School of Earth and Environment
INSTITUTE FOR CLIMATE AND ATMOSPHERIC SCIENCE
UNIVERSITY OF LEEDS

Long-lived ultra-fine ash particles within the Mt Pinatubo volcanic aerosol cloud and their potential impact on its global dispersion and radiative forcing

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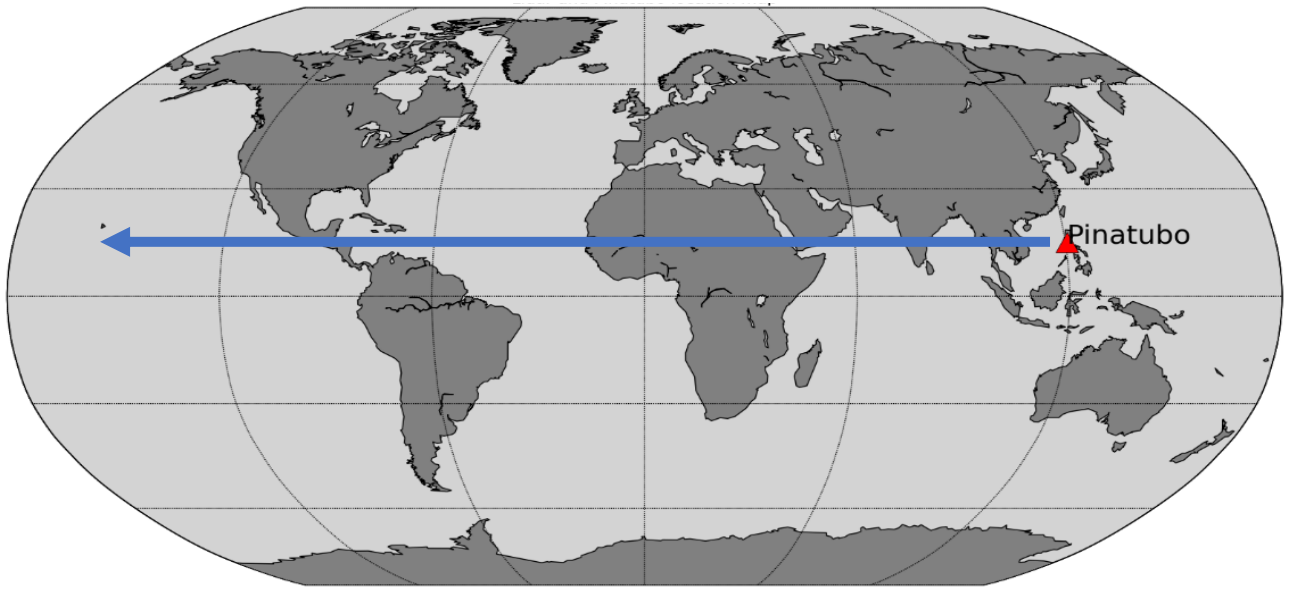
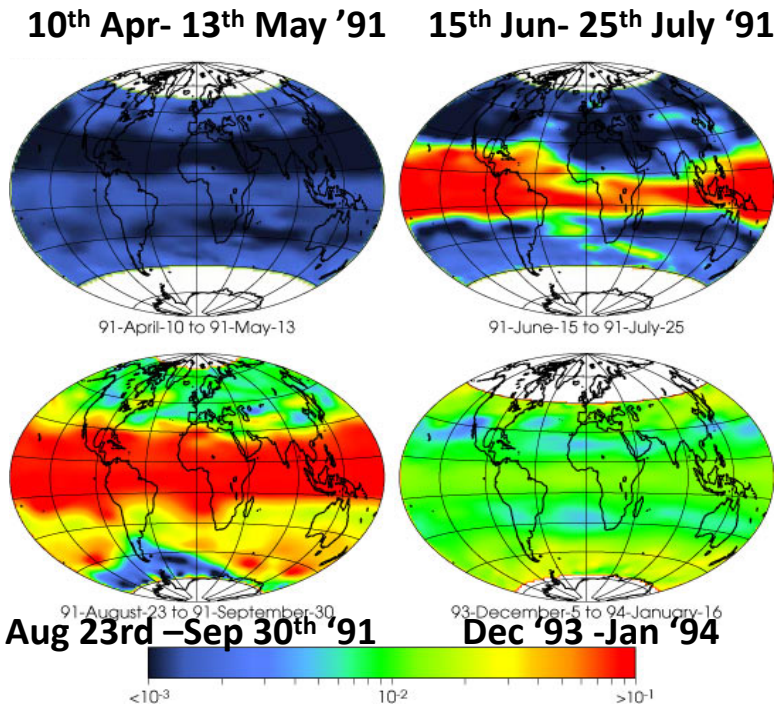
Very large magnitude tropical eruption of Mt Pinatubo

- VEI 6 eruption on 15th June 1991 in Philippines
- 14-23 Tg SO_2, ~50 Tg ash emitted at ~21-23km -- well above tropopause
- Largest eruption of 20th C, & observed by several satellite instruments, ground-based lidar at Mauna Loa (19N) & range of mid-latitude sites balloon-borne particle counter soundings at Laramie, USA & Lauder, NZ.



Credit: USGS



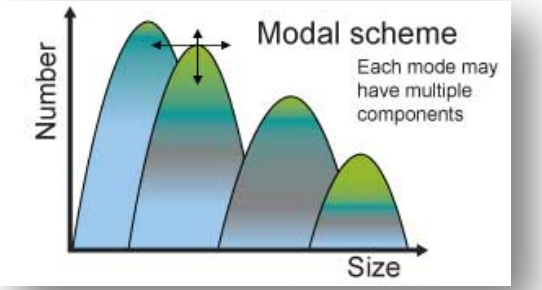
Credit: NASA Earth Observatory

https://earthobservatory.nasa.gov/images/1510/global-effects-of-mount-pinatubo

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

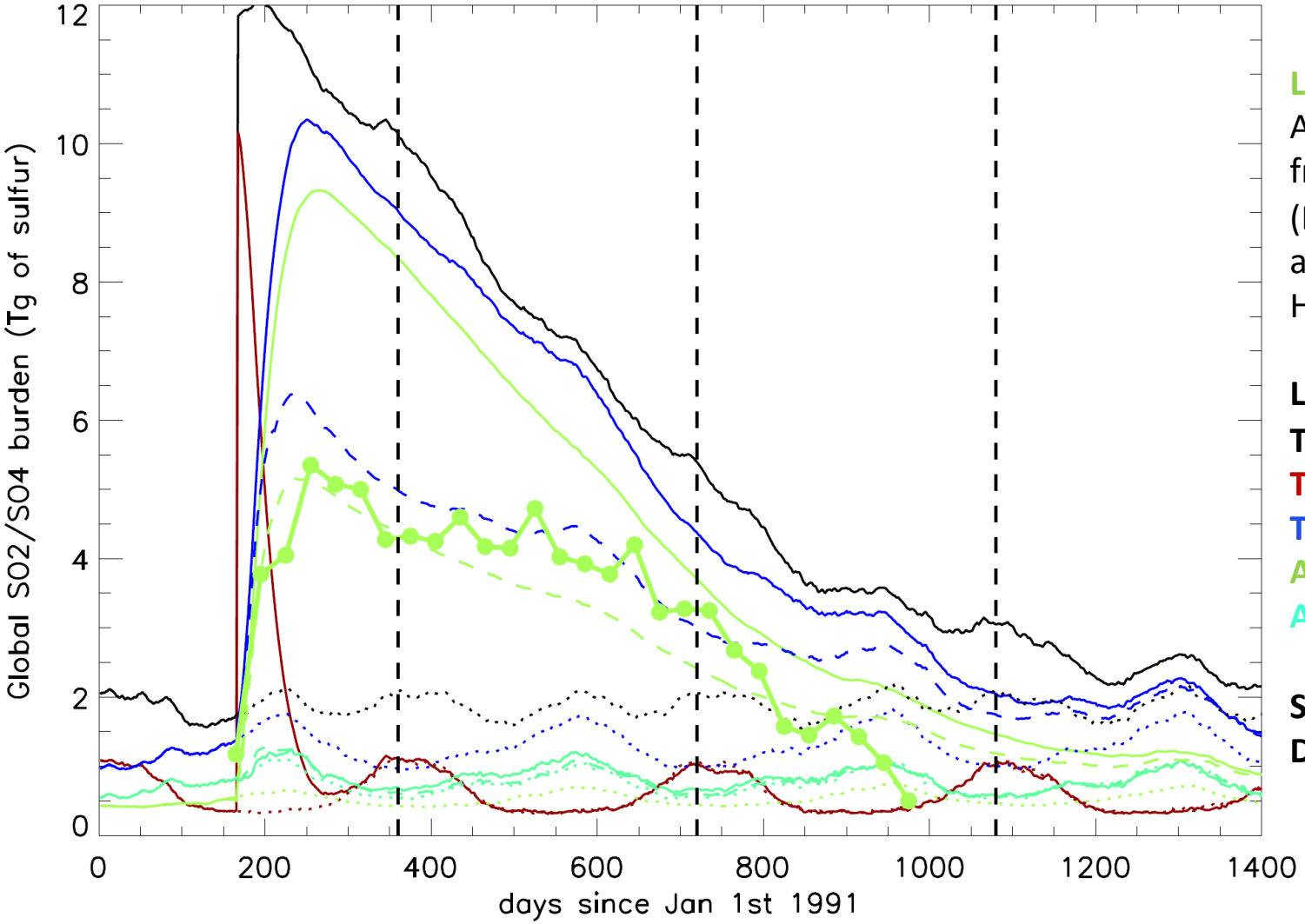
- Multi-component aerosol microphysics scheme (GLOMAP)

www.ukca.ac.uk

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

- UKESM includes UKCA chemistry-aerosol sub-model so that it simulates strat-trop ozone and strat-trop aerosol interactively, each radiatively coupled for composition-dynamics interactions.

Global column sulphur-loadings of SO_2 & aerosol



Large Green Dots: 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

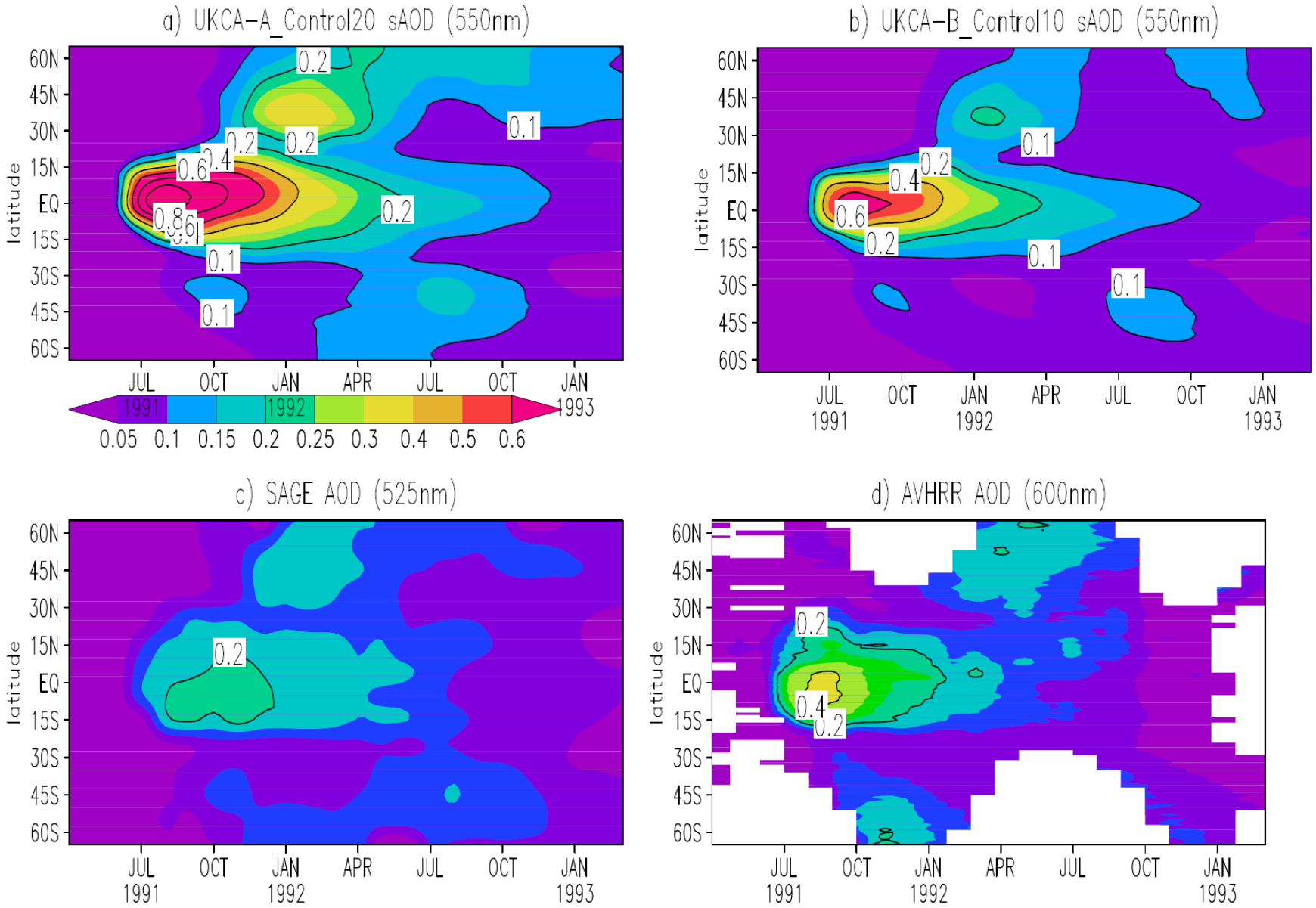
Solid = 20Tg Pin
Dashed = 10Tg Pin

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

Simulated aerosol uncoupled from dynamics in this paper (double-call)

HadGEM-UKCA N48L60 CheS+GLOMAP. Dhomse et al. (ACP, 2014)

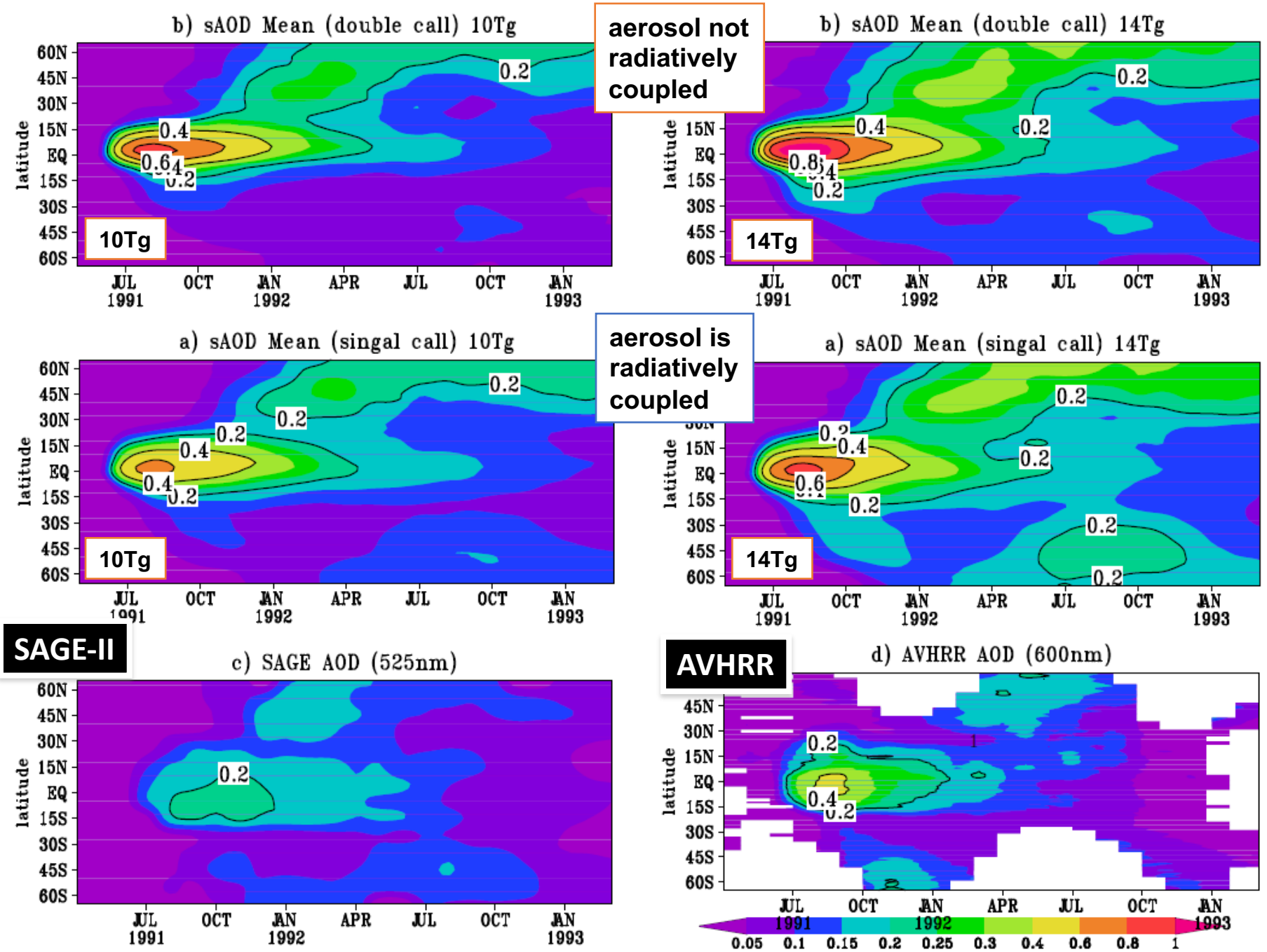
Stratospheric aerosol optical properties



v7.3 UM-UKCA N48L60 CheS+GLOMAP.

Dhomse et al. (ACP, 2014)

Radiative heating effect on sAOD evolution vs SAGE-II sAOD & AVHRR anomaly

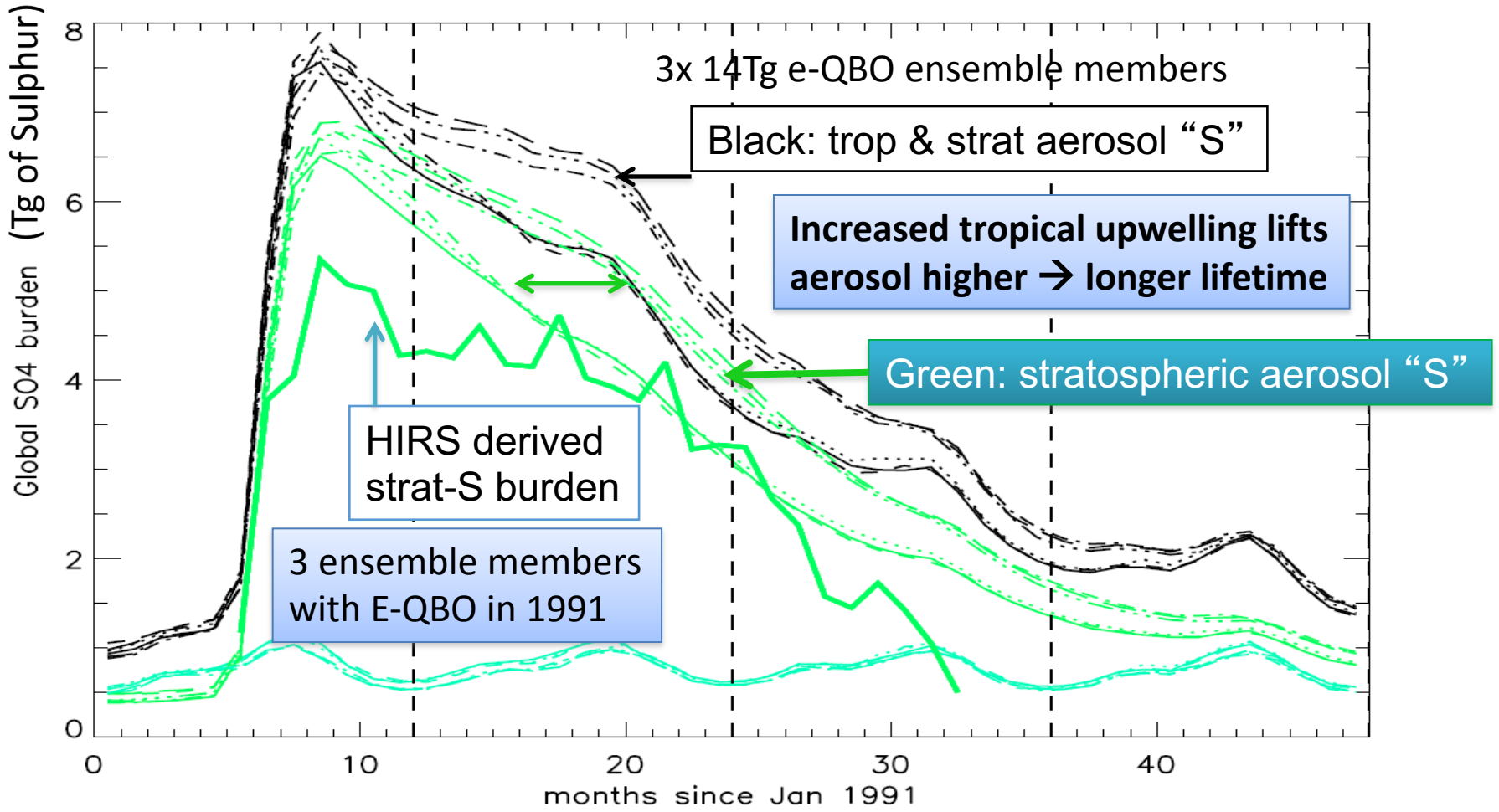


v7.3 N48L60 CheS+GLOMAP with radiative coupling

(runs in Dhomse14 had no strat-heating)

v7.3 CheS+GLOMAP N48L60

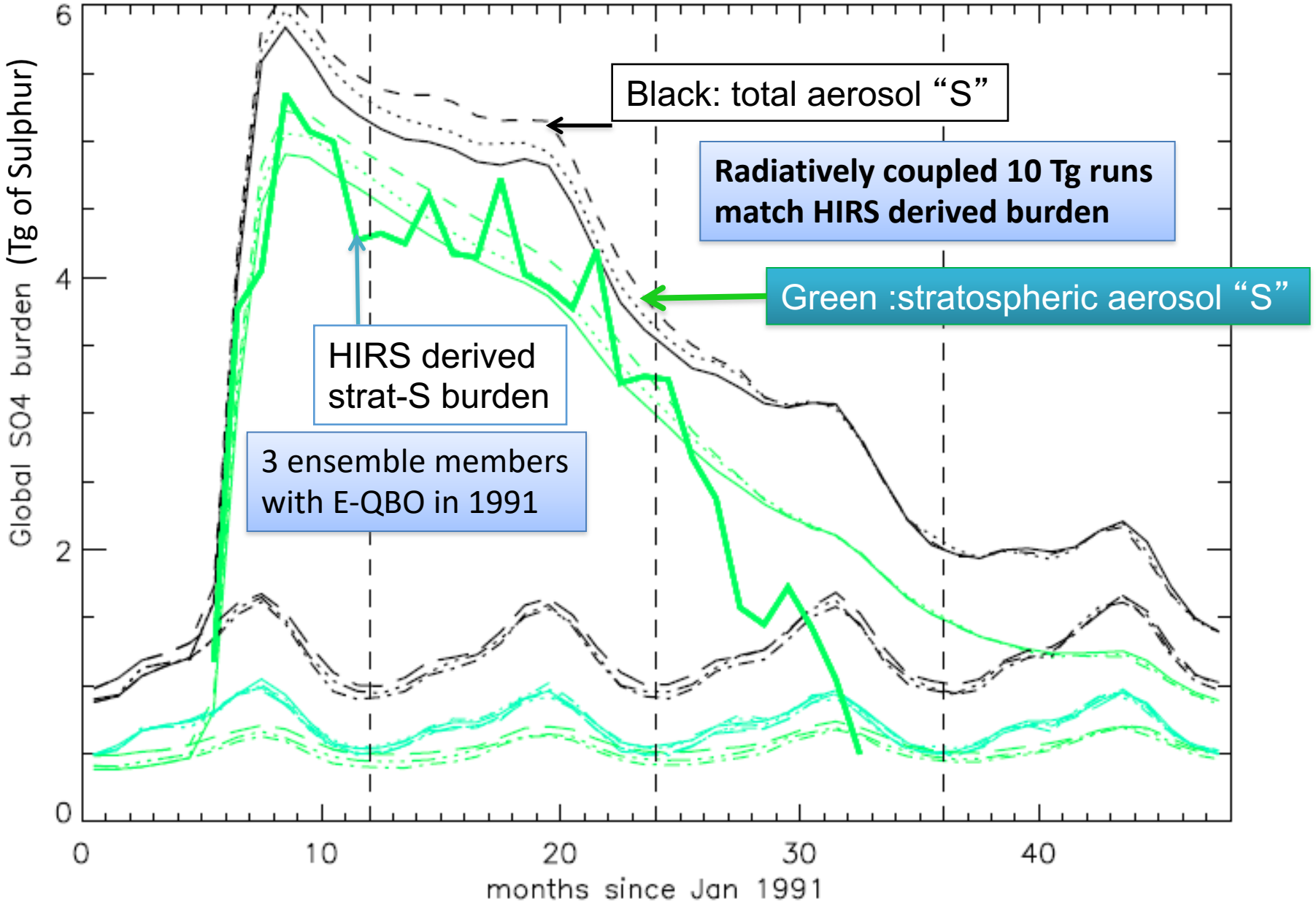
Stratospheric aerosol sulphur burden in UM-UKCA (thin green) vs HIRS (thick green)

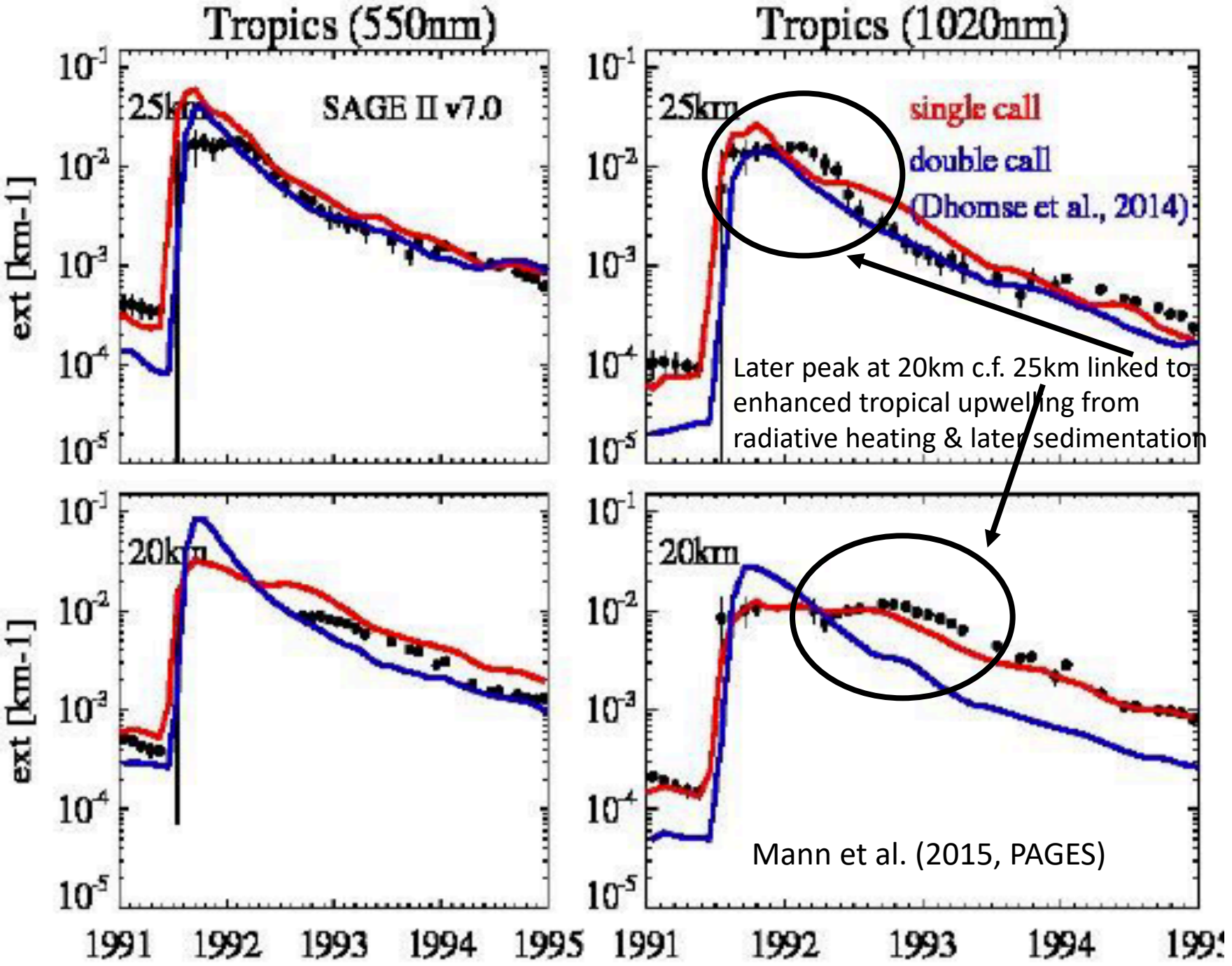


Impact of radiative coupling on lifetime in stratosphere

v7.3 CheS+GLOMAP N48L60

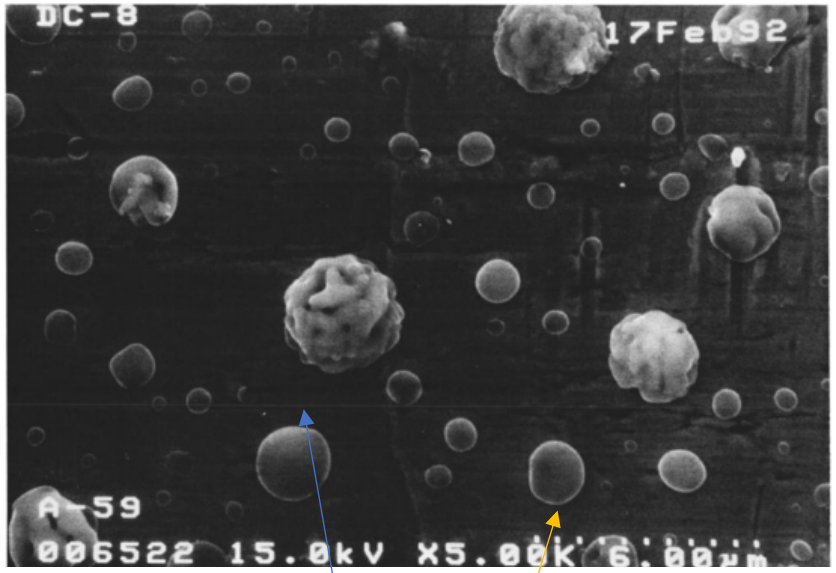
Stratospheric aerosol sulphur burden in UM-UKCA (thin green) vs HIRS (thick green)



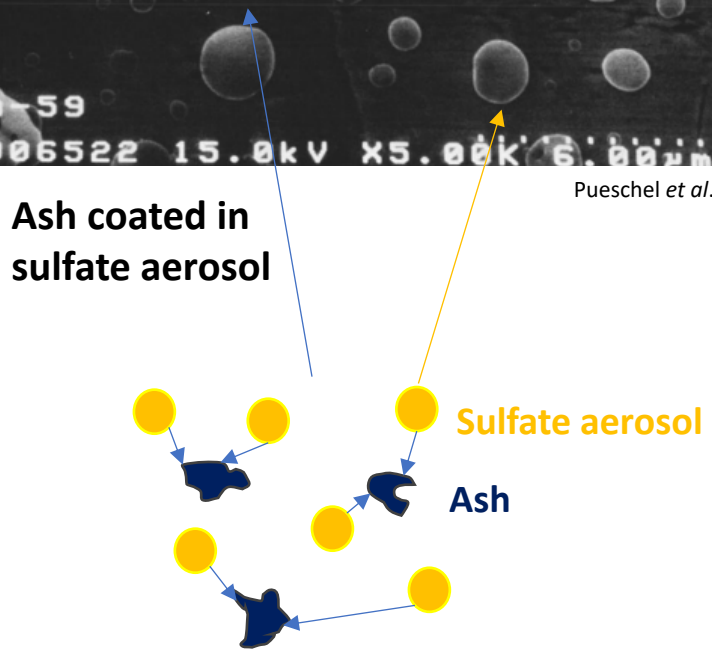

Tropics (550nm)
Tropics (1020nm)
25km
20km
SAGE II v7.0
single call
double call
(Dhomse et al., 2014)
ext [km-1]
Later peak at 20km c.f. 25km linked to enhanced tropical upwelling from radiative heating & later sedimentation
Mann et al. (2015, PAGES)
1991
1992
1993
1994
1995

Here explore influence from co-emitted ash

- Volcanic ash mostly omitted in global composition-climate model studies with particles assumed to sediment from plume in ~ 1 week.
- However, ash absorption of incoming solar (& outgoing LW) shown to affect the progression of the volcanic aerosol clouds from 1991 Pinatubo (Niemeier et al., 2009), 2014 Kelut (Zhu et al., 2020) and from 2019 Raikoke (Muser et al., 2020).
- Also, impactors on ER-2 & DC-8 aircraft surveys of Pinatubo aerosol cloud during AASE II campaign (Jan 1992 – Mar 1992) collected particles from the Pinatubo plume clearly showing the lower portion of the plume contained ash particles ~0.6-2 µm diameter, even through to February 1992.



Pueschel *et al.*, 1994



Mixed “ash-sulphuric particles” remained present in lowest ~10% of Pinatubo aerosol cloud (~10km) even 8 months after the eruption

Measurements from impactors on **ER-2** (~20km) and **DC8** (~10km), see Pueschel et al., JGR, 1994)

of individual droplets by SEM, as shown in Figure 1. Thirty five of the ER-2 samples and 21 from the DC-8 that were amenable to the size discrimination analysis (examples of which are shown in Figures 1 and 2) are summarized in Tables 1a and 1b, respectively. This represents a sufficiently large sample population to demonstrate the effects of the 1991 Pinatubo volcanic eruption on the physical and elemental characteristics of the stratospheric aerosol.

It follows from Table 1 that on a few occasions at ER-2 altitudes and quite regularly at the lower DC-8 altitudes, a third large-particle mode with geometric mean radius around 0.8 μm existed. SEM imagery identified the shape of these large particles as slightly nonspherical (Figure 3), in contrast to the particles comprising modes 1 and 2 (Figure 1). X ray energy-dispersive analysis (Figure 4b) determined an elemental composition of these particles that is typical of mineral ash. This is different from the X ray energy spectra of the ER-2 samples (Figure 4a), the morphology of which is shown in Figure 1. In these samples the only peak aside from

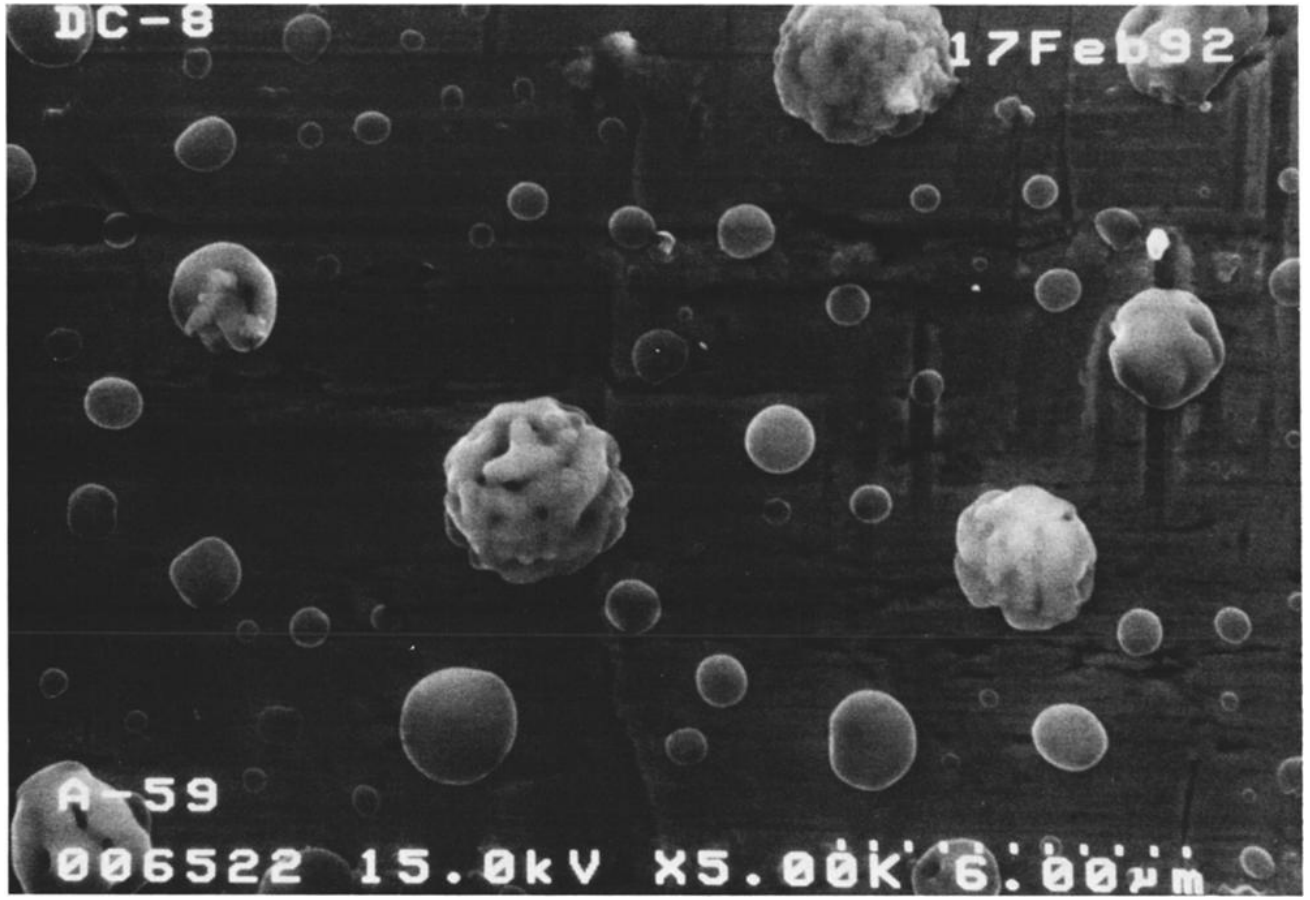


Figure 3. Plane view of stratospheric H_2SO_4/H_2O droplets and sulfuric-acid-coated volcanic ash particles collected on February 17, 1992, near (53°N; 67°W) at 10.7 km msl.

8 months after the Pinatubo eruption (Feb 92) At 53°N, 67°W, 10.7km

Table 1b. Lognormal Characteristics of Particle Size Distributions From DC-8 Samples Collected Between 9.5-and 12.6-km

3rd "ash-sulphuric mode" ~0.6-2μm mean diam

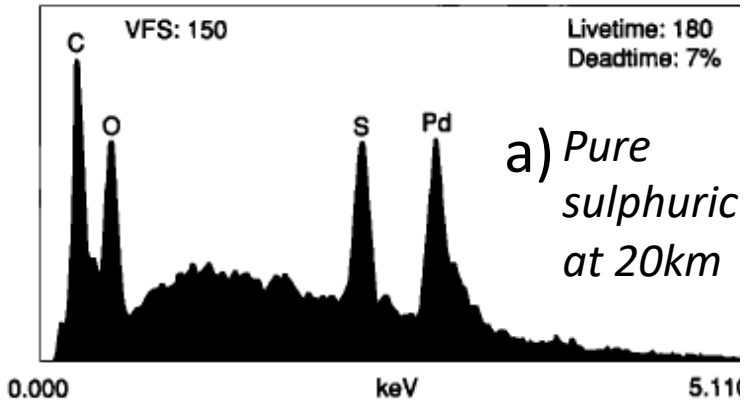
6-8 months after the Pinatubo eruption

At latitudes 42-87N

Sample	Date	Lat	Long	Alt, km	Mode 1 N_{01}, cm^{-3}	Mode 1 r_{g1}, μm	Mode 1 σ_{g1}	Mode 2 N_{02}, cm^{-3}	Mode 2 r_{g2}, μm	Mode 2 σ_{g2}	Mode 3 N_{03}, cm^{-3}	Mode 3 r_{g3}, μm	Mode 3 σ_{g3}
1	Jan. 14, 1992	N65.0	W108.0	11.3				0.8	0.29	1.6			
2	Jan. 14, 192	N67.0	W128.5	12.6				3.0	0.17	1.4	0.3	0.77	1.1
3	Jan. 14, 1992	N67.0	W139.0	12.6	1.7	0.12	1.6	1.3	0.41	1.4			
4	Jan. 16, 1992	N87.0	W93.0	11.3	7.5	0.14	1.9						
5	Jan. 16, 1992	N82.0	W53.0	11.3	9.0	0.13	2.0						
6	Jan. 16, 1992	N66.0	W17.5	12.0	9.1	0.14	1.8				0.3	0.81	1.1
7	Jan. 19, 1992	N66.0	W51.0	11.3	4.1	0.14	1.9				0.1	1.03	1.2
8	Jan. 19, 1992	N65.0	W67.0	11.3	5.0	0.10	2.1						
9	Jan. 19, 1992	N59.0	W68.0	11.3	4.7	0.12	2.0				0.3	0.80	1.2
10	Jan. 22, 1992	N63.0	W100.0	11.3	7.8	0.19	1.6				0.5	0.83	2.2
11	Jan. 22, 1992	N63.0	W100.0	11.3	2.5	0.04	1.6	1.5	0.20	1.4			
12	Jan. 23, 1992	N68.0	W87.0	11.3	12.5	0.07	1.4	8.0	0.16	1.7	0.4	0.86	1.1
13	Feb. 12, 1992	N52.0	W122.0	10.7	7.7	0.07	1.3	5.5	0.13	1.3	4.8	0.28	1.6
14	Feb. 12, 1992	N71.0	W115.0	10.7	8.5	0.10	1.8	3.7	0.31	1.3	0.6	0.62	1.3
15	Feb. 12, 1992	N73.0	W127.0	12.0	2.2	0.07	1.3	4.8	0.23	1.8			
16	Feb. 17, 1992	N69.5	W13.0	10.7	6.8	0.05	1.3	3.4	0.14	1.8	0.4	0.86	1.1
17	Feb. 17, 1992	N76.0	W53.0	11.3	4.8	0.06	1.2	9.8	0.17	1.7	0.4	0.77	1.2
18	Feb. 17, 1992	N51.5	W67.0	11.3	7.7	0.06	1.2	8.3	0.20	1.7	0.7	0.78	1.1
19	Feb. 20, 1992	N42.0	W72.0	9.5	10.1	0.13	1.2				0.6	0.84	1.1
20	March 14, 1992	N87.5	W8.0	10.1	24.9	0.08	1.5	3.2	0.28	1.4	0.6	0.71	1.2
21	March 20, 1992	N44.0	W106.0	11.6	16.9	0.05	1.2	5.3	0.13	1.5	3.2	0.41	1.6

X-ray aerosol composition analysis

Measurements from impactors on ER-2 and DC8
(Pueschel et al., JGR, 1994)



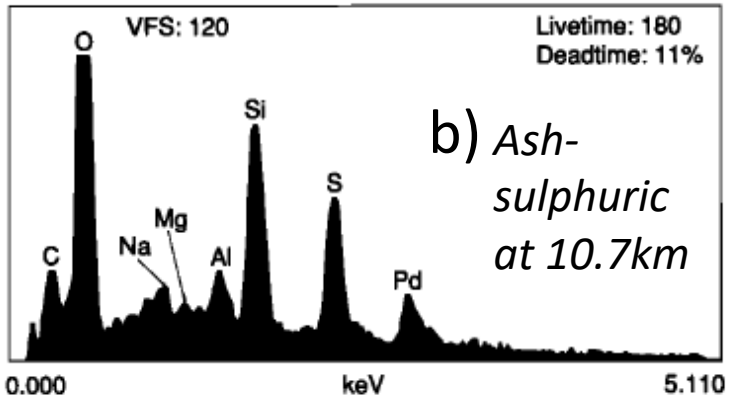


Figure 4. X ray energy spectra of samples collected on Feb. 17, 1992, at (a) 20- and (b) 10.7-km pressure altitudes.

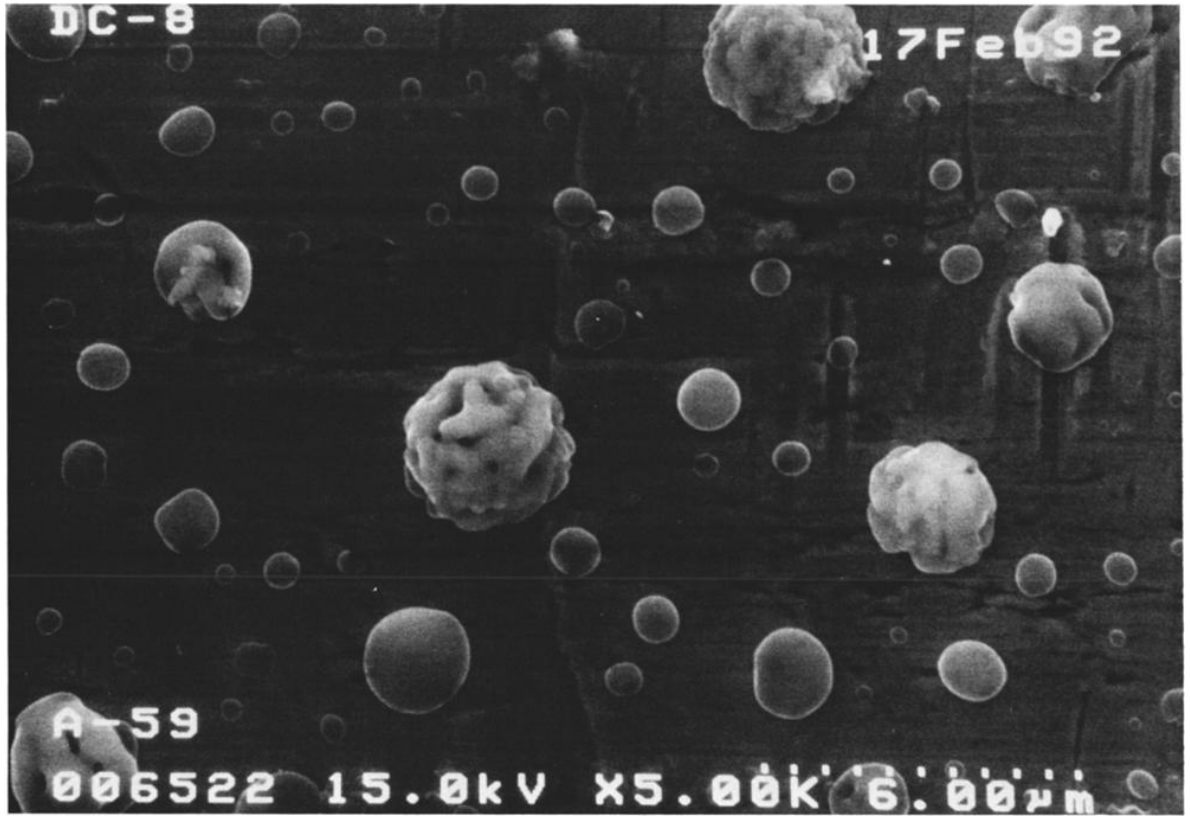


Figure 3. Plane view of stratospheric H_2SO_4/H_2O droplets and sulfuric-acid-coated volcanic ash particles collected on February 17, 1992, near (53°N; 67°W) at 10.7 km msl.

contrast, a nonspherical particle of a DC-8 sample (Figure 3) shows additional peaks (Figure 4b) corresponding to the K_α lines of Na at 1.05 keV, of Al at 1.48 keV and of Si at 1.74 keV. Since these elements are typical of minerals, including volcanic ash, we conclude that the large nonspherical particles that were collected aboard the DC-8 are those of ash coated with sulfuric acid. Their predominant location near the bottom of the stratospheric aerosol layer alludes to a higher settling velocity due to both a larger size and greater density of these particles than of the H_2SO_4/H_2O droplets. This finding explains the occasional depolarization of lidar backscattering near the bottom of the Pinatubo layer [*Browell et al.*, 1993].

8 months after Pinatubo eruption (Feb 92) At 53°N, 67°W, 10.7km

Q: How widespread are these ash-sulphuric particles?

Southern Hemisphere Lidar Measurements of the Aerosol Clouds from Mt Pinatubo and Mt Hudson

Stuart A. Young, Peter J. Manson and Graeme R. Patterson,
CSIRO, Division of Atmospheric Research,
Private Bag No 1, Mordialloc, Vic, Australia, 3195.

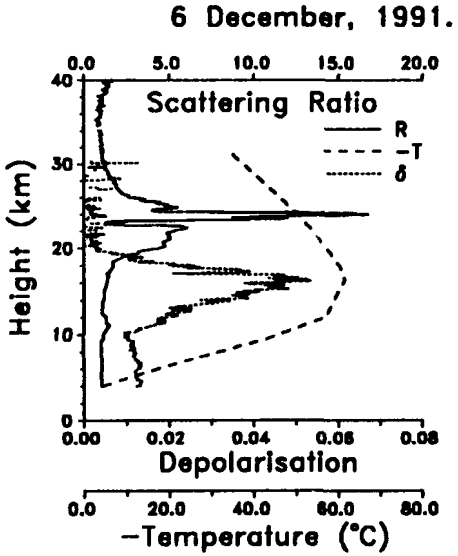


Fig 6

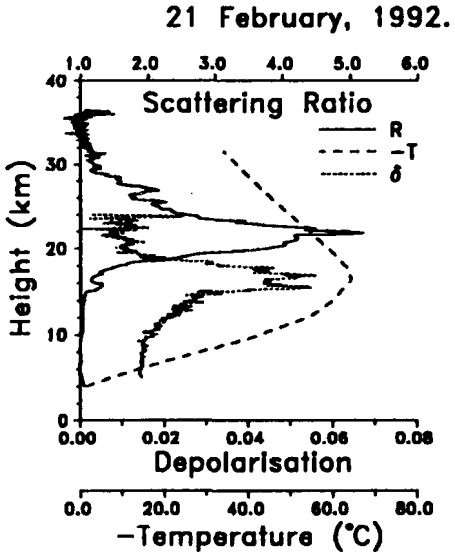


Fig 7

Depolarisation Measurements.

Profiles of scattering ratio, depolarisation ratio (total cross polarised power / total parallel polarised power) and mean monthly temperature for 6th December 1991 and 21st February 1992 are plotted in Figures 6 and 7 respectively. The depolarisation data have been scaled to a value of 0.014 for the clear air below the tropopause (approx. 10 km). Most noticeable is the very low depolarisation in the region of the main Pinatubo layer (19 - 25 km) and the relatively highly depolarising layer around 16 km. The fact that the layer is still present at the same height on both dates and is not falling suggests that it is not the primarily the result of fallout of irregular dust particles. Other possible explanations for the enhanced depolarisation are the agglomeration of partially frozen droplets or a complete phase change (E. Browell, personal communication). Support for this latter suggestion comes from the temperature profiles which show a minimum at the height of peak depolarisation.

δ < 0.002 in 20-24km (main layer) 6th Dec '91

δ > 0.01 @10-19km (base of the layer) 6th Dec '91

Young et al. (1994, ILRC92 extended abstracts)

Young, S. A. et al. (Extended Abstracts of the 1992 International Laser Radar Conference, 1994)

Lidar measurements of Mt. Pinatubo aerosols at Aberystwyth from August 1991 through March 1992

G. Vaughan, D.P. Wareing, S. B. Jones, L. Thomas, N. Larsen[1]

Physics Department, University of Wales, Aberystwyth, United Kingdom

Lowest few km of Pinatubo cloud clearly depolarizing Aug91 to Feb92 In NH mid-latitude stratosphere.

Can see the steady progression with the depolarizing region slowly descending, consistent with slow sub-μm ash removal

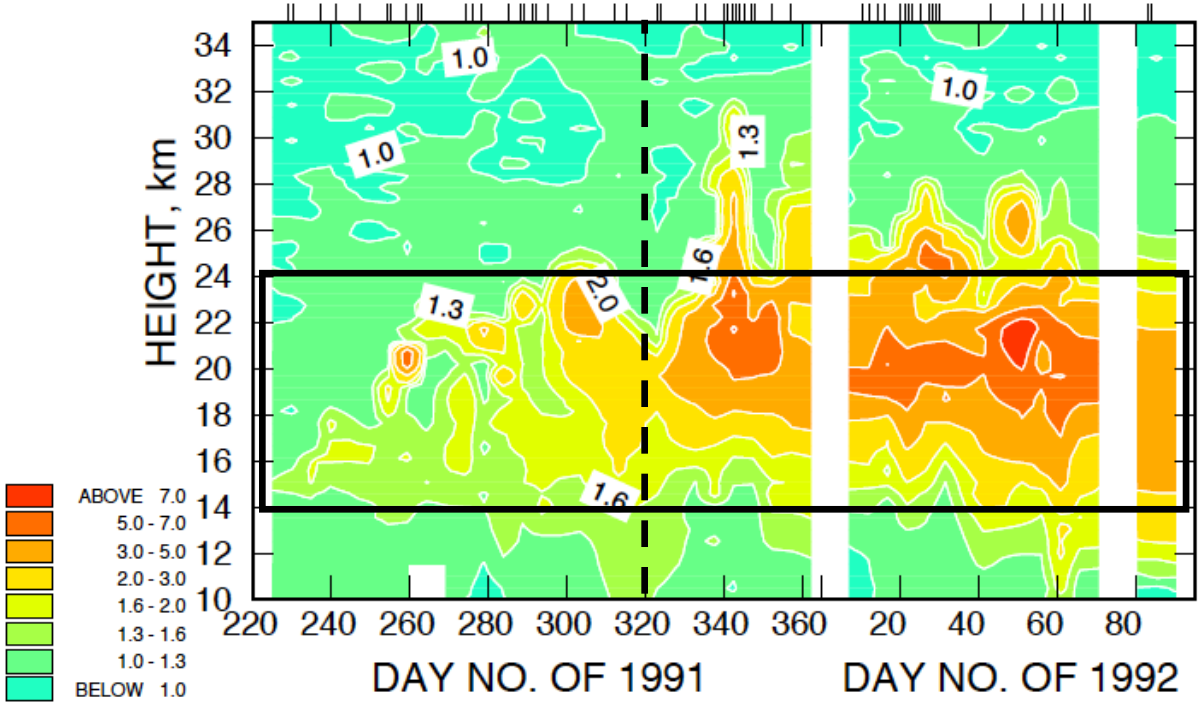


Fig.3: Contour plot of backscatter ratio (in the parallel channel). Vertical bars along the top denote nights when observations were made. Data were averaged over 450 m to produce this plot, thus the maximum values shown differ from those in fig.1. The darkest shading corresponds to R > 7 and the next darkest to R > 5.

Vaughan et al. (1994, GRL)

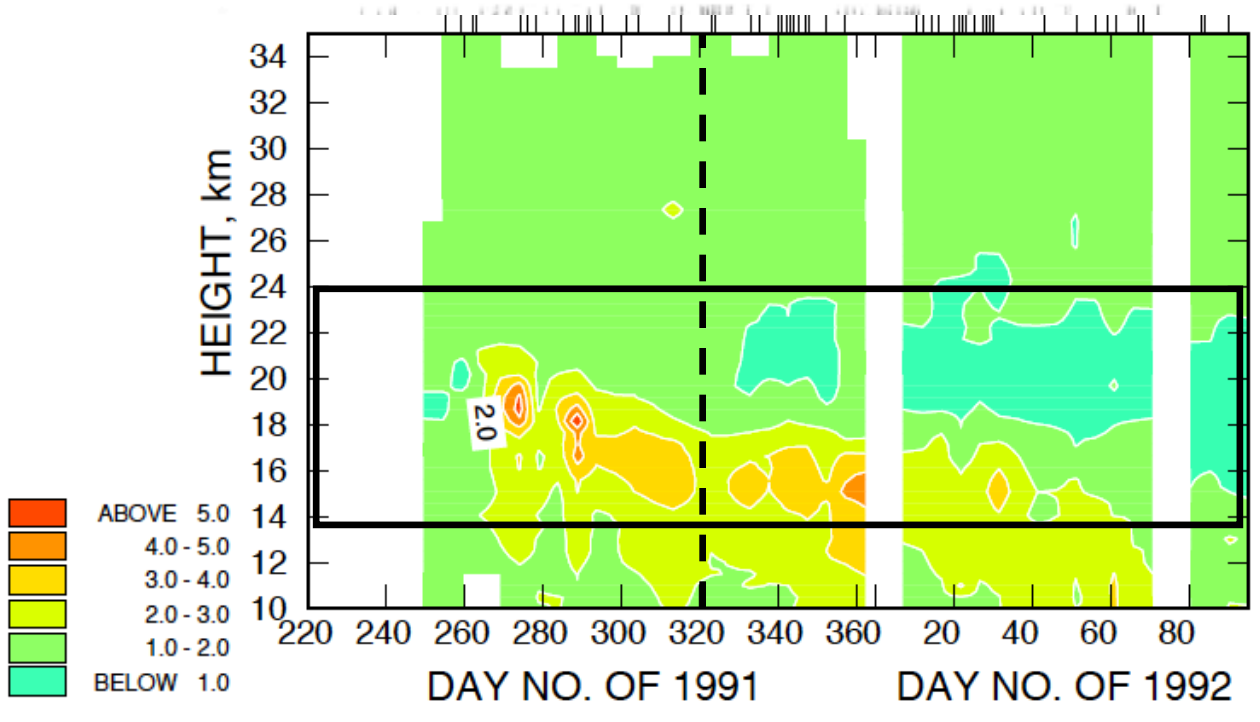


Fig.5: As fig.3 for depolarisation ratio. Contour interval is 1%.

The presence of the depolarizing ash-sulphuric particles clearly evident in lidar measurements from Aberystwyth.

-- peak depolarization between 18-20km in Aug 1991

-- descends steadily to 15-17km Sep-Dec and ~12km Jan-Feb 1992

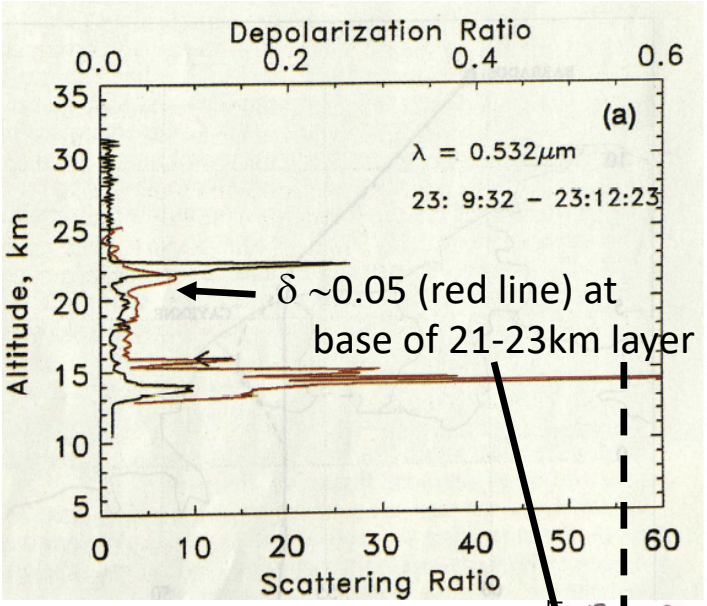


Photo of color GRL Figure from Dave Winker (NASA)
[only b&w Fig in online pdf]

PRELIMINARY ANALYSIS OF OBSERVATIONS OF THE PINATUBO VOLCANIC PLUME WITH A POLARIZATION-SENSITIVE LIDAR

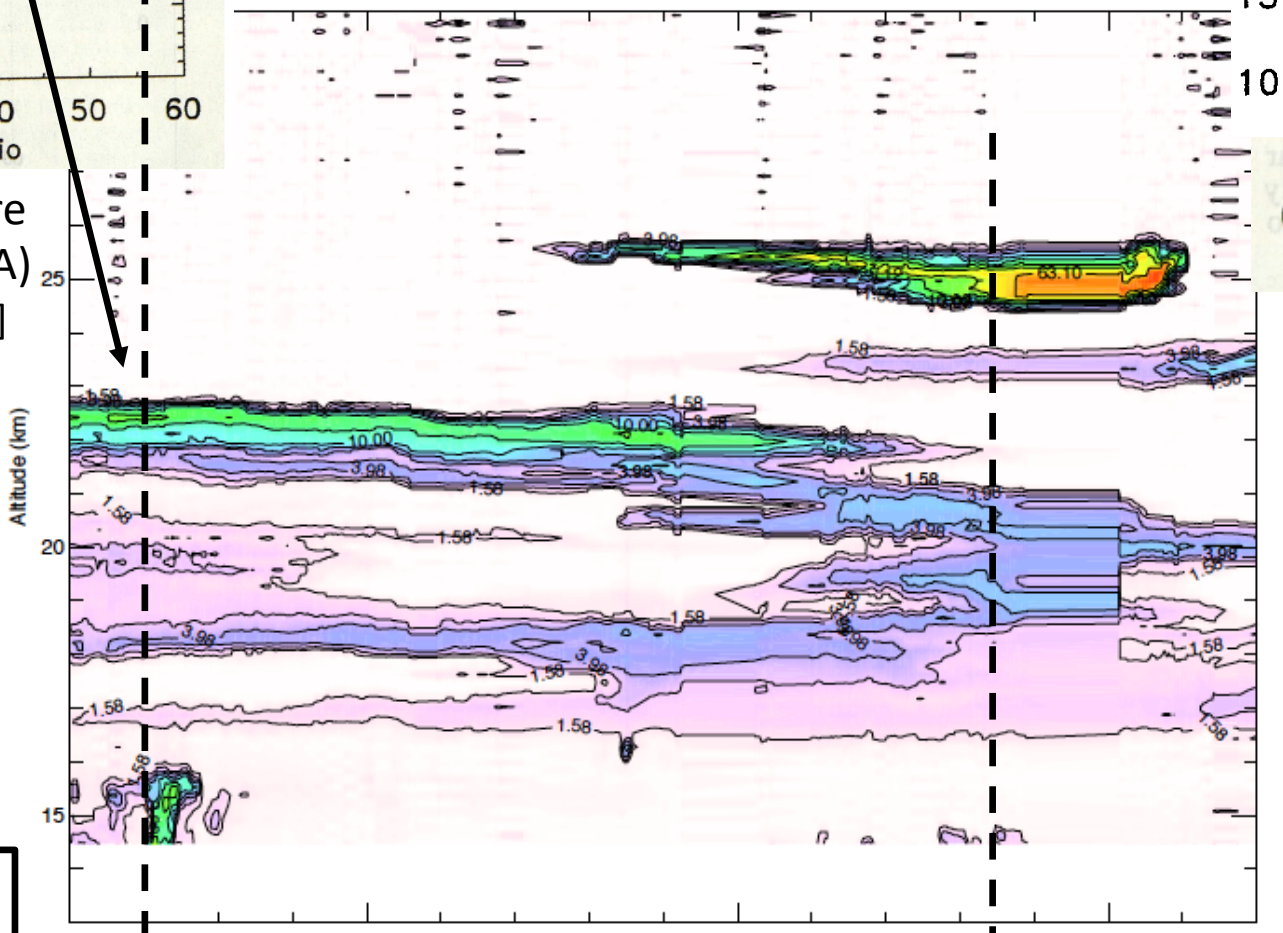
D. M. Winker

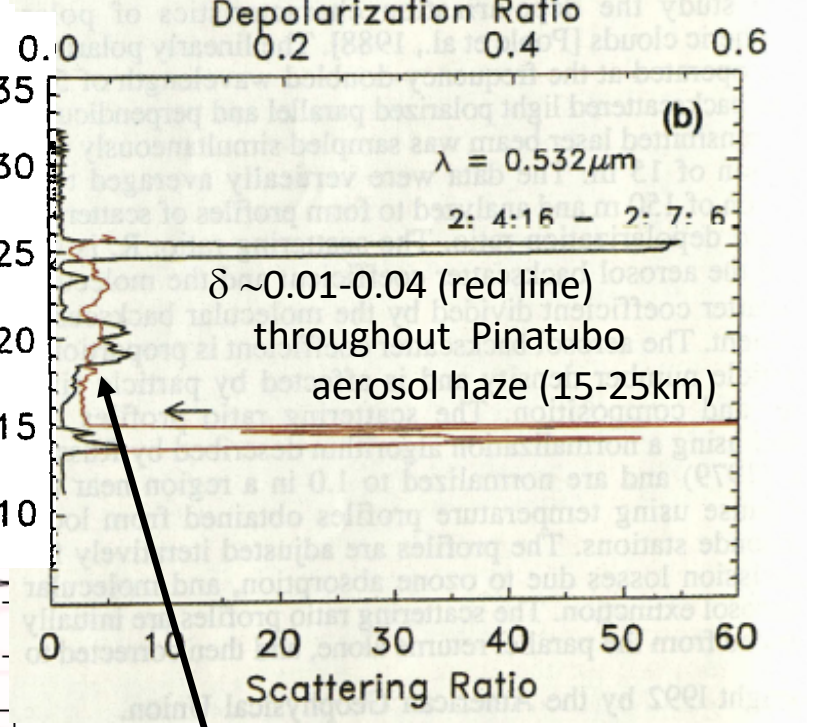
Atmospheric Sciences Division, NASA Langley Research Center

M. T. Osborn

Hughes STX Corporation

Fig. 3. Profiles of scattering ratio (black) and depolarization (red) from July 12-13 at (a) 4.2°S, 53.6°W; (b) 8.5°N, 55.6°W.





Orange = backscatter ratio of > 60
Modest depolarization throughout the full depth of the volcanic cloud

Early stages of the Pinatubo cloud

just a few weeks after the eruption in the tropics

532nm backscatter ratio from July 12-13 NASA Electra flight measuring the Pinatubo plume (4 weeks after the eruption)

Winker & Osborne (1992b, GRL)

Winker & Osborne (1992a, GRL)

Stratosphere-enabled GLOMAP and applications

- GLOMAP developed to simulate the global variation in particle size distribution (new particle formation and growth via coagulation, condensation and cloud processing).
- Initially applied only for the tropospheric aerosol layer (Mann et al., 2010; Bellouin et al., 2013; Turnock et al., 2015)
- Then adapted in UM-UKCA to simulate aerosol microphysics across the stratosphere & troposphere (Dhomse et al., 2014)
- Through 2016-7, “strat-enabled GLOMAP” further developed to form stratospheric aerosol particles on meteoric smoke particles, alongside homogeneously nucleated particles
- Strat-enabled GLOMAP within UM-UKCA applied for VolMIP Tambora-ISA expt (Marshall et al., 2018; Clyne et al., 2021).
- And to simulate major volcanic aerosol from 1963 Agung, 1982 El Chichon & 1991 Pinatubo (Dhomse et al., 2020).

CAMS43-Leeds PhD at Leeds on volcanic aerosol (Sarah Shallcross)

Part of co-funded PhD studentship developed GLOMAP v8.3 further to co-emit volcanic ash with volcanic SO_2 → understand radiative & microphysical effects on plume dispersion.

UM-UKCA now has GLOMAP simulating uptake of H_2SO_4 onto volcanic ash and radiative effects:

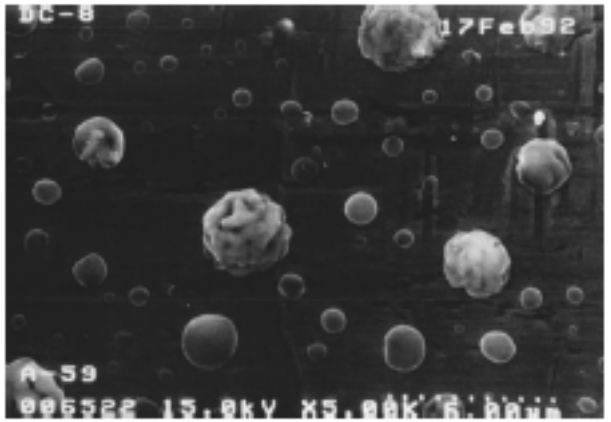


Figure 5. Stratospheric H_2SO_4/H_2O droplets and ash covered in H_2SO_4. From Pueschel *et al.* (1994), collected on February 17th 1992 (53° N, 67° W).

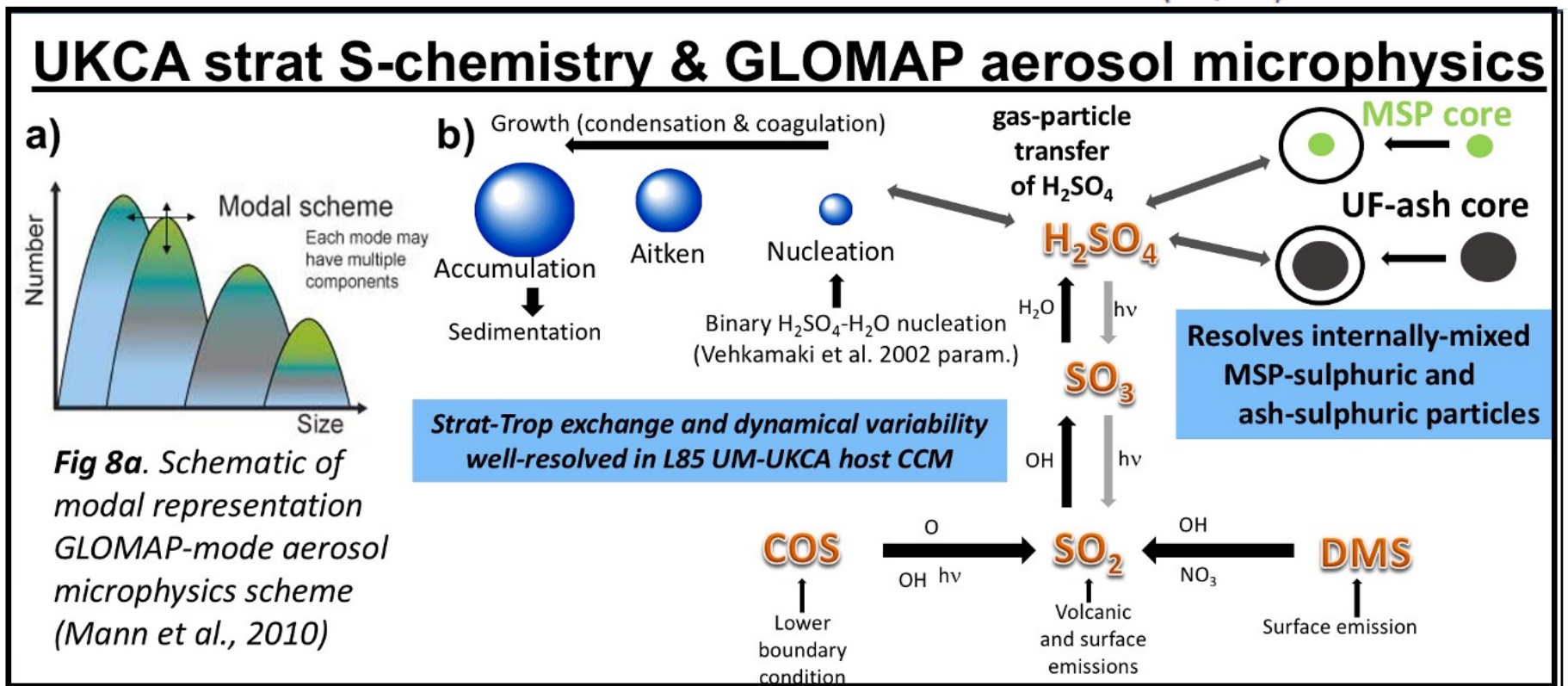


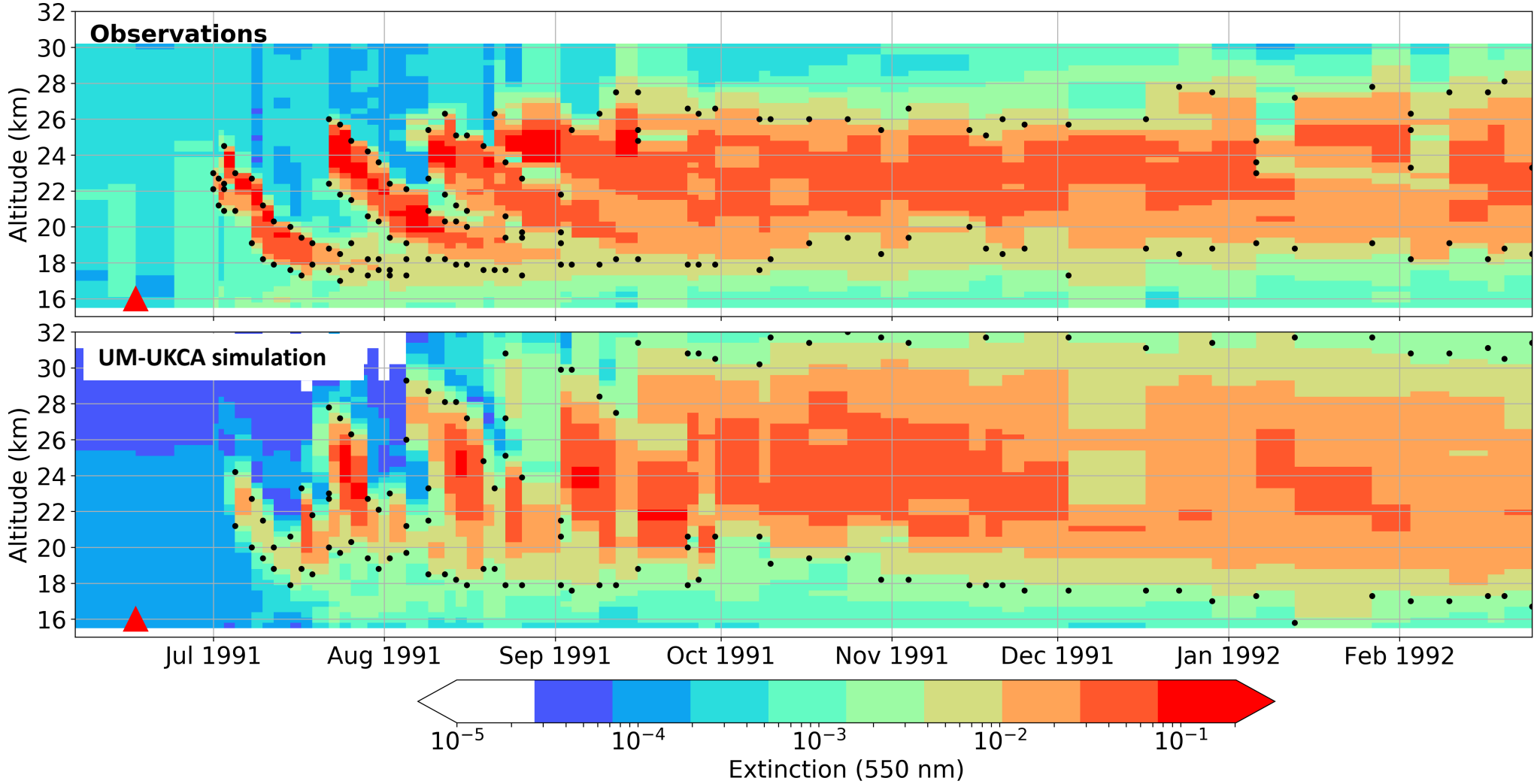
***Fig 8a**. Schematic of modal representation GLOMAP-mode aerosol microphysics scheme (Mann et al., 2010)*

Evaluate 21-23km, 18-20km, 18-25km injection height UM-UKCA simulations, comparing to lidar measurements at Mauna Loa, and at NH mid-latitudes.

14 Tg of SO2 emitted **<u>at 21-23km altitude</u>**

Extinction (550 nm) at Mauna Loa

This is standard UM-UKCA Pinatubo with only SO2 (no co-emitted ash)



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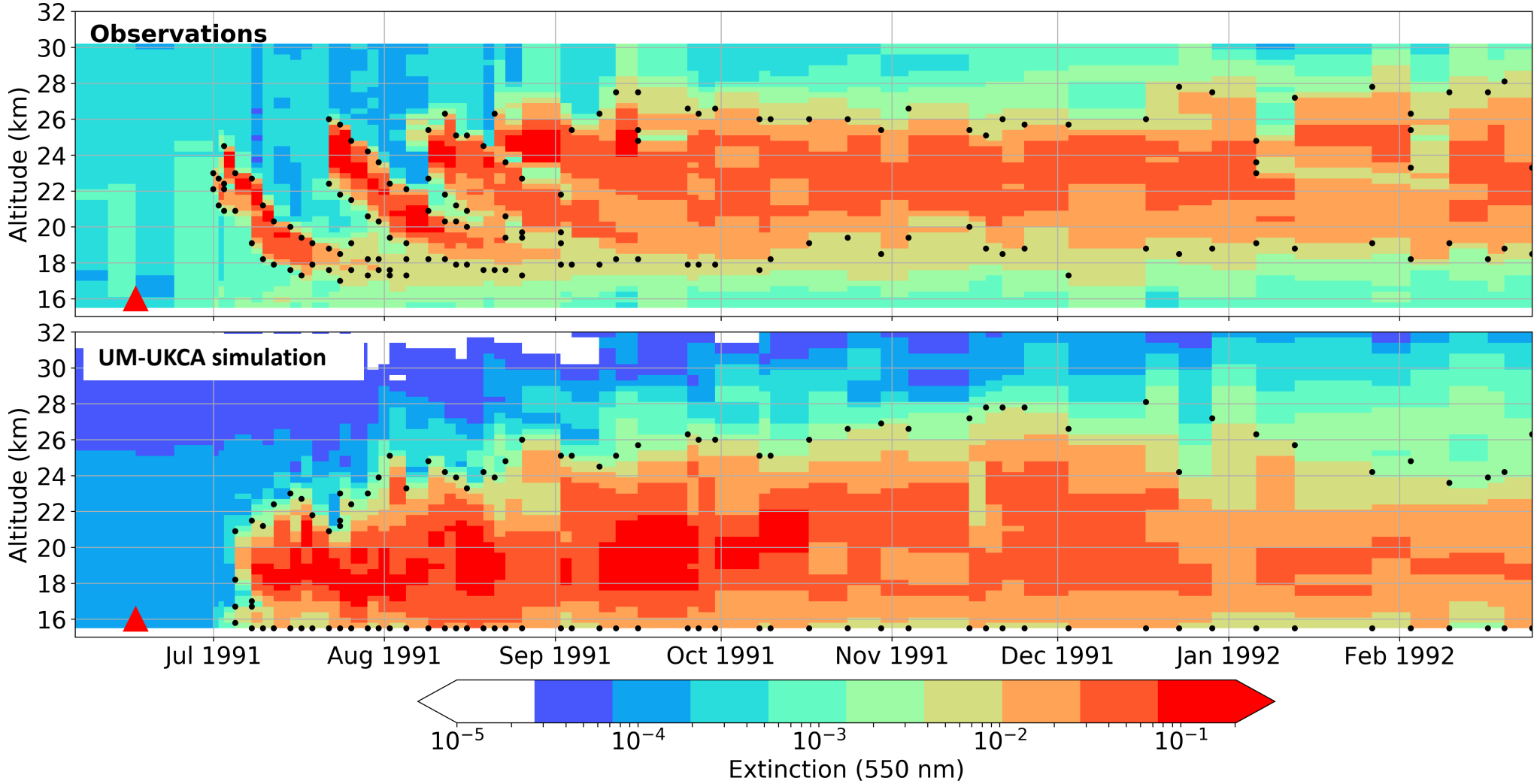
Extinction (550 nm) at Mauna Loa

This is standard UM-UKCA Pinatubo with only SO2 (no co-emitted ash)

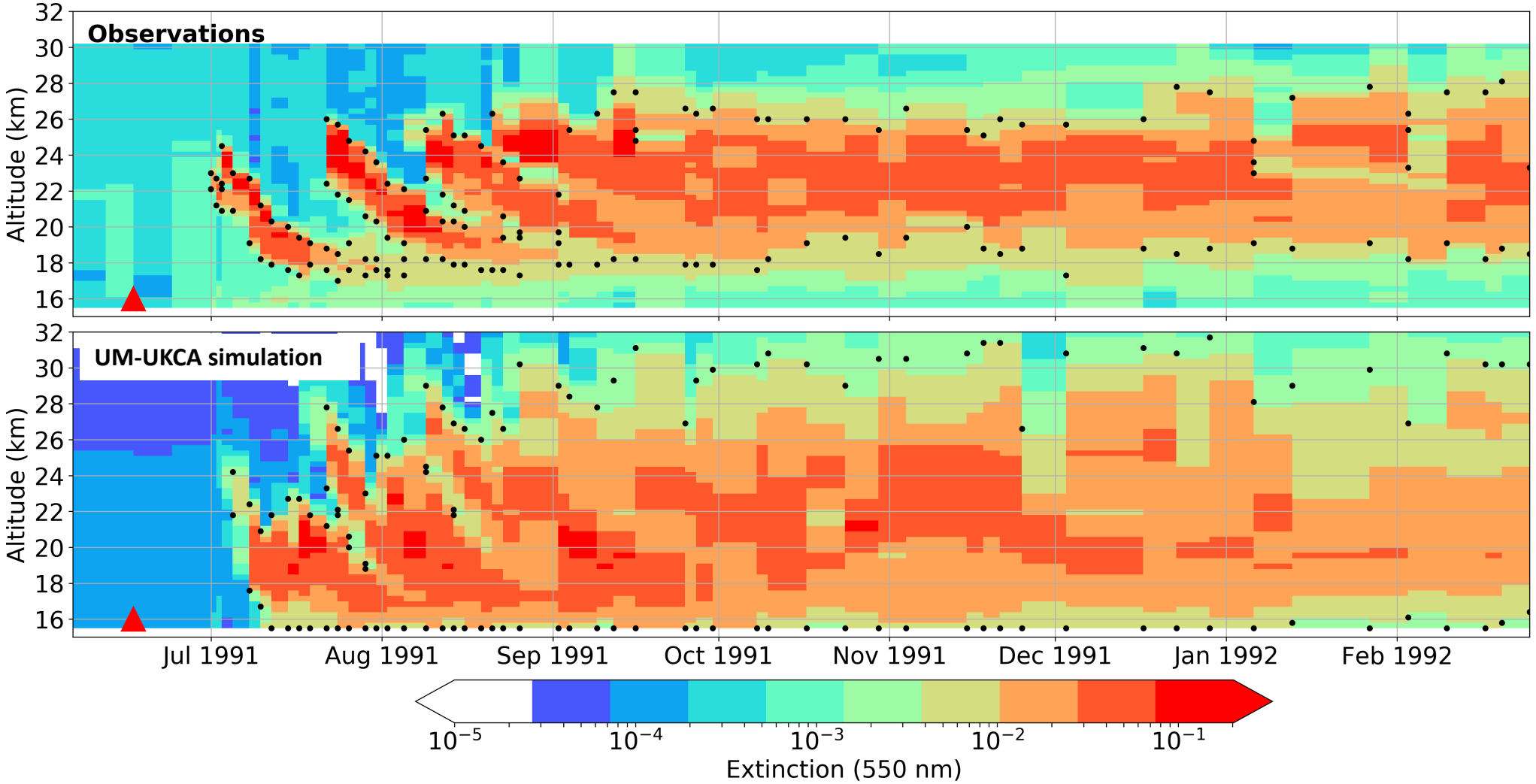


Evaluate 21-23km, 18-20km, 18-25km injection height UM-UKCA simulations, comparing to lidar measurements at Mauna Loa, and at NH mid-latitudes.

14 Tg of SO2 emitted **<u>at 18-25km altitude</u>**

Extinction (550 nm) at Mauna Loa

This is standard UM-UKCA Pinatubo with only SO2 (no co-emitted ash)



UM-UKCA interactive strat-aerosol

<u>Initial 10-day test Pinatubo ash runs co-emitting SO_2 & different sized ash</u> (1, 3.16, 10 μm)

(21-23km emission ht)

n.b. ash particles represented within coarse-insoluble mode (mode 7) with σ_g=2.0

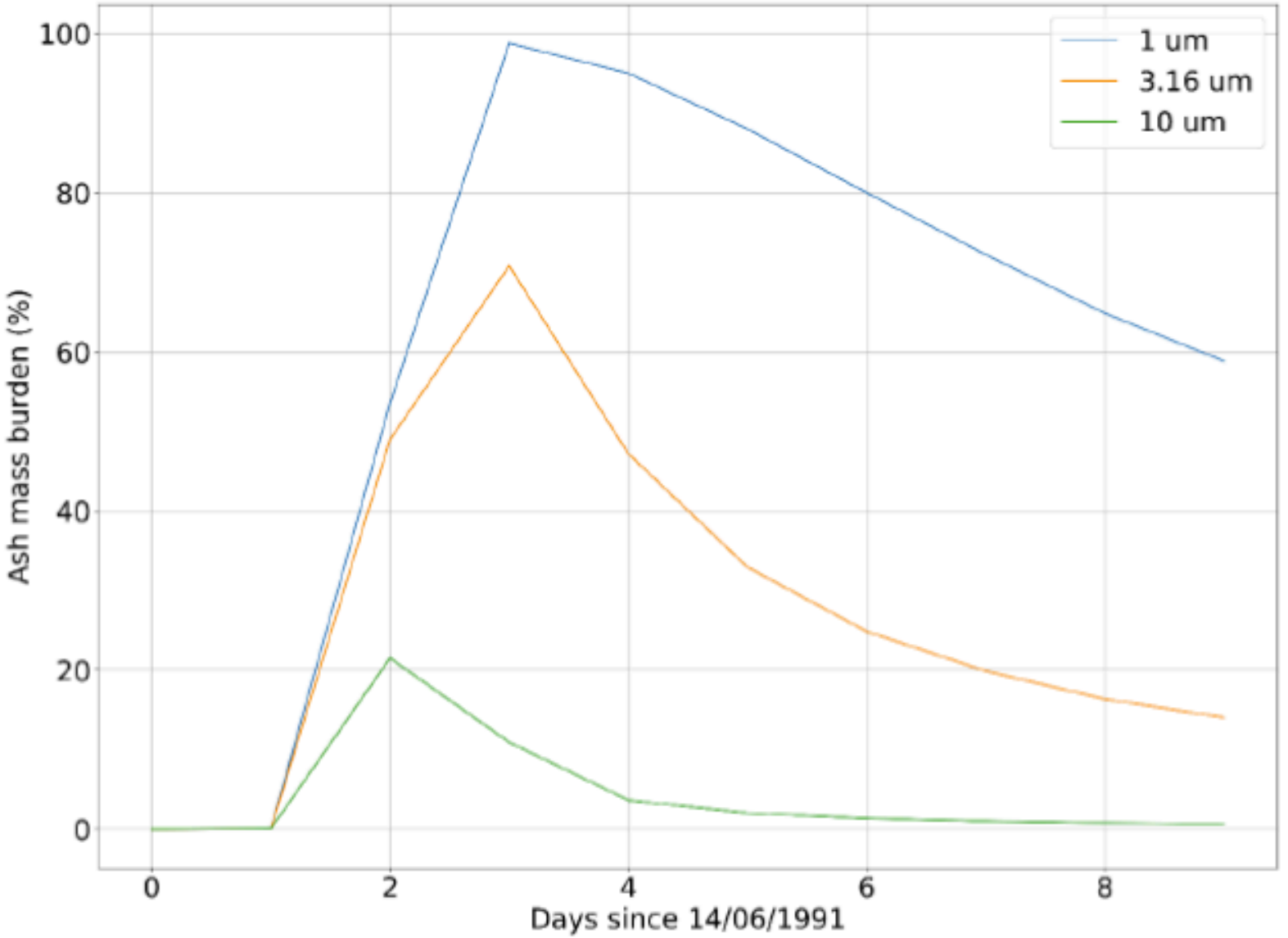


Figure 6-1 Percentage mass of ash over a one-week period following the eruption for 1, 3.16 and 10 μm ash sizes.

UM-UKCA interactive strat-aerosol

<u>100-day Pinatubo volcanic ash & SO_2 experiments with sub-μm sized ash</u> (0.10, 0.316, 1.0 μm)

(21-23km emission ht)

n.b. ash particles represented within coarse-insoluble mode (mode 7) with σ_g=2.0

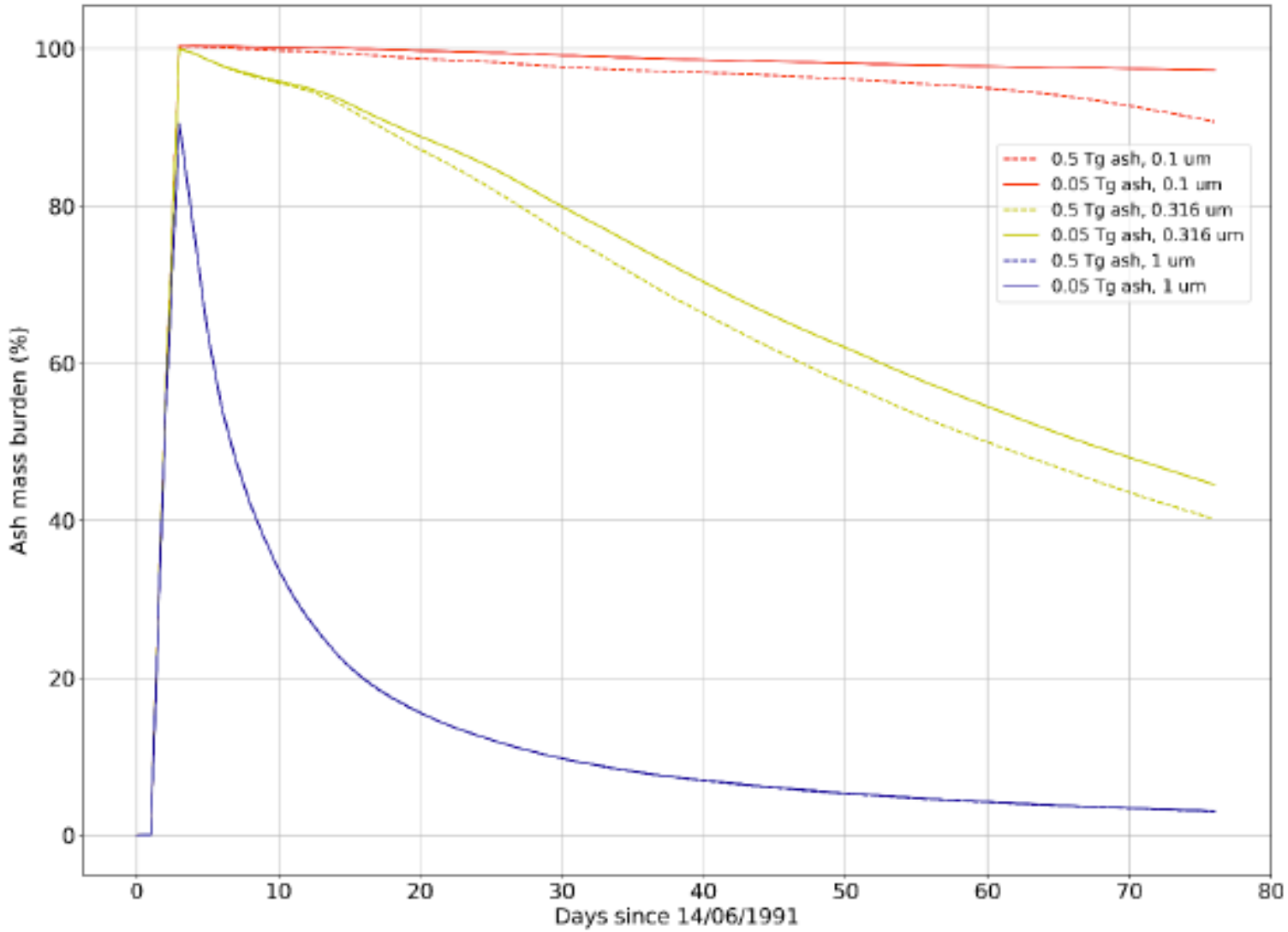


Figure 6-2 Percentage mass of ash in the first 3 months following the 1991 Mount Pinatubo eruption, for 3 different ash sizes (0.1, 0.316 and 1 μm) for 0.05 and 0.5 Tg of ash injected. Straight lines denote 0.05 Tg, dashed denote 0.5 Tg ash.

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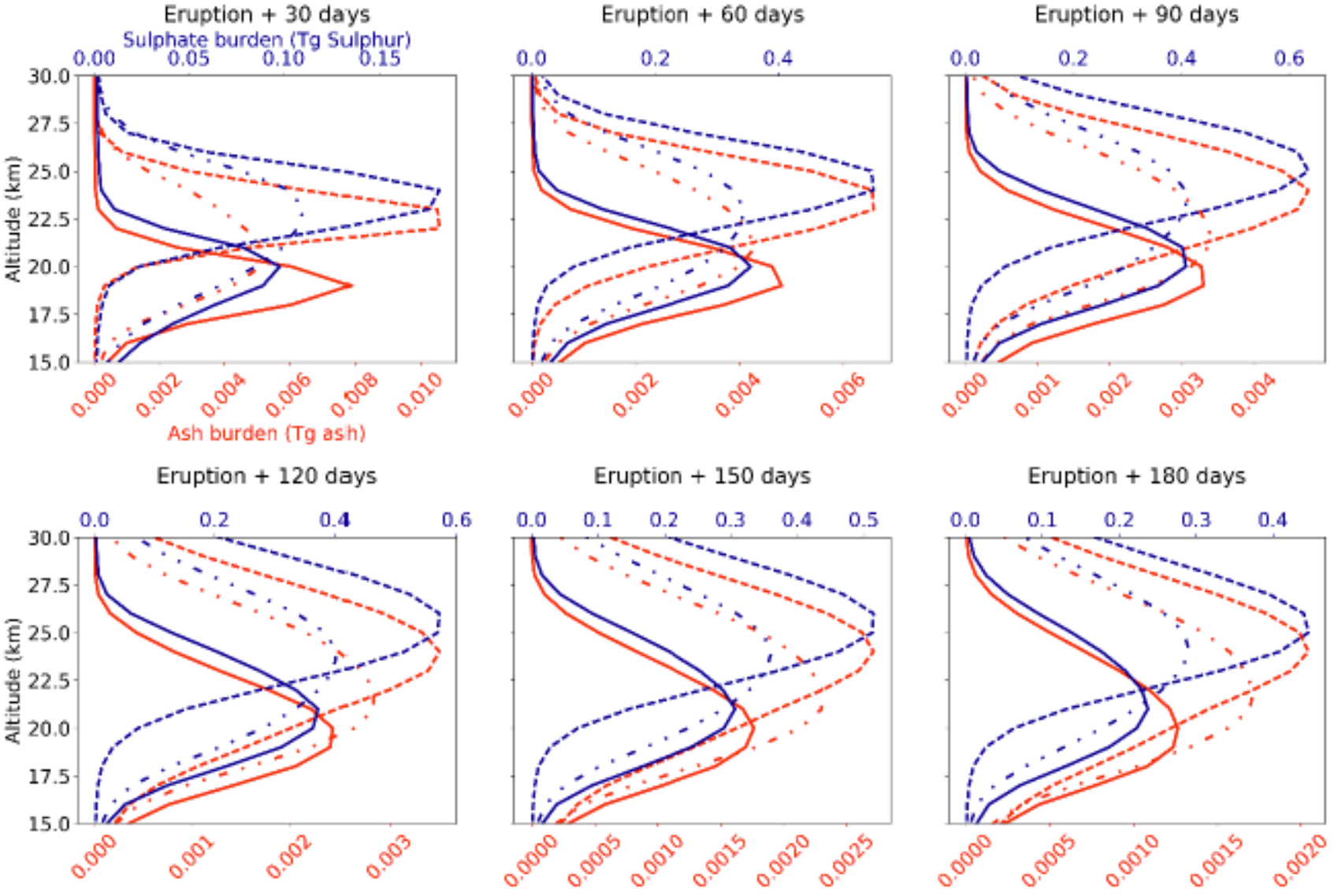
<u>180-day Pinatubo volcanic ash & SO_2 experiments with sub-μm sized ash</u> (with 0.10μm g.s.d.)

-- <u>3 different injection height scenarios</u> matching ISA-MIP HErSEA experiment specifications (21-23, 18-21, 18-25km)

n.b. ash particles represented within coarse-insoluble mode (mode 7) with σ_g=2.0



ash burden
SO_4 burden

Figure 6-4 Monthly average ash (red) and sulfate (blue) burden for the tropics (20°S-20°N) for a 14 Tg SO_2 and 0.05 Tg ash injection mass at 18-20 km (solid lines), 21-23 km (dashed lines) and 18-25 km (dot-dashed line).

Assess impacts of the co-emitted ash on Pinatubo sulphate aerosol

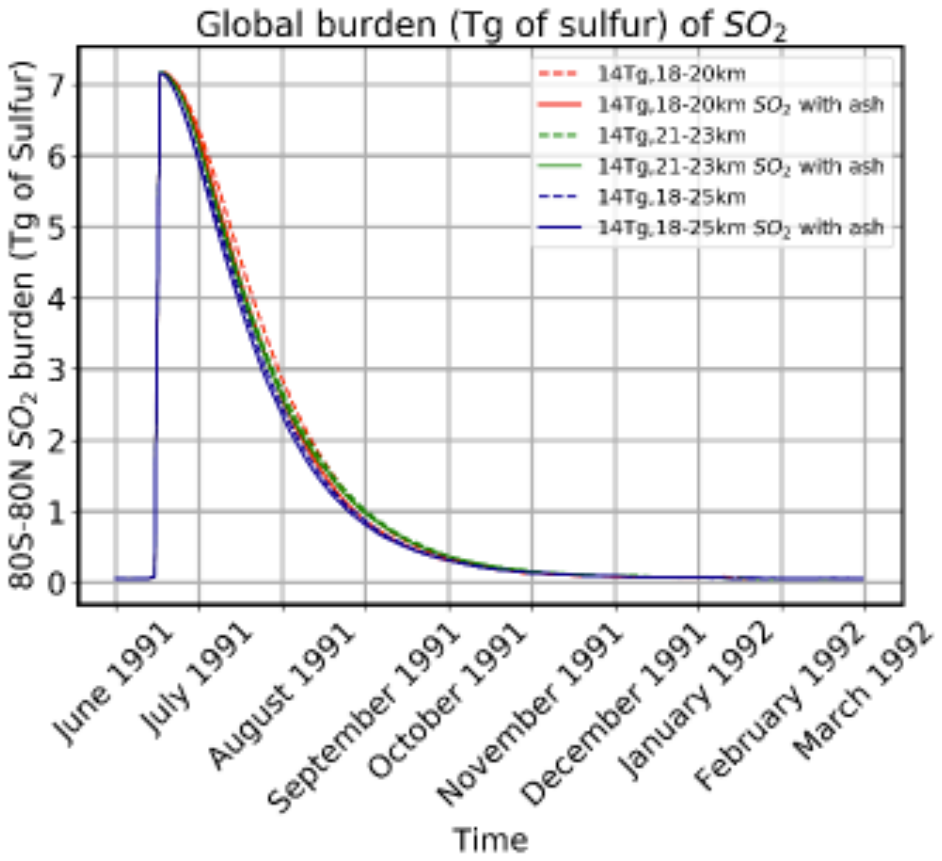
(Global SO_2 & SO_4 burden)

UM-UKCA interactive strat-aerosol

180-day Pinatubo volcanic ash & SO_2 experiments with sub-μm sized ash (with 0.10μm g.s.d.)

-- 3 different injection height scenarios matching ISA-MIP HErSEA experiment specifications (21-23, 18-21, 18-25km)

n.b. ash particles represented within coarse-insoluble mode (mode 7) with σ_g=2.0



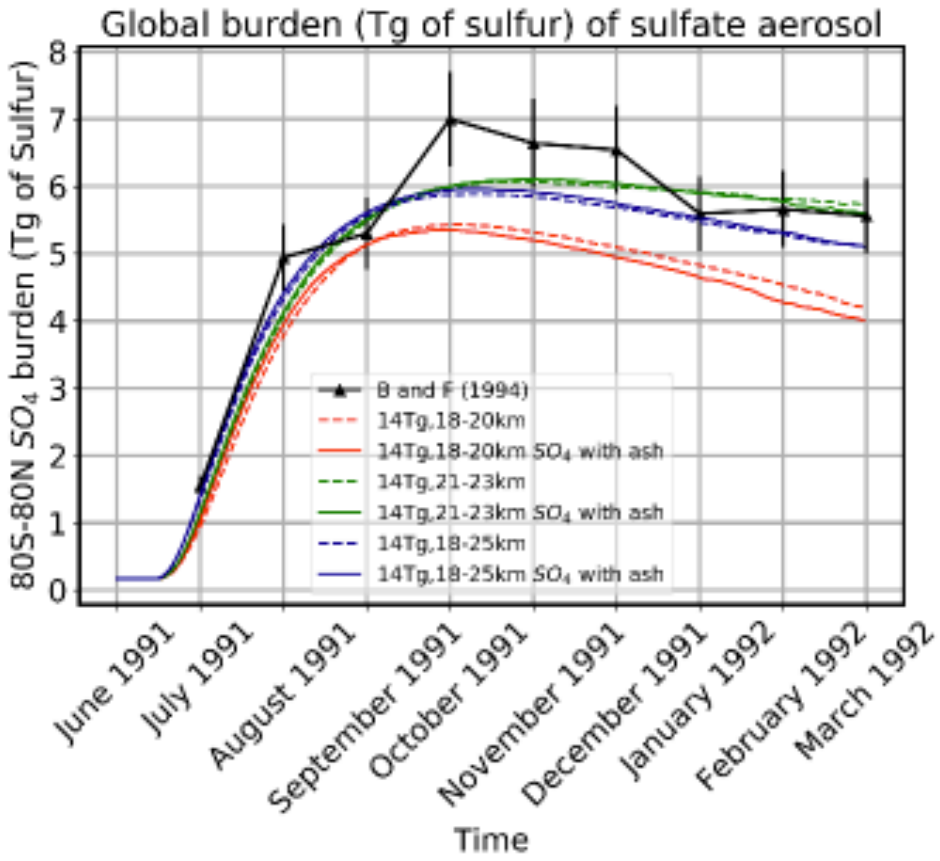


Figure 6-13 Global sulfur burden for (left) SO_2 gas-phase sulfur and (right) sulfate aerosol for 14 Tg injected SO_2 at all injection heights comparing with and without ash.

Only a small effect of sub-micron ash when consider the global sulphate burden

Assess impacts of the co-emitted ash on Pinatubo sulphate aerosol

(Tropical SO_2 & SO_4 burden)

UM-UKCA interactive strat-aerosol

180-day Pinatubo volcanic ash & SO_2 experiments with sub-μm sized ash (with 0.10μm g.s.d.)

-- 3 different injection height scenarios matching ISA-MIP HErSEA experiment specifications (21-23, 18-21, 18-25km)

n.b. ash particles represented within coarse-insoluble mode (mode 7) with σ_g=2.0

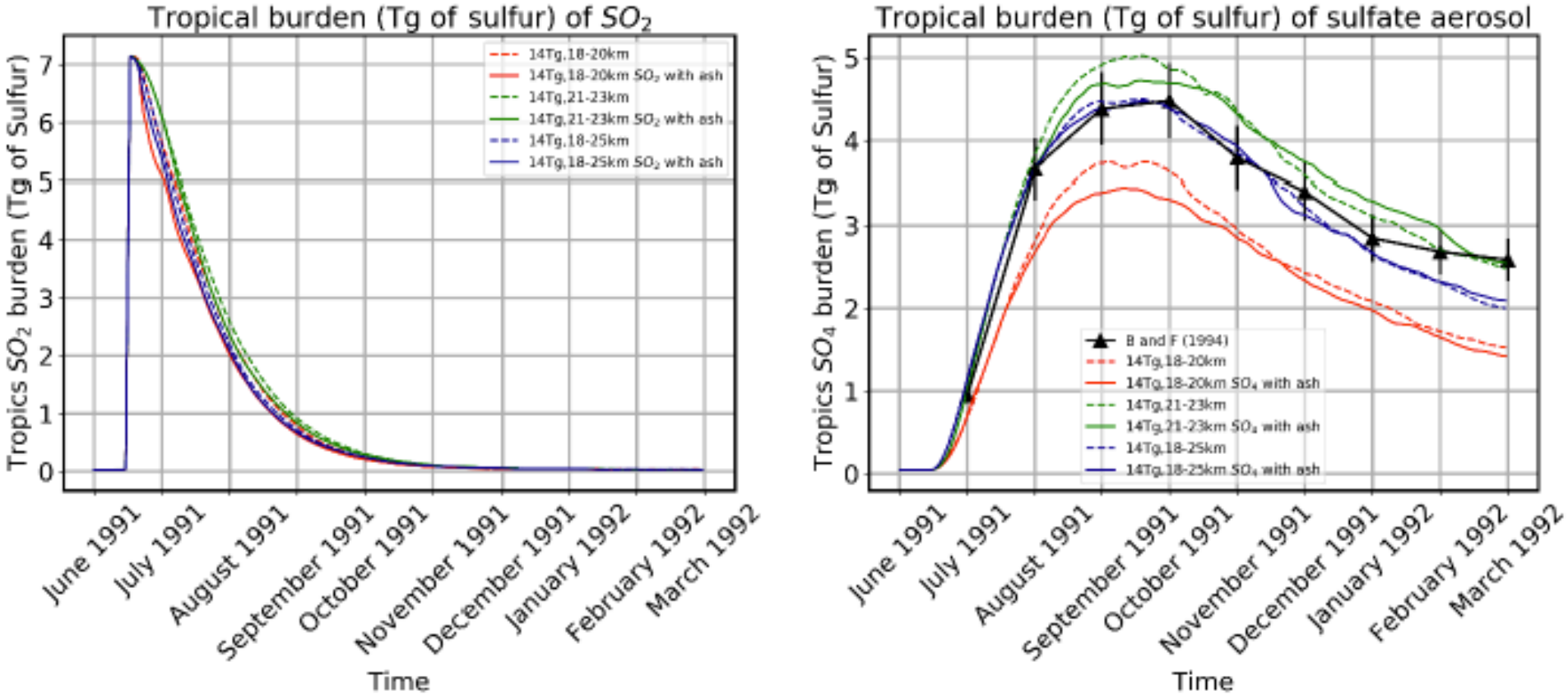


Figure 6-10 Tropical (Left) SO_2 burden and (Right) SO_4 burden for 14 Tg ash (solid line) and non-ash (dashed) simulations.

Peak tropical SO4 burden reduces slightly (~10%) when sub-micron ash included.

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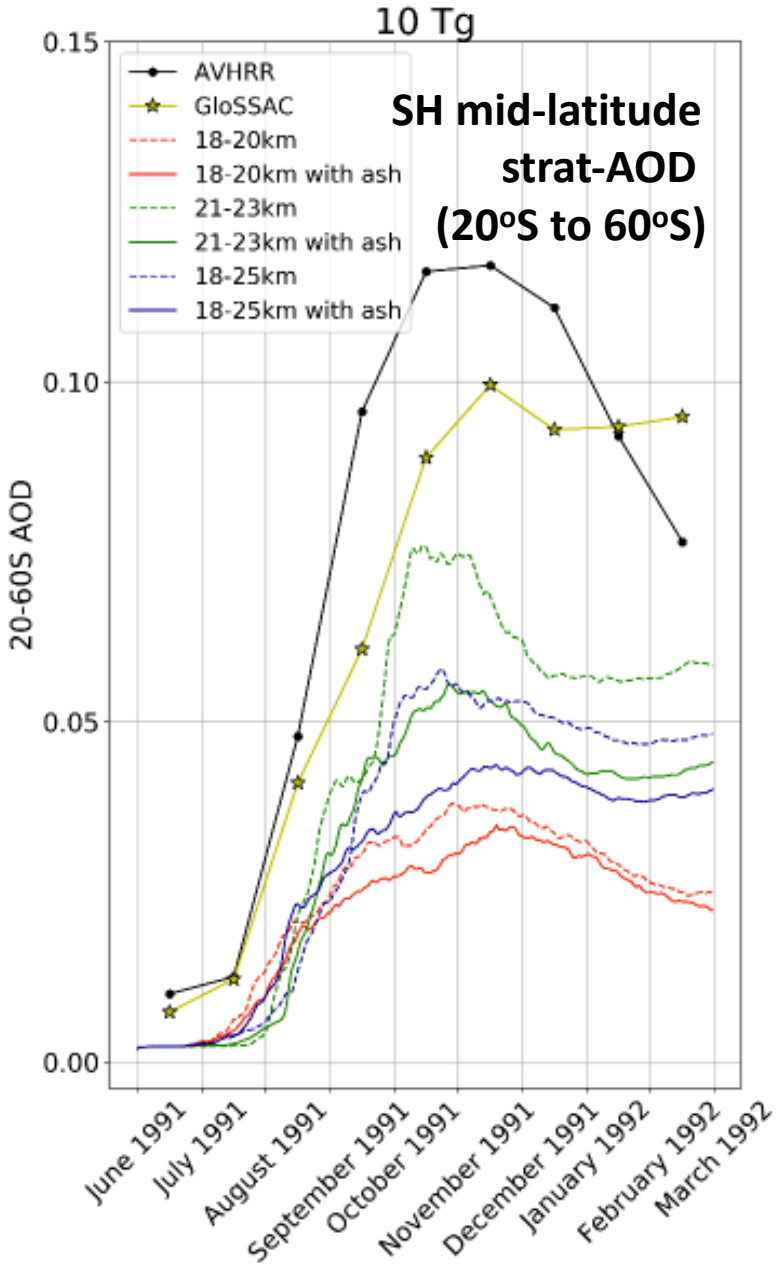
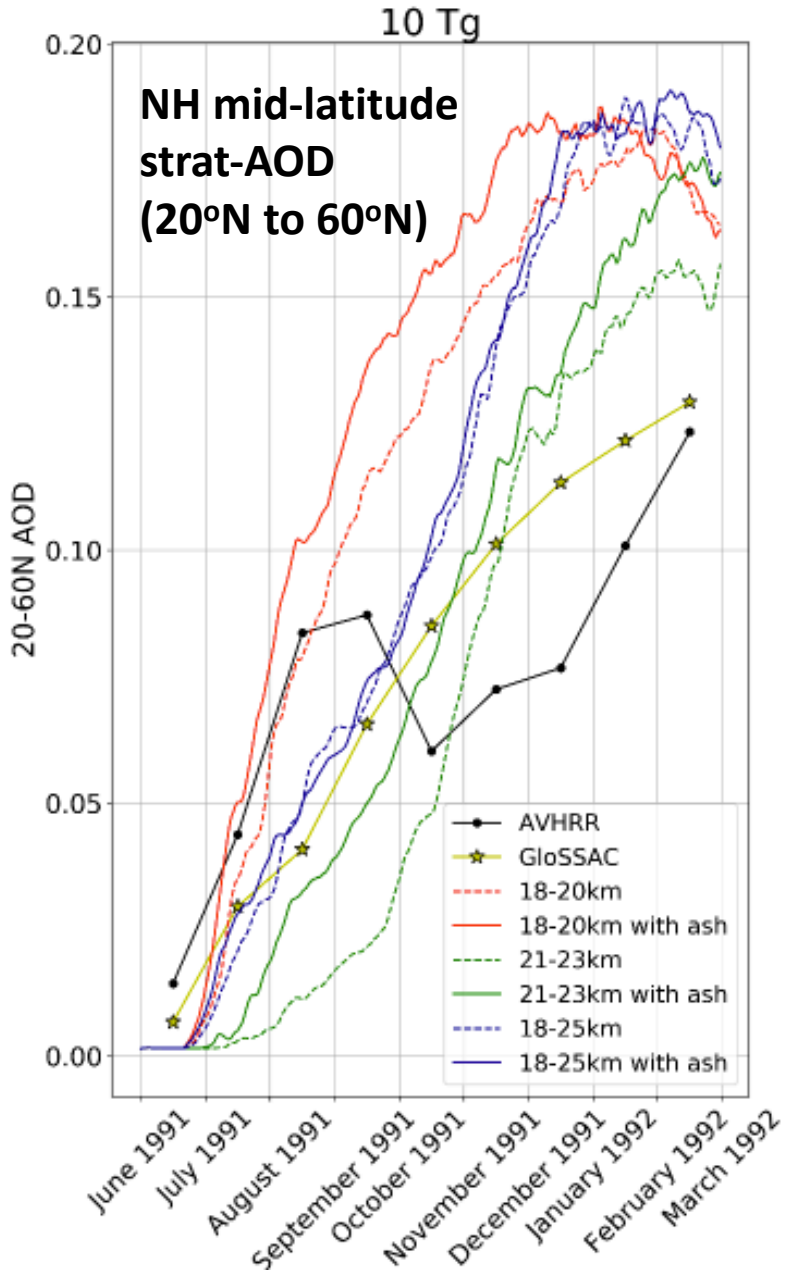
<u>180-day Pinatubo volcanic ash & SO_2 experiments with sub-μm sized ash</u> (with 0.10μm g.s.d.)

-- <u>3 different injection height scenarios</u> matching ISA-MIP HErSEA experiment specifications (21-23, 18-21, 18-25km)

n.b. ash particles represented within coarse-insoluble mode (mode 7) with σ_g=2.0





<u>Substantial increase in transport to Southern Hemisphere when UF-ash co-emitted</u>

UM-UKCA interactive strat-aerosol

Comparison to Mauna Loa lidar (19°N)

<u>180-day Pinatubo volcanic ash & SO_2 experiments with sub-μm sized ash</u> (with 0.10μm g.s.d.)

-- <u>3 different injection height scenarios</u> matching ISA-MIP HErSEA experiment specifications (21-23, 18-21, 18-25km)

n.b. ash particles represented within coarse-insoluble mode (mode 7) with σ_g=2.0

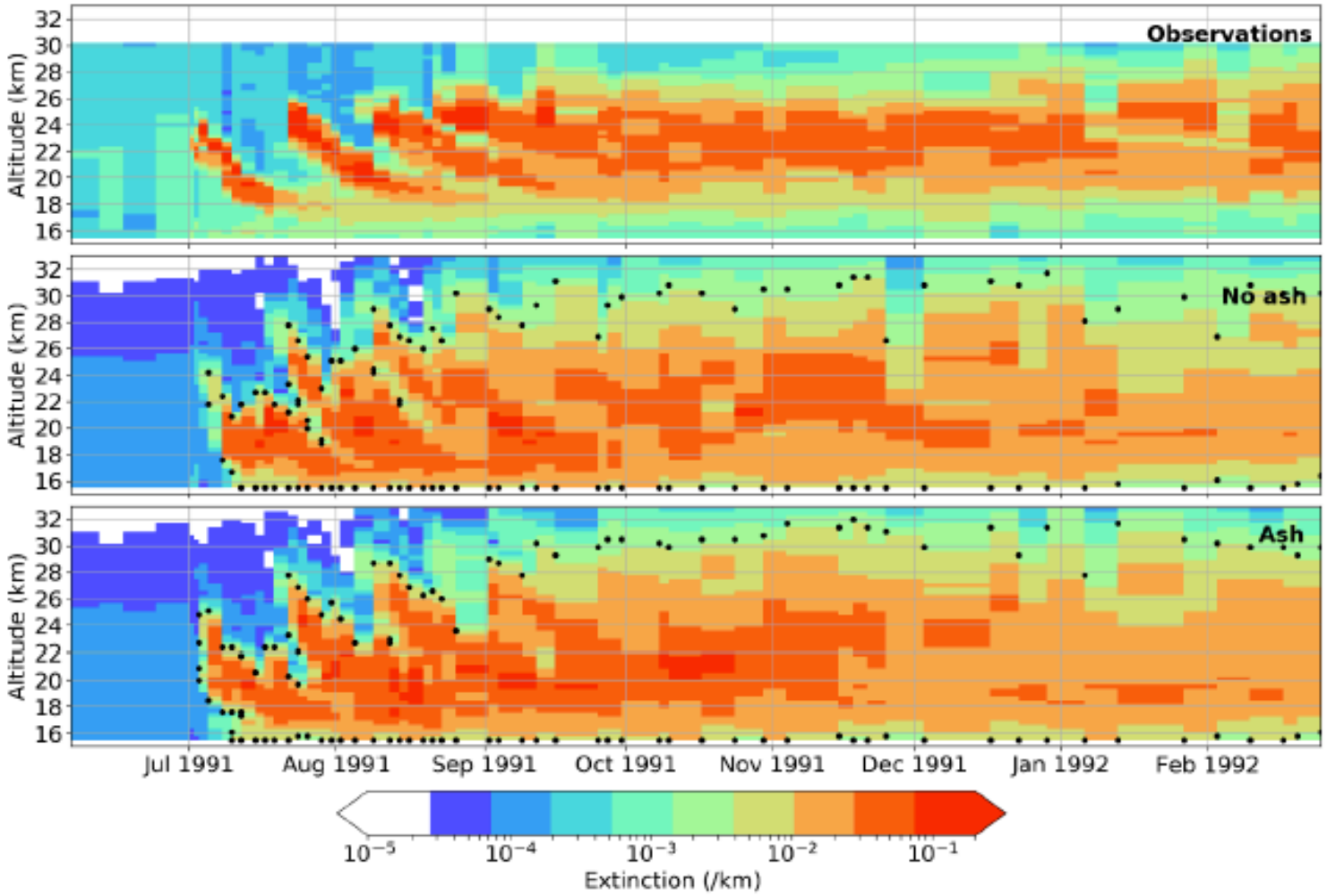


Figure 6-17 Extinction plots for MLO with 14 Tg SO_2 and 18-25 km injection height. Plots show observations (top), no ash (middle) and with ash (bottom). Black dots denote where layers are picked out from the layer finding algorithm.

Heating effect from ultra-fine ash <u>causes a modest change to initial progression of Pinatubo plume in tropical reservoir → more concentrated to lower portion</u>

UM-UKCA interactive strat-aerosol

Comparison to Hautes Provences lidar (44°N)

<u>180-day Pinatubo volcanic ash & SO_2 experiments with sub-μm sized ash</u> (with 0.10μm g.s.d.)

-- <u>3 different injection height scenarios</u> matching ISA-MIP HErSEA experiment specifications (21-23, 18-21, 18-25km)

n.b. ash particles represented within coarse-insoluble mode (mode 7) with σ_g=2.0

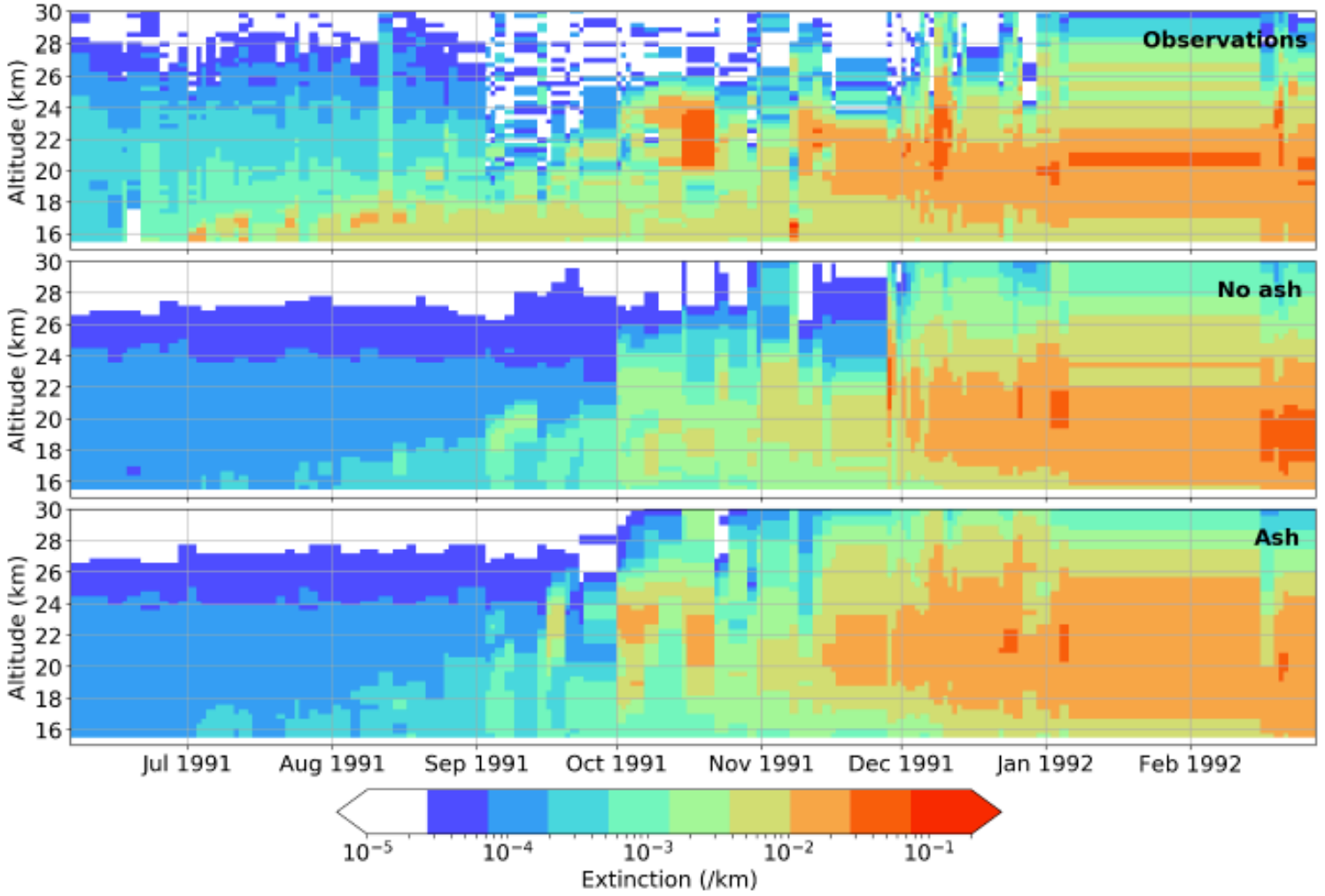


Figure 6-19 Extinction plots for OHP with 14 Tg SO_2 and 21-23 km injection height. Plots show observations (top), no ash (middle) and with ash (bottom).

Heating effect from ultra-fine ash <u>causes earlier transport to NH mid-latitudes in better agreement with the timing observed from Hautes Provence</u>

Assess vertical distribution of Pinatubo ultra-fine ash in NH mid-latitudes

(Aberystwyth lidar backscatter and depolarisation)

UM-UKCA interactive strat-aerosol

180-day Pinatubo volcanic ash & SO_2 experiments with sub-μm sized ash (with 0.10μm g.s.d.)

-- 3 different injection height scenarios matching ISA-MIP HErSEA experiment specifications (21-23, 18-21, 18-25km)

n.b. ash particles represented within coarse-insoluble mode (mode 7) with σ_g=2.0

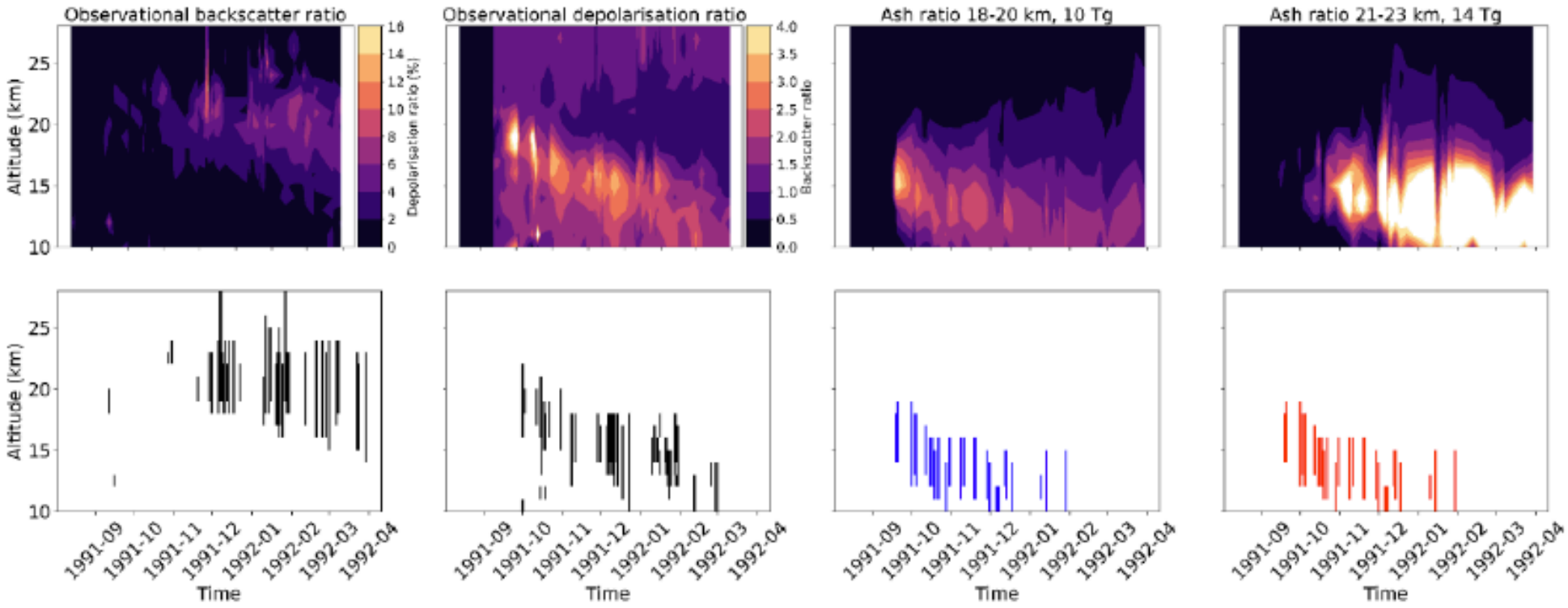


Figure 6-20 (Top) Contour plots of backscatter ratio and depolarisation data from Aberystwyth compared to ash ratio model data in 2 scenarios, (bottom) depth of cloud from the layer finding algorithm for observations and the same 2 model scenarios from the top row.

The altitude of the depolarization observed from the Aberystwyth lidar agrees well with the 21-23km injection run --> UF-ash can explain the signal observed

Conclusions

- GA4 “strat-enabled” UM-UKCA simulates aerosol microphysics across the stratosphere & troposphere (Dhomse et al., 2014; Mann et al., 2015)
- Benchmark GA4 “strat-UKCA v3” model (with GLOMAP v8.2) applied VolMIP Tambora-ISA expt (Marshall et al., 2018; Clyne et al., 2021), for volcanic forcing Perturbed Parameter Ensemble expt (Marshall et al., 2019) and to simulate the volc-aerosol clouds from Agung, El Chichon & Pinatubo (Dhomse et al., 2020).
- *Further developed for volcanic ash* within PhD studentship jointly funded by CAMS43 (IFS global aerosol development) & Leeds Univ (Shallcross et al., 2020): http://homepages.see.leeds.ac.uk/~amtgwm/SarahShallcross_PhD_thesis_Corrected.pdf
- Case study on Pinatubo to co-emit volcanic ash with SO_2 (see chapter 6)
- Ash particles larger than 1 micron sedimented from Pinatubo cloud in ~1 week
  But “ultra-fine ash” particles remained within the Pinatubo cloud for ~9 months
- Heating effect from UF-ash important, and model confirms hypothesis that observed depolarization of lidar backscatter at Aberystwyth caused by UF-ash.
- Next add SO_2 reactive uptake (het. ox.) – removes ~40% for Kelud (Zhu et al. (2020).