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

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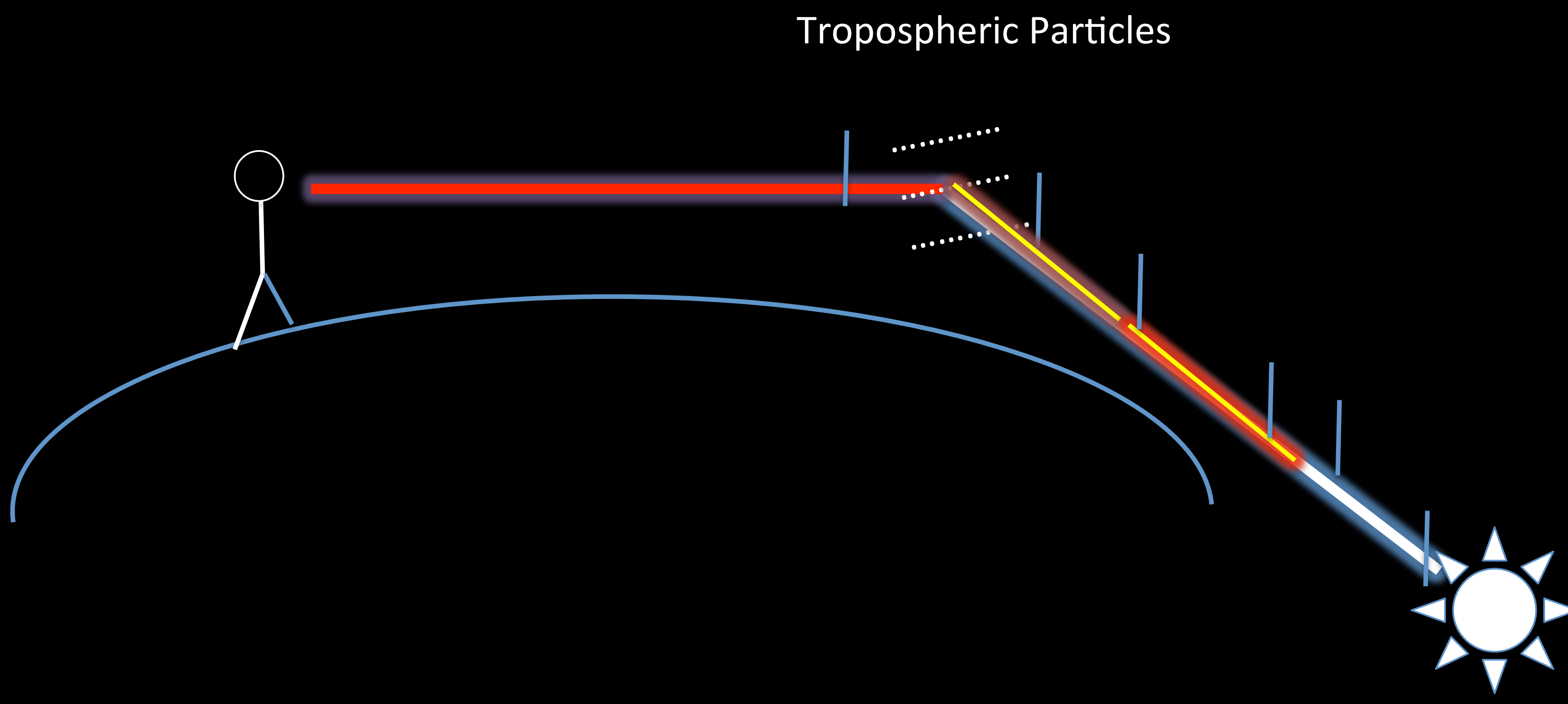
Volcanic clouds impact climate by scattering sunlight; twilight is delayed and turned purple

Sunset in Zimbabwe on July 27, 2015 after the April 22, 2015 eruption of Calbuco in Chile

Peter Lowenstein

Physics of normal sunsets involves Rayleigh scattering of blue light and tropospheric particles scattering light toward you



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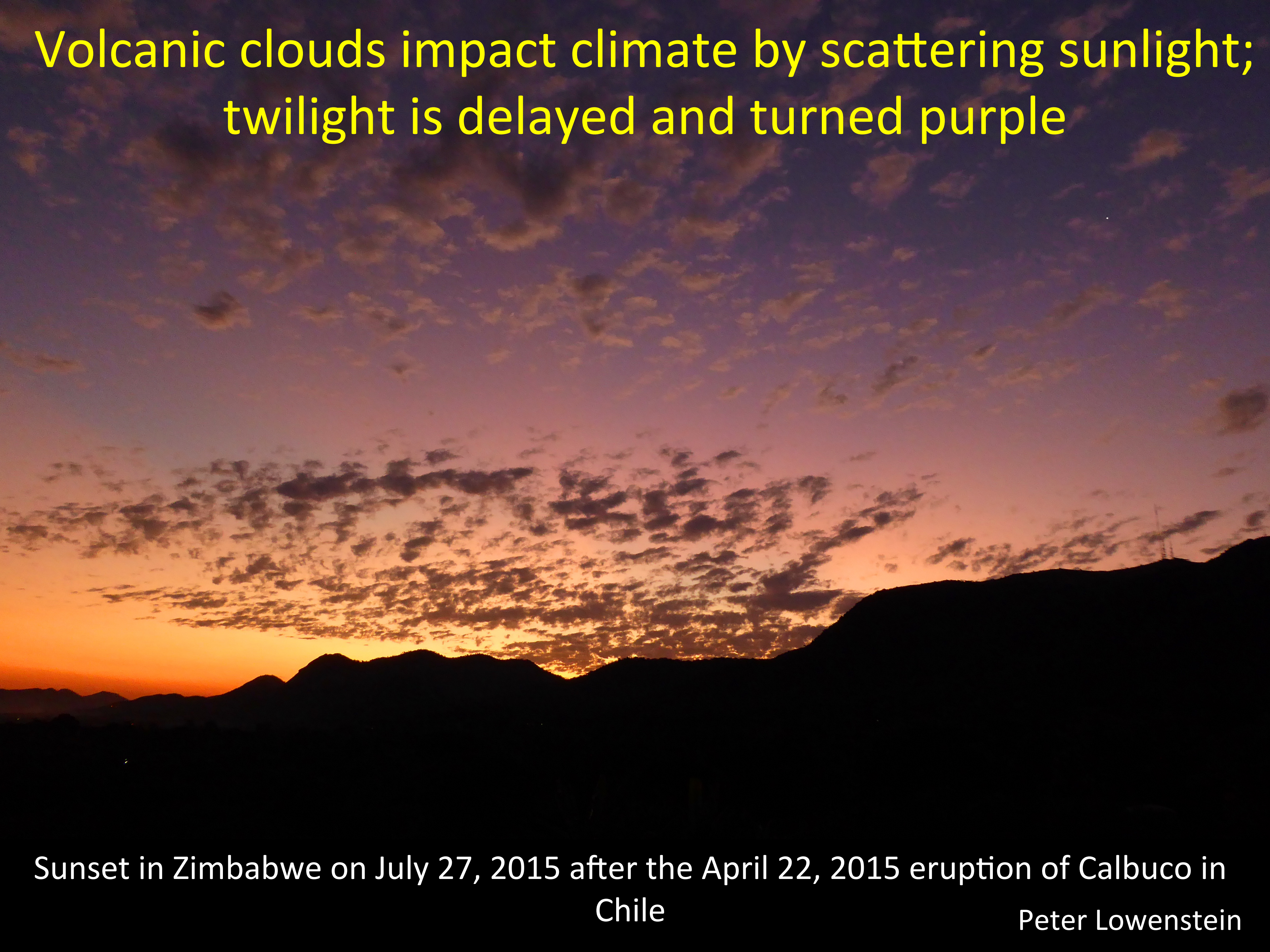
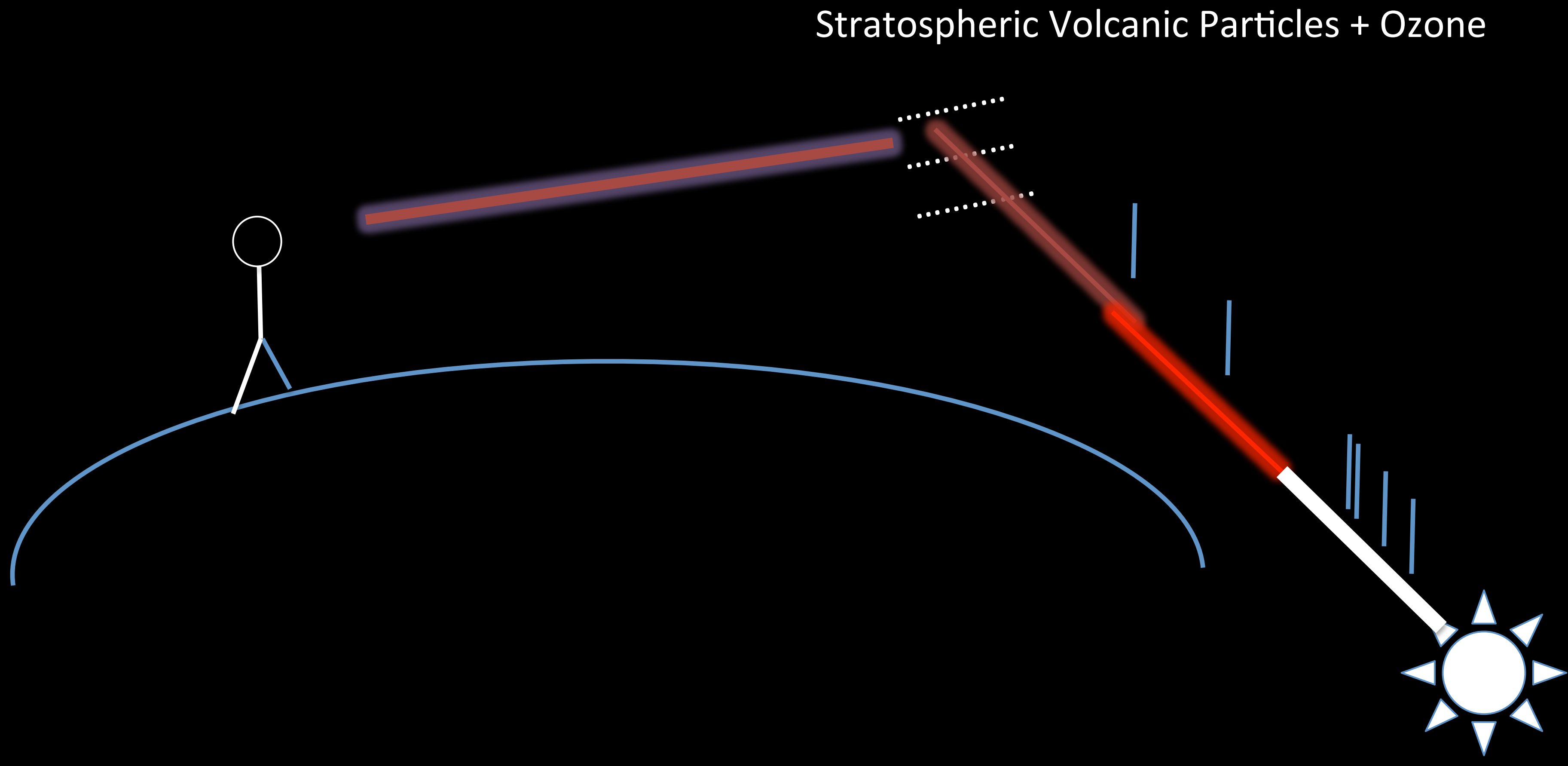


Sunset in Zimbabwe on July 27, 2015 after the April 22, 2015 eruption of Calbuco in Chile

Peter Lowenstein

Physics of volcanic sunsets involves Rayleigh scattering of blue light, ozone absorption of red light, volcanic particles scattering towards you



Volcanic clouds impact climate by scattering sunlight; twilight is delayed and turned purple

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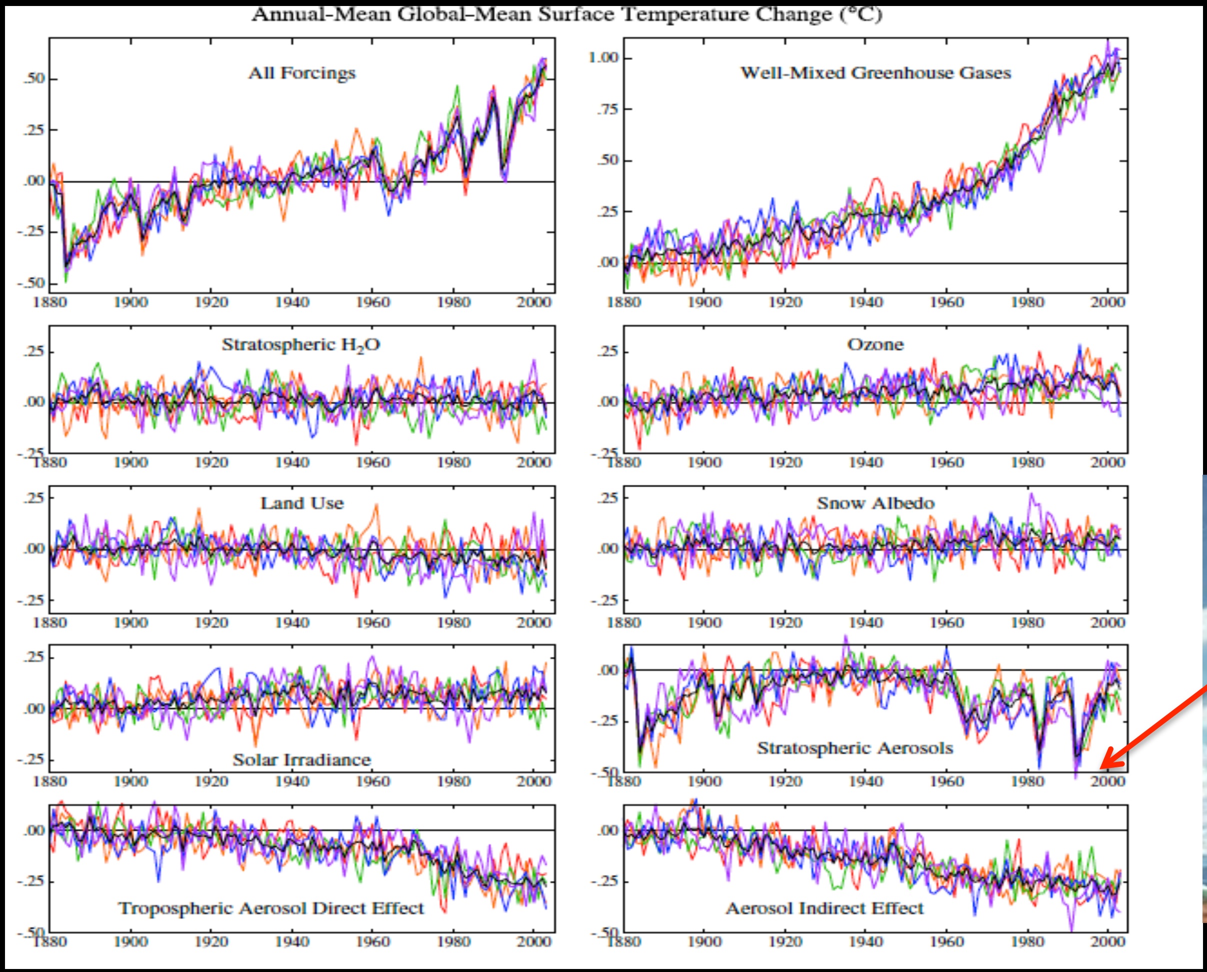
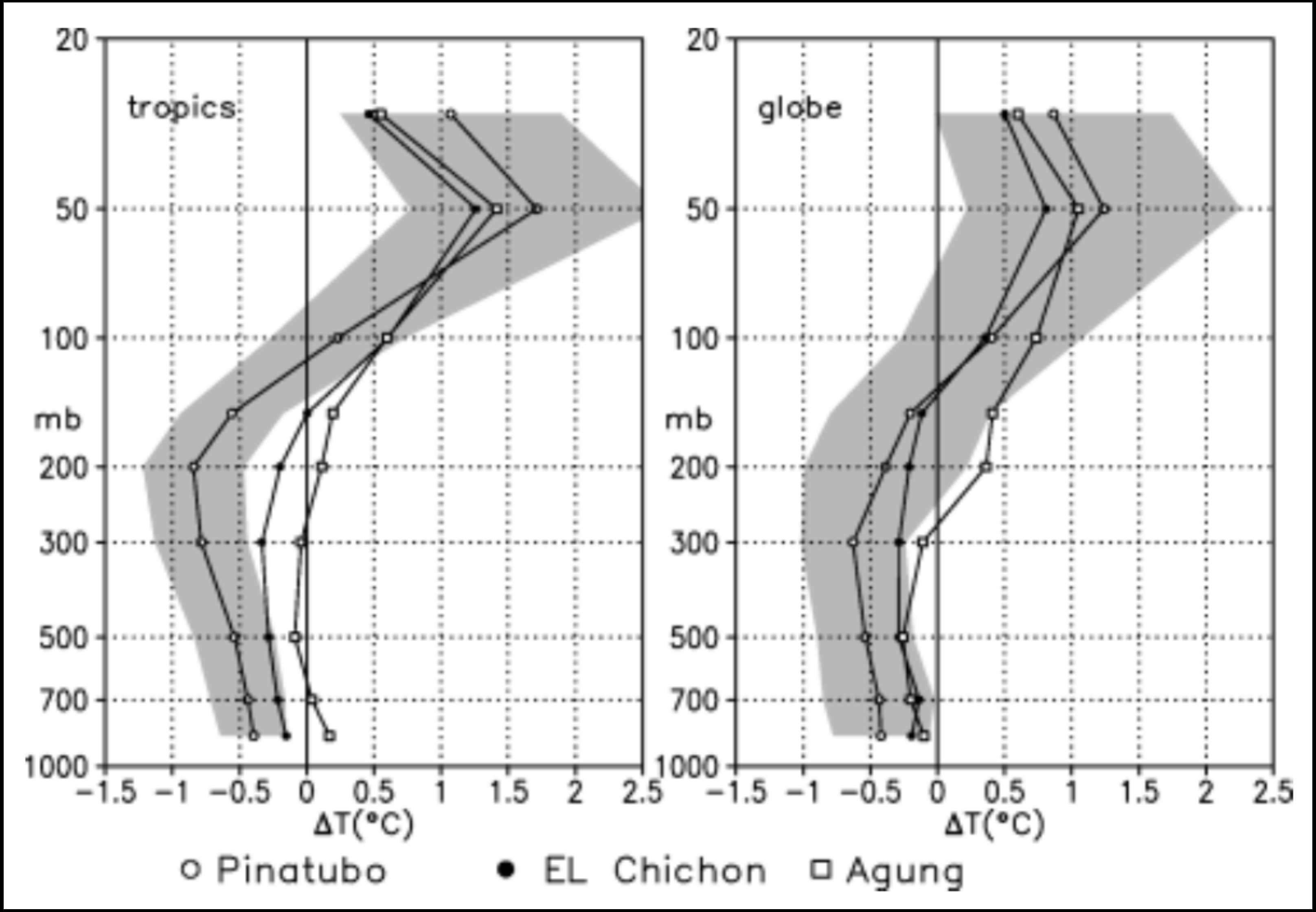
Volcanic aerosols cool the planet



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

Most focus has been on temperature



Free and Angell, 2002

Mt. Tambora, April 1815 largest known eruption in 1000 years

Tambora and the Year Without Summer-1816

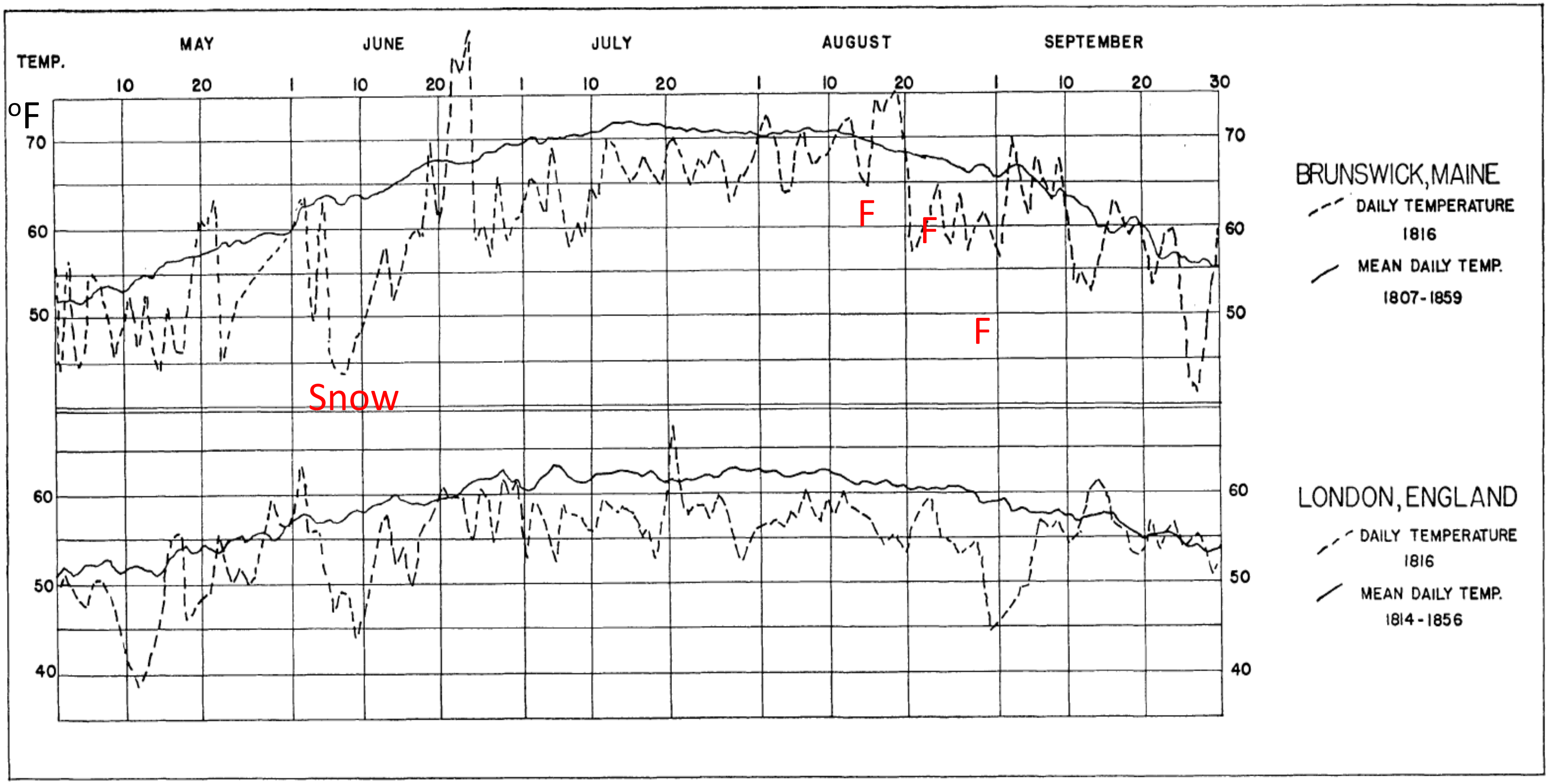


FIG. 6. Daily and mean daily temperatures—Brunswick, Maine, and London, England.

Hoyt, Assoc. Am. Geographers,1958

Food prices jumped after Tambora eruption

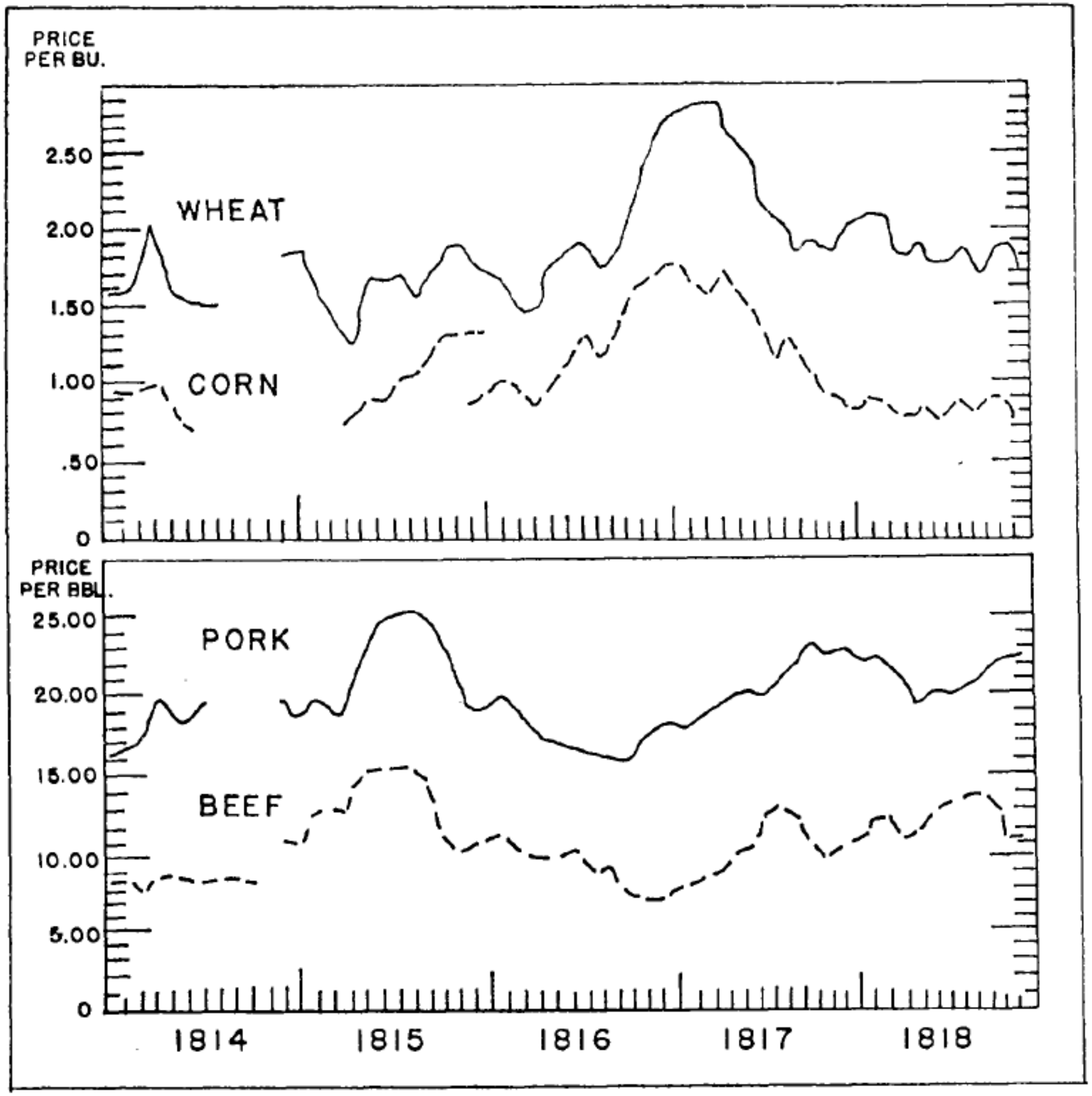


FIG. 5. Monthly average wholesale food prices, produce market, New York, 1814–18.

Hoyt, Assoc. Am. Geographers,1958

People fled New England post Tambora

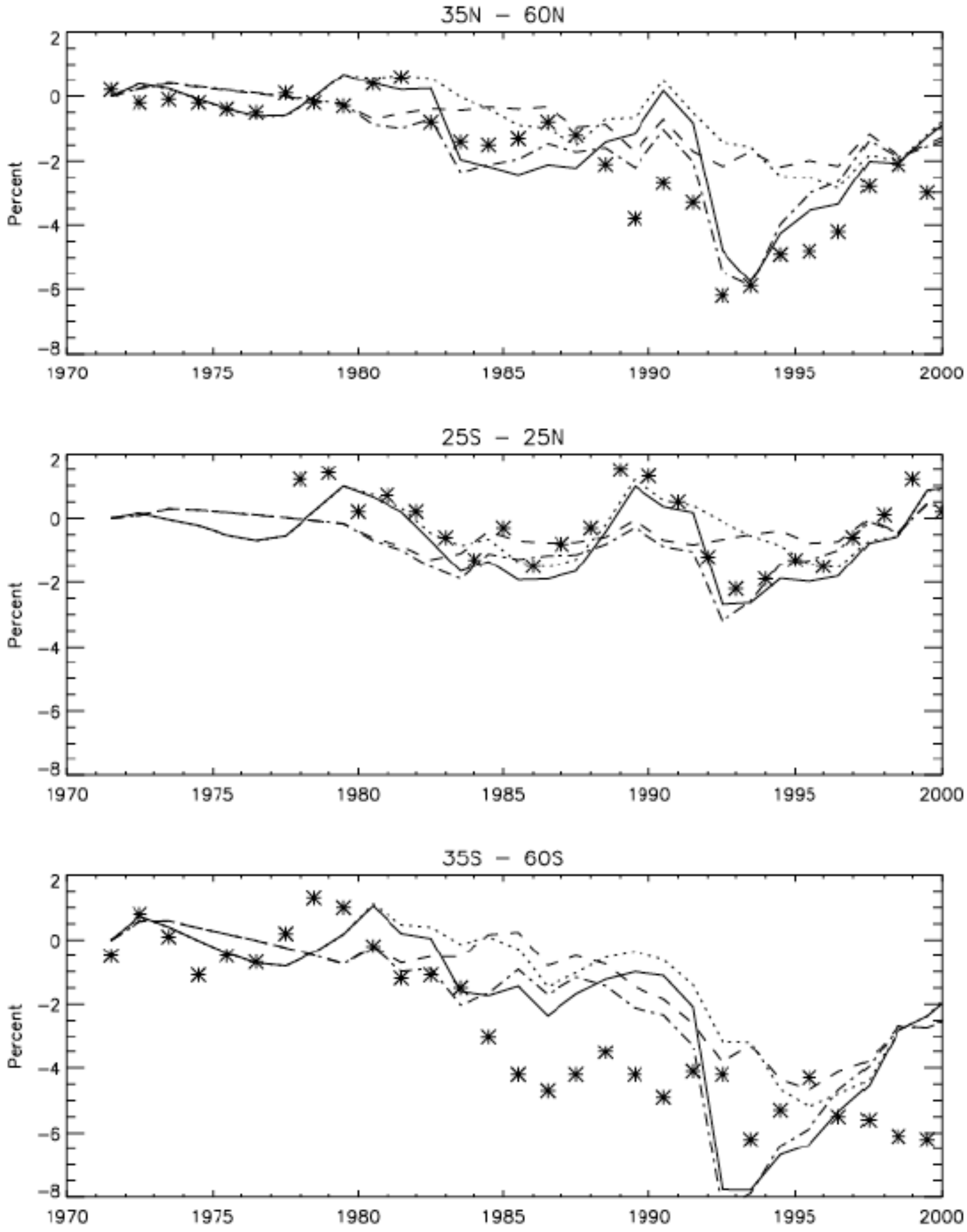
TABLE 1.—RATES OF POPULATION INCREASE, NEW ENGLAND STATES, 1790–1860

Area	Rates of increase, in percentages						
	1790 to 1800	1800 to 1810	1810 to 1820	1820 to 1830	1830 to 1840	1840 to 1850	1850 to 1860
United States	35	36	33	33	32	36	36
New England	34	19	13	18	14	22	15
Maine	57	51	30	34	26	16	8
New Hampshire	30	16	14	10	6	12	3
Vermont	82	40	8	19	4	8	0.3
Massachusetts	12	11	10	17	21	35	24
Connecticut	6	4	5	8	4	19	24
Rhode Island	0.4	11	8	17	11	18	36

Hoyt, Assoc. Am. Geographers,1958

Many changes observed after eruptions

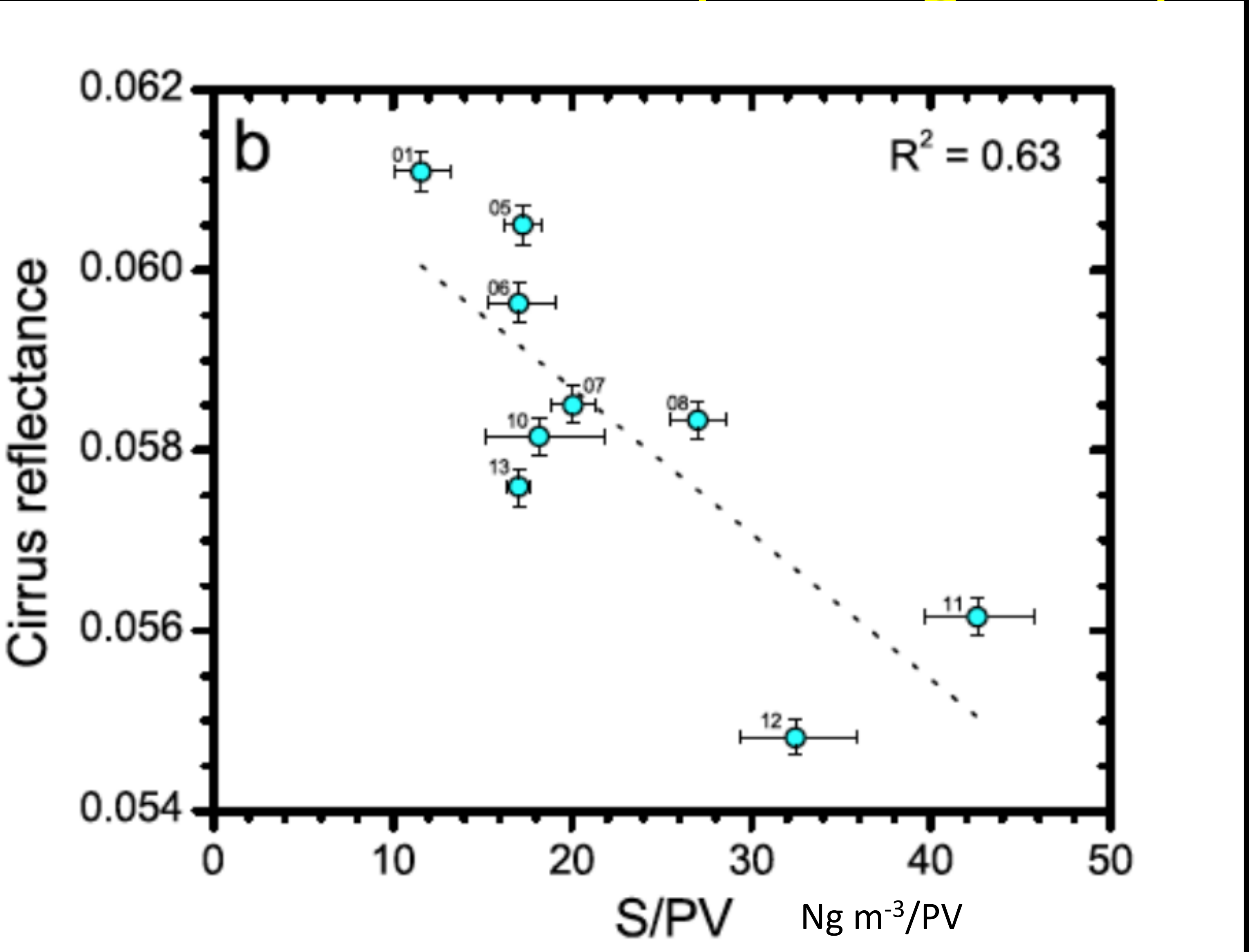
Observed	**Probable cause**
Cooling troposphere and surface	Reduction in shortwave forcing by aerosol
Tropopause and stratospheric warming	Sunlight and ir absorption by aerosol
Mid-lat. N.H. winter warming	Strat./troposphere dynamical interaction
Rapid spread of volcanic clouds	Alteration of atmospheric 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



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

Geller and Smyshlyaev

Cirrus reflectivity decreases as sulfur in lower stratosphere goes up

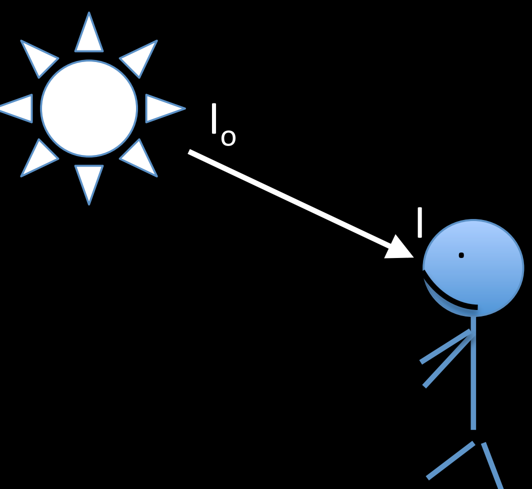


Friberg et al., 2015

Need to know three things to calculate radiation field

AOD (AOT) = Aerosol extinction Optical Depth (Thickness)

1. Extinction optical depth



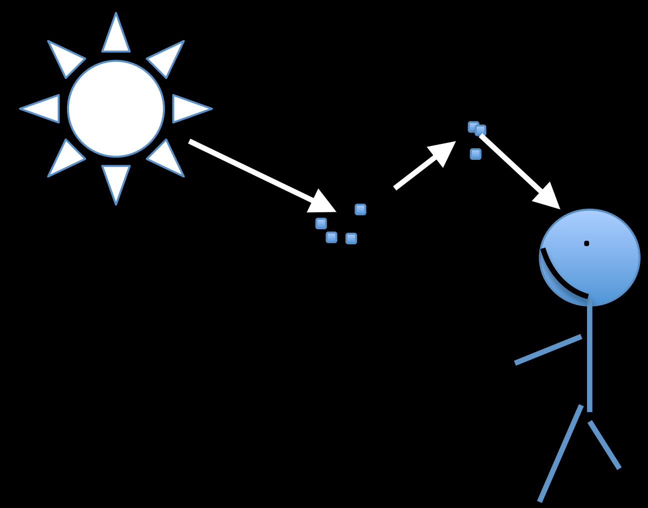
$$\tau_{e/\cos\theta} = \ln(I/I_o)$$

θ=zenith angle

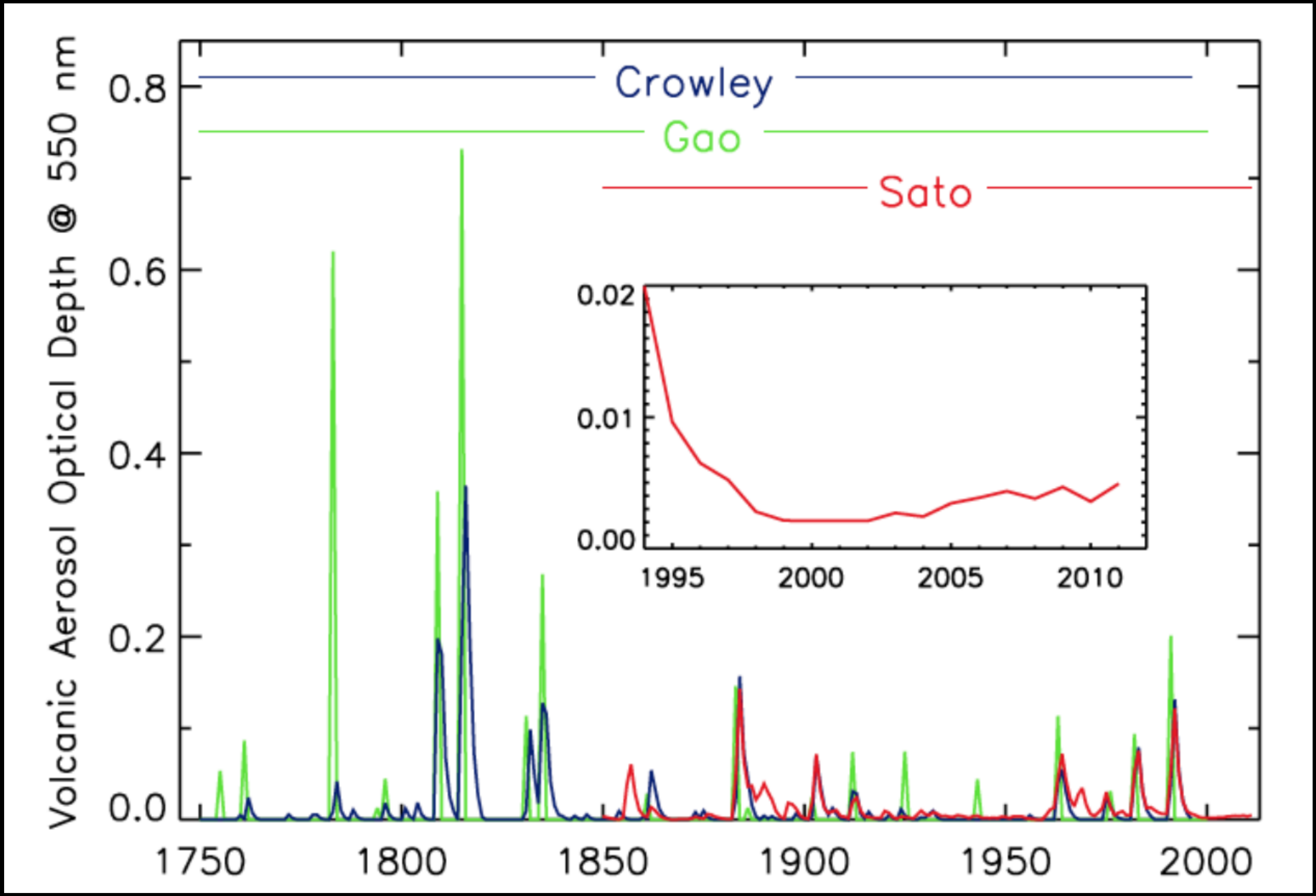
2. Absorption or scattering optical depth

$$\tau_e = \tau_a + \tau_s$$

3. Scattering phase function

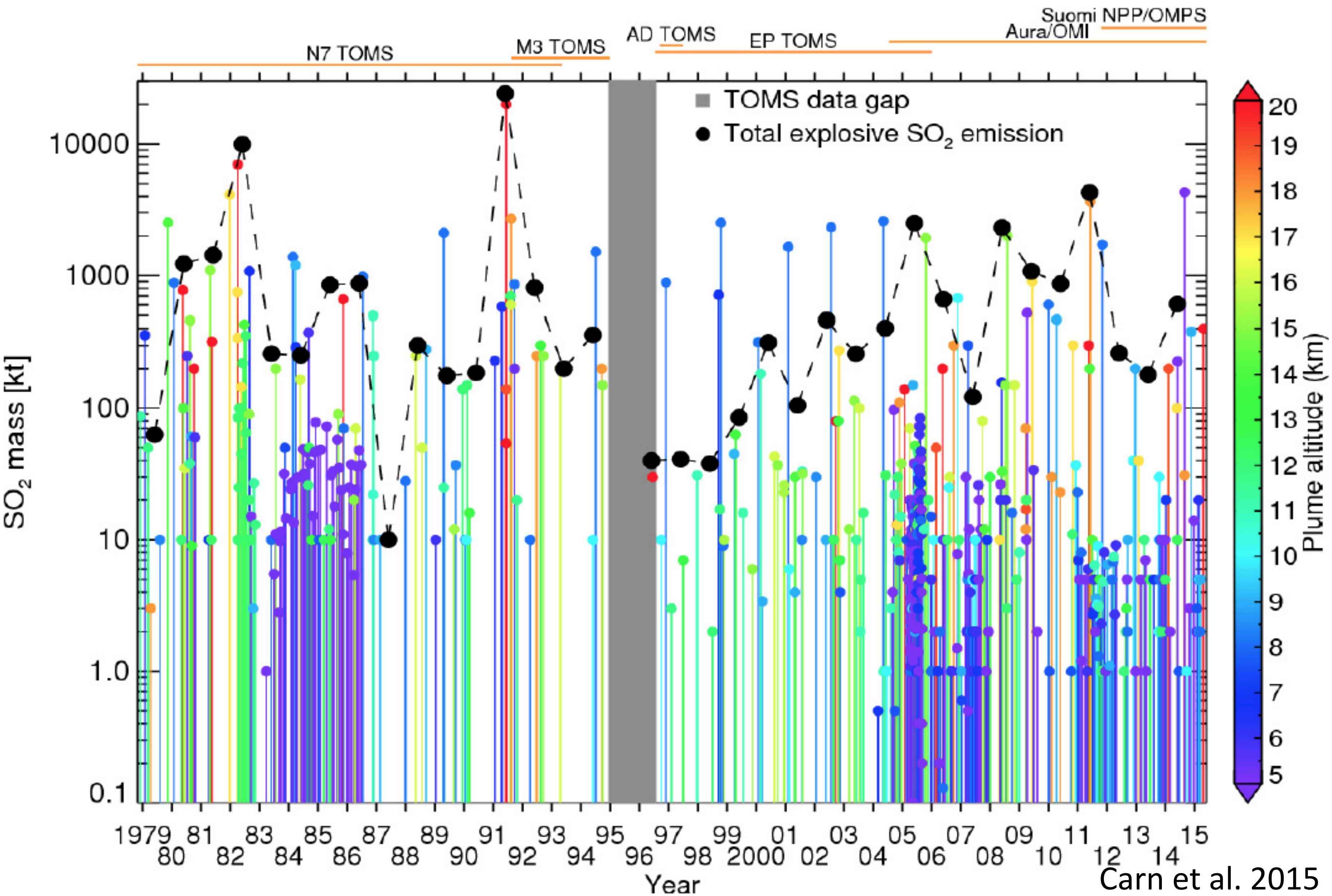


Early studies used volcanic explosivity to rank eruptions but it is not relevant to optical depth



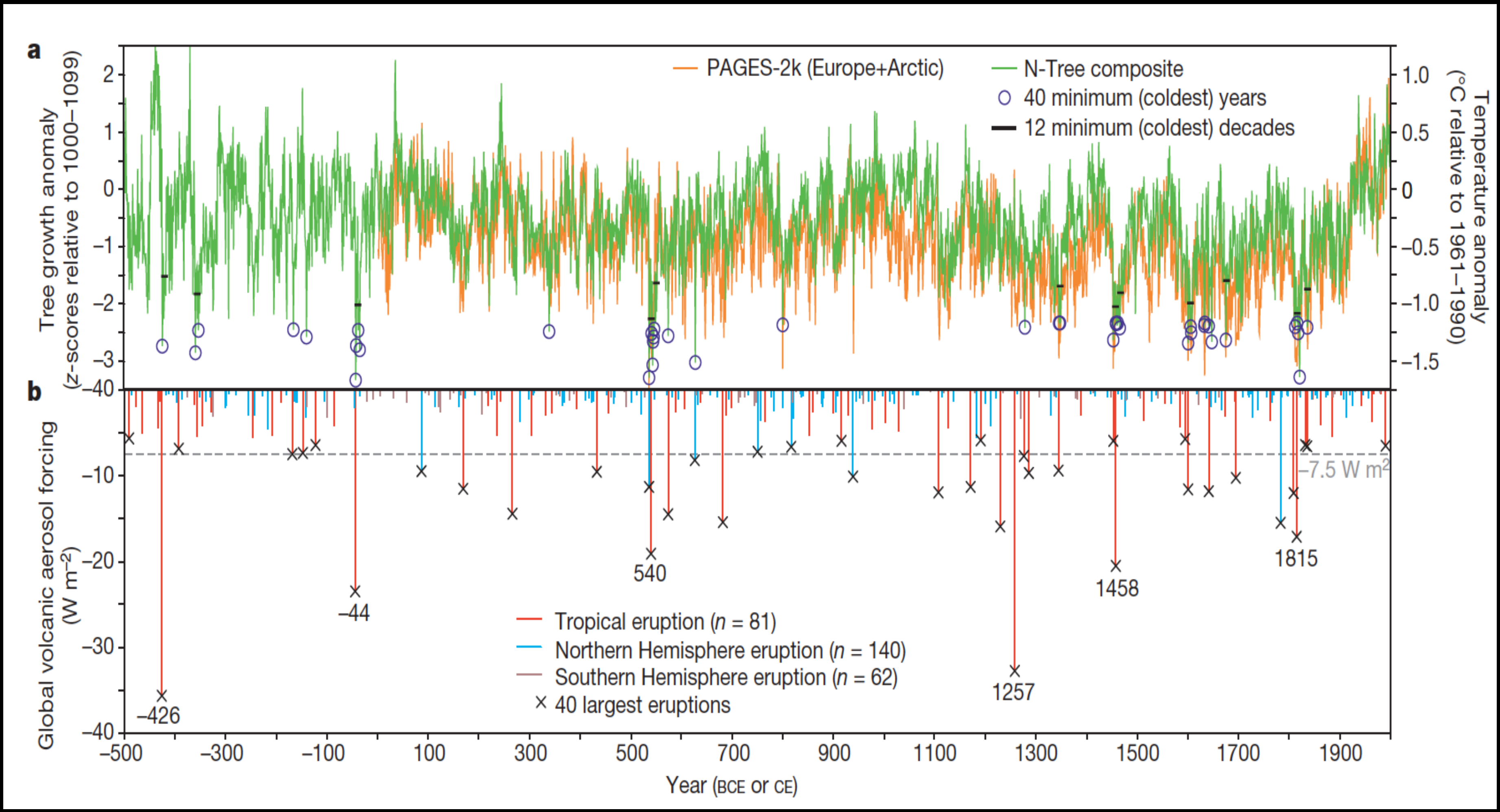
Myhre et al., 2013

SO_2 injection is key to volcano climate effects



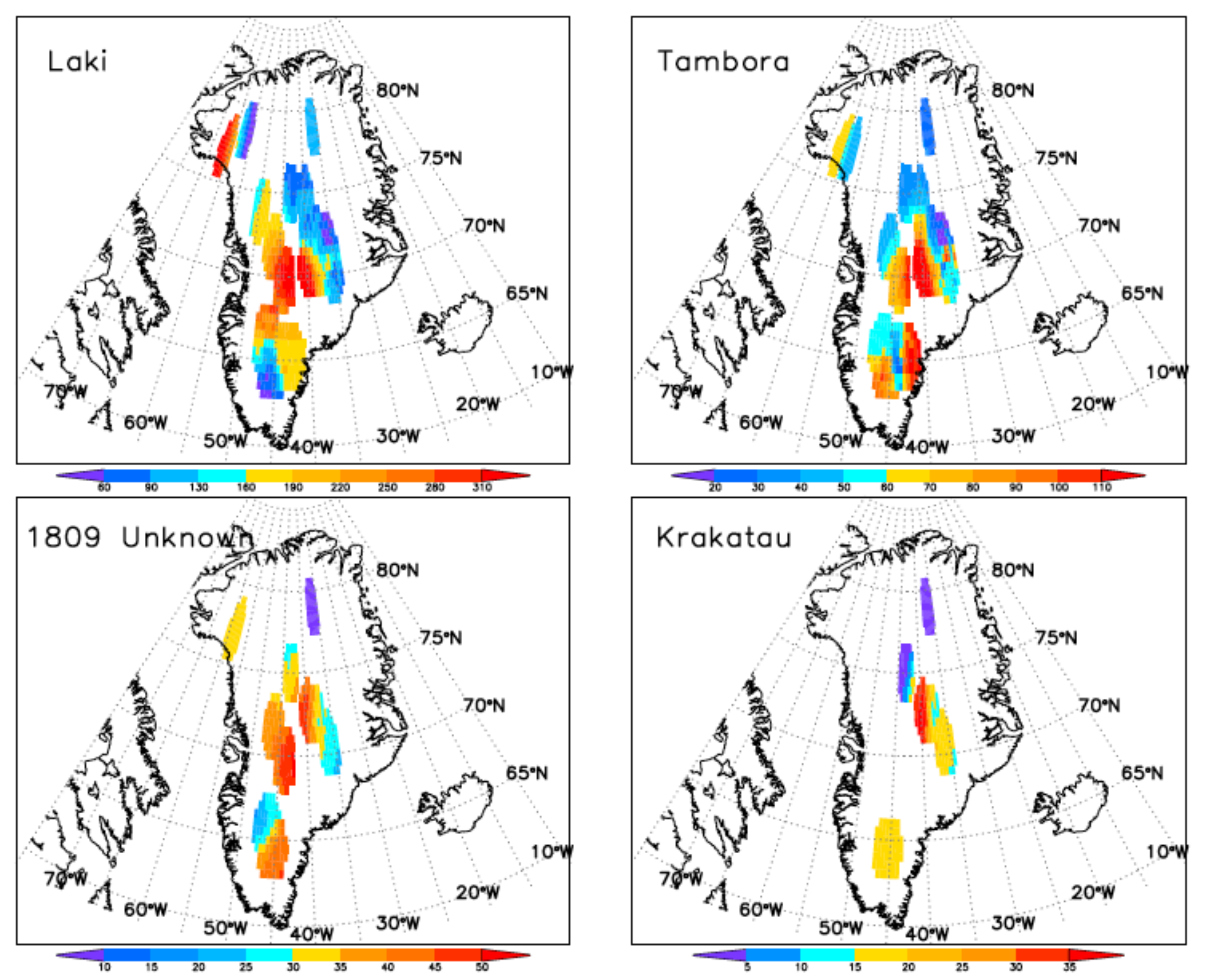
Carn et al. 2015

2500 years of volcanic forcing and climate change (Europe/Arctic)



Sigl et al., Nature,doi:10.1038/nature14565,2015

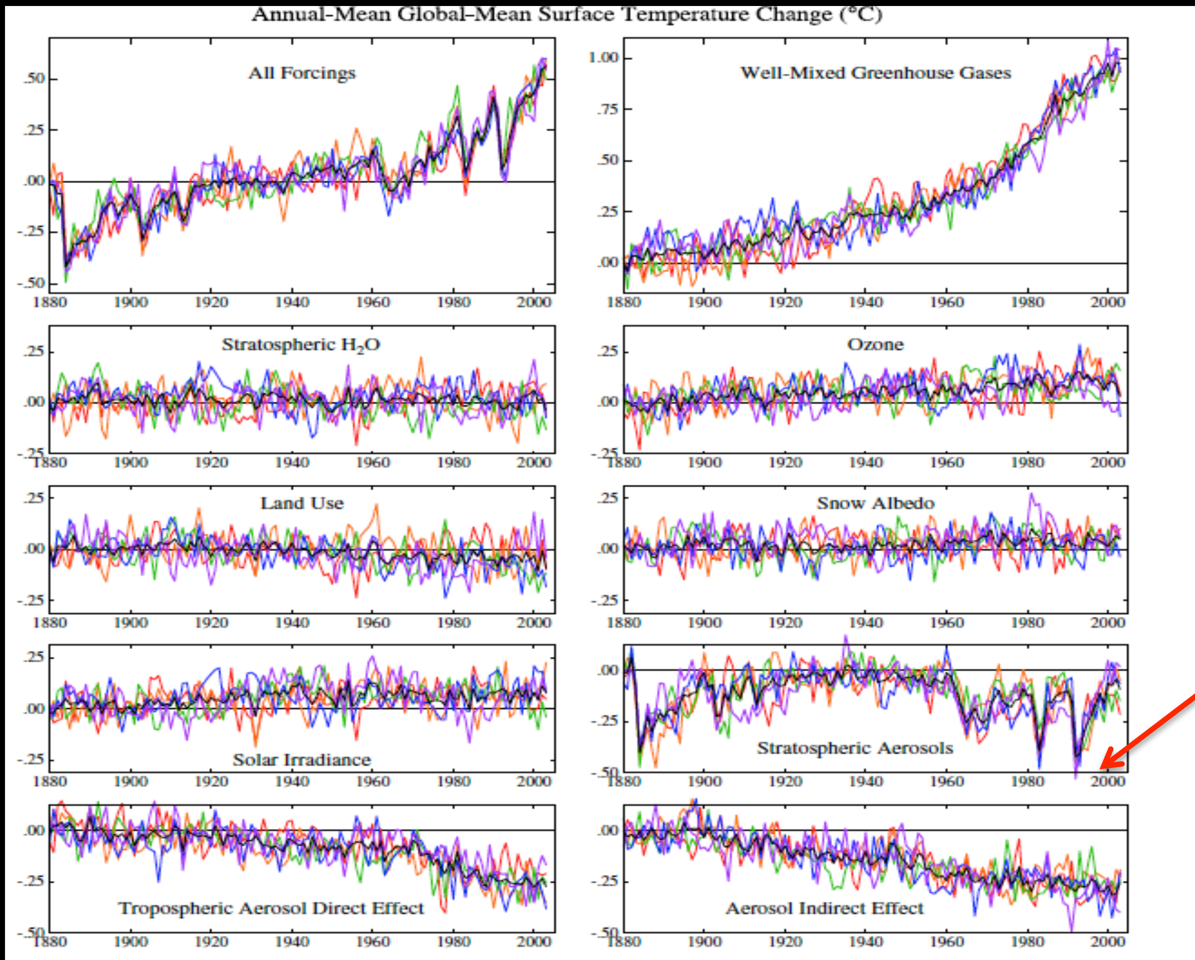
Polar core sulfate is highly variable



kg SO_4/km^2

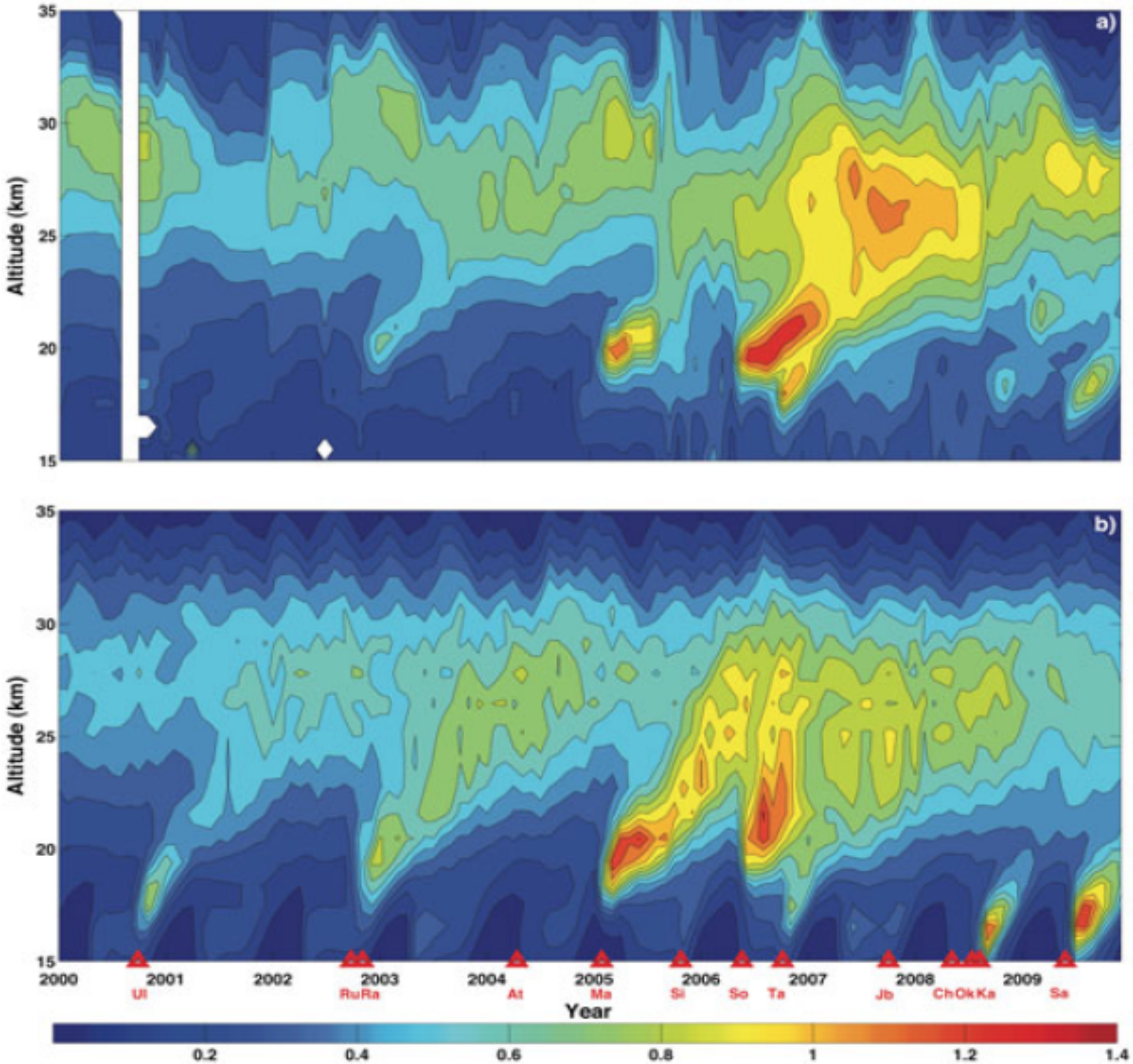
Gao et al., 2007

Large, rare, volcanic eruptions cool the planet



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

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

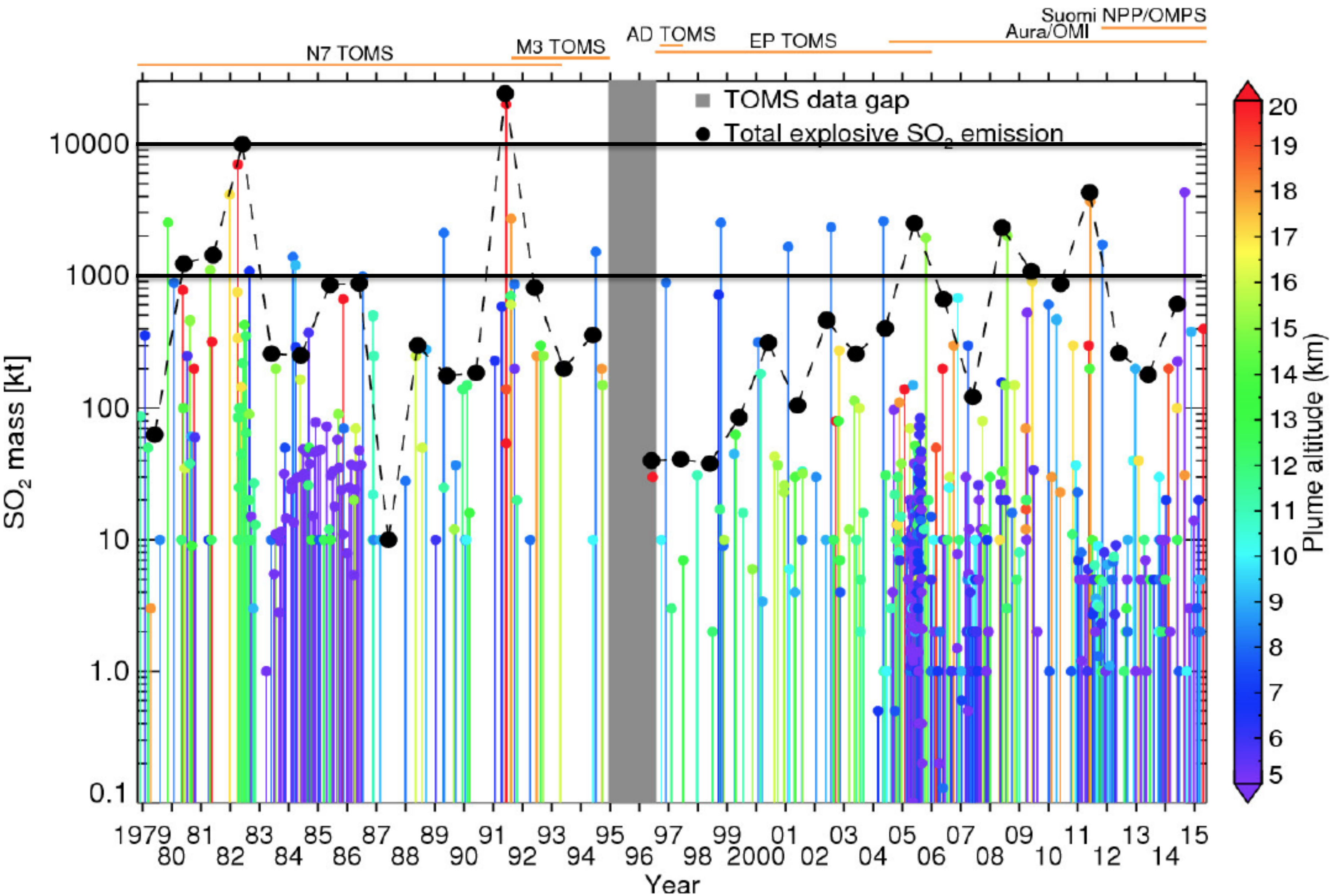


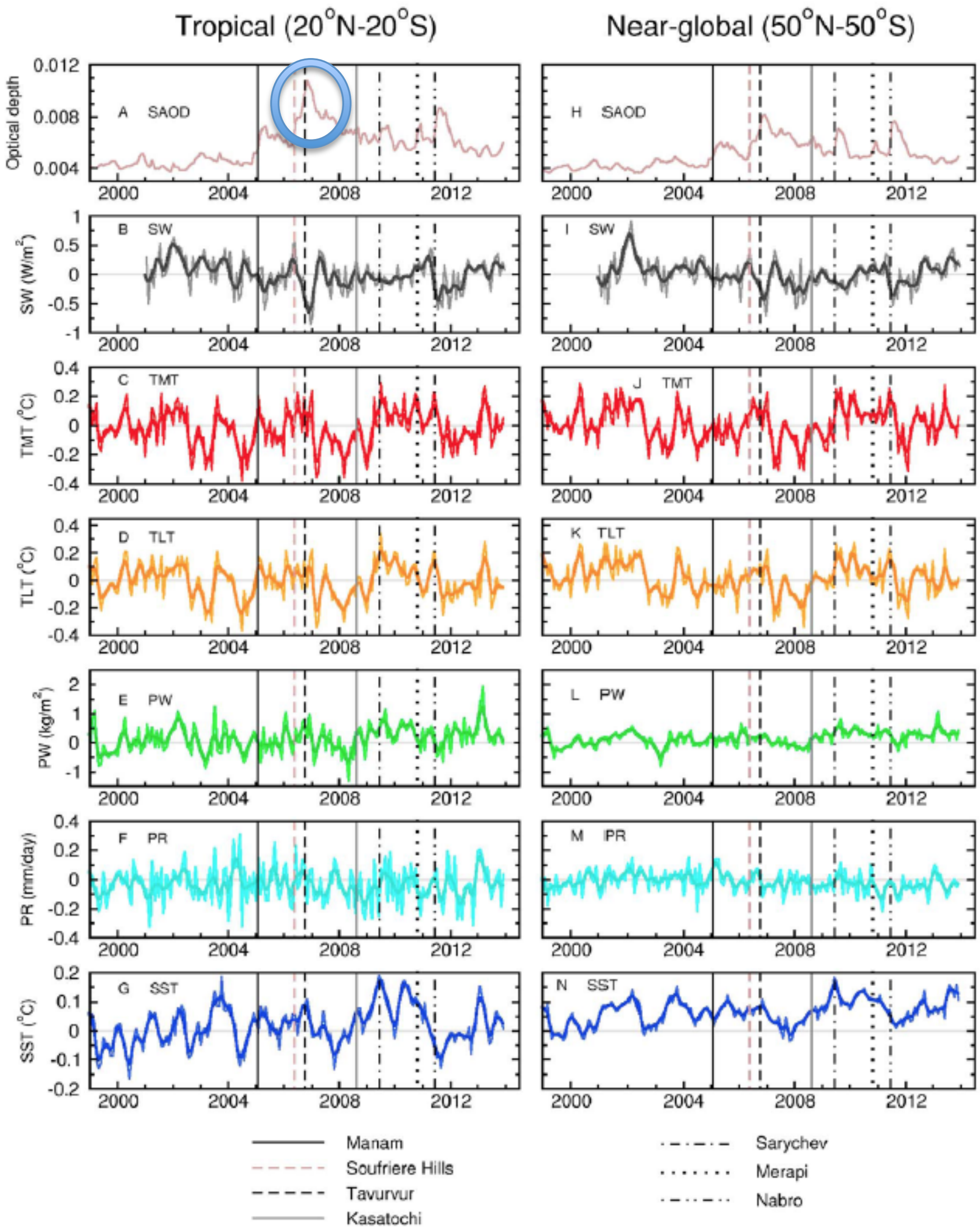
Data
Vernier et al., 2011

Model
Neely III et al., 2013

Extinction ratio

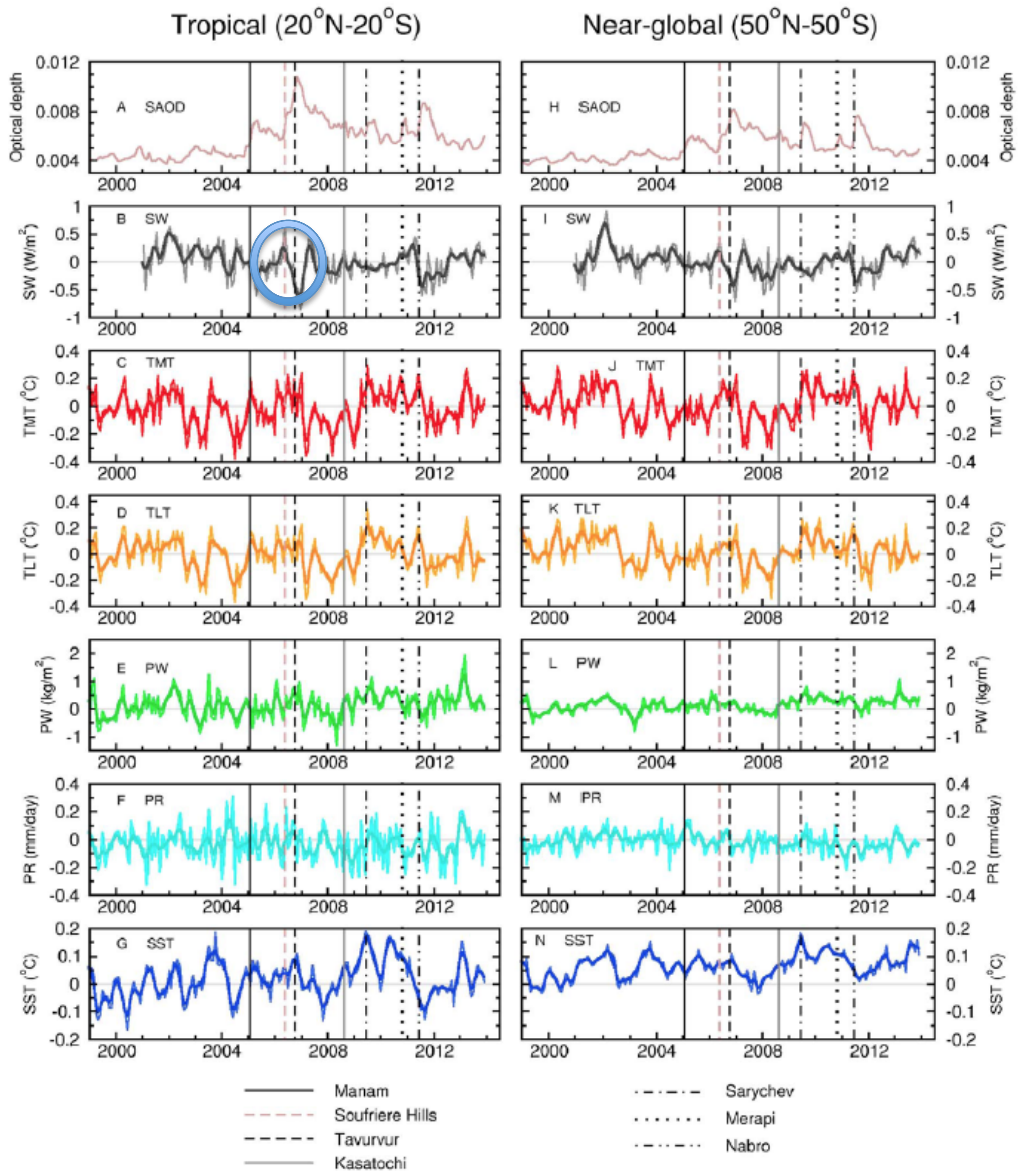
SO_2 is key to volcano climate effects





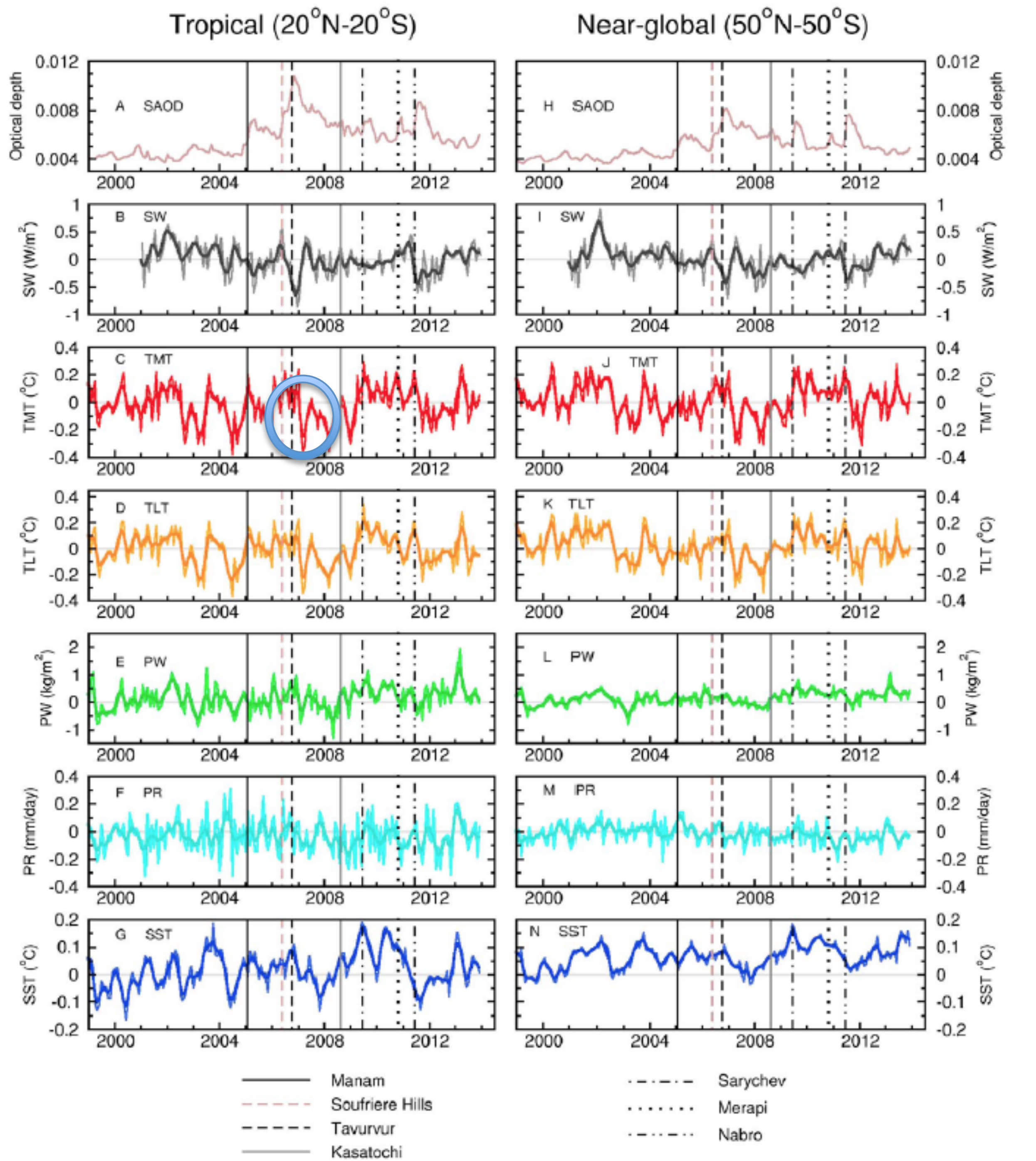
Small, common, eruptions have detectable signals in aerosol optical depth

Santer et al. 2015



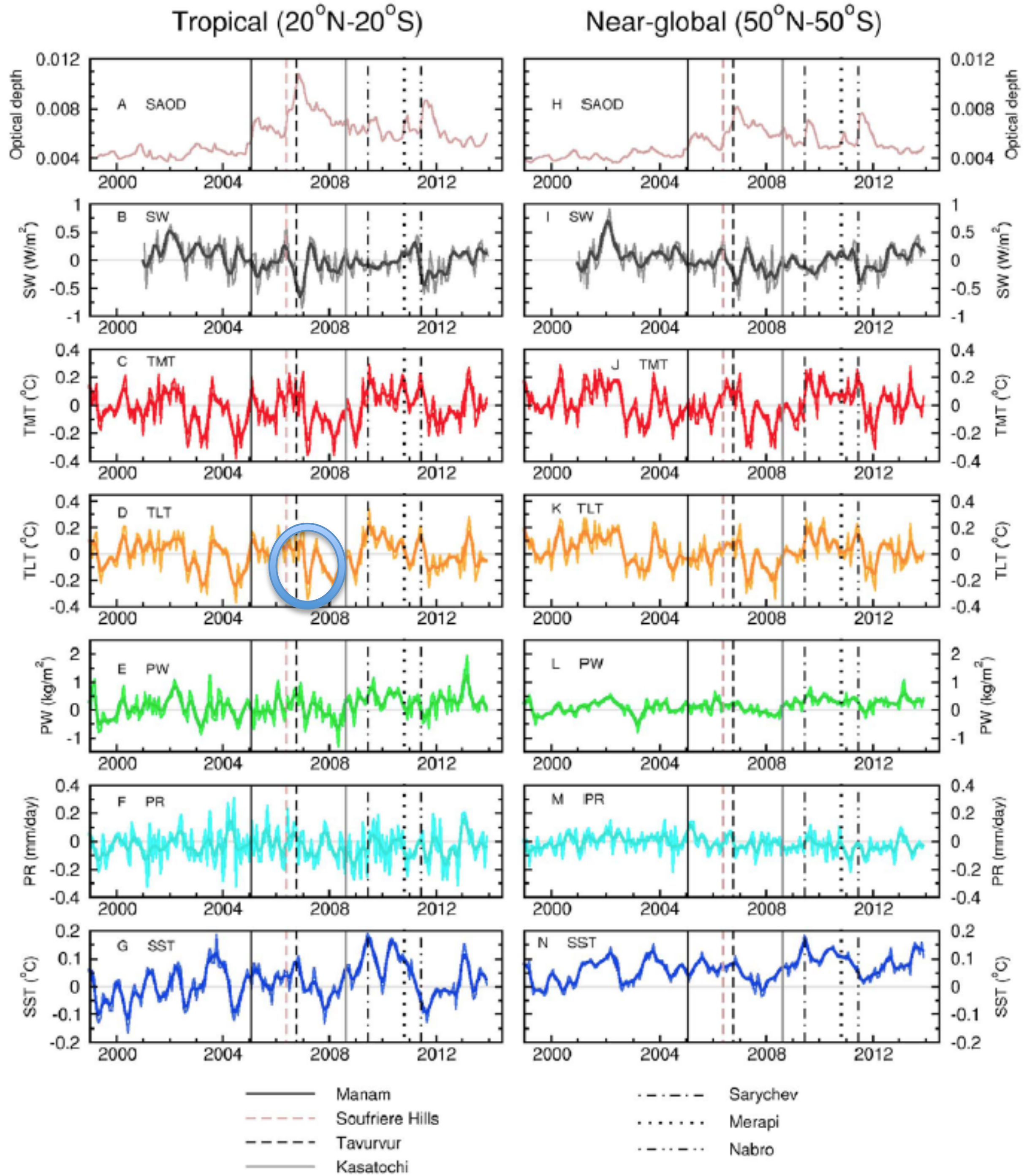
Small, common, eruptions have detectable signals in short wave flux

Santer et al. 2015



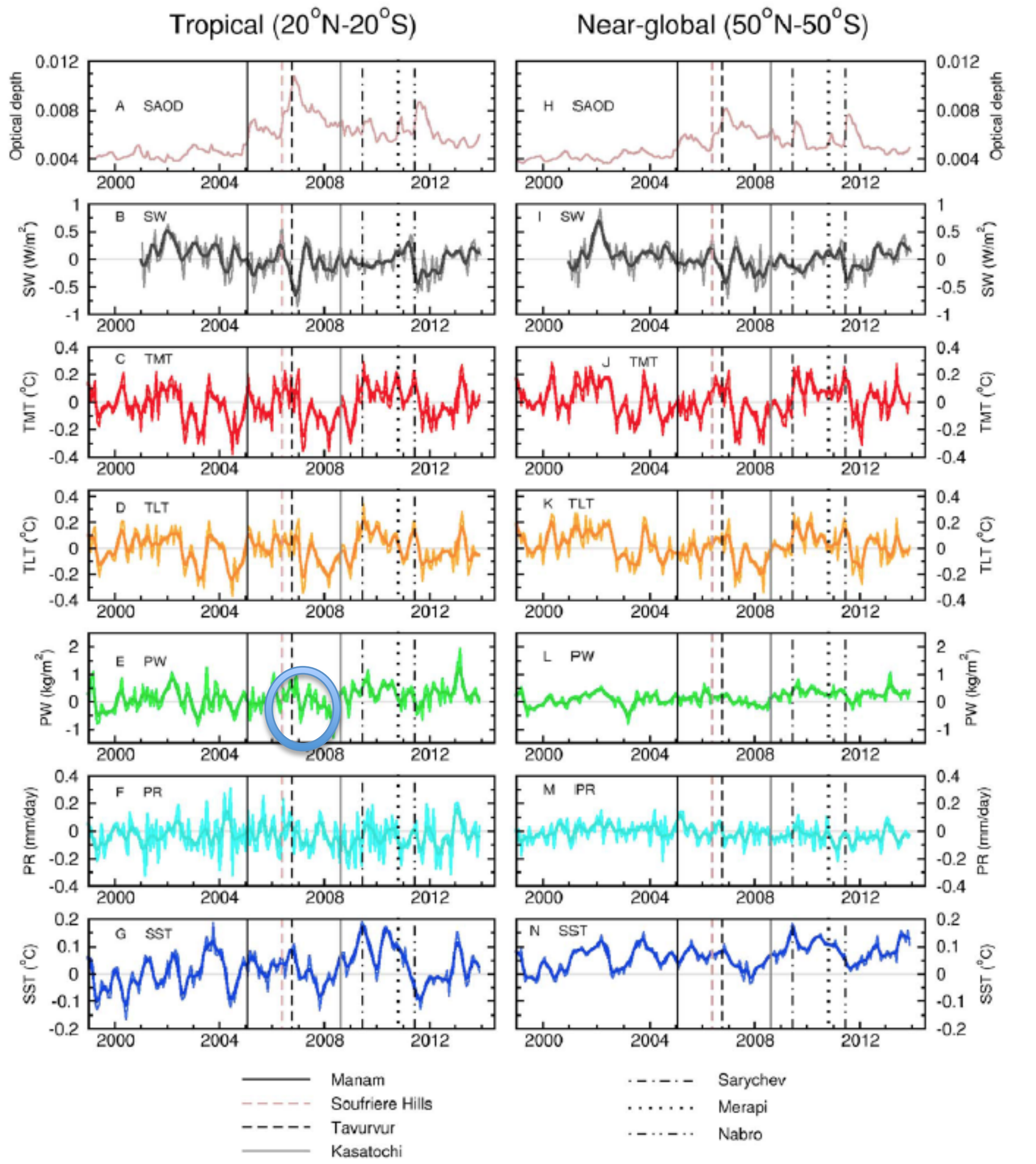
Small, common, eruptions have detectable signals in temperature of middle and upper troposphere

Santer et al. 2015



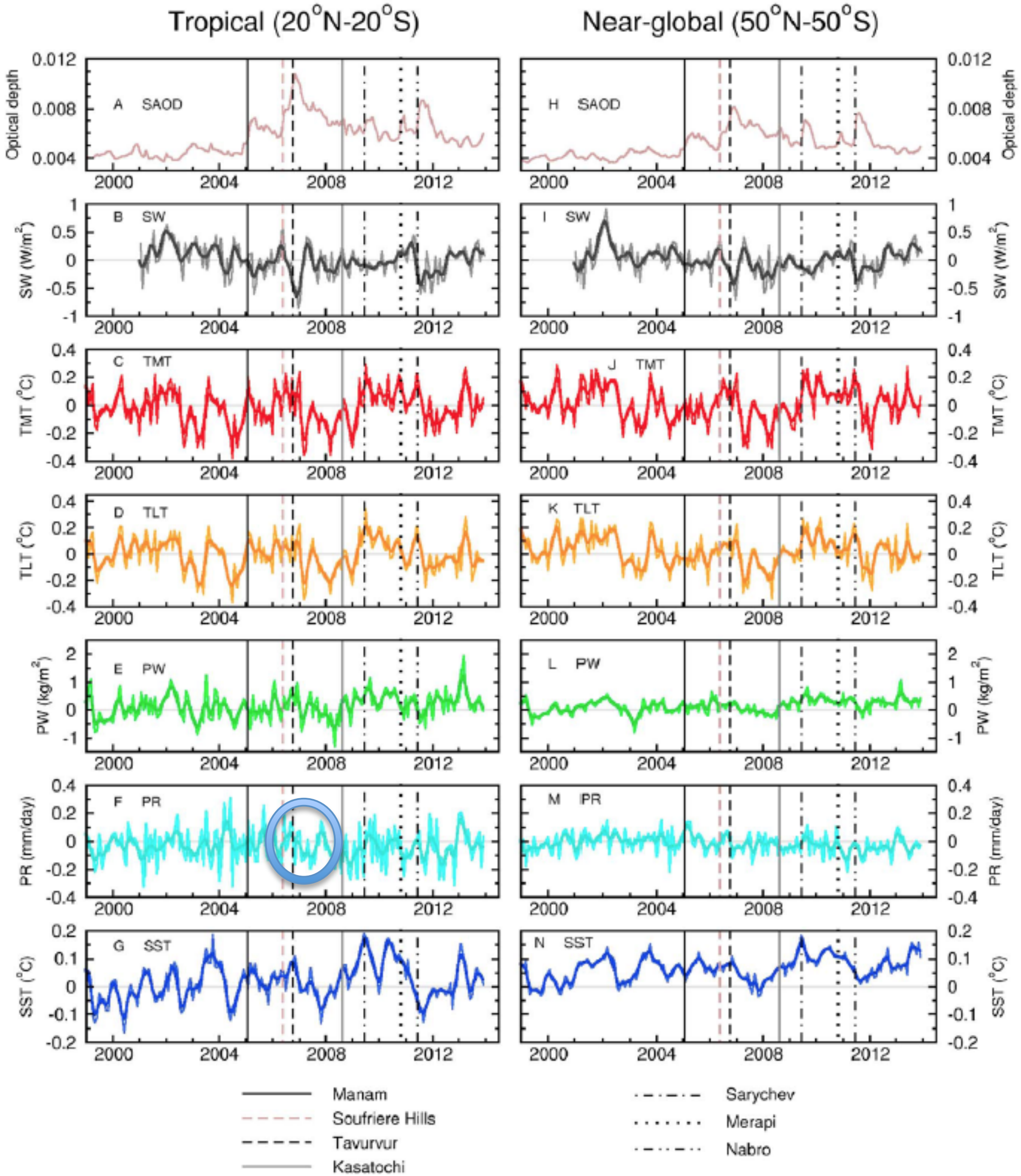
Small, common, eruptions have detectable signals in temperature of lower troposphere

Santer et al. 2015



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

Santer et al. 2015



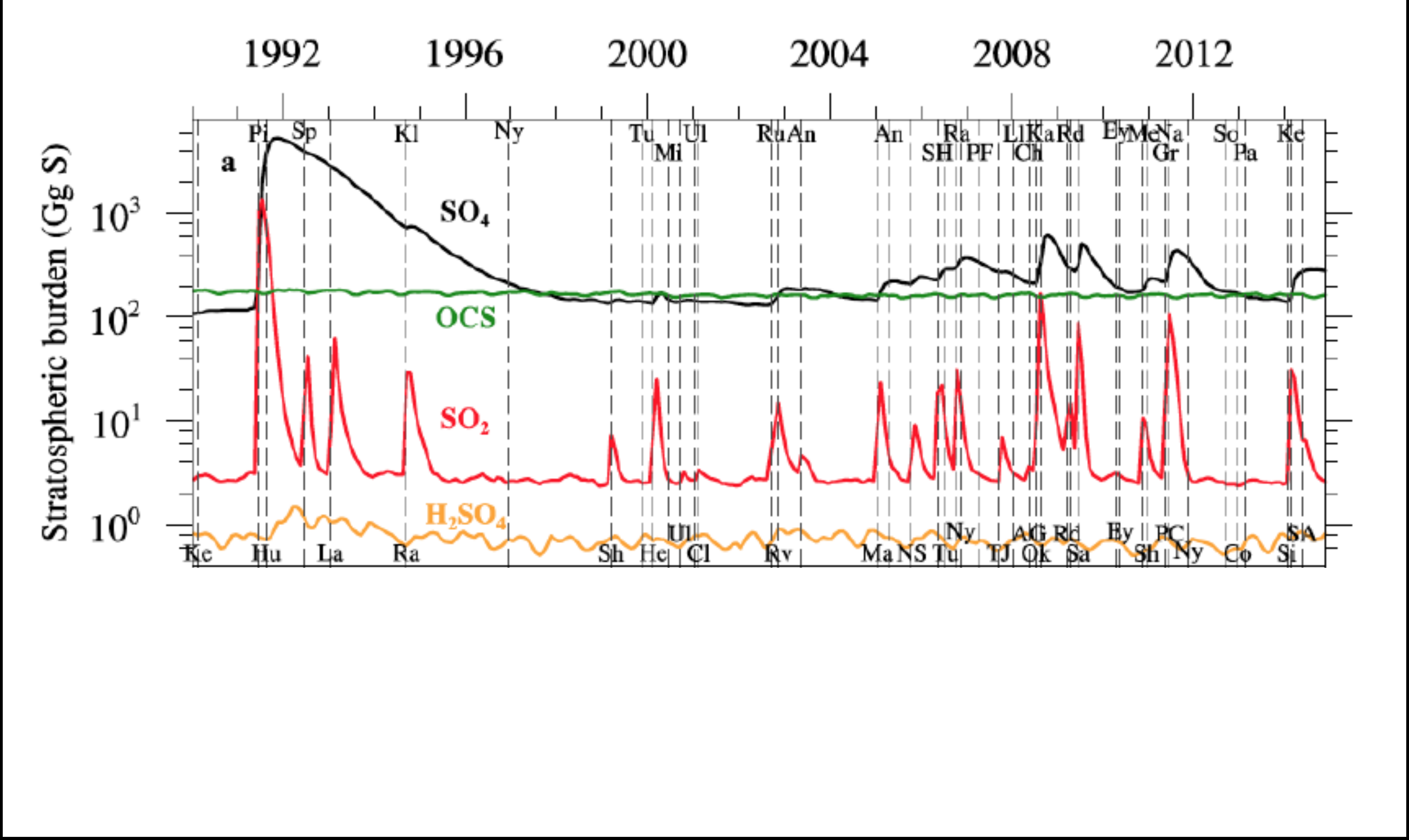
Small, common, eruptions have detectable signals in precipitation

Santer et al. 2015

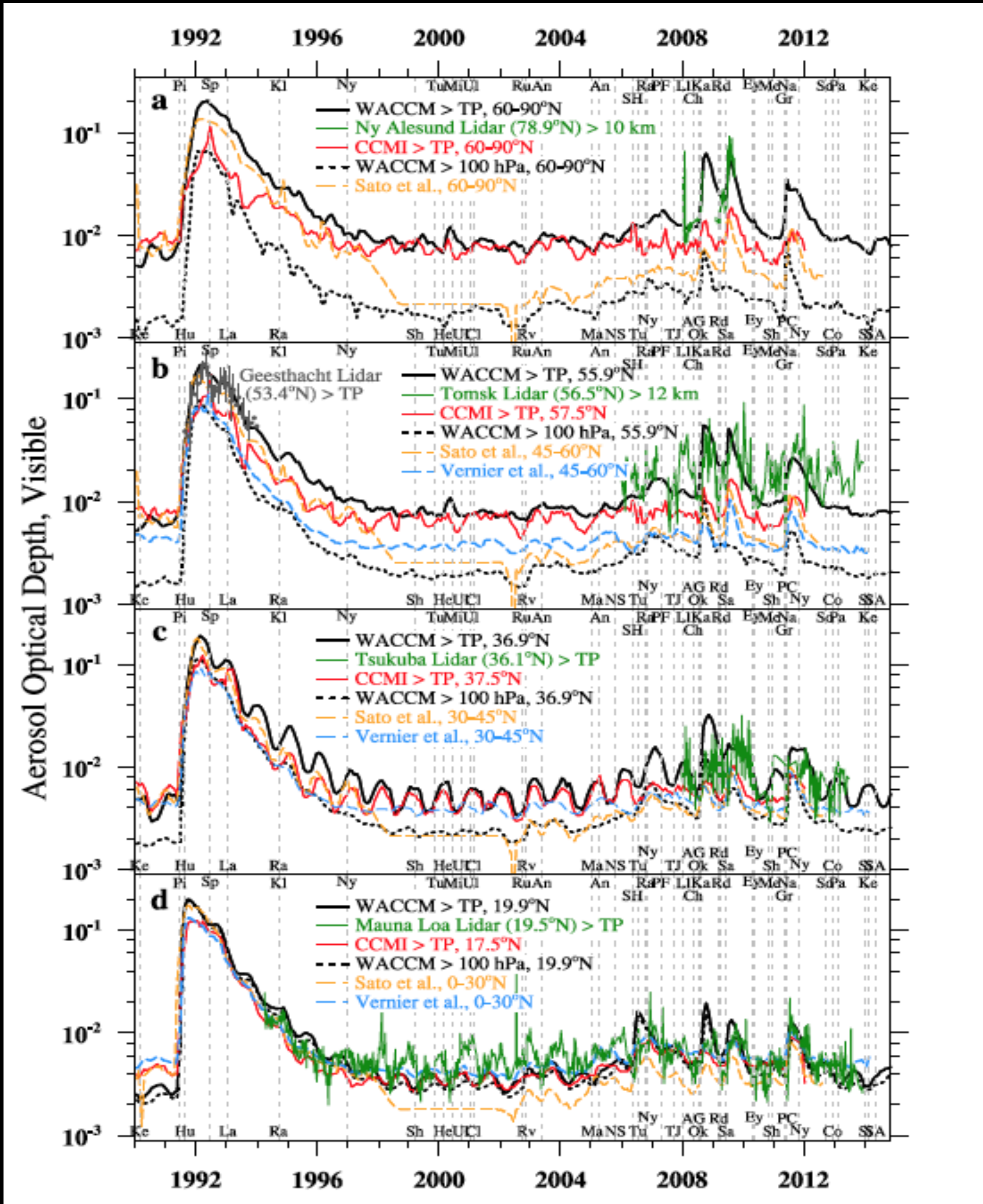
Need to know optical properties to compute radiative changes-emphasis on microphysical models

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 **o**ptical depth	0.001 to 1
Scattering optical depth	0.001 to 1
Absorption optical depth	0.001 to 1
Scattering phase function	

Microphysical models can predict sulfur chemistry



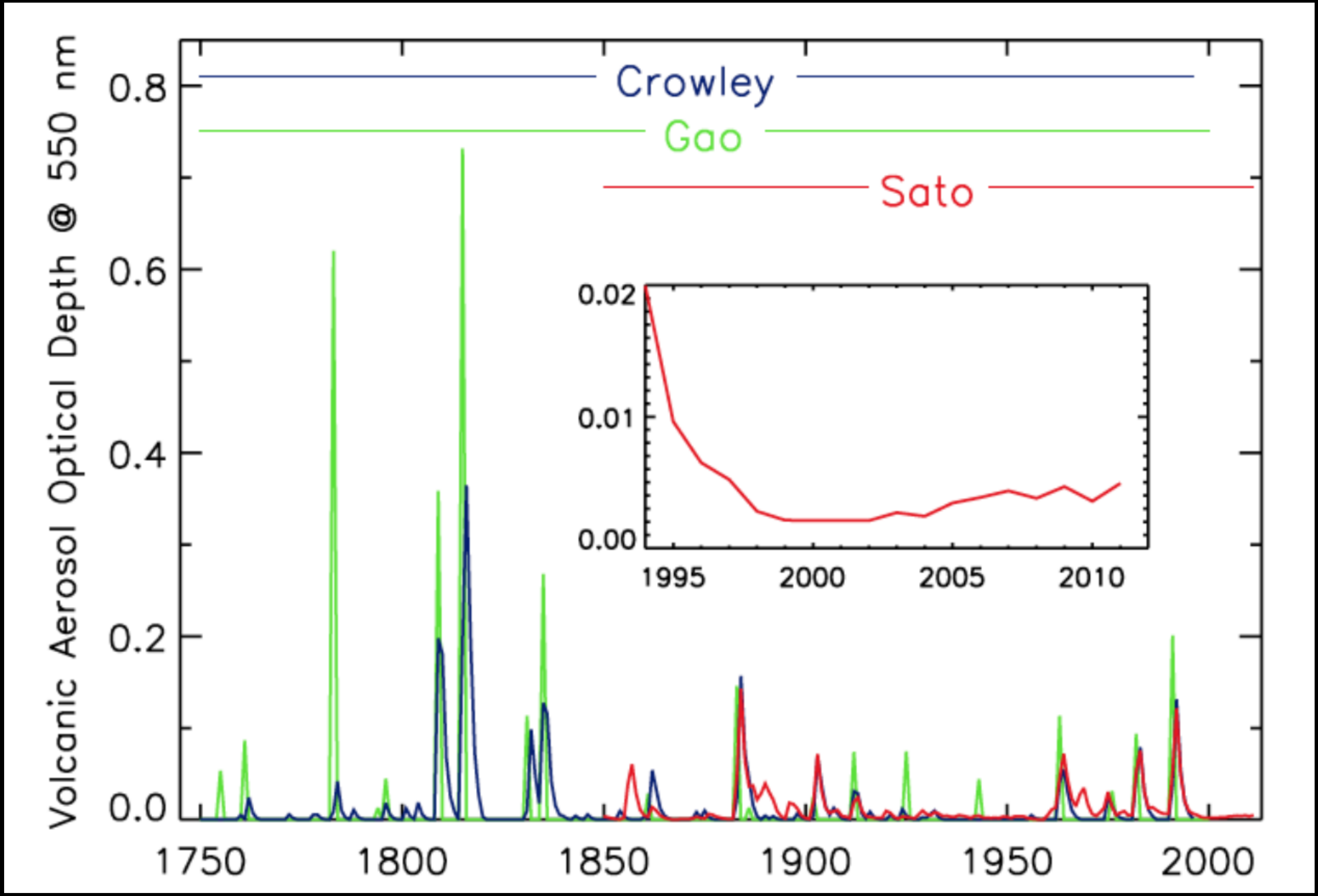
Mills et al., 2016



Models can reproduce the optical depth given SO_2 from observations

Mills et al., 2016

Geologists are not using microphysical models to reconstruct optical depth, what is error source?

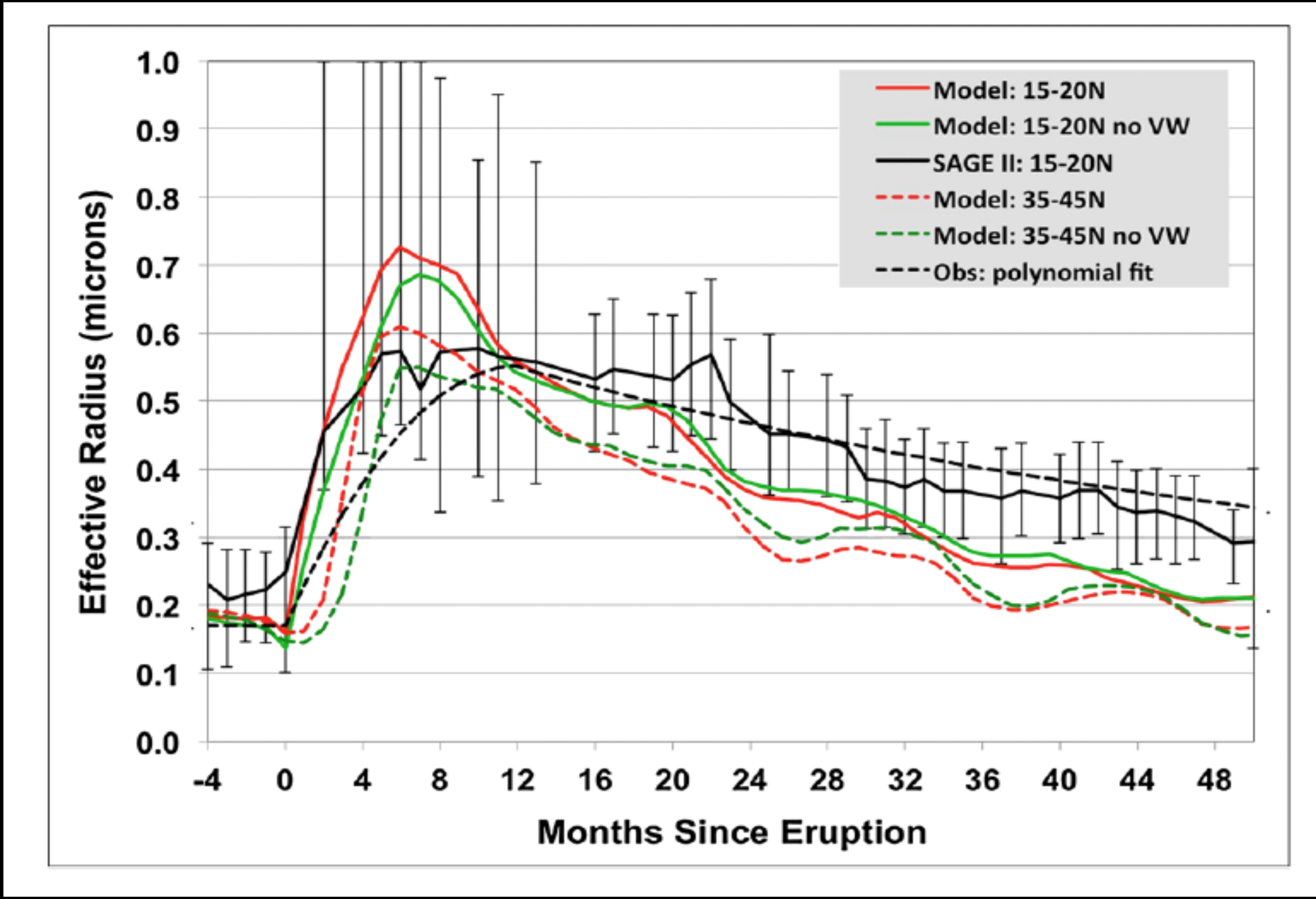


Myhre et al., 2013

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

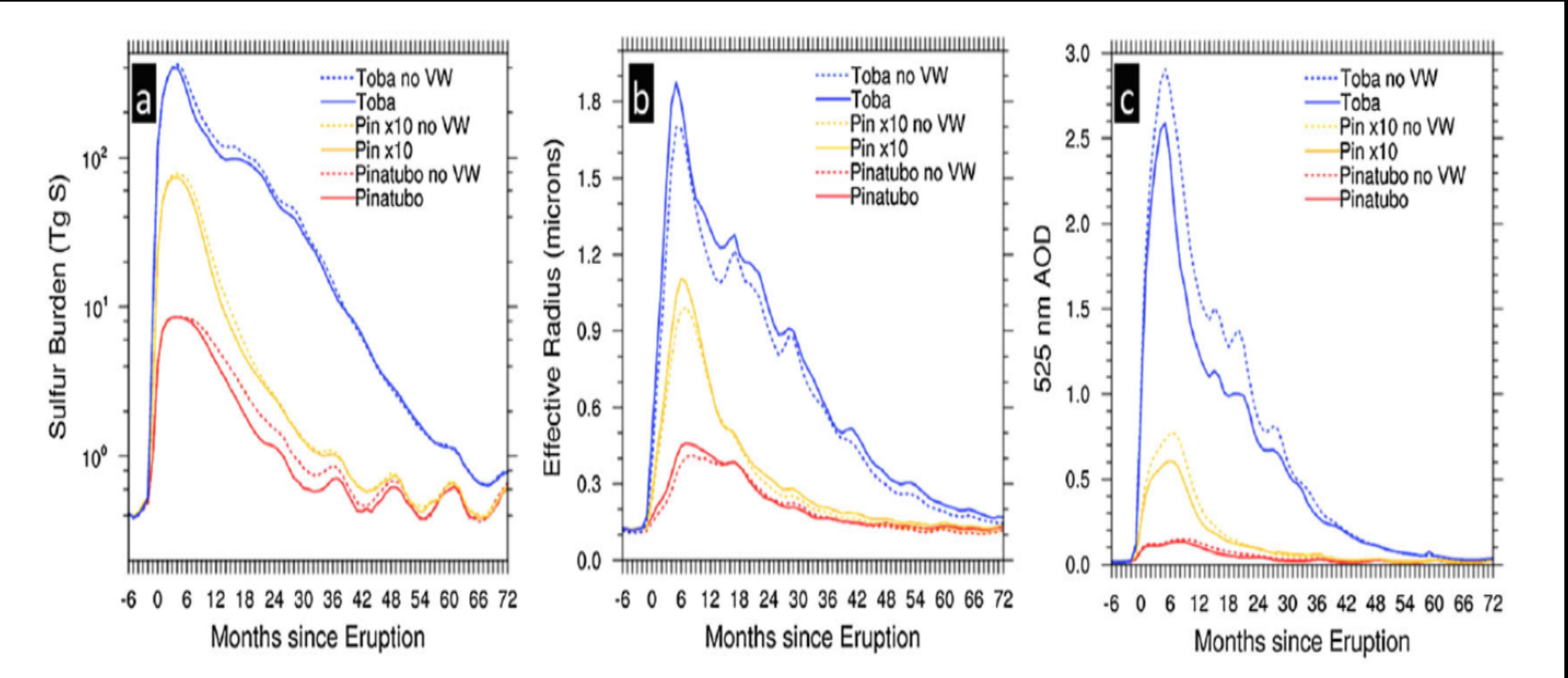
$$r_{eff} = \frac{\int r(\pi r^2 n(r) q_{ext}(m, \lambda / r))\, dr}{\int \pi r^2 n(r) q_{ext}(m, \lambda / r)\, dr} \approx \frac{3}{4} \frac{V}{A_c}$$

The effective radius after Pinatubo was not constant in time



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

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

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

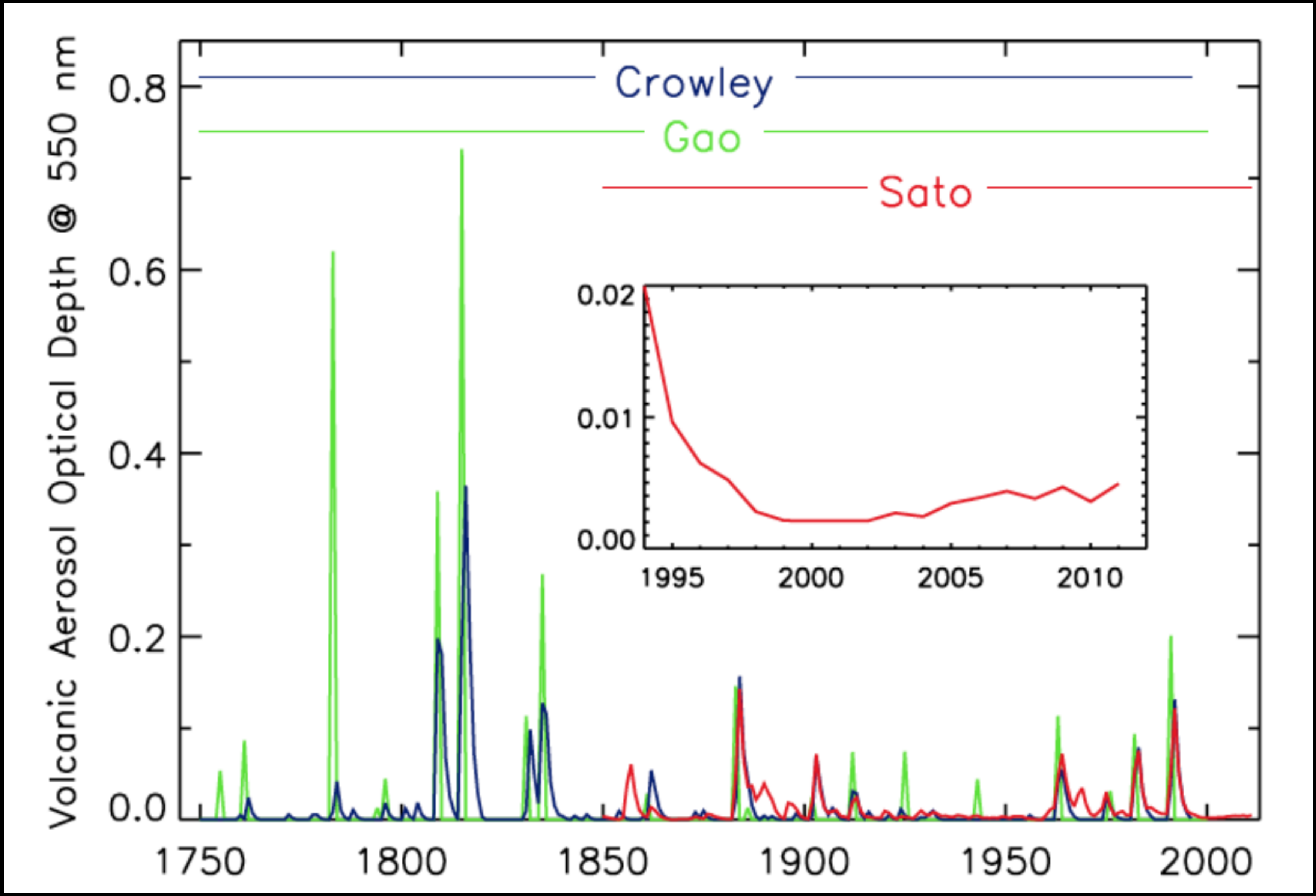
$$N = \frac{N_0}{1 + \frac{1}{2}KN_0 t}$$

for large time

$$N = \frac{2}{Kt}$$

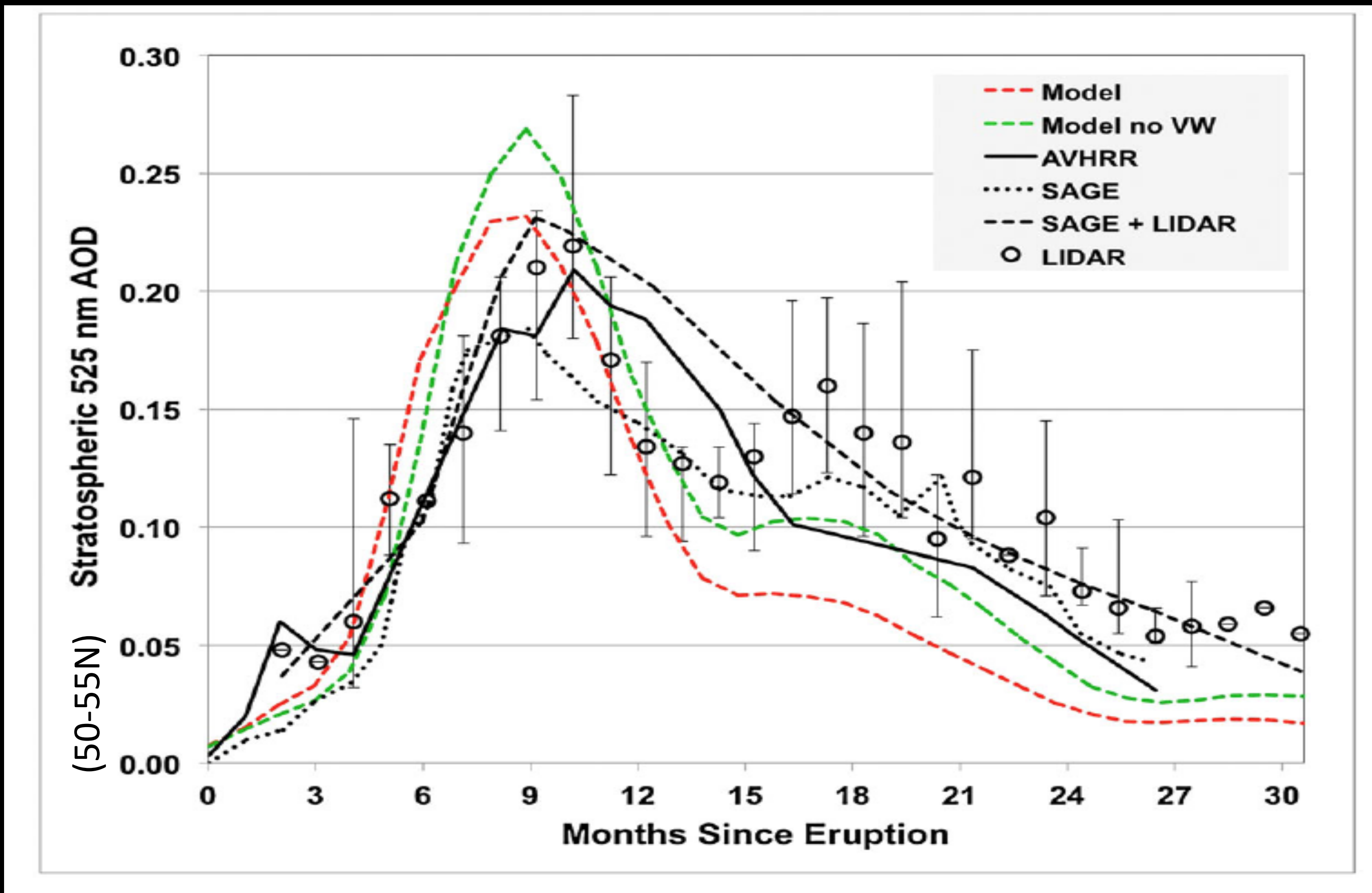
Reff not constant because coagulation limits number

Is a global average optical depth good enough?



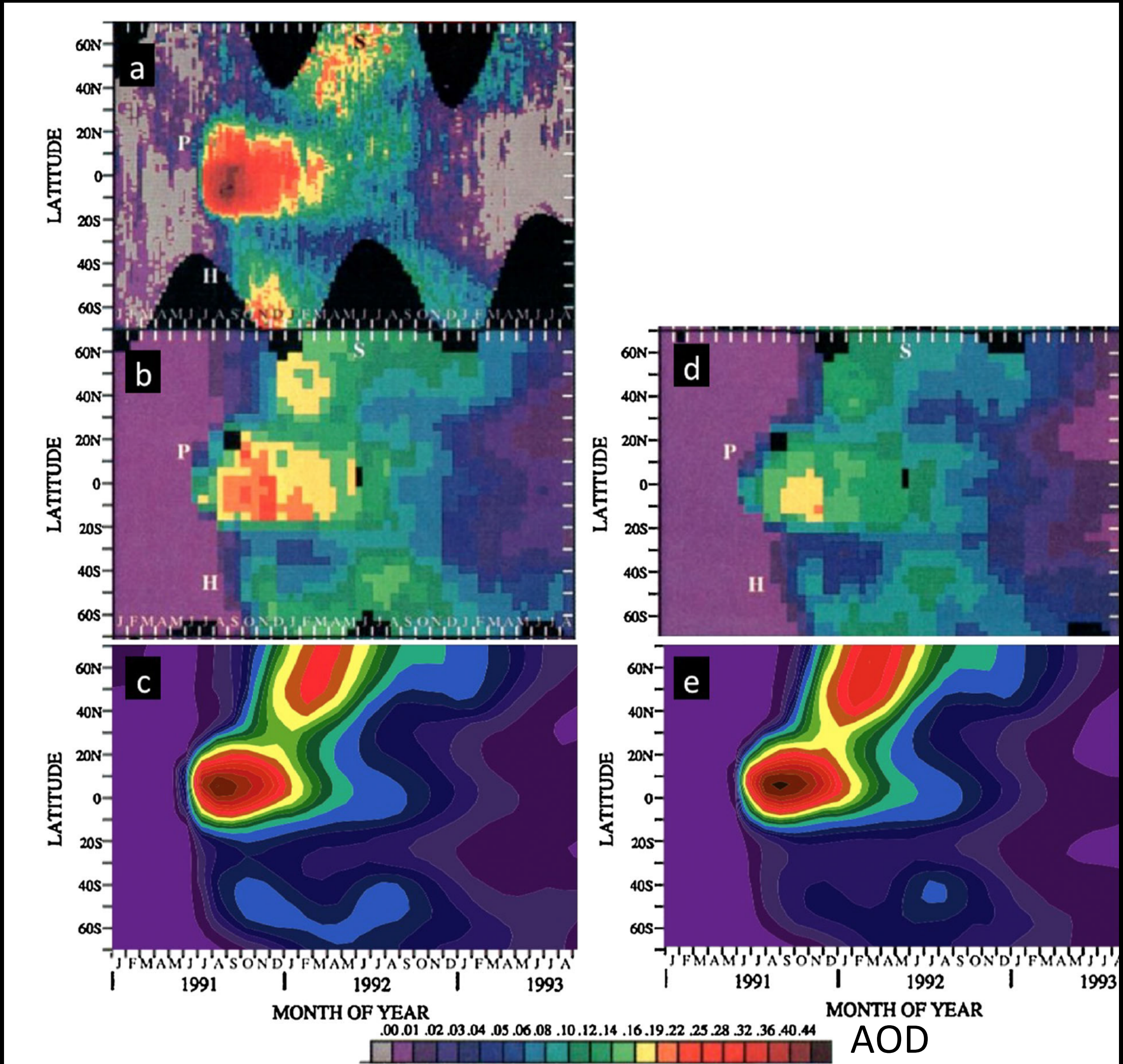
Myhre et al., 2013

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.

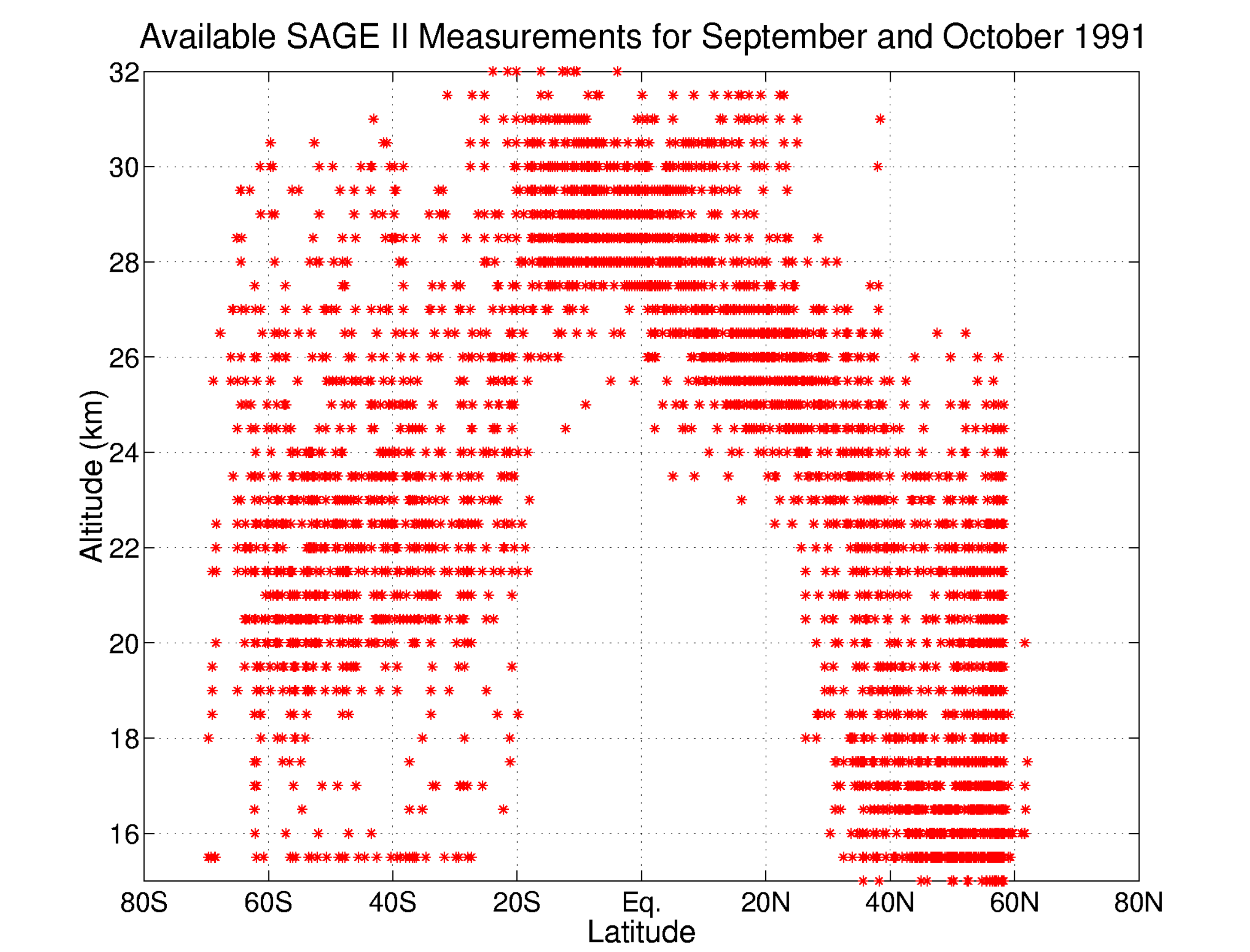


AVHRR, 500nm

SAGE II

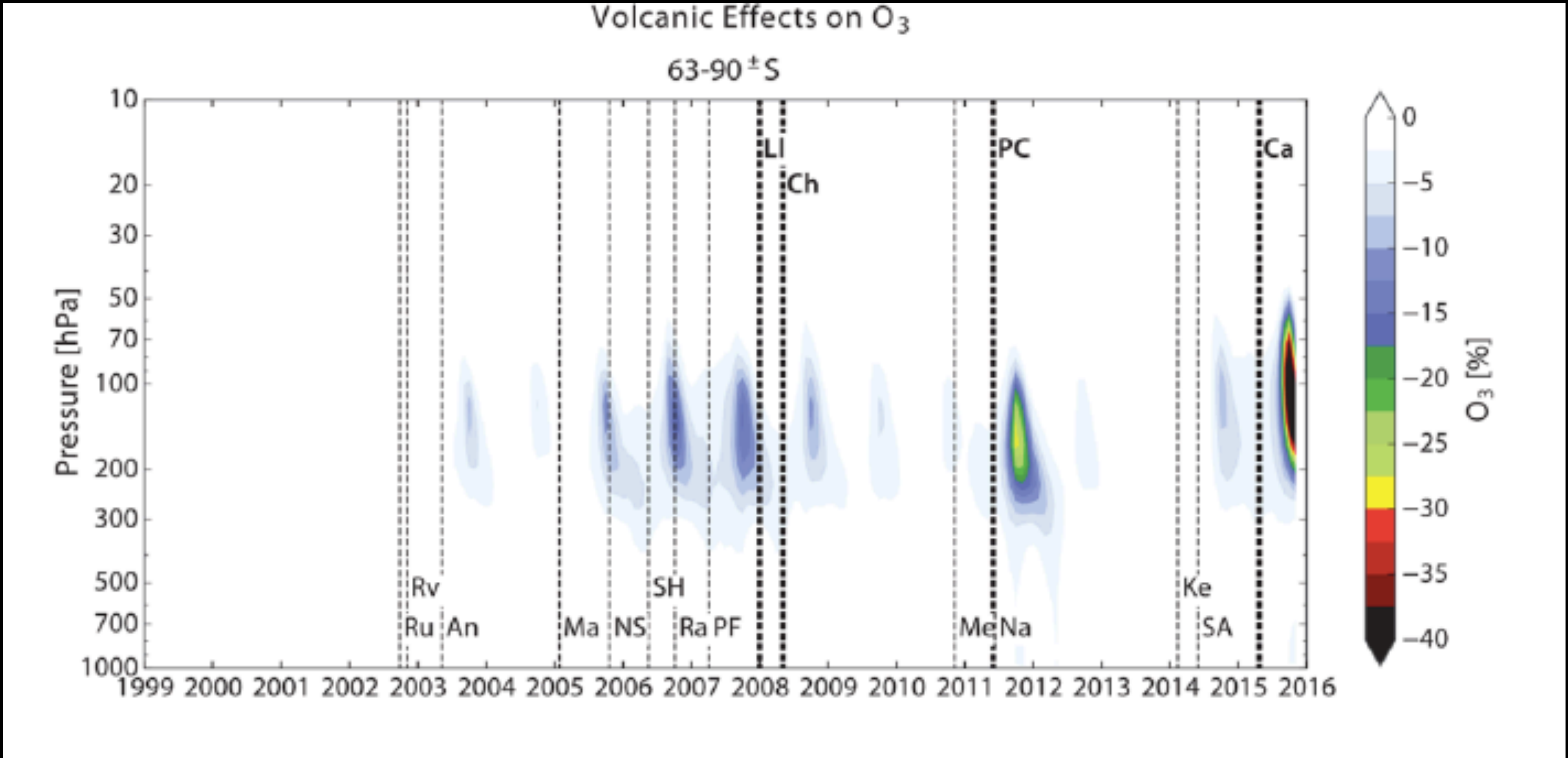
Model 525,1024nm
English et al., 2013

Limb sounders are blocked by Pinatubo sized events



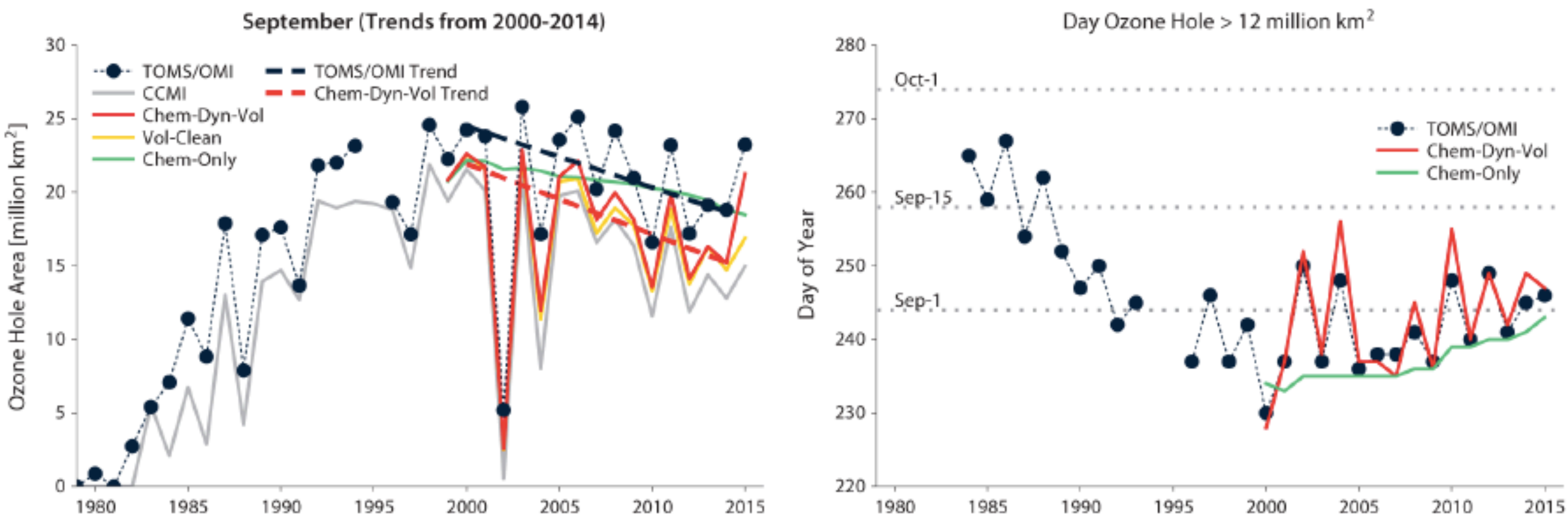
Plot by Juan Carlos Antuña
Courtesy Alan Robock

Small eruptions may cause polar ozone loss

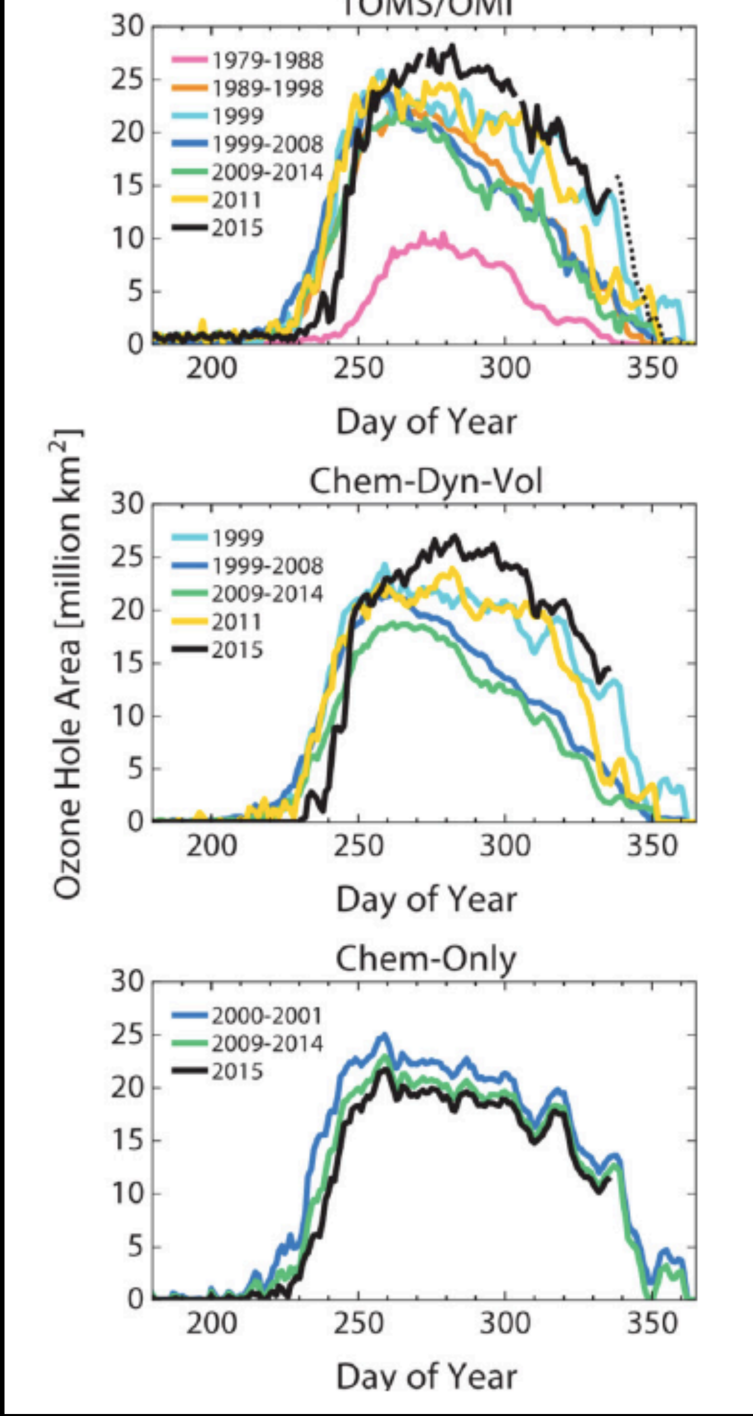


Solomon et al., Science 2016

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

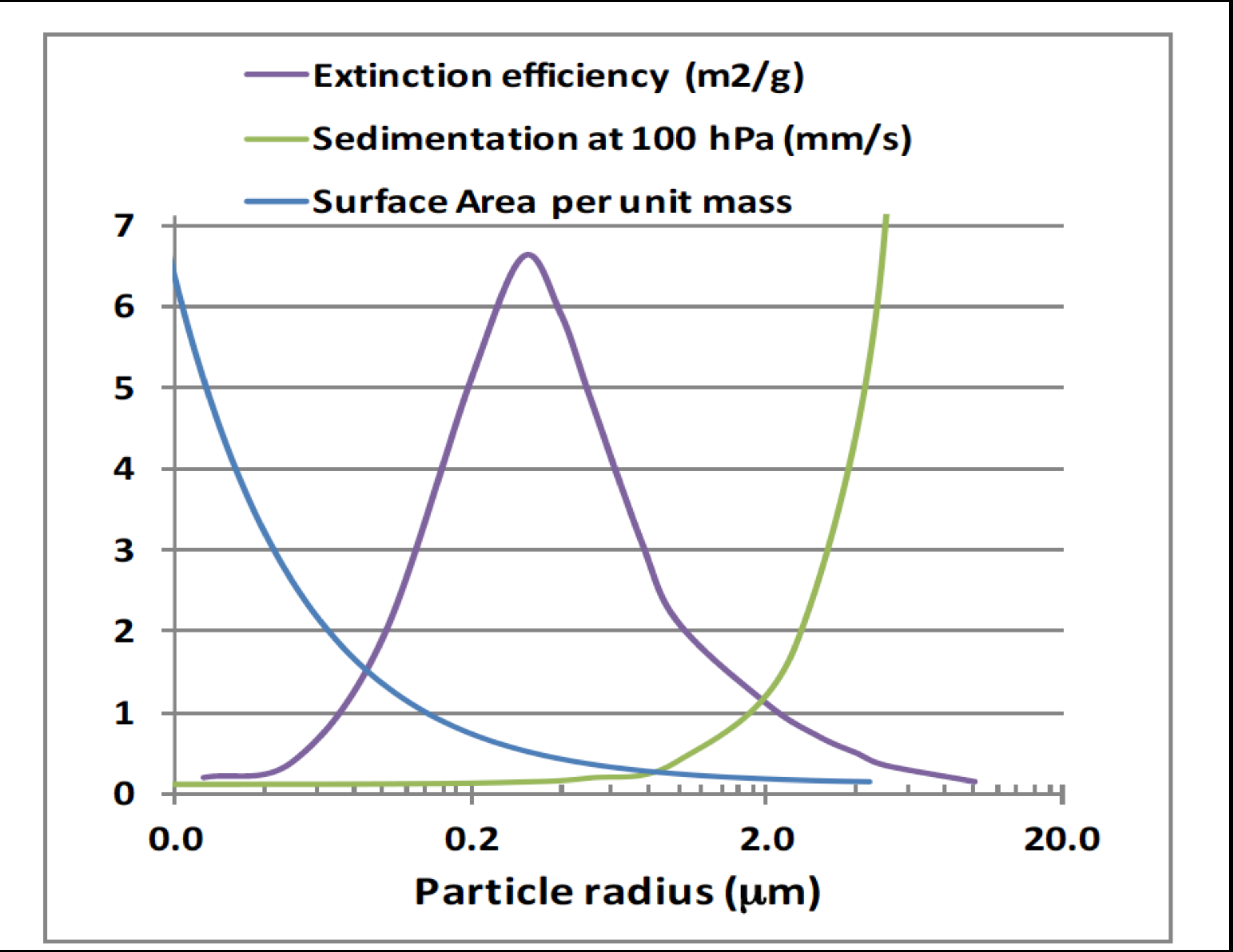
Summary

- 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.

What could you do?

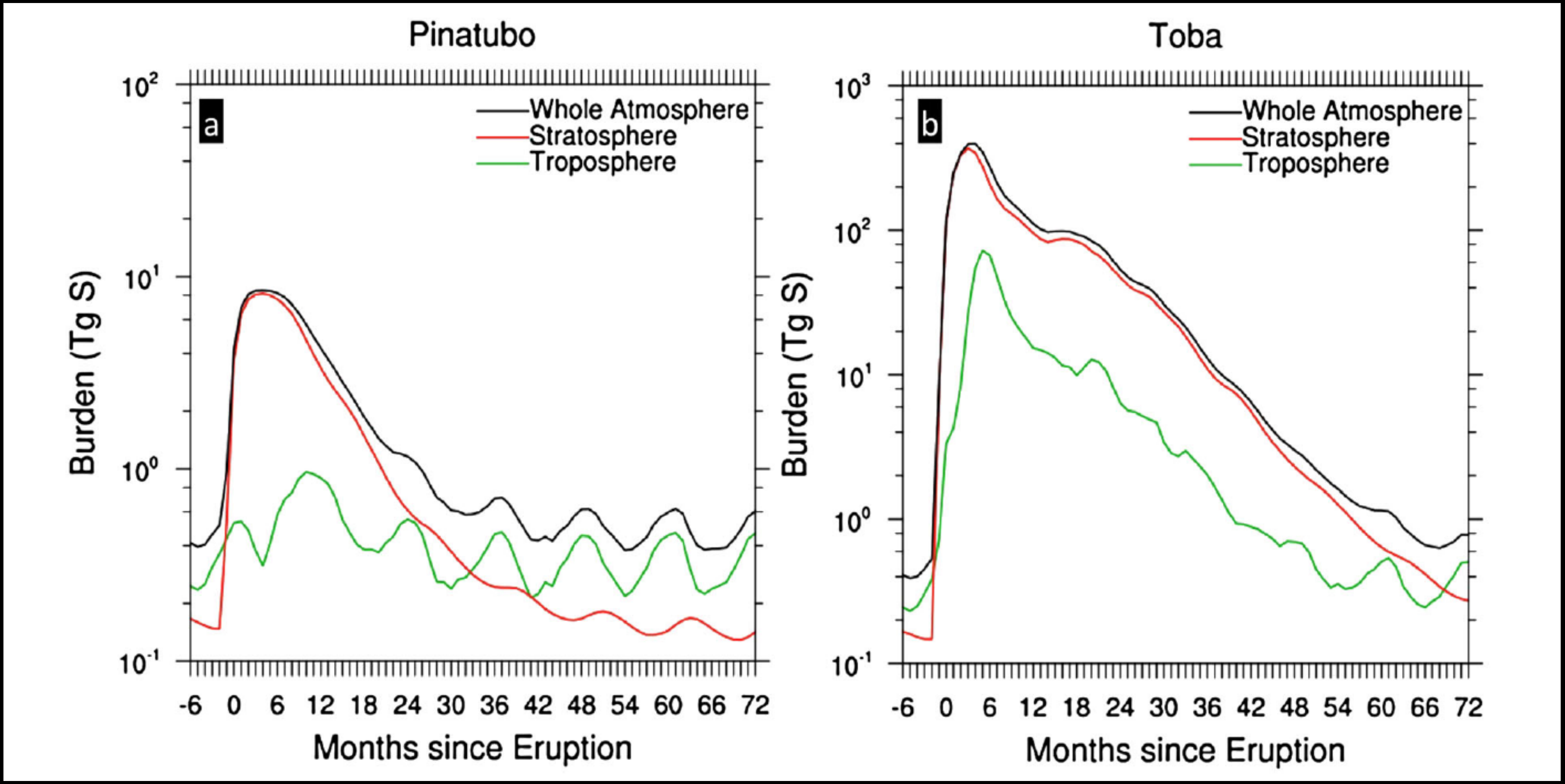
- Formulate plan for national response to measure changes after next eruption.
- Consider how to better determine importance of historic eruptions.
- Make improved models/ observations of volcanic effects on ozone, climate, cirrus

Reff is not enough to compute physics

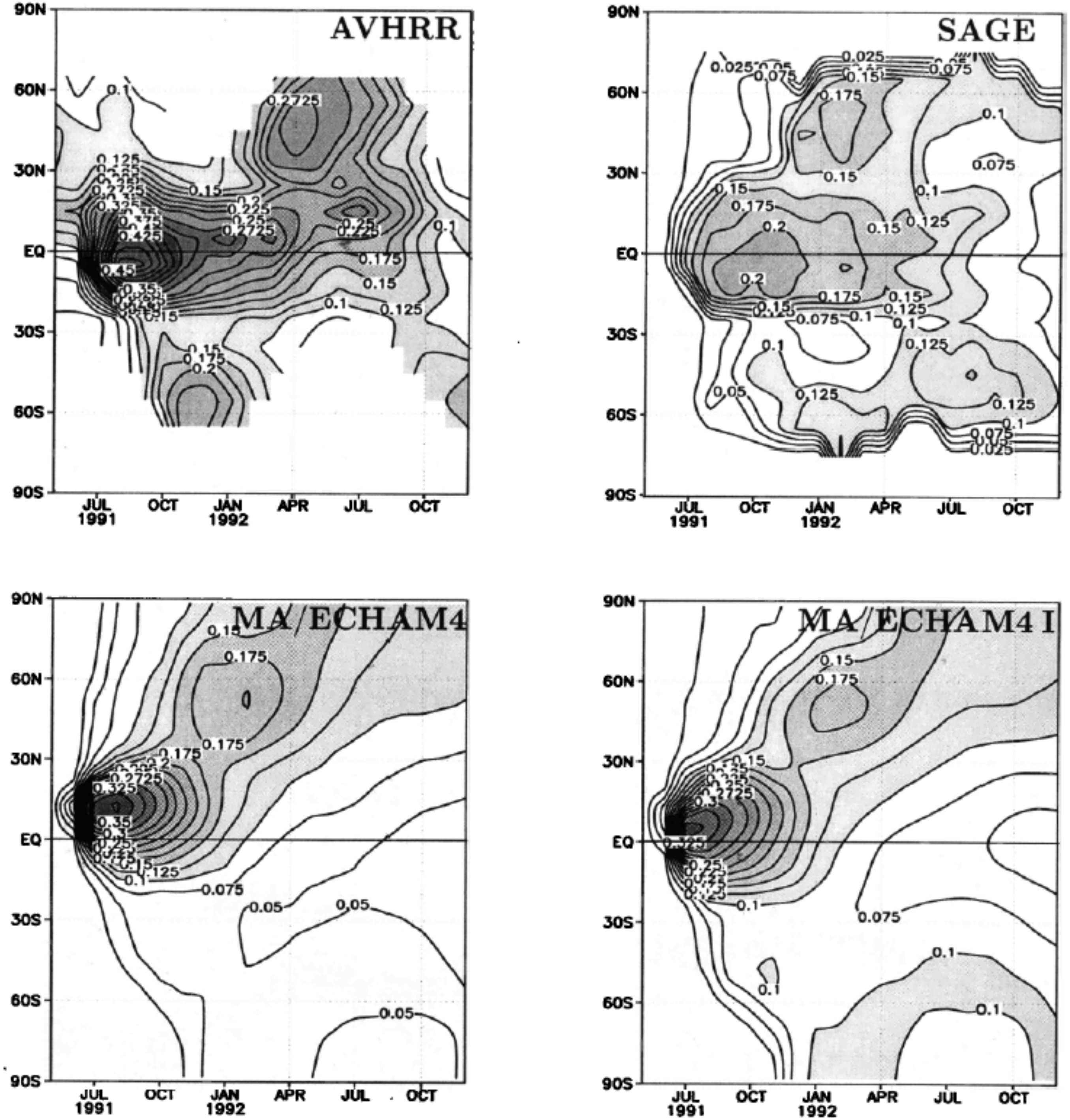


Courtesy of Jason English

A lot of sulfate can be present in the troposphere



English et al., 2013



Radiative heating in Pinatubo cloud affects its spatial distribution

Timmreck et al., 1999