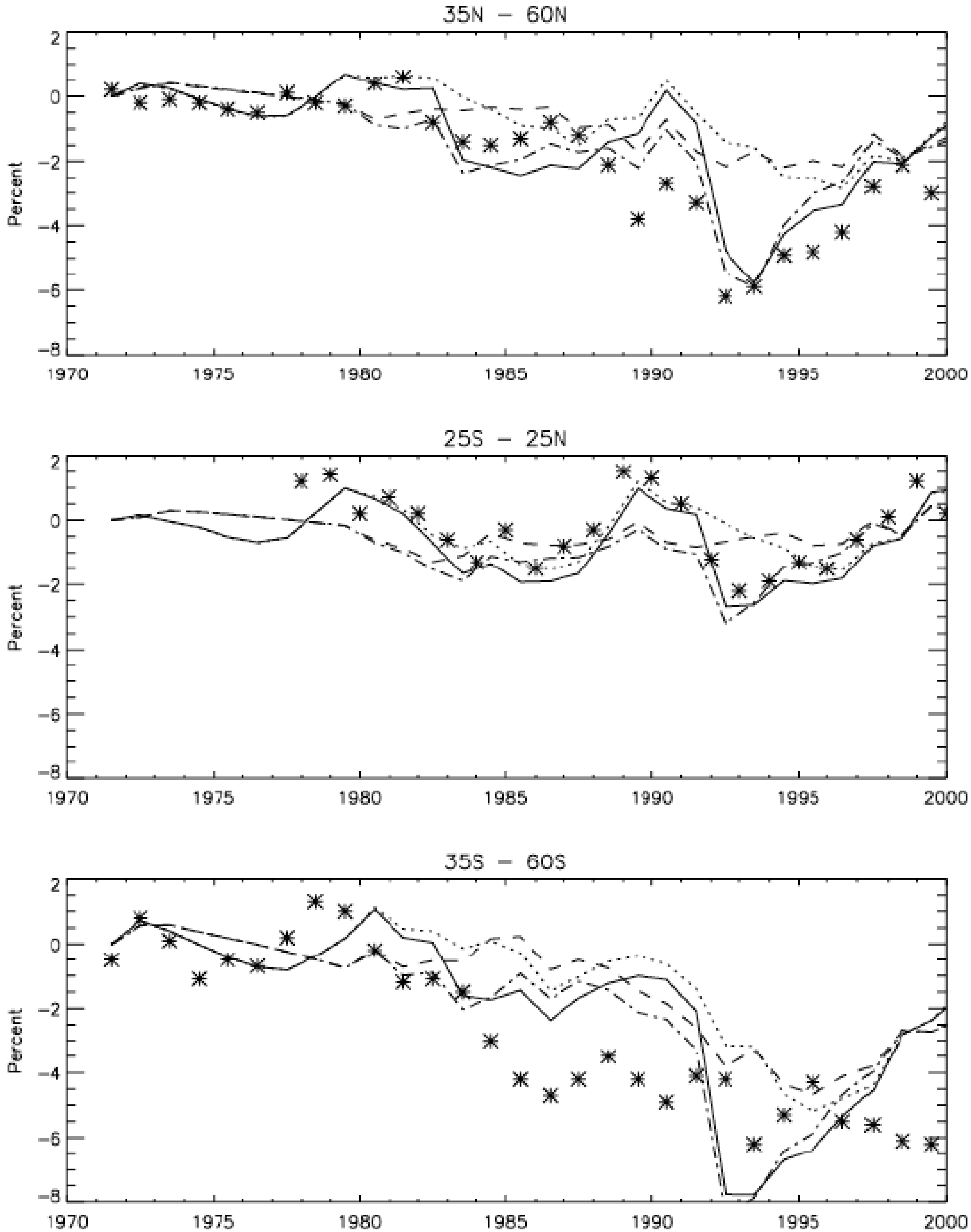


FIG. 6. Daily and mean daily temperatures—Brunswick, Maine, and London, England.

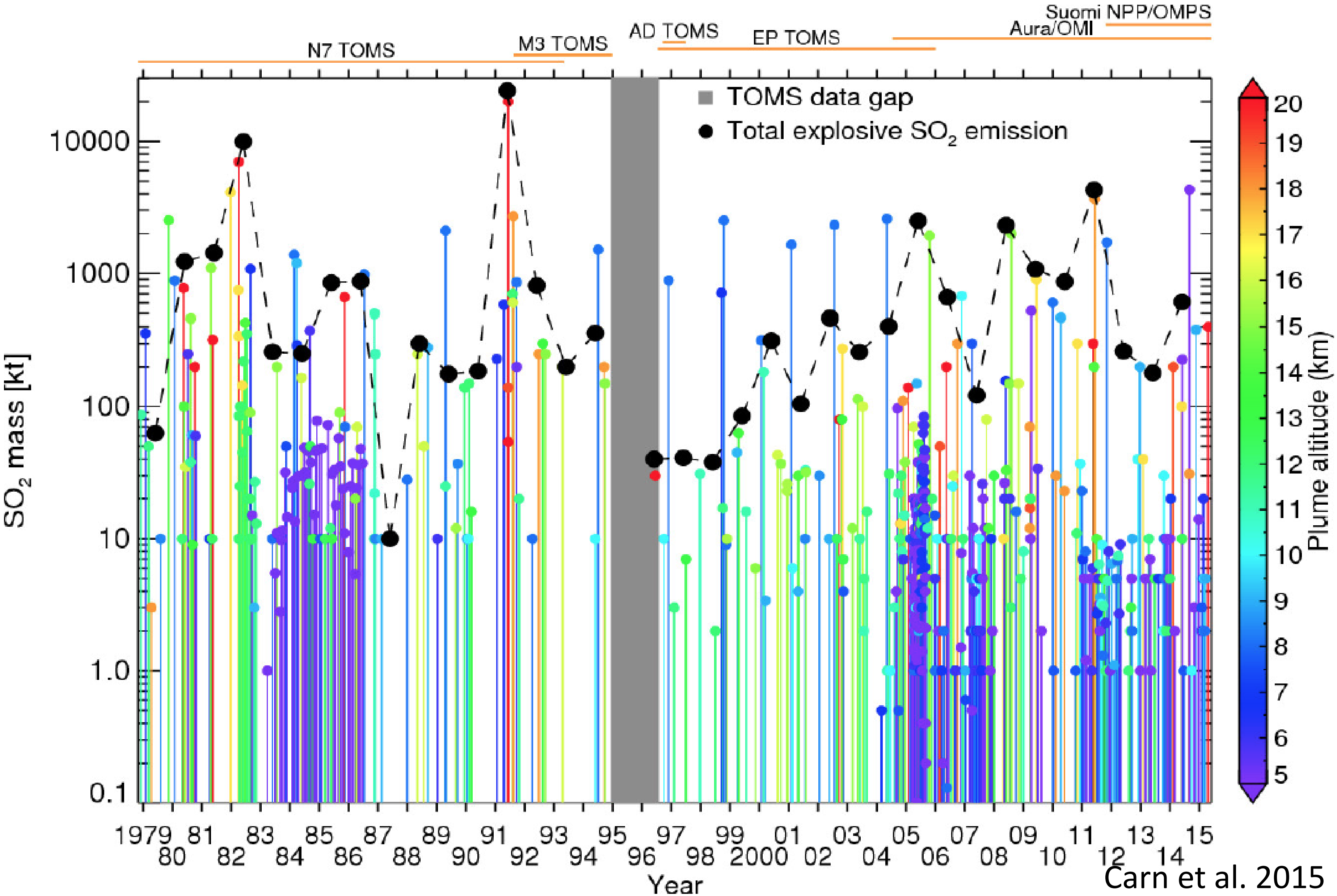
Hoyt, Assoc. Am. Geographers, 1958



Column ozone depleted by El Chichon (82) and Pinatubo (91), but likely not important in earlier eruptions

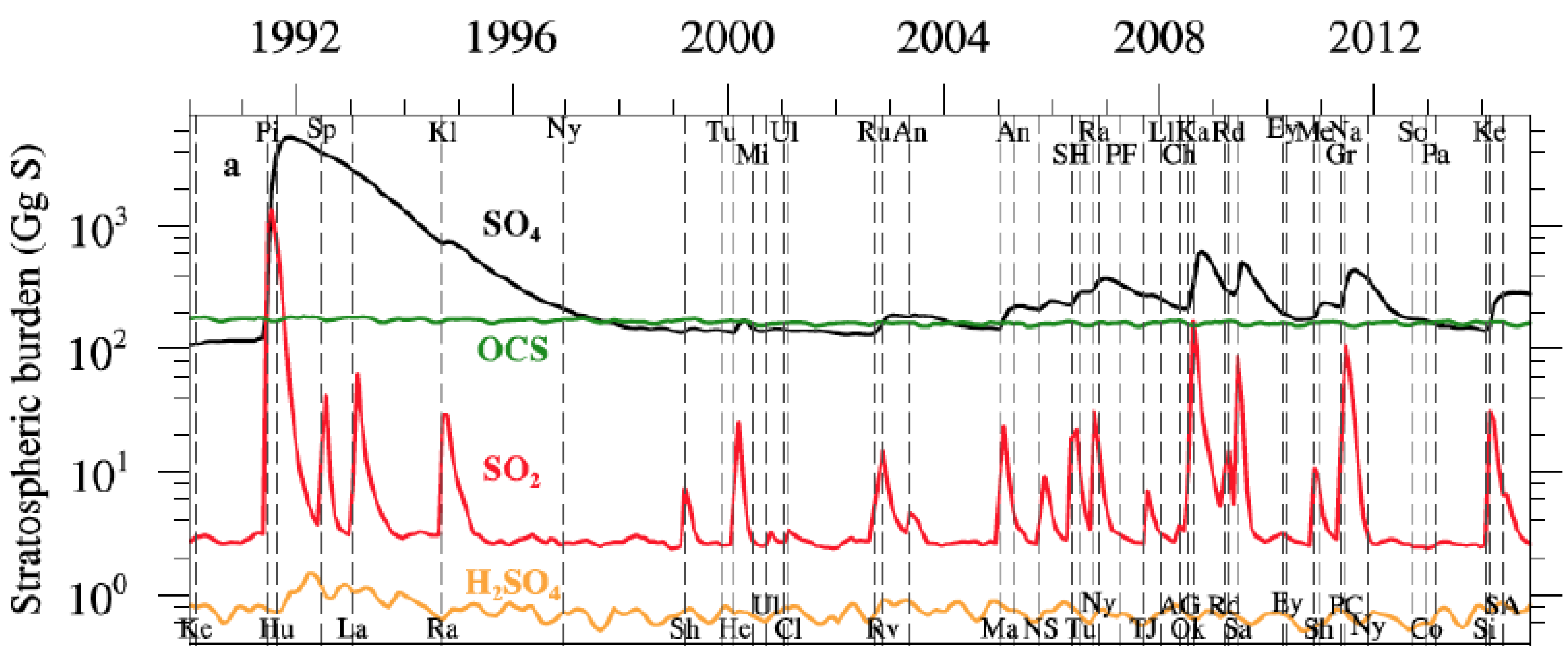
Geller and Smyshlyaev

SO_2 injection is key to volcano climate effects



Carn et al. 2015

Microphysical models can predict sulfur chemistry



Mills et al., 2016

Many changes observed after eruptions

Observed	**Probable cause**
Cooling troposphere and surface	Reduction in shortwave forcing by aerosol
Tropopause and stratospheric warming	Sunlight and ir absorption by aerosol
Mid-lat. N.H. winter warming	Strat./troposphere dynamical interaction
Rapid spread of volcanic clouds	Alteration of atmospheric dynamics
Ozone loss	Heterogeneous reactions on sulfate aerosols
Hazy skies/bright twilights/ reduction in shortwave at surface	Scattering by aerosols
Change in stratospheric CH_4, H_2O	Change in dynamics, tropopause T
Change in tropospheric CO_2, CO, CH_4	Increase/Reduction in UV in troposphere, drop in sea surface T, coincidence
Reduction in water vapor column	Sea surface cooling
Reduction in precipitation	Reduction of solar heating of sea surface
Expected	
Cirrus cloud increase/decrease	Seeding by large sulfate particles
Cooler days	Loss of sunlight
Cooler nights	Loss of sunlight, little IR change
Polar amplification	Decreased poleward energy flux
Increase in sea ice	Polar cooling

Need to know optical properties to compute radiative changes-emphasis on microphysical models

Particle properties to measure	Possible ranges
Composition	Dust, sulfates
Size distribution	nm to tens of microns
Number	1 to 10^4
Mass	
Area	
Shape	Spheres/fractals
Optical constants	Dust
Extinction optical depth	0.001 to 1
Scattering optical depth	0.001 to 1
Absorption optical depth	0.001 to 1
Scattering phase function	

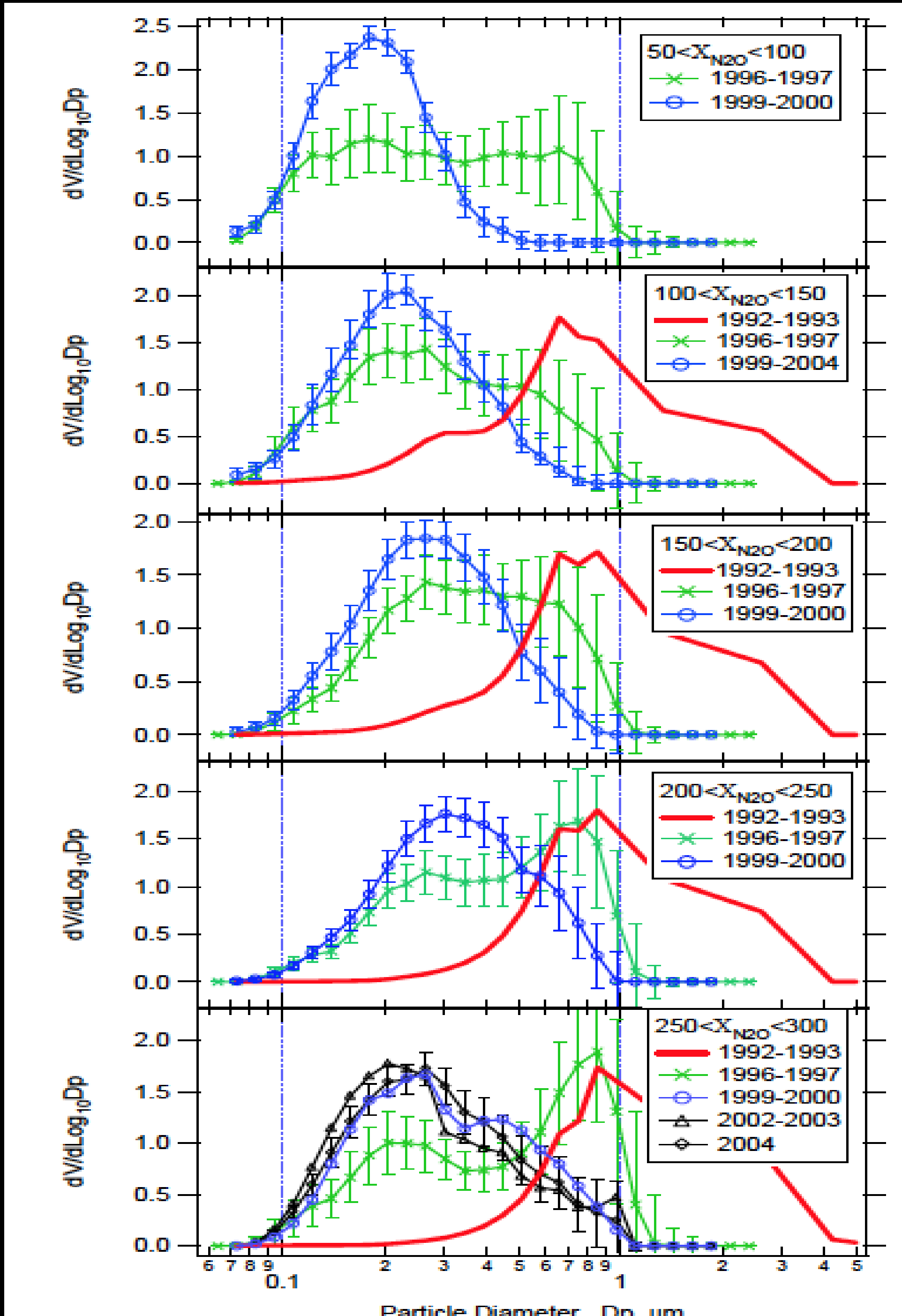
$$\frac{dN}{dt} = - \frac{1}{2} K N^2$$

$$N = \frac{N_0}{1 + \frac{1}{2} K N_0 t}$$

for large time

$$N = \frac{2}{Kt} \; so \;\; AOD \sim M$$

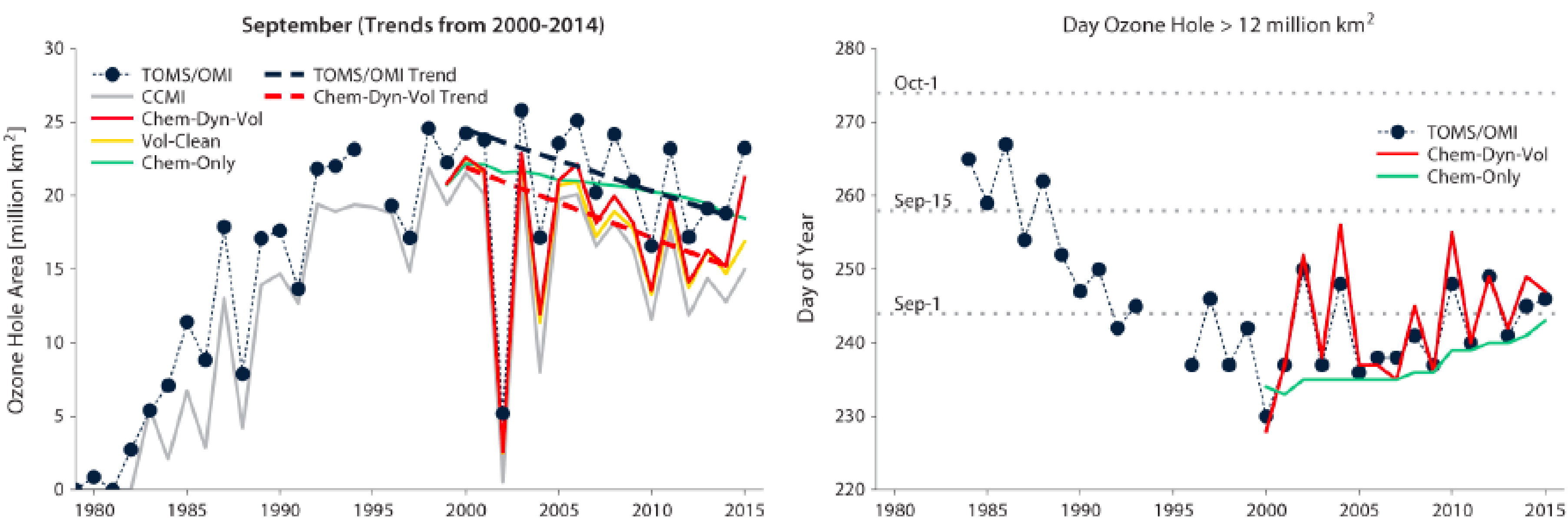
Reff not constant because coagulation limits number



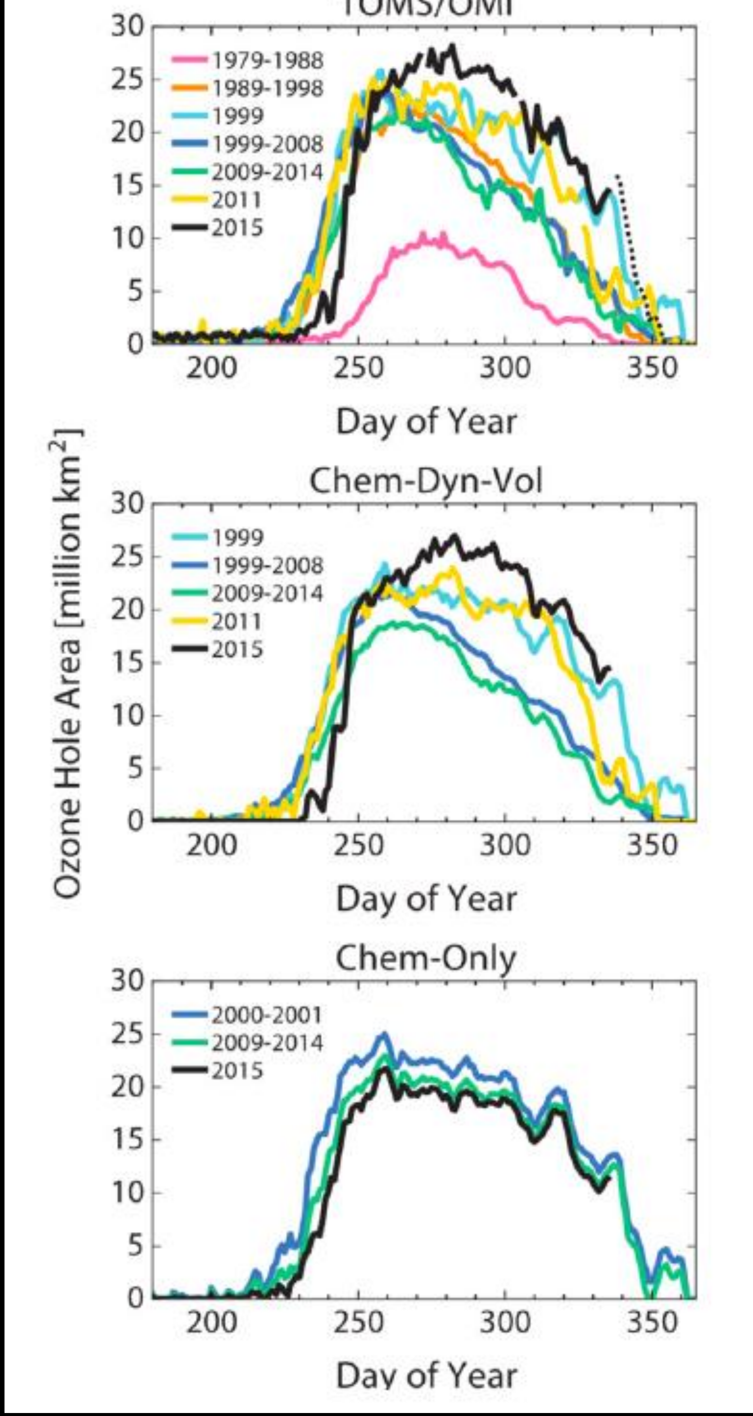
Particles sizes span a large range, only slowly recover to background and vary with altitude

Wilson et al., 2008

The ozone hole is recovering, but eruptions are delaying it



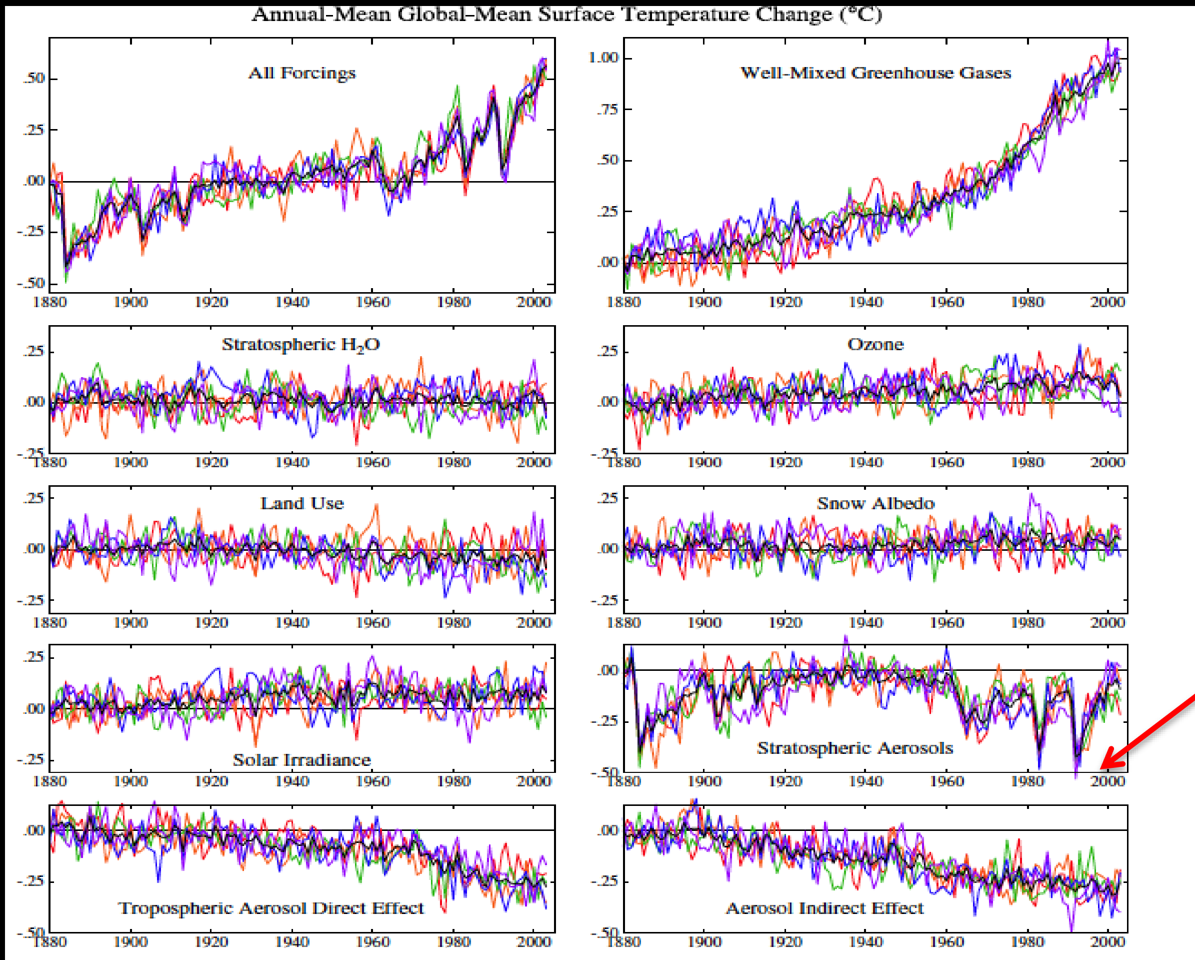
Solomon et al., 2016



Volcanic eruptions may cause the ozone hole to expand, but it is starting later in the year

Solomon et al., 2016

Large, rare, volcanic eruptions cool the planet



Hansen et al., 2007
Clim. Dyn. 29,661