Interactive stratospheric aerosol microphysics simulations for realistic volcanic radiative forcings

Observational constraints for Agung period

Graham Mann

(NCAS, School of Earth & Environment, Univ. of Leeds)

Sandip Dhomse, Lauren Marshall, Anja Schmidt,
Ryan Neely, Sarah Shallcross,
Ken Carslaw, Lindsay Lee, Martyn Chipperfield

(School of Earth & Environment, Univ. of Leeds)

Kathryn Emmerson, Stuart Young

(CSIRO, Melbourne, Australia)

Acknowledgements to others in the UKCA team

Coin Johnson, Fiona O'Connor, Mohit Dalvi (Hadley Centre, UK Met Office)

Nicolas Bellouin (University of Reading)

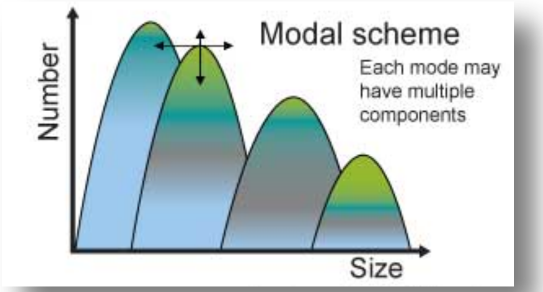
Luke Abraham, Paul Telford, Peter Braesicke, Alex Archibald, John Pyle (University of Cambridge)

UK Chemistry and Aerosol project

- Collaboration between UK National Centre for Atmospheric Science (Leeds, Cambridge, Oxford) & UK Met Office since 2005

- Has built aerosol-chemistry sub-model in the UK Met Office Unified Model, being applied for a range of applications (climate, air quality, Earth system science, weather)

- Chemistry schemes & aerosol configurations including for stratosphere-troposphere



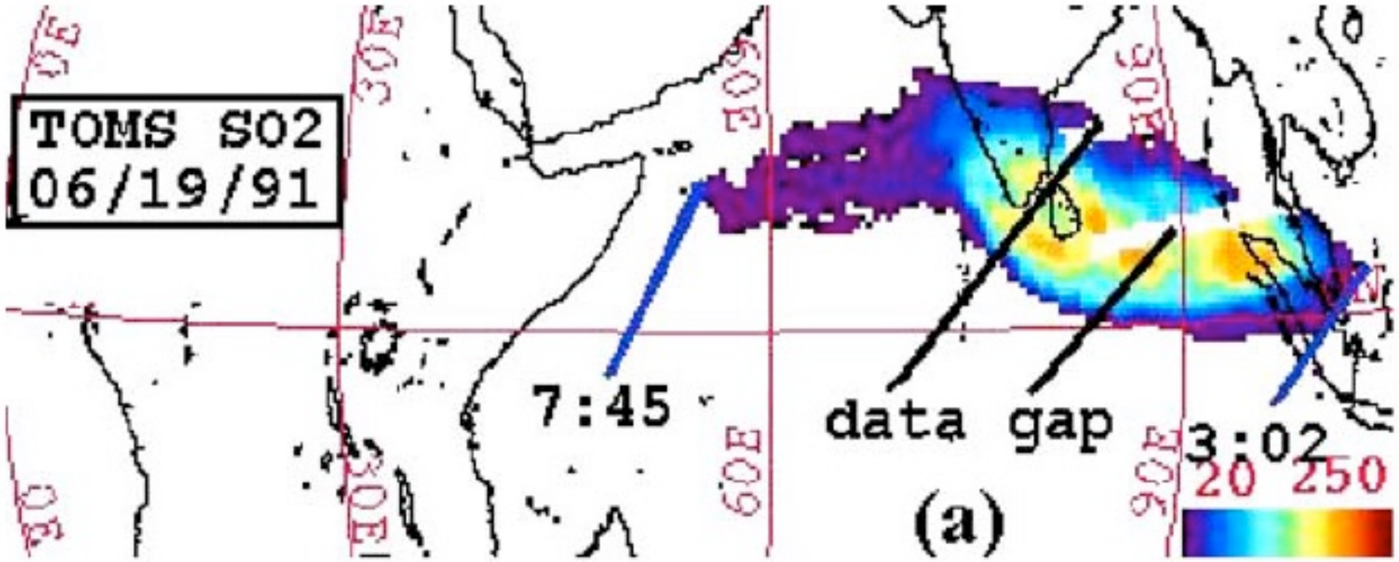
- Multi-component aerosol microphysics scheme (GLOMAP)

www.ukca.ac.uk

- Global variations in particle size distribution → sedimentation and SW & LW radiative effects

- The UK Earth System model UKESM (HadGEM3) simulates strat-trop ozone and strat-trop aerosol interactively and radiatively coupled with composition-dynamics interactions

The 1991 Mount Pinatubo eruption



Satellite measurements indicate 14 to 23 Tg of SO_2 (7 to 11.5 TgS) was present in the tropical stratosphere shortly after the eruption.

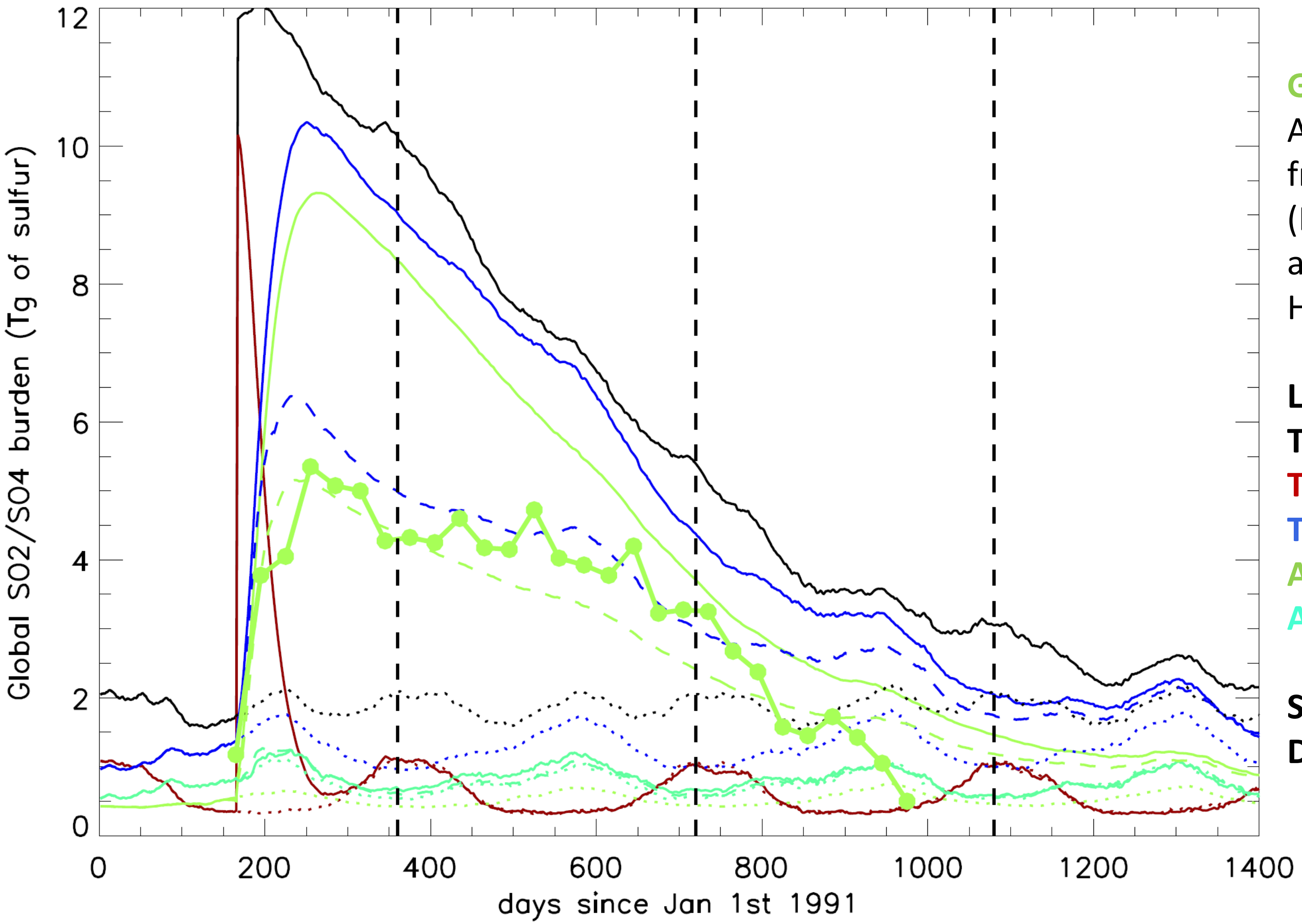
The stratospheric aerosol loading peaked several months later in the range 19-26 Tg (Lambert et al., 1993). Assuming 59 to 77% sulphuric acid (Grainger et al., 1993) gives a range of 3.7 to 6.7 TgS.

Investigate the eruption's impact on the stratospheric aerosol in UKCA with runs which inject 10 & 20 Tg of SO_2 into the tropical stratosphere

HadGEM-UKCA N48L60 CheS+GLOMAP.

Dhomse et al (2014, ACP)

Global column sulphur-loadings of SO_2 & aerosol



Green Dotted-Line: Aerosol sulphur from HIRS satellite (Baran & Foot, 1994) assuming 75% by wt H_2SO_4

Lines-with-no-dots:
Total SO_2 + aerosol
Total SO_2
Total aerosol
Aerosol p<300 hPa
Aerosol p>300 hPa

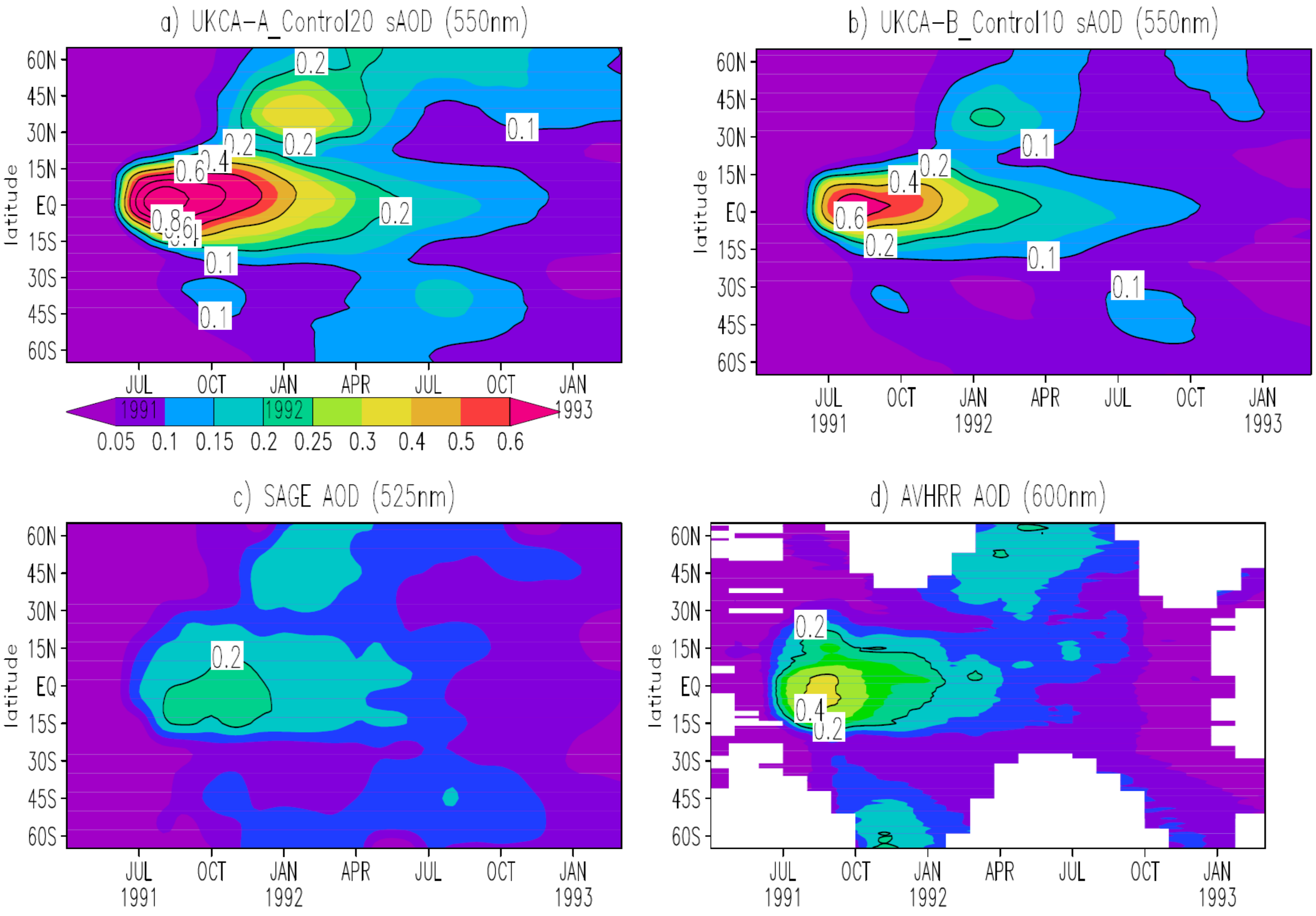
Solid = 20Tg Pin
Dashed = 10Tg Pin

Experiments to critically evaluate simulated AOD particle size & assess appropriate SO_2 to emit

Simulated aerosol uncoupled from dynamics in this paper (double-call) Dhomse et al (2014, ACP)

HadGEM-UKCA N48L60 CheS+GLOMAP.

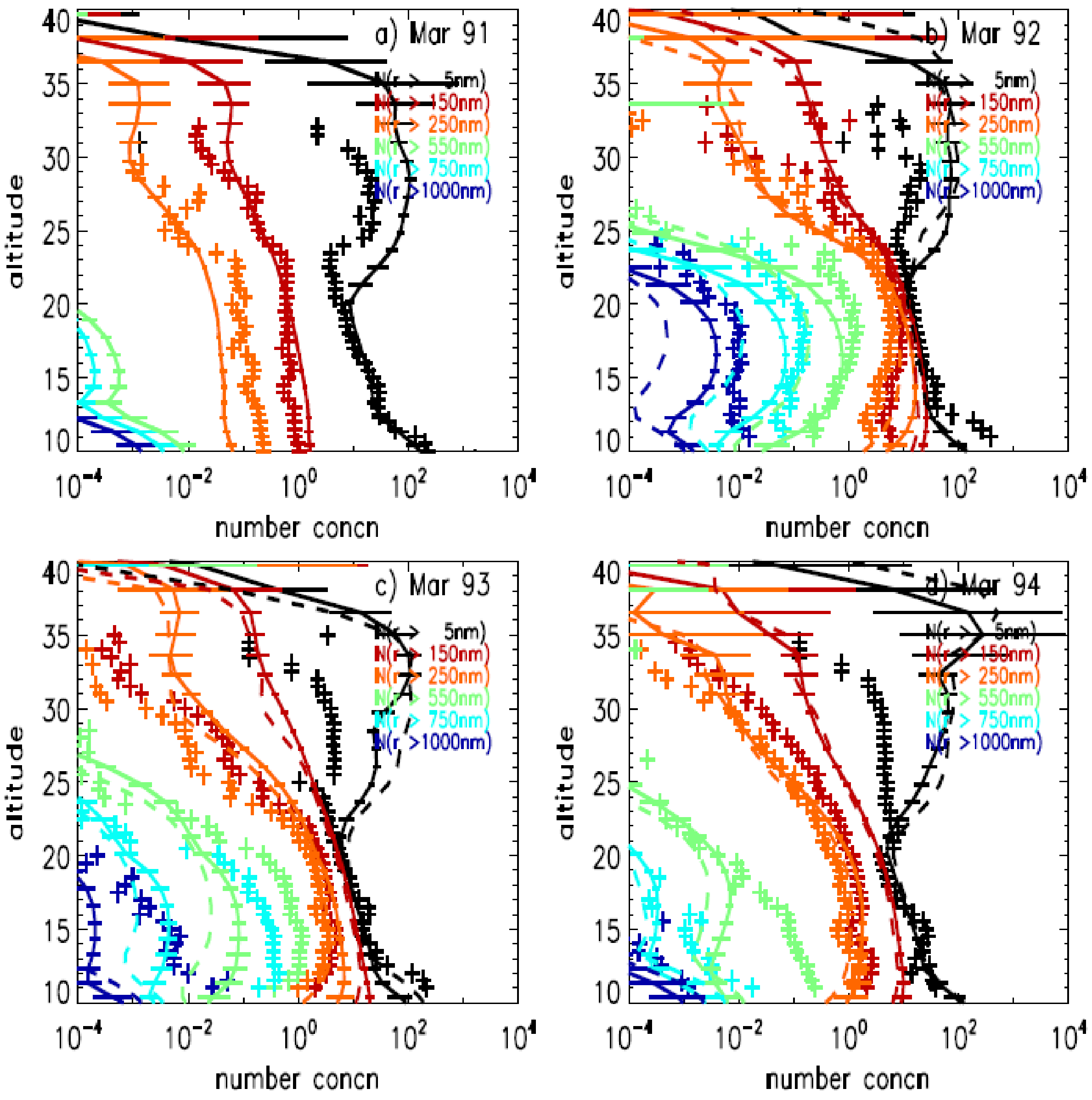
Stratospheric aerosol optical properties



HadGEM-UKCA N48L60 CheS+GLOMAP.

Dhomse et al (2014, ACP)

Stratospheric aerosol: particle size



Balloon-borne CPC & OPC measurements of size-resolved particle concentrations N(r>10, 150, 250, r>550, 750, 1000nm) made at Laramie, Wyoming, U.S.A. (Deshler et al., 2003)

Very good agreement vs size distribution measurements in March 1991 & 1992.

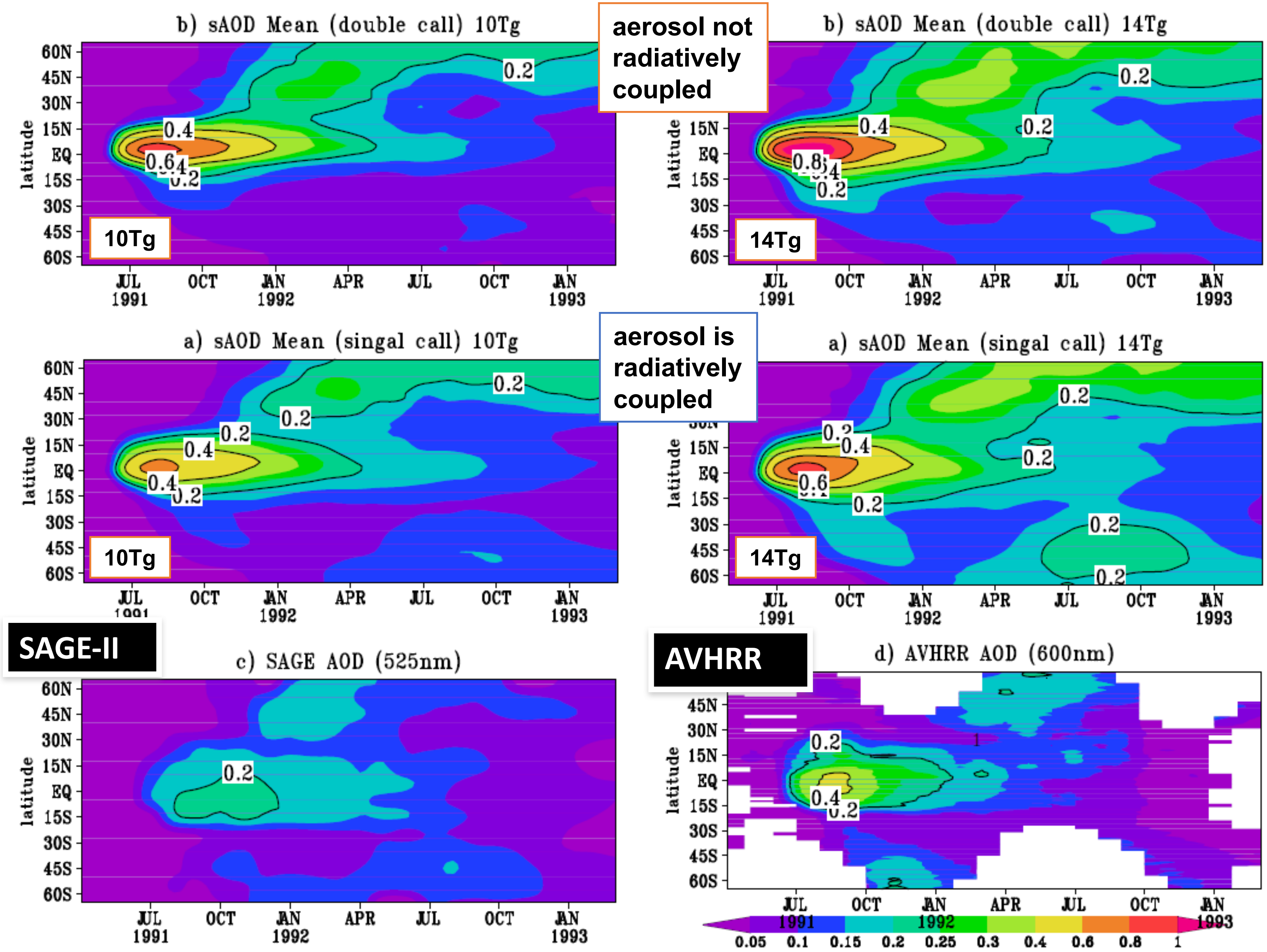
N(r>150mm) high bias 10-20km with too delayed recovery to background.

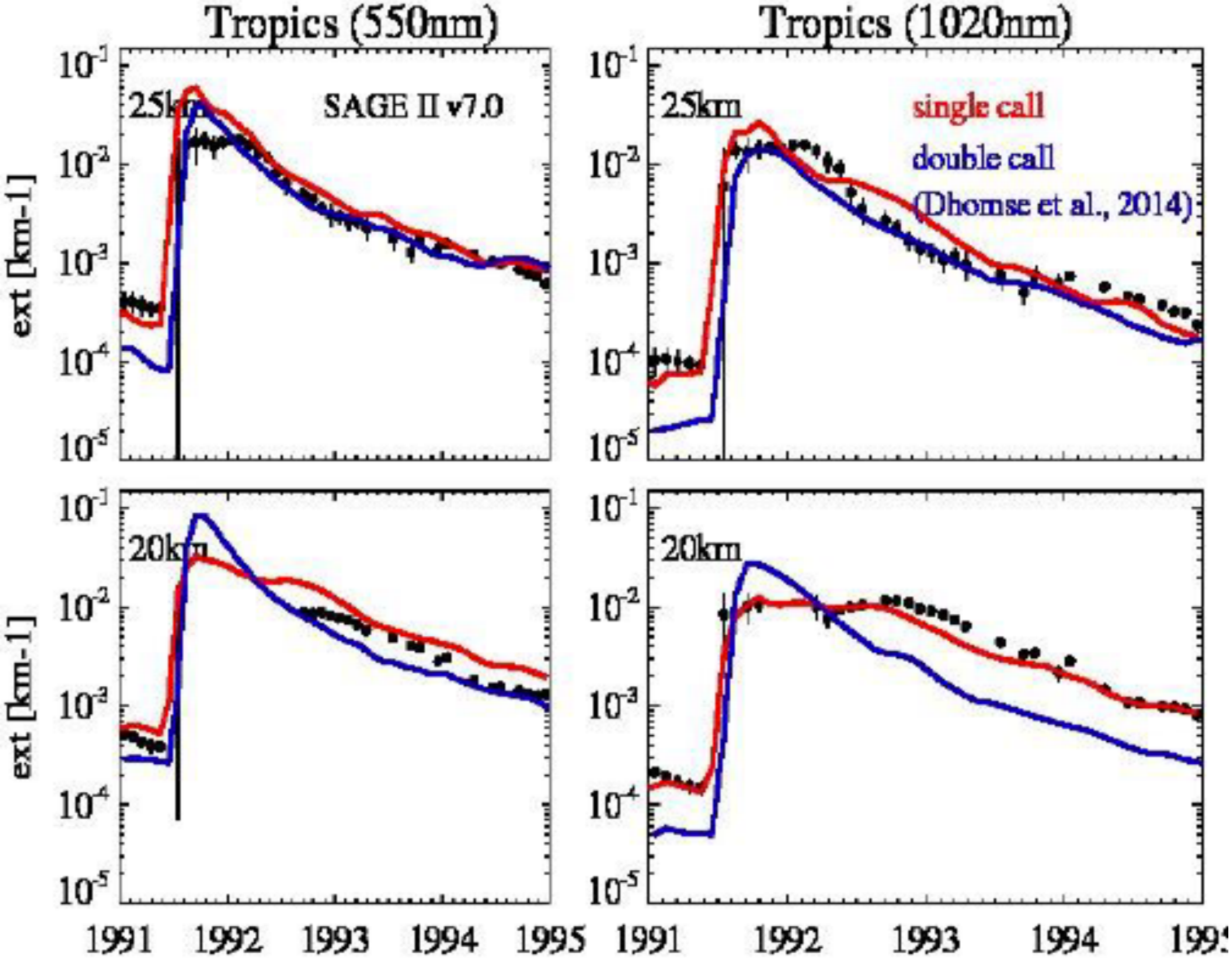
N(r>250nm) agrees well

Dhomse et al (2014, ACP)

HadGEM-UKCA N48L60 CheS+GLOMAP.

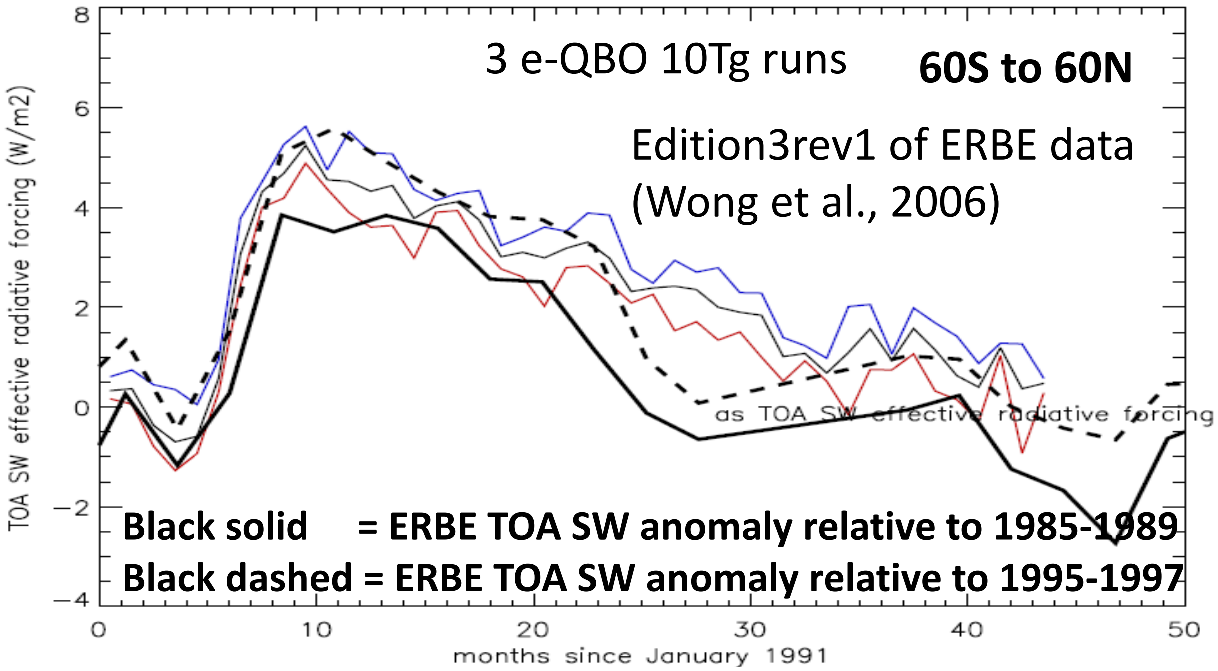
v7.3 CheS+GLOMAP N48L60: sAOD evolution vs SAGE-II sAOD & AVHRR anomaly

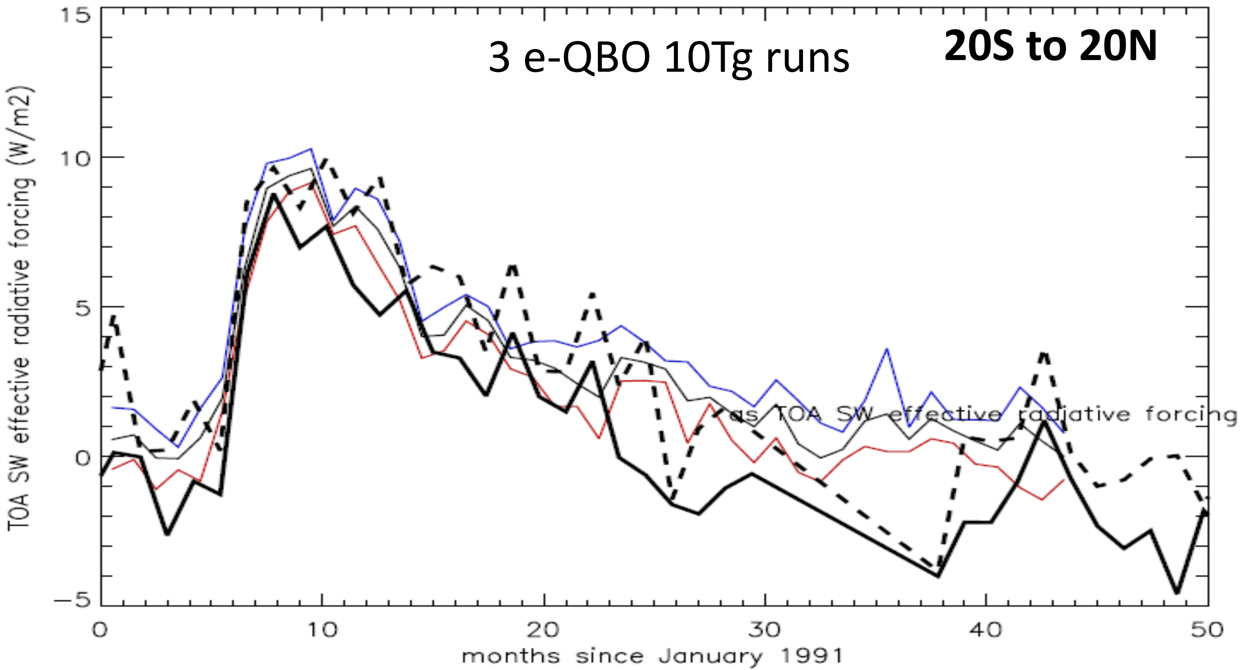




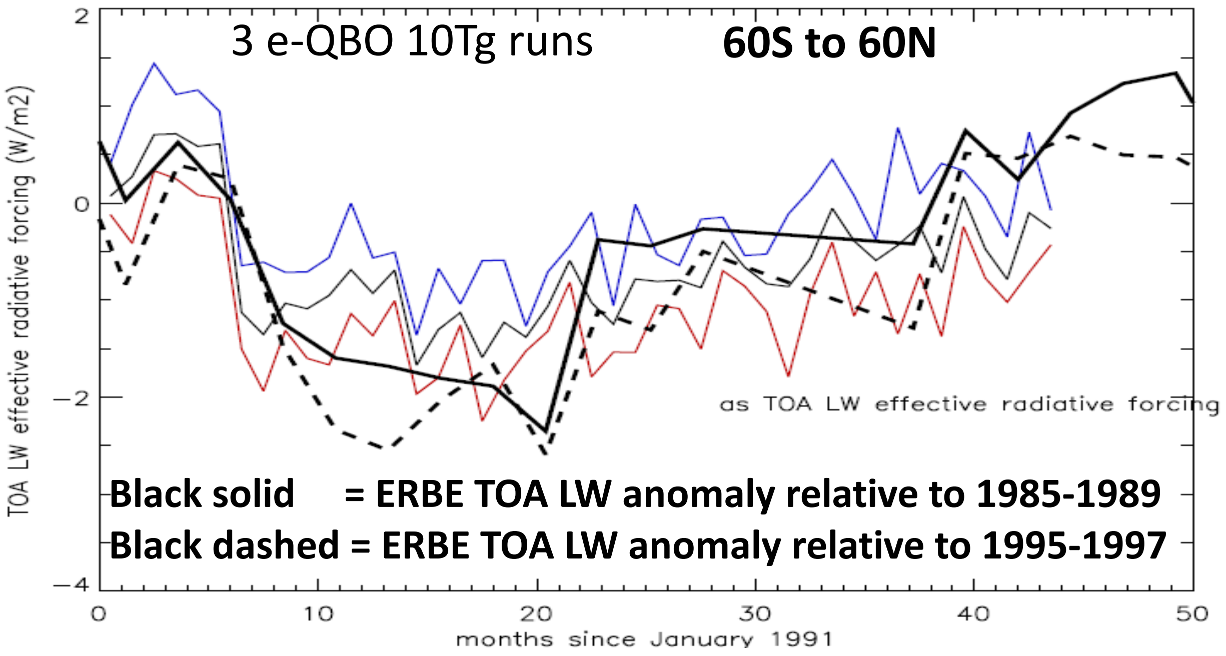
Mann et al (2015, PAGES)

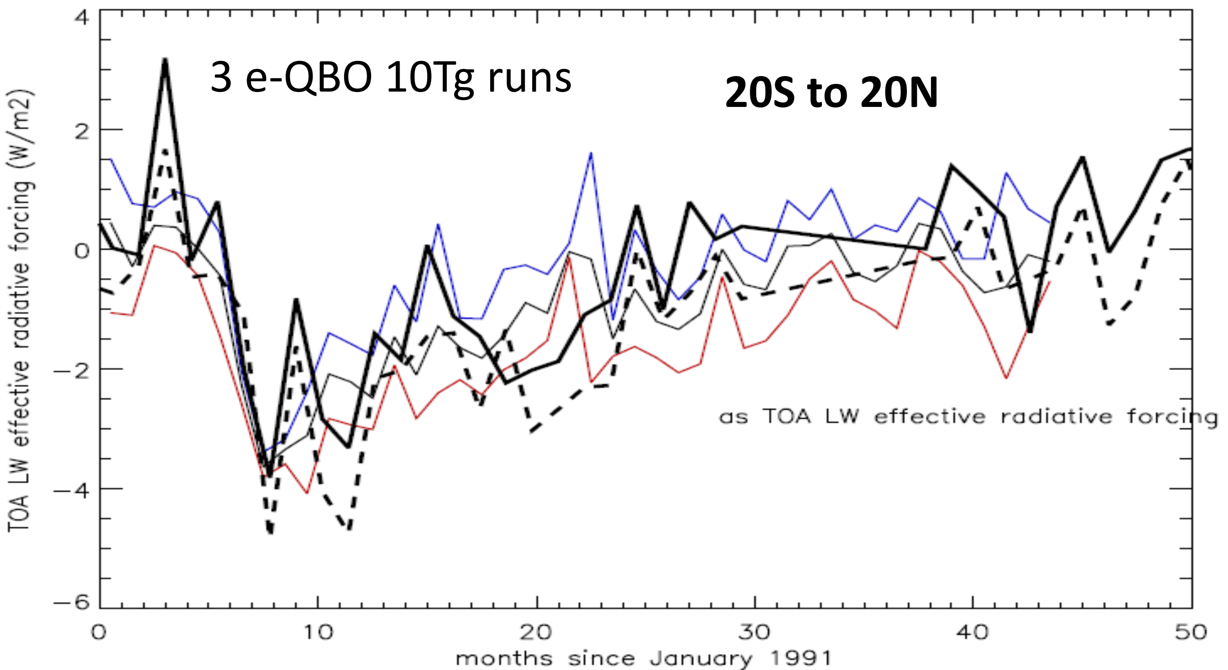
All-sky TOA SW radiative forcing timeseries from UM-UKCA





All-sky TOA LW radiative forcing timeseries from UM-UKCA





ISA-MIP model intercomparison: HErSEA experiment

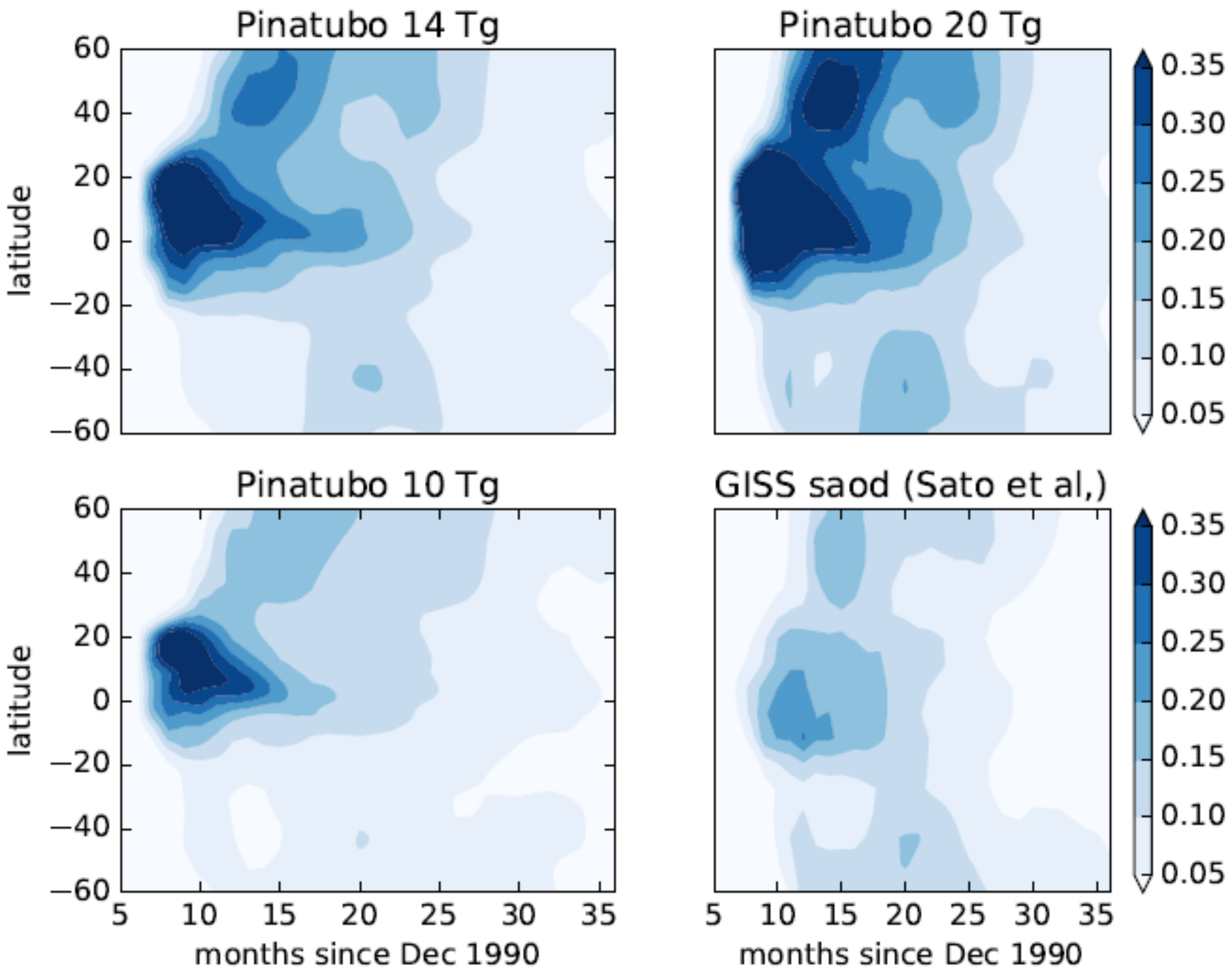
One element of the current SPARC “Stratospheric Sulphur and its Role in Climate” involves a model intercomparison project “ISA-MIP” for Interaction Stratospheric Aerosol models like UM-UKCA.

One of the 4 co-ordinated experiments alligns with the Dhomse et al. (2014) analysis of how different properties of the stratospheric aerosol layer were perturbed by Pinatubo. ”Historical Eruption SO2 Emissions Assessment” (HErSEA) – Timmreck et al. (for GMD)
Test how SO2 translates into sulphuric aerosol and radiative effects in different ISA models

Eruption	Location	Date	SO_2 (Tg)	Shallow x 2	Deep	QBO
Pinatubo	15N,120E	15/06/1991	10-20 (14)	18-20,21-23km	18-25km	Easterly
El Chichón	17N,93W	04/04/1982	5-10 (7)	22-24,24-26km	22-27km	Westerly
Agung	8S,115E	17/03/1963	6-12 (9)	17-19,20-22km	17-23km	Westerly

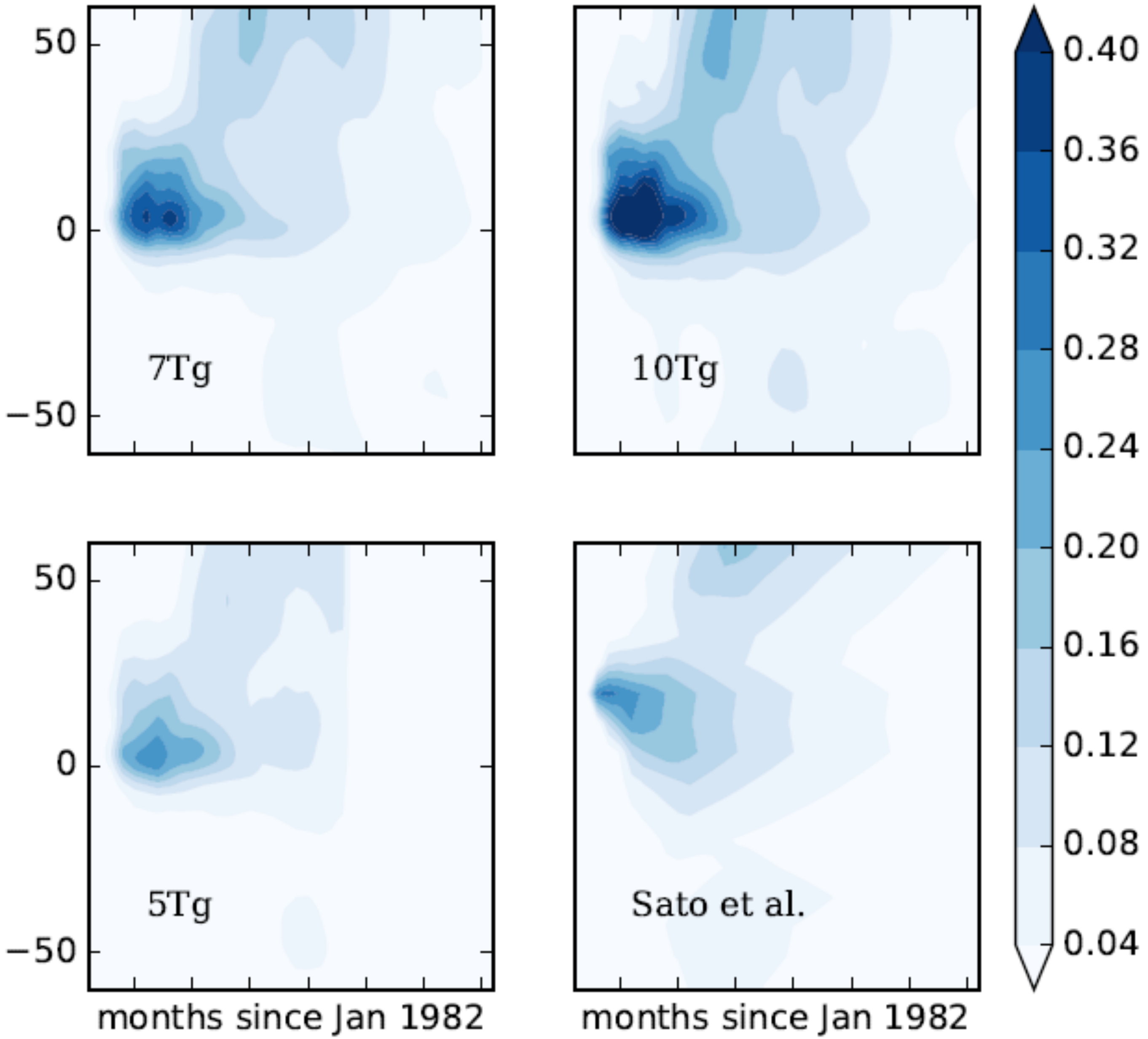
Table 3.3.1 Settings to use for initialising the mini-ensemble of interactive stratospheric aerosol simulations for each eruption. The SO_2 emissions fluxes are from Textor et al. (2004) with a factor-2 assumed uncertainty range. For Pinatubo, injection height ranges for the two shallow and one deep realisations are taken from Antuna et al. (2002). The El Chichón values are based on the tropical lidar signal from Figure 4.34 of Hamill and Brogniez (2006), whereas for Agung we considered the measurements presented in Dyer and Hicks (1968) including balloon soundings (Rosen, 1964) and ground-based lidar (Grams and Fiocco, 1967).

HErSEA Pinatubo mid(14Tg), max(20Tg), min(10Tg) median-injection height (21-23km)



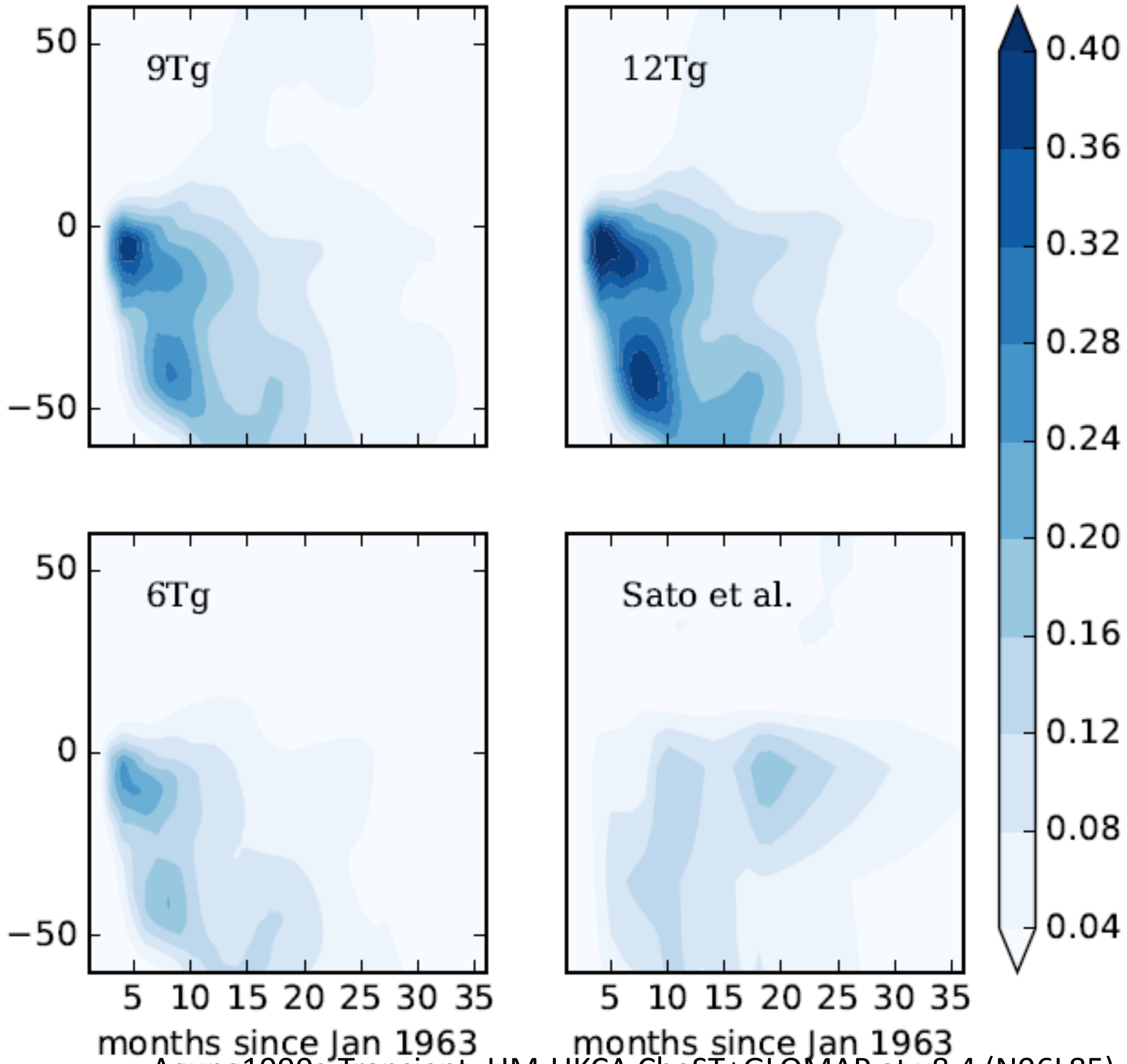
Pinatubo 1990s-Transient: UM-UKCA CheST+GLOMAP at v8.4 (N96L85)

HErSEA El Chichon mid(7Tg), max(10Tg), min(5Tg) median-injection height (21-23km)



El Chichon1990s-Transient: UM-UKCA CheST+GLOMAP at v8.4 (N96L85)

HErSEA Agung mid(14Tg), max(20Tg), min(10Tg) median-injection height (21-23km)



Agung1990s-Transient: UM-UKCA CheST+GLOMAP at v8.4 (N96L85)

Sato et al. (1993) volcanic forcing dataset

Agung-perturbed period based on compilation of surface radiation measurements by Dyer and Hicks (1968)

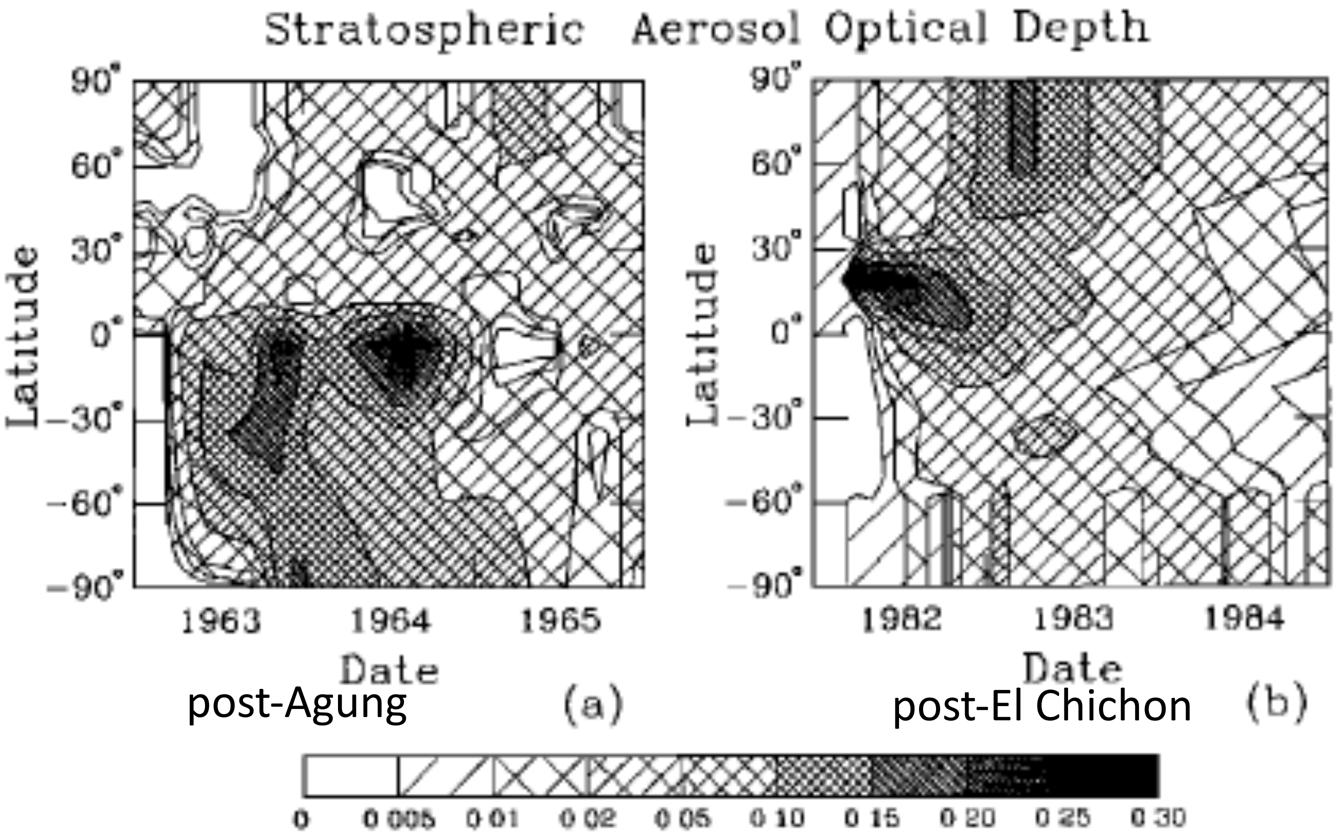


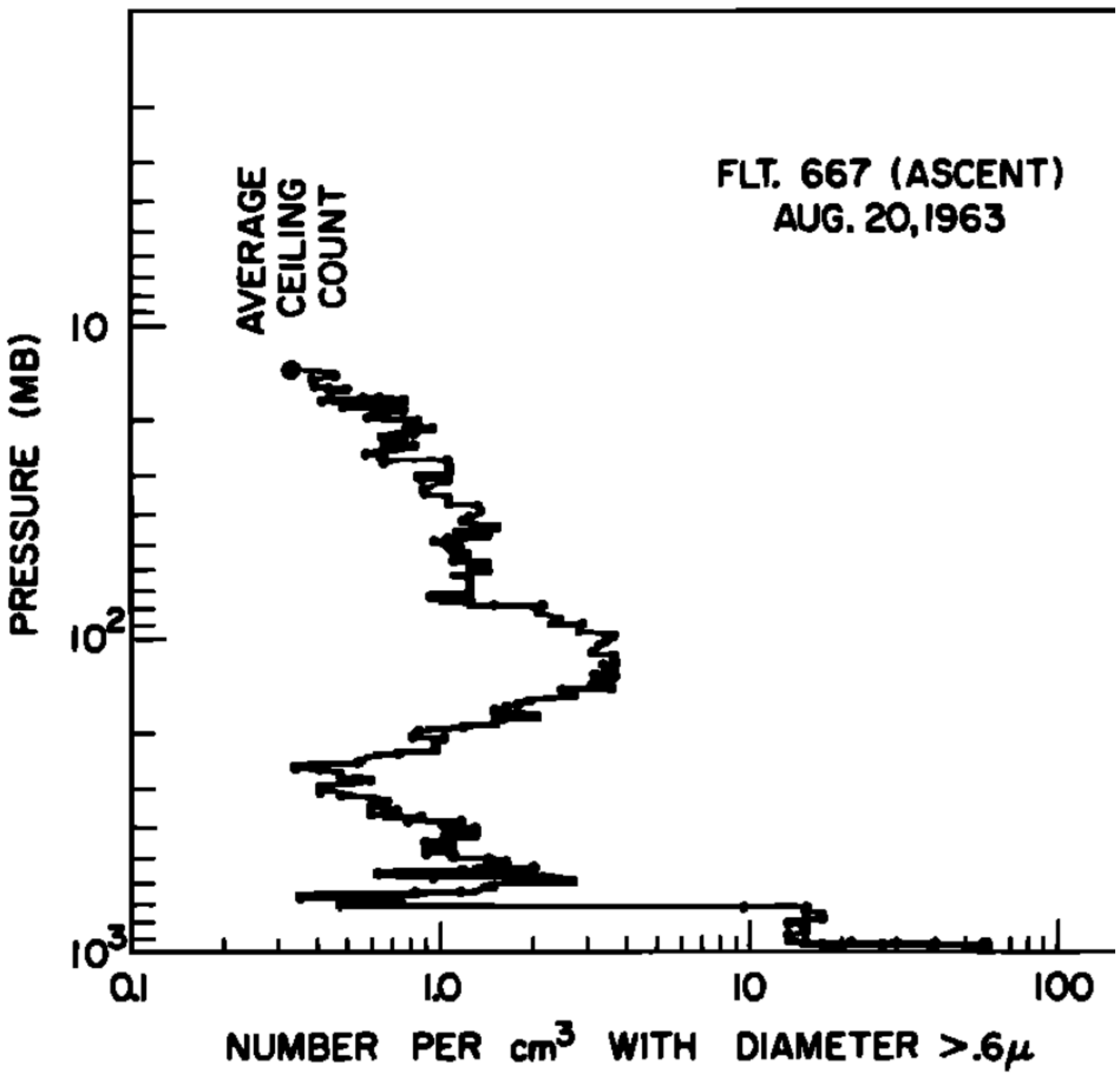
Fig. 2. Estimated stratospheric aerosol optical depth at $\lambda = 0.55$ μm as a function of latitude and time: (*a*) period after Agung and (*b*) period after El Chichon.

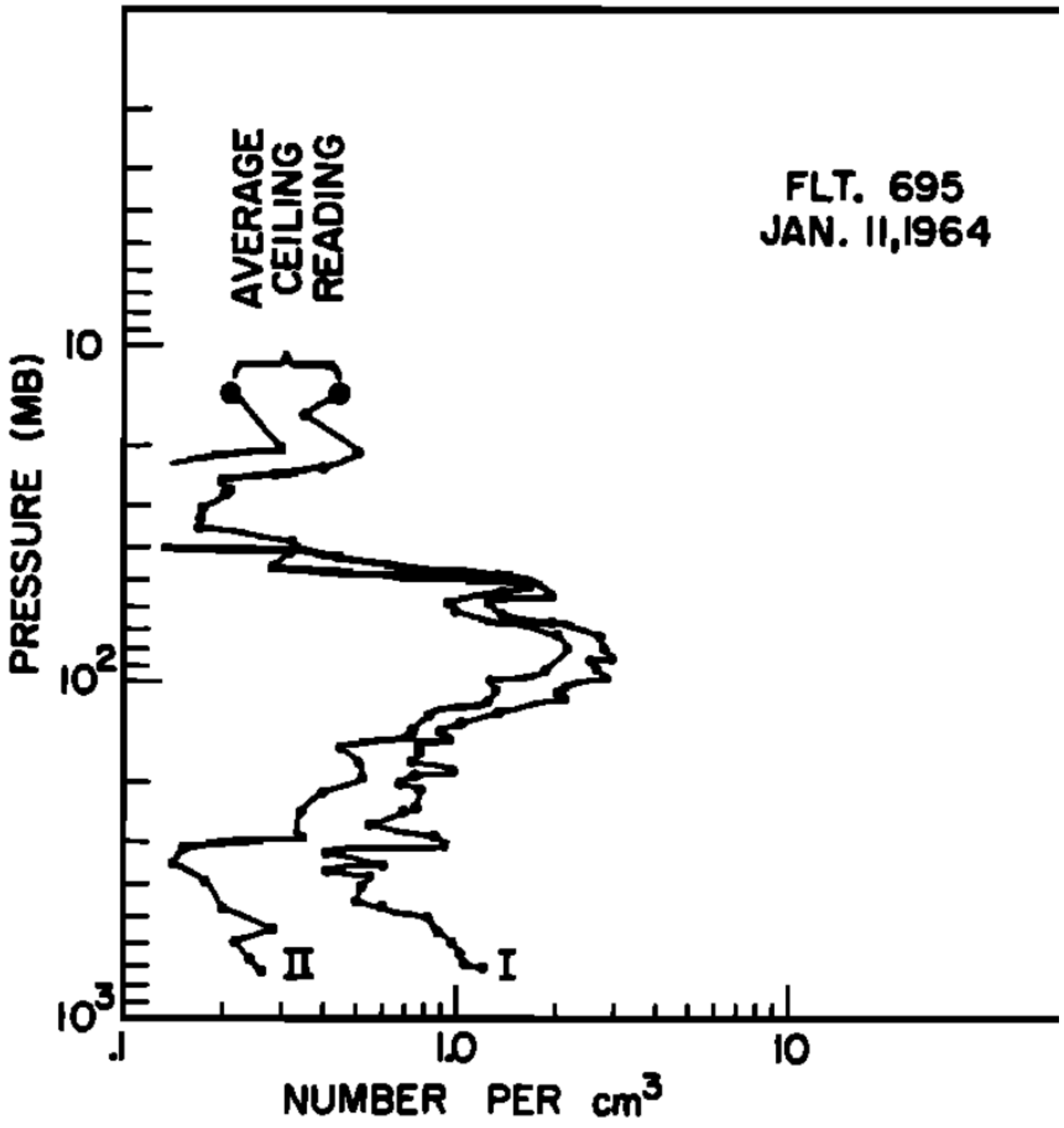
Dyer and Hicks [1968] give aerosol optical depth for nine latitude bands for the period 1961–1965. We interpolate these data to our general circulation model (GCM) grid for climate simulations; the resulting optical depth as a function of latitude and time is shown in Figure 2*a*. Dyer and Hicks note that their sampling is very poor in the southern hemisphere, especially at low latitudes. Thus the nature of the double maximum of the optical depth, with a peak in mid-1964, should not be taken too seriously, but it is clear that there were very large optical depths in the southern hemisphere from mid-1963 through 1964. Integrated over the globe the maximum annual mean optical depth after the Agung eruption is 0.08 in 1964 (Figure 1). This is consistent with the eclipse value 0.13 of *Keen* [1983] which refers to a day in December 1963 and weights the southern hemisphere more than the northern hemisphere. Also *Lockwood and Thompson* [1986], with observations at Cerro Tololo (30°S) and Lowell Observatory (35°N), found values consistent with those of Dyer and Hicks, including the four to one ratio of southern hemisphere and northern hemisphere optical depths.

For the period 1966–1978 we use the optical depths of *Keen* [1983] based on lunar eclipse data, interpolated linearly between the dates of observations. The optical depths are small during this period, the largest contribution being from Fernandina (Galapagos, 0.4°S, 1968). Because of the generally small values and the equatorial location of Fernandina, we take the aerosols as uniformly distributed in the period 1966–1978.

In addition to surface radiation measurements compilation from Dyer and Hicks (1968), also range of stratospheric aerosol measurements of the Agung perturbation to the Junge layer.

Agung	Surface radiation measurements (global dataset gathered in Dyer and Hicks; 1968)	Dyer and Hicks (1965), Pueschel et al. (1972) Moreno and Stock (1964), Flowers and Viebrock (1965)
	Balloon-borne measurements	Rosen (1964), Rosen (1966), Rosen (1968), Pittock (1966)
	Ground-based lidar, searchlight and twilight measurements	Clemesha et al. (1966), Grams & Fiocco (1967), Kent et al. (1967) Elterman et al., (1969), Volz (1964), Volz (1965), Volz (1970)
	Aircraft measurements	Mossop et al. (1963), Mossop et al. (1964), Friend et al., (1966)

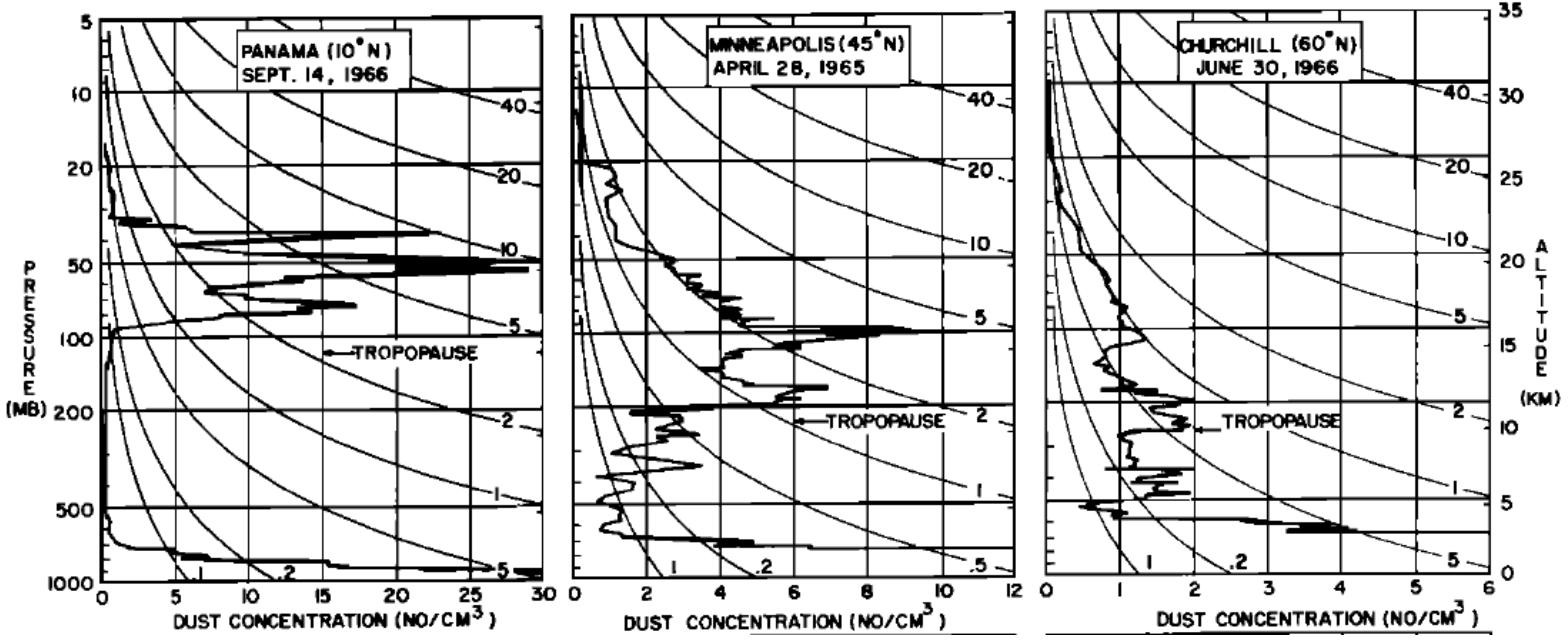




Mineapolis balloon soundings (Rosen, 1964) with photoelectric particle counters.

-- August 20th 1963 sounding measured N(Dp>600nm)

-- January 1964 sounding measured N(Dp>550nm) and N(Dp>750nm).



In 1965 and 1966 further balloon soundings (Rosen, 1968) in tropics (Panama, 10N), and at higher latitude (Churchill, Canada, 60N) with an improved SPEC photoelectric particle counter.

-- the SPEC measured N(Dp>250nm) – representative of 11 other dust-soundings at that latitude.

Email from James Rosen (Jan 2015) from SOCCESS proposal which sought funding for PDRA to combine interactive stratopsheric aerosol CCM simulations with these measurements (and others).

From: jnmrosen@comcast.net [mailto:jnmrosen@comcast.net]
Subject: Re: Mineapolis OPC data from the post-Agung eruption period

Hi Graham,
Thanks for the inquiry. The digitized data from Minneapolis is available on the NDACC web site. You should read the Meta Data file that goes with the OPC/Dustsonde stuff…..
…. The Minneapolis data is from the early days of the dustsonde and the size calibration is somewhat more uncertain compared the the Wyoming data. Thus, the optical properties of the Agung decay period as determined from the dustsonde data would be more uncertain than for the El Chichon period. Also the Agung decay period may have been disturbed by other smaller eruptions.
I might also mention that there are two dustsonde soundings from Ft. Churchill, Canada (June, 1966) and 4 soundings from Panama (Sept 1966, April 1968 available in digital form but not at the NDACC site. I would have to send them separately if you need them. As it turned out, the first Panama soundings were under the heavy influence of recent volcanic eruption.
Hope this helps with your proposal. It sounds like a good idea to me to revisit these eruptions taking advantage of the many years new knowledge developed in the scientific community. In the beginning I had no idea of what was a volcanic signal in the stratosphere and what was normal and that greatly affected the early conclusions.
Good Luck,
Jim

14 from Minneapolis (Aug63, Nov63, Jan64, May64, Aug64, Oct64, Apr65, Jul65, Oct65, Dec65, Jun66, Jul67, Aug67, Jan68)
4 from Panama (12th and 14th Sep 1966, 8th and 9th Apr 1968), 2 from Churchill (27th and 30th Jun 1966)

Compilation of example lidar measurements in Rosen (1969)

All during post-Agung period.

Exctinction profiles from tropics and NH mid-latitude and high-latitude.

Combining these profiles observations from the Rosen dust soundings and the early lidar measurements together with interactive stratospheric aerosol simulations.

We will be producing new "microphysically-consistent volcanic forcing dataset" for Agung from UM-UKCA that agree with these 1960s stratospheric aerosol observations.

A recent modification of the searchlight method has been made by using a pulsed laser and operating in a manner similar to radar systems (FIOCCO and GRAMS, 1964; GRAMS and FIOCCO, 1967; COLLIS and LIGDA, 1966; CLEMESKA *et al.*, 1966; BAIN and SANDFORD, 1966; LAWRENCE *et al.*, 1968). All of the laser soundings have been

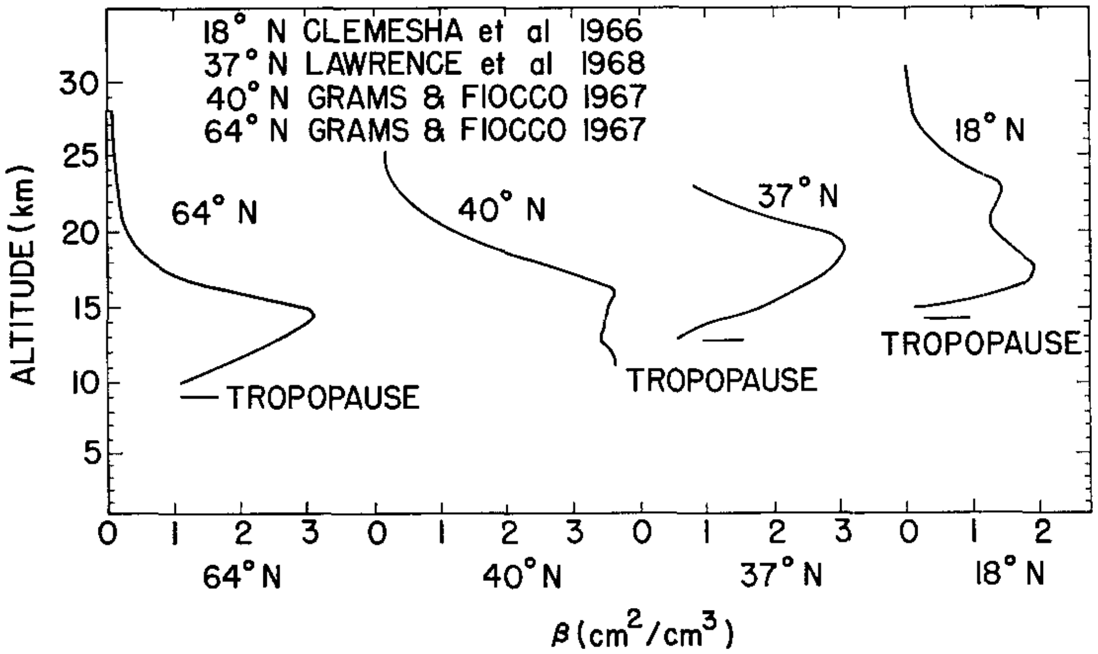


Fig. 3. The vertical distribution of the non-Rayleigh extinction coefficient at several latitudes as determined by laser probing techniques. The absolute values of the back scattering cross-sections depend rather heavily on the real and imaginary components of the index of refraction.

made after the Bali eruption and are available for a wide variety of latitudes. A comparison of the results are shown in Figure 3, which illustrates a large degree of consistency between the various observers.

Aircraft measurements of particle concentrations down to 100nm at 20km through the 1st year after 17th March 1963 Agung eruption.

Table 1. SIZE AND CONCENTRATION OF VOLCANIC PARTICLES AT 20 KM

Date	Elapsed time since eruption (days)	Latitude limits of collection (degrees south latitude)	Concentration (particles per l.)	Sampled volume (l.)	Particle dimensions (μ)		
					Maximum	Minimum	Median
11.4.63	25	15–35	8	17	3·6	0·4	1·1
14.5.63	58	19–32	41	7	3·4	0·2	0·9
28.5.63	72	18–25	160	2·6	2·5	0·2	0·85
11.6.63	86	21–28	145	2·6	2·3	0·1	0·6
9.7.63	114	15–21	150	2·6	4·8	0·1	0·55
6.8.63	142	15–21	140	1·3	2·6	0·1	0·55
12.12.63	270	15–19	107	1·3	1·1	0·1	0·3
2.4.64	382	15–18	32	2·0	0·9	0·1	0·3
23.4.63	37	42–39	0·7	83	6	0·6	2·0
7.5.63	51	44–41	30	7	8	0·2	1·0
21.5.63	65	44–40	7	13	2·5	0·2	1·0
4.6.63	79	45–41	59	2·6	2·8	0·2	0·75
18.6.63	93	45–40	84	2·6	2·4	0·2	0·65
3.7.63	108	40–44	89	2·1	1·7	0·1	0·55
30.7.63	135	41–44	102	2·6	2·0	0·1	0·45
3.12.63	261	43–44	38	1·3	0·8	0·1	0·25
7.4.64	387	41–45	35	2·0	1·0	0·1	0·2

Mossop (1964, Nature)

Summary

Extending 1990s Pinatubo analysis from Dhomse et al. (2014) and Mann et al. (2015) to assess how the stratospheric aerosol layer was pertubed by other major eruptions.

Approach is to combine different observational datasets with the interactive stratospheric aerosol microphysics model and explore how different SO2 emissions amounts and injection heights translate into volcanically-enhanced Junge layer.

For 1960s post-Agung period have gathered dust-sonde (balloon-borne OPC) measurements from NH mid-latitude (Minneapolis), tropical (Panama) and from the Arctic (Churchill, Alaska) and will combine also with lidar measurements made at several locations spanning the Northern Hemisphere.

One experiment within SSiRC intercomparison of Interactive Stratospheric Aerosol models (ISA-MIP) will involve other models running these experiments to assess how the emitted SO2 translates into enhanced stratospheric aerosol and volcanic forcing.

Volume size distributions measured by the FCAS instrument observe particles down to dry-diameters ~60-70nm (~30nm dry-radius).
(NMASS measures down to 4 to 60nm diameter)

Airmasses with the lowest N2O vmr (50-100 ppbv) (i.e. descended from the upper Junge layer) have smaller particle size than in the lower Junge layer, (in quiescent and volcanically perturbed conditions).

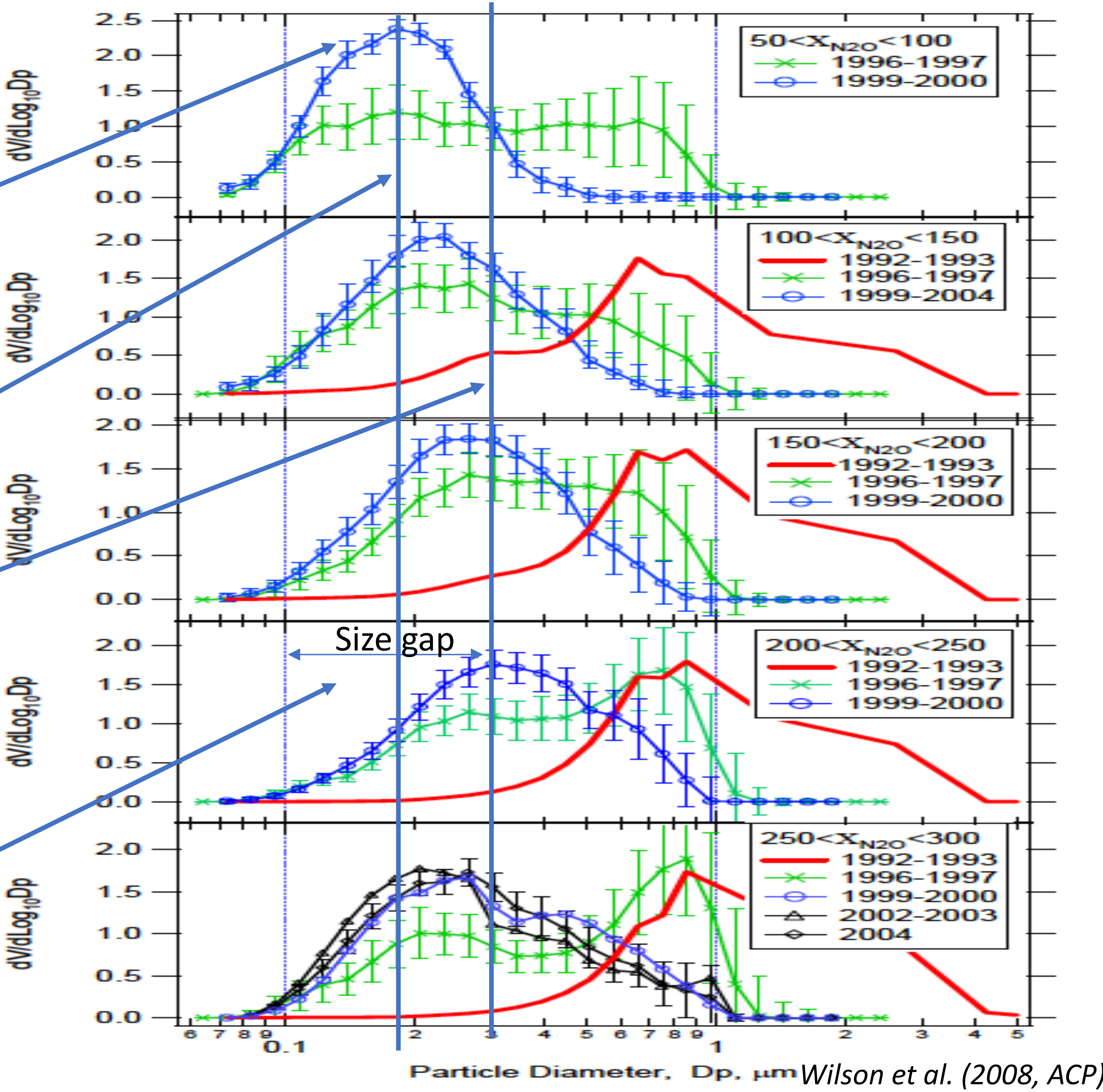
In quiescent, volume-median diameter ~180nm (i.e. most particles radius <100nm).

The sulphuric particles in these air masses are almost all invisible to the balloon-borne OPC, whose channel with the smallest "size-cut" is at Dp=0.3um.

Even in 1996/7, 5 years after Pinatubo, the FCAS observations show that about half the sulphuric particle volume is at sizes not measured by the OPC.

The CPC measurements do observe these particles but what size-dis in this 5nm<R<150nm "size gap"?

Q: Analysis of NMASS & FCAS number size distbns?



Wilson et al. (2008, ACP)

<u>Number size distributions</u> in the Arctic lower stratosphere measured by the NMASS and FCAS instruments on the ER2 during SOLVE campaign.

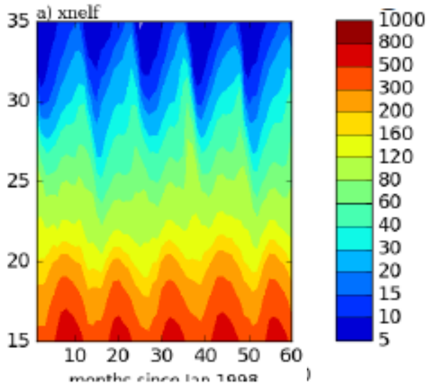
Upon entry into the upper Junge layer, modelling suggests the particles are Dp~30nm (e.g. Bardeen et al., 2008).

Tracking the transport and growth of the meteoric-sulphuric particles in an extra mode within the GLOMAP aerosol module (within UM-UKCA) tracks how particles then grow larger with greater depth into the mid- & lower layer.

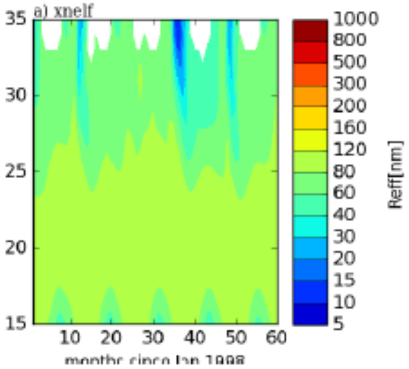
Since the observations and modelling suggest meteoric material is present within the vast majority of particles, it could well be that there is a size mode present throughout the upper Junge layer indicating the transport & growth of meteoric-sulphuric particles.

SOLVE ER2 obs show homogenous NPF in March but also maxima at 60-100nm.

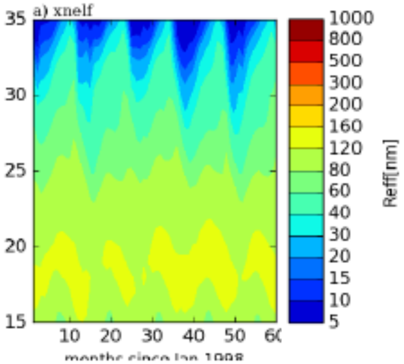
meteoric-sulphuric reff (nm)



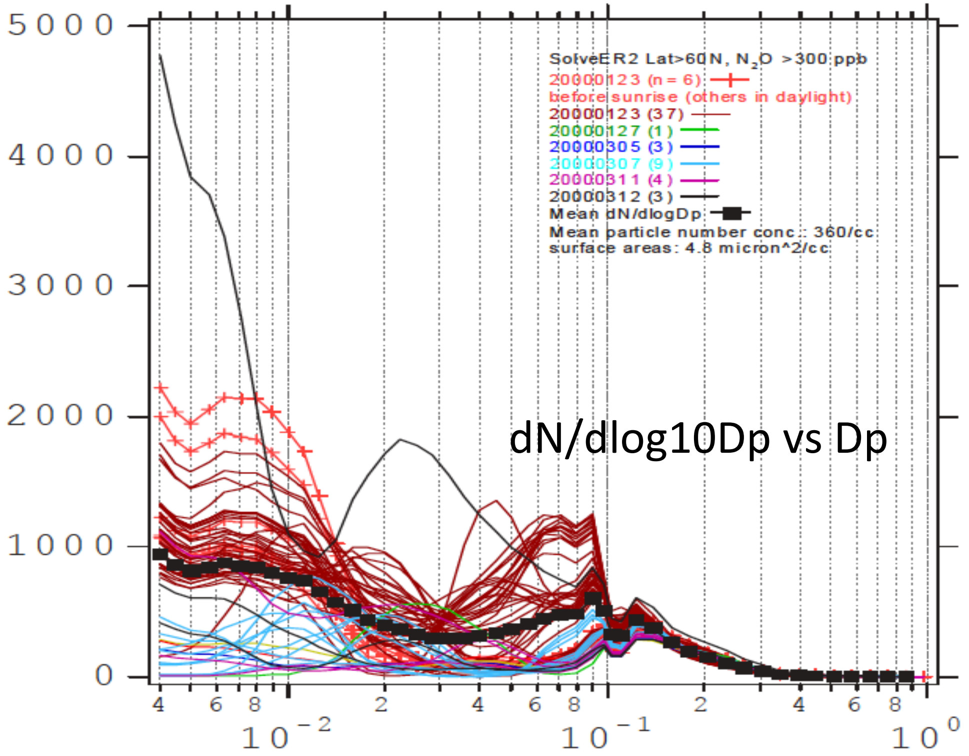
pure-sulphuric reff (nm)



overall-sulphuric reff (nm)



Northern Hemisphere mid-latitudes (30-60N)



"Mixing ratios of particles having diameters less than 180nm were clearly enhanced in descending air (Air with the lowest N2O mixing ratio is assumed to have descended from the highest altitude.)

The measurements show that by the time the air reached ER-2 altitudes (~20 km and below), most particles were in the 30 to 180 nm diameter range."

From chapter SPARC ASAP report (2006)