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

The forcing efficacy of tropical volcanic SO2 injection : a case study around the 1991 Mount Pinatubo eruption

Sandip Dhomse, Graham Mann, Lauren Marshall, Anja Schmidt, Martyn Chipperfield, Ken Carslaw (Leeds),

Nicola Bellouin (Reading), Olaf Morgenstern (NIWA, NZ), Fiona O'Connor, Colin Johnson (Met. Office)

Use CCM simulations with interactive stratospheric aerosol to assess:
What would have happened if

I. Pinatubo would have erupted during westerly phase of QBO
II. Ozone chemistry is not influenced by sulphate particles (ideal particle)

SSIRC workhsop – 25th Apr 2016 s.s.dhomse@leeds.ac.uk

Volcanically enhanced stratospheric aerosol & complex–feedback mechanisms ♪

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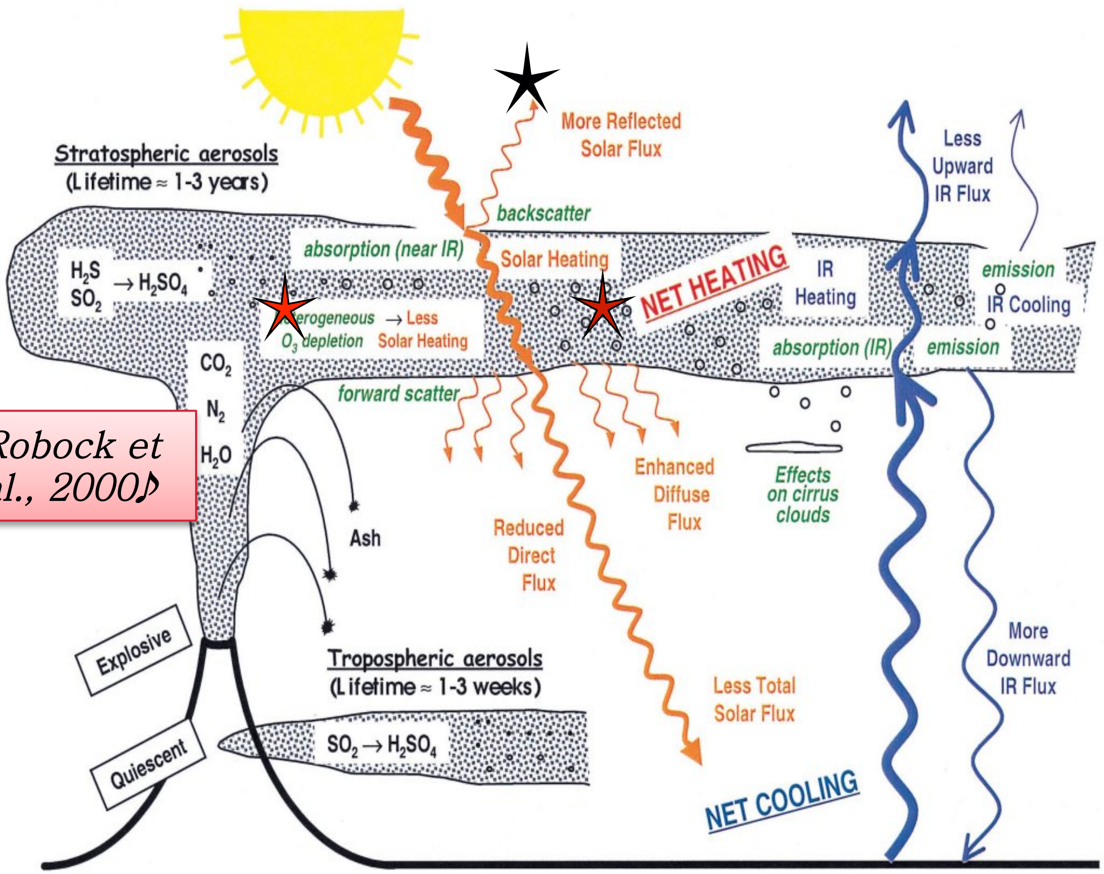


Robock et al., 2000♪

Accurate quantification of volcanically induced changes just in the stratosphere is challenging ♪

(a) direct SW scattering

(b) absorption of LW ♪

(c) ozone loss from heterogeneous chemistry♪

(d) Changes in tropic to pole temp. gradient♪

→These radiative, chemical and dynamical processes inherently coupled (e.g. Dhomse et al., GRL, 2015, no ozone loss in the SH.)♪

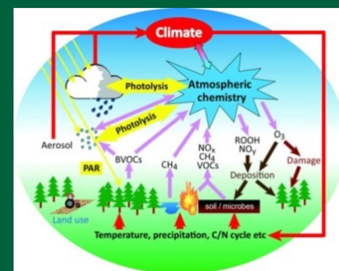
♪

→Use CCM simulations with interactive aerosol model and compare against observations to better understand feedback pathways♪

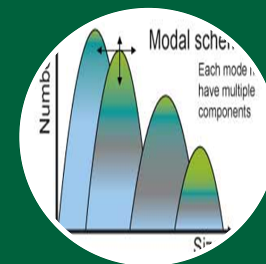
UK Chemistry and Aerosol Model (UKCA)

Met Office

Dynamics + radiation (UM)



Interactive strat-trop chemistry (CheST)



Interactive aerosol microphysics (GLOMAP-mode)

UM-UKCA has tropospheric & stratospheric chemistry (CheST) and interactive aerosol microphysics (GLOMAP-mode) with online radiative-dynamical coupling within the UK Met Office Unified Model (high-top ~80km version of HadGEM3 model).

Stratospheric Sulphur chemistry within CheST and coupled to GLOMAP aerosol

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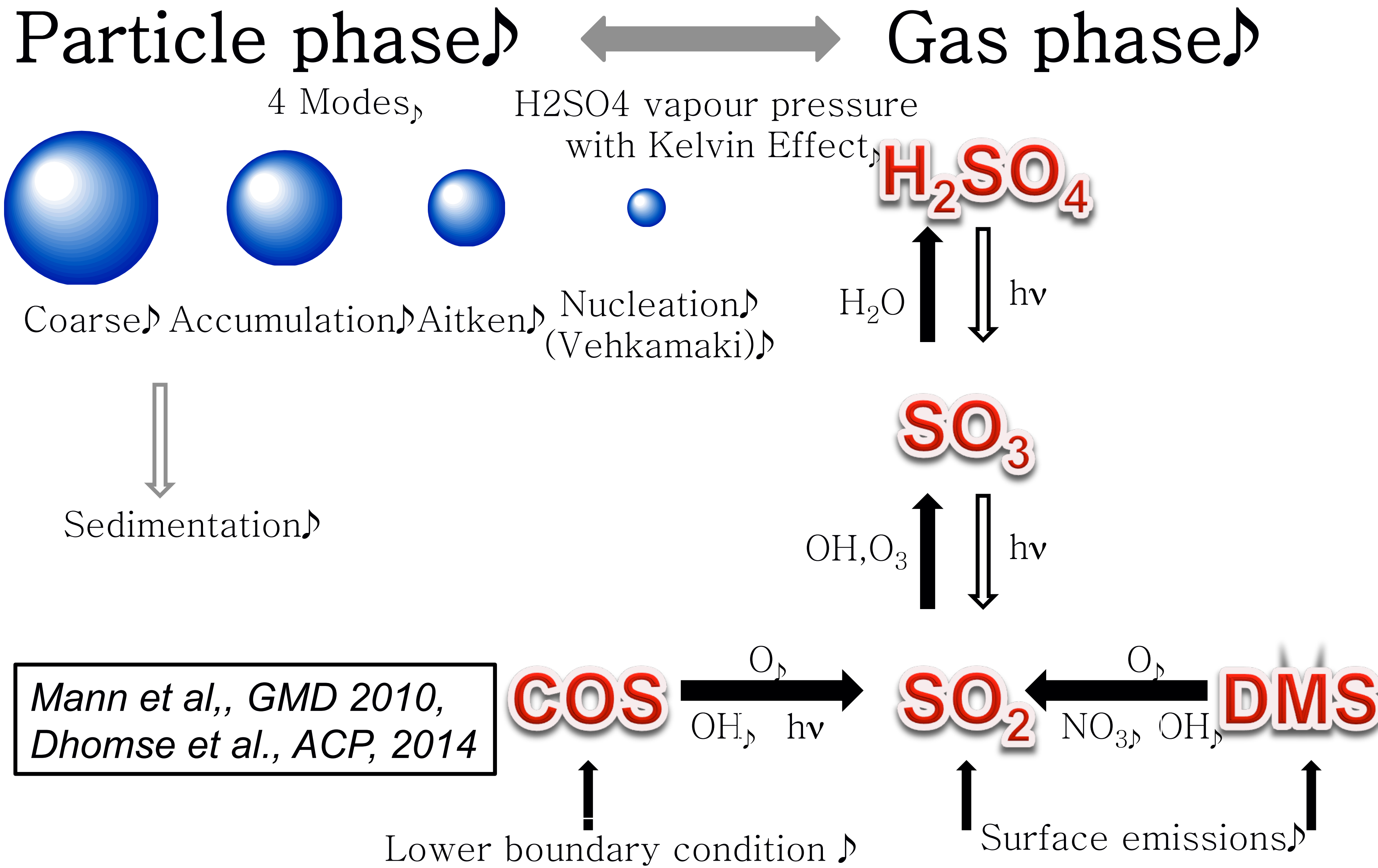

Mann et al,, GMD 2010,
Dhomse et al., ACP, 2014

Model Experimental Set up ♪
♪

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➢Important updates since Dhomse et al., ACP (2014): (a) UM v8.4 (L96L85), (b) aerosol are coupled with radiation scheme (RADAER), (c) implemented meteoric smoke particle interactions ♪

➢ Transient simulations through 1990s Pinatubo-perturbed period♪

➢ Experiments injecting 14Tg SO2 injection, 21-23km (mid-point injection settings for Pinatubo in HErSEA intercomparison for Interactive Stratospheric Aerosol models (ISA-MIP) (see posters X3.10, X3.12)♪

➢Paired on/off experiments include both the heterogeneous chemistry and the dynamically-induced changes use prescribed SAD datasets ♪

♪

eqbo → 3 member ensemble initialised with easterly QBO♪

wqbo → 3 member ensemble initialised with westerly QBO♪

feqbo → 3 member ensemble initialised with easterly QBO but fixed surface area density (SAD)♪

For more info see poster X3.14

QBO in timeslice control run

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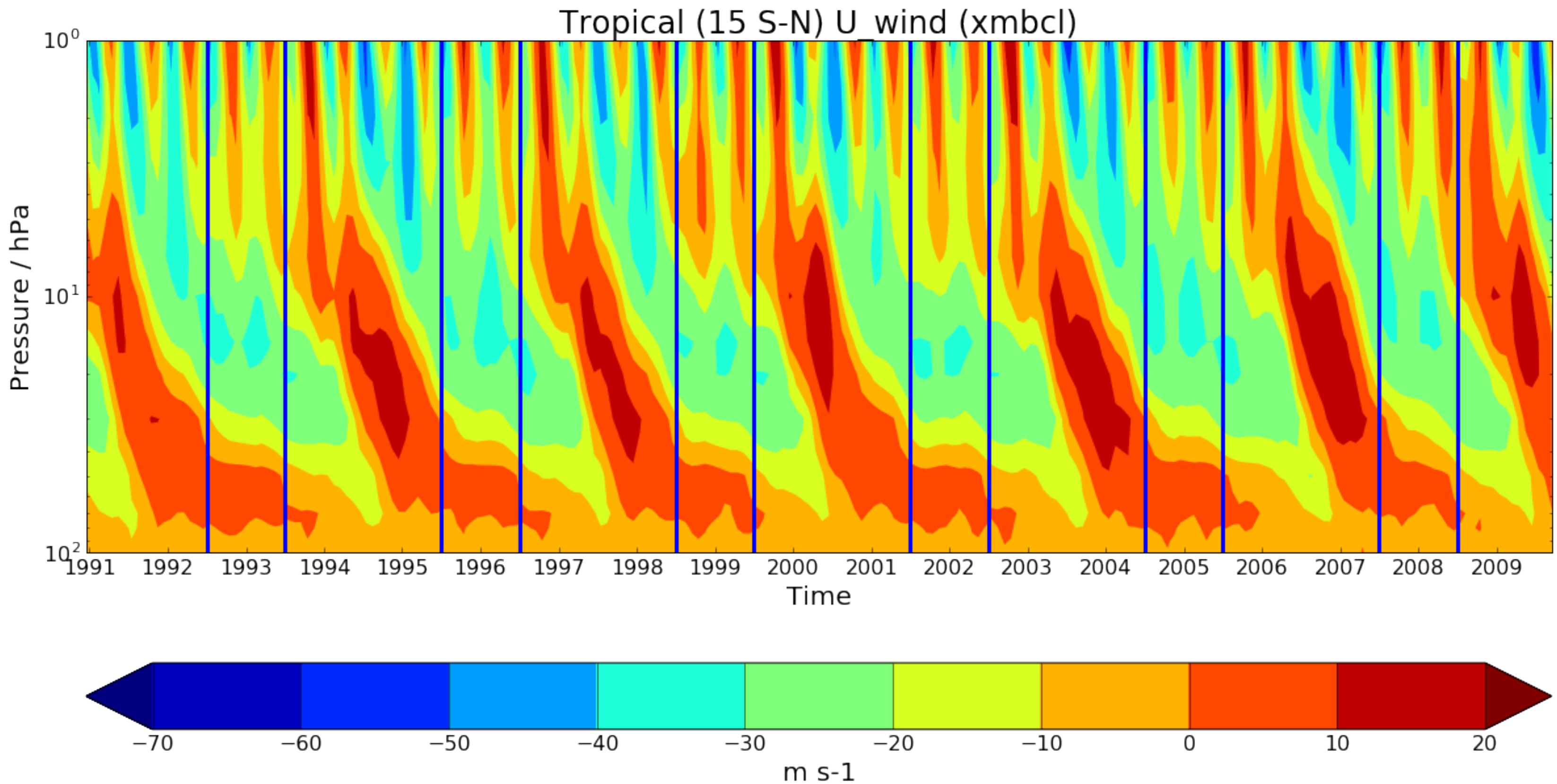

Model has internally-generated QBO and its amplitude and period shows reasonable agreement with the observations, but has slightly younger age of air at the poles (e.g. Dhomse et al., 2014)

Easterly vs Westerly initialisations♪

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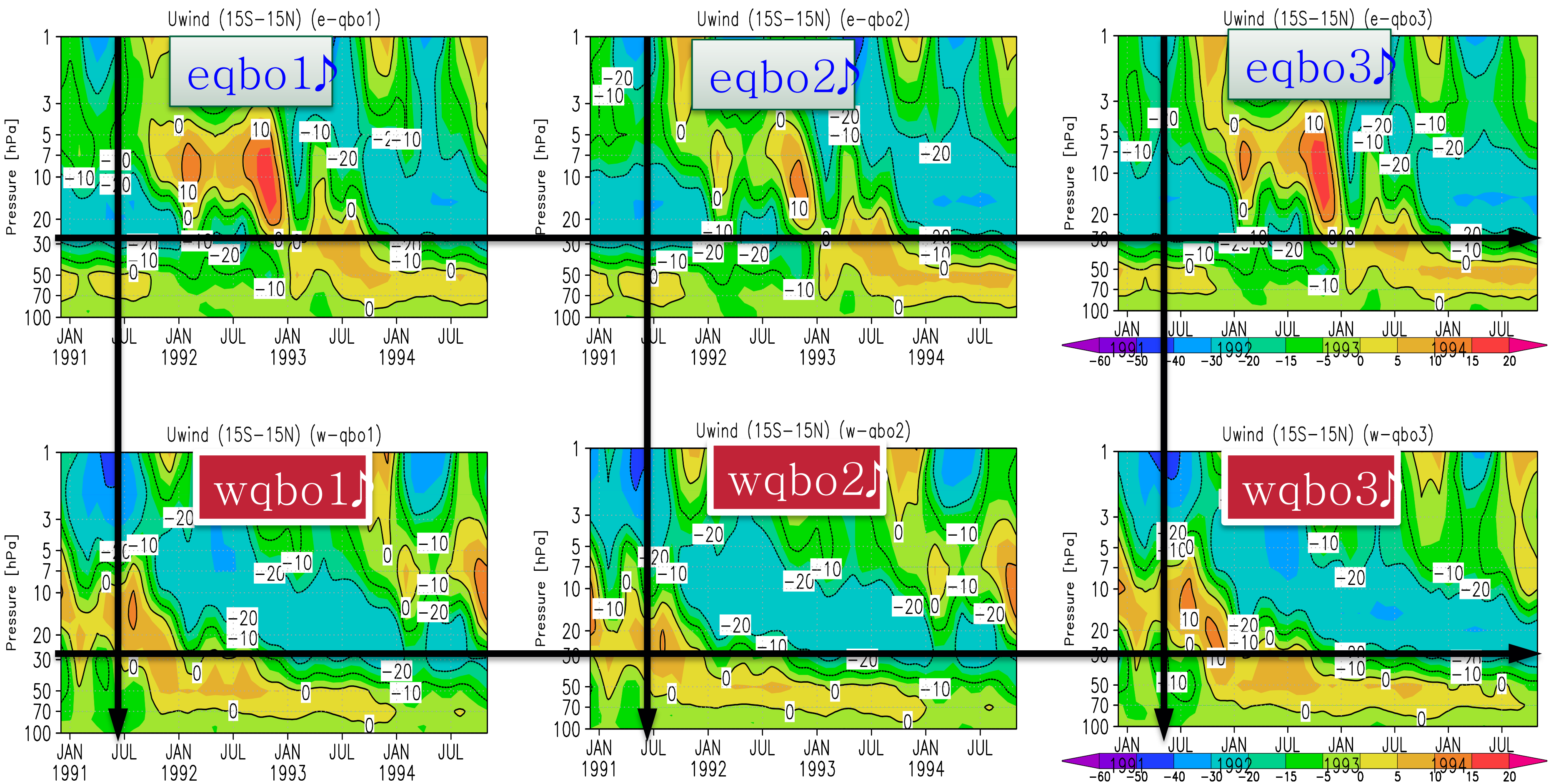

Top : 3 ensemble members with at least 6mo <u>easterly</u> QBO (Jun91–Dec91)♪

Bottom: 3 ensemble members with at least 6mo <u>westerly</u> QBO (Jun91–Dec91)♪

Evolution of Stratospheric AOD

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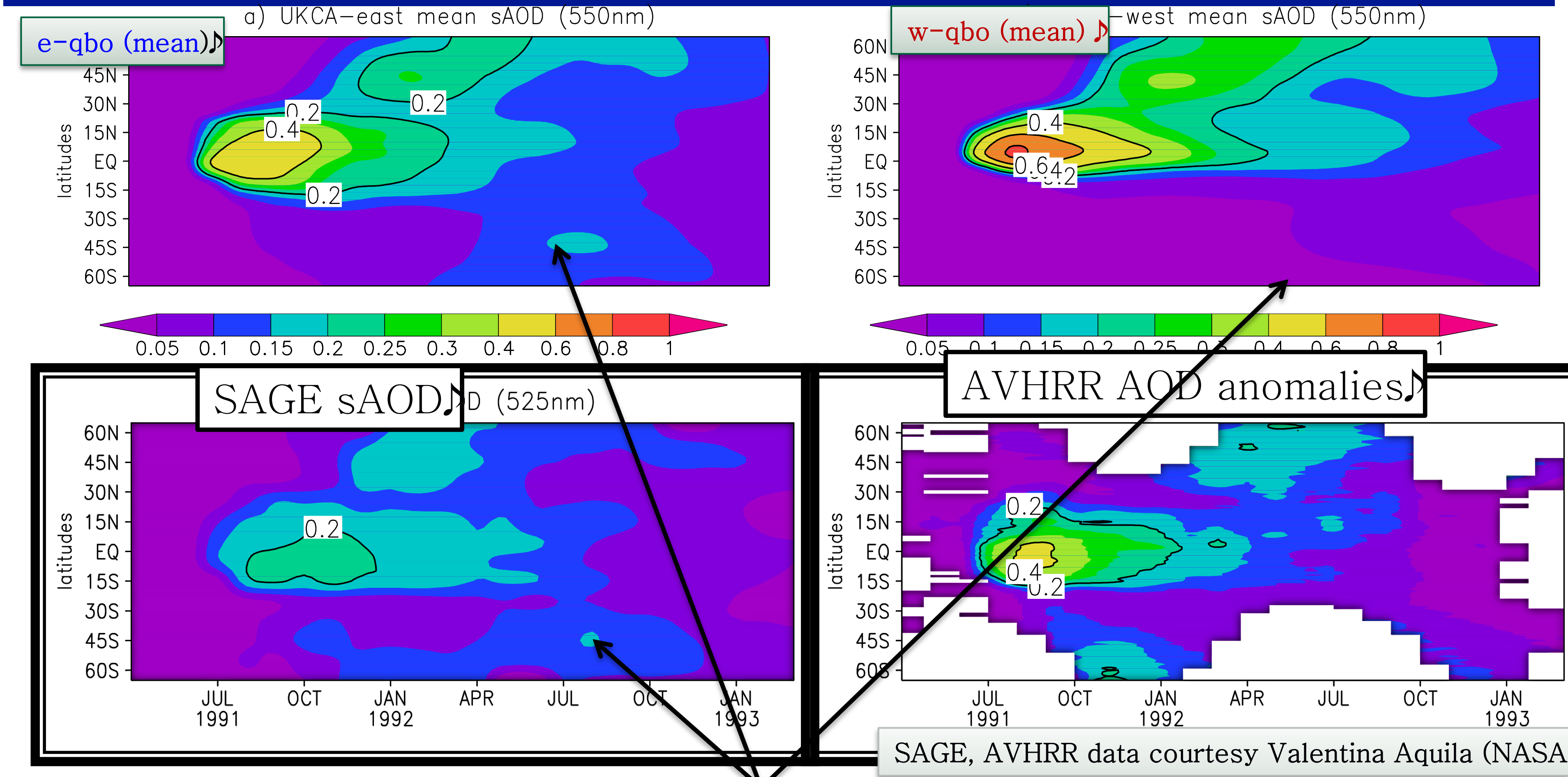

W- qbo: insignificant transport in the SH and high biases in the tropical AOD and aerosol plume is transport mainly in the NH

Extinction at 550 nm and 1020 nm

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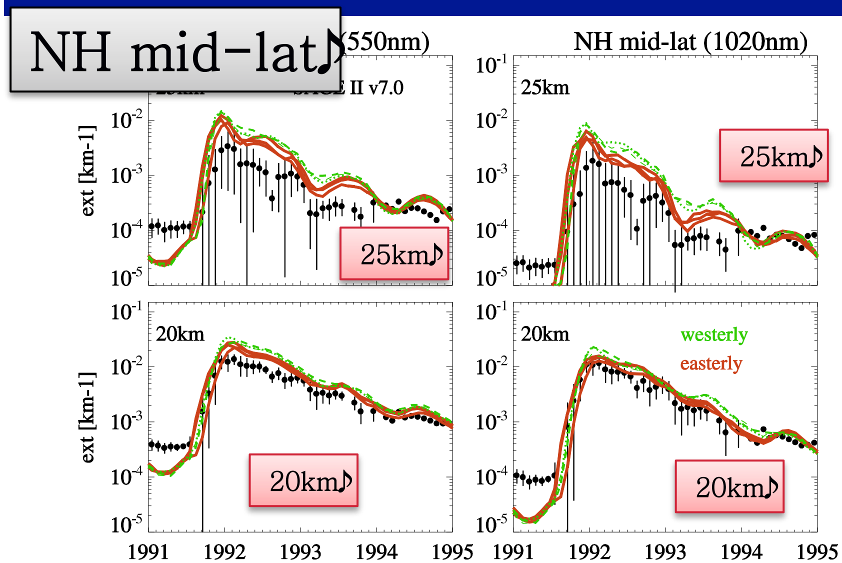

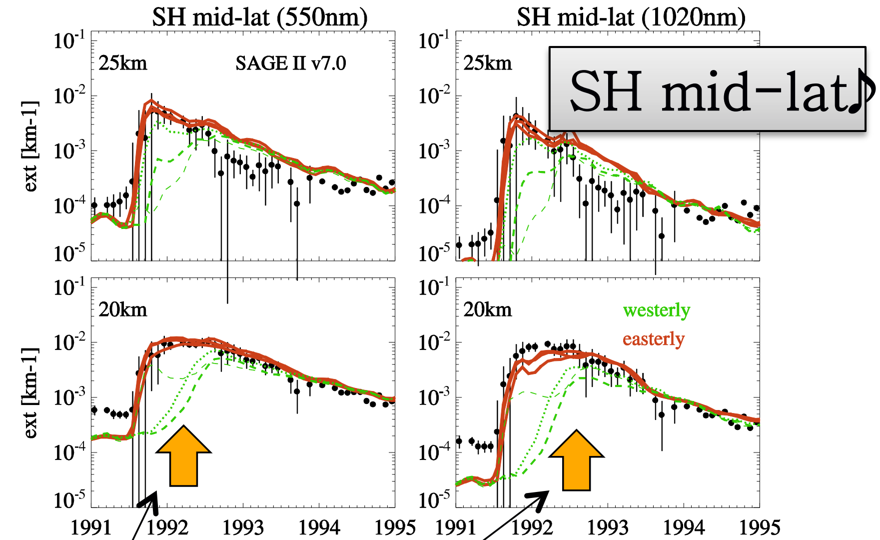

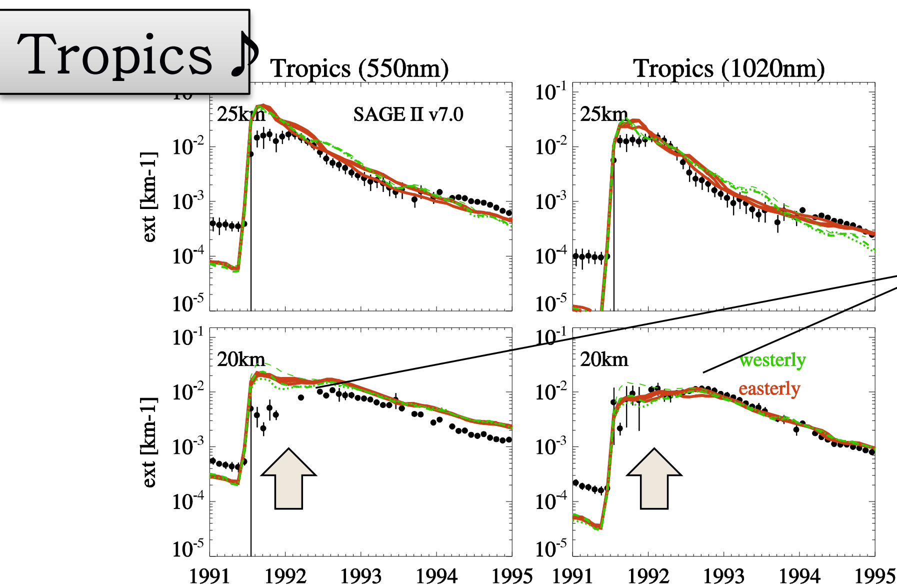

- **Modelled extinction with e-qbo show reasonable → model stratospheric aerosol e-folding time agrees with the observations (updates from Dhomse et al., 2014)**
- **Large error in SAGE II observations during peak aerosol loading → plateau in extinction in the tropics is not well understood**
- **Simulation with w-qbo → worst in the SH**

Effective Radius at 20 & 25km

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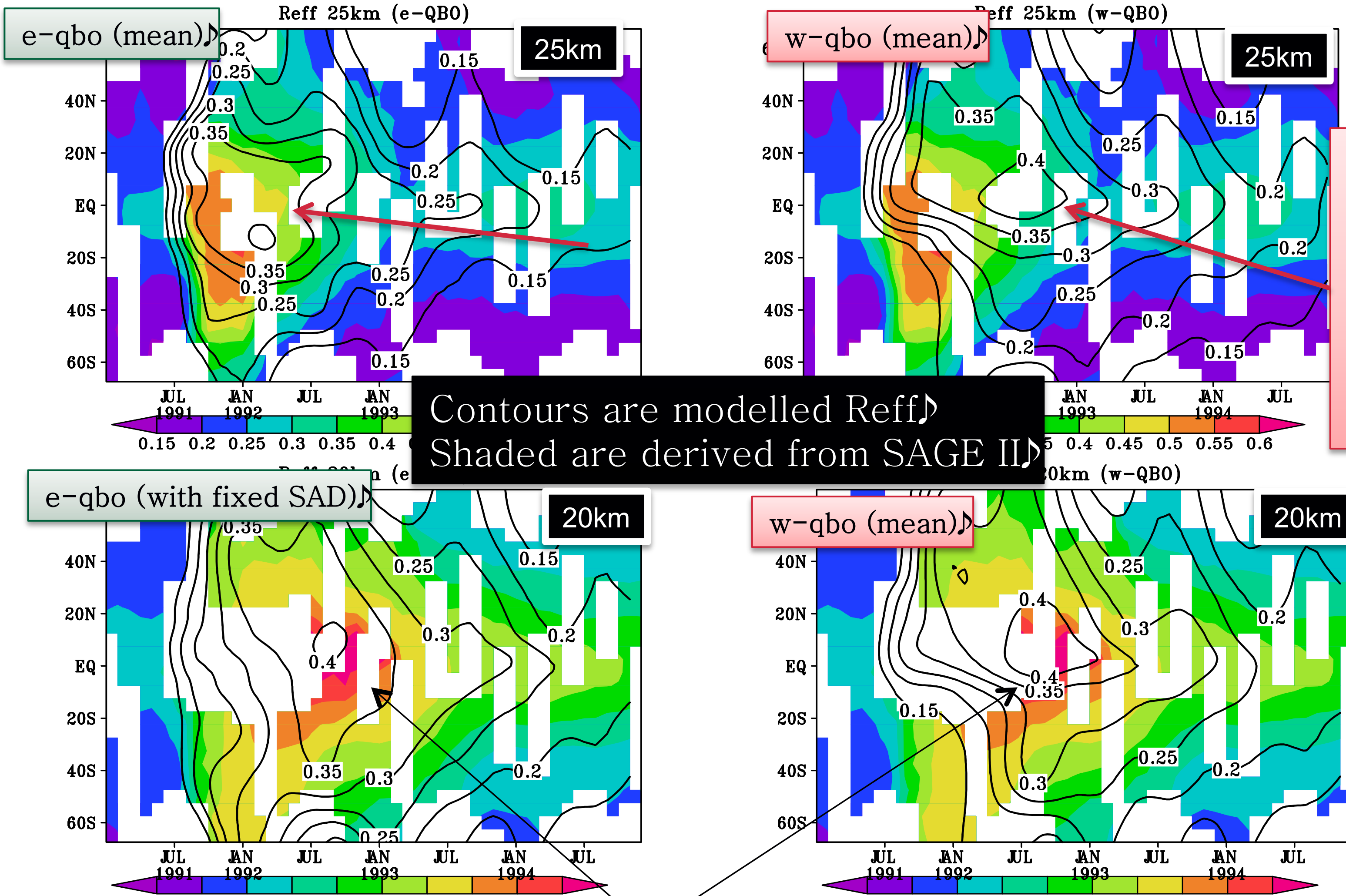

@25km peak in Reff would have been much later in w-qbo runs

SAGE II Reff courtesy Philip Russell (NASA)

Modelled Reff is bit low biased and evolution agrees with SAGE at 20km, but biases are larger in the w-qbo runs

SW clear-sky volcanic forcing♪

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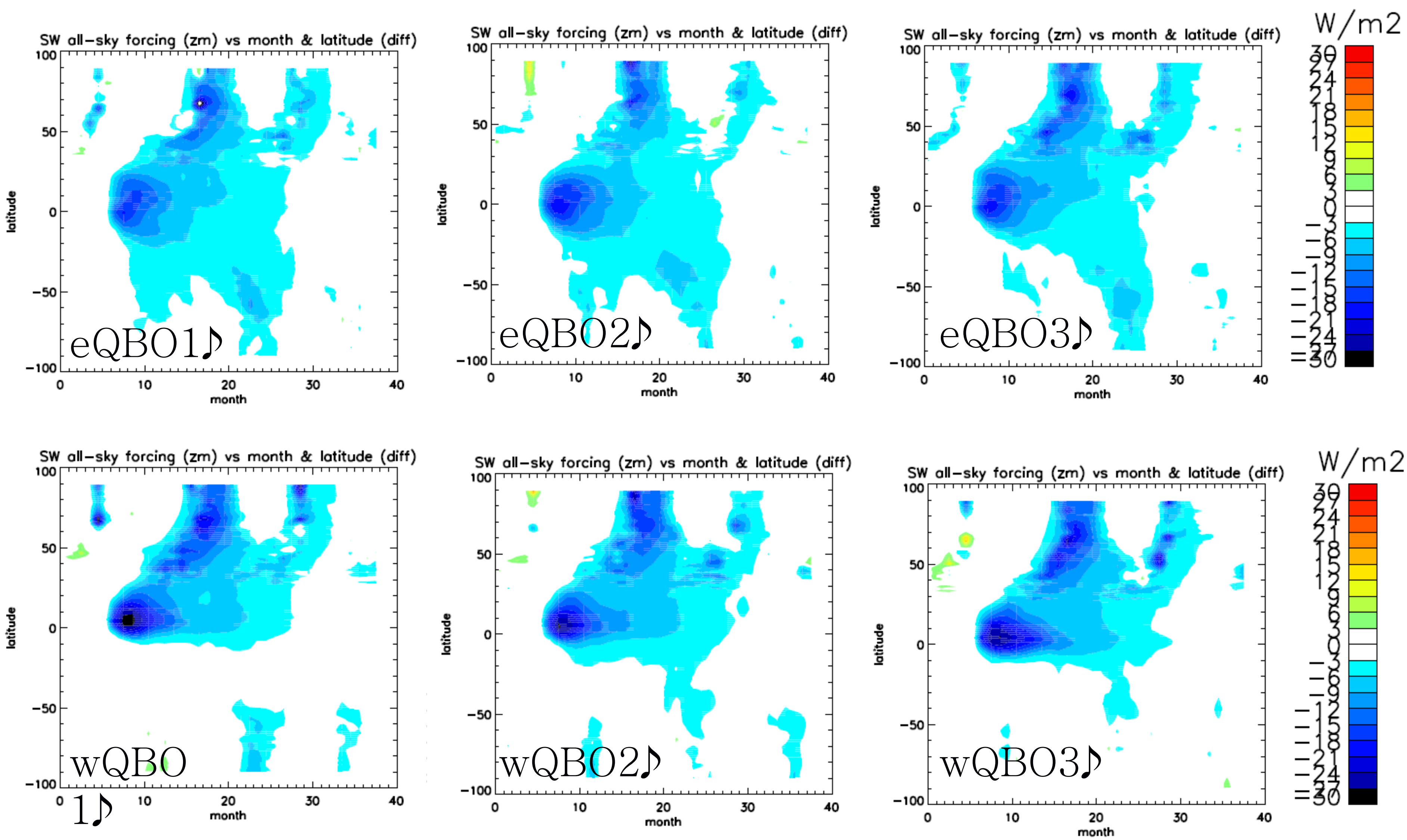
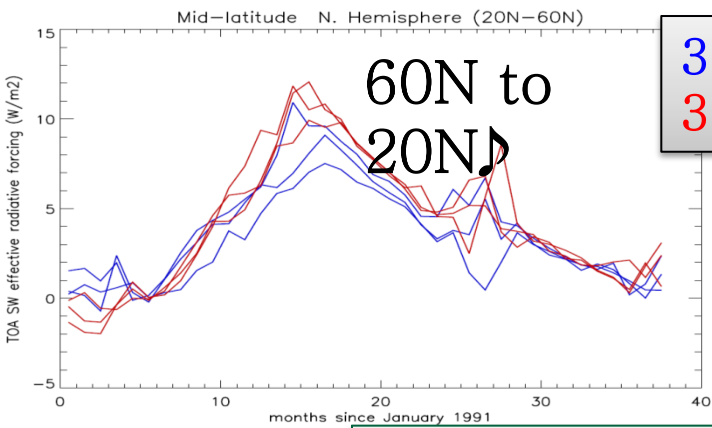
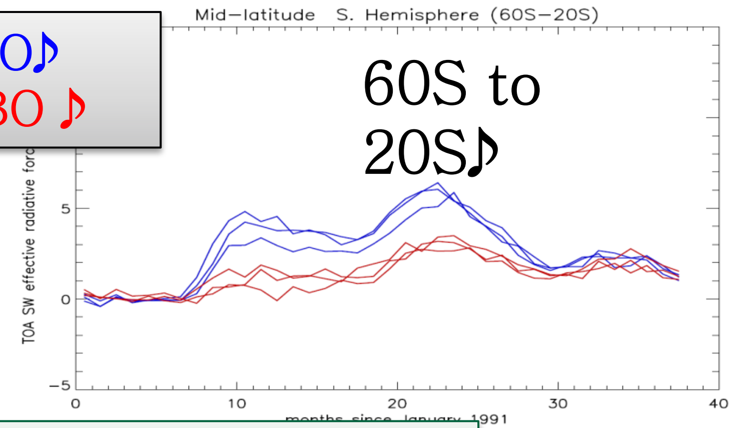


SW and LW forcing♪

3 e-QBO♪
3 w-QBO ♪

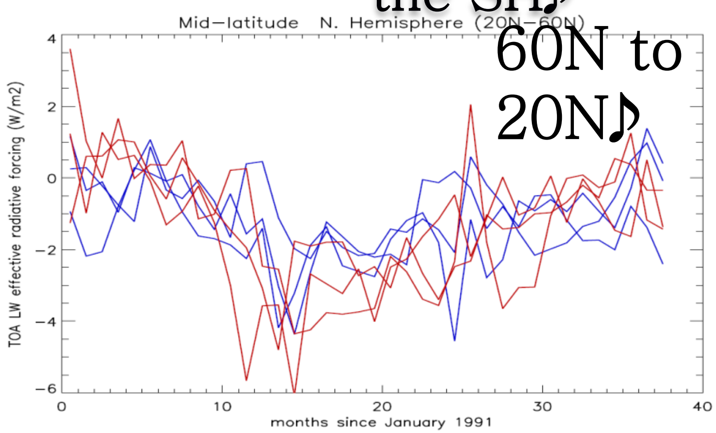
Pinatubo SW volcanic ERF ♪

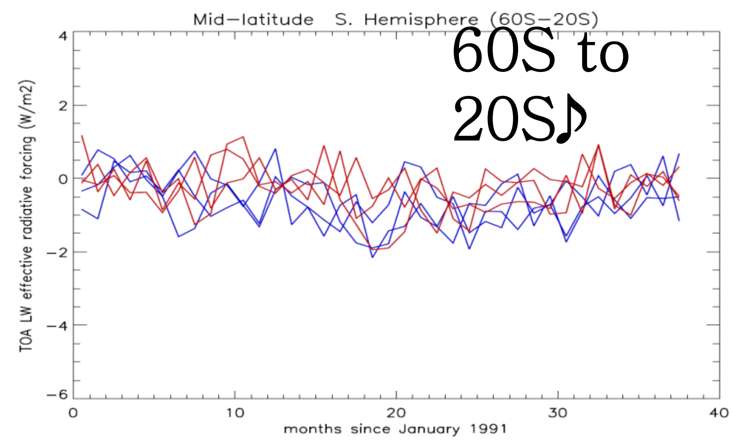




w-qbo: slightly more positive forcing in the NH but negligible in the SH♪

Pinatubo LW volcanic ERF ♪





Comparing SW & LW volcanic forcing to ERBE anomaly ♪

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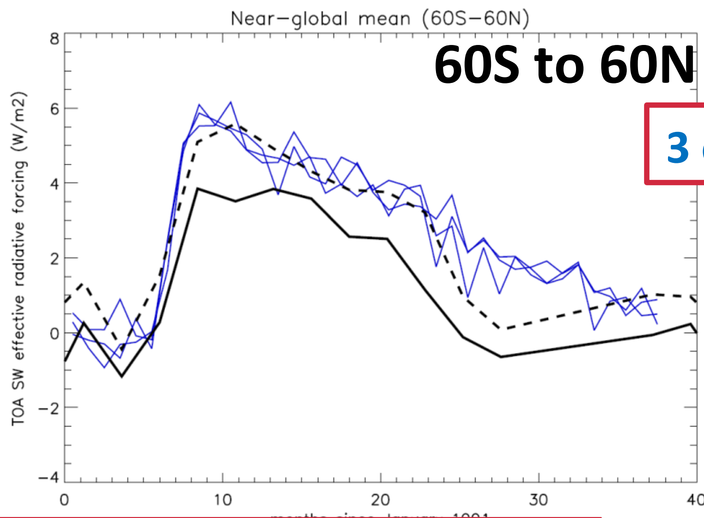
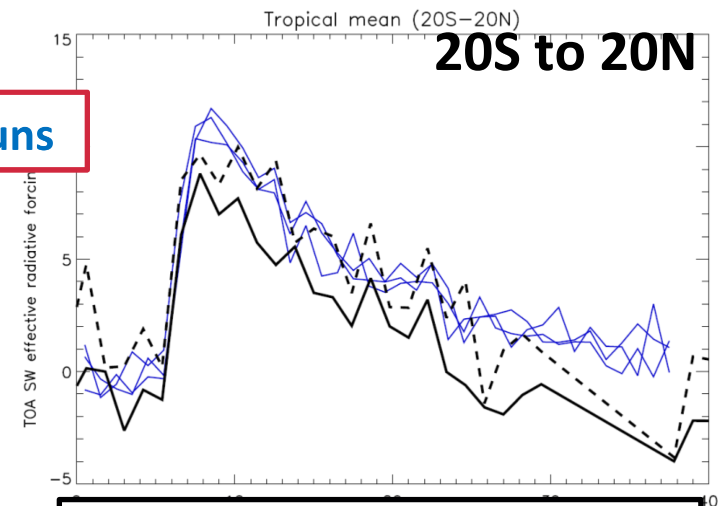
Pinatubo SW volcanic ERF ♪



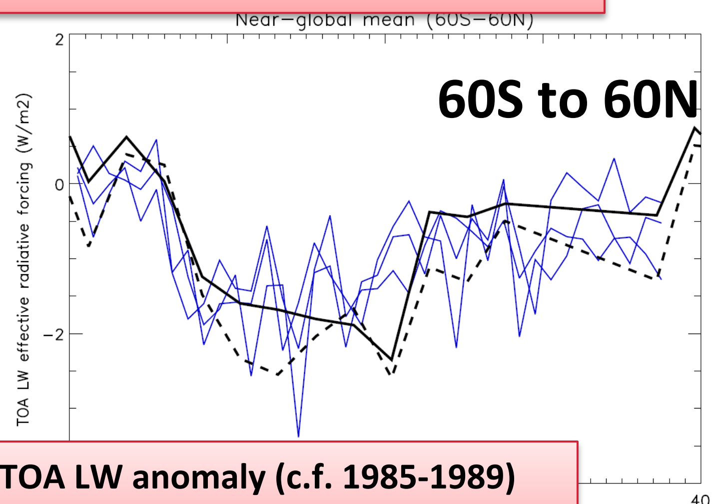
3 e-QBO runs

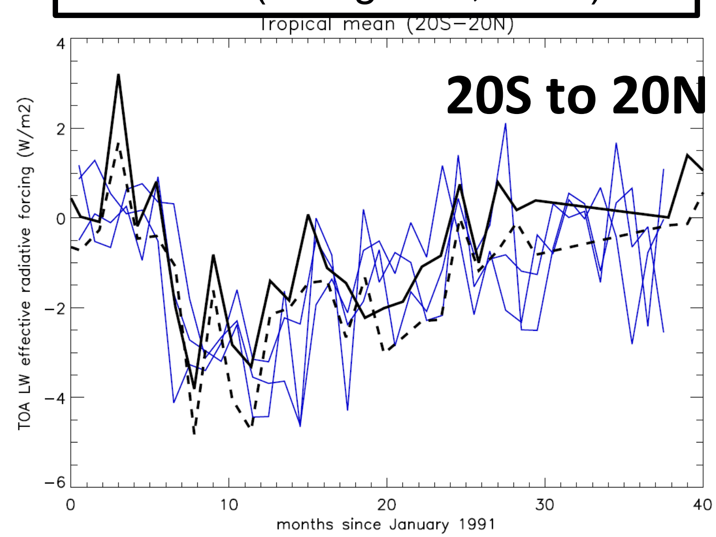


Black solid = TOA SW anomaly (c.f. 1985-1989)
Black dashed = TOA SW anomaly (c.f. 1995-1997)

Black: ERBE from ERBE data ed3 rev1 (Wong et al, 2006)

Pinatubo LW volcanic ERF ♪





Black solid = TOA LW anomaly (c.f. 1985-1989)
Black dashed = TOA LW anomaly (c.f. 1995-1997)

Aerosol inducted warming in the tropical stratosphere

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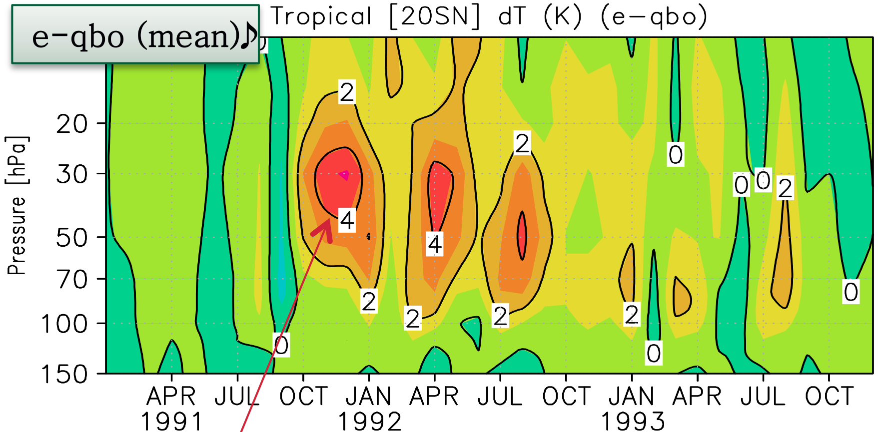

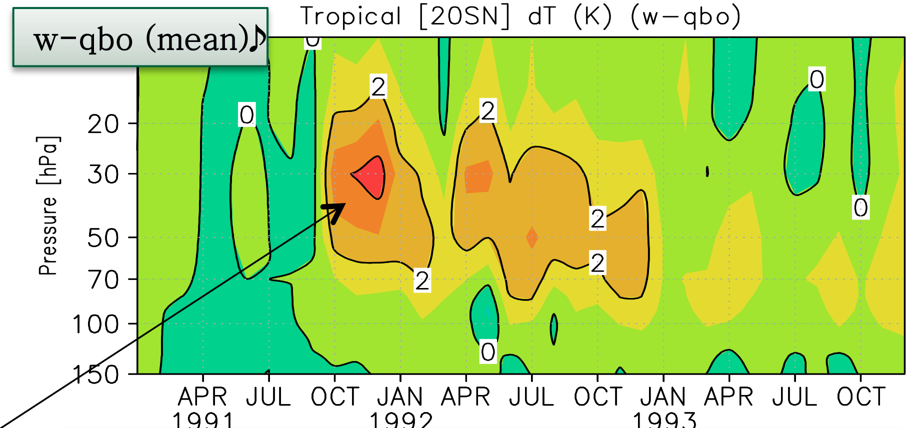

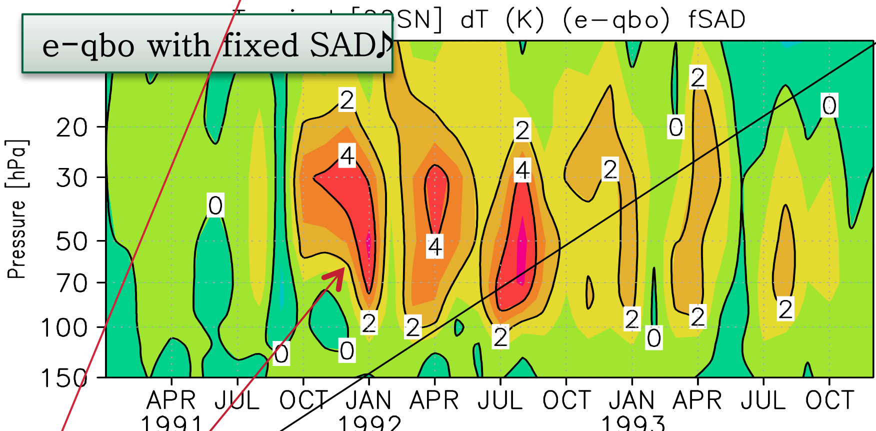

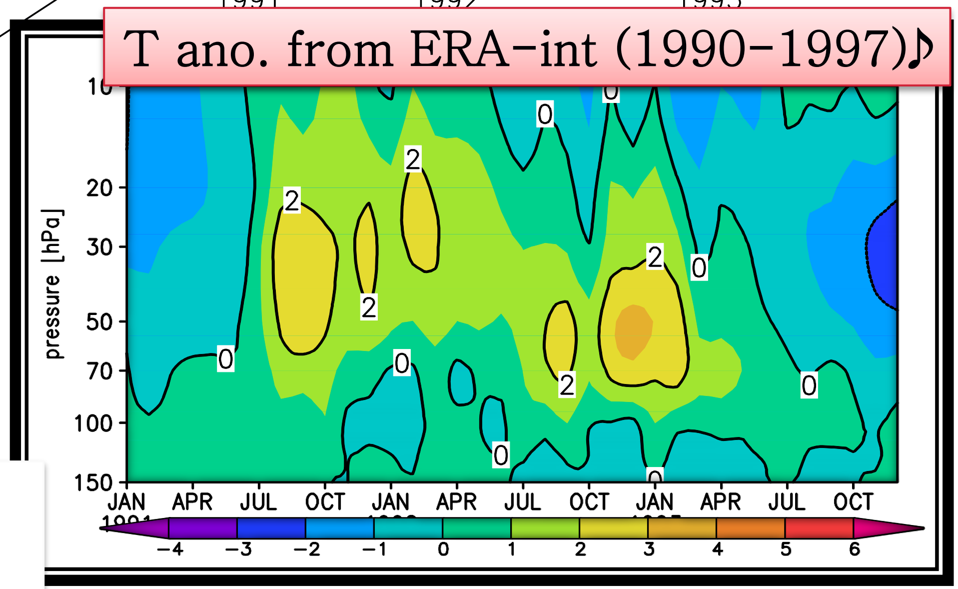

- Positive biases in warming and it peaks at slightly higher altitudes
- W-qbo shows lesser biases
- With ozone losses –more heating

1991/92 –moderate El-Nino

Change in tropical H2O (%)

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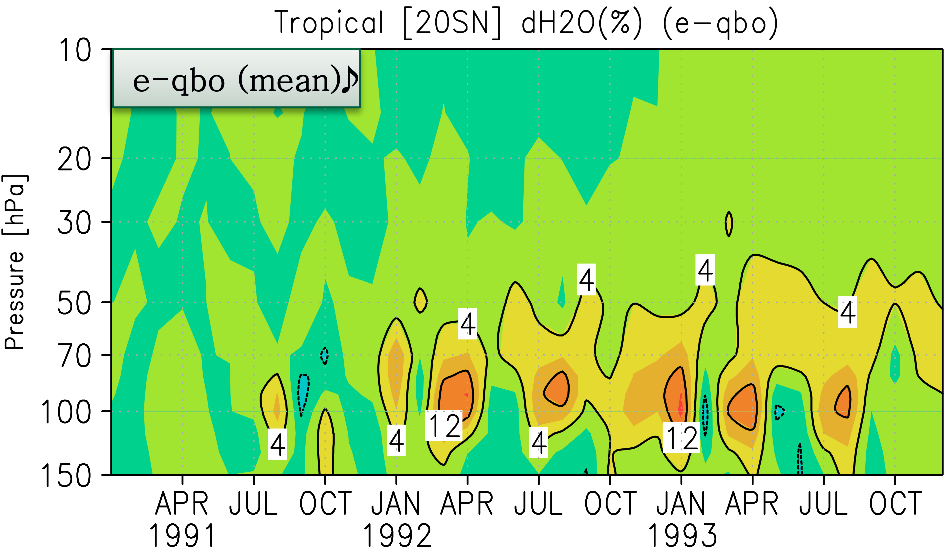

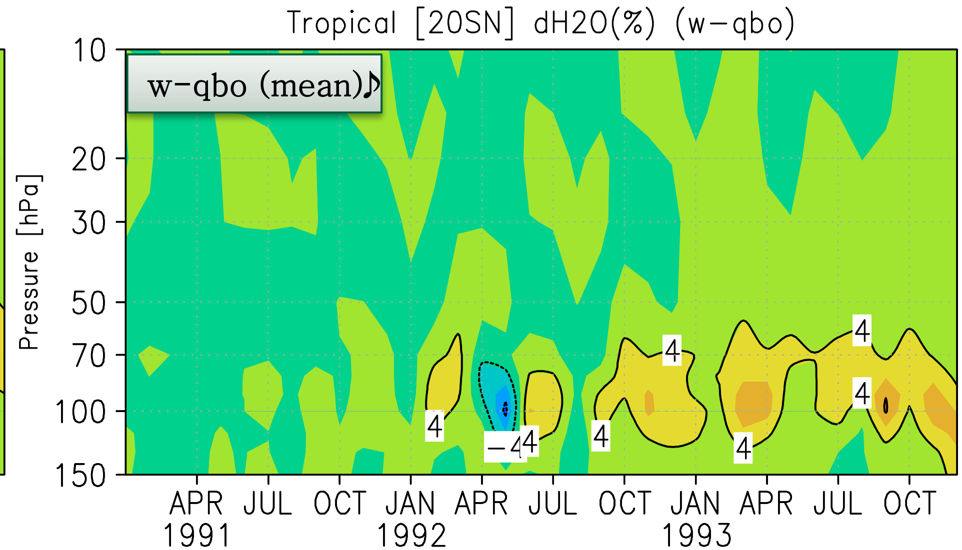

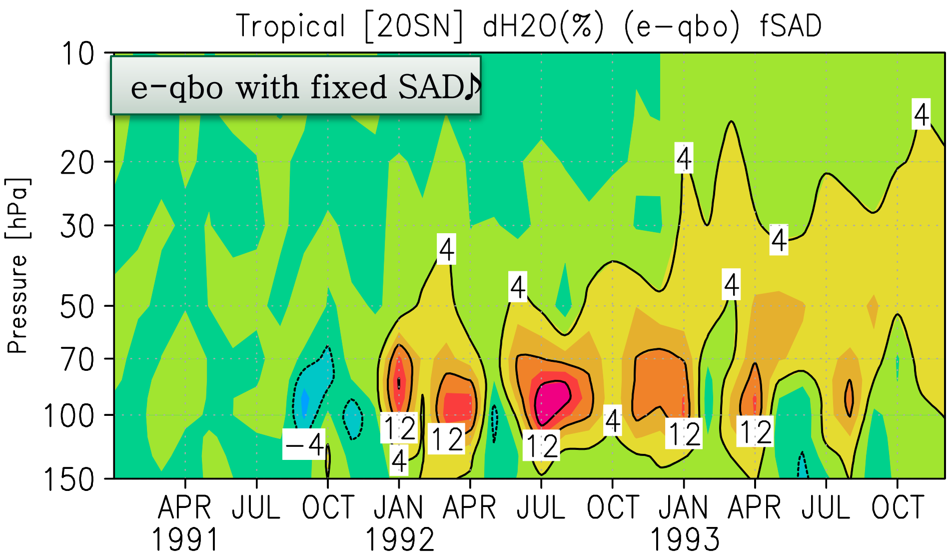

Heating in the tropical lower stratosphere enhances amount of water vapour entering in the stratosphere

Changes in total ozone (DU)

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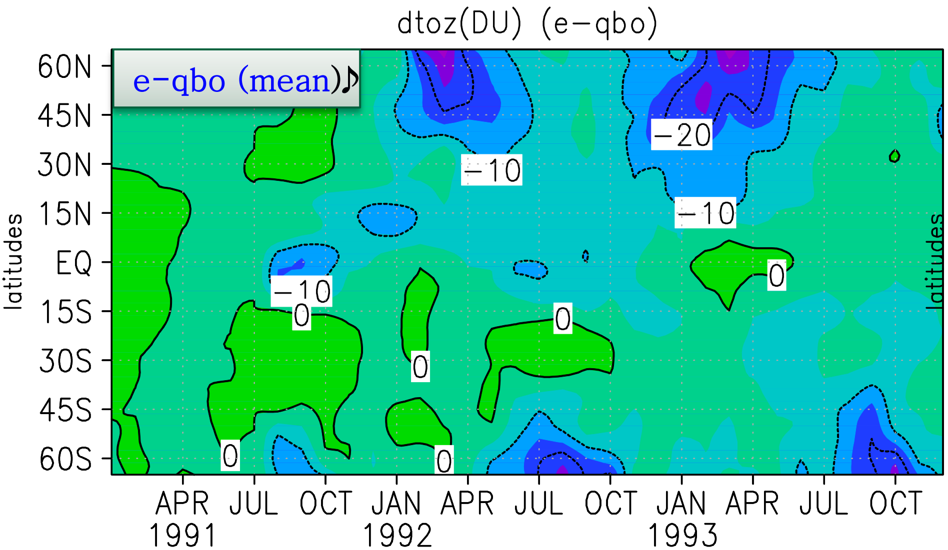

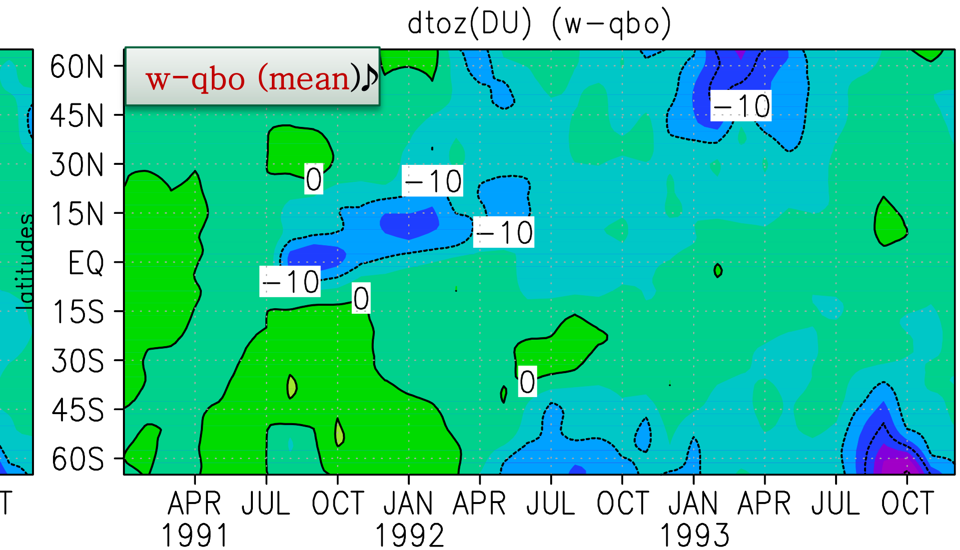

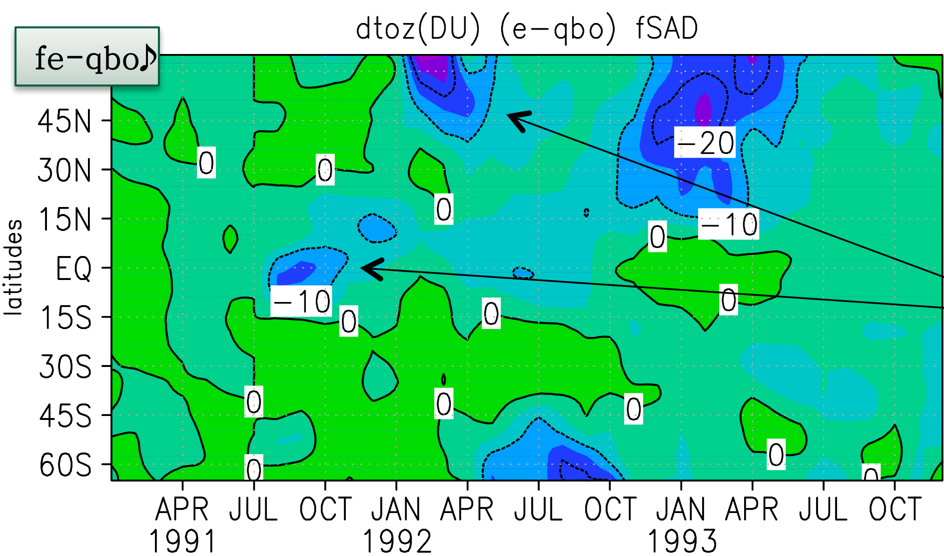

- Inter-hemispheric asymmetry in total ozone changes seem to in agreements with the observations (See Dhomse et al., 2015, GRL)
- Simulation with fixed SAD suggest nearly 10 DU toz dynamical ozone loss in the tropics as well as contribute to mid-lat ozone losses

Summary and Outlook♪

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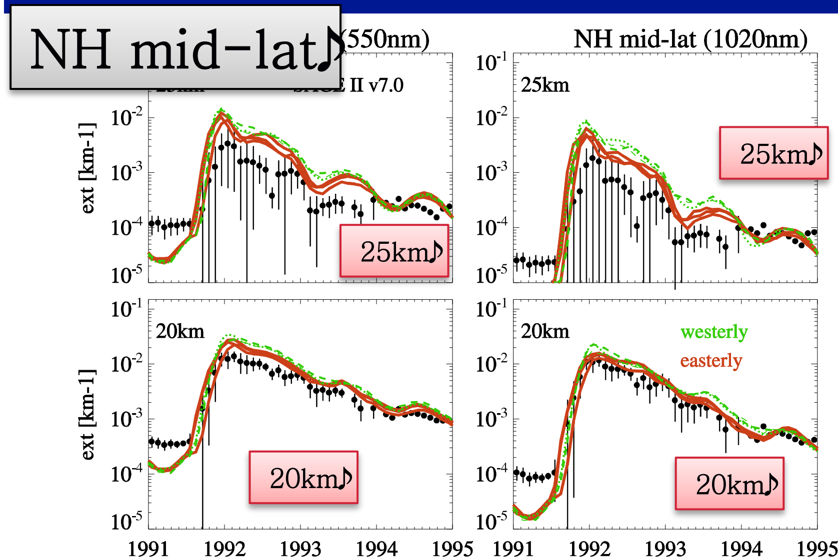
- Used CCM with interactive stratospheric aerosol to investigate how the QBO phase modulates the effects from major tropical eruptions♪
- Simulated aerosol properties with e-QBO and 14Tg SO2 injected between 21-23 km are consistent with most of the observations. ♪
- Simulations initialised with w-QBO enhances inter-hemispheric asymmetry in stratospheric aerosol♪
- Aerosol induced heating significantly modifies the stratospheric transport and causes up to 10 DU toz changes in the tropics. ♪

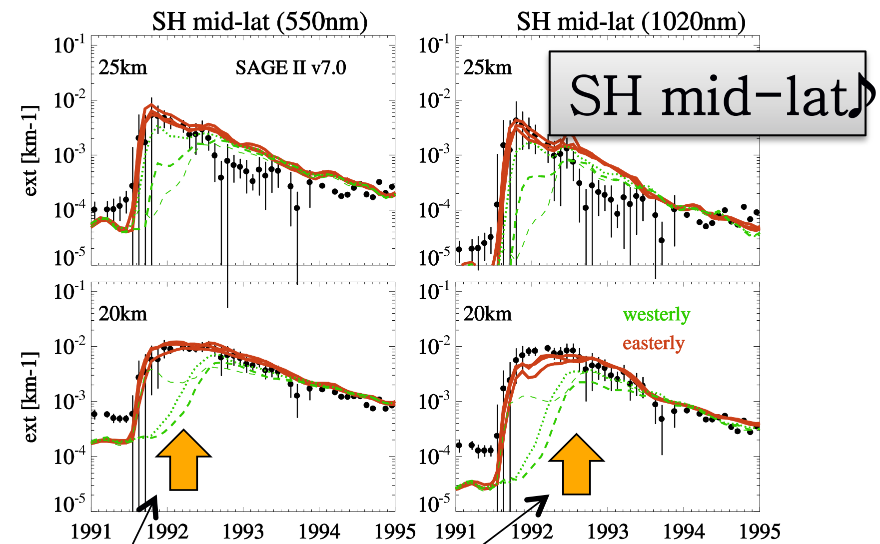
- Experiments to♪

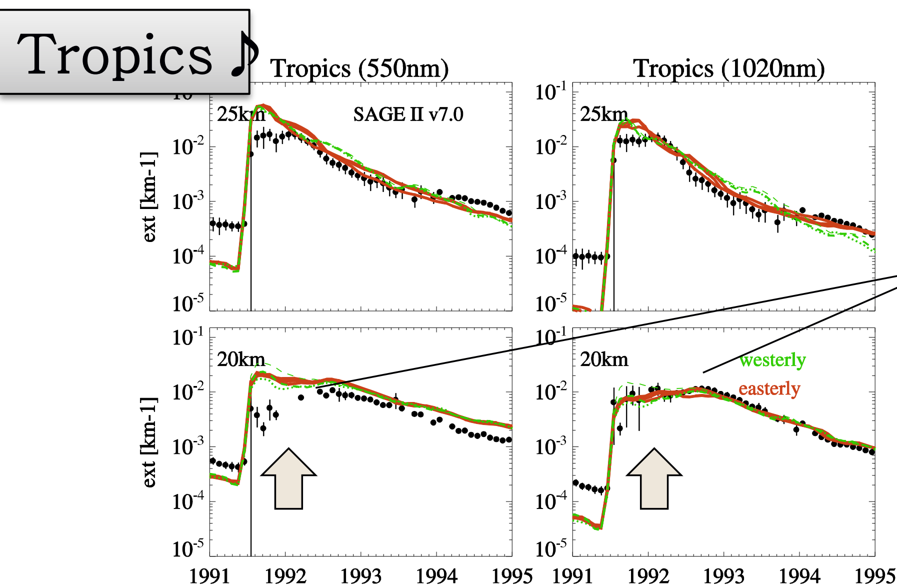
(a) analyse effects from major historical tropical eruption♪

(b) investigate post 2000 stratospheric aerosol increase (hiatus?)♪

Extinction at 550 nm and 1020 nm







- Modelled extinction with e-qbo show reasonable → model stratospheric aerosol e-folding time agrees with the observations (updates from Dhomse et al., 2014)
- Large error in SAGE II observations during peak aerosol loading → plateau in extinction in the tropics is not well understood
- Simulation with w-qbo → worst in the SH

Sensitivity to Injection Heights

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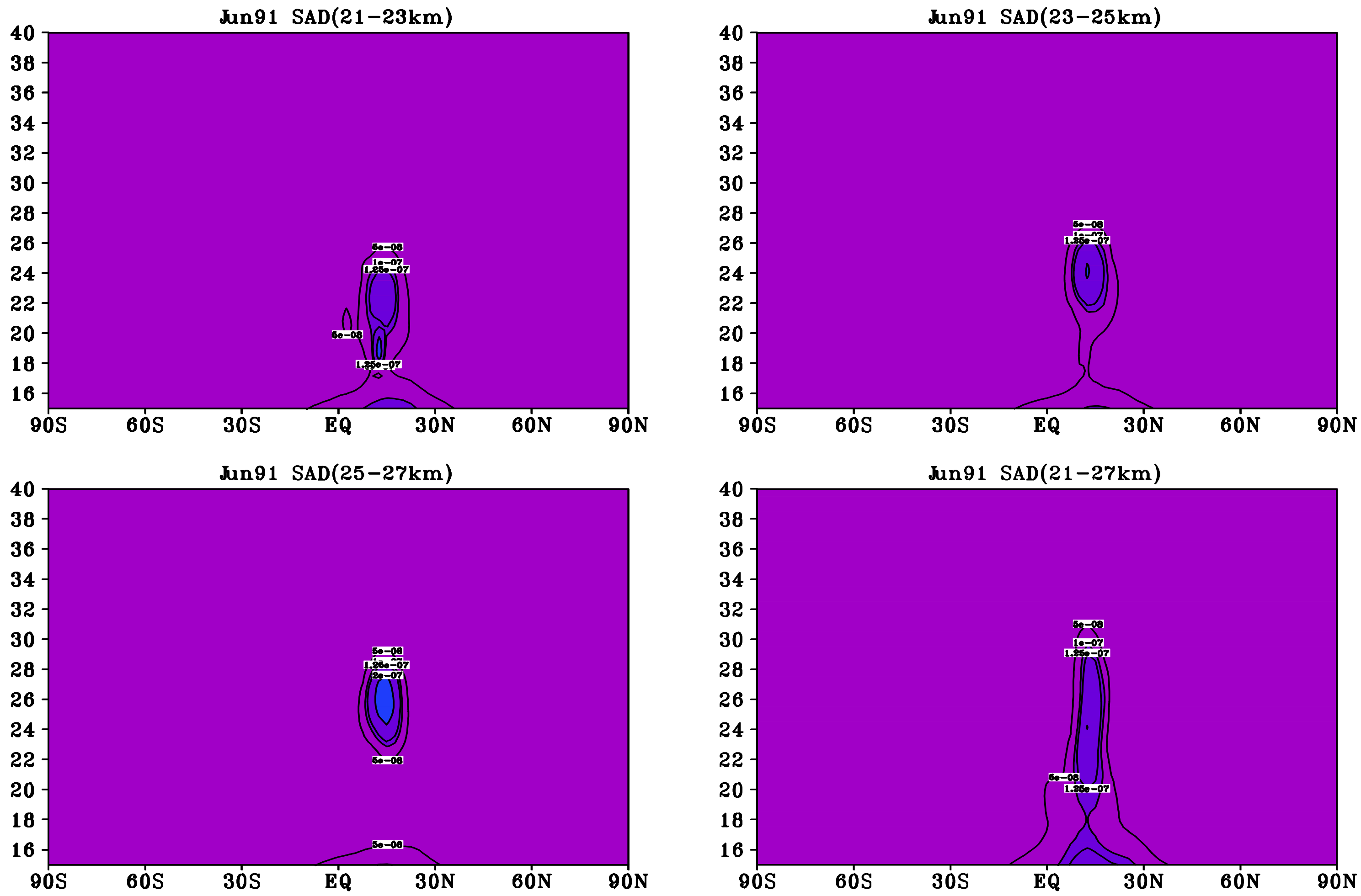

20 tonnes of SO_2 is emitted at 15N at different altitudes

Sensitivity to Injection Heights

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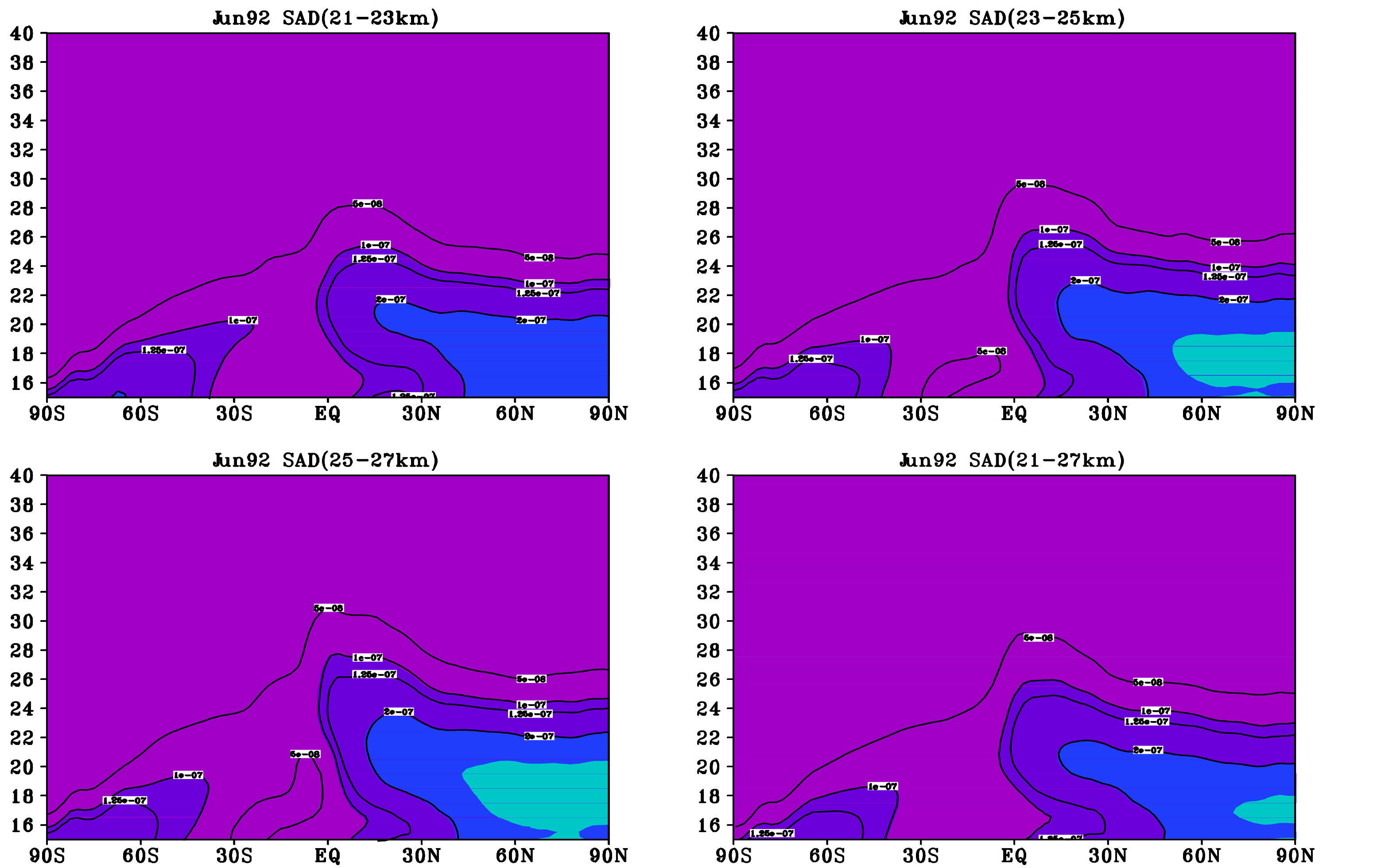

Lower the injection height – faster removal into the troposphere

NO2 Changes- Sunrise and Sunset

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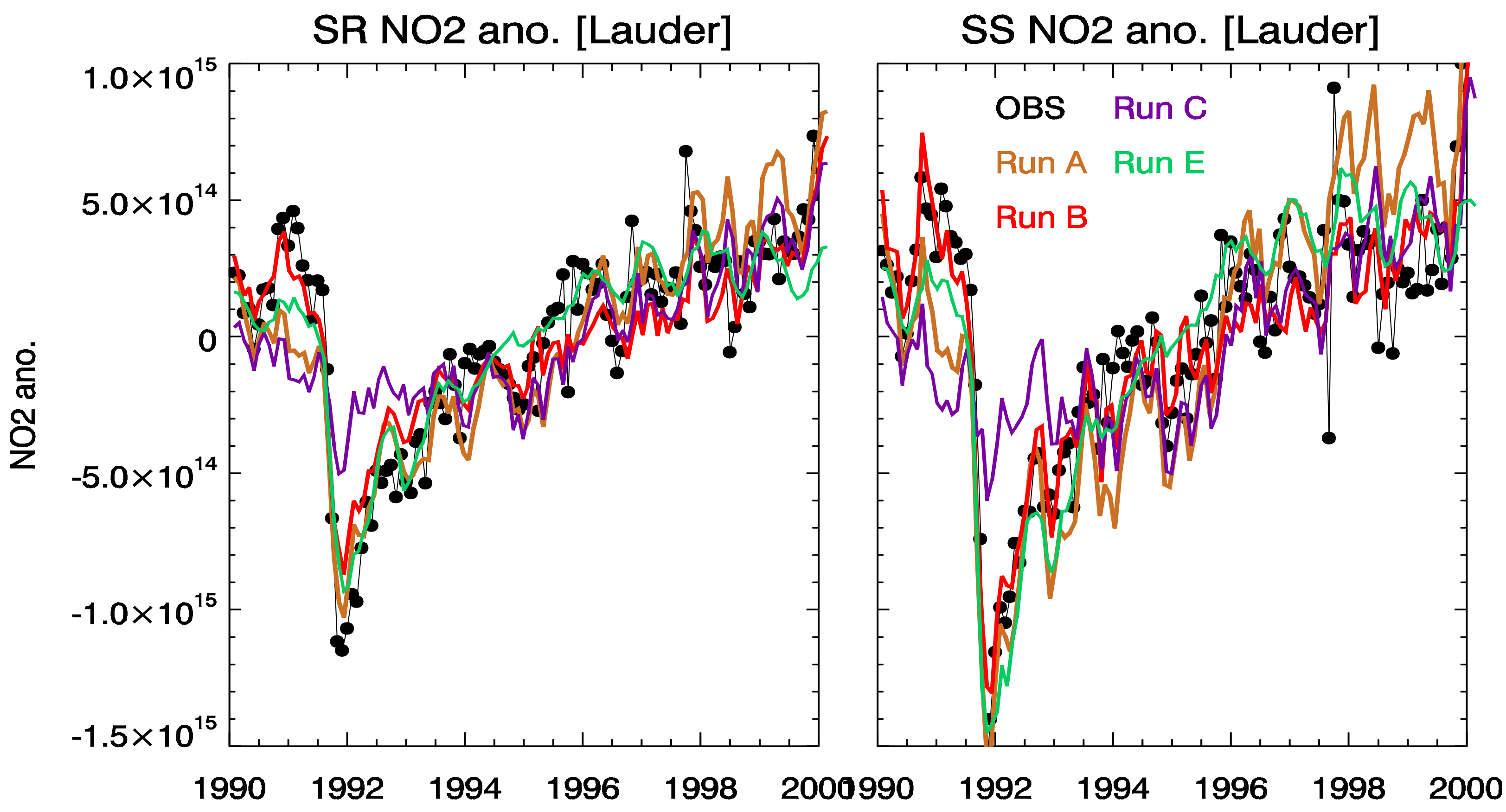

Simulations with time-varying aerosols capture NO2 changes

Chemical ozone loss

Cohen and Murphy

N2O5 + H2O→ 2HNO3♪

ClONO2 + H2O→ HNO3 ♪
+ HOCl♪

HCl + ClONO2 → Cl2 + H2O♪

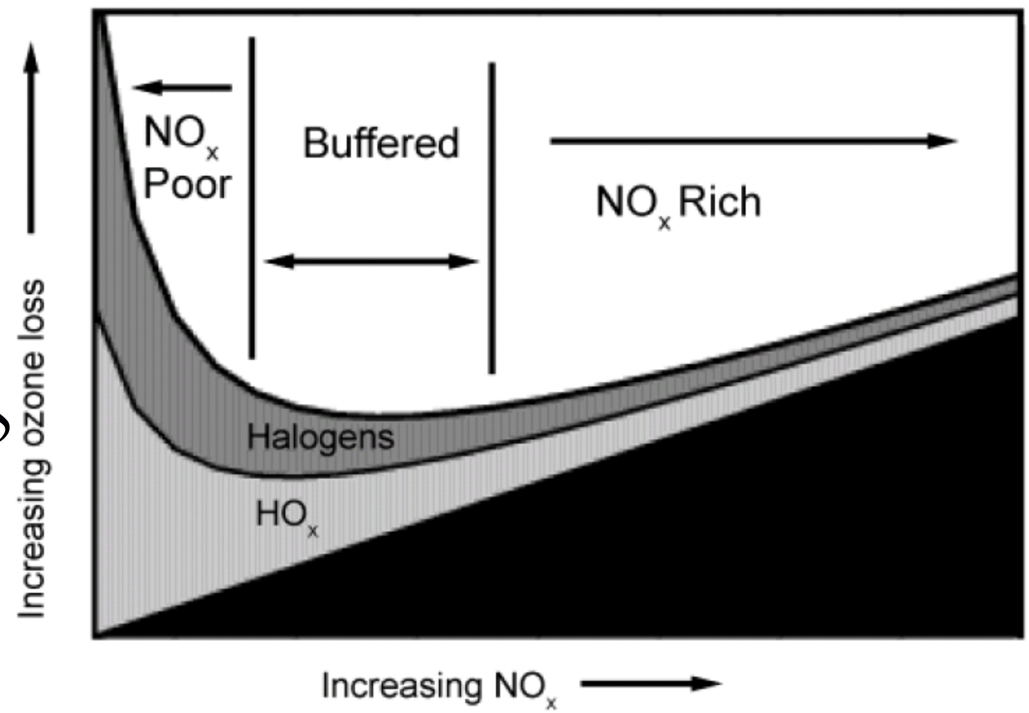

Figure 2. Ozone loss from each type of catalytic cycle as a function of NO_x abundance.

NOx→ HNO3→ less NO2→ more Cl, Br♪

Solar Cycle, QBO and Ozone – connection♪

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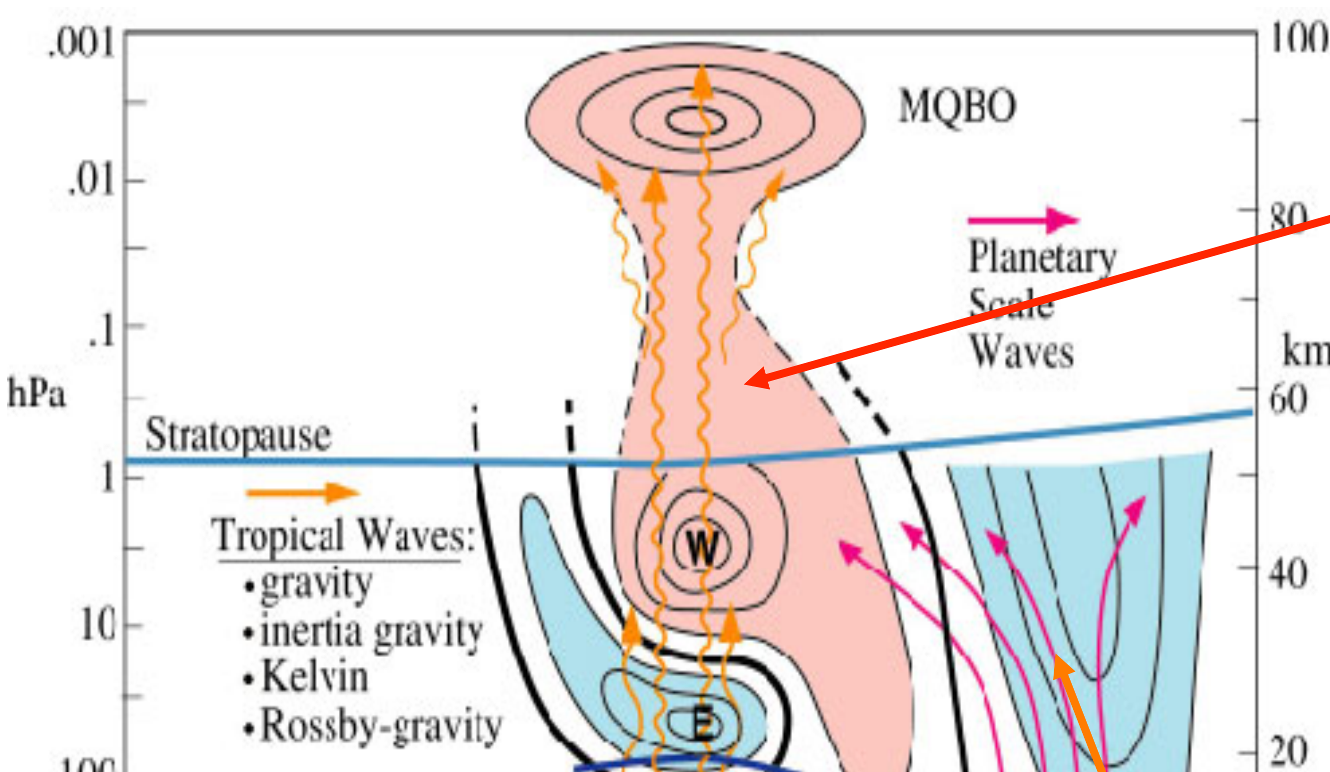


Changes in UV♪
Upto 6% near 250 nm♪

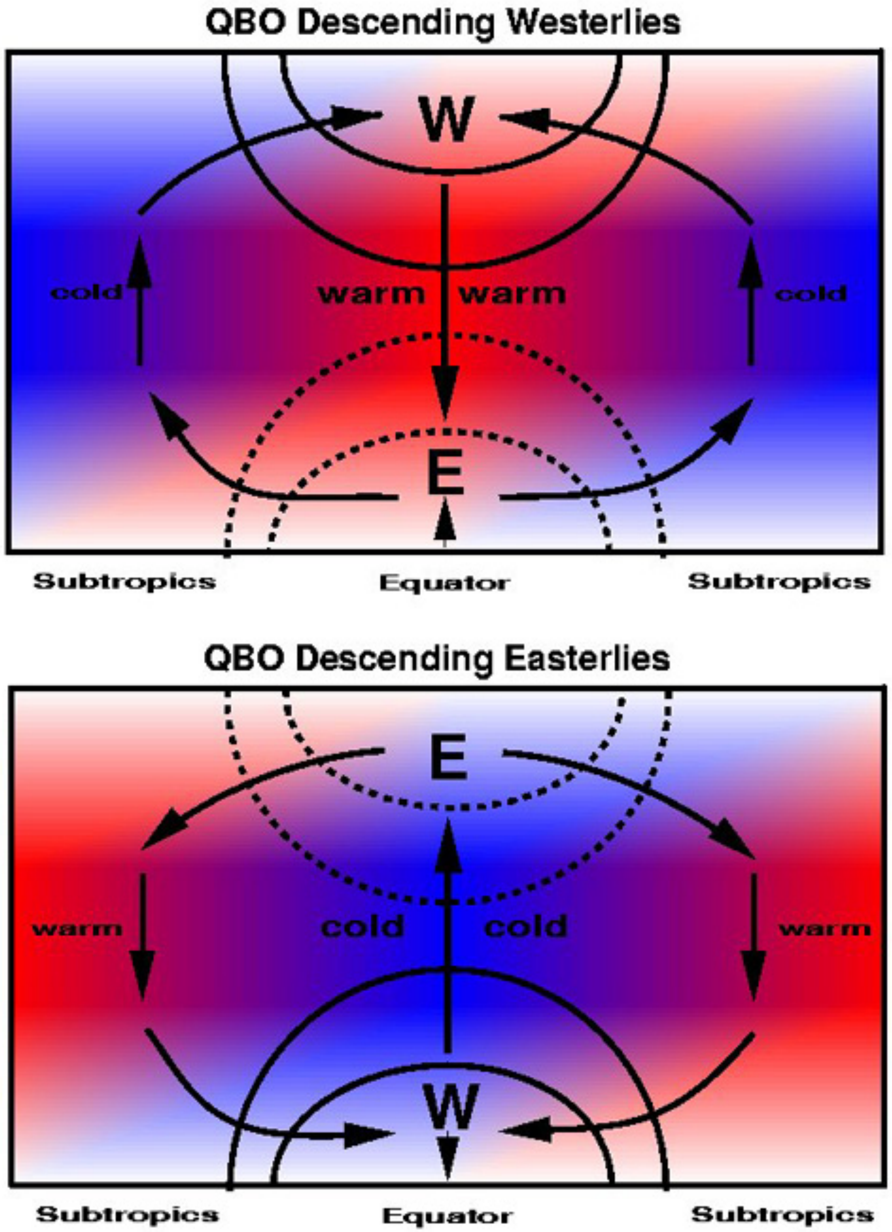
Changes in zonal ♪
Mean T and wind due♪
to O_3 heating♪

Changes in Planetary♪
wave propagation♪

What would have happened if

I. Pinatubo would have erupted during westerly phase of QBO

II. Ozone chemistry is not influenced by sulphate particles (ideal particles for geo-engineering?)



Schematic illustration of the tropical QBO showing the mean wind pattern, mean circulation, and mean thermal pattern

Pinatubo signal in CCMs (CCMVal-2)

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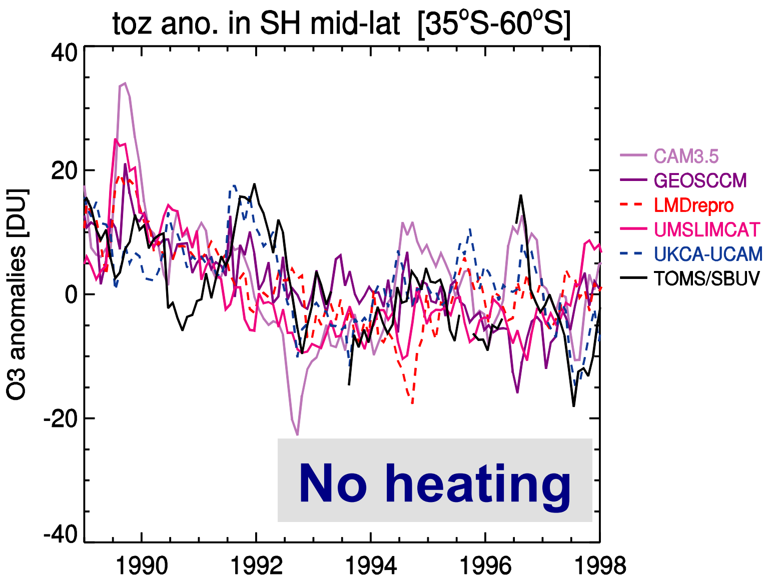

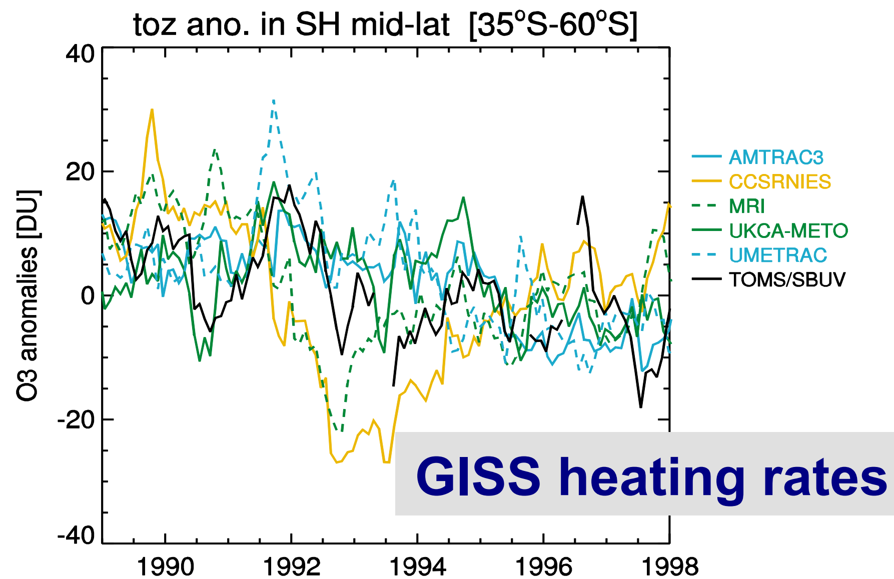

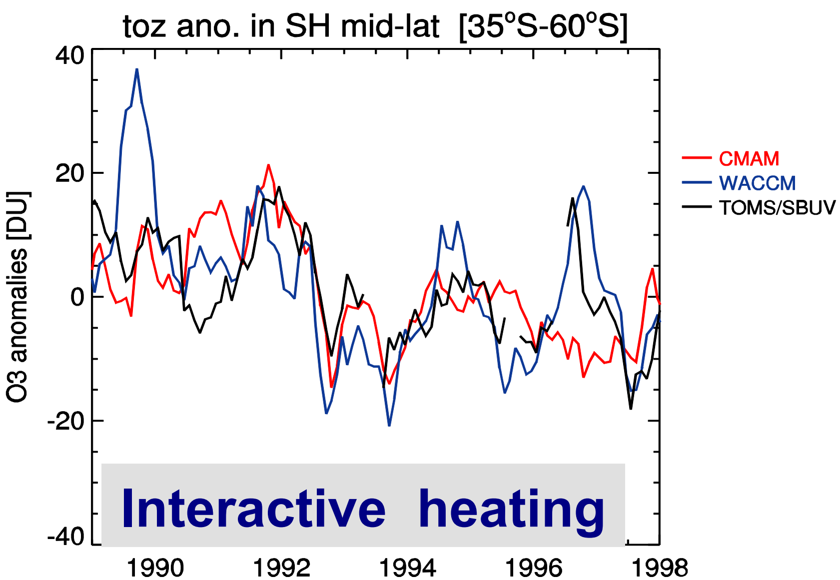

None of the CCM could simulate Pinatubo ozone loss correctly - SPARC Report 2010, WMO 2011

Slowdown in Global Warming (IPCC 2013)

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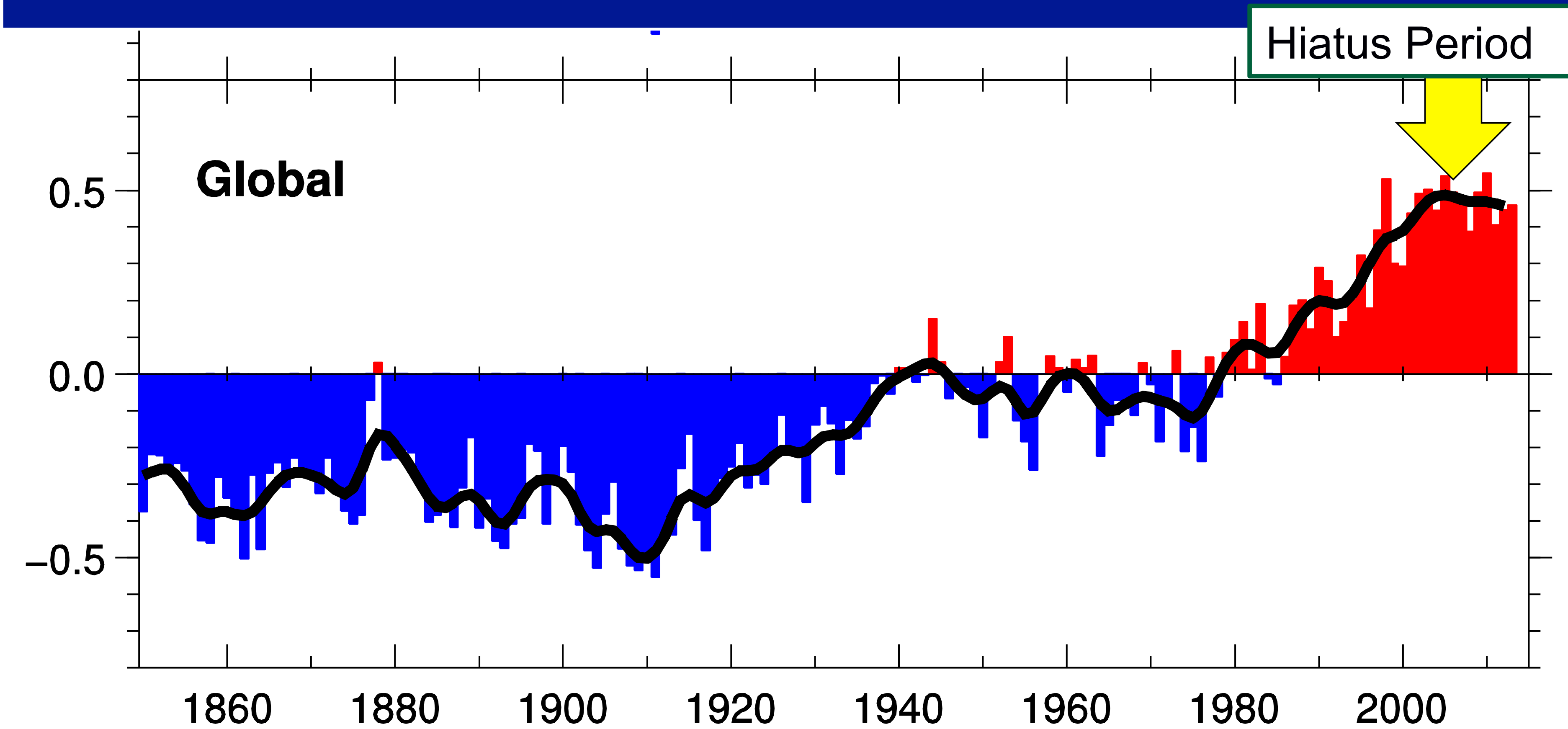

GHGs still increasing- Models also simulate warming but observations show very little increase (Hadley Centre data)

Piers's talk on Thursday!

Suggested Hypotheses

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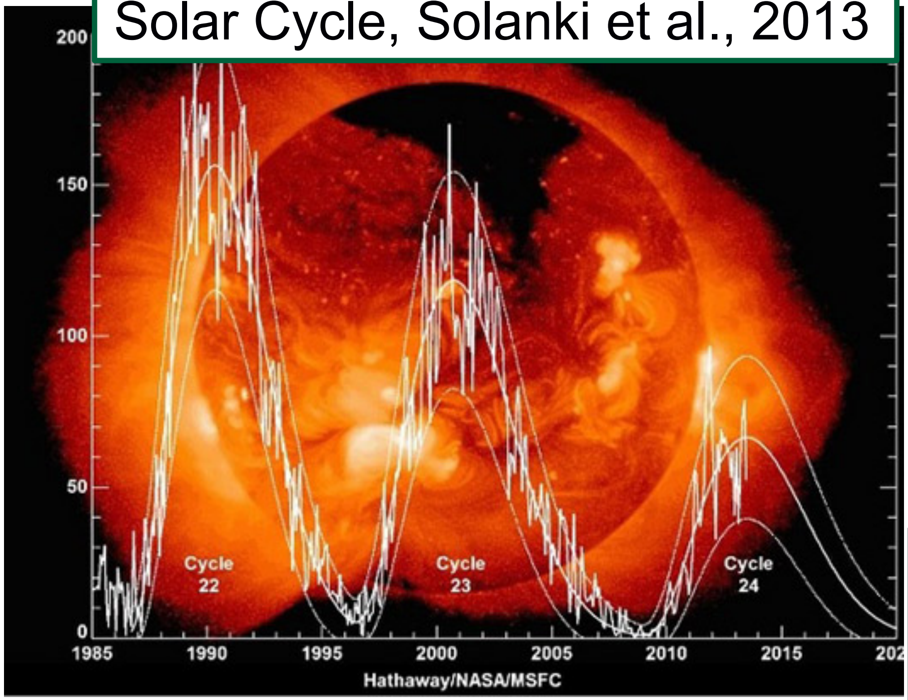
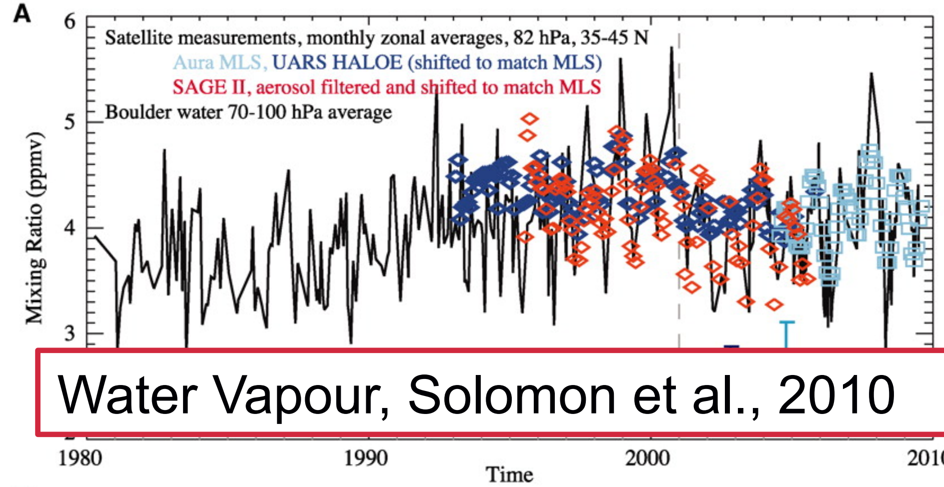
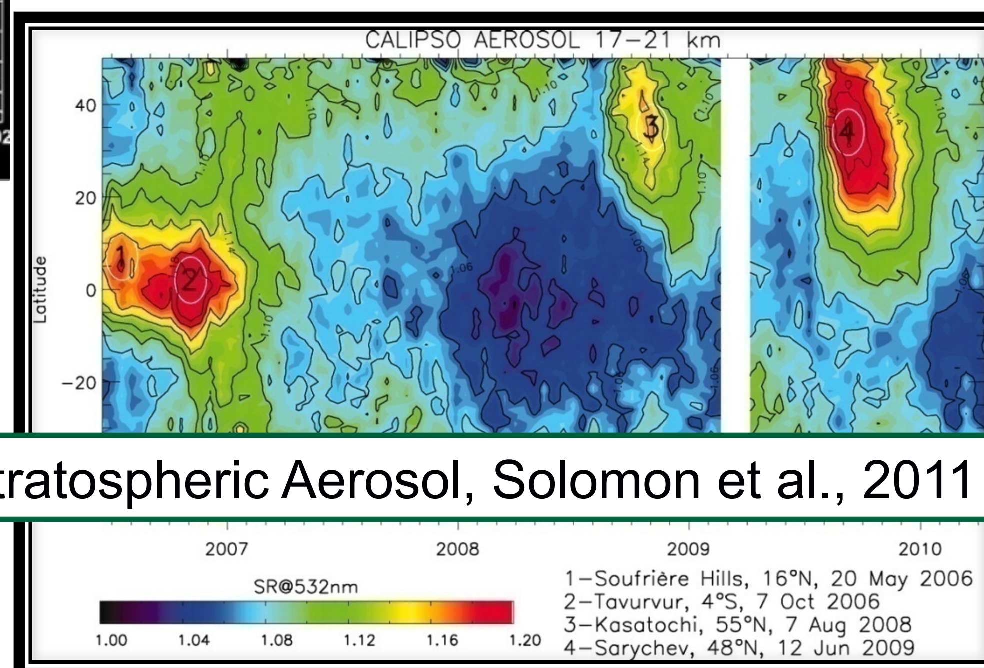


Solar Cycle, Solanki et al., 2013



Water Vapour, Solomon et al., 2010



Stratospheric Aerosol, Solomon et al., 2011

- **Ocean heat uptake**
- **Strat. Aerosol**
- **Stra. Water vapour**
- **Solar cycle**

Sulphate Area Density (SAD) Comparison

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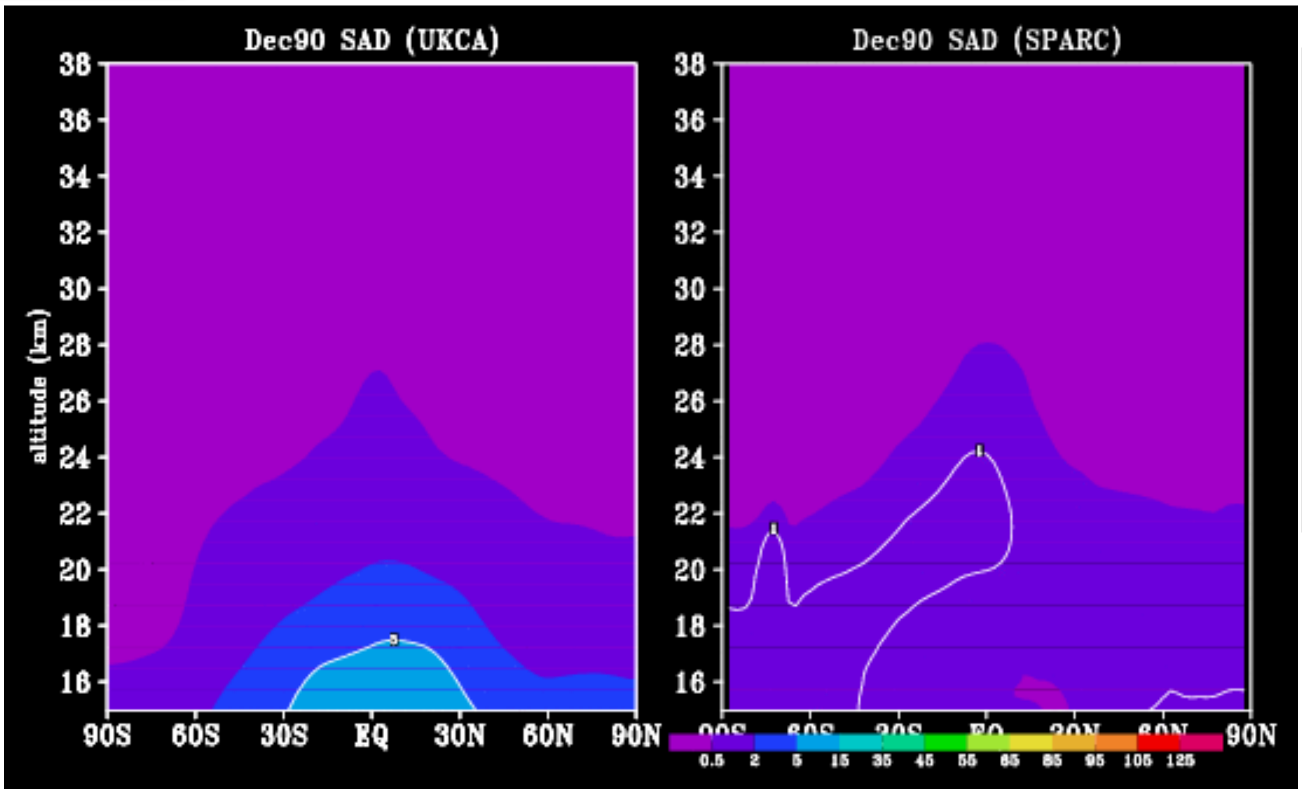
Simulation with 20 Mt SO2

SAD data- SPARC 2010

UKCA **Satellite**



Satellite data – longer wavelengths/ larger particles

- SAGE –Vis/IR
- CLAES- Micro
- HALOE -IR

Larger SAD immediately after the eruption

Densities in Different Modes

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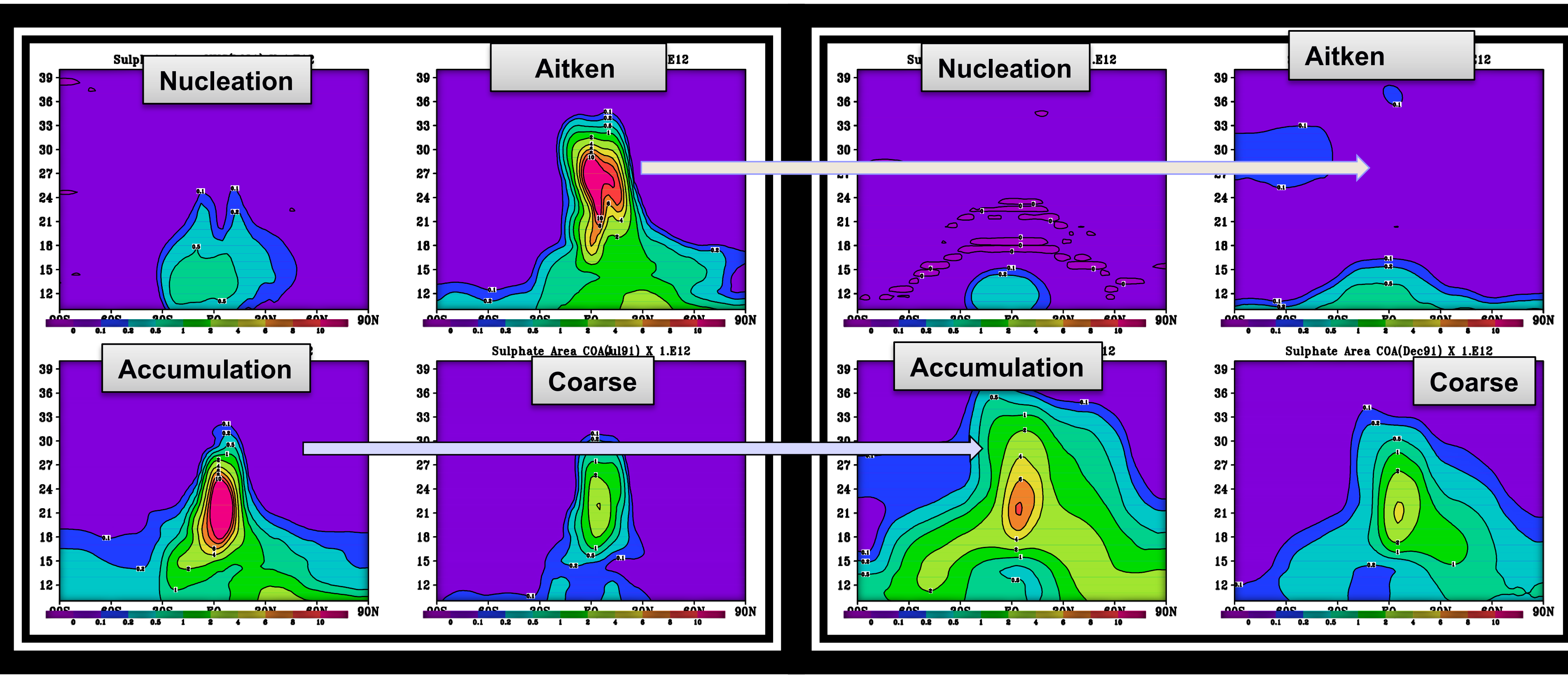
4 months

Jul 1991 → Dec 1991



Varying mass and numbers between different modes