Whole-atmosphere aerosol microphysics simulations of the Mount Pinatubo eruption: an evaluation

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1. Introduction to UKCA sub-model

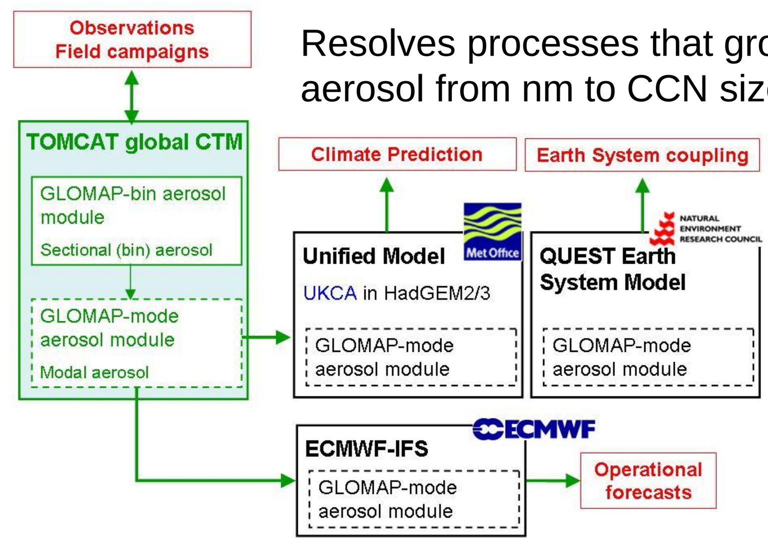
- Major collaboration since 2005 to develop composition-climate model. Main partners are Univ. Leeds, Univ. Cambridge and the UK Met Office.
- Aerosol-chemistry sub-model in UK Met Office Unified Model environment for a range of applications (climate, Air Quality, Earth System science)
- Tropospheric and stratospheric chemistry schemes available. Aerosol precursor extension to UKCA chemistry schemes so that climate model simulated aerosol is coupled to atmospheric chemistry.
- Improved representation of aerosol in UK climate model simulations
  -- new particle formation & growth using GLOMAP aerosol microphysics
  -- internally mixed aerosol (e.g. BC & sulphate) affect optical properties
  -- biogenic secondary organic aerosol from monoterpene oxidation
- UKCA interactive ozone, methane and aerosol (direct/indirect) radiative effects for fully coupled composition-climate simulations.
- Enhances UK capability in aerosol-climate-earth system modeling and provides integration for UK Universities and UK Met Office initiatives.
- HadGEM3-ES model in development for AR6 will include UKCA with GLOMAP.

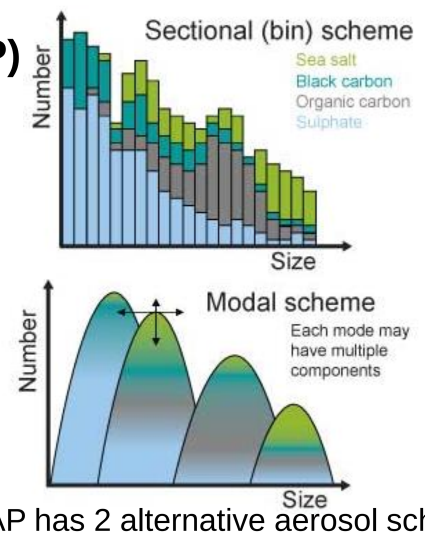
2. GLOMAP aerosol microphysics module

Global Model of Aerosol Processes (GLOMAP)

Developed in Leeds since 2003 to simulate global aerosol with size-resolved number andcomposition.

Resolves processes that grow aerosol from nm to CCN sizes.



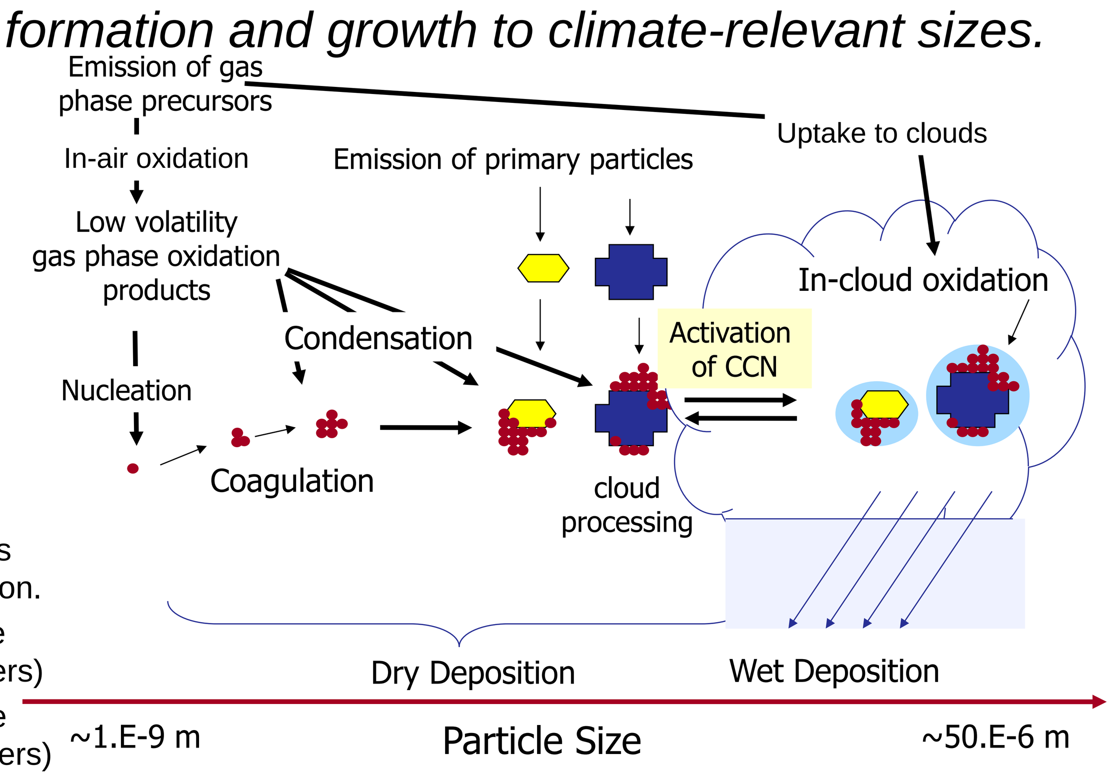


GLOMAP has 2 alternative aerosol schemes using the same/similar process representation.

GLOMAP-mode = 2-moment modal scheme (Mann et al, 2010) (~15-30 aerosol tracers)

GLOMAP-bin – 2-moment sectional scheme (Spracklen et al, 2005) (60-250 aerosol tracers)

Simulates aerosol lifecycle resolving new particle formation and growth to climate-relevant sizes.



3. Impacts of Pinatubo eruption

- Mount Pinatubo eruption in June 1991 injected ~14-20 Tg of SO_2 into the tropical stratosphere thickening Junge layer ~21-28km altitude.
- Sulphur dioxide chemically converted to sulphuric acid vapour and readily taken up into the stratospheric aerosol particle phase.
- Thicker stratospheric aerosol layer caused heating of tropical stratosphere and cooling of troposphere and Earth surface.
- Warming of tropical stratosphere caused enhanced upwelling with effects on meridional transport & dynamical ozone & H_2O changes.
- Global veil of enhanced stratospheric sulphuric acid aerosol formed over 3-6 months with surface area density factor-100 higher initially, and still factor-10 higher at all latitudes 2 years after the eruption.
- Enhanced surface-area-density increased heterogeneous chemical conversion of N_2O_5 into less reactive HNO_3.
- Pinatubo aerosol effects may also have enhanced PSCs causing increased reactive chlorine and polar ozone loss.
- Stronger tropical upwelling also transported more low-ozone air into lower stratosphere causing dynamical decrease in stratospheric ozone.
- The stratospheric heating may have caused anomalous positive Arctic Oscillation causing Europe to be much warmer in subsequent winter.
- Entrainment of enhanced stratospheric aerosol into troposphere may also have caused changes to cirrus & tropospheric aerosol properties.

4. GLOMAP-mode simulates stratospheric aerosol evolution in whole-atmosphere UKCA composition-climate model

Fig 1a. Pinatubo erupted on June 15th 1991, injecting 14-20 Tg SO_2 up to 28 km In the atmosphere

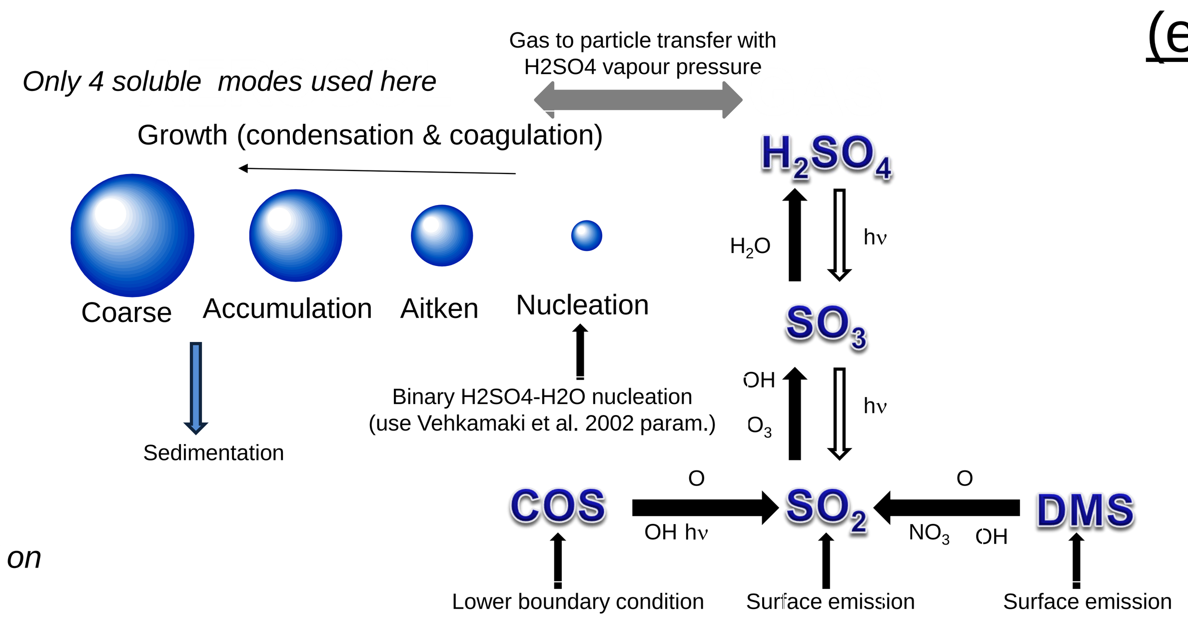


Fig 1b. Schematic of HadGEM-UKCA Stratospheric Sulphur chemistry and coupling to GLOMAP-mode aerosol microphysics module

- UKCA includes comprehensive stratospheric chemistry scheme (CheS) (Morgenstern et al., 2009)
- Free-running simulations in high-top (80km) version of HadGEM3-A-r2.0 general circulation model.
- Extended CheS with stratospheric sulphur chemistry & coupled to GLOMAP-mode (Mann et al, 2010)
- Simulations here use double-call forcing configuration (no aerosol feedback on model dynamics)

5. Comparison of simulated stratospheric surface area density (SAD) vs satellite derived dataset used by Chemistry-Climate Models (e.g. as used in SPARC CCMVAL-2).

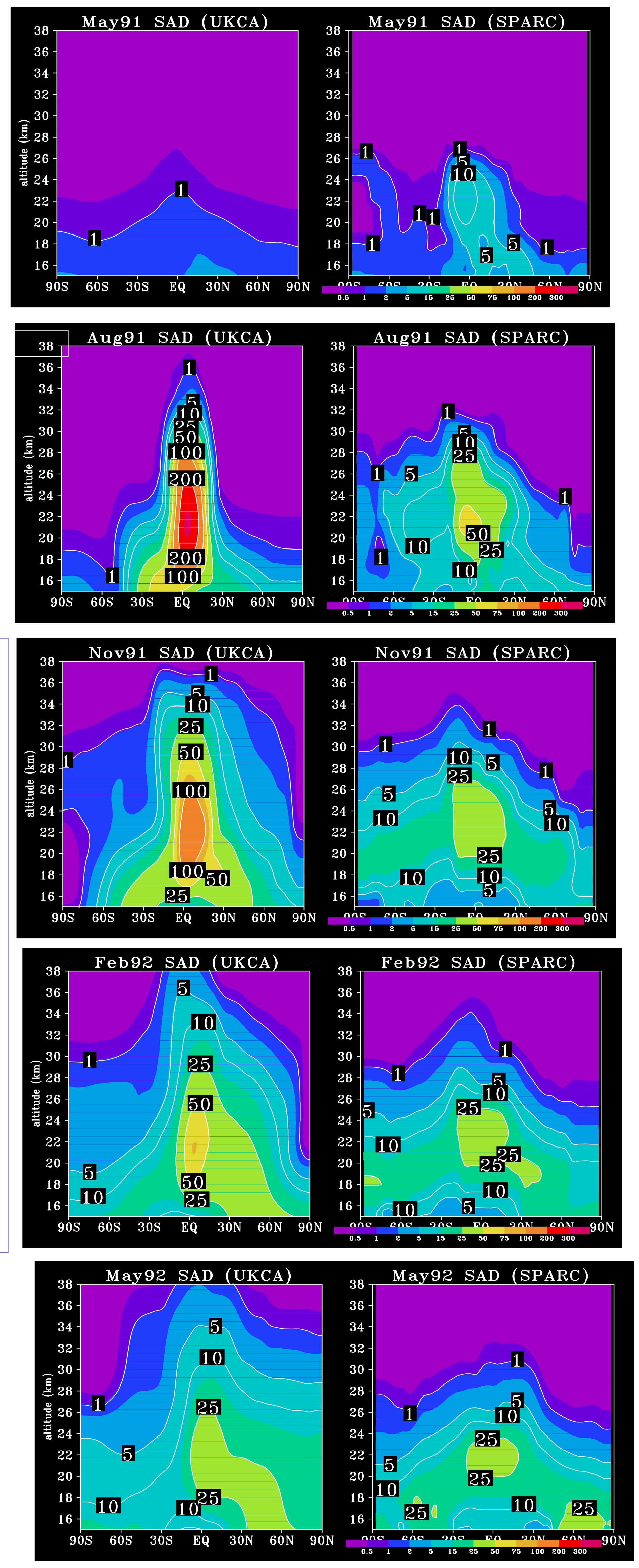


Figure 2: Background and Pinatubo-perturbed stratospheric Surface Area Density compare well to derived product from satellite observations (Thomason et al., 1997 as used for CCMVAL-2). Pinatubo plume centred at equator in model. But observations suggest more of plume into SH. General SAD high bias compared to satellite product.

6. Stratospheric Dynamics in UKCA

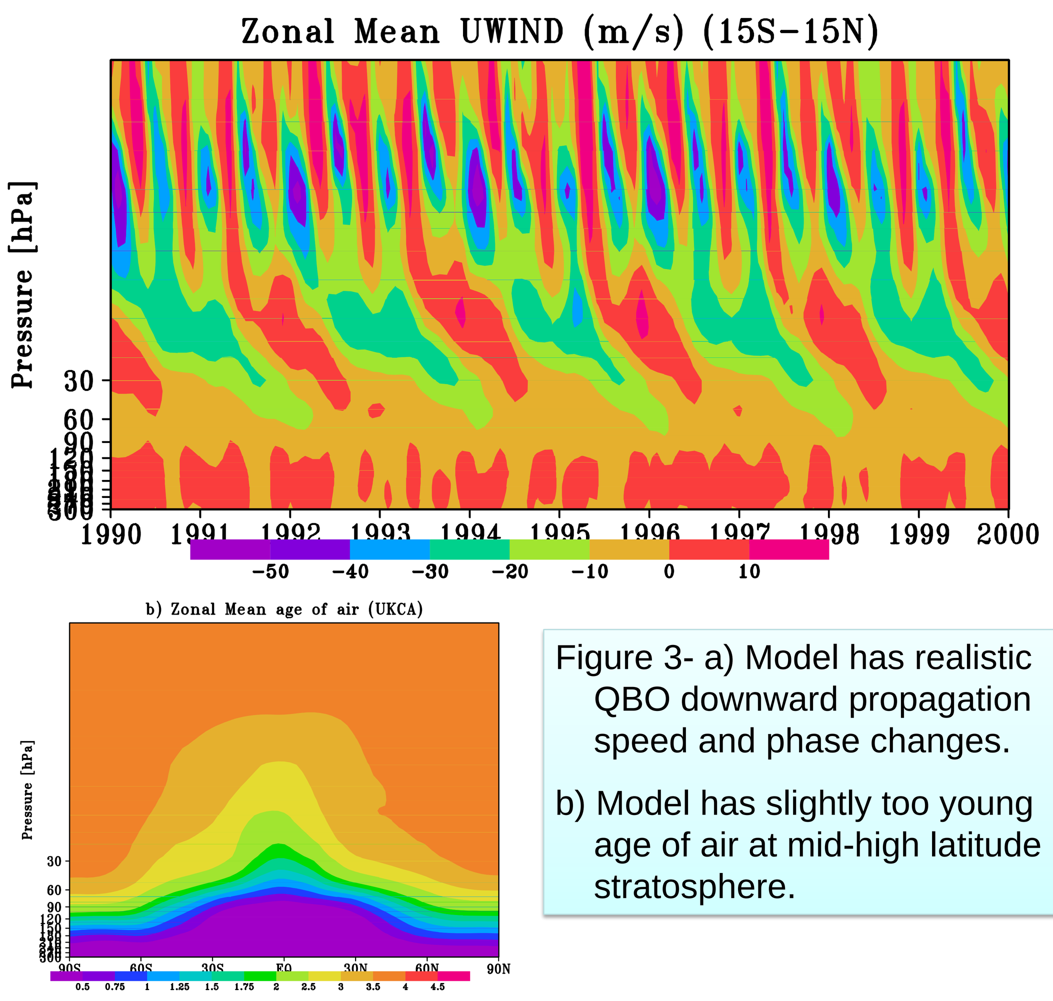


Figure 3- a) Model has realistic QBO downward propagation speed and phase changes.

b) Model has slightly too young age of air at mid-high latitude stratosphere.

7. Aerosol Optical Depth comparison

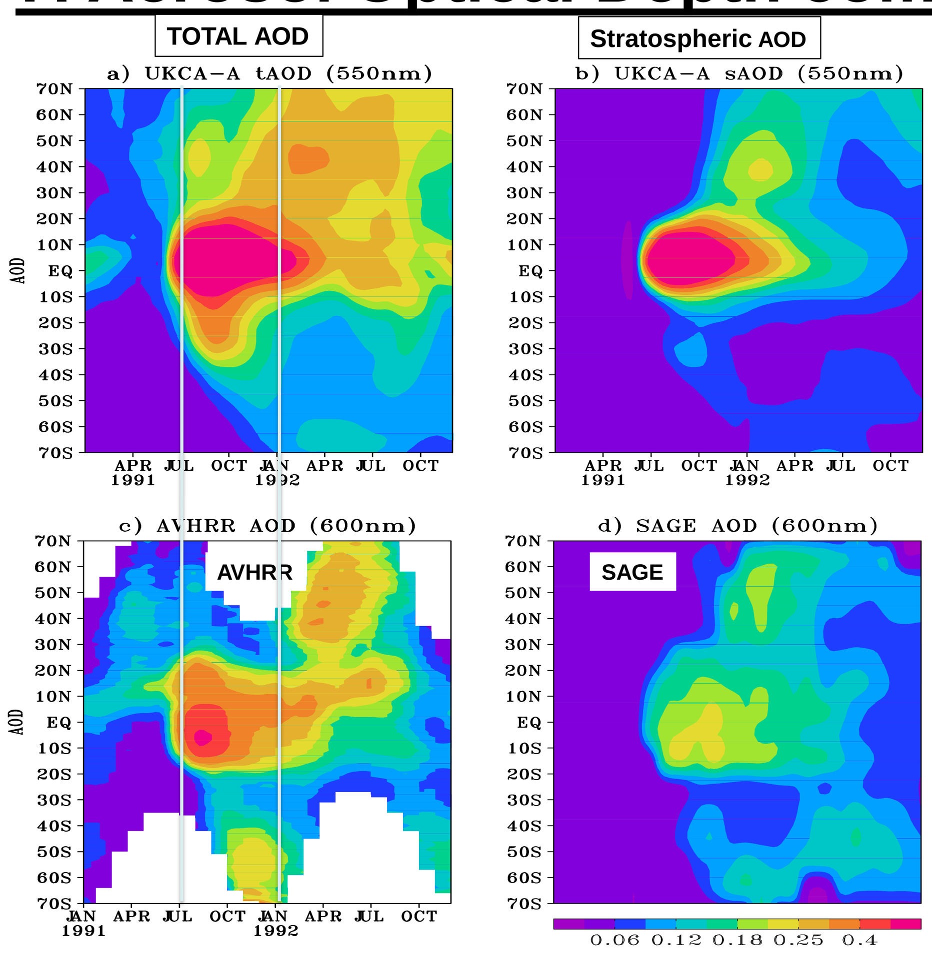
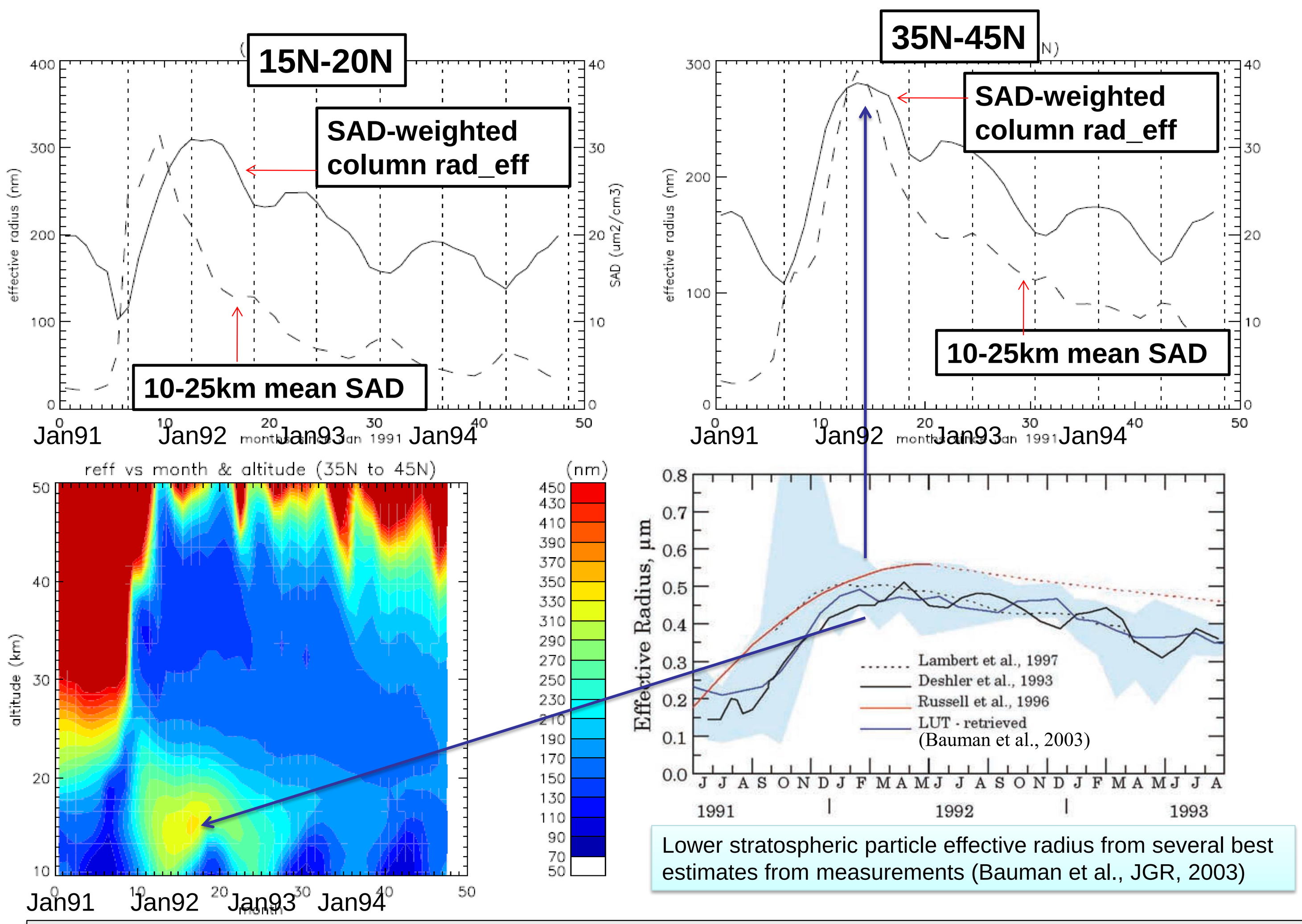


Figure 4- Comparison of simulated aerosol optical depth (AOD) with satellite data sets.

- (a) and (b) are total & stratospheric only AODs from model simulations
- (c) and (d) are AODs derived from AVHRR and SAGE II measurements.
- Temporal AOD evolution is well captured by model simulations, but have slightly higher biases compared to the observations.
- Timing of AOD peaks well captured
  -- in tropics at Aug-Sep 1991
  -- in NH mid-latitudes Jan/Feb AODs generally well captured by model with slight high-bias
- But transport to S. Hemisphere not well captured in these simulations (n.b. no feedback on dynamics here).

8. Evolution of particle effective radius



Lower stratospheric particle effective radius from several best estimates from measurements (Bauman et al., JGR, 2003)

- Tropics: Model effective radius peaks several months later than model SAD and reff decays more slowly than SAD back to non-volcanic background values.
- NH mid-latitudes: SAD peak is several months later than in the tropics. But NH mid-lat effective radius peak at ~ same time as in tropics (~ same as SAD)
- Model simulations underpredict effective radius compared to the observations which could indicate either that the model is generating too many small particles or that growth/sedimentation is not well captured by the modal aerosol dynamics.

9. Extinction comparison (tropics)

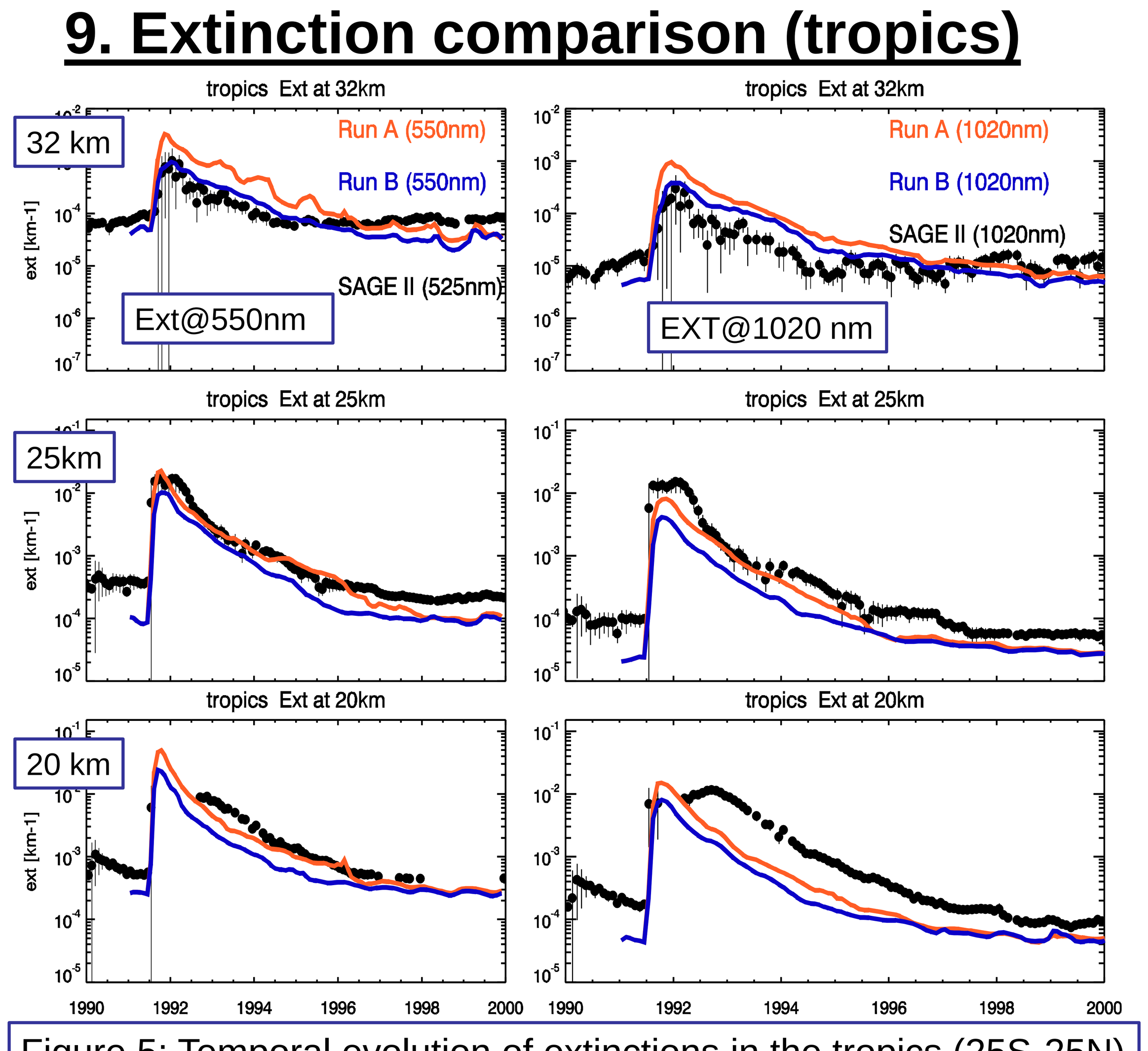


Figure 5: Temporal evolution of extinctions in the tropics (25S-25N) at 20km, 25km, 32km (as Figure 6.30 in SPARC ASAP, 2006).

- Shows extinction at 550nm (left panels) & 1020nm (right panels)
- Orange and blue coloured lines are model simulatons with 20Mt and 10Mt SO2 injected (21-27km) on 15th June 1991.
- SAGE II extinctions are shown with black circles.
- Overall good agreement between model & observed extinctions.
- But in lower stratosphere (~20km) low-bias in 1020 ext. may be due to modal treatment of growth & subsequent sedimentation.
- Many other uncertainties (injection height, primary aerosol, etc.)
- Pinatubo Ensemble Study using emulation to investigate this

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10. Summary and Conclusions

- High-top HadGEM-UKCA model simulates evolution of the stratospheric aerosol size distribution with new particle formation and growth coupled to stratospheric chemistry.
- Simulated stratospheric aerosol optical properties through Pinatubo-perturbed period (1991-95) compare well with a range of observations but have general moderate high-bias
- Observed timing of tropical (~Sep91) & NH mid-latitude (~Jan92) peaks in AOD/extinction well captured by the model.
- Model effective radius evolution also well captured but lower than observed indicating model has too many small particles?

11. References

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