School of Earth and Environment
INSTITUTE FOR CLIMATE & ATMOSPHERIC SCIENCE

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UKCA tutorial: GLOMAP-mode aerosol

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Met Office Hadley Centre

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

GLOMAP
Global Model of Aerosol Processes

Sources of aerosol particles – a complex mix

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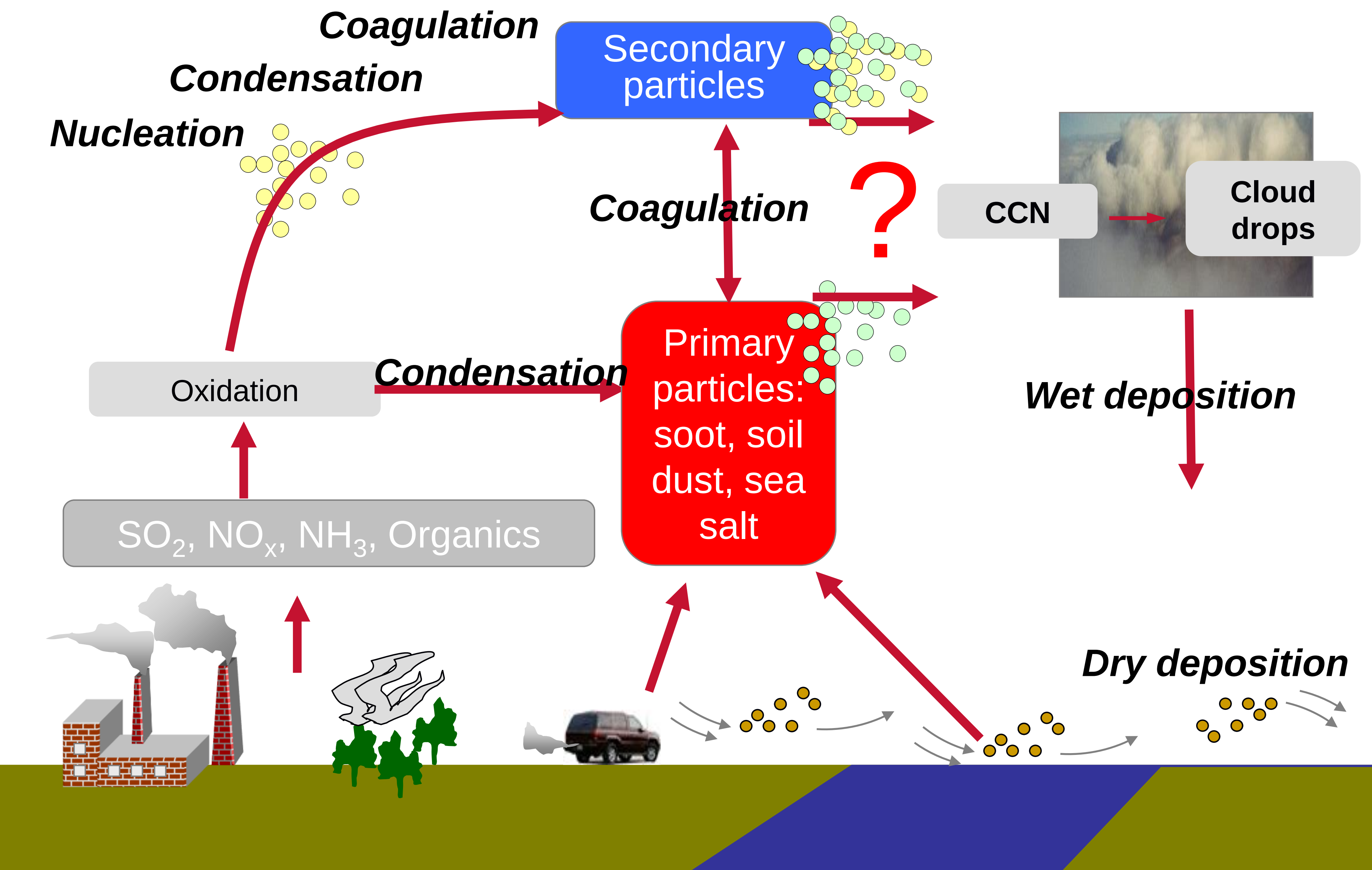
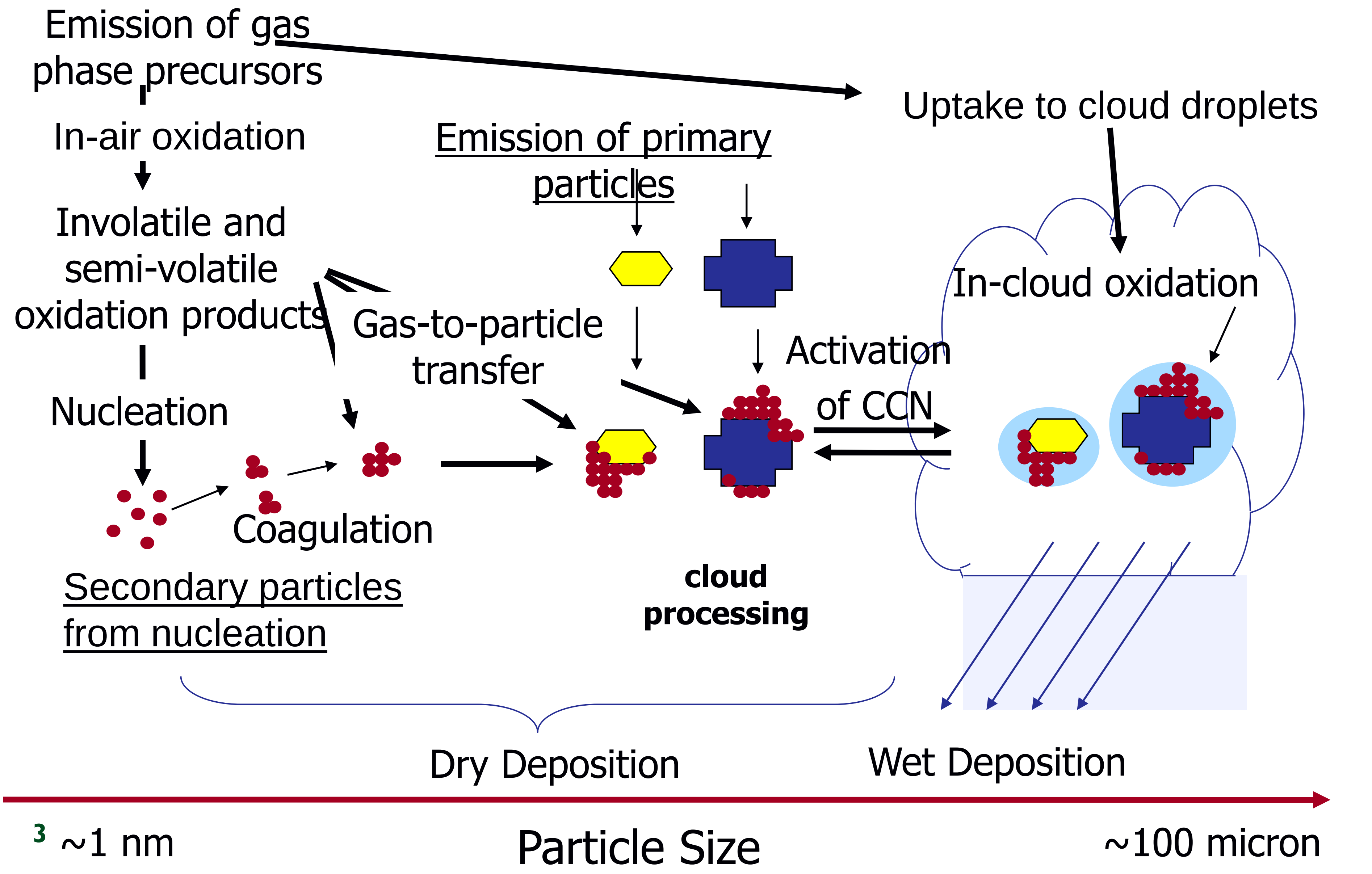


Processes control particle size & composition



UK Chemistry & Aerosols project (UKCA)

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- Collaboration between NCAS & UK Met Office Hadley Centre since 2005. Universities of Leeds, Cambridge and Oxford are main NCAS partners

- Aerosol-chemistry sub-model in Met Office Unified Model environment for a range of applications (climate, Air Quality, Earth System science etc.)

- Tropospheric and stratospheric chemistry schemes.
  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 NCAS and Met Office initiatives.

UKCA aerosol scheme is GLOMAP-mode

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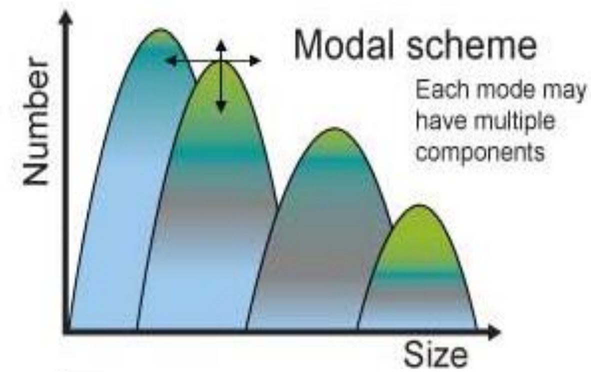
UK Chemistry and Aerosol project has developed aerosol-chemistry sub-model of the Met Office Unified Model suitable for climate, air-quality & aerosol effects on NWP

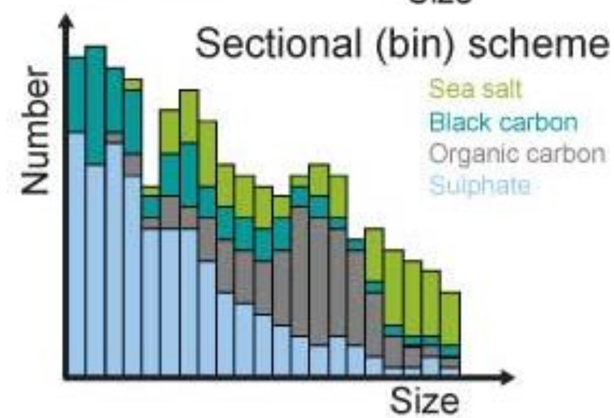
Aerosol scheme is called GLOMAP-mode (sometimes MODE or UKCA-MODE in UM)
Transported tracers are size-resolved component mass & particle number mixing ratios

Uses size-resolved aerosol microphysics from GLOMAP-bin scheme but using log-normal size modes rather than bins:

- Primary emissions (sulphate, BC/OC, sea-salt, dust)
- Secondary sulphate particle formation (nucleation)
- Coagulation (within modes, between modes).
- Condensation (of sulphuric acid, bulk condensible organic)
- Cloud processing
- Dry deposition and sedimentation
- In-cloud and below-cloud scavenging

Benchmark MODE scheme vs detailed BIN scheme in CTM.





<u>Simulates size-resolved multi-component aerosol lifecycle including new particle formation & growth.</u>

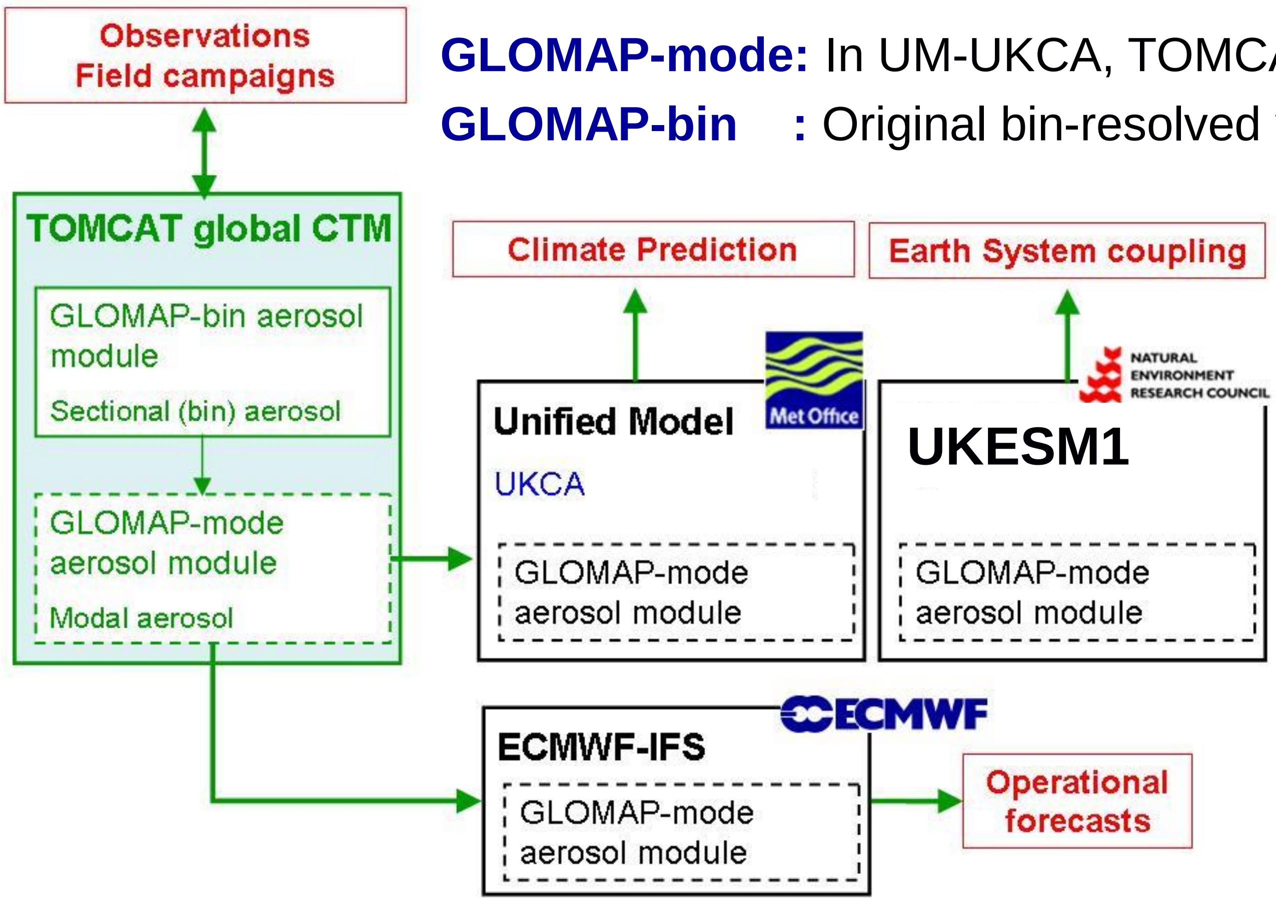
GLOMAP-bin : Spracklen et al. (ACP 2005a,b, 2006, 2007), Korhonen et al (JGR, 2008), ….
GLOMAP-mode: Manktelow et al (GRL, 2007), Woodhouse et al (Atmos Env, 2008; ACP, 2010), Schmidt et al (ACP,2010), Mann et al, (GMD,2010), Mann et al (ACP, 2012)

UKCA Aerosol Strategy

UM-UKCA is one of several model frameworks which include GLOMAP.

GLOMAP-mode: In UM-UKCA, TOMCAT CTM & ECMWF-IFS

GLOMAP-bin : Original bin-resolved version in TOMCAT CTM



Strong connection between the future development of UM-UKCA and improvements and developments to GLOMAP in the TOMCAT CTM and ECMWF-IFS

UM-UKCA release job at v8.4 with GLOMAP & CheST stratosphere-troposphere chemistry with extension for aerosol precursor chemistry

Importance of size distribution: AOD

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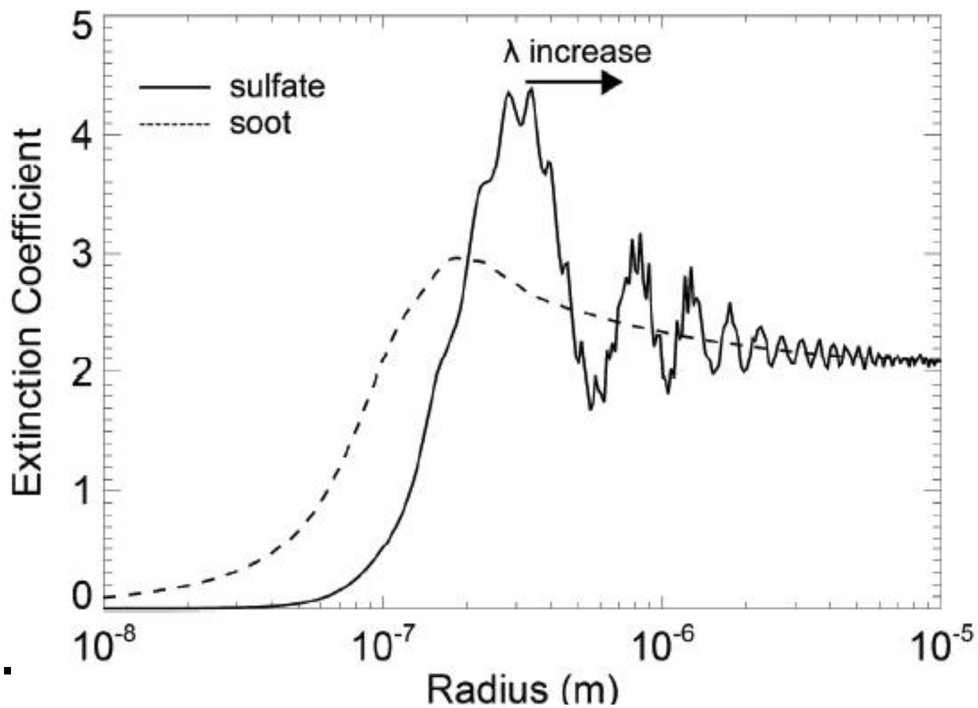
Differences in particle size distribution strongly affect the extinction.

Constant mass extinction efficiency will not capture variability from changes to the particle size distribution.



$$b_{ext} = \pi \sum_{i=0}^{n} Q_{ext} R_i^2 \frac{dN_i}{d\ln R_i} \Delta \ln R_i \qquad \tau_\lambda = \int_0^{z_{top}} b_{ext}(\lambda) dz \, ,$$

<u>Same mass distributed in different sizes gives different AOD</u>

Cloud droplet vs aerosol from observations

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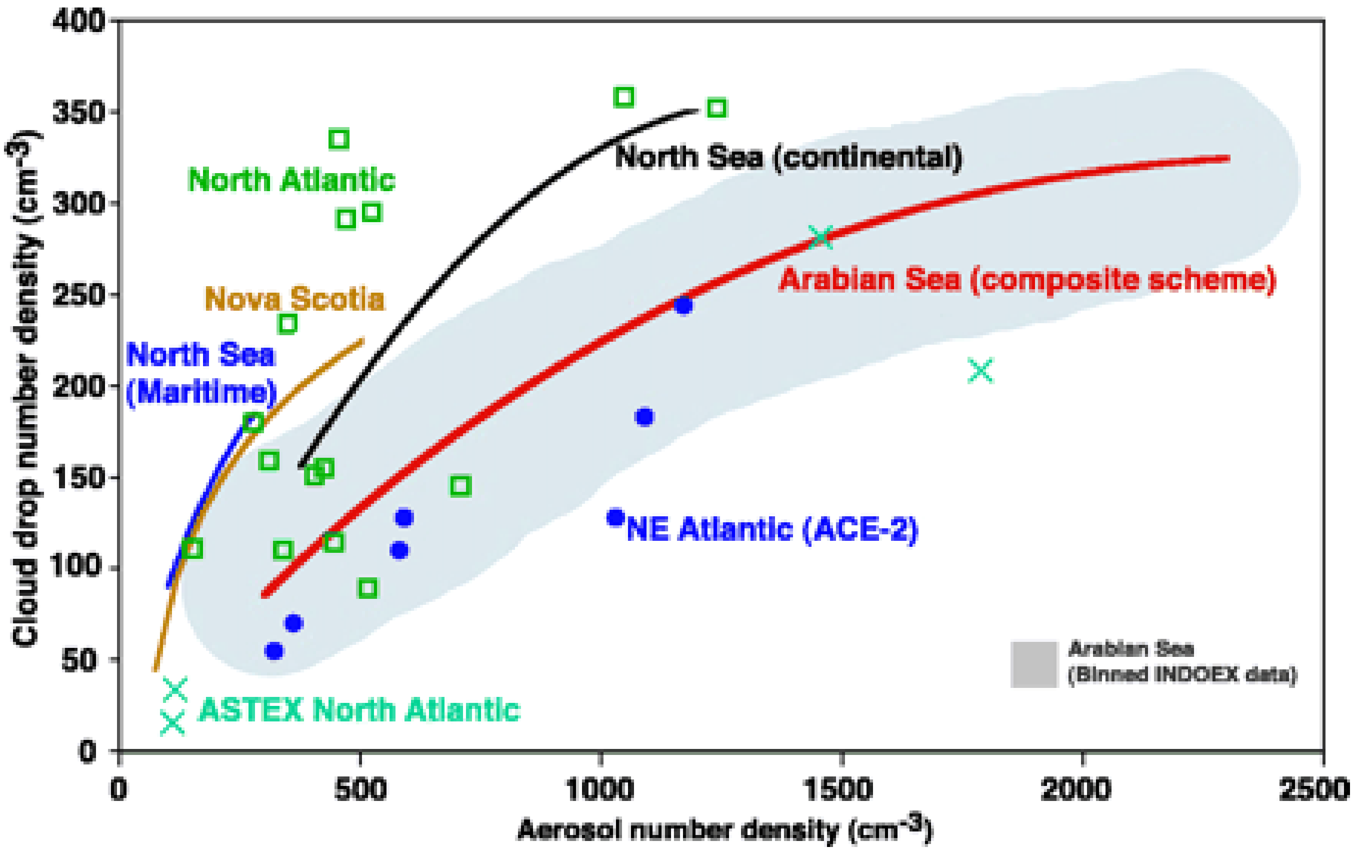
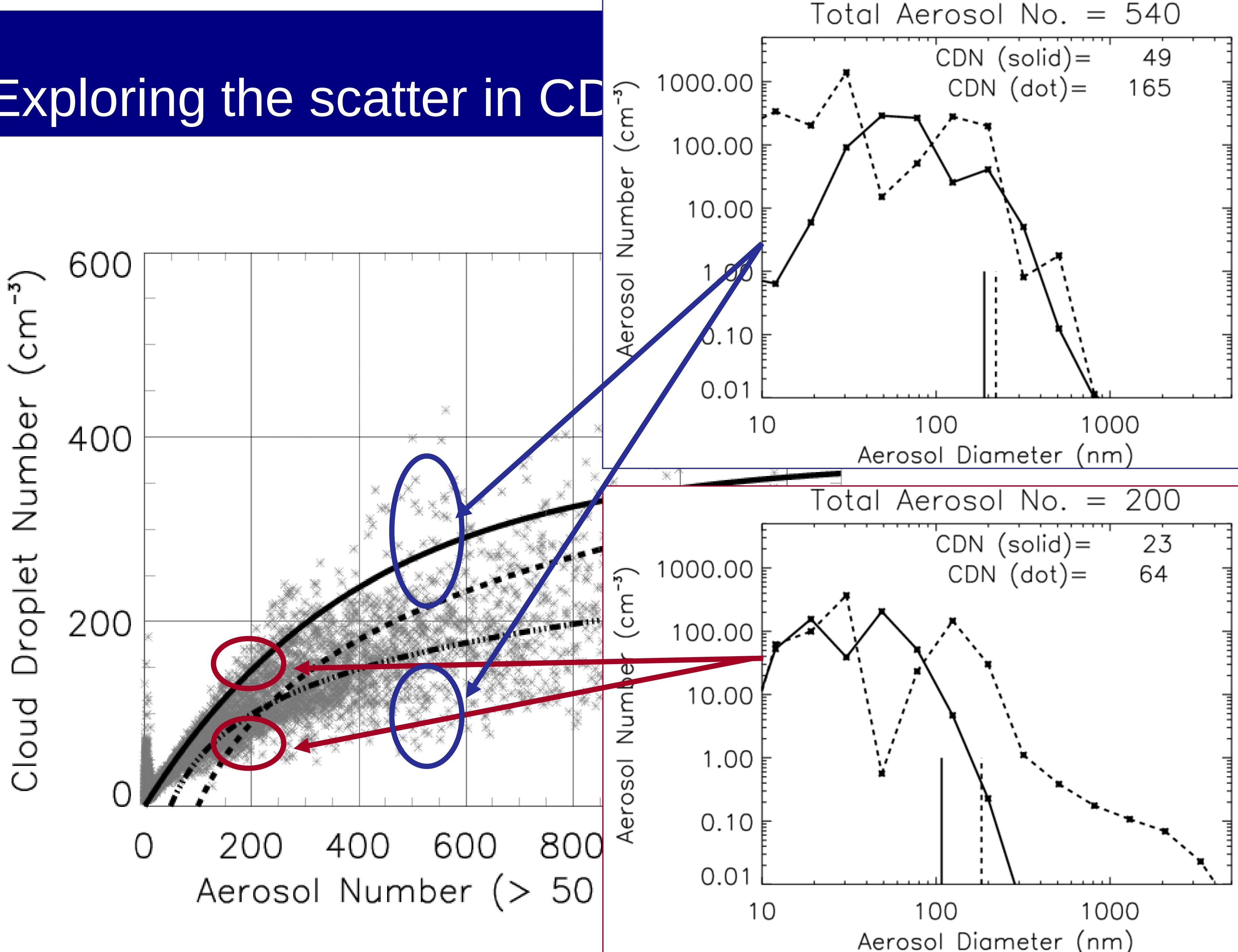


Ramanathan et al. (2001, Science)

No single relationship

Different particle types, compositions, size distributions, etc

Exploring the scatter in CD



Mass-based UM aerosol scheme (CLASSIC)

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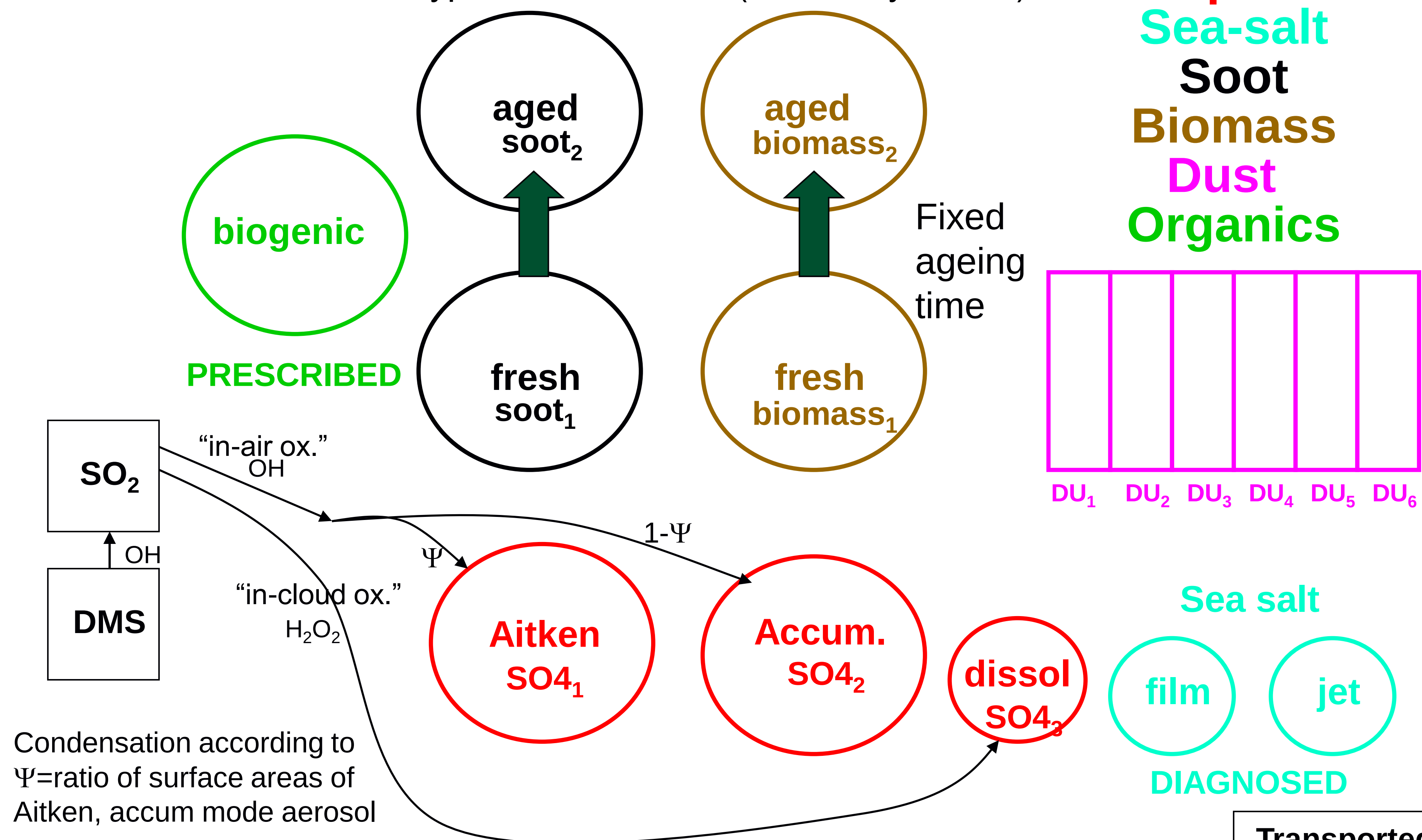
Has aerosol mass as "types" of fixed size (externally mixed)



<u>Aerosol optical properties & CCN derived based on fixed size distribution</u>

Transported tracers=13

GLOMAP 7-mode aerosol configuration

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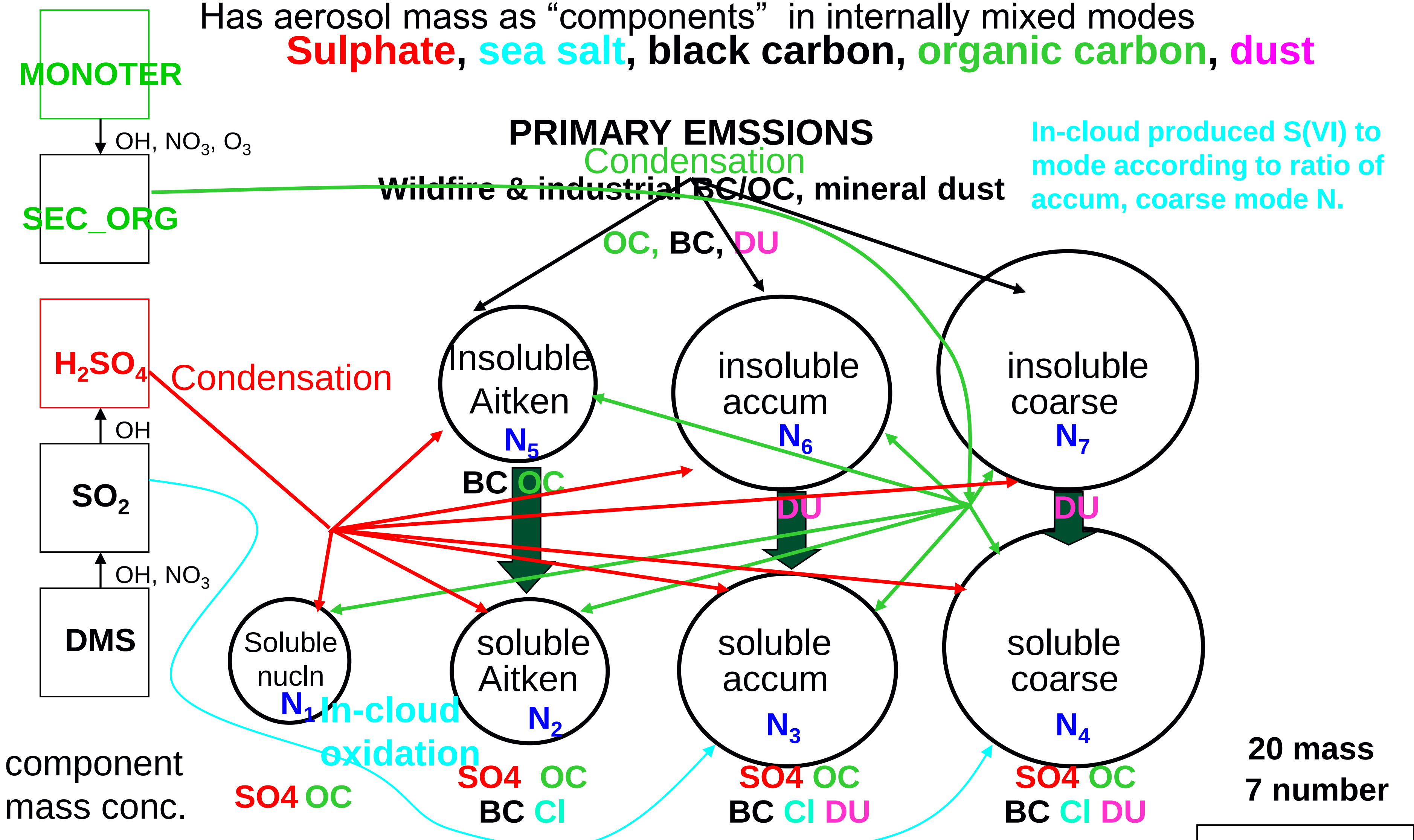
Has aerosol mass as "components" in internally mixed modes

Sulphate, sea salt, black carbon, organic carbon, dust



Transported tracers=27

AOD, CCN determined by size-resolved emission, processes & removal.

UM-UKCA uses 5-mode GLOMAP plus 6-bin dust

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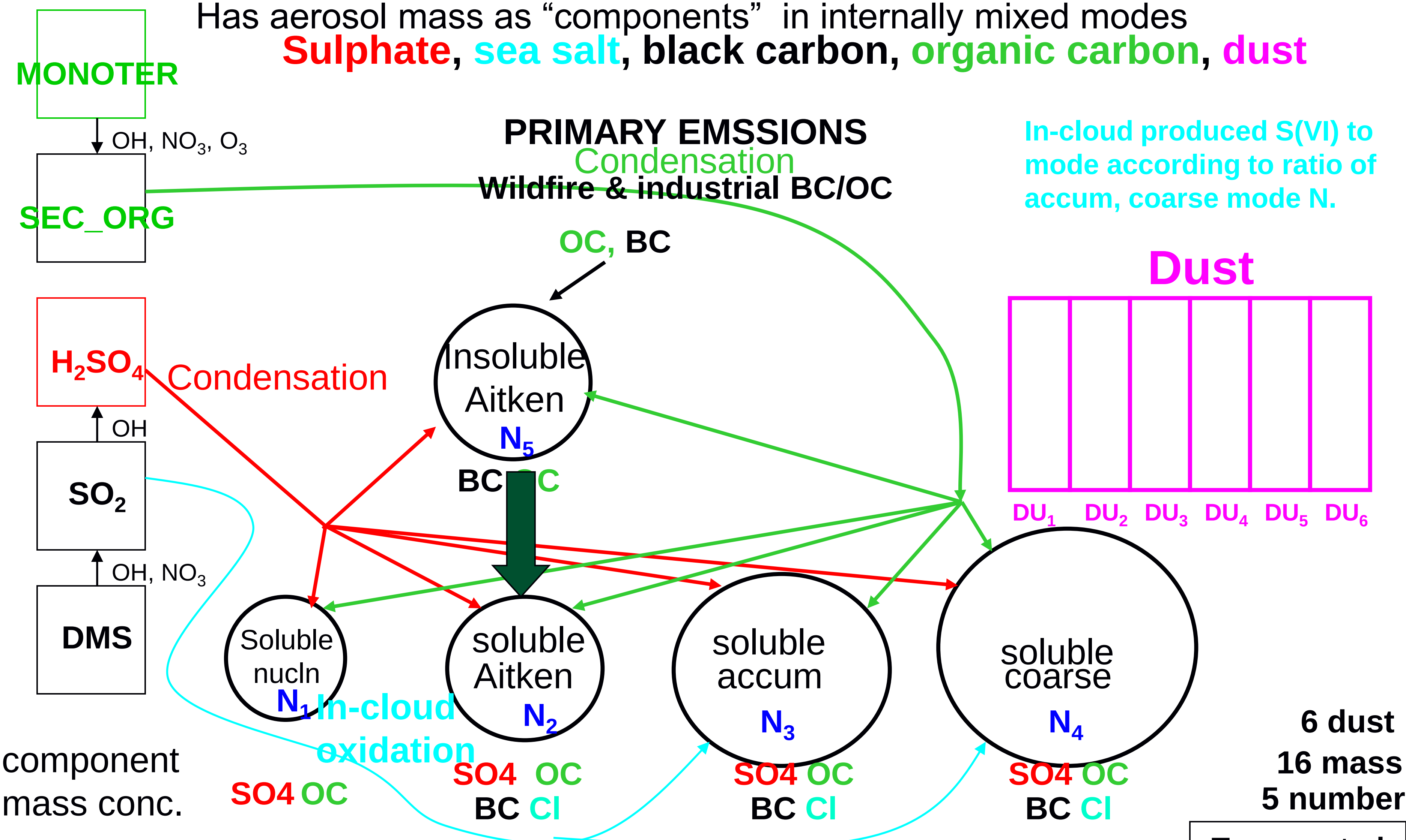
Has aerosol mass as “components” in internally mixed modes

Sulphate, sea salt, black carbon, organic carbon, dust



AOD, CCN determined by size-resolved emission, processes & removal.

Transported tracers=27

CLASSIC and UKCA compared

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	CLASSIC	UKCA
Transported particle types	Associated with emissions (sulphate, biomass, etc)	Defined by microphysics (Aitken, accumulation, etc)
Size distribution	Prognostic m Fixed size N derived from m and size	Prognostic N, m Variable size Log-normal modes
Mixed composition	No	Yes
Chemistry	Simple S-chem driven by offline oxidants or UKCA	Coupled chemistry
Cloud drop number	From mass	From size, N, mixed composition
Particulate tracers	13	27 for full 7 modes (21 for 5-mode setup)

“Standard” UKCA Aerosol Scheme

Mode name	Mean rad range nm	Composition	Production	Comments
nucleation soluble	< 5	SO4	nucleation	Currently only binary H_2SO_4-H_2O, later BLN
Aitken insoluble	5 – 50	BC, OC	primary BC/OC emissions	Separation to handle BC/OC ageing (necessary if timescale for ageing > lifetime in grid box)
Aitken soluble	5 – 50	SO4, BC, OC	growth of nucl. soluble, condensation (sol,ins Ait), primary SO4 ems, coag.	
Accum. insoluble	50 – 500	DU	primary DU emissions	Separation to handle dust ageing (as above
Accum. soluble	50 – 500	SO4, SS, DU, BC, OC	growth of Aitken soluble, condensation (sol,ins acc) primary SS ems, coag.	Primary accum. mode BC/OC ageing?
Coarse insoluble	>500	DU	primary DU emissions	Separation to handle dust ageing
Coarse soluble	>500	SO4, SS, DU, BC, OC	growth of accum soluble, primary SS emission	

UKCA-aerosol applications : Volcanic aerosol: impacts on climate

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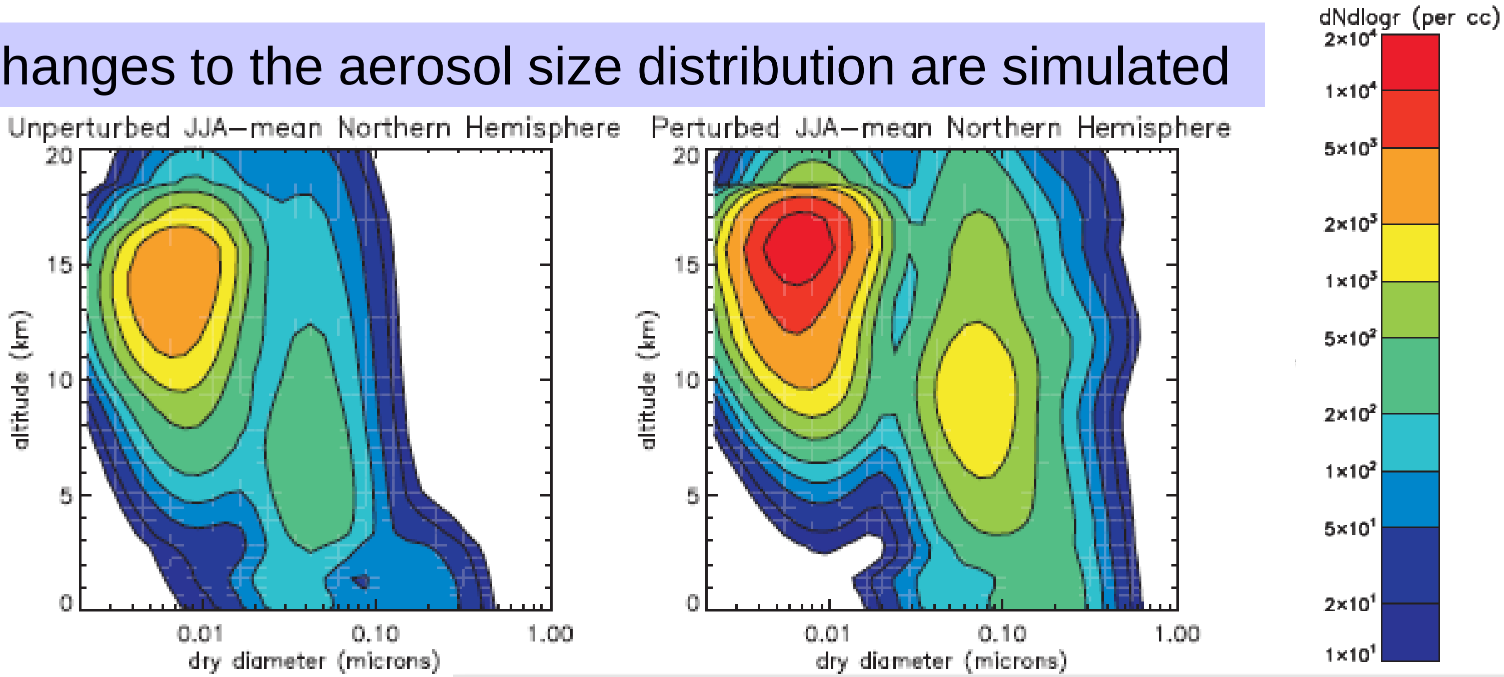
- Simulate aerosol from 1783 Laki eruption of 120 TgS over 8 months.
- Revisits Stevenson et al (2003) and Highwood & Stevenson (2003) studies with GLOMAP-mode aerosol microphysics (in CTM with coupled-chemistry)

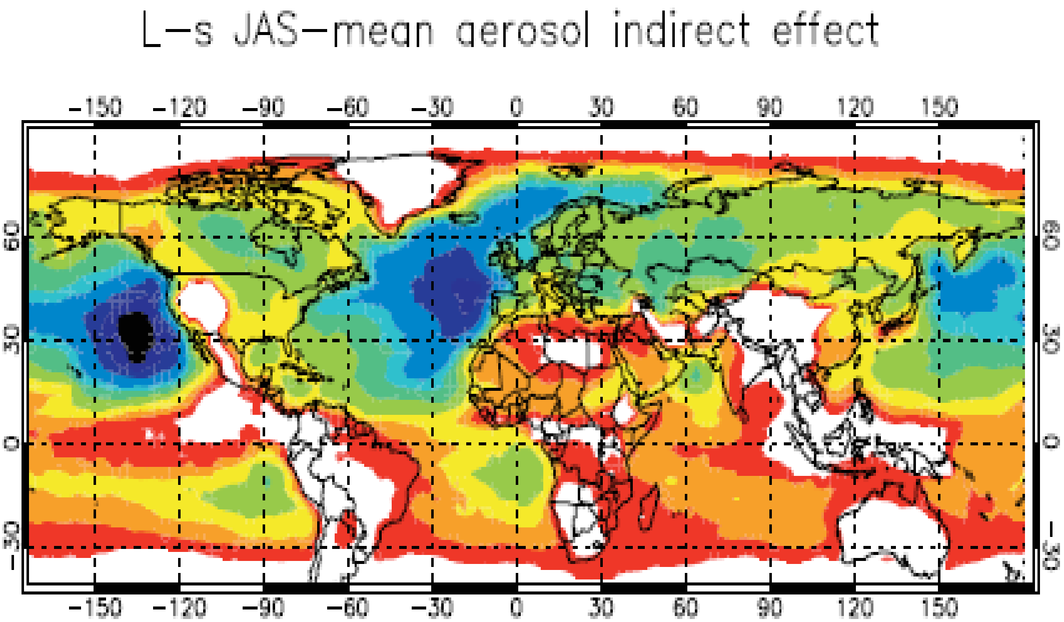
Enormous changes to the aerosol size distribution are simulated

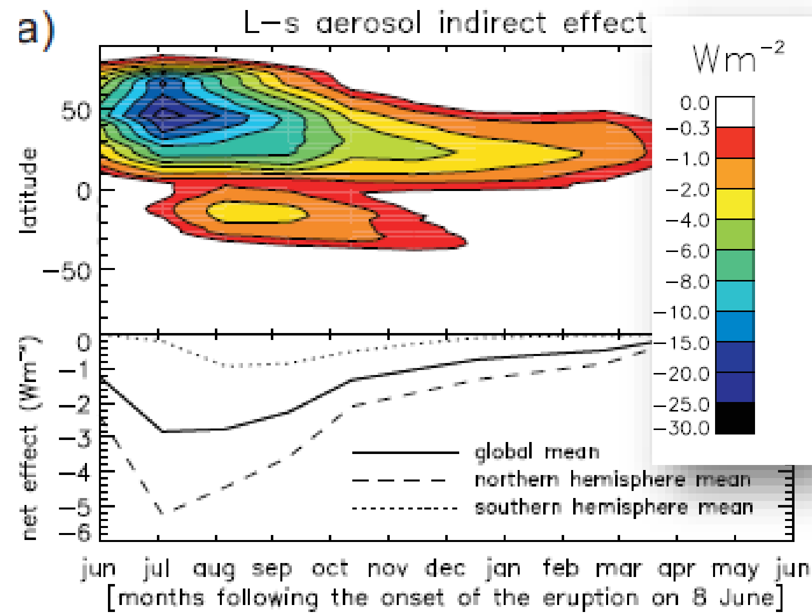


Schmidt et al (2010, ACP)

Eruption leads to stronger UT nucleation & growth → strong accum mode ~100nm

1783 Laki eruption: aerosol indirect climate effects





1st indirect forcing as large as the direct forcing, but spatially much more widespread (due to nucleation and growth)

Schmidt (PhD Thesis, 2011)

UKCA-aerosol applications:
Strat-geoengineering & Large volcanic eruptions

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Why UKCA?

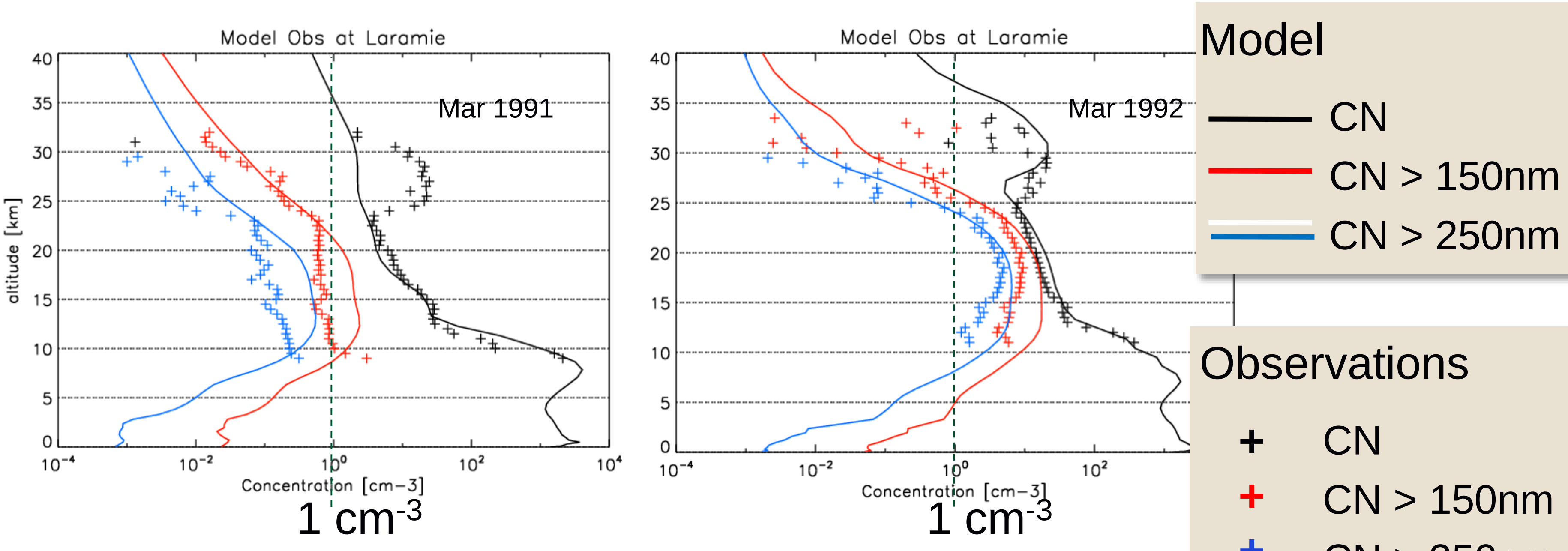
• Particle size distribution of the perturbed stratospheric sulphate aerosol is a major factor in predicting direct radiative forcing from stratospheric injection of SO_2 (affects growth, sedimentation, particle lifetime)

• In volcanically quiescent conditions, stratospheric aerosol particles are much smaller than following volcanic eruptions

• Climate forcing of very large volcanic eruptions is greatly reduced when the growth of sulphate droplets is accounted for (Timmreck et al., 2009, 2010)

• Applying UM-UKCA in coupled-AO to simulate stratospheric injection of SO_2 will maximise realism of predicted radiative forcings and climate responses

UKCA StratChem + Saerchem + MODE N48L60



3 months before Pinatubo 9 months after Pinatubo

Balloon measurements of number concentration at Laramie, Wyoming (Deshler et al, 2003)

See Dhomse et al. (2014, ACP)

UKCA-aerosol applications: Role of natural aerosol in the Earth System

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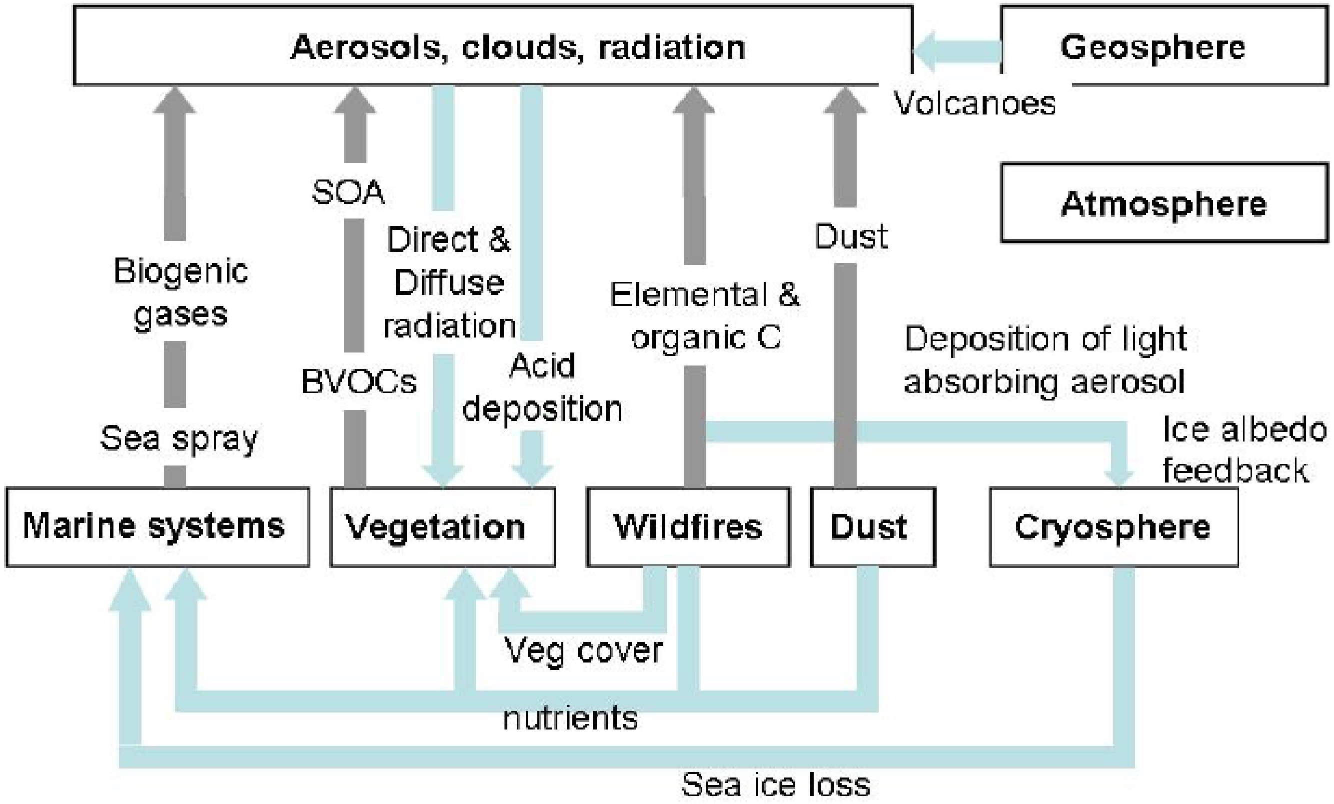
Carslaw et al (2010) review of *Natural aerosol interactions in the Earth System*



Offline CTM simulations have examined the role of these sources.
UKCA chemistry & size-resolved aerosol microphysics will allow state-of-the-science studies of these within the new UKESM1 AO-GCM.

UKCA experiments on DMS-climate feedbacks

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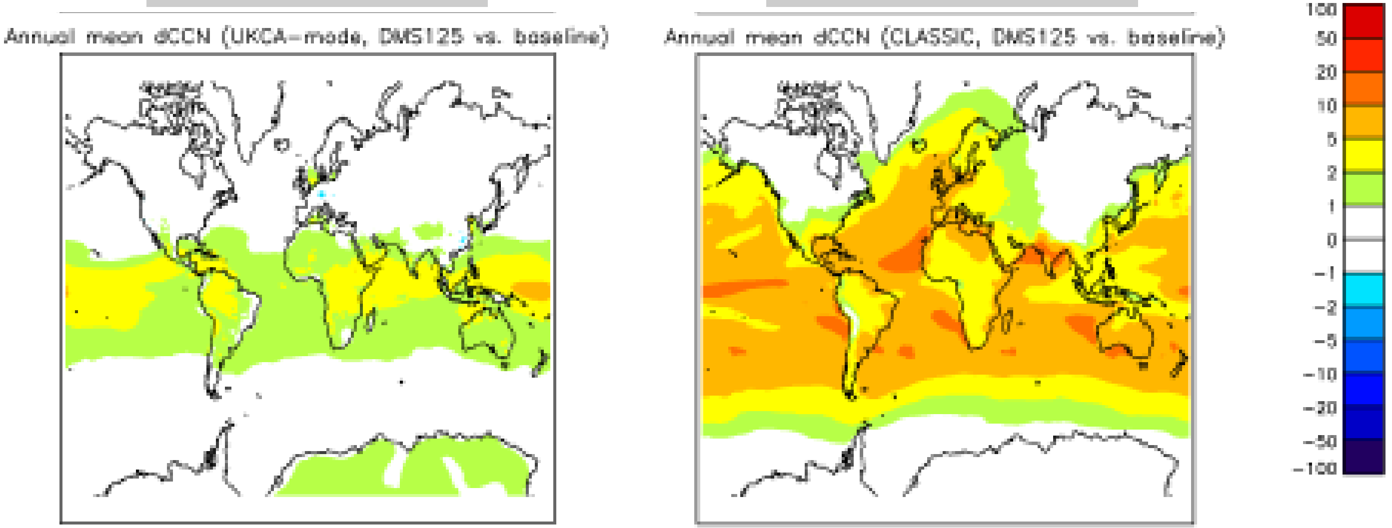
Change in CCN due to 25% increase in DMS emissions

- UKCA-mode predicts a much smaller response of CCN

UKCA-mode | UM-CLASSIC



Matt Woodhouse (Leeds) : from PhD thesis 2010.

UKCA experiments on DMS-climate feedbacks

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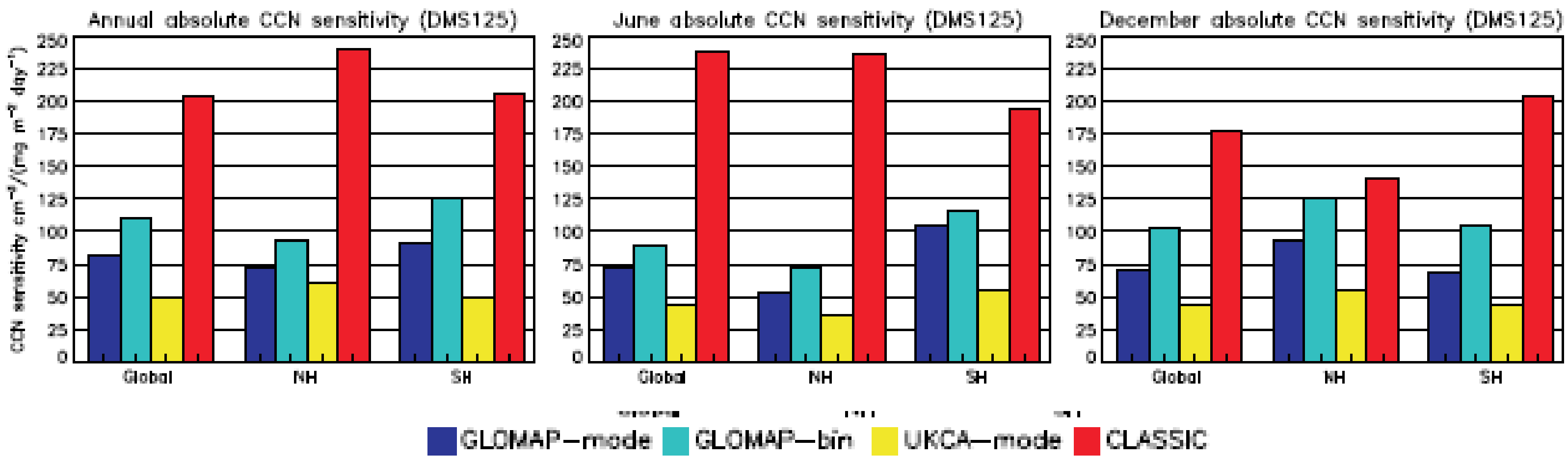

CLASSIC mass-based aerosol scheme (in HadGEM2-ES for IPCC AR5) overestimates CLAW feedback because increase in aerosol mass (e.g. from in-cloud oxidation of SO_2) increases cloud drops

GLOMAP simulates particle growth (conserves number), hence changes to CCN and indirect climate effects more realistic.

Matt Woodhouse (Leeds) : from PhD thesis 2010.

Percentage of primary and nucleated CCN

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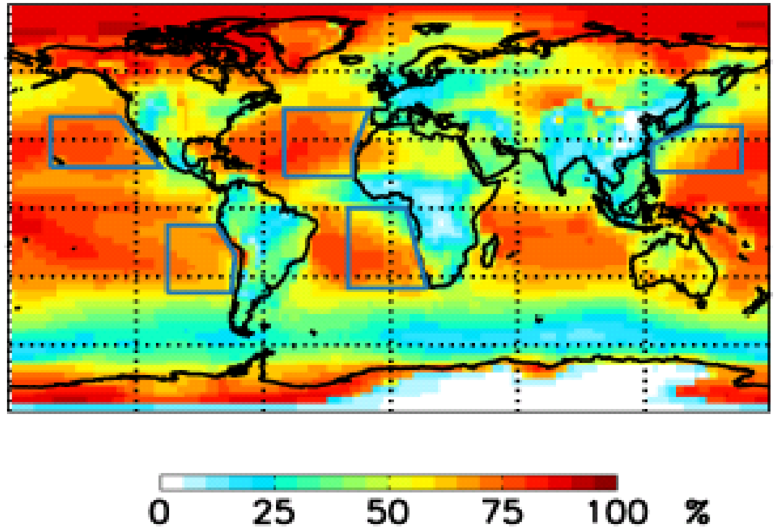
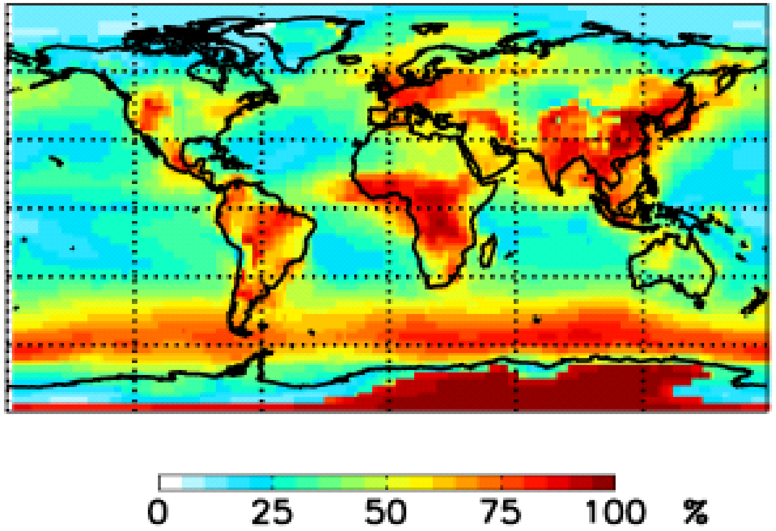
Nucleated particles important for aerosol indirect effects.
Growth to CCN sizes via coagulation and gas to particle transfer.

CCN from nucleation



CCN from primary emissions



Merikanto et al (2009, ACP)

Globally:

39% of low cloud-level CCN are from nucleation, 61% from primary particles

Nucleated CCN dominate in cleaner regions.

UT nucleation contribution to CN, CCN in UKCA

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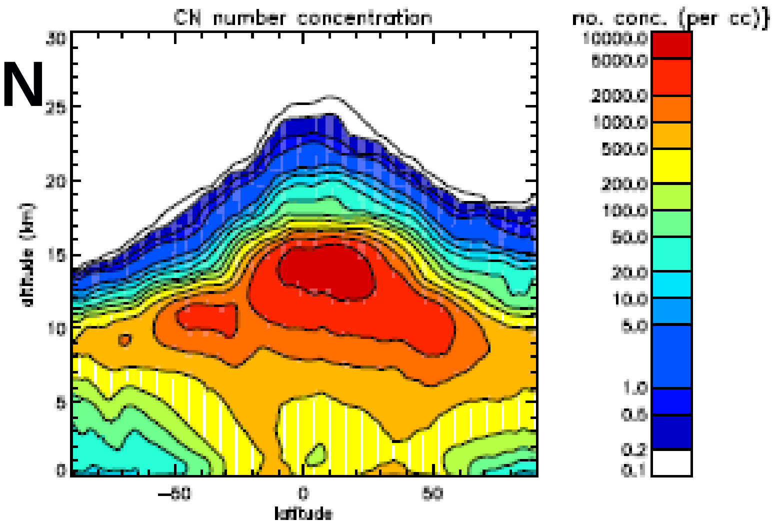
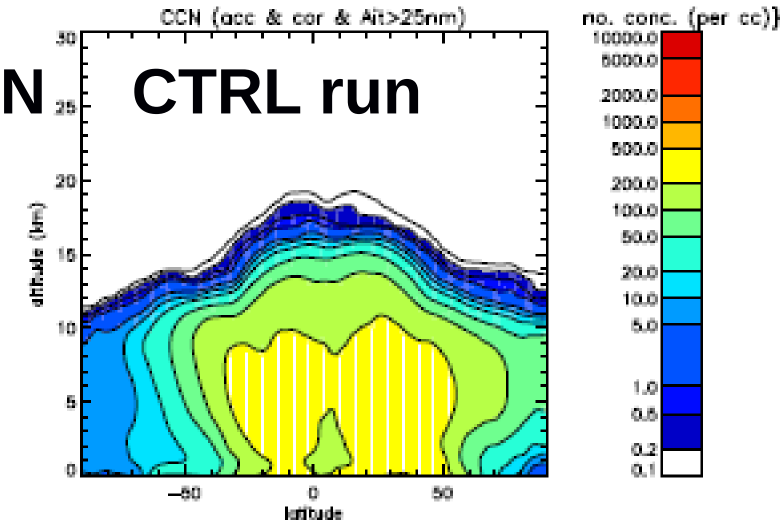
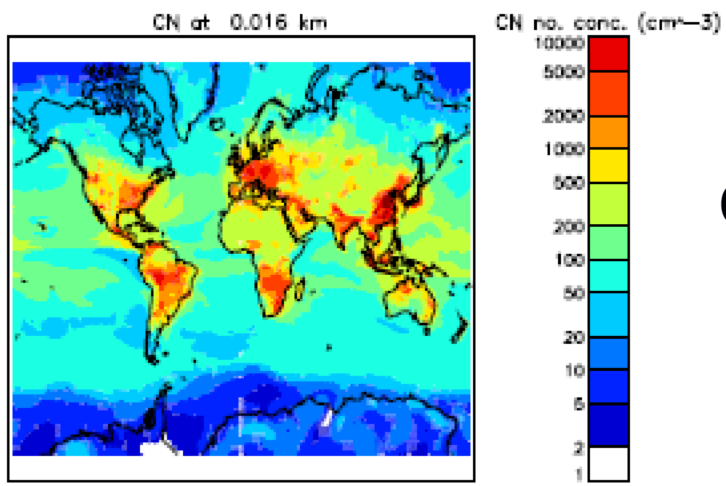
CN



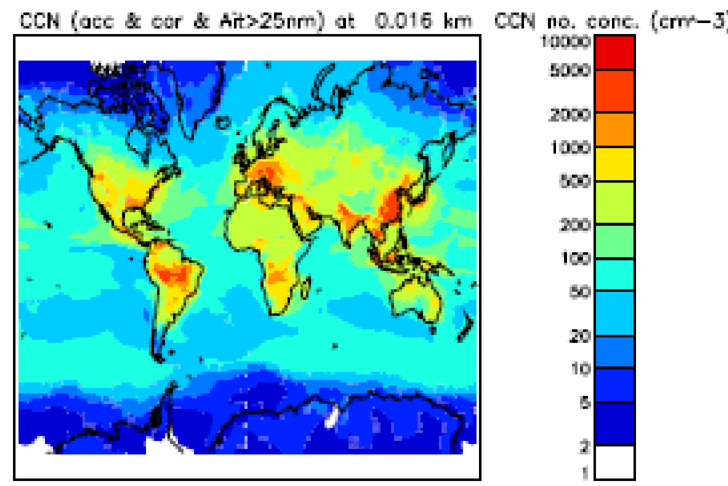
CCN



CN



CCN



UT nucleation contribution to CN, CCN in UKCA

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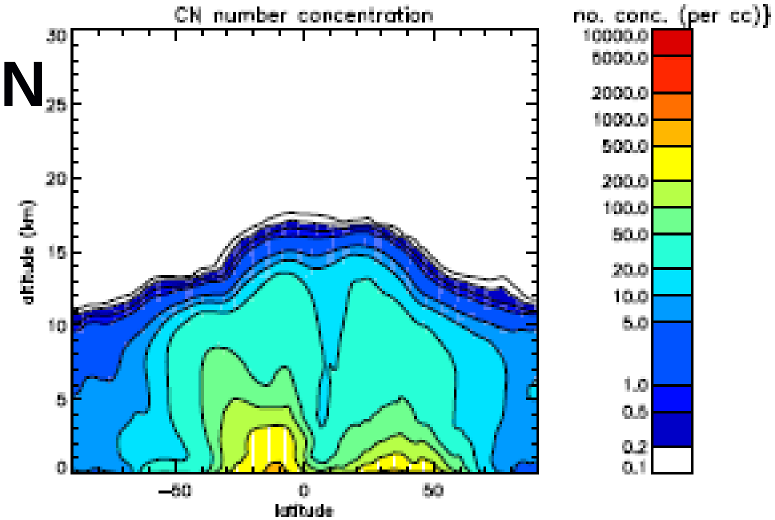
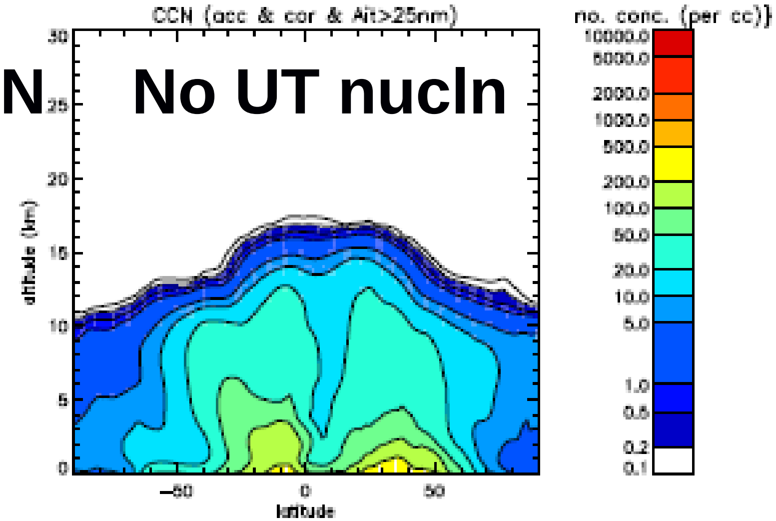
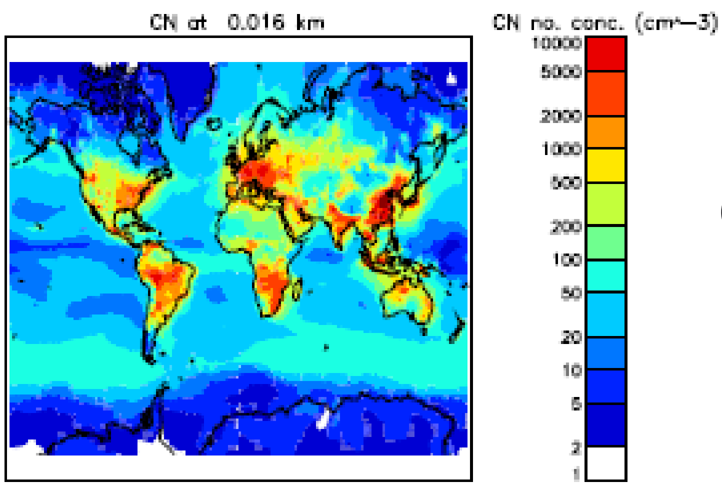
CN



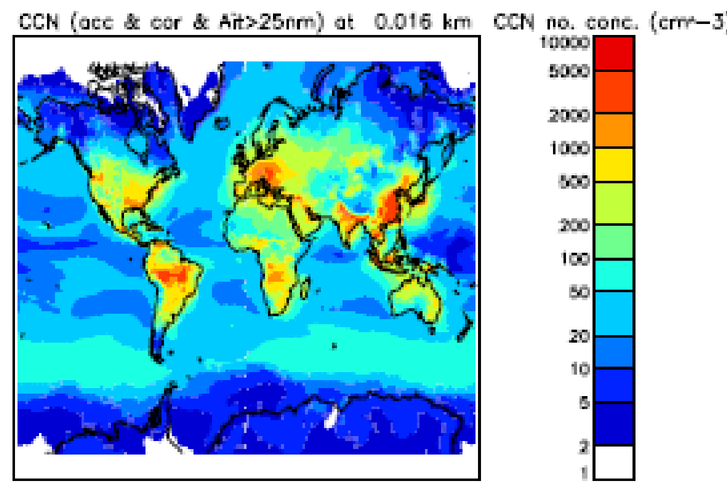
CCN



CN



CCN



Large proportion of marine CN & CCN from secondary (FT nucleated) particles.
Need to consider nucleation for realistic aerosol indirect effects on climate

Marine BL particle size distribution in UKCA

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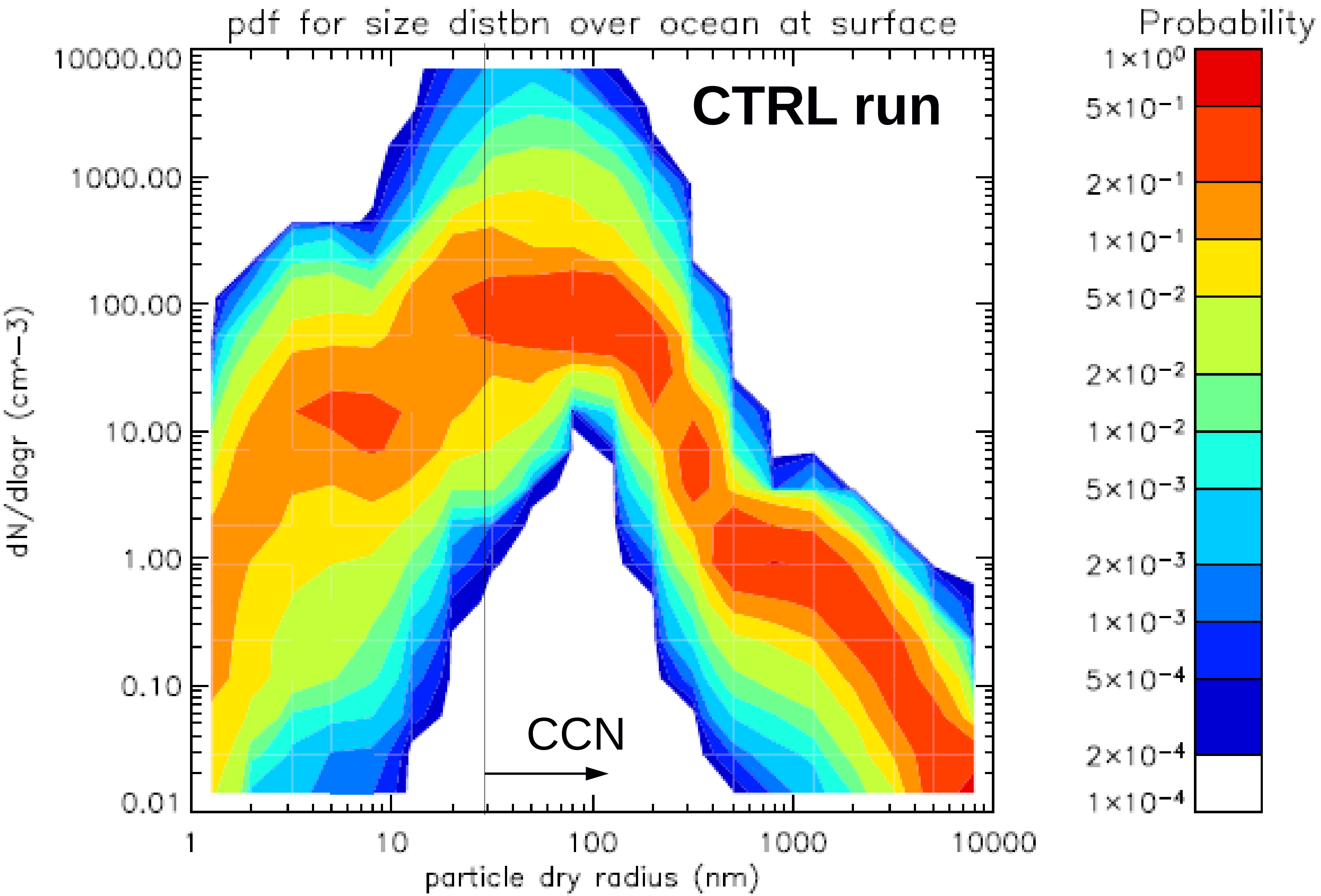

Marine BL particle size distribution in UKCA

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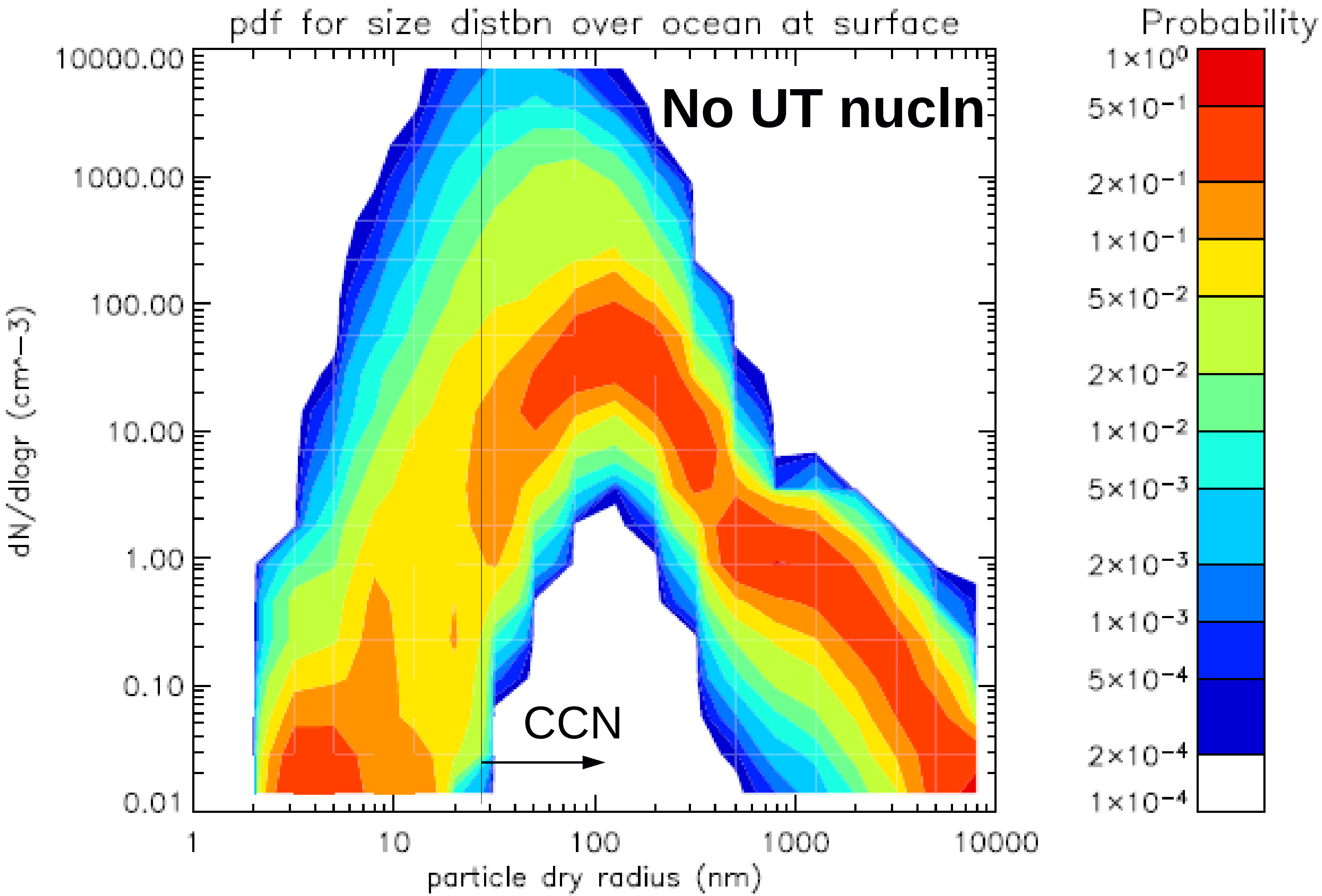

UKCA-aerosol applications: Nucleation effects on climate

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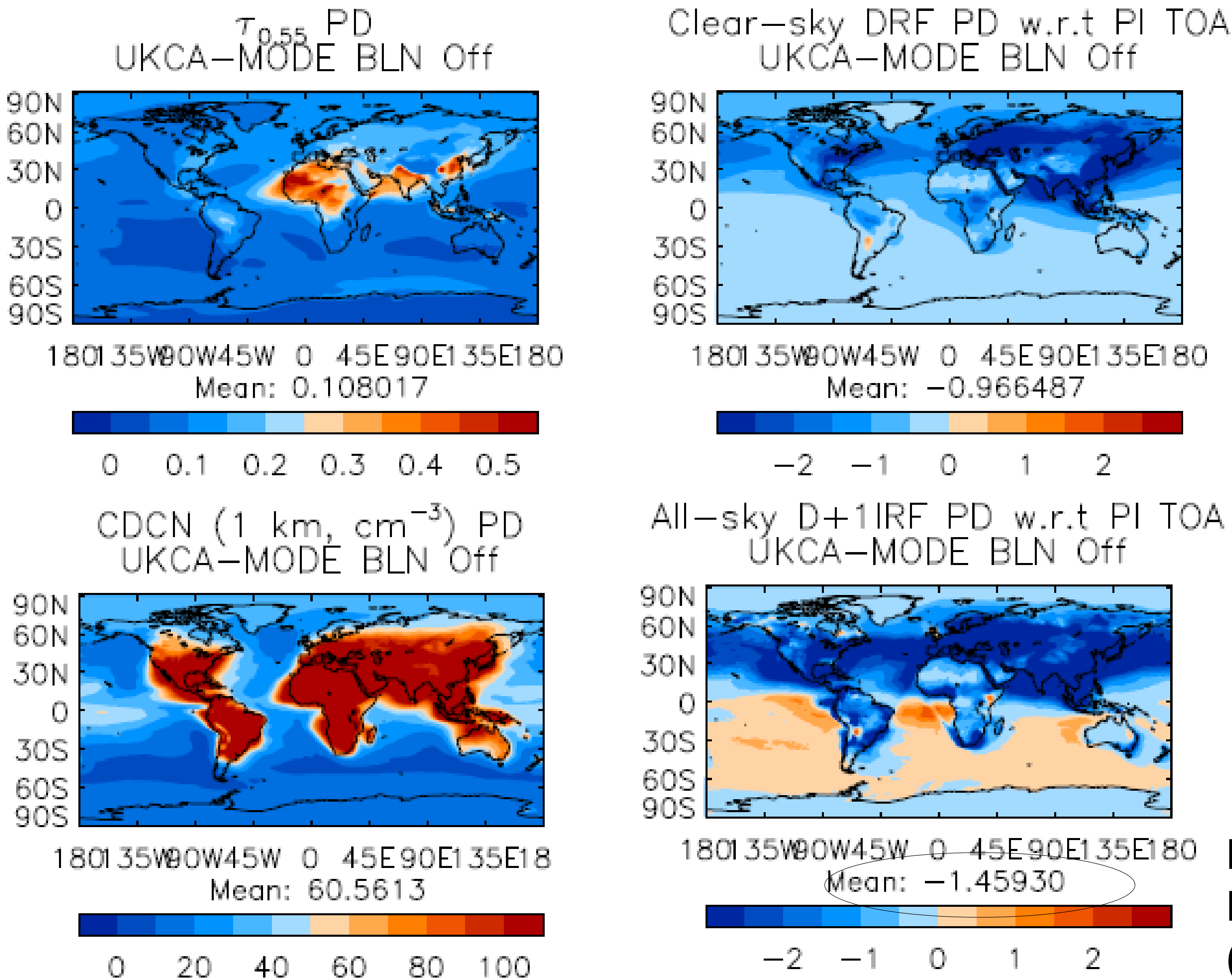

Nicolas Bellouin (Met Office)

UKCA aerosol applications: Nutrient availability to marine phytoplankton

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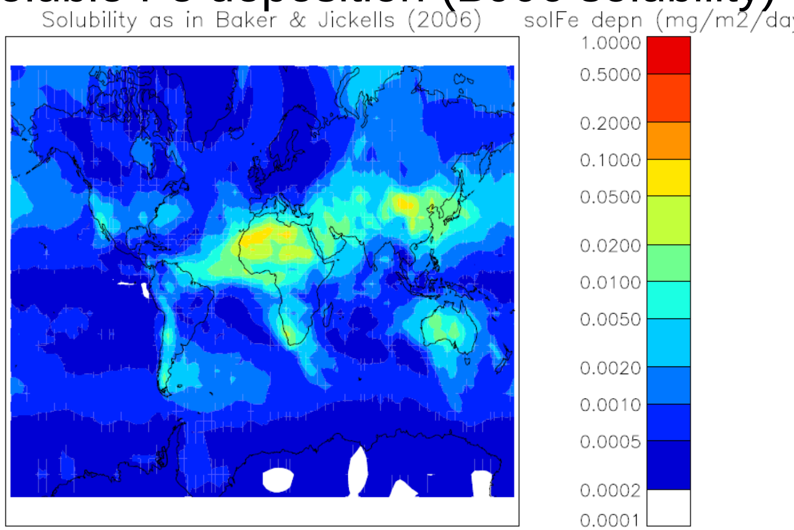
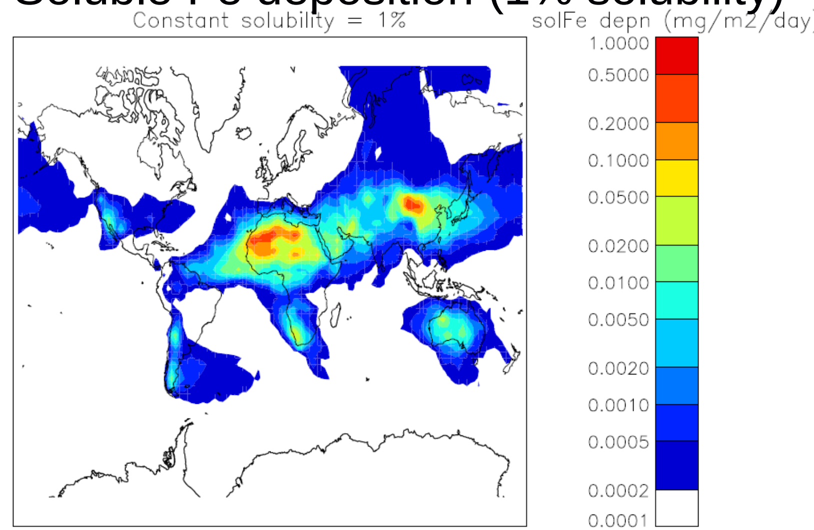
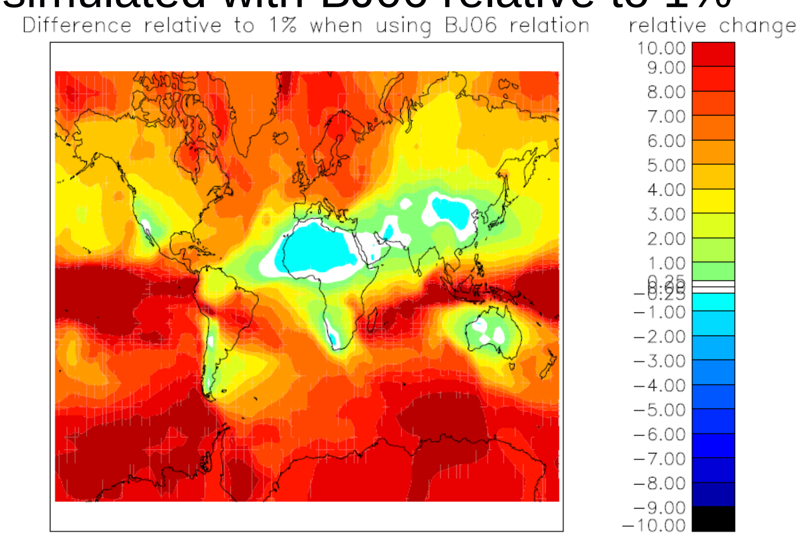
Soluble Fe deposition (BJ06 solubility)



Soluble Fe deposition (1% solubility)



Difference in soluble Fe deposition simulated with BJ06 relative to 1%



GLOMAP dust deposition → Fe to marine biota

Soluble Fe deposition simulated by UKCA will perturb nutrient availibility for phytoplankton in ocean biogeochemistry model in UKESM1.

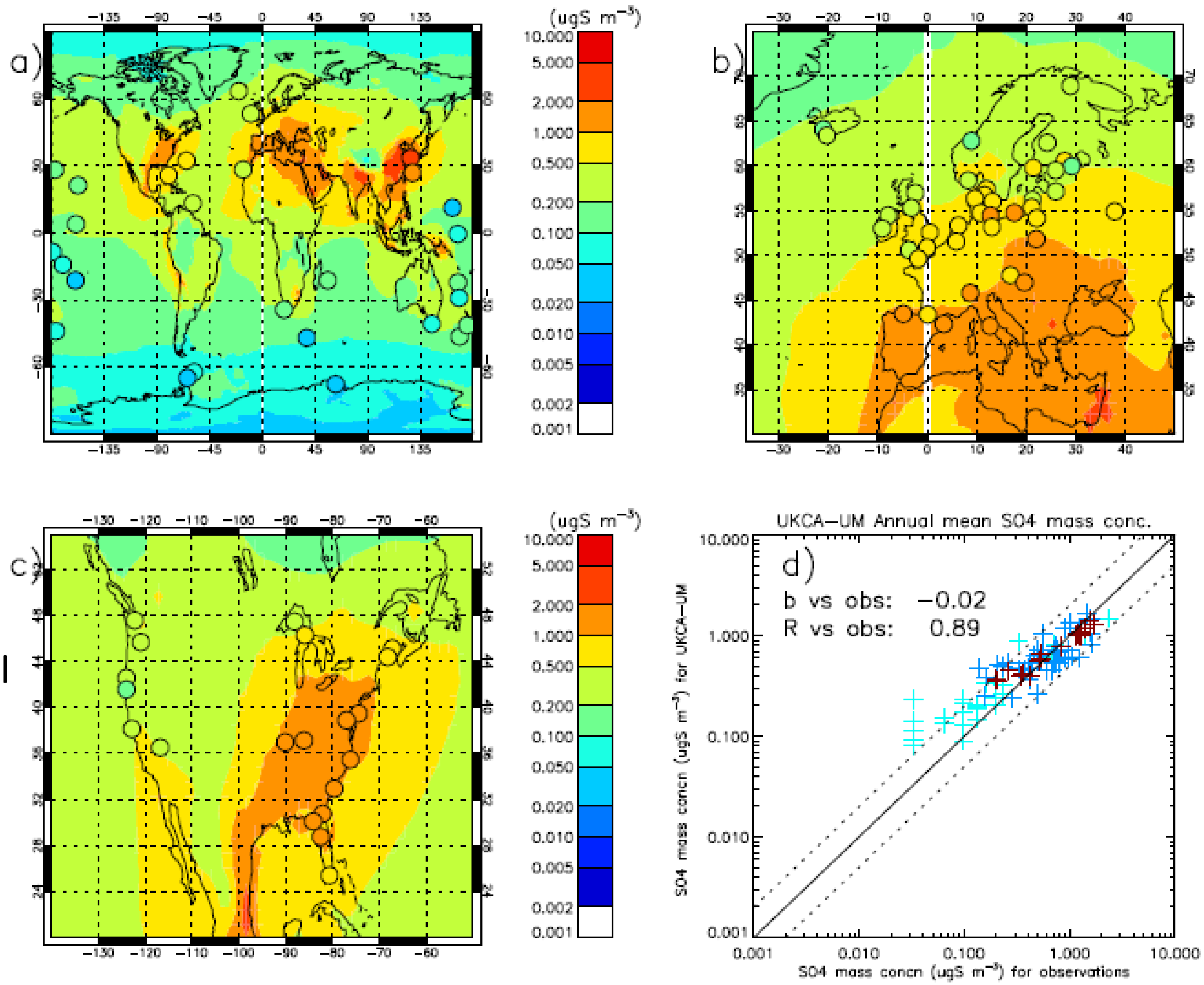
Observations suggest far-field deposited dust much more soluble than that near source.

Having fresh and aged dust modes in UKESM allows variation in Fe solubility due to size and atmospheric processing (ageing) to be resolved.

UM-UKCA v8.4 GA4 CheST+GLOMAP RC6.2(xkjgj): Evaluation vs Sulphate mass measurements Europe (EMEP : Loevblad et al., 2004) & N. America (IMPROVE network; Malm et al., 2002) and from marine sites (U. Miami network, Savoie et al., 2001)

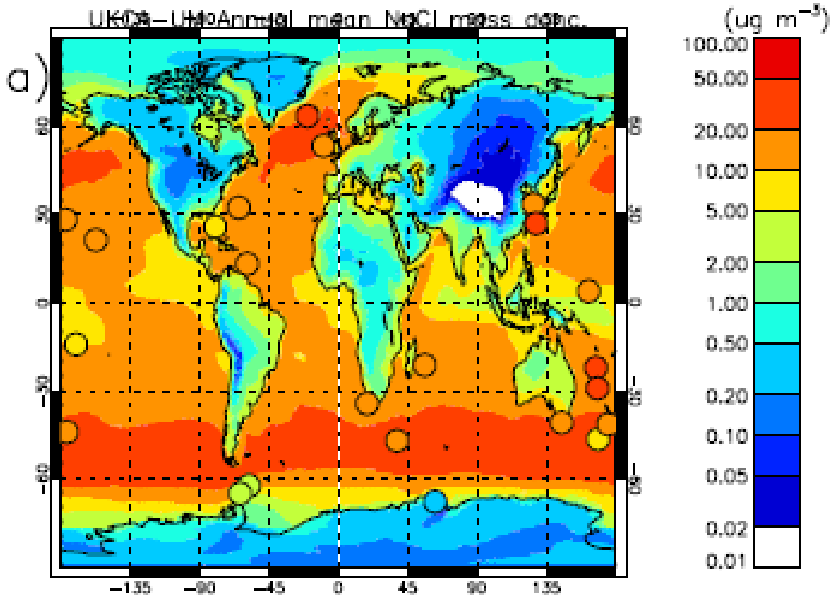
Annual mean

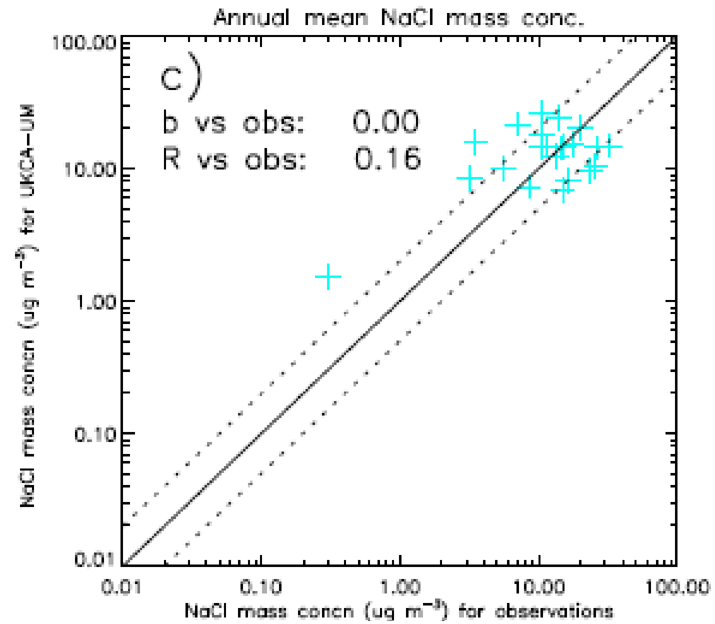
Annual mean



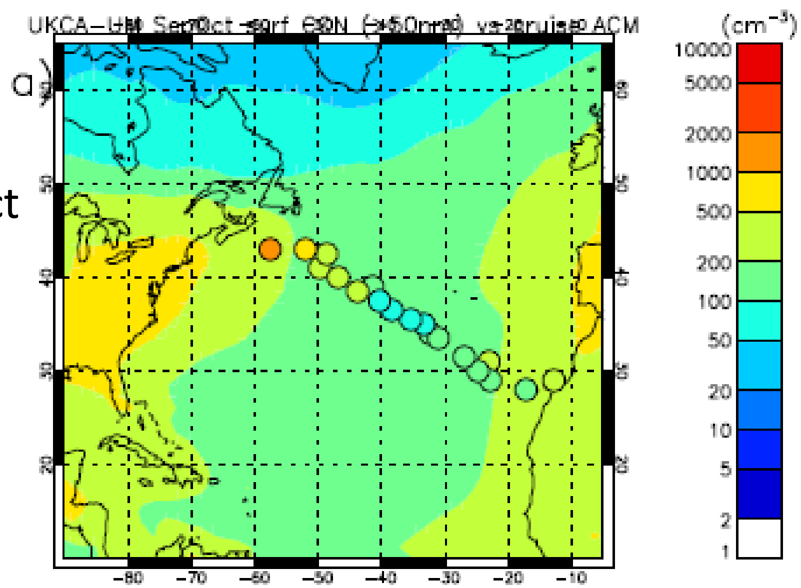
UM-UKCA v8.4 GA4 CheST+GLOMAP RC6.2(xkjgj): Evaluation vs sea-salt mass measurements (U. Miami network, Savoie et al., 2001) and cruise CCN conc'ns (Van Dingenen et al., 1995)

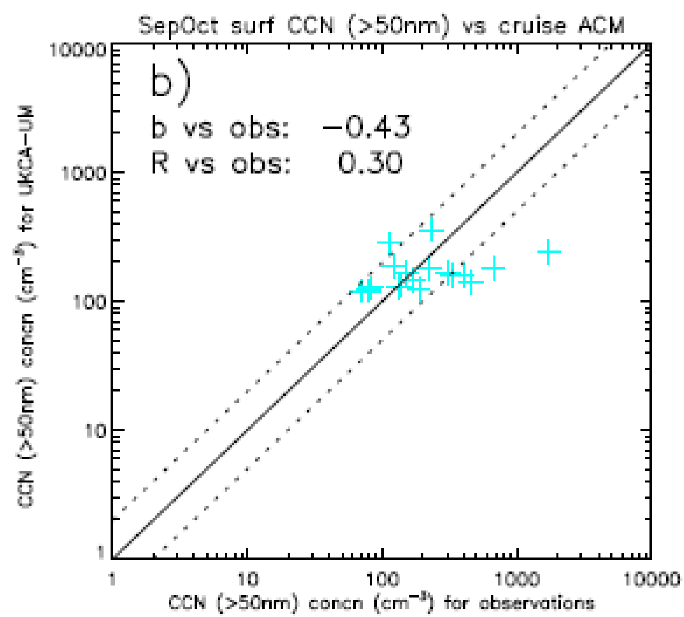
Annual mean



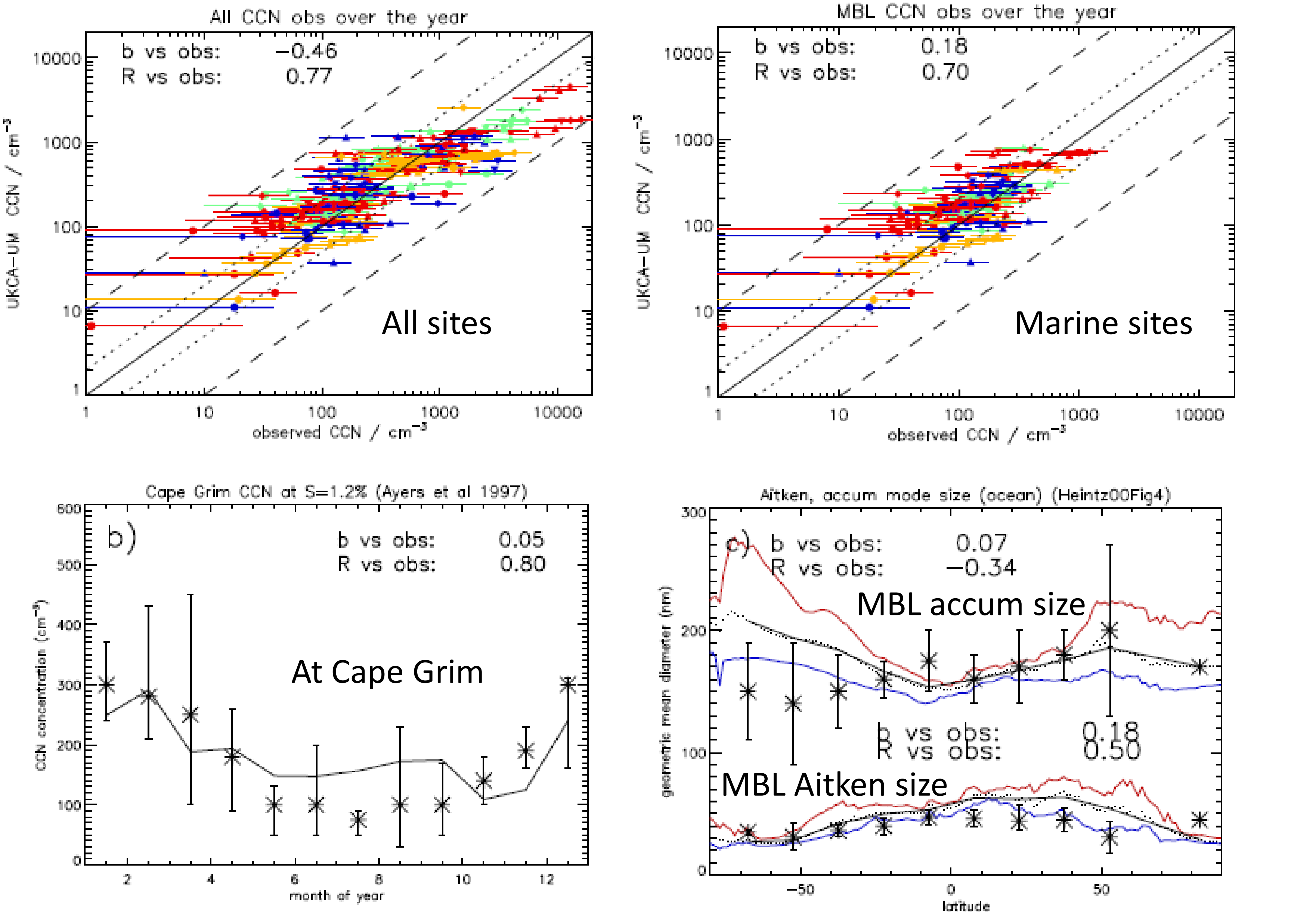


SepOct mean





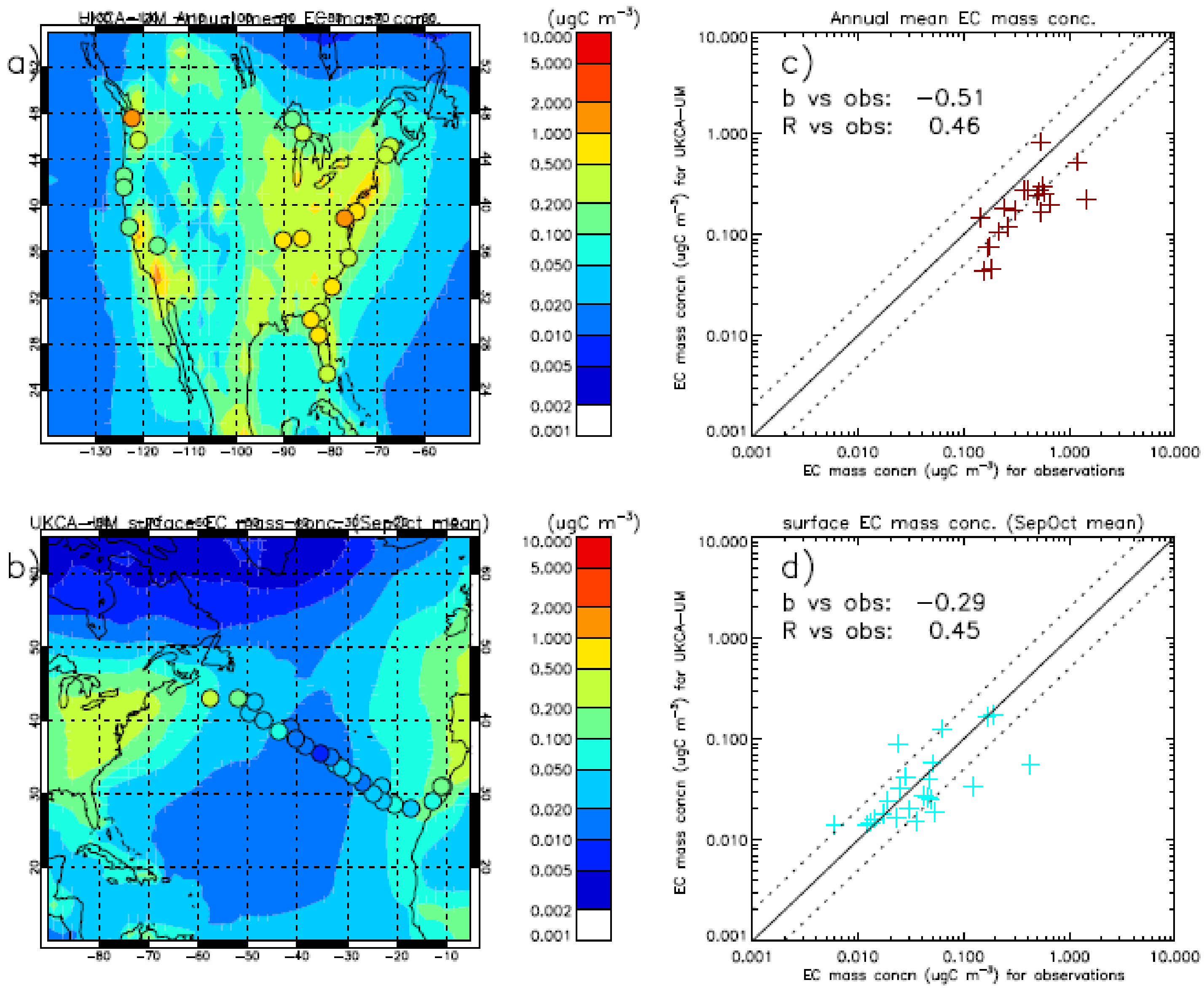
UM-UKCA v8.4 GA4 CheST+GLOMAP RC6.2(xkjgj): Evaluation vs compilation of CCN concn measurements (Spracklen et al., 2011) and Aitken/accum mode size vs Heintzenberg (2000)



UM-UKCA v8.4 GA4 CheST+GLOMAP RC6.2 (xkjgj) --- Evaluation vs EC/BC mass measurements N. America (IMPROVE network) and from N. Atlantic cruise (Van Dingenen, 1995)

Annual mean

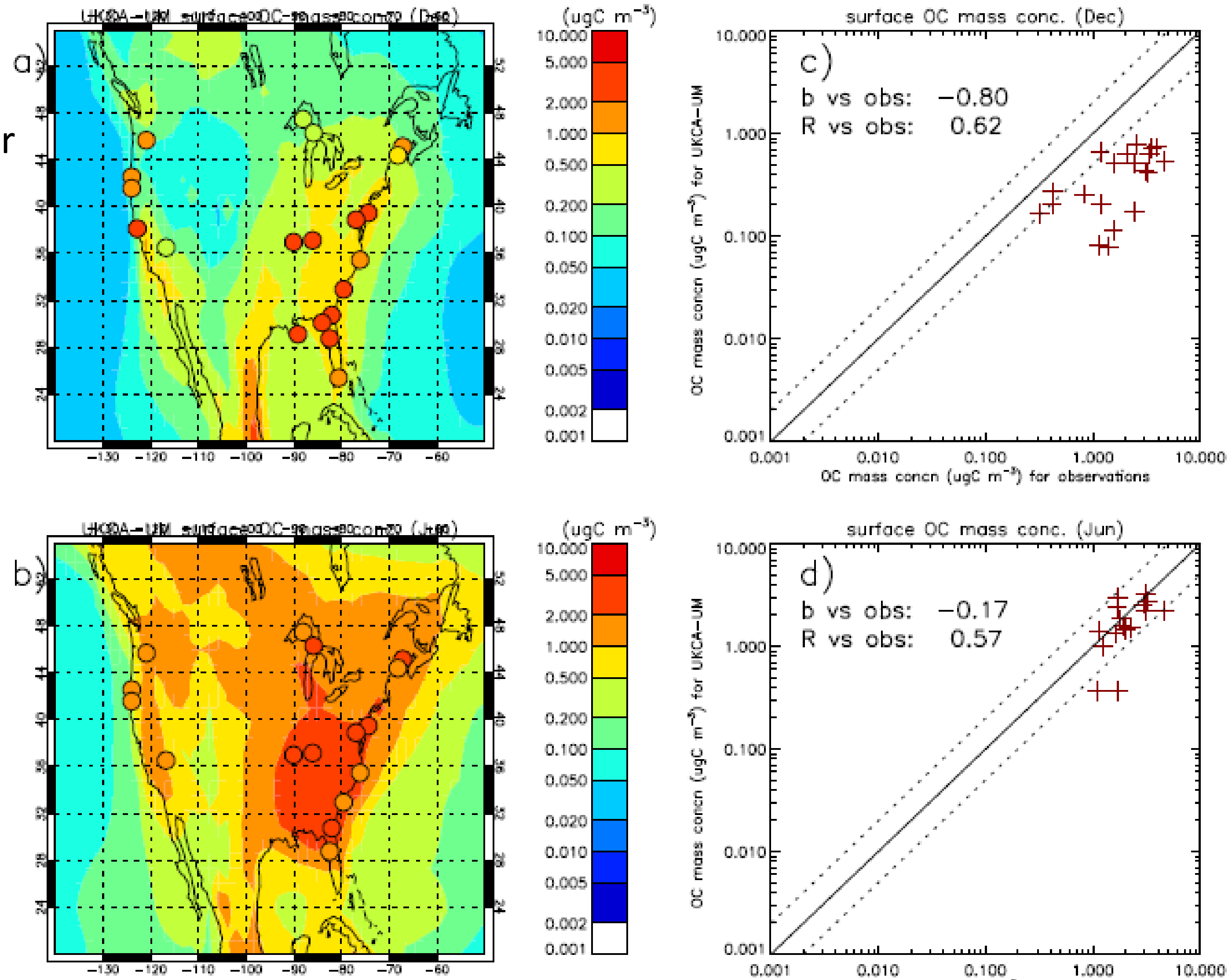
SepOct mean



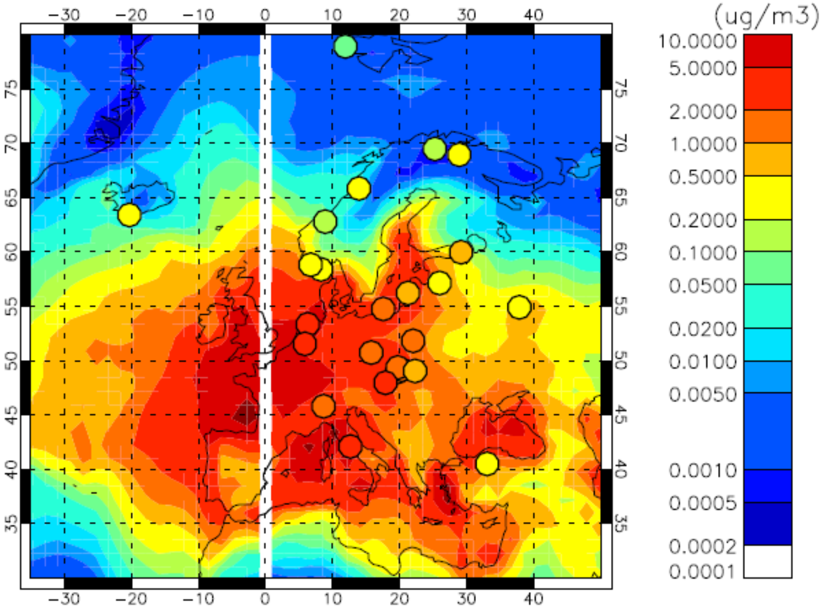
UM-UKCA v8.4 GA4 CheST+GLOMAP RC6.2(xkjgj): Evaluation vs Organic Carbon measurements from North America (IMPROVE visibility network; Malm et al., 2002)

December

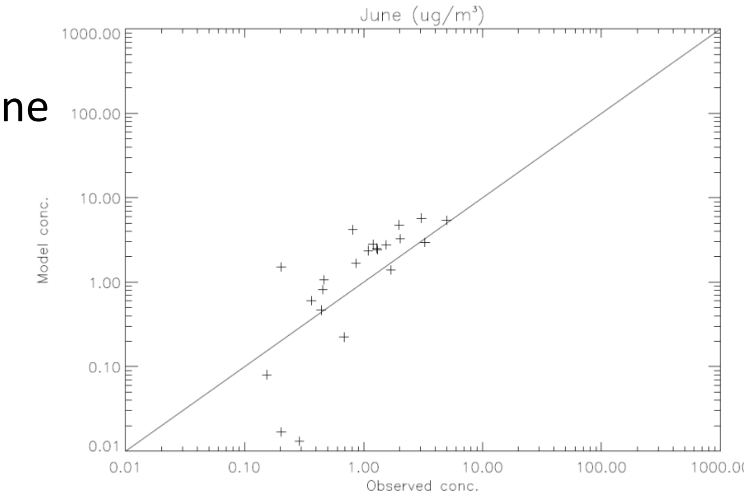
June

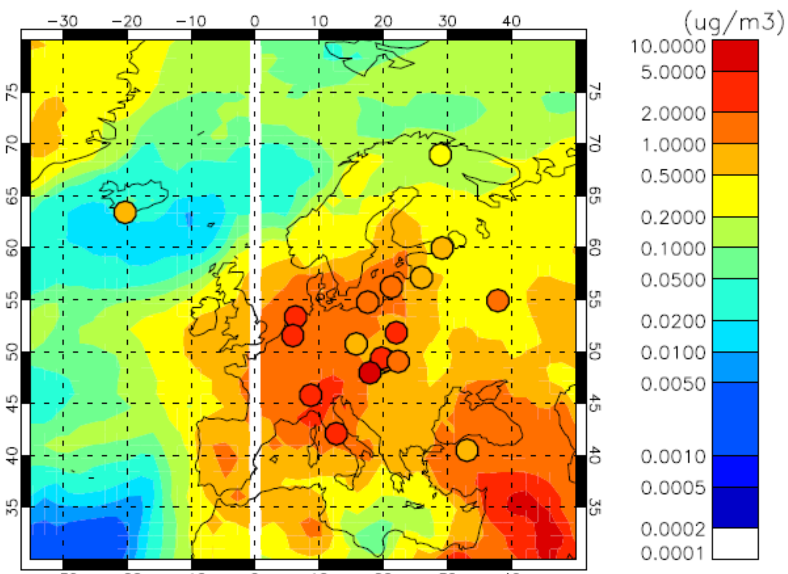


UM-UKCA v7.3 HG3-A-r2 CheT+GLOMAPnit (xiupl) - Evaluation vs nitrate measurements (June and Dec) over Europe (EMEP network; Loevblad et al., 2004)

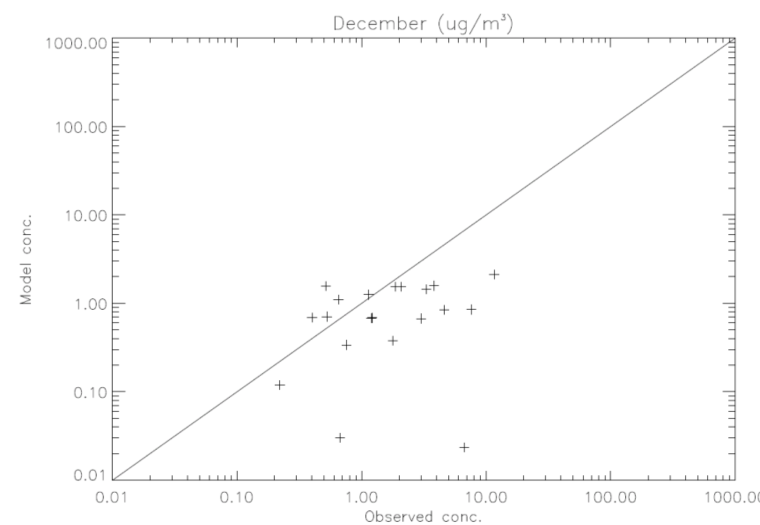


June



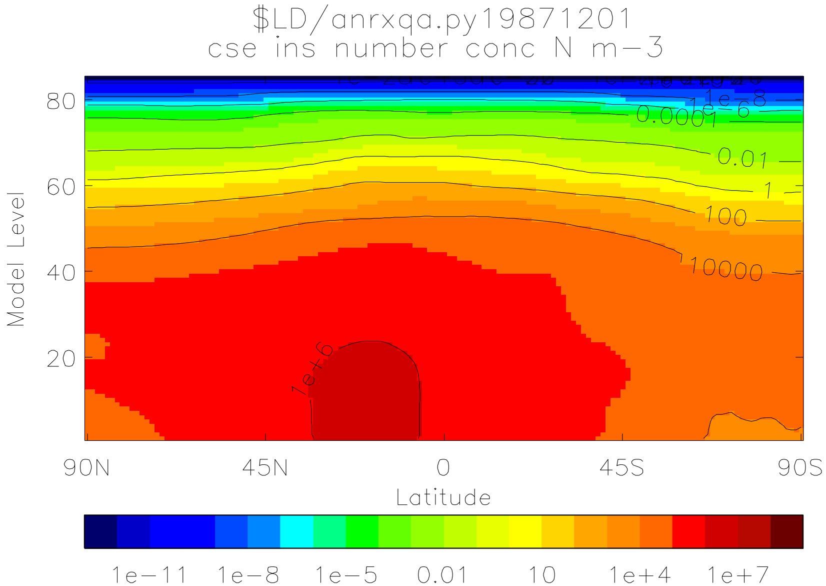


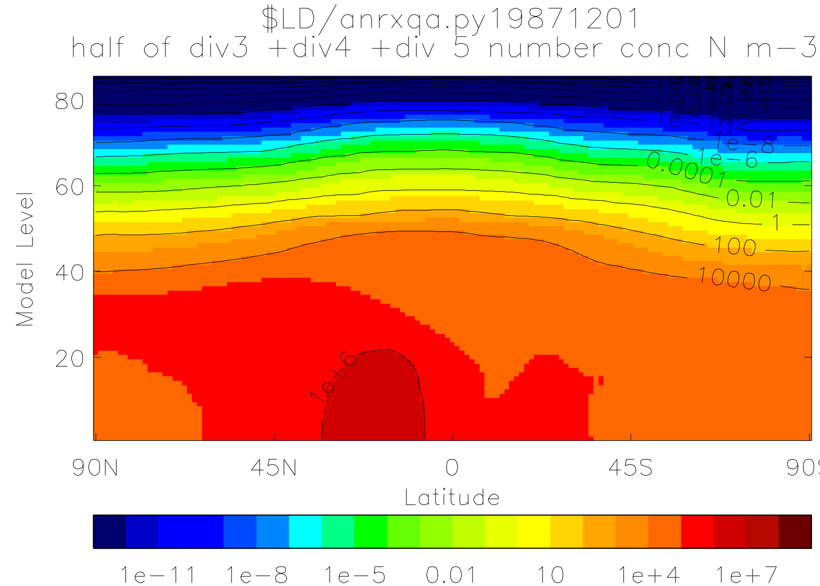
Dec

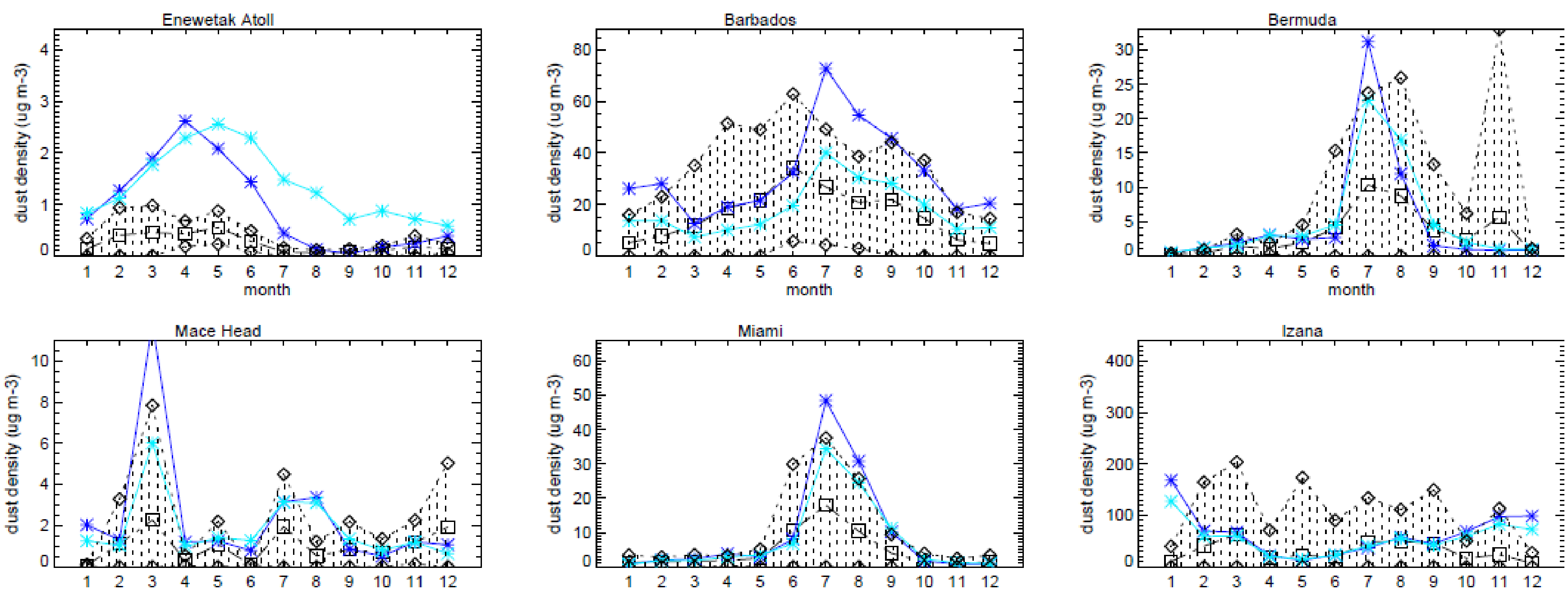


Hannah Pearce, MO CASE PhD student, Leeds

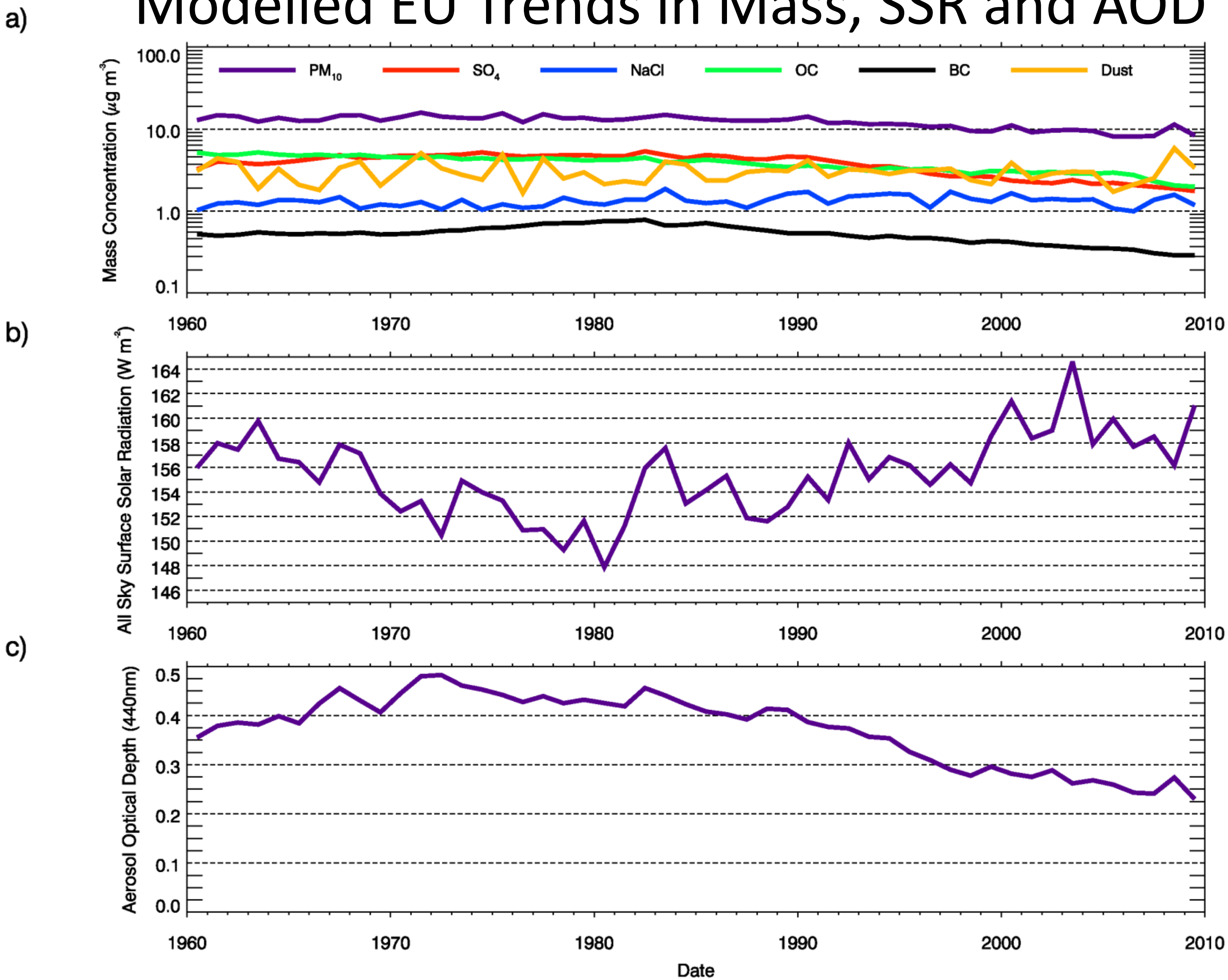
UM-UKCA v8.3 GA4 nochem+GLOMAP vs CLASSIC & Evaluation vs dust measurements (S Steph Woodward, Met Office (U. Miami network, Savoie et al., 2001)





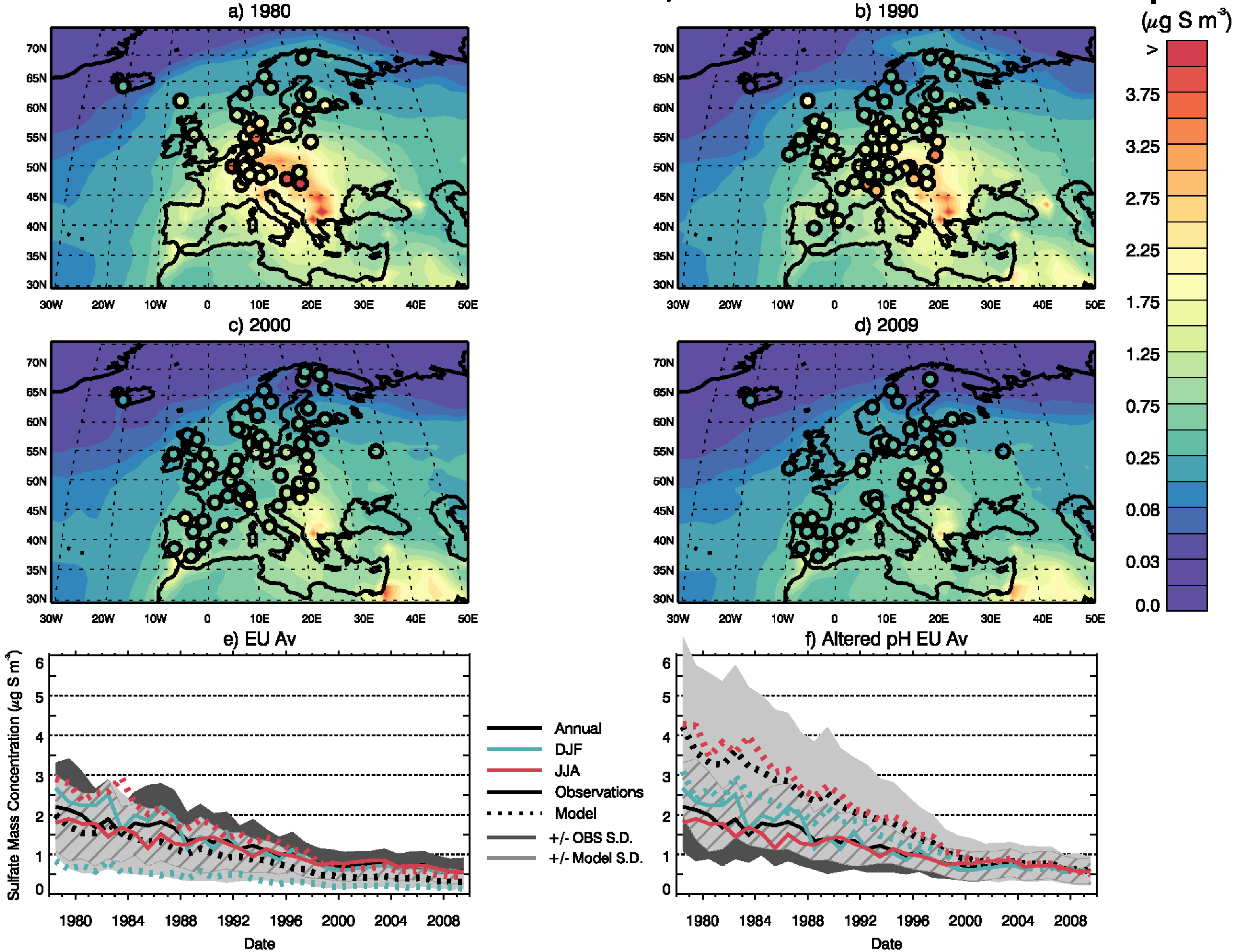


UM-UKCA v7.3 HG3-A-r2 CheT+GLOMAP Modelled EU Trends in Mass, SSR and AOD



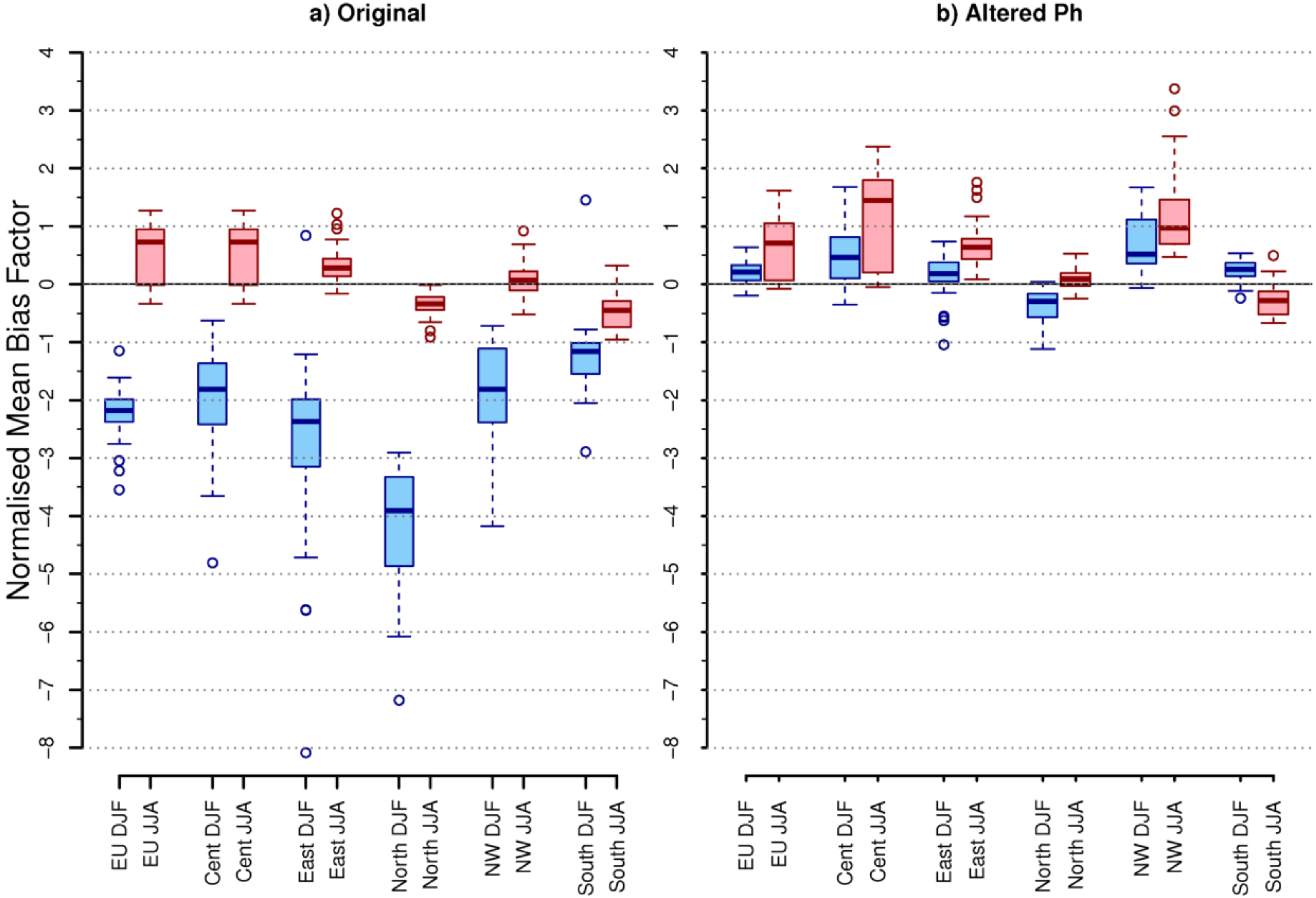
Steven Turnock, MO CASE PhD student, Leeds

UM-UKCA v7.3 HG3-A-r2 CheT+GLOMAP
Simulated SO4 trends vs EMEP, influence of cloud pH



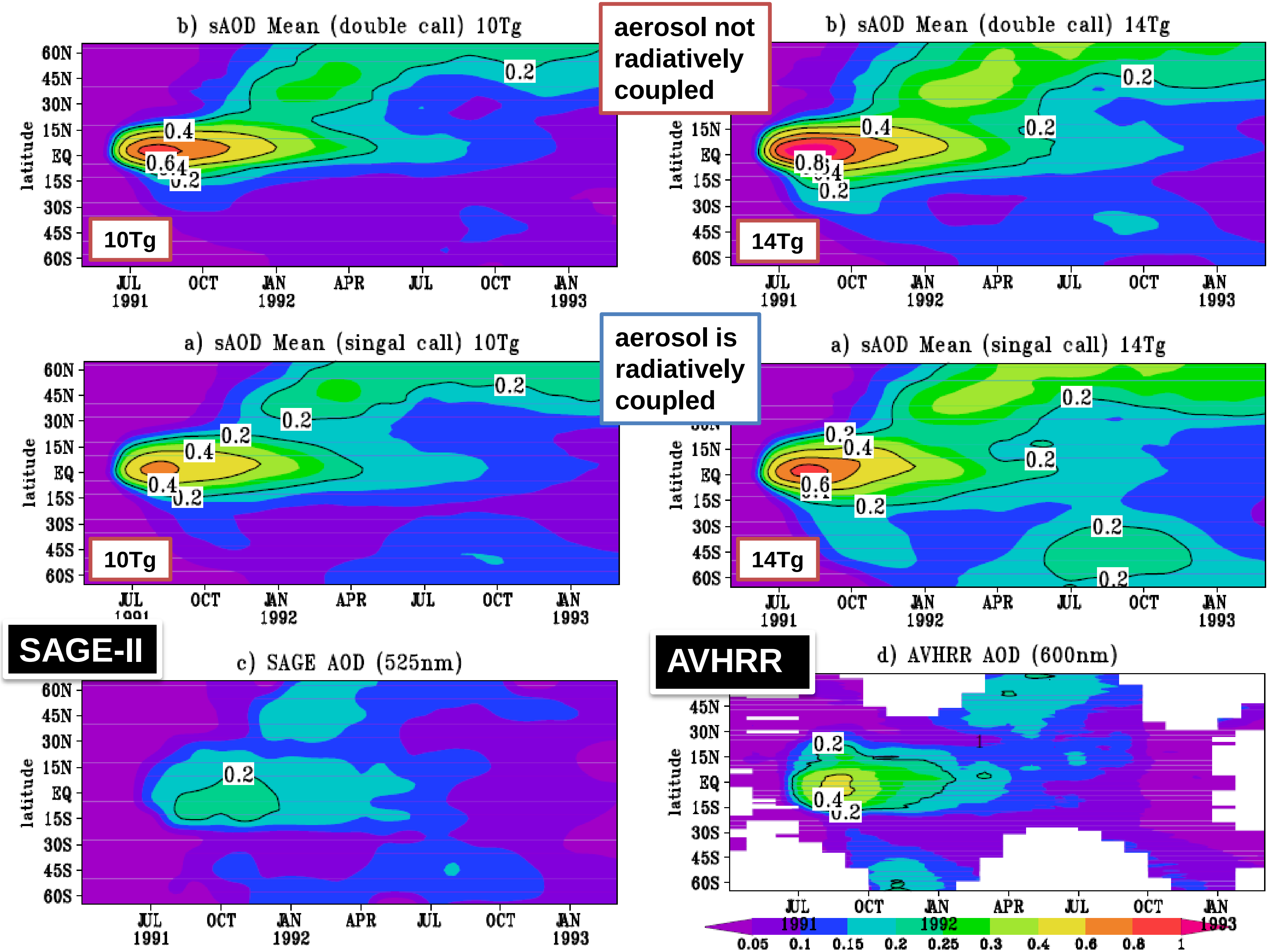
Steven Turnock, MO CASE PhD student, Leeds

UM-UKCA v7.3 HG3-A-r2 CheT+GLOMAP
NMBF for SO4 vs EMEP (plus new pH) DJF, JJA



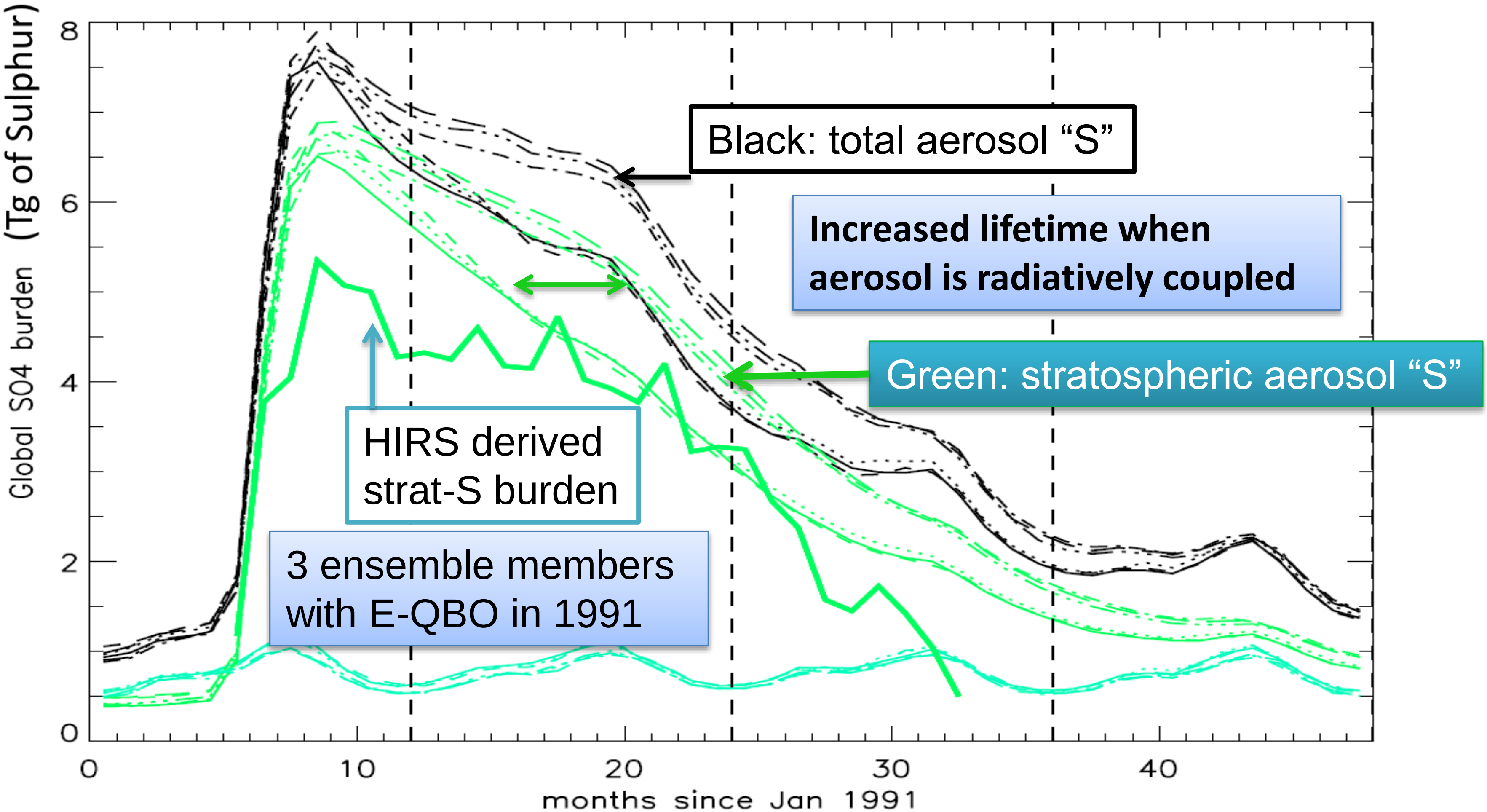
Steven Turnock, MO CASE PhD student, Leeds

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



v7.3 CheS+GLOMAP N48L60

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

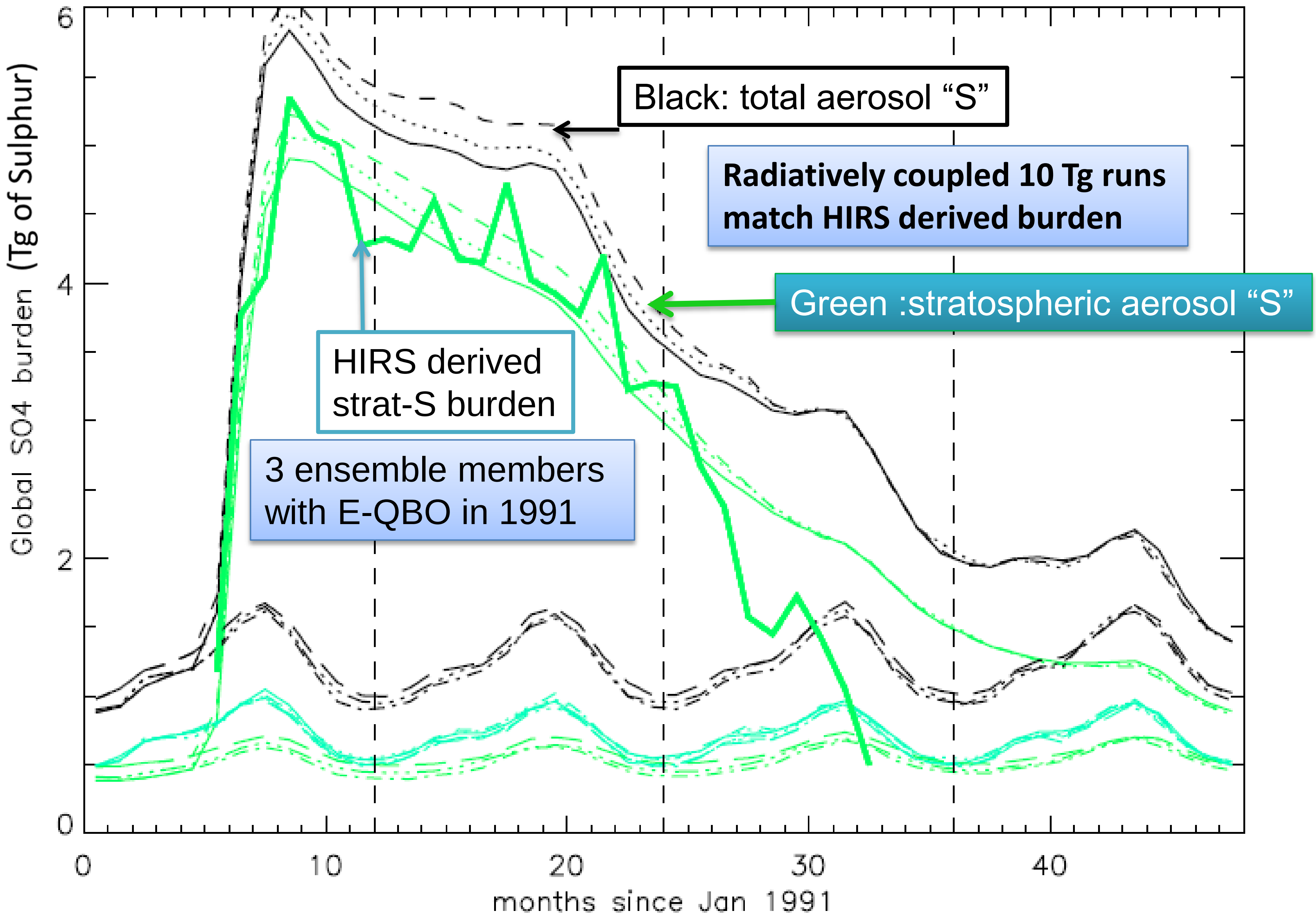


Impact of radiative coupling on lifetime in stratosphere

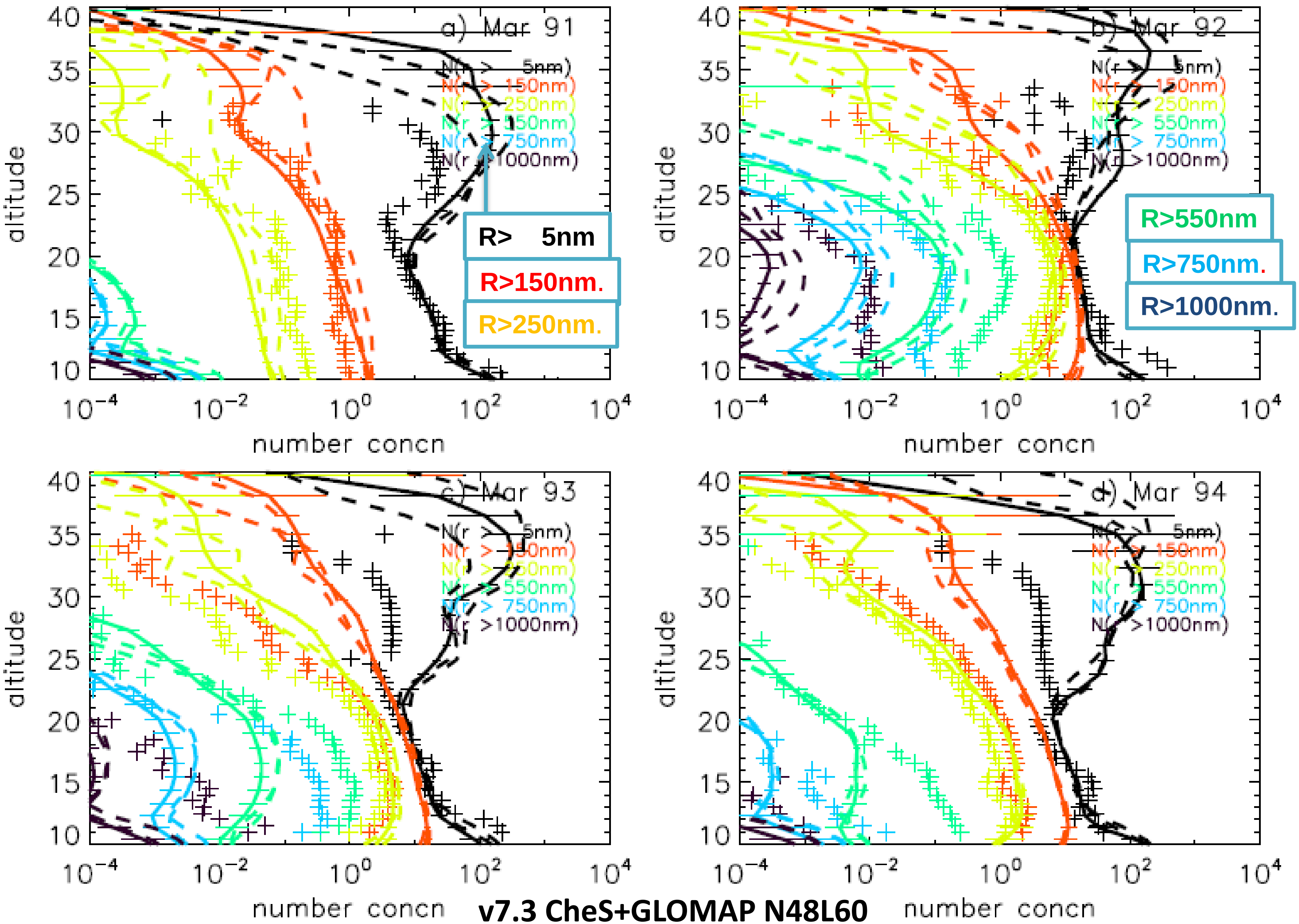
Mann et al., in preparation

v7.3 CheS+GLOMAP N48L60

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

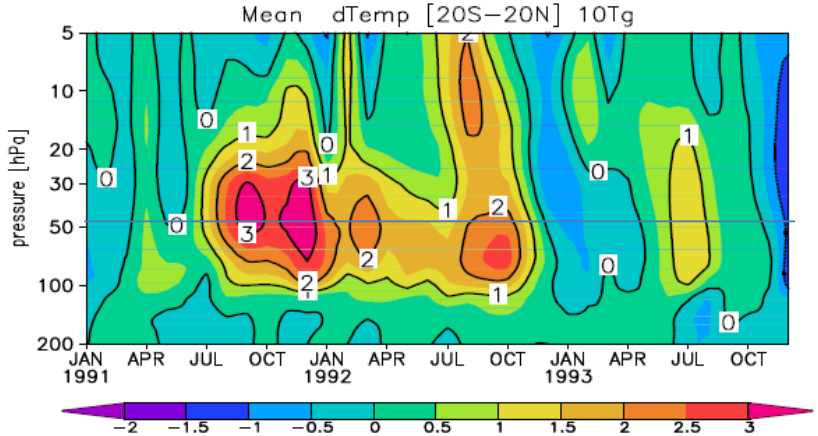


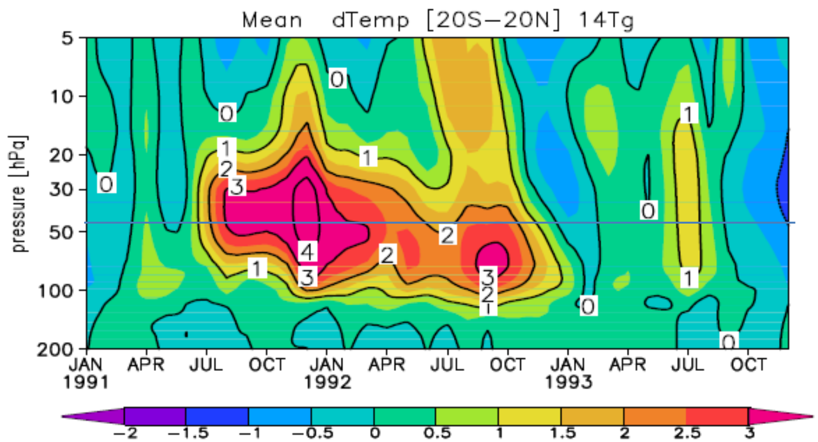
Stratospheric particle concentration profiles in UM-UKCA vs Laramie CPC/OPC (pluses)

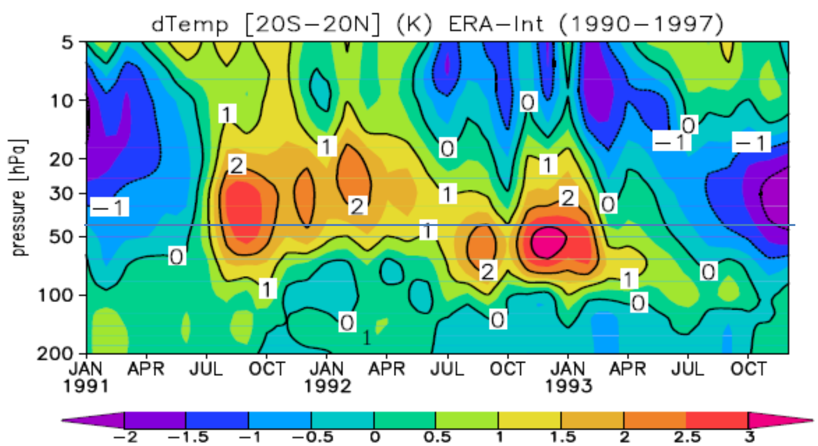


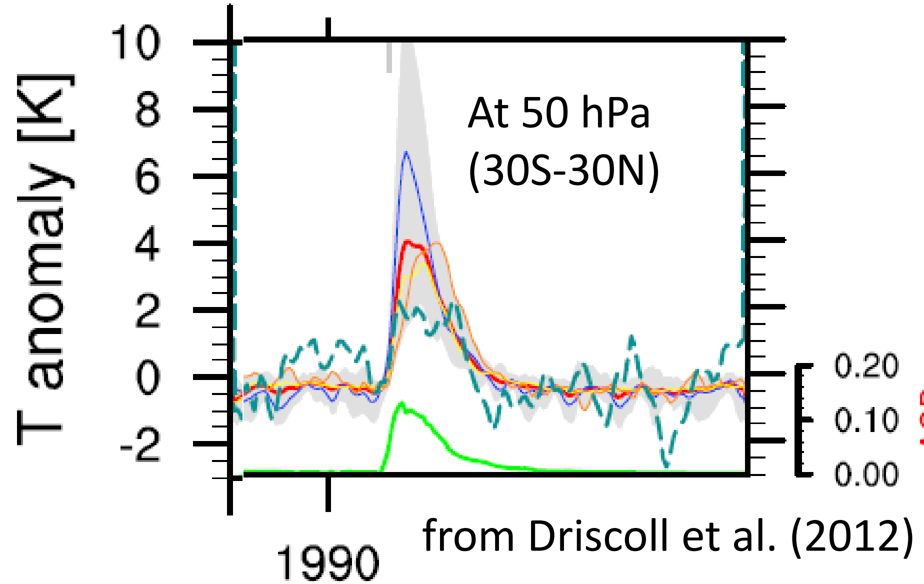
v7.3 CheS+GLOMAP N48L60

Post-eruption warming evolution in tropical stratosphere in UM-UKCA vs ERA-interim









from Driscoll et al. (2012)

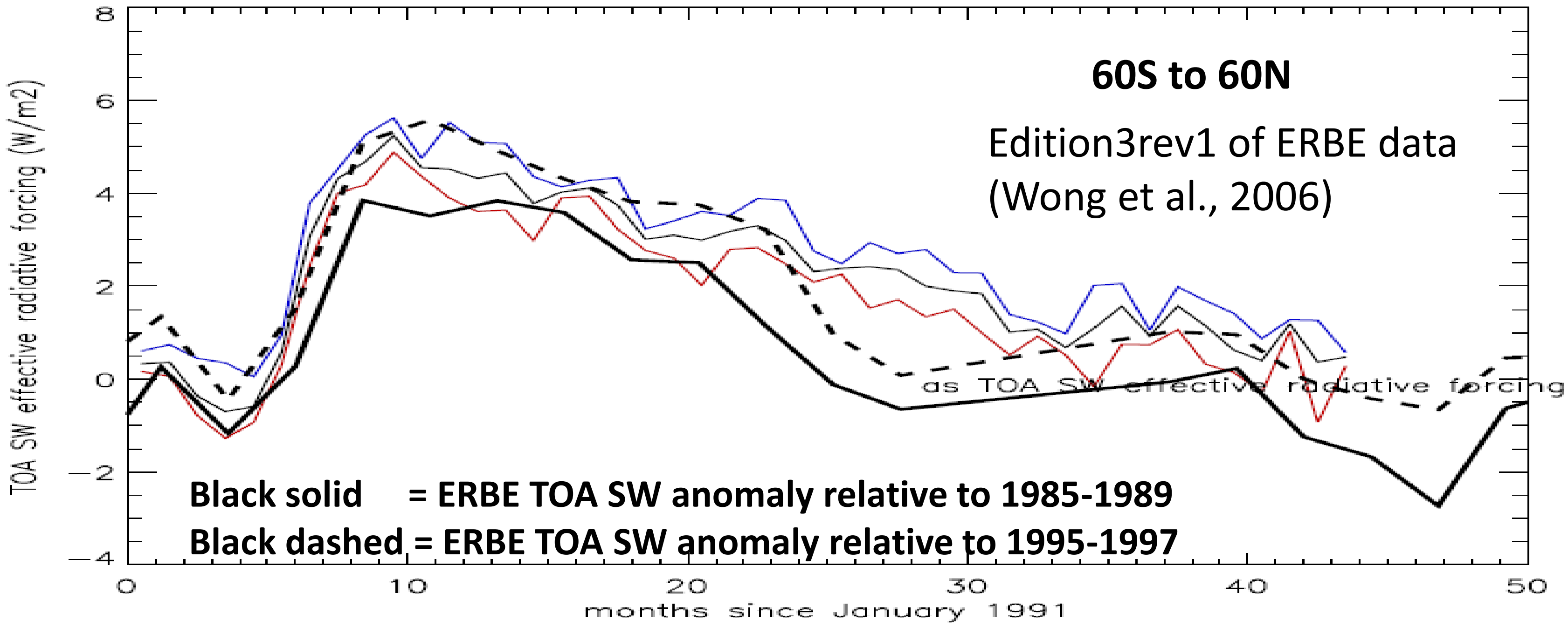
Stratospheric warming from 10 Tg Pinatubo simulation captures approximately the peak seen in the ERA-interim re-analyses.

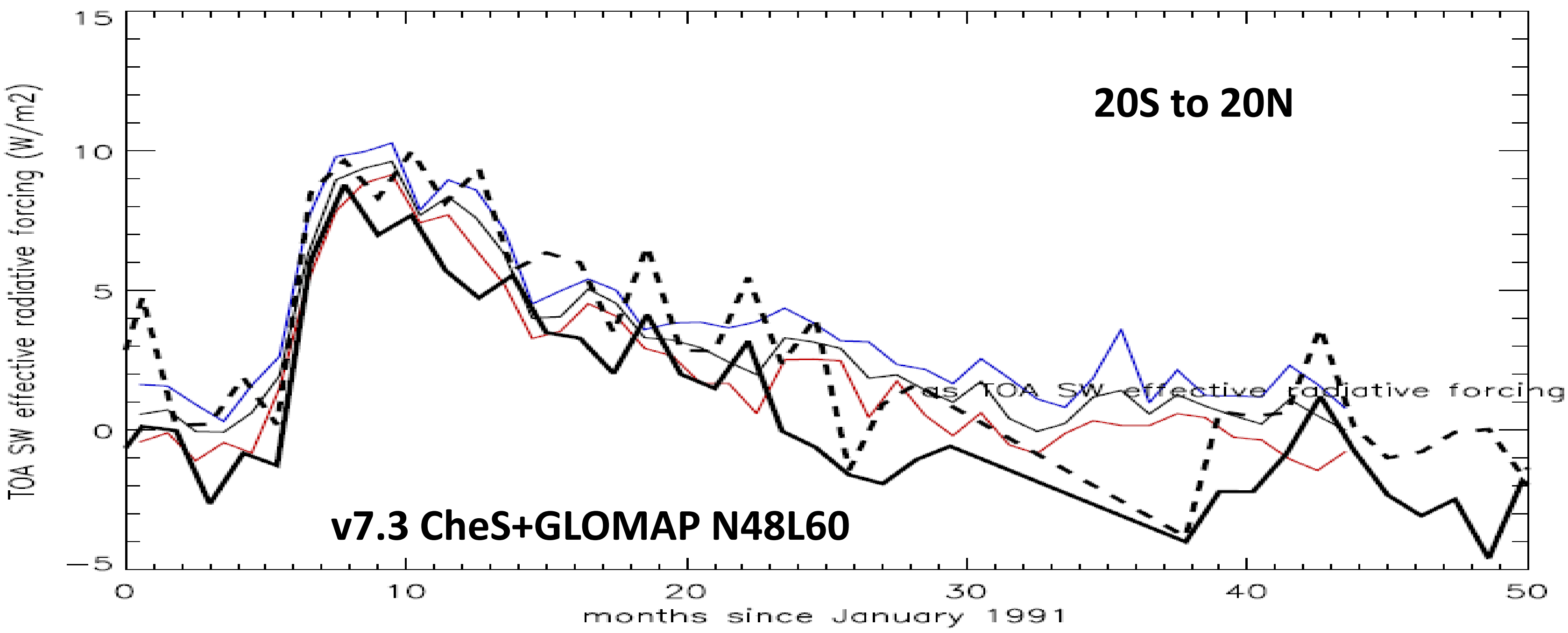
14 Tg Pinatubo injection over-estimates the warming.

Note the delta-Ts include any offset from cooling of the tropical lower stratosphere that results from any chemical and dynamical ozone losses.

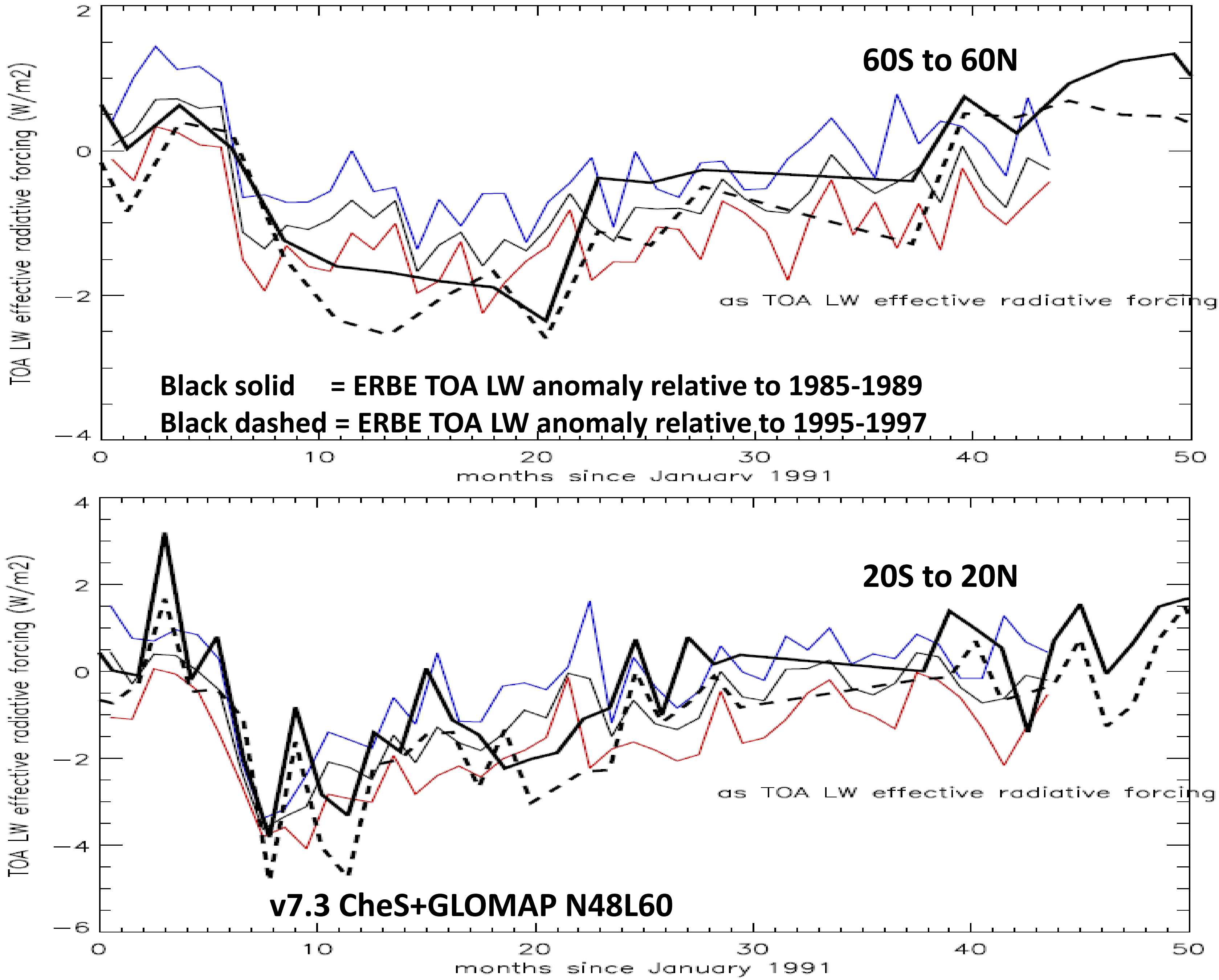
v7.3 CheS+GLOMAP N48L60

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





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



Summary of UKCA evaluation

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UKCA evaluation suite includes comparisons to sulphate, BC, POM, sea-salt at surface sites. Comparisons to dust, nitrate also carried out.

Also wider evaluation against CCN, size-resolved particle concentrations

Trends in sulphate, PM, AOD, surface solar radiation across Europe

Modal dust scheme now operating well compared to bin scheme

Evaluation of stratospheric aerosol properties against range of datasets covering both quiescent and volcanically perturbed conditions

Simulated SW and LW Pinatubo forcings in excellent agreement with observed anomalies from ERBE for 10 Tg injection of SO_2

Observed global variation and evolution of strat-AOD, strat-S-burden, stratospheric warming, and TOA radiation anomalies all consistent with simulations with 10 Tg SO_2 injection

Stronger efficacy of Pinatubo forcing per unit mass of aerosol sulphur

UM-UKCA next steps

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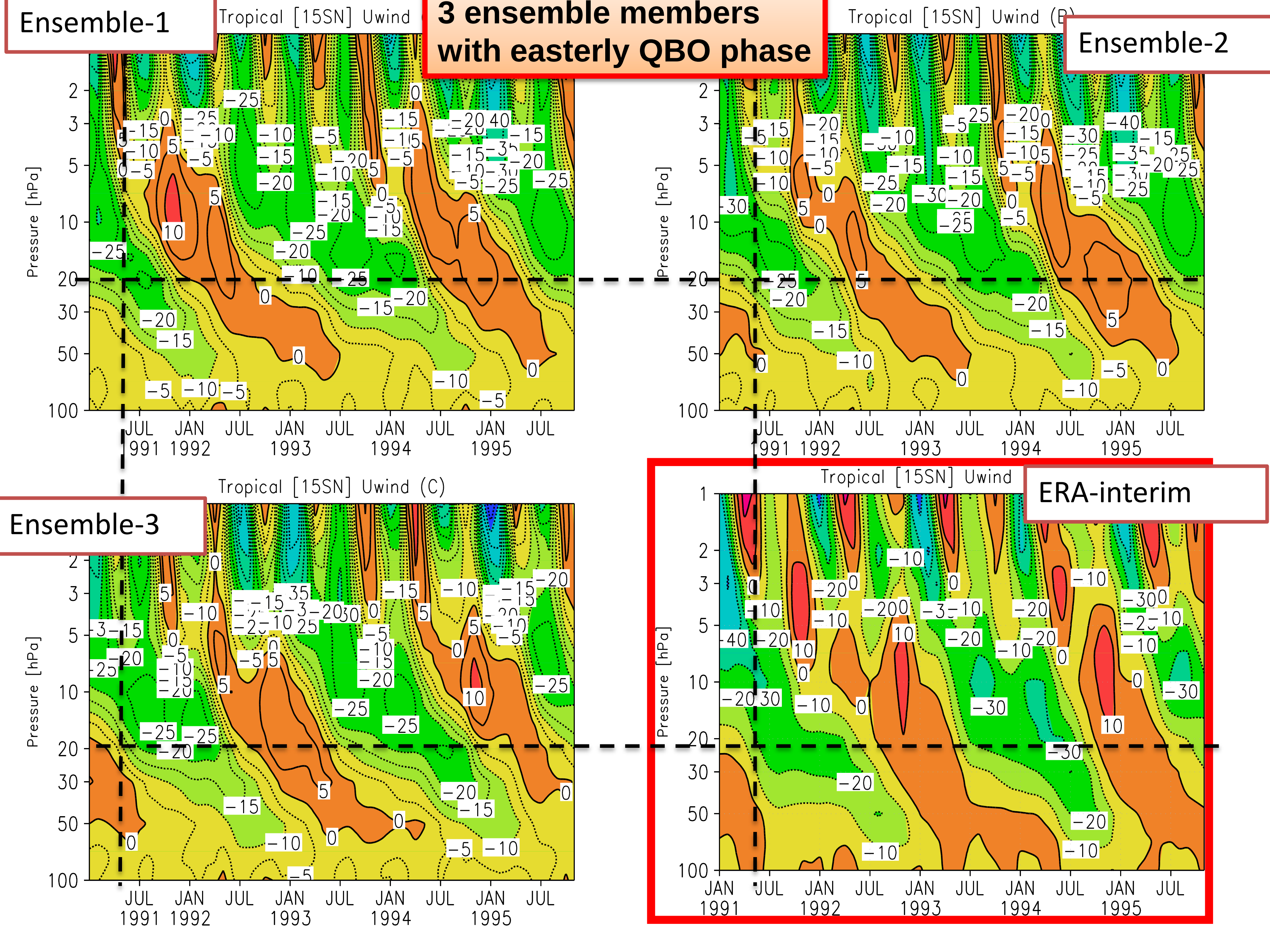
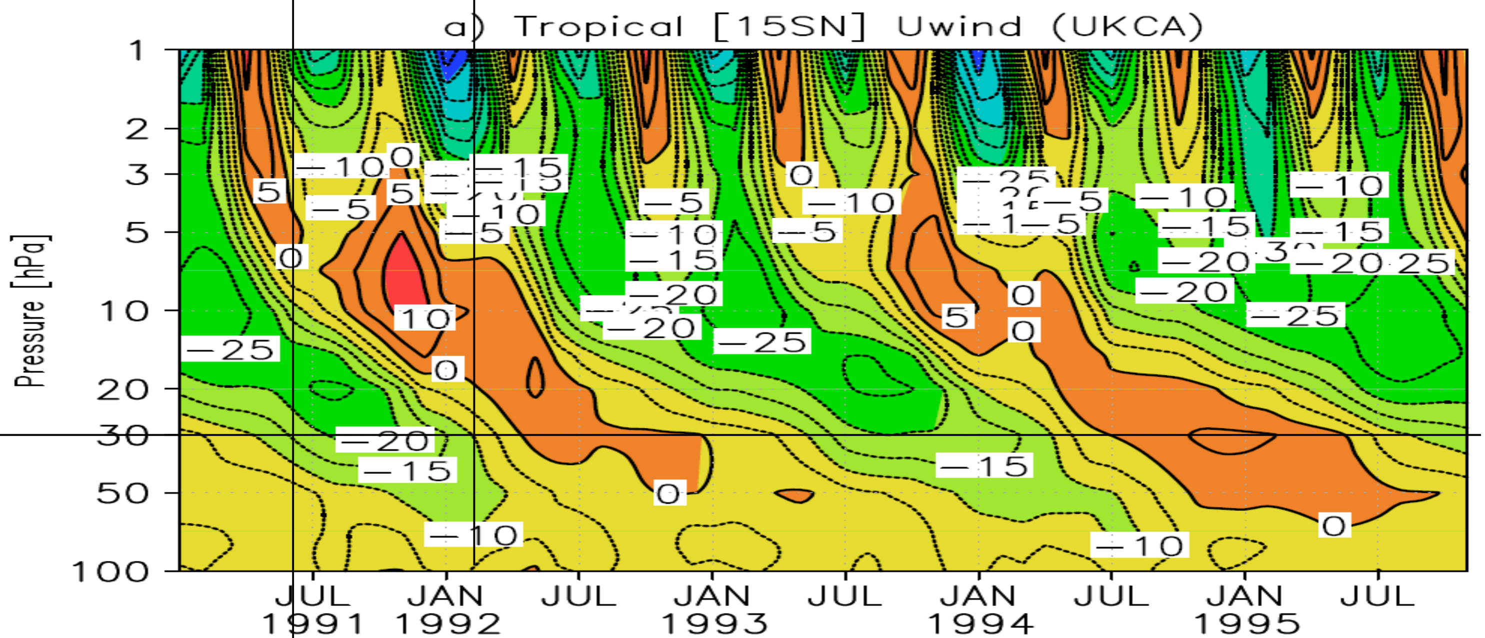
First stage of UKCA is complete whereby UKCA aerosol scheme using GLOMAP aerosol microphysics is fully integrated within the UM at GA7

Next steps in UKCA development and science:

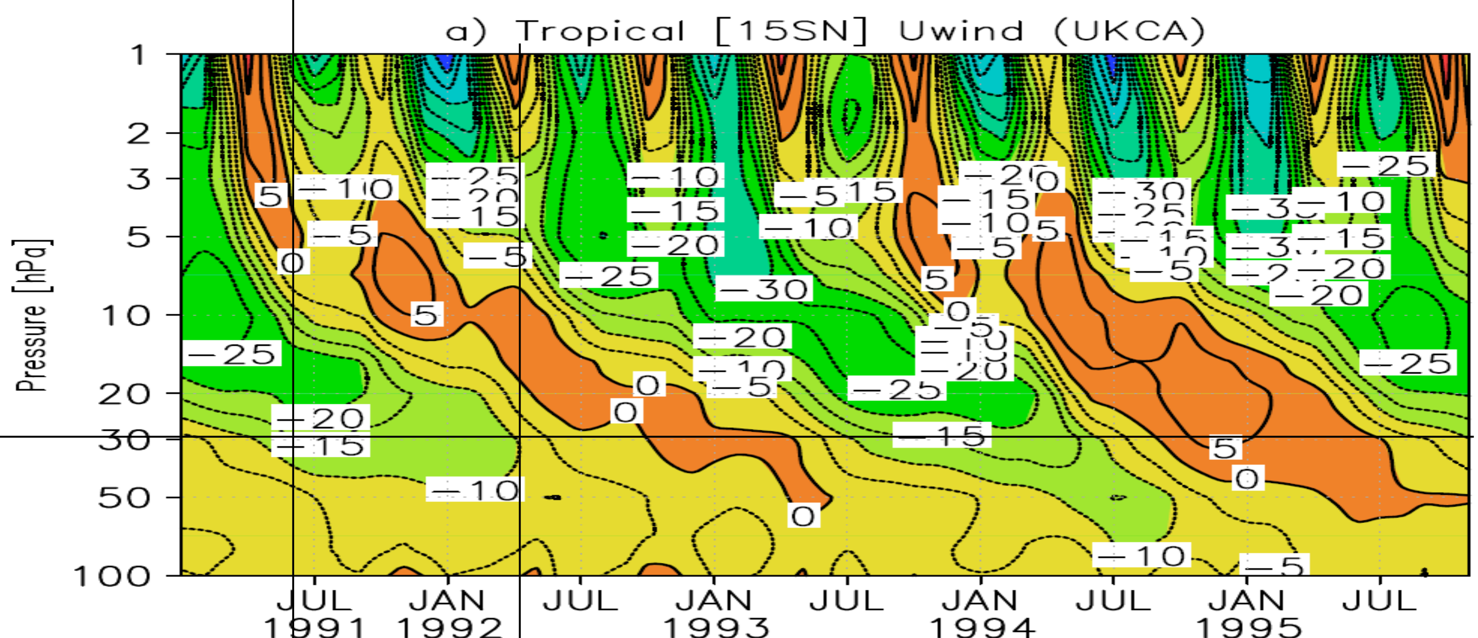
- Full GLOMAP configuration with modal dust for Earth System science
- Aerosol Optical Depth assimilation for aerosol re-analyses via implementation of GLOMAP into ECMWF Integrated Forecasting System (IFS) (EU-funded MACC projects have built on capability from GEMS project).
- Fully coupled aerosol-climate and aerosol-ES simulations in UKCA and QUEST Earth System Model – explore aerosol-related ES interactions.
- Extended UKCA inorganic composition simulating size-resolved NH4 & NO3 Scheme developed by Francois Benduhn to be incorporated into UKCA.
- Secondary organic aerosol chemistry scheme to more realistically simulate production of biogenic and anthropogenic SOA in UKCA
- Stratospheric aerosol and geoengineering simulations


3 ensemble members with easterly QBO phase
Ensemble-1
Tropical [15SN] Uwind
Ensemble-2
Tropical [15SN] Uwind (B)
Ensemble-3
Tropical [15SN] Uwind (C)
ERA-interim
Tropical [15SN] Uwind
Pressure [hPa]
JUL 1991
JAN 1992
JUL
JAN 1993
JUL
JAN 1994
JUL
JAN 1995
JUL
JAN 1991

Impact of radiative coupling: strat. dynamics



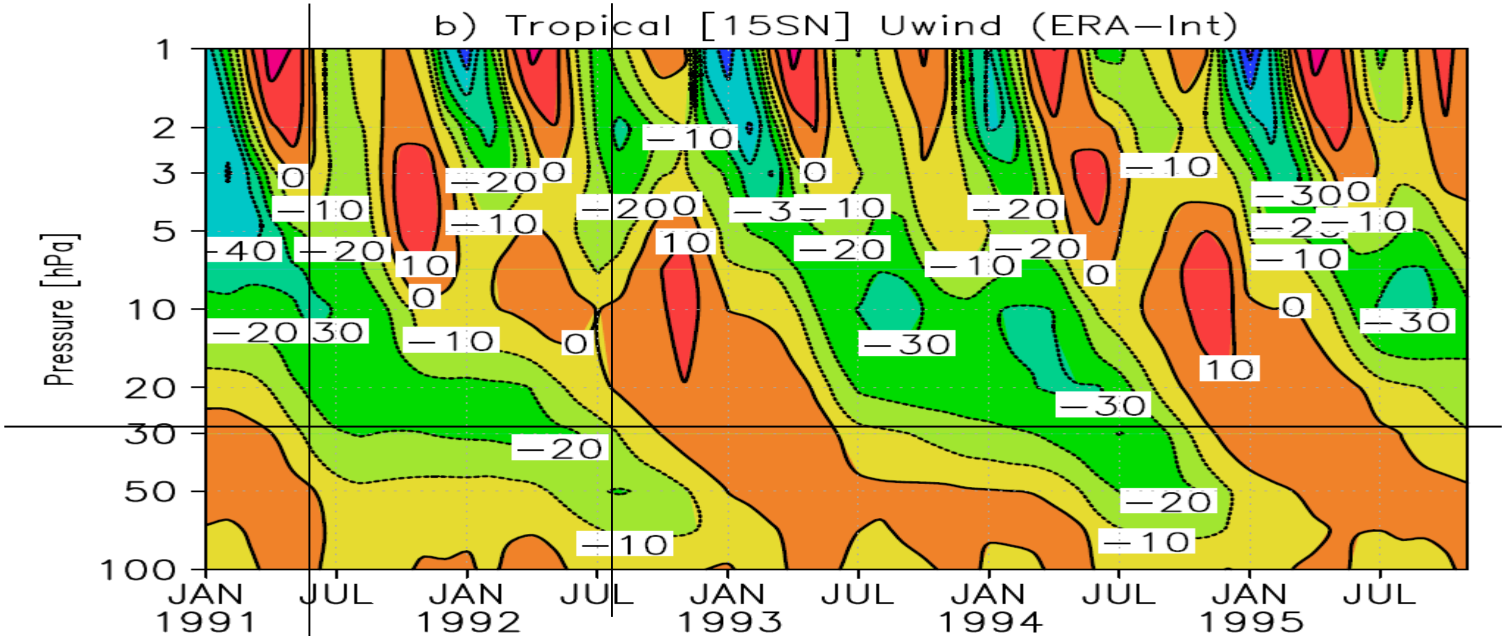
Tropical zonal mean zonal wind for “no Pinatubo” run



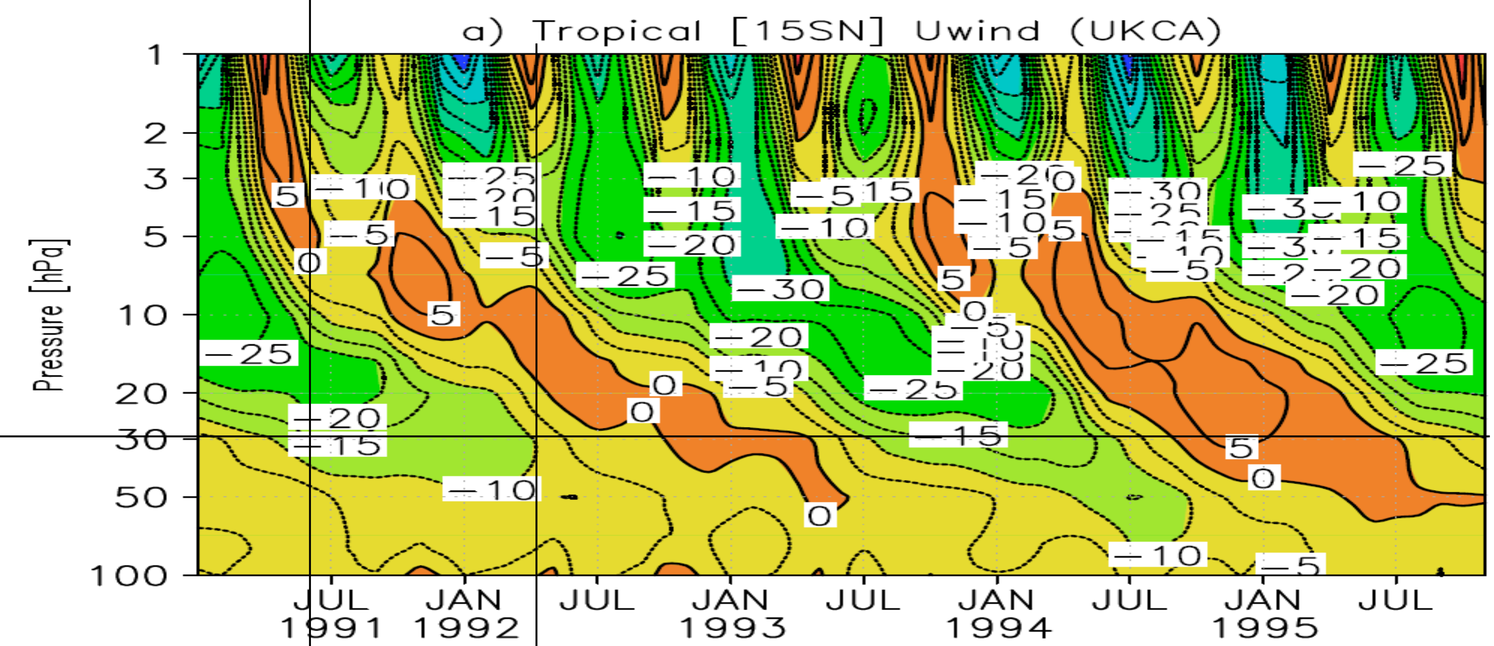
Tropical zonal mean zonal wind for “Pinatubo20” run

Mann et al (in prep.)

Impact of radiative coupling: strat. dynamics

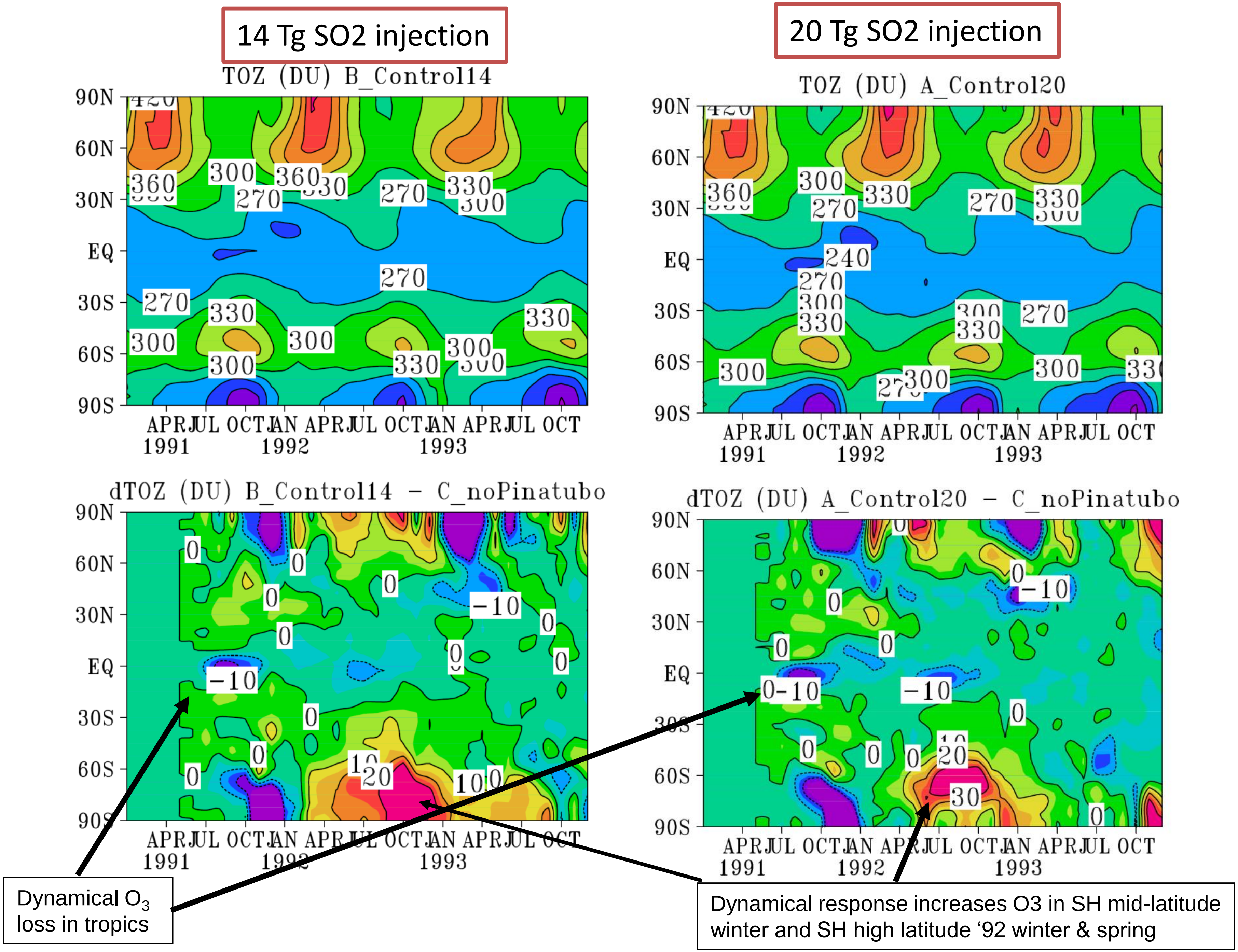


Tropical zonal mean zonal wind for ERA-interim re-analysis



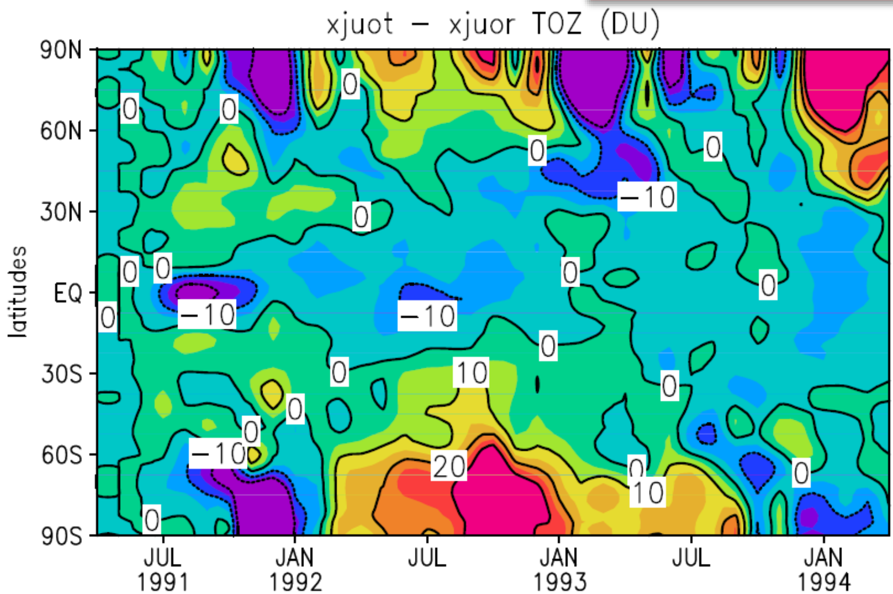
Tropical zonal mean zonal wind for "Pinatubo20" run

Mann et al (in prep.)

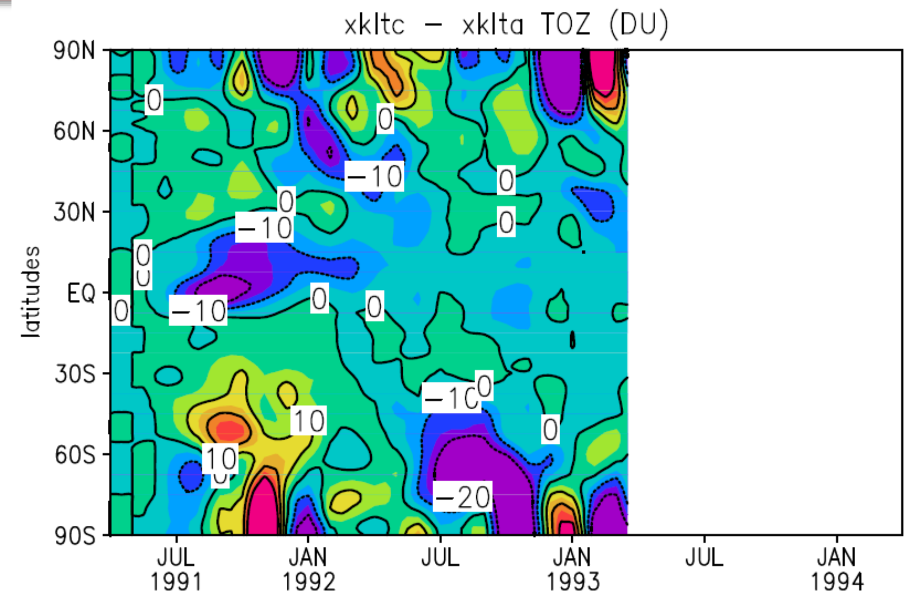

14 Tg SO2 injection
20 Tg SO2 injection
TOZ (DU) B_Control14
TOZ (DU) A_Control20
dTOZ (DU) B_Control14 – C_noPinatubo
dTOZ (DU) A_Control20 – C_noPinatubo
90N
60N
30N
EQ
30S
60S
90S
APR JUL OCT JAN APR JUL OCT JAN APR JUL OCT
1991
1992
1993
Dynamical O_3 loss in tropics
Dynamical response increases O3 in SH mid-latitude winter and SH high latitude '92 winter & spring

3 14Tg ensemble members with easterly QBO phase

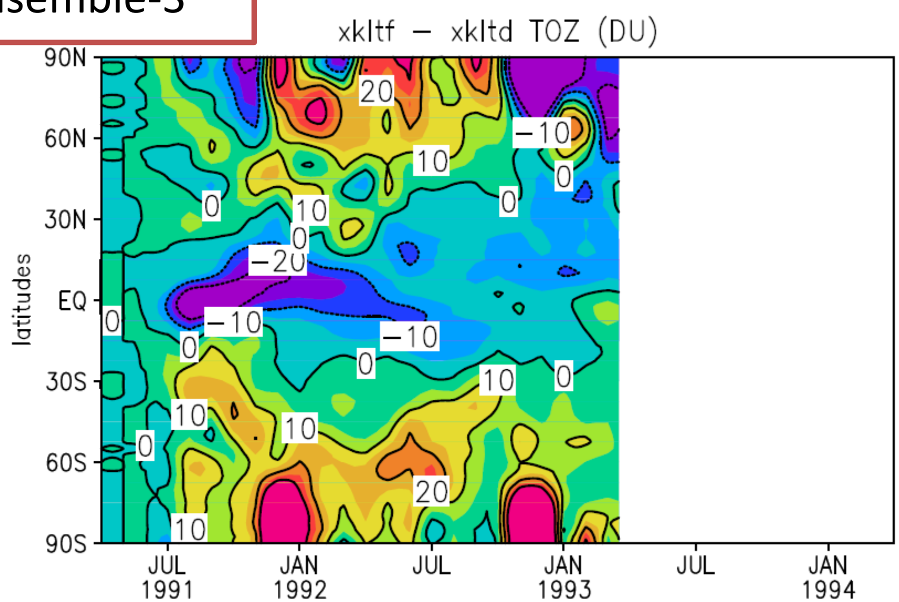
Ensemble-1



Ensemble-2



Ensemble-3

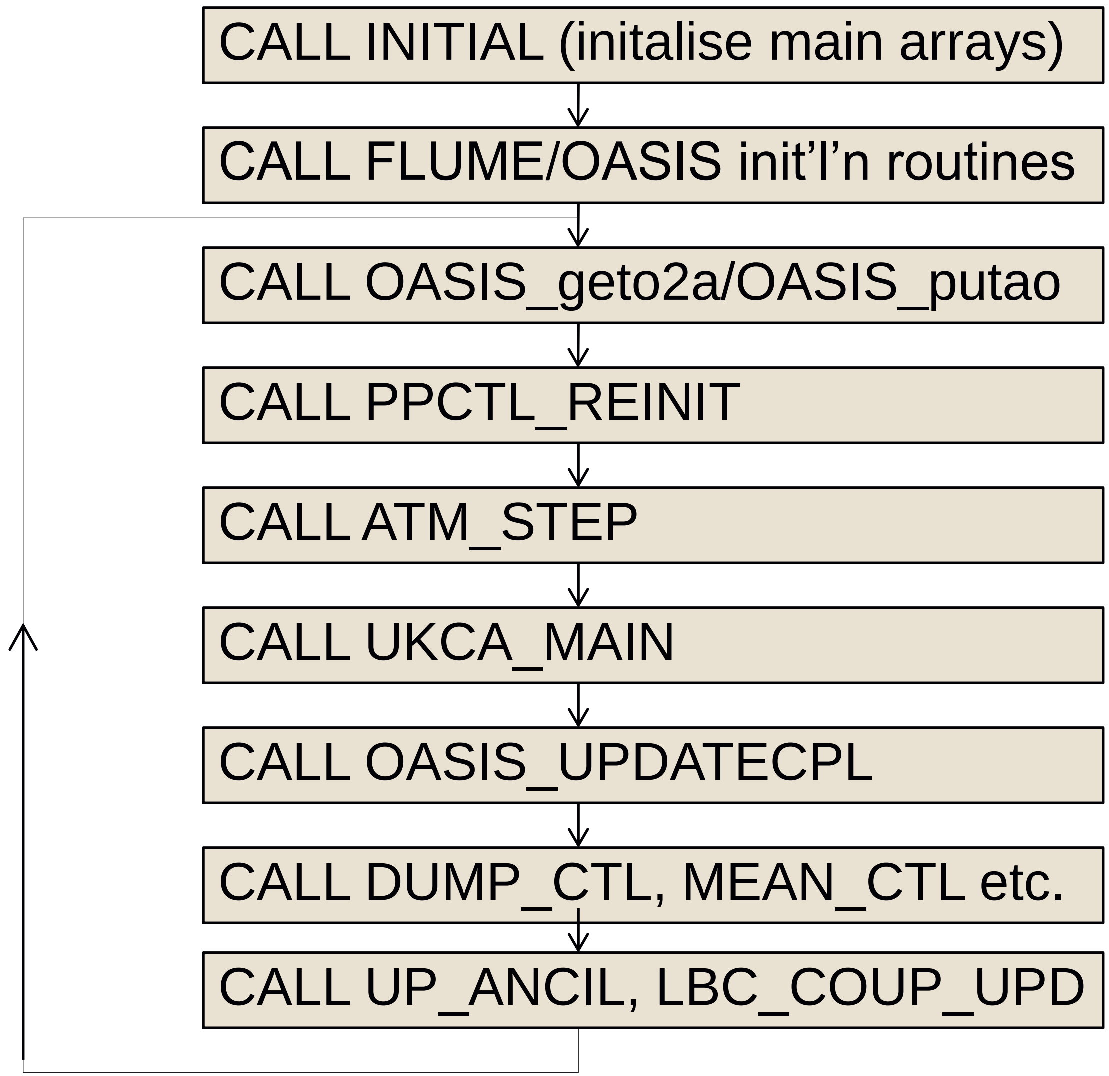


Pinatubo-on and Pinatubo-off runs both use time-varying SAD with volcanic enhancement.

So delta-ozone shown here is that induced from the radiative heating of the stratospheric aerosol layer and the subsequent dynamical response.

UKCA-MODE code in UM (U_MODEL)

UKCA_MAIN is called from U_MODEL after the call to ATM_STEP



UKCA-MODE code in UM (UKCA_MAIN)

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UKCA_AERO_CTL called from UKCA_MAIN after UKCA_CHEMISTRY_CTL

Initialise aerosol configuration via subroutines in UKCA_MODE_SETUP and UKCA_SETUP_INDICES)

↓

CALL GETD1FLDS & initialise arrays

↓

CALL UKCA_DUST_CTL & FASTJ

↓

CALL UKCA_CALC_TROPOPAUSE

↓

CALL UKCA_EMISSION_CTL

↓

CALL UKCA_CHEMISTRY_CTL

↓

CALL UKCA_AERO_CTL

↓

CALL UKCA_ACTIVATE

↓

CALL PUTD1FLDS

Set MODE COMPONENT

Update gases for emissions

Update gases for chemistry, BL mix & dry/wet dep

Update aerosol for emissions, BL mixing, dry/wet dep & microphys.

UKCA-MODE code in UM (UKCA_AERO_CTL)

UKCA_AERO_STEP called from UKCA_AERO_CTL

Set input parameters related to primary emissions, dry/wet removal, aqueous SO_4 prodn, cloud processing

↓

Set input params for aero processes (nucleation, condensat'n, coagulat'n)

↓

Copy 3D/2D input UM/UKCA arrays to required 1D arrays for MODE

↓

CALL TR_MIX for aerosol tracers.

Updates tracers for BL mixing

↓

Copy emisn fluxes, gaseous (S0) & aerosol tracers (ND,MD) → 1D arrays

↓

CALL UKCA_AERO_STEP

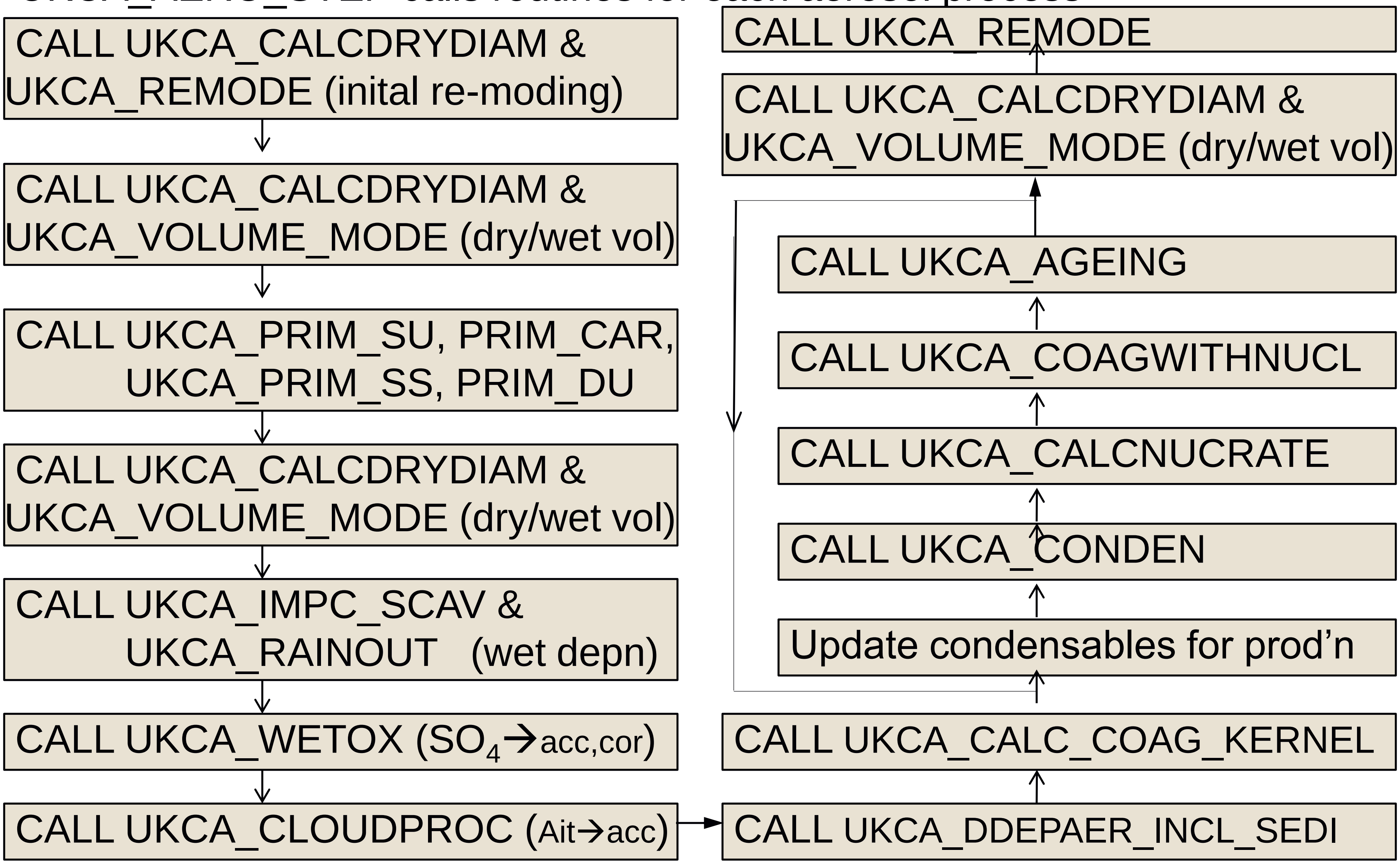
Updates aerosol tracers for primary ems, dry/wet depn, nucleation, coagulation, condensation (H_2SO_4 & SECORG) and cloud proc.

↓

Copy updated ND,MD,S0 → tracers

UKCA-MODE code in UM (UKCA_AERO_STEP)

UKCA_AERO_STEP calls routines for each aerosol process



UKCA-MODE inputs (copied 3D→1D)

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-- temperature & pressure
(temp→T,pres→PMID,p_bdrs→PUPPER/PLOWER)
-- precip. rates (crain/drain → CRAING/DRAING,
CRAING_UP/DRAING_UP)
-- autoconversion rates (FCONV_CONV/FCONV_DYN)
and raining fractions (FBOX_CONV/FBOX_DYN)
currently set to constant values)
-- moisture (rh3d→RH, q→S)
-- cloud (cloud_liquid_wat→LWC,
-- cloud_frac→LOWCLOUD,[VFAC=1])
-- surface layer variables (u_s→USTR,u_10m→US10M,
z0m→ZNOTG)
-- sea-ice, land-frac
(sea_ice_frac→SEAICE,land_fraction→LAND_FRAC)
-- mass of air and surface area (mass → SM, area → SURF)
-- aqueous SO_4 production tendencies (delso2_wet_h2o2→DELSO2
delso2_wet_o3 → DELSO2_2)
-- H_2SO_4 vapour prod'n tendency
(delso2_dry_oh→ S0G_DOT_CONDENSABLE)

UKCA-MODE outputs (copied 1D→3D)

-- updated number concentration in each mode
(ND → mode_tracers, ND=tr_rs*AIRD
-- updated molecules-per-particle for SO4,BC,POM.NaCl.DU
(MD → mode_tracers, MD=tr_rs*(MM_DA/MM_AER)*AIRD/ND)
-- diagnosed CN, CCN, CDN concentrations → STASH sec38, 437-441
-- diagnosed geometric mean dry/wet diameter
(DRYDP, WETDP → STASH section 38, items 401-411)
-- diagnosed aerosol water content (molecular
(MDWAT → STASH section 38, items 412-415)
-- diagnosed mode densities
(RHOSOL → STASH section 38, items 430-436)
-- diagnosed surface-area concentrations
(SAREA → STASH section 38, items 416-422)
-- diagnosed volume concentrations
(VCONC→ STASH section 38, items 423-429)
-- diagnosed partial volumes for each component and water
(PVOL, PVOL_WAT → STASH section 38, items 442-468)
-- diagnosed molecular-fluxes through each process
(BUD_AER_MAS → STASH section 38, items 201-387)