School of Earth and Environment
INSTITUTE FOR CLIMATE & ATMOSPHERIC SCIENCE

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State-of-the-science in aerosol-climate models Current and future science with UKCA aerosol

Graham Mann (NCAS-climate, University of Leeds)

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Colin Johnson, Nicolas Bellouin, Mohit Dalvi, Olivier Boucher (UKMO)

Philip Stier, Rosalind West, Zak Kipling (University of Oxford)

Luke Abraham (NCAS, University of Cambridge)

Thor Thordarson (School of Geosciences,University of Edinburgh)

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Met Office Hadley Centre

GLOMAP
Global Model of Aerosol Processes

IPCC AR4 radiative forcing estimates

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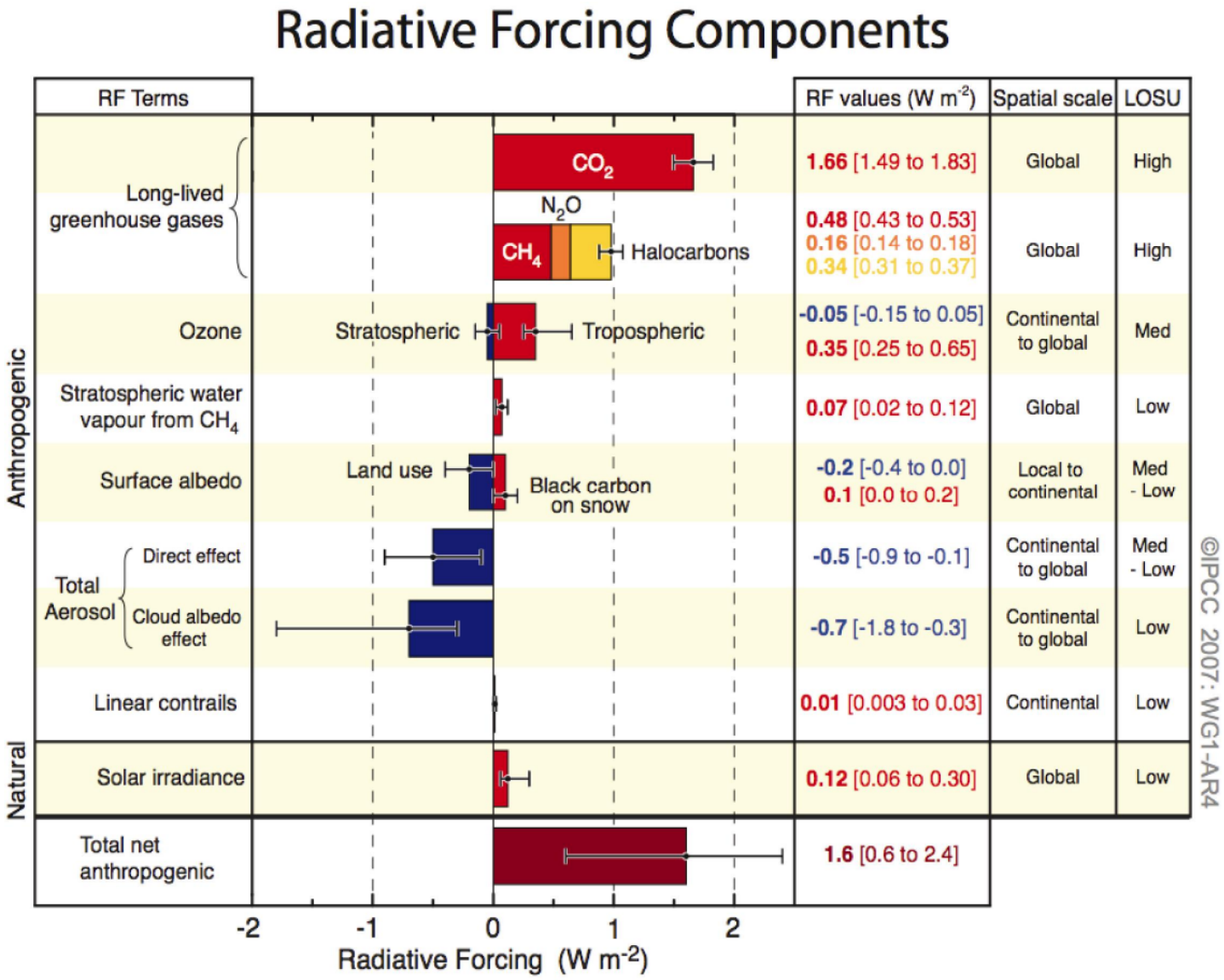
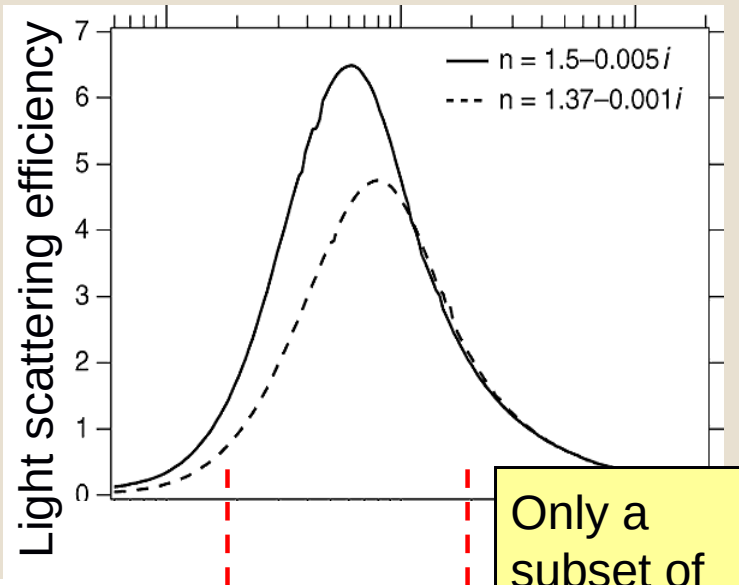
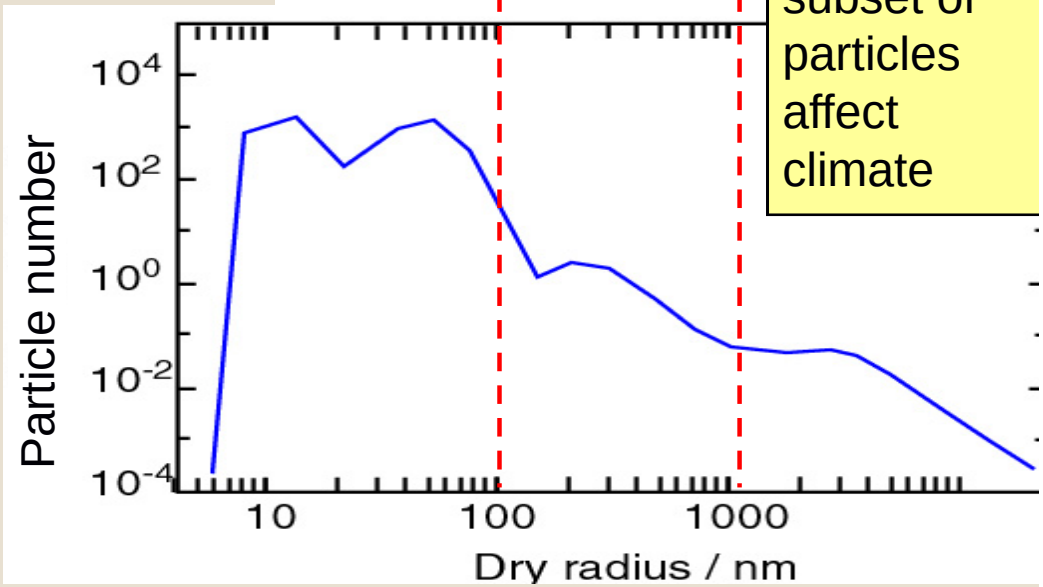


Direct Effect





Only a subset of particles affect climate

Indirect effect

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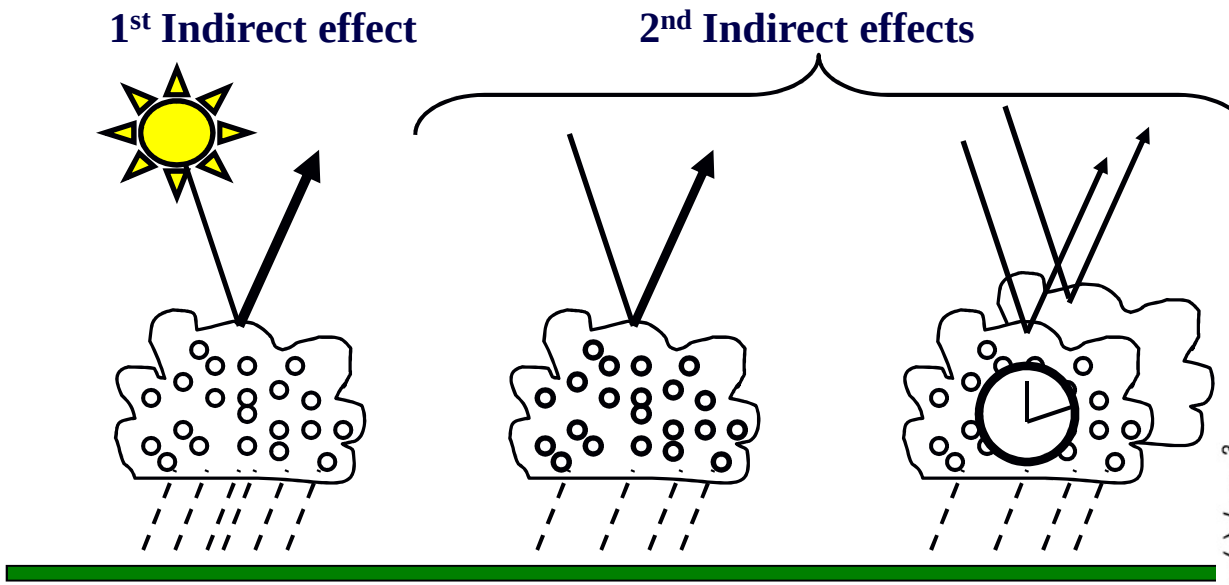


Increased drop N^{o} (constant cloud water)

Drizzle suppression (increased cloud water)

Increased cloud lifetime

More reflective clouds

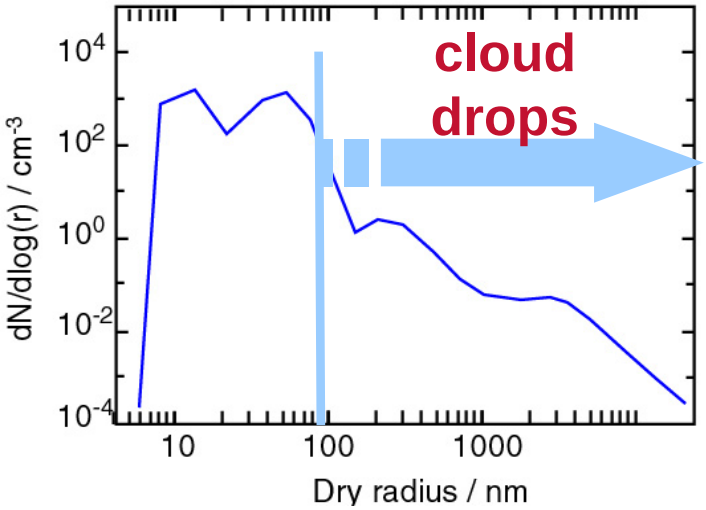
COOLING

More reflective clouds

COOLING

More clouds

COOLING



Aerosol in climate models

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Mass of chemical components (e.g., SO_4, black carbon, dust) as advected quantities

For size-dependent processes: An assumed size distribution

Direct aerosol forcing: Use composition-dependent mass scattering efficiency (or assume a fixed size distribution)

e.g. for SO_4, AOD can change only via change in mass.

Indirect forcing: Use empirical cloud drop—aerosol relations, e.g., Lowenthal et al: $\log(CDN) = 2.38 + 0.49\log(M_{SO_4})$, maybe different for marine/continental

--- any change in mass causes increase in CDN.

Importance of size distribution: Aerosol optical depth

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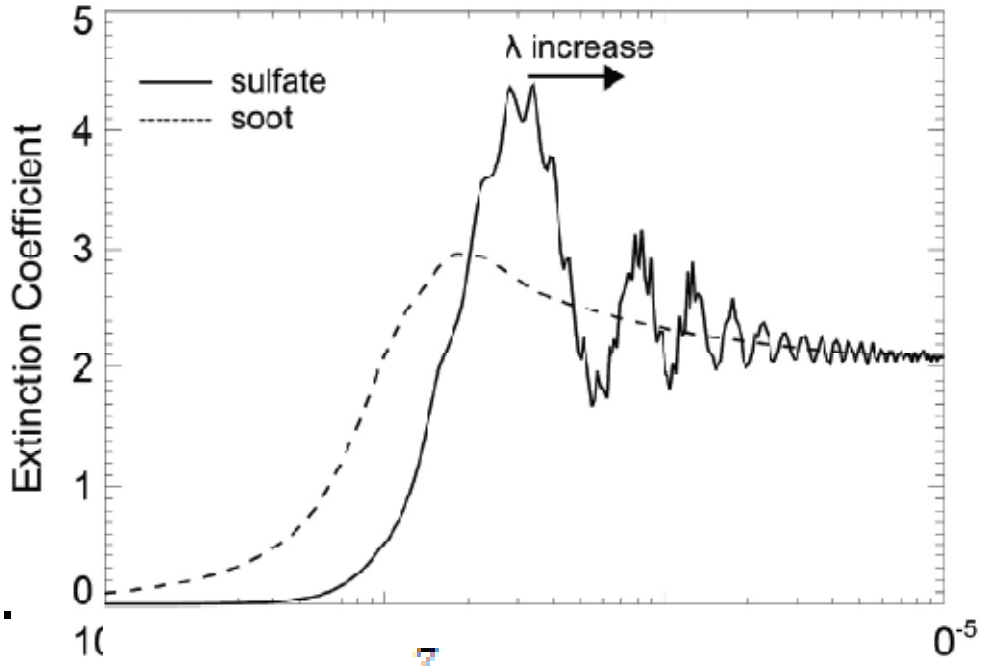
Differences in particle size distribution strongly affect the extinction.

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



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

Changes in size distribution lead to different AOD
Even when the process conserves mass.

Importance of size distribution: Aerosol optical depth

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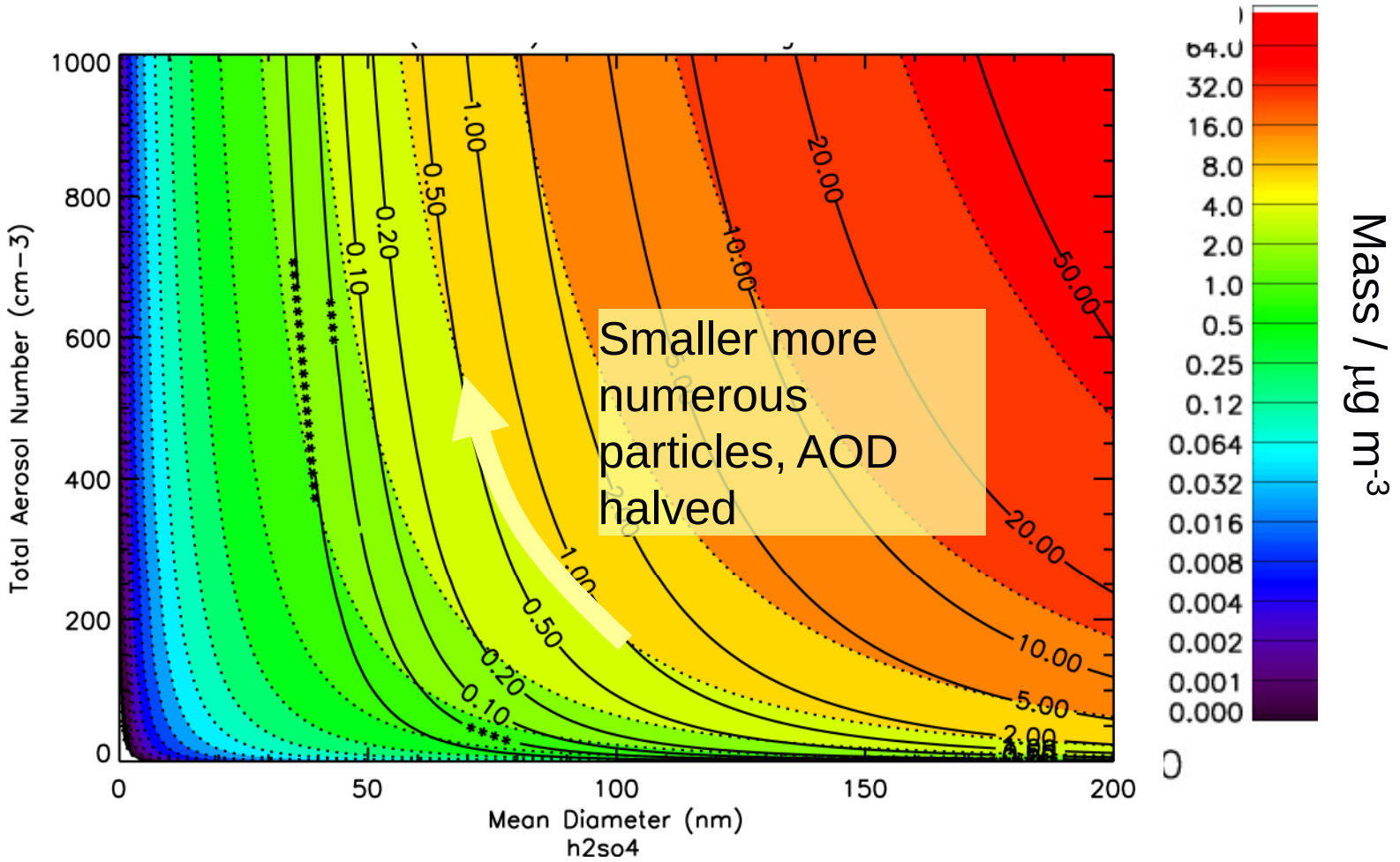
Mie calculations based on log-normal sulphate aerosol



Kirsty Pringle, PhD thesis, 2007

Calculating CDN in GCMs

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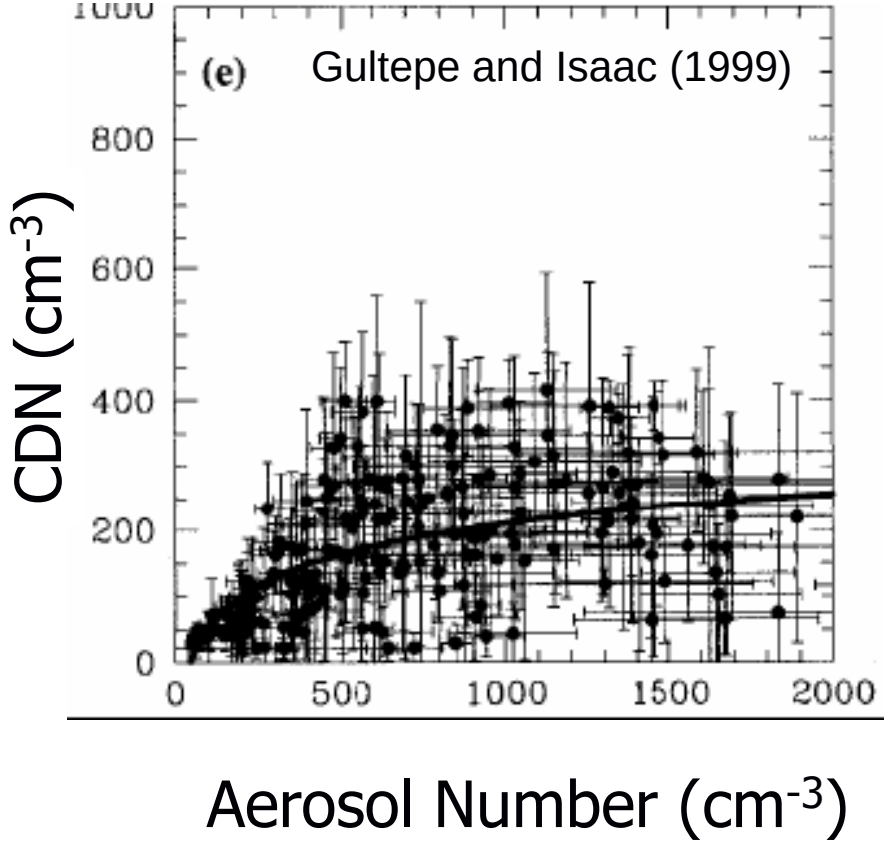

GCM procedure:

1. Measure CDN and aerosol mass (or number) > certain size in same airmass

2. Fit CDN-mass (or number) relation

In mass-only GCM, number is diagnosed not prognosed (i.e., calculated by assuming a size distribution)

Composite of CDN-aerosol observations from many sites

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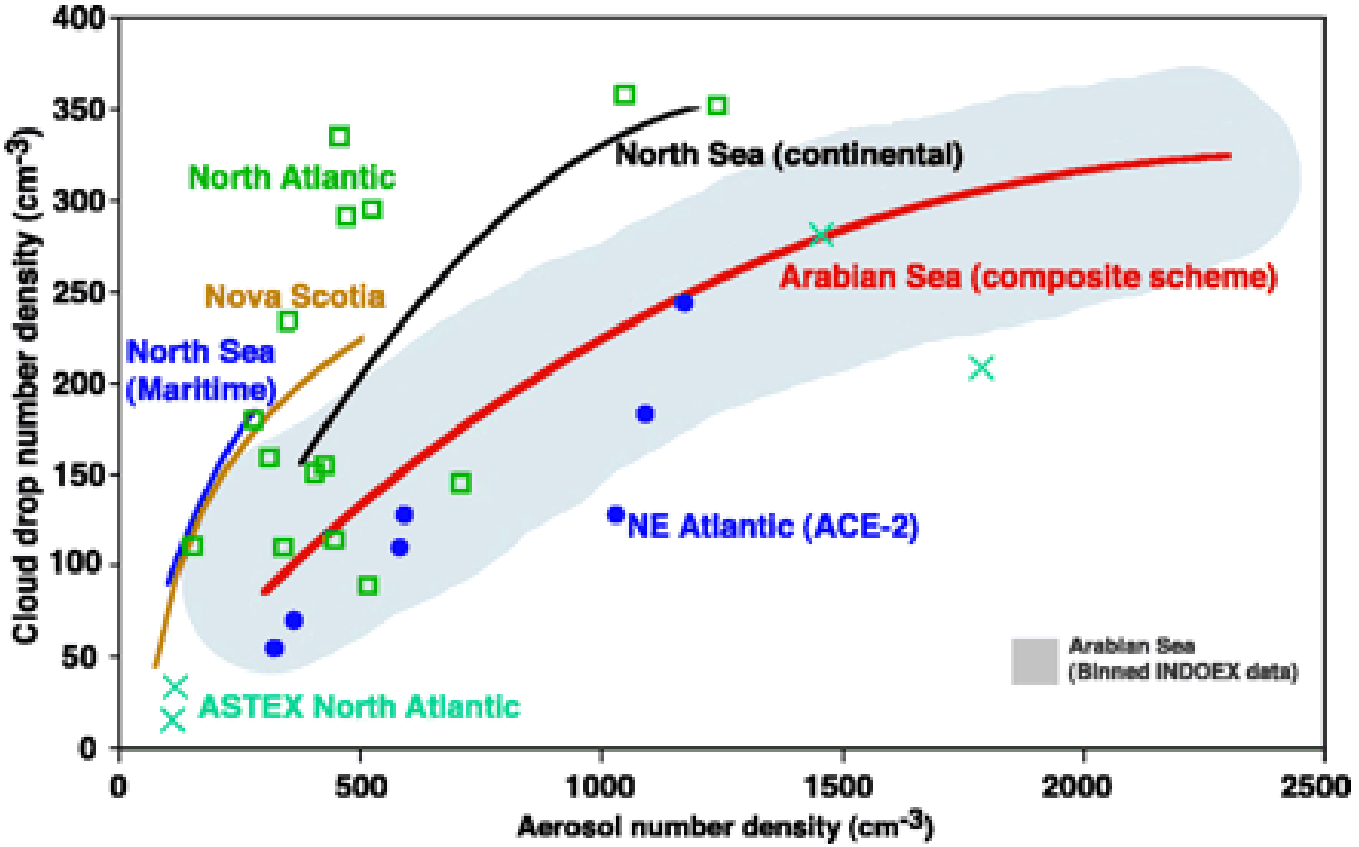

From Ramanathan and Crutzen

No single relationship

Different particle types, compositions, size distributions, etc

Importance of the size distribution: CCN

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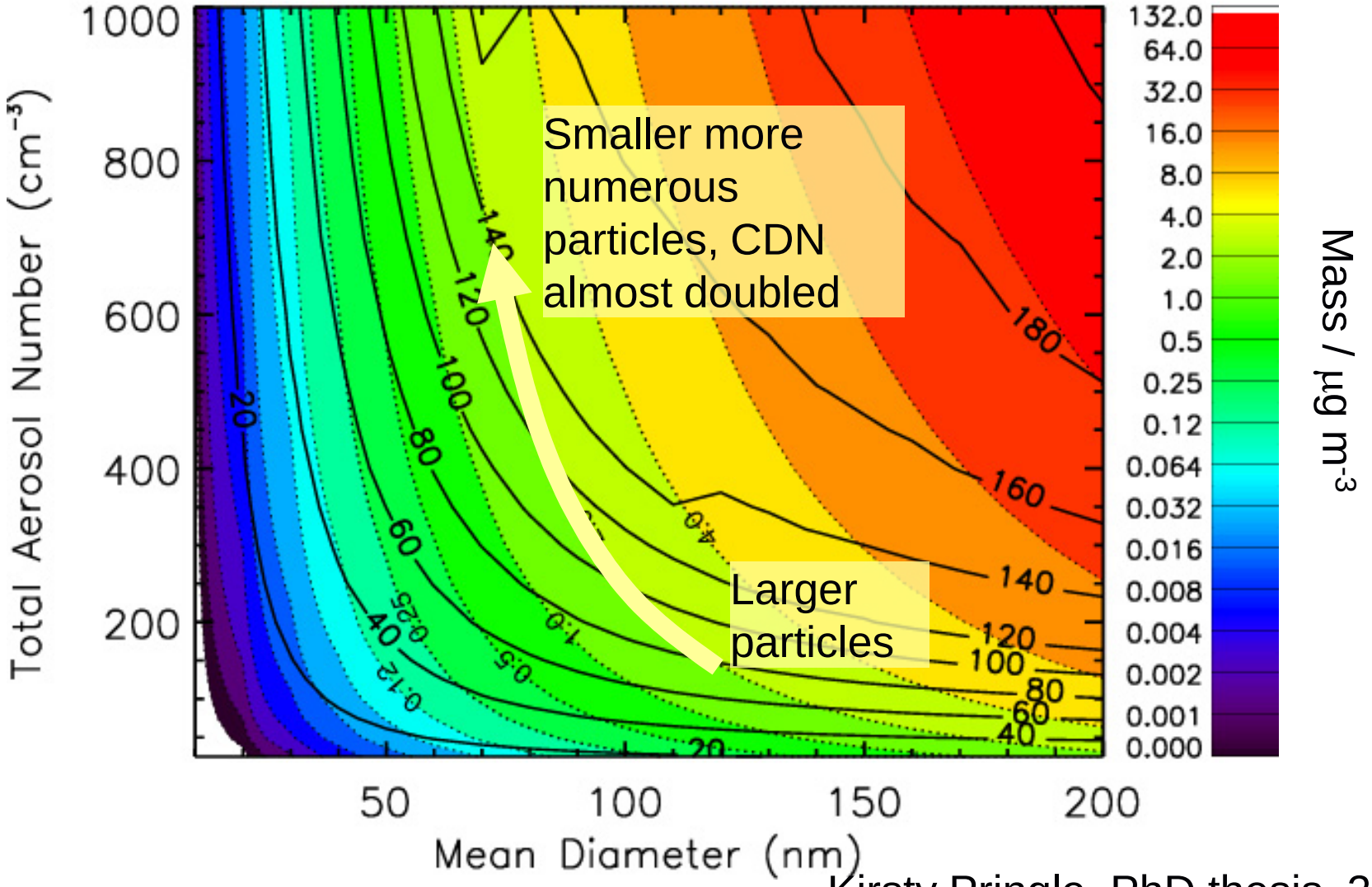
Parcel model calculation of cloud drop number from log-normal aerosol



Kirsty Pringle, PhD thesis, 2007

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Development of process-based global aerosol microphysics models

Process models can include high complexity

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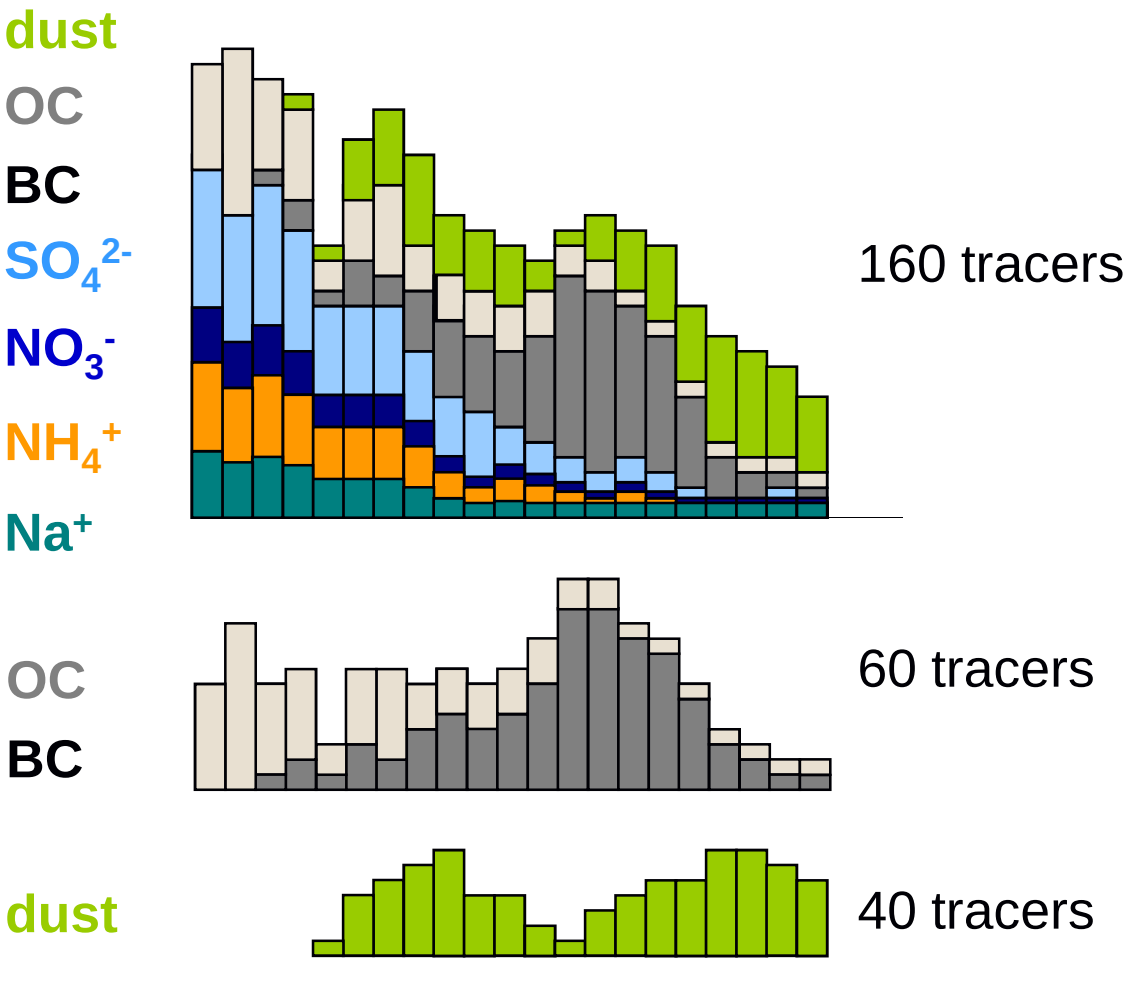
In box models, 2D models or 3D offline models of short integrations, one can afford to track high degree of sophistication

160 tracers for a basic fully internally mixed size and composition resolved distribution

~260 tracers to resolve basic 'fresh' particles

>400 tracers to resolve ageing of fresh particles

But in a climate model (e.g. HadGEM): **25** tracers for aerosol considered high



Evolution of complexity in aerosol-climate models

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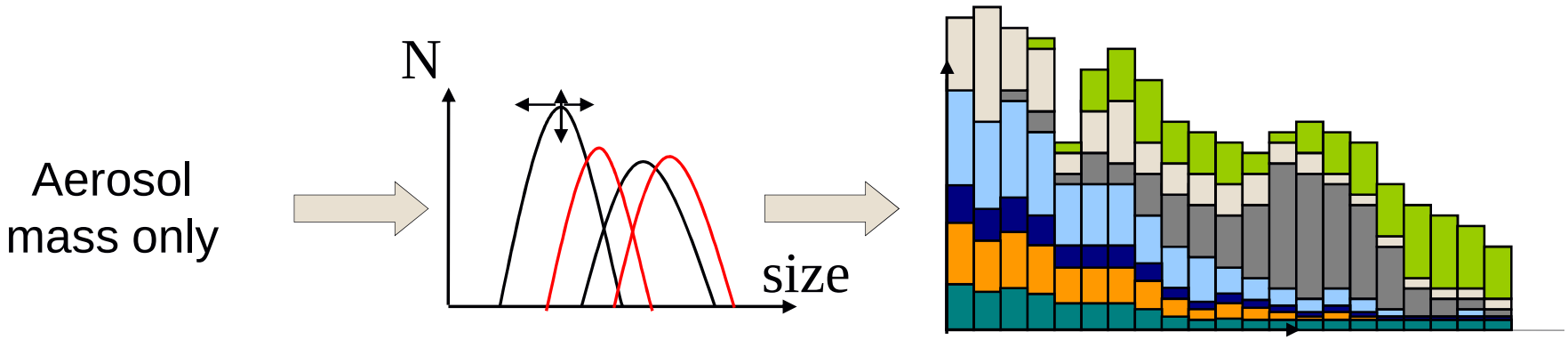
Current state-of-the-science in aerosol-climate models has moved on from 1st generation mass-based only models.

Established recognition now that aerosol-climate models need to simulate particle number to allow size distribution to evolve according to the chemical & microphysical processes, and represent of size-resolved chemical composition



1st generation climate model schemes

New generation of climate models with modal aerosol dynamics

"Research models" bin-resolved Future GCMs?

UK Chemistry & Aerosols project (UKCA)

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- Collaboration between NCAS & UK Met Office Hadley Centre since 2005. Universities of Leeds & Cambridge 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 & stratospheric chemistry schemes → whole-atmosphere. 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.

Development of GLOMAP and UKCA models

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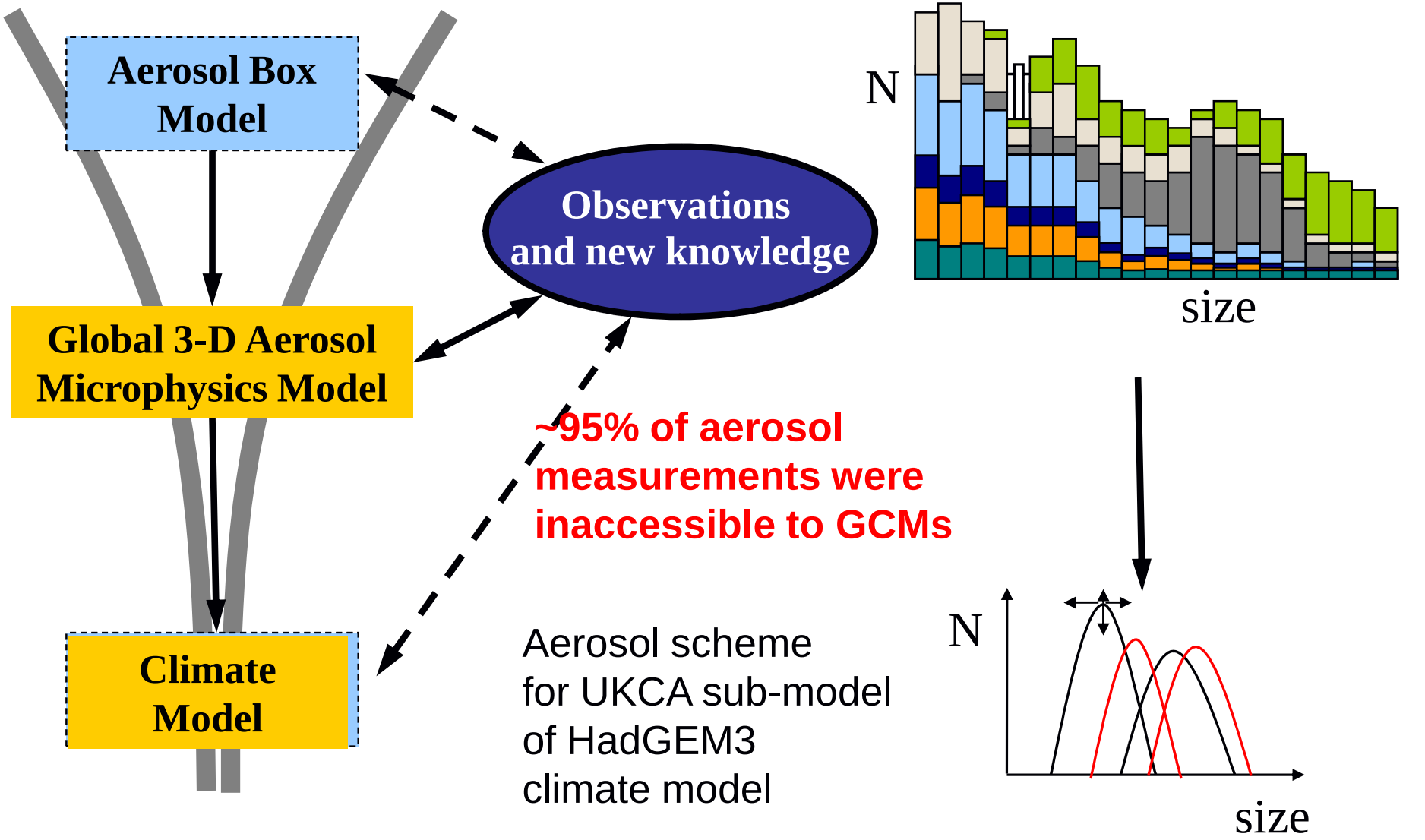

Aerosol scheme for UKCA sub-model of HadGEM3 climate model

Primary & secondary sources of aerosol

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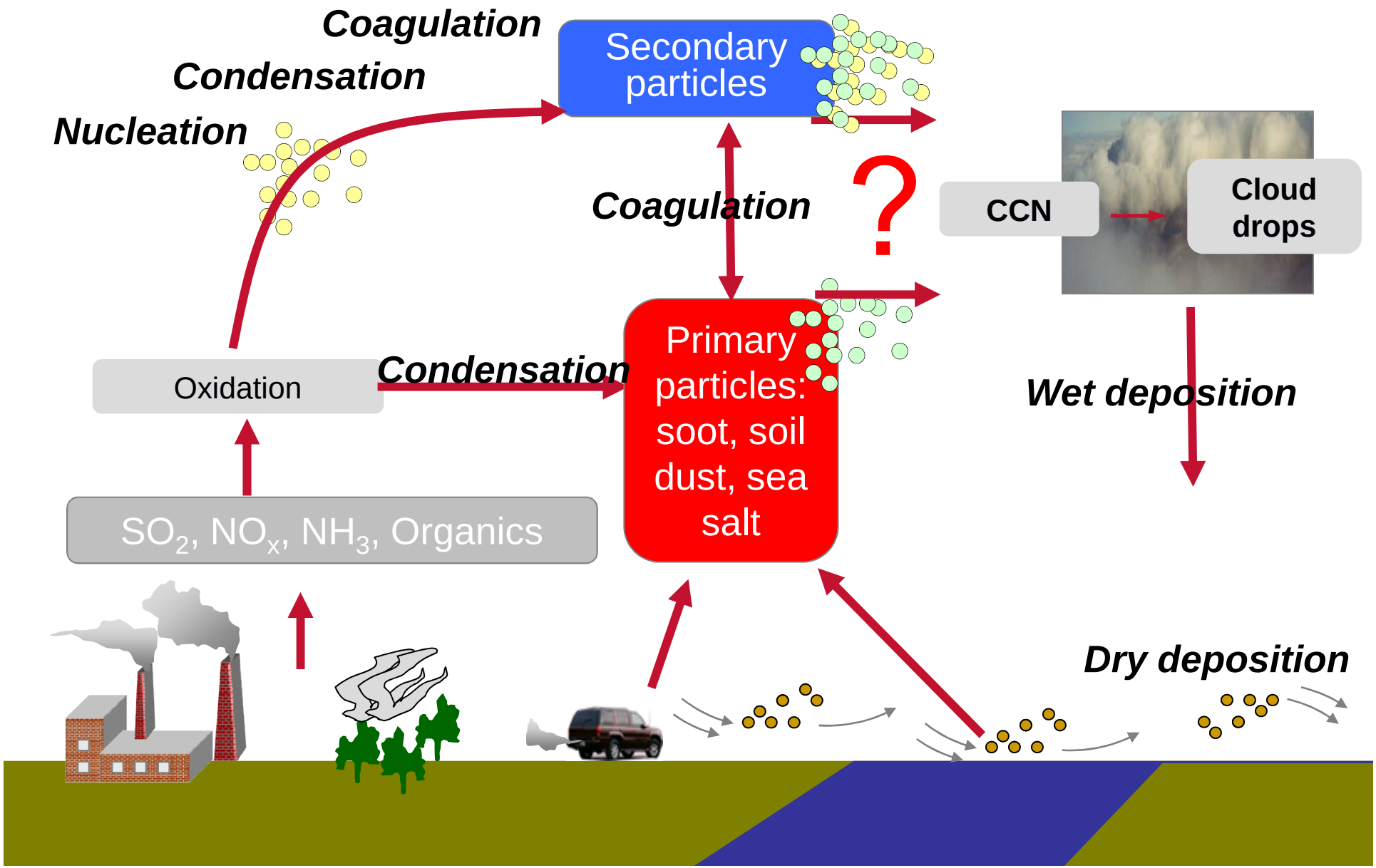

Global Model of Aerosol Processes (GLOMAP)

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Global CTM forced by 6-hourly ECMWF winds

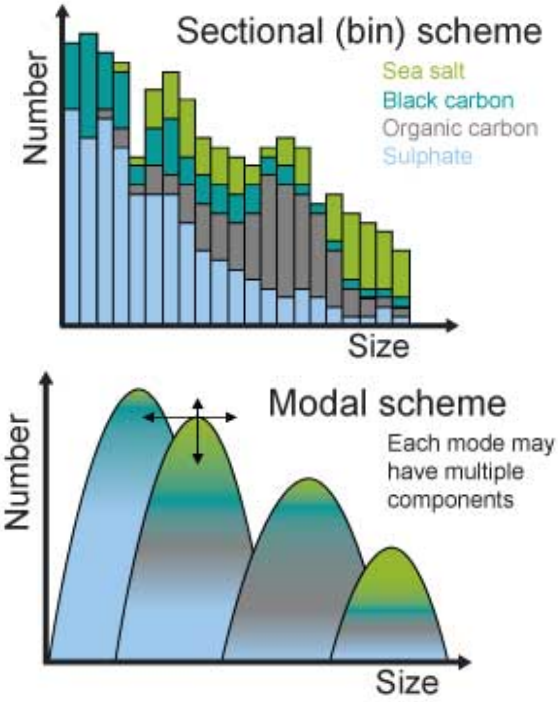
Usually run at T42L31 (2.8^ox2.8^o) resolution

Sectional aerosol scheme: 20 bins, 3 nm – 20 μm
Modal scheme: 7 or 4 log-normal modes

In TOMCAT CTM usually driven by offline oxidants, now coupled to tropospheric chemistry

Aerosol transport, new particle formation, growth by coagulation, condensation, cloud processing.

Wet and dry deposition of gases & aerosol particles



Emissions of DMS → SO_2 → H_2SO_4; monoterpenes → biogenic SOA

Primary emissions of sea salt, dust,
black & organic carbon (fossil and biofuels, vegetation fires)

Nucleation via binary homogeneous nucleation of H_2SO4-H_2O
and also now implemented boundary layer nucleation mechanism

GLOMAP-bin : Spracklen et al. (ACP, 2005), Spracklen et al (GRL, 2008)
GLOMAP-mode: Mann et al (GMD, 2010), Woodhouse et al (2010), Schmidt et al (2010)

Family of models using GLOMAP-mode

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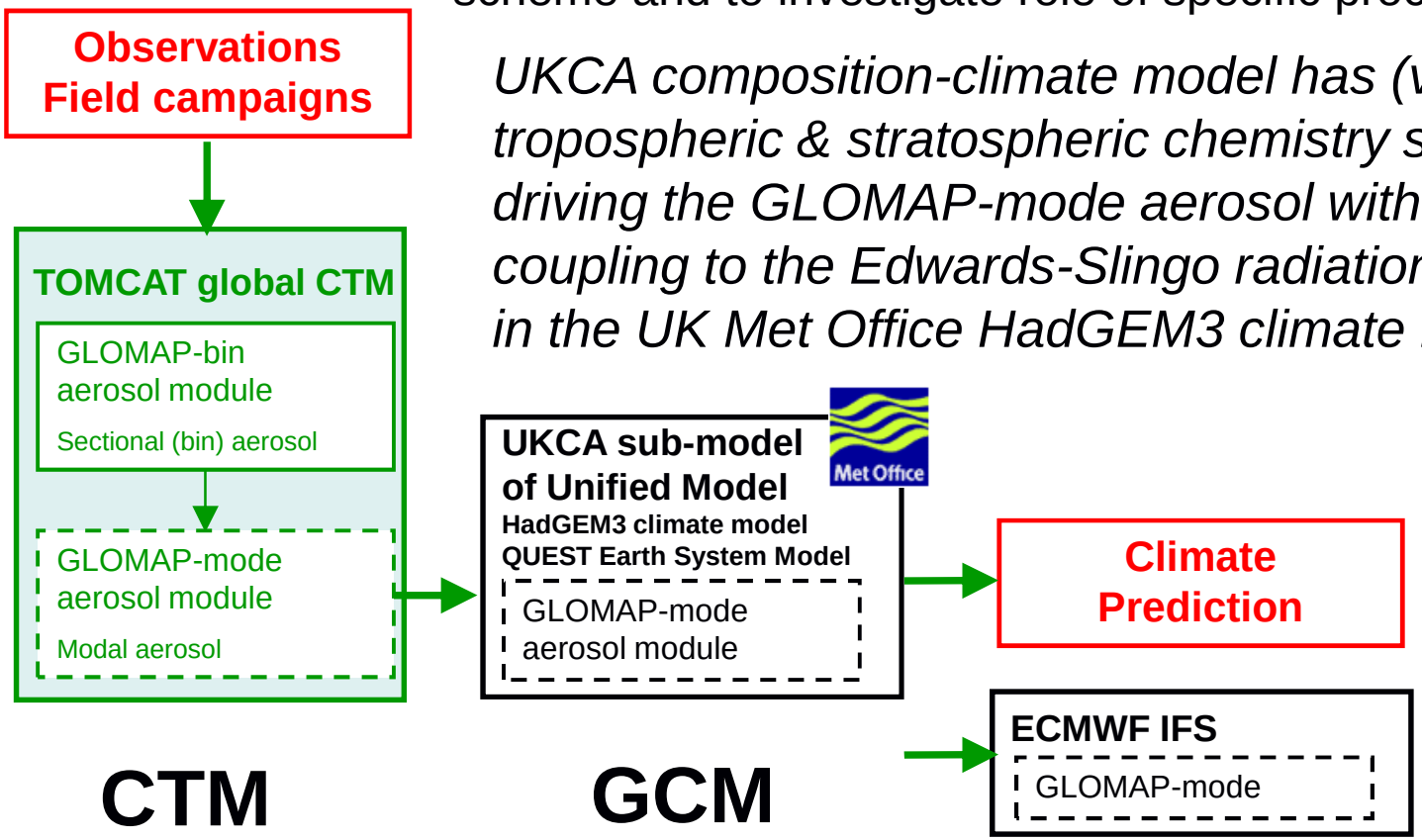
Simplified GLOMAP version (GLOMAP-mode) benchmarked in chemistry transport model (CTM) against detailed GLOMAP-bin scheme.

UKCA composition-climate model uses GLOMAP-mode as aerosol scheme.

CTM framework used as a test-bed for improvements to climate model aerosol scheme and to investigate role of specific processes.

UKCA composition-climate model has (via ASAD) tropospheric & stratospheric chemistry schemes driving the GLOMAP-mode aerosol with online coupling to the Edwards-Slingo radiation scheme in the UK Met Office HadGEM3 climate model.



Benchmark GLOMAP-mode vs bin in CTM

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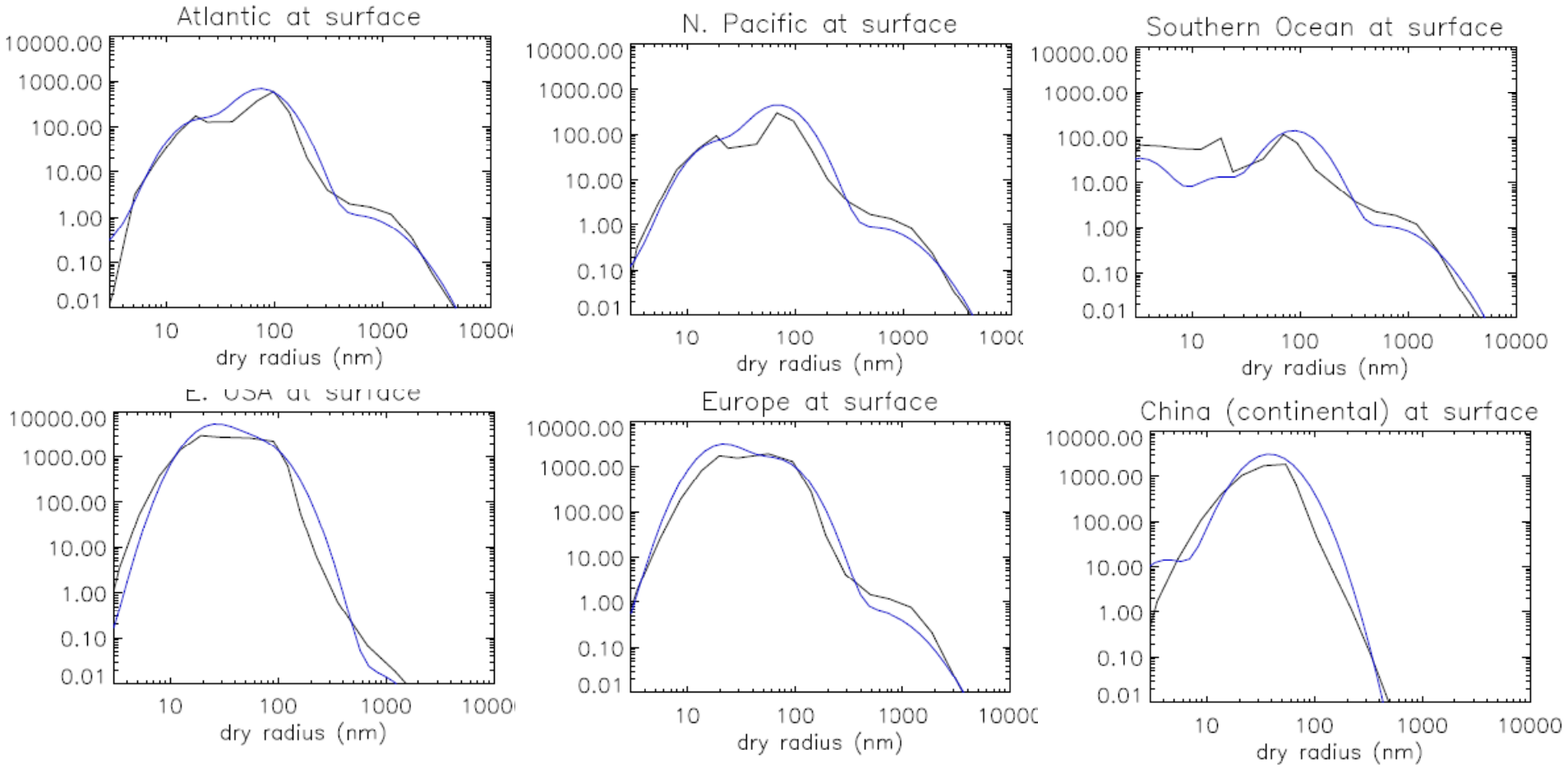

Mann et al, in prep, 2011

GLOMAP-bin

GLOMAP-mode (sigma-acc=1.59, dplim34=1000nm as M7)

Benchmark GLOMAP-mode vs bin in CTM

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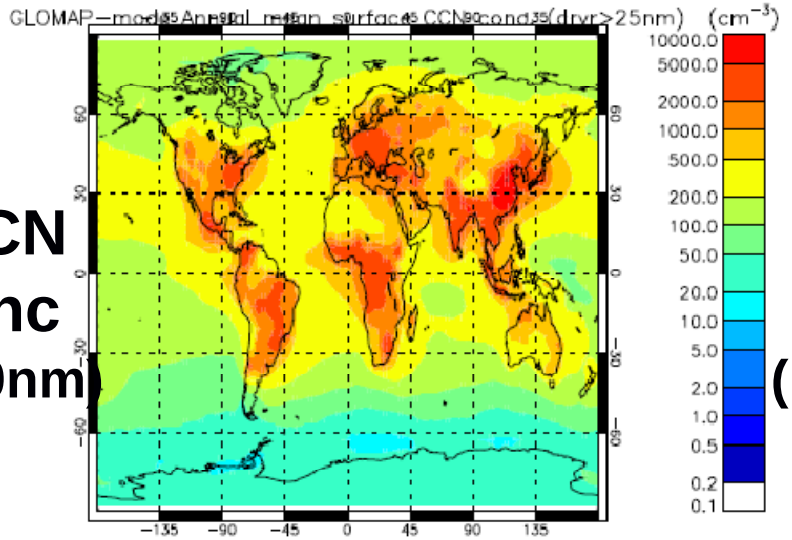
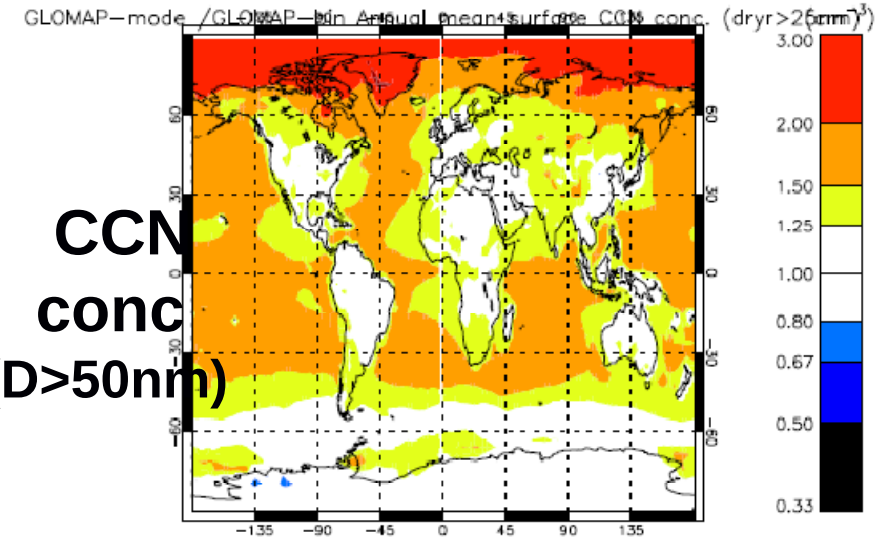
CCN conc (D>50nm)



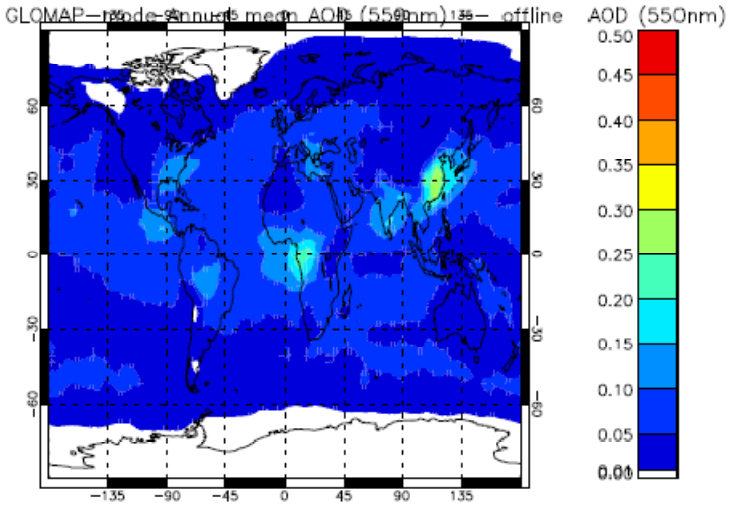
GLOMAP-mode

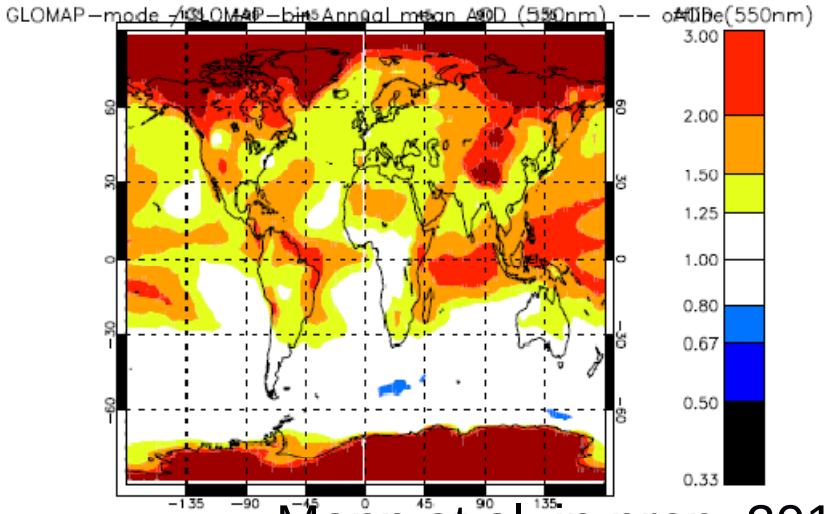
CCN conc (D>50nm)



ratio mode/bin

AOD (550nm)





Mann et al, in prep, 2011

Improve GLOMAP-mode vs bin in CTM

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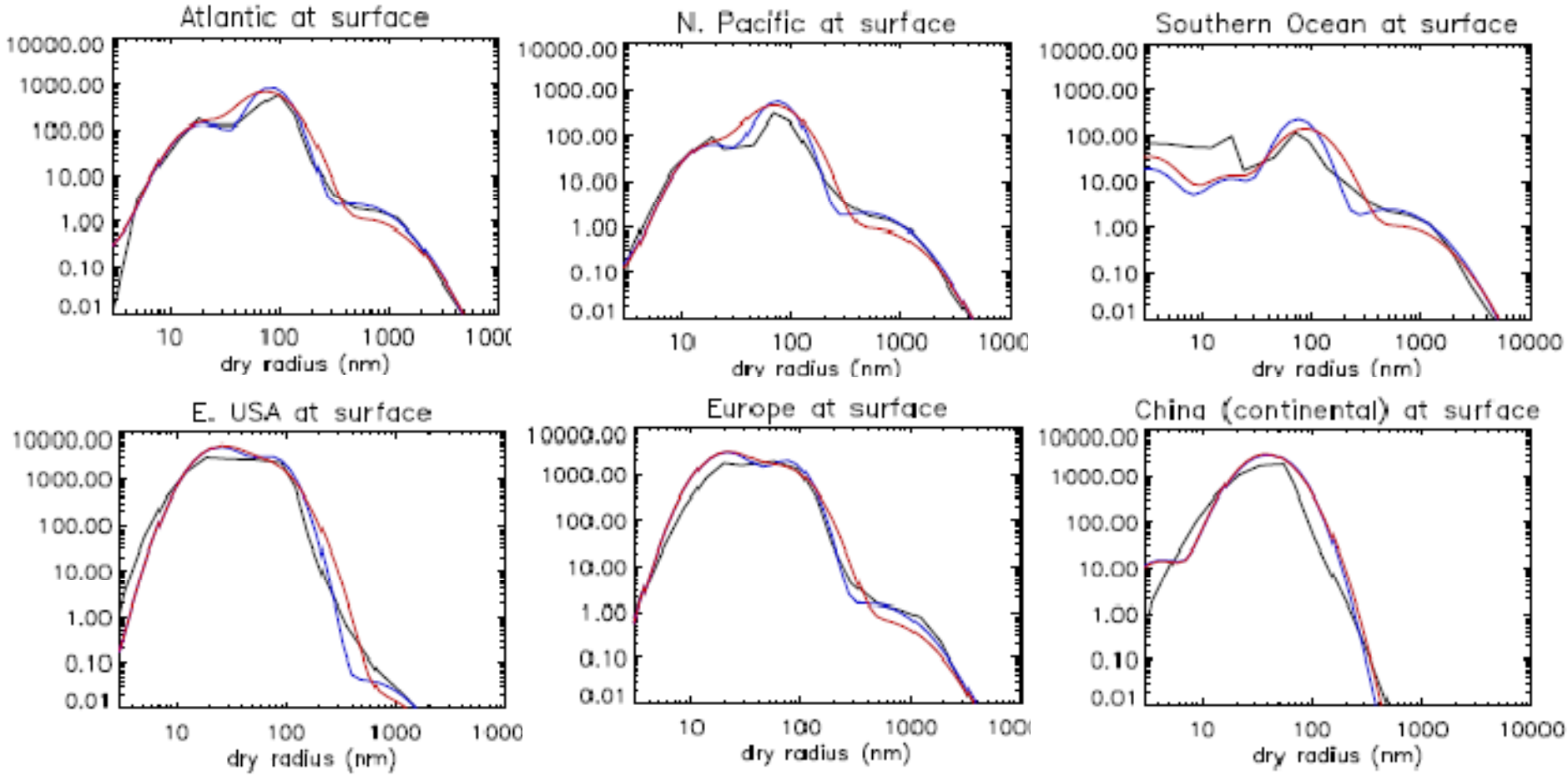

Mann et al, in prep, 2011

GLOMAP-bin

GLOMAP-mode (sigma-acc=1.59, dplim34=1000nm as M7)

GLOMAP-mode (sigma-acc=1.40, dplim34= 500nm)

Improve GLOMAP-mode vs bin in CTM

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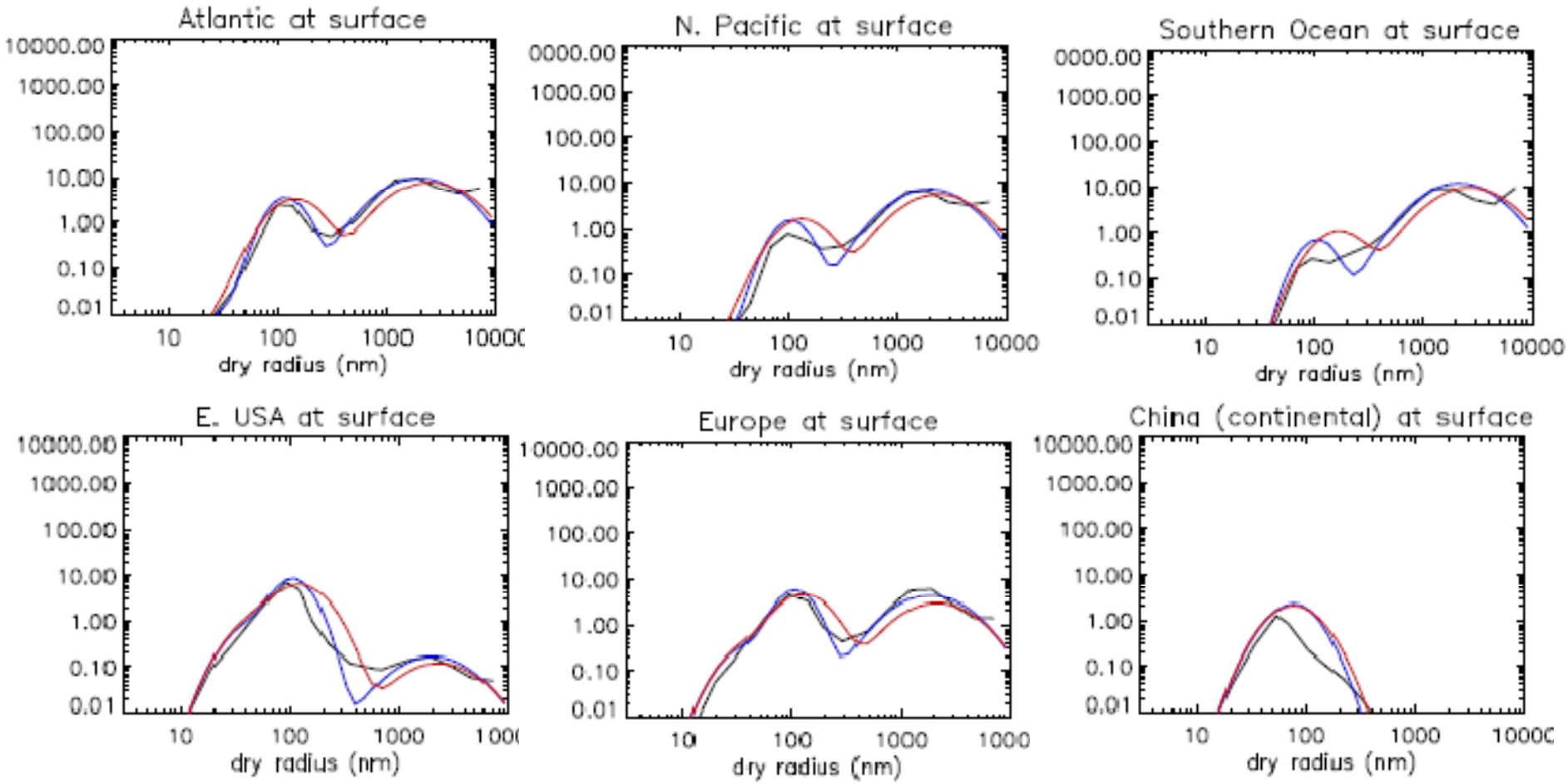

Mann et al, in prep, 2011

GLOMAP-bin

GLOMAP-mode (sigma-acc=1.59, dplim34=1000nm as M7)

GLOMAP-mode (sigma-acc=1.40, dplim34= 500nm)

Improve GLOMAP-mode vs bin in CTM

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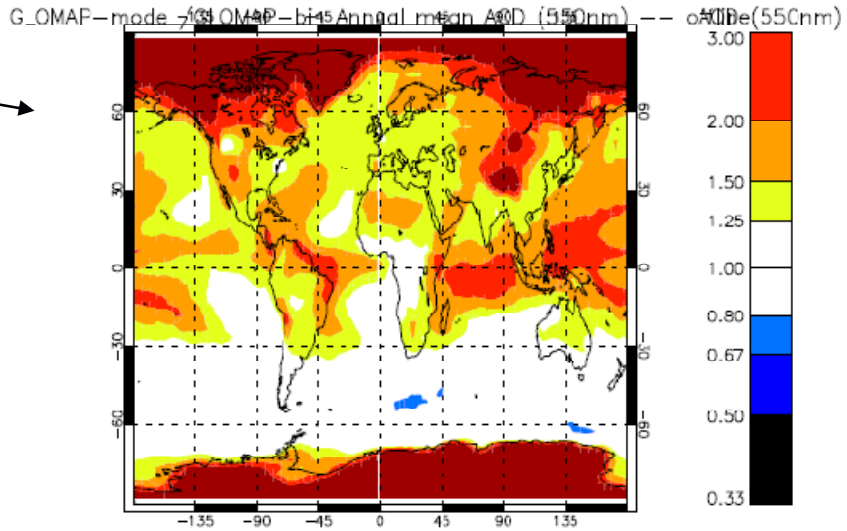
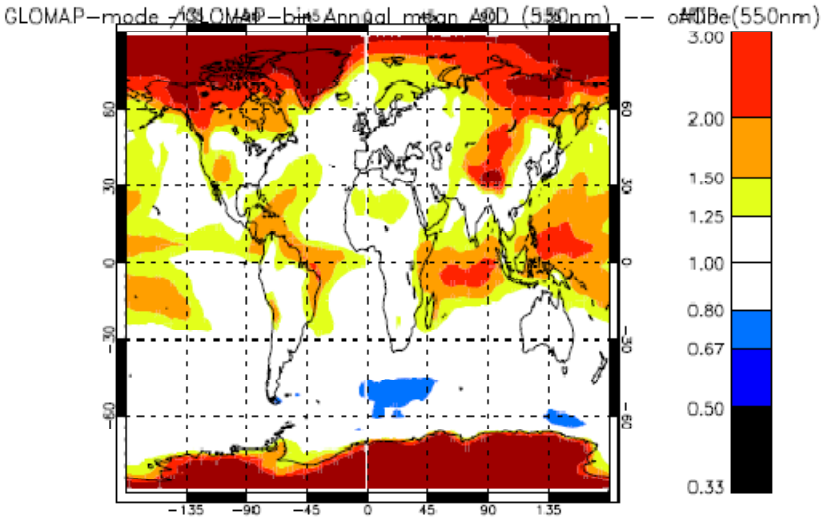
Original model

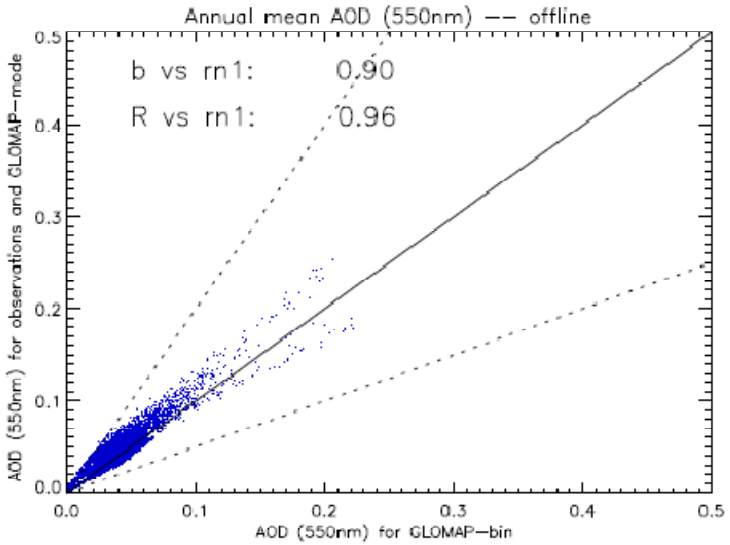
AOD high-bias greatly reduced due following examination of size-distbns

Revised model

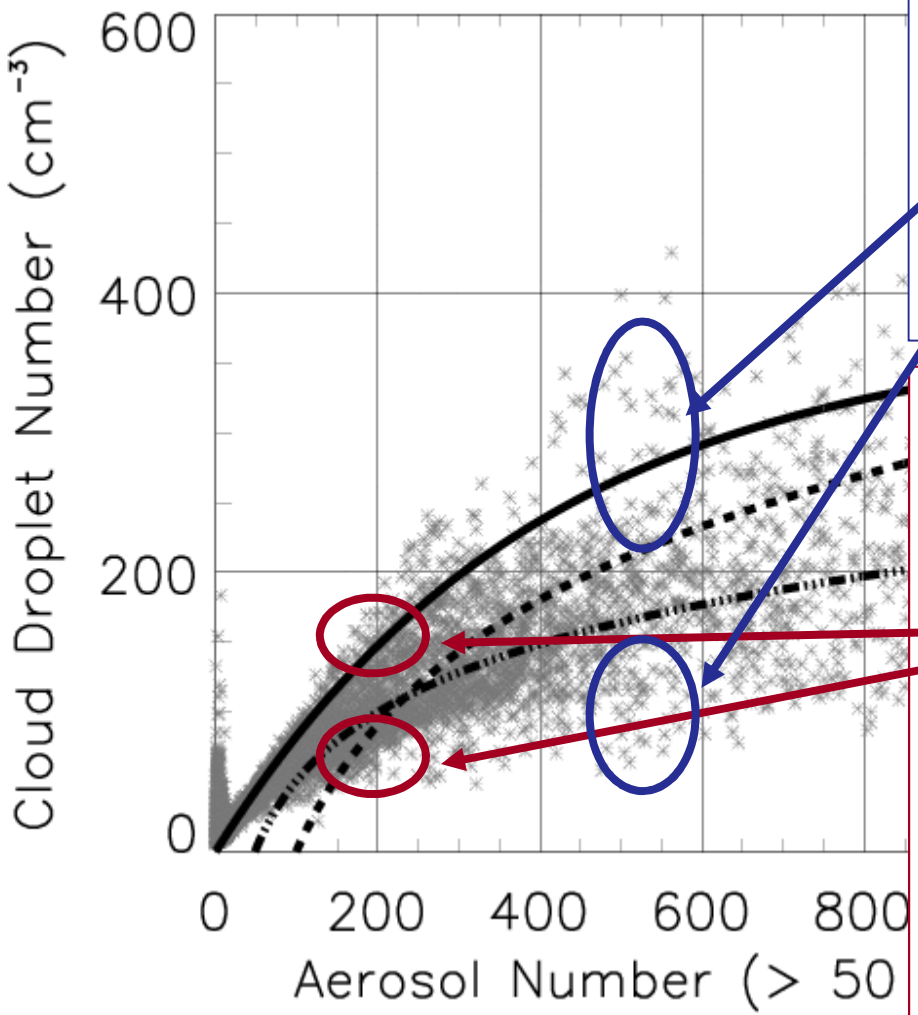


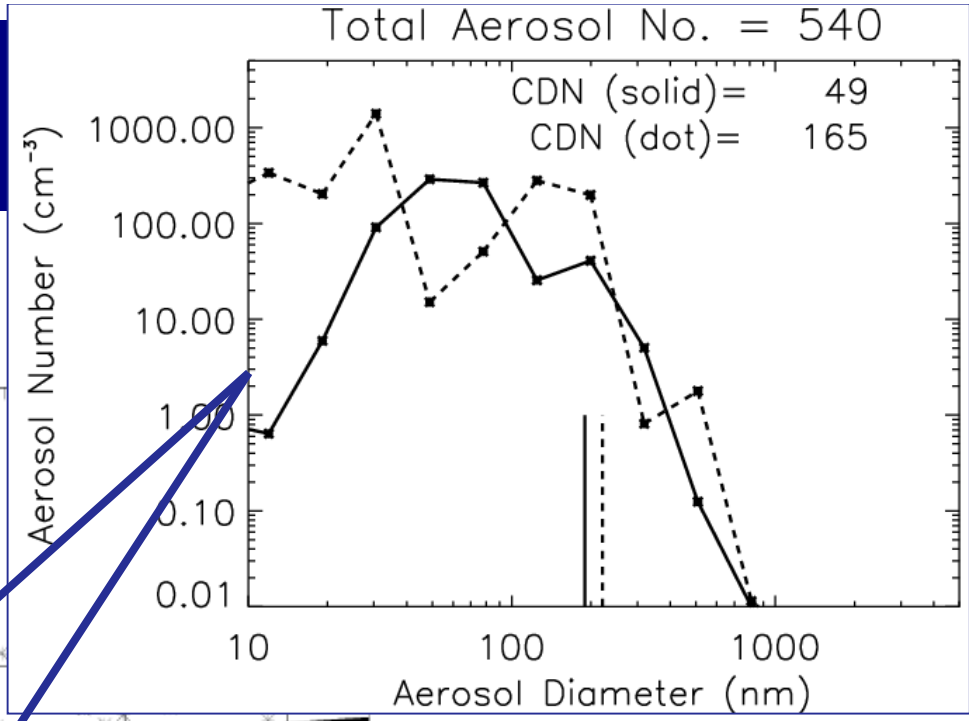


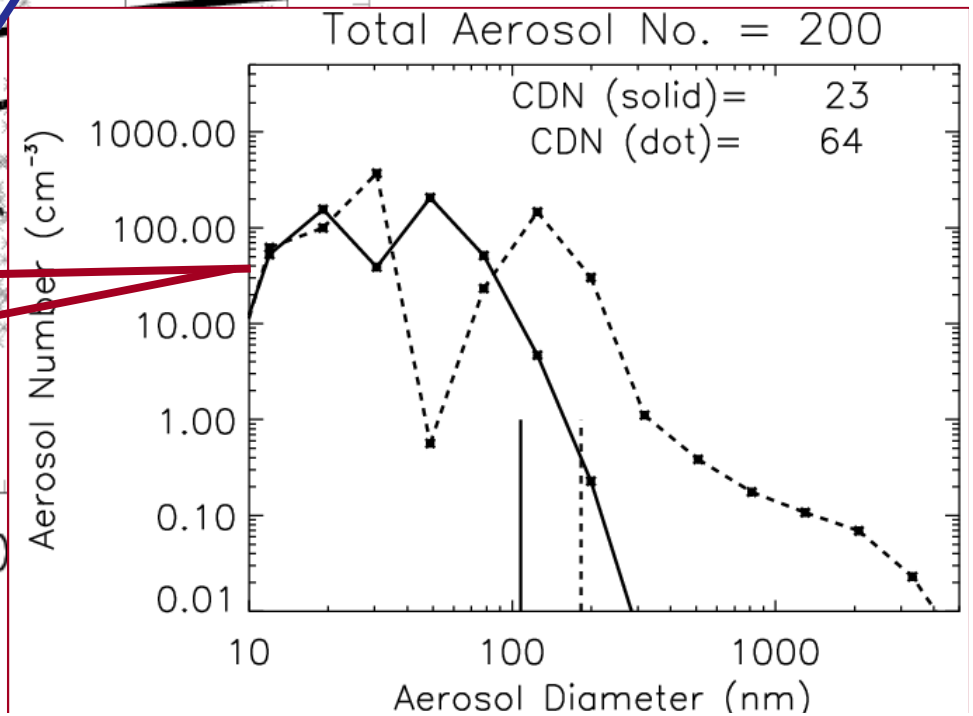
Mann et al, in prep, 2011



Exploring the scatter in model CDN-aerosol







Variability in predicted CDN

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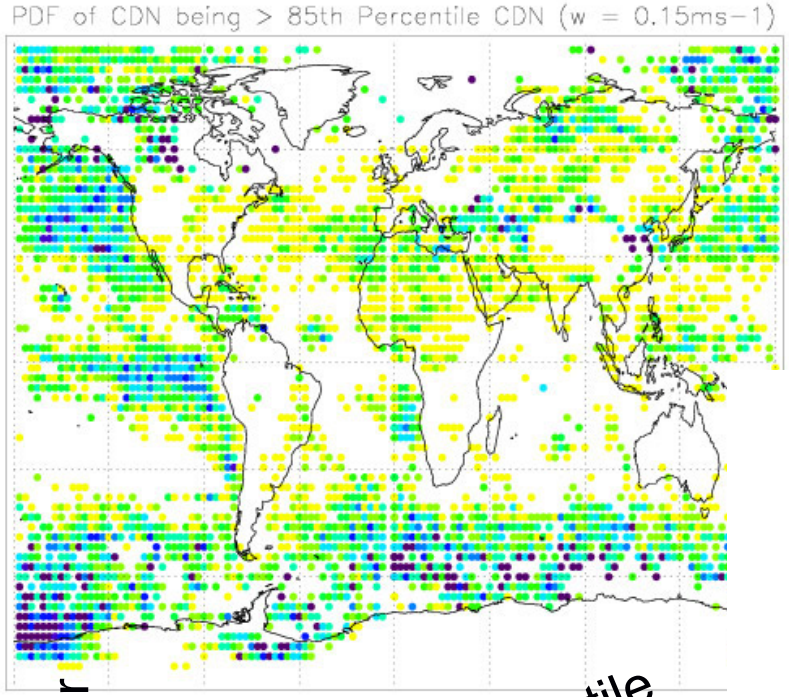
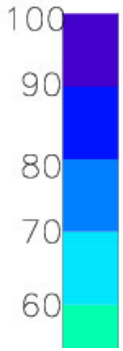
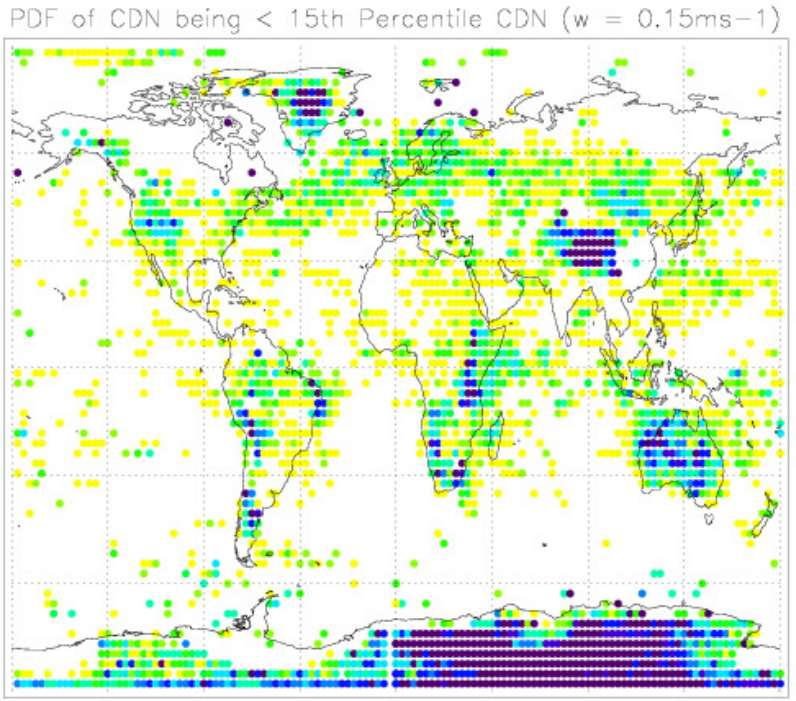
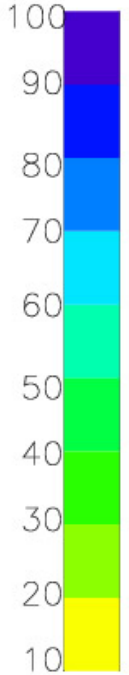
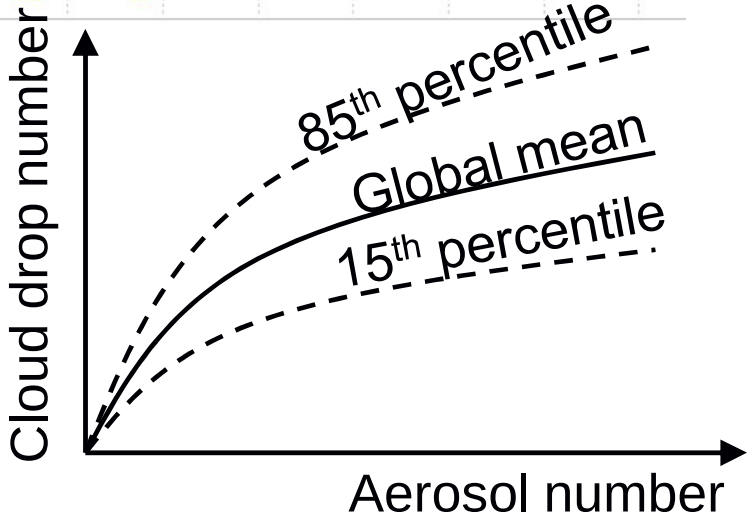




Percent of days that exceed 85th percentile







Global CDN prediction based on single-region CDN-aerosol relation

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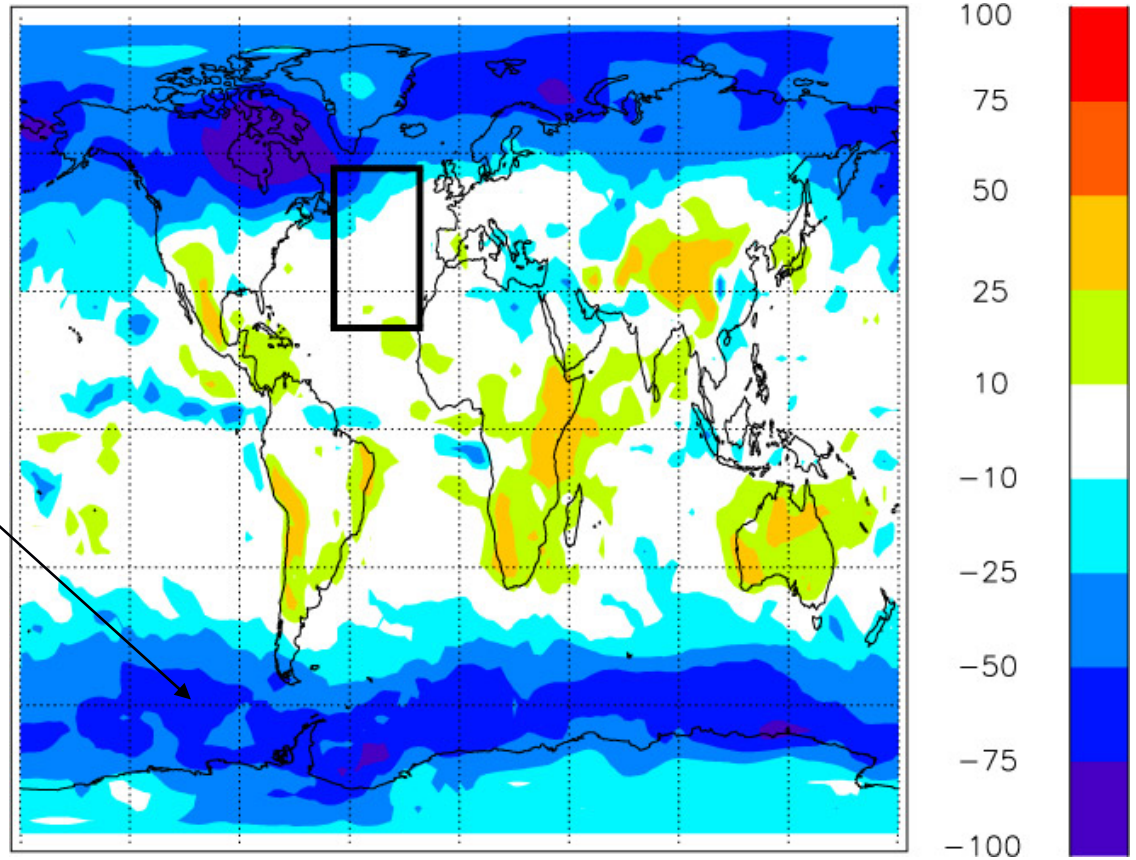
Use model output to generate CDN-aerosol empirical fit

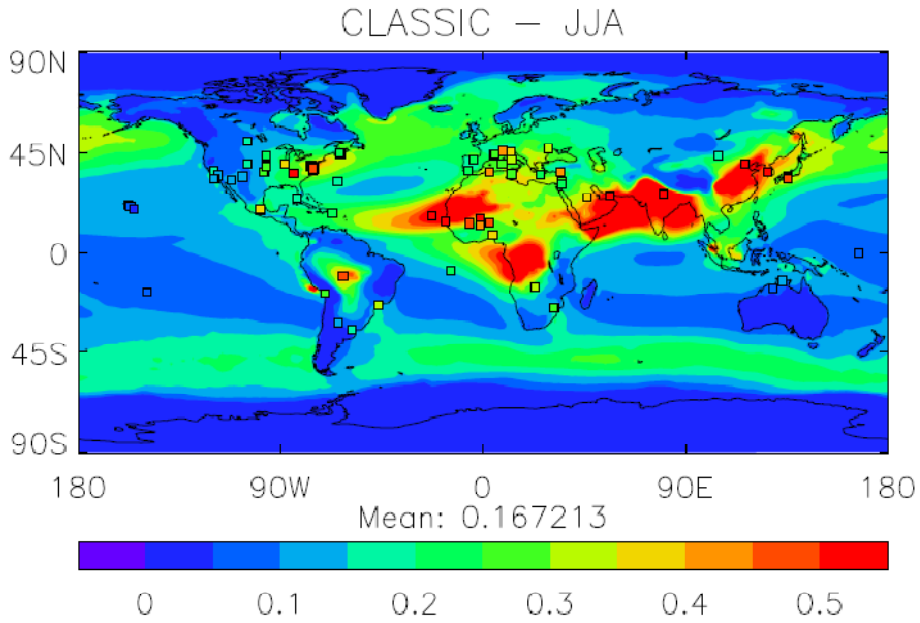
Use the fit to calculate global CDN

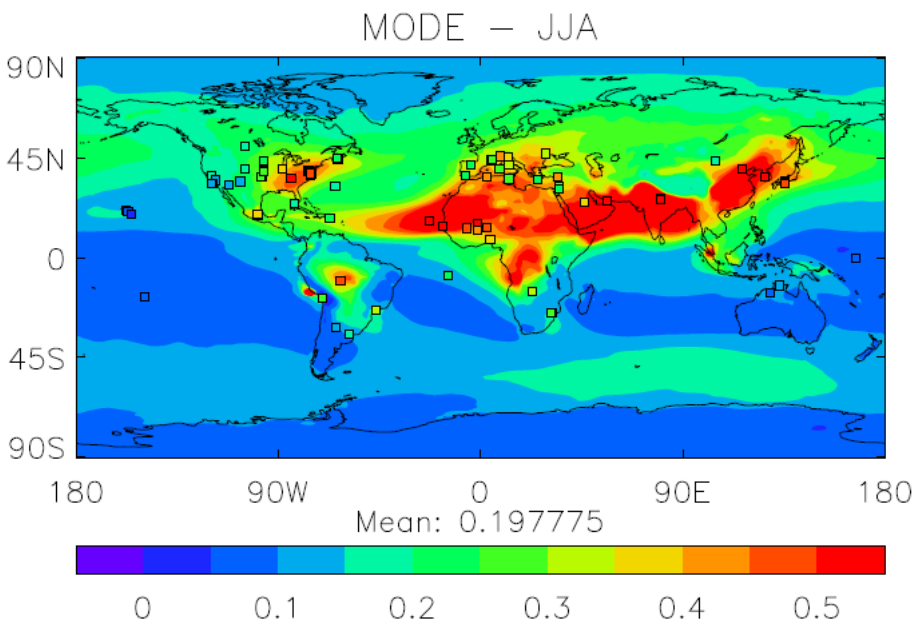
Calculate the %difference from mechanistic CDN calculation

75% more CDN than predicted from CDN-aerosol relation over the Atlantic

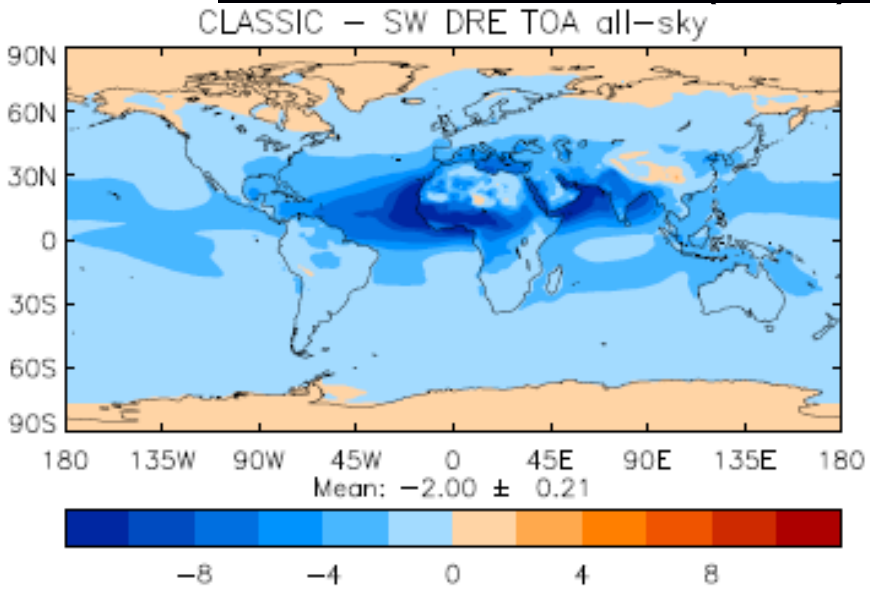


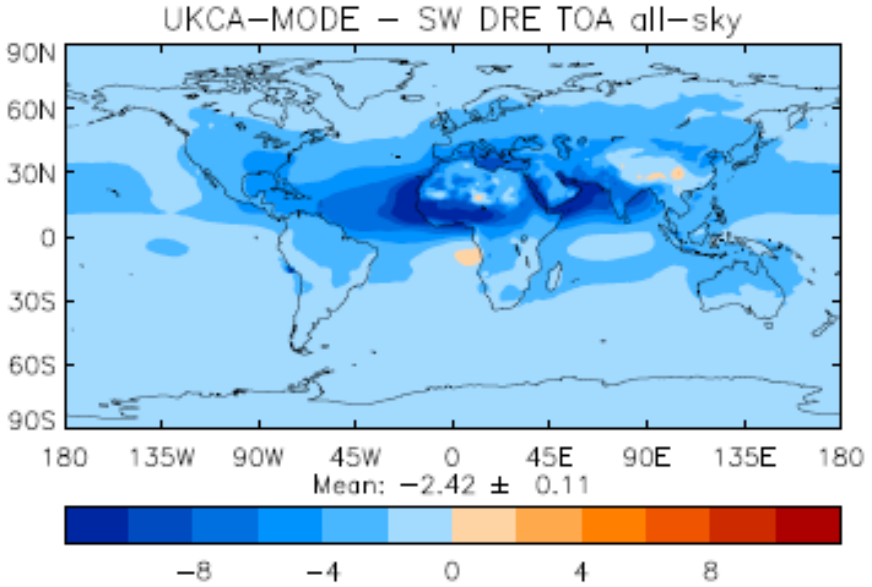
Aerosol Optical Depth (440nm) vs CLASSIC and observations (AERONET, 2000)





SW TOA all-aerosol (2000) direct radiative effect vs CLASSIC





From Nicolas Bellouin (Met Office) -- report to Integrated Climate Programme

CCN number concentrations vs range of observations

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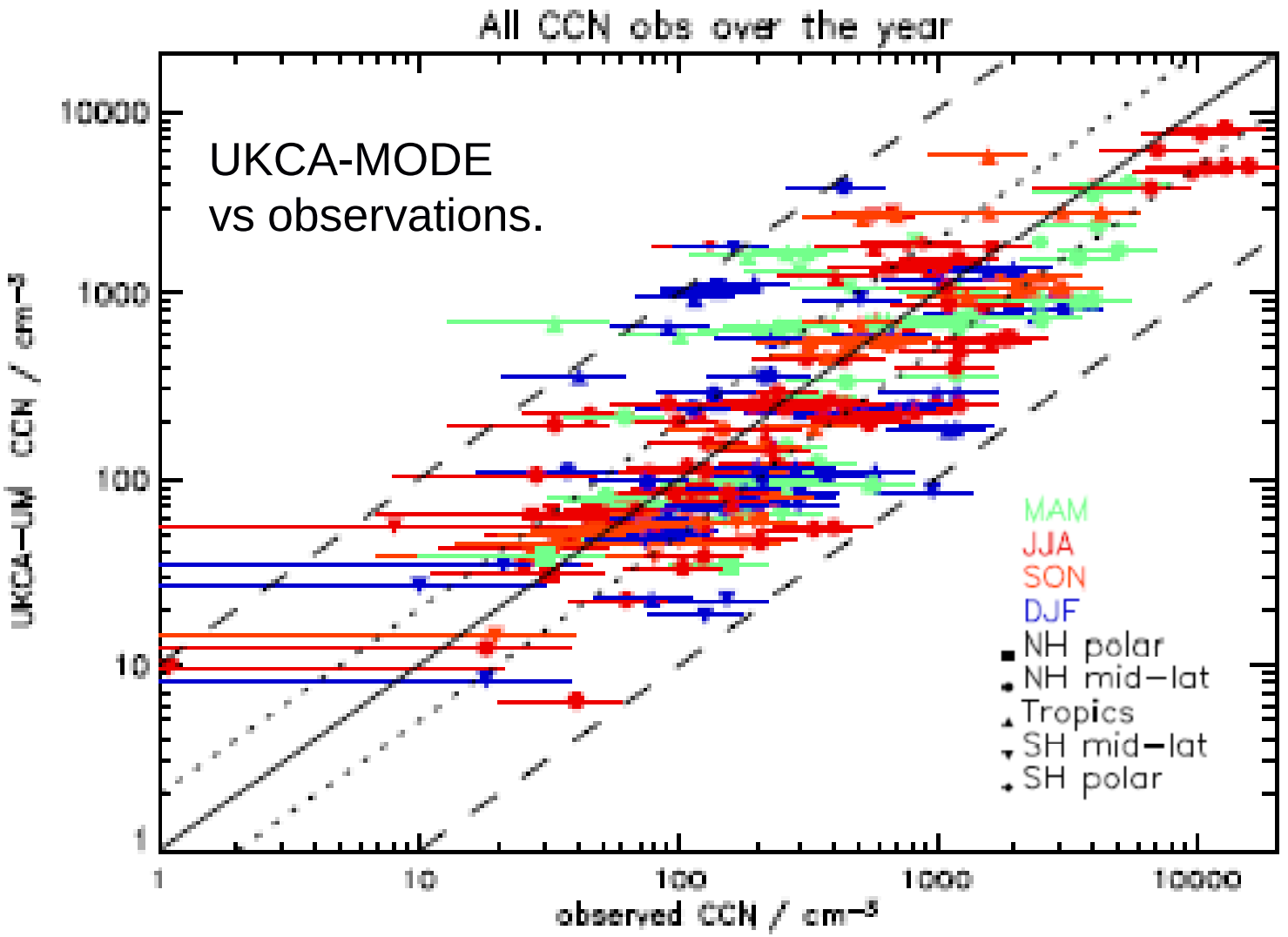

CCN observations compiled by Dominick Spracklen (Leeds)

UKCA to be used at Met Office on range of scales

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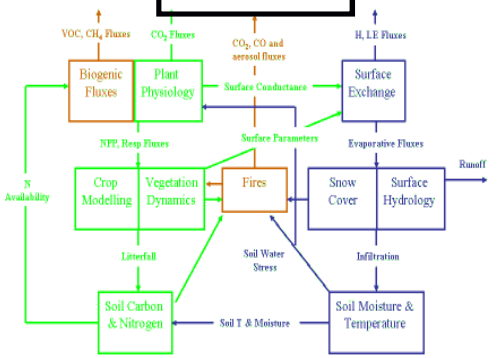
UM

Seamless prediction

UKCA Troposphere & Stratosphere & Aerosols

Biogenic emissions

JULES



Land surface

MACC project

AQUM project

Aerosol forcing

UKCA-trop
UKCA-strat

UKCA-whole atm
UKCA-MODE

Short-term numerical weather prediction & Visibility forecasts

AQ forecasts

Seasonal forecasting

Decadal prediction

Climate projections AR5 - HadGEM2-ES

Climate projections Post-AR5 HadGEM2/3-ES

Slide from O. Boucher, Met Office

Now I've transformed into Luke Abraham (NCAS-Climate, Cambridge)

UKCA Release Models

- UKCA is currently running in UM7.3 HadGEM3-A
- There are a number of different horizontal resolutions and level schemes available
  - QESM resolution at N48 (2.5° x3.75°) with 60 vertical levels up to ~84km
  - Standard Tropospheric Version is N96 (1.25° x1.875°) with 63 vertical levels up to ~40km.
  - Standard Stratospheric version is N96 with 85 vertical levels up to 85km (L63 + 22 levels – c.f. L60)
  - Also have N96 version with 38 vertical levels up to ~40km
- Can also run above models in **nudged** mode

(Luke Abraham, NCAS)

UKCA Release Models

Chemistry	Resolution	Notes	Released
Tropospheric + MODE	N48L60	RADAER, QESM	
Tropospheric + MODE	N96L38	RADAER	✔
Tropospheric + MODE	N96L38	RADAER, Nudging	✔
Tropospheric + Isoprene	N48L60	QESM	✔
Tropospheric + Isoprene	N96L63		
Stratospheric	N48L60	QESM	✔
Stratospheric	N96L85		

http://www.ukca.ac.uk/wiki/index.php/UKCA_Release_Jobs

(Luke Abraham, NCAS)

UKCA Standard Jobs

1. Tropospheric Chemistry + MODE
   - Emissions into 8 species
   - Simulates Ox, HOx and NOx chemical cycles and the oxidation of CO, ethane and propane
   - Includes a sulphur & terpene oxidation scheme to drive MODE
   - Direct and indirect effects can be calculated online from MODE
     - Dynamical feed-back can also be included
   - N96L38 jobs are currently available (nudged and un-nudged)

(Luke Abraham, NCAS)

New Developments

- Satellite Emulator
- Fast-JX
- Flight-Track Simulator
- Tropospheric Chemistry with Isoprene and MODE
- CheST Chemistry
- Atmosphere-Ocean UKCA
- Interactive Emissions
- Emissions Profiling

(Luke Abraham, NCAS)

Using UKCA

- I am happy to help with model queries and problems
  - Email: Luke.Abraham@atm.ch.cam.ac.uk
- UKCA website/wiki: http://www.ukca.ac.uk/wiki
  - Documentation of Release Jobs
  - Accounts available on request
- UKCA is a Community Model
  - Feedback on your experiences are important to us
  - What would else you like to see UKCA to do?

(Luke Abraham, NCAS)

Upgraded UKCA-MODE jobs now tested

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UKCA-MODE tropospheric aerosol-chemistry jobs

-- Early HadGEM3-A model at N96L38 now → HadGEM3-A r2.0 at N96L63.

-- Std Tropospheric Chem in B-E solver → IsopTrop/CheT with N-R solver.

-- IsopTrop/CheT extended with DMS, SO2 & monoterpene oxidation.

-- Direct & 1st indirect aerosol forcing included (single-call to radiation).
(Uses "RADAER "module to calculate optical properties of each of the externally-mixed modes based on their size & internally-mixed composition.

-- Can also run with double-call to radiation scheme to diagnose forcings.

UKCA-MODE stratospheric aerosol-chemistry jobs

-- HadGEM3-A r2.0 at N48L60 (high-top model up to 80km, QESM resolution)

-- StratChem/CheS extended with SO2, SO3, H2SO4 chemistry & photolysis

-- UKCA-MODE adapted for stratospheric aerosol
(water content, density, nucleation, H_2SO_4 vapour pressure)

Now merging these jobs for whole-atmosphere aerosol-chemistry simulations

Evaluation of simulated aerosol (sulphate)

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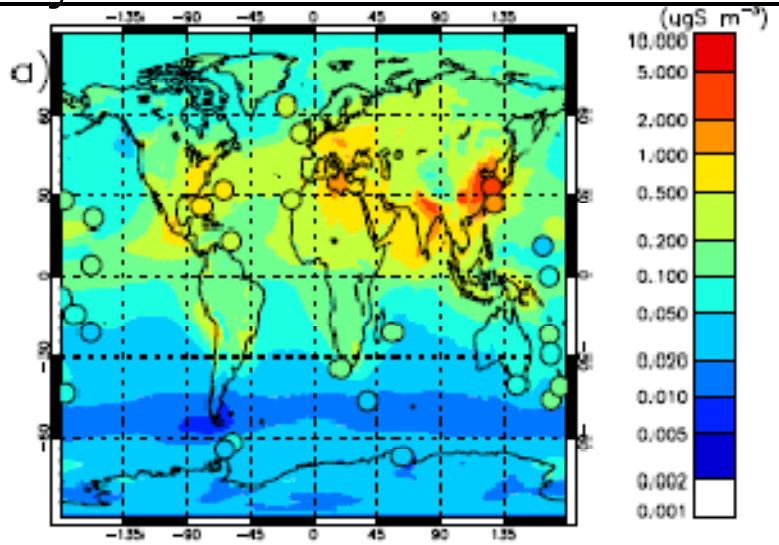
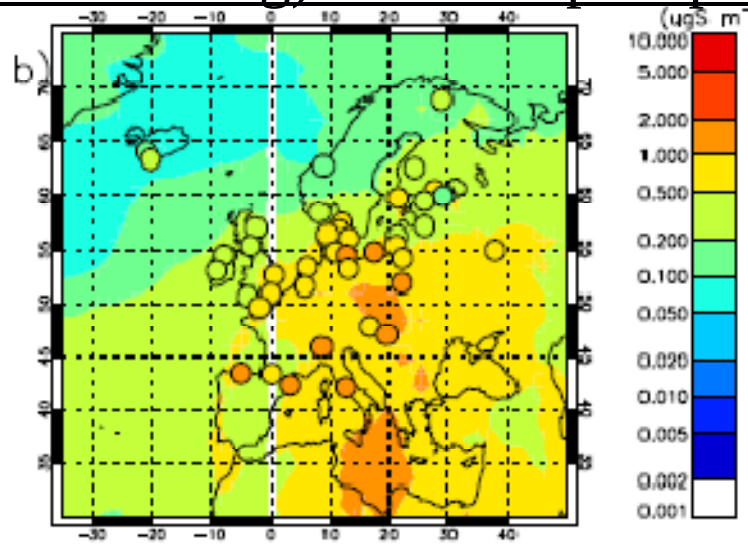
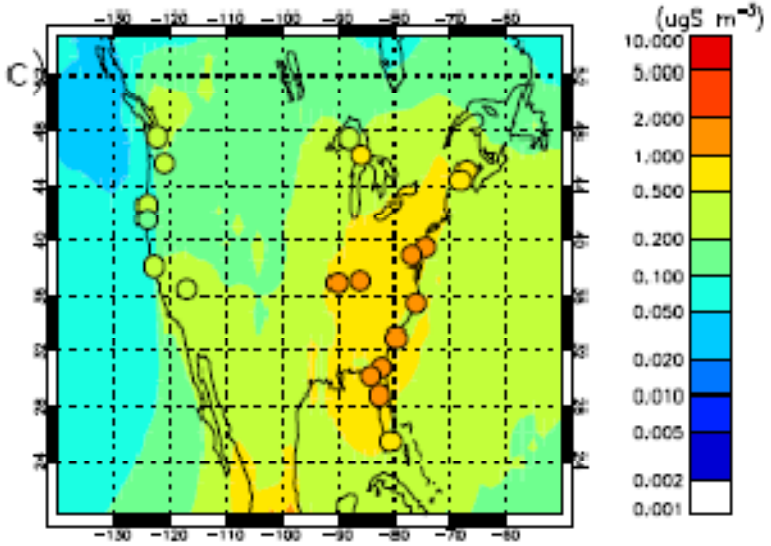
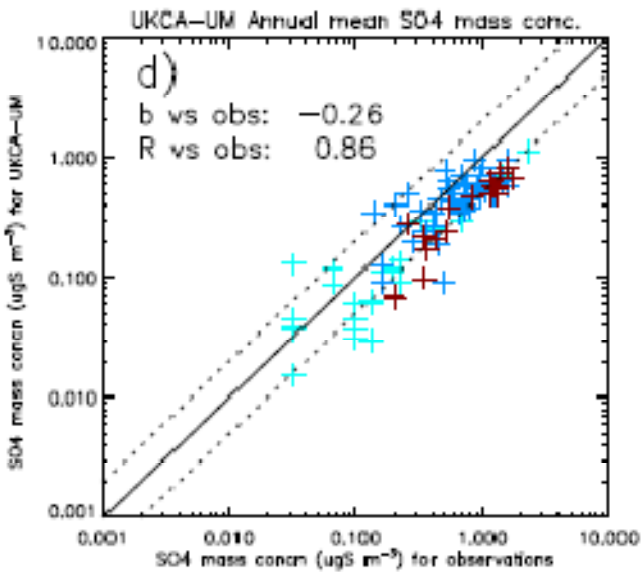
xfxiy UKCA-UM N96L63 2000 (free-running) : N-R IsopTrop+achem





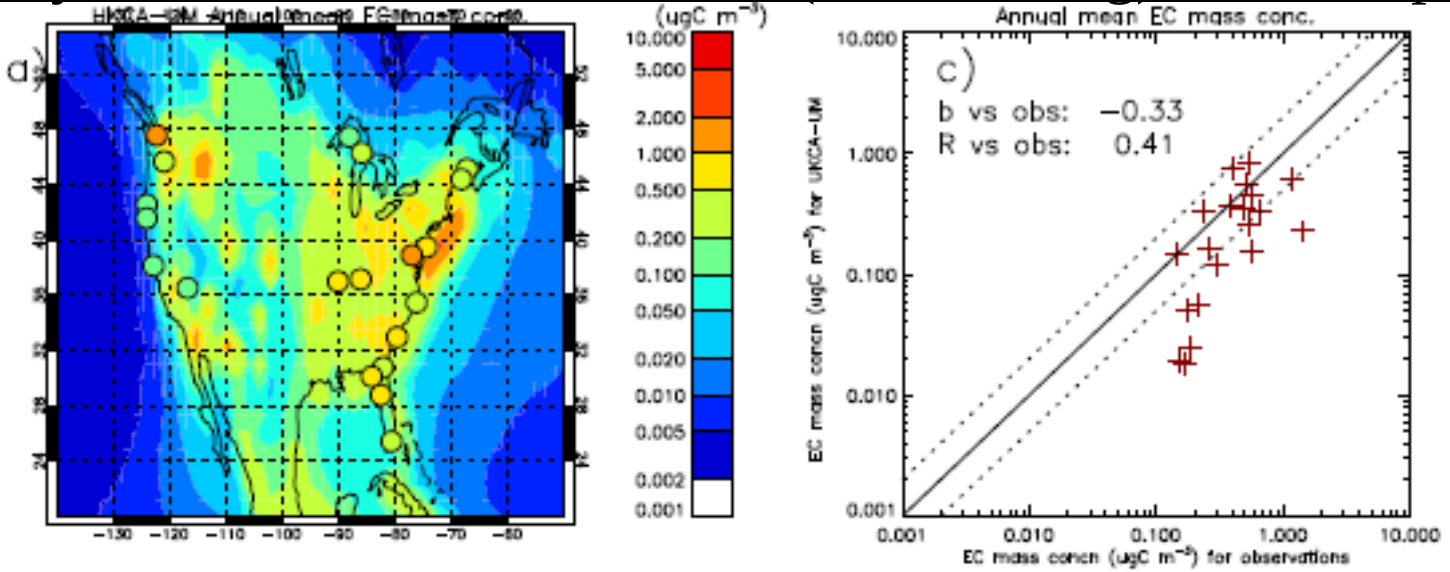


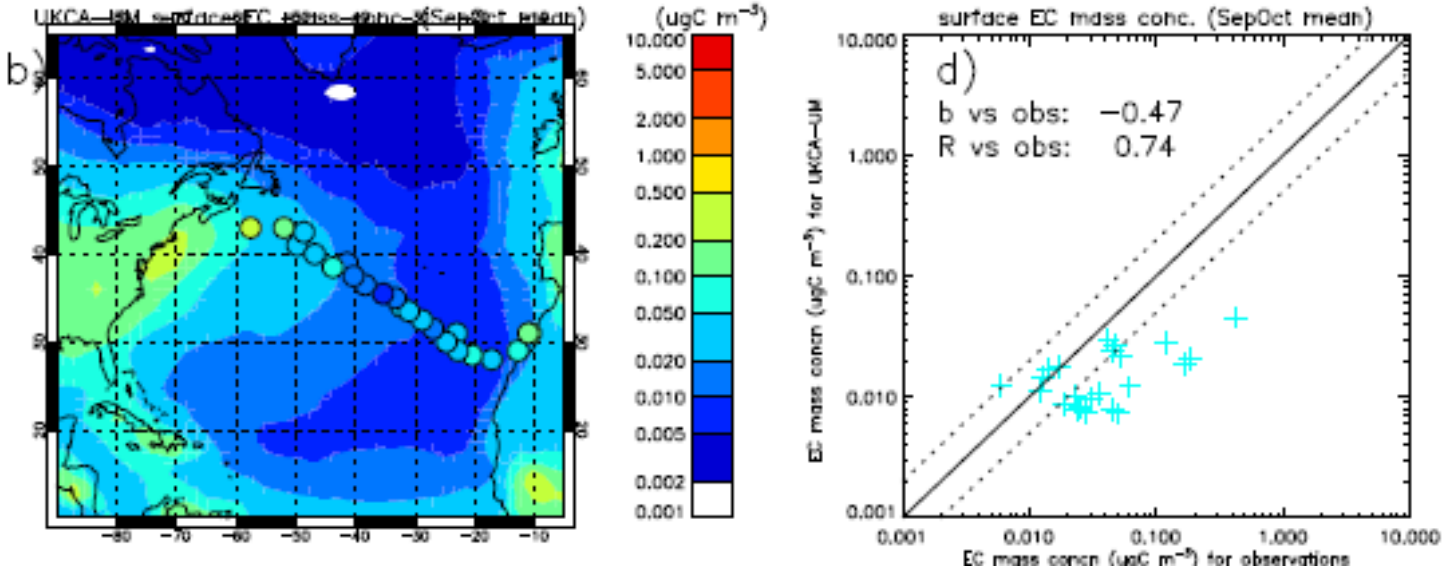


Evaluation of simulated aerosol (black carbon)

UNIVERSITY OF LEEDS

xfxiy UKCA-UM N96L63 2000 (free-running) : N-R IsopTrop+achem

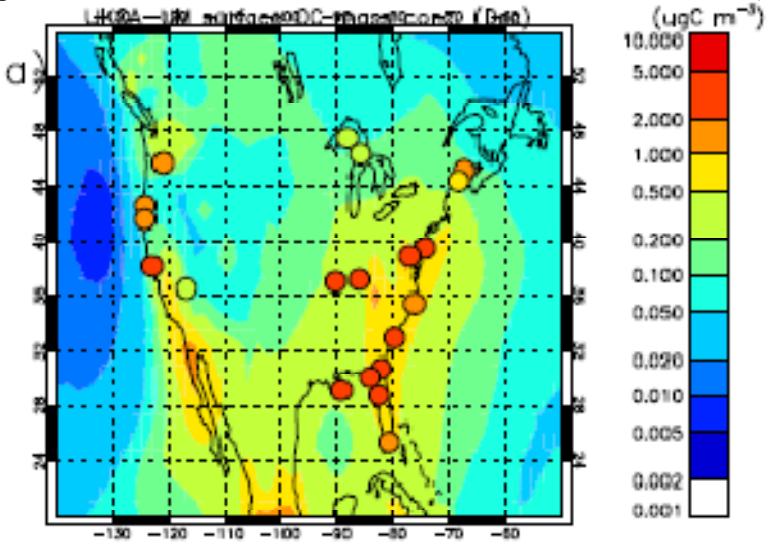


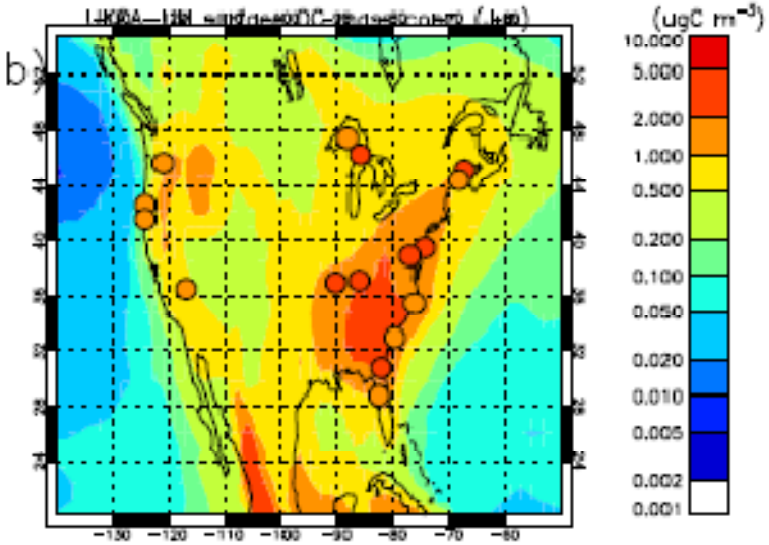


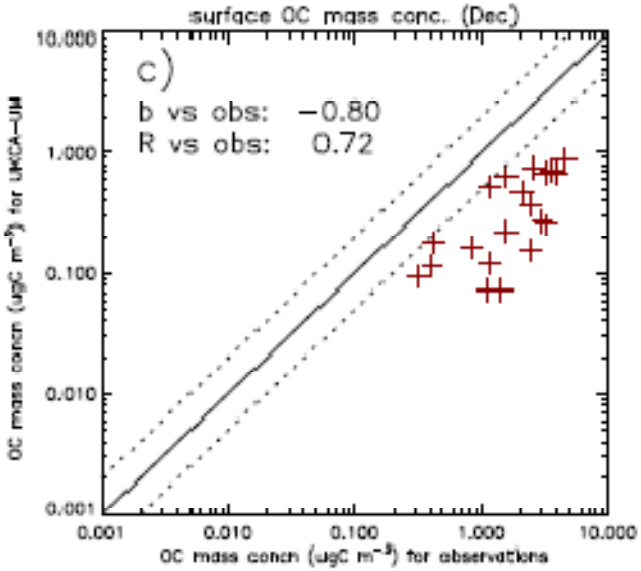
Evaluation of simulated aerosol (organics)

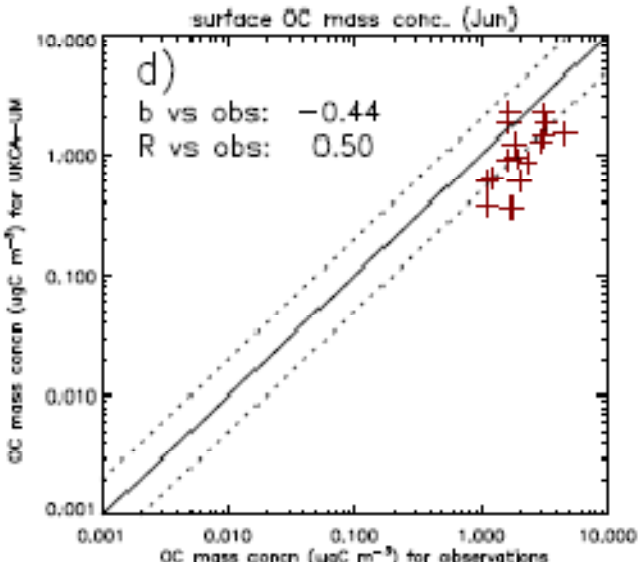
UNIVERSITY OF LEEDS

xfxiy UKCA-UM N96L63 2000 (free-running) : N-R IsopTrop+achem









Evaluation of simulated aerosol (no. concns)

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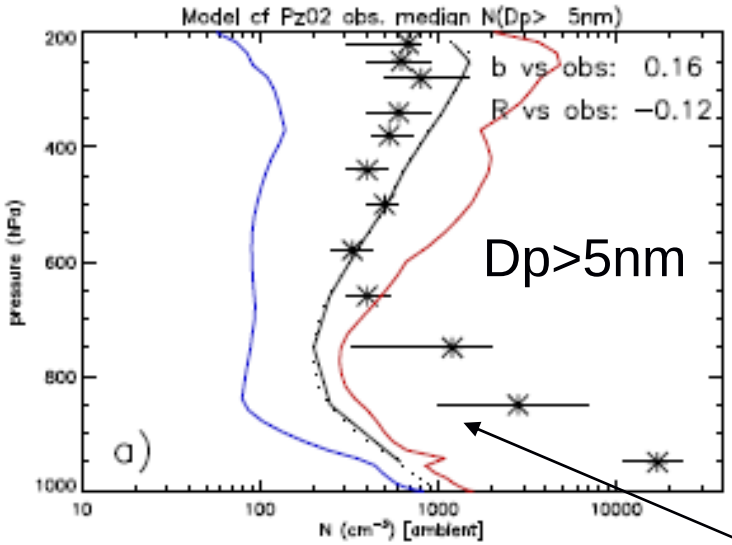
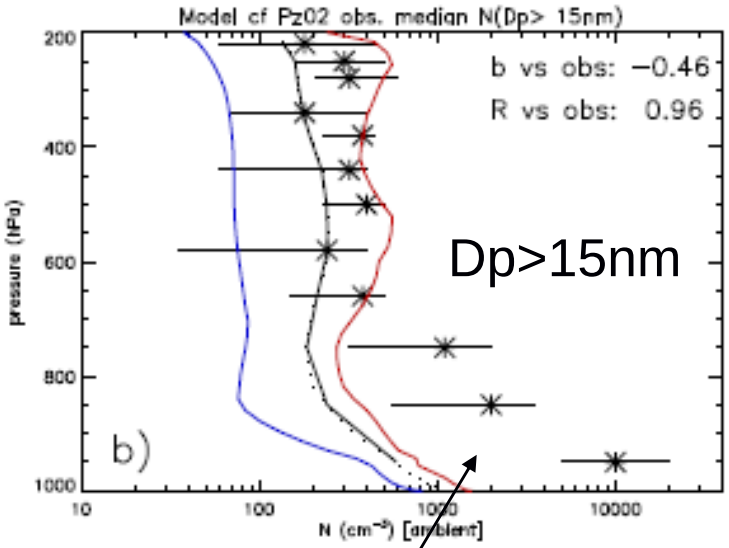
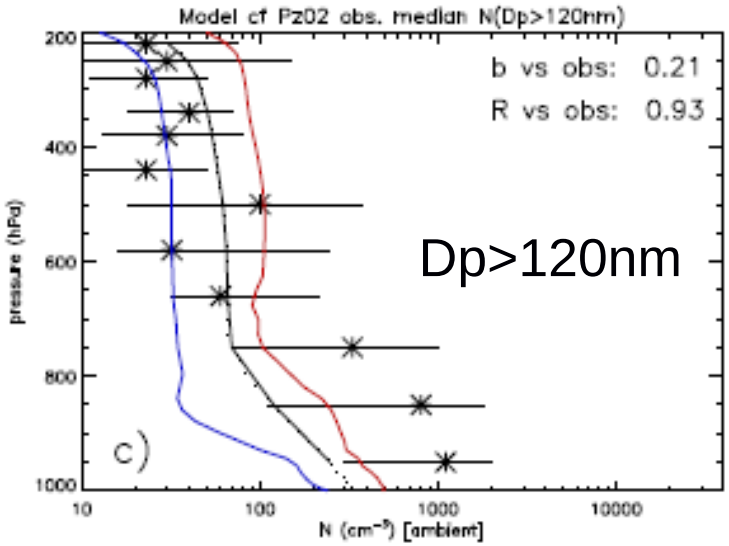
xfxiy UKCA-UM N96L63 2000 (free-running) : N-R IsopTrop+achem







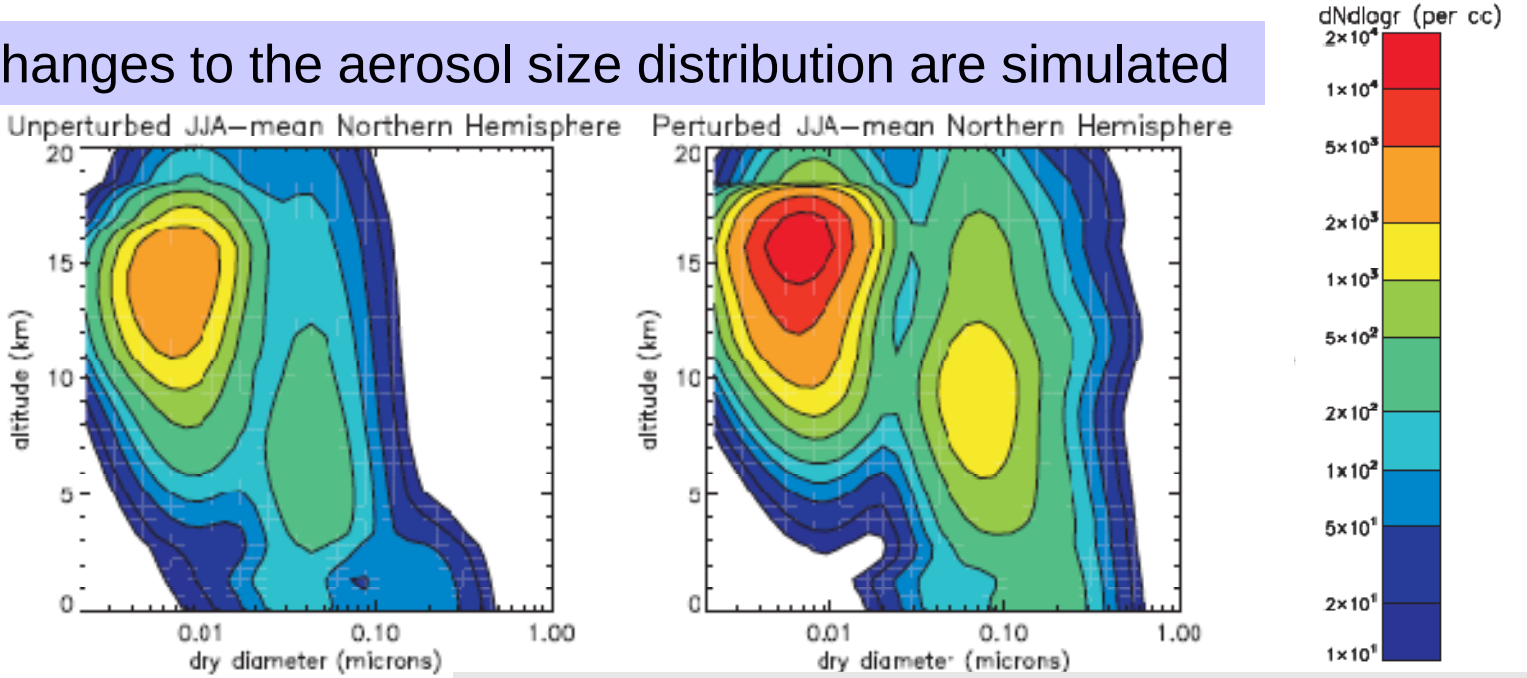
Boundary layer nucleation not included in this run (increases BL CN by factor 10)

UKCA-aerosol applications (1): Volcanic aerosol: impacts on climate

UNIVERSITY OF LEEDS

- 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

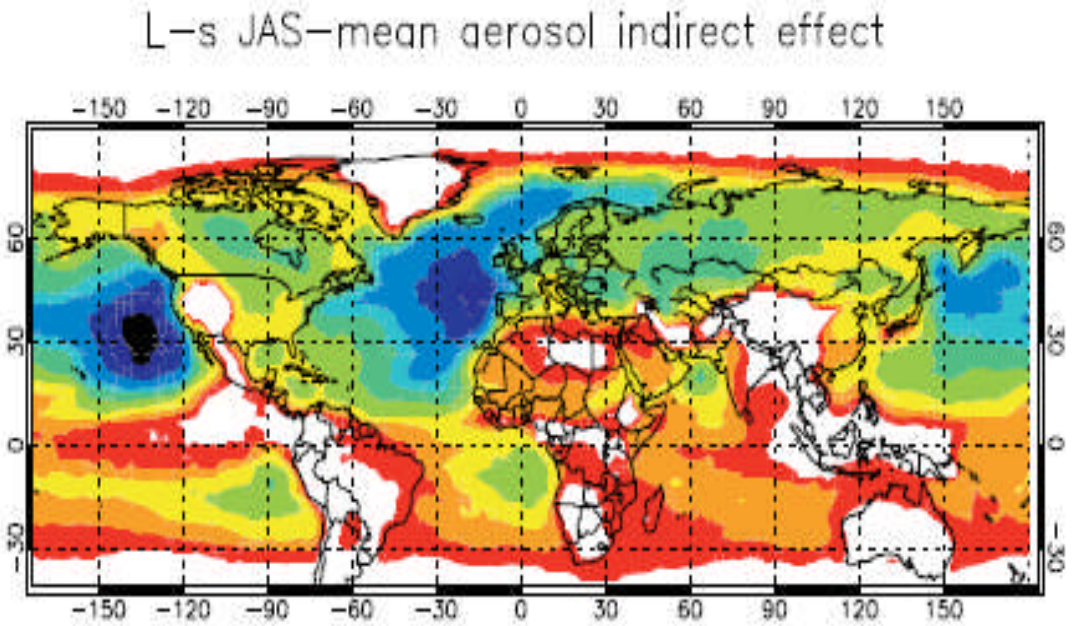


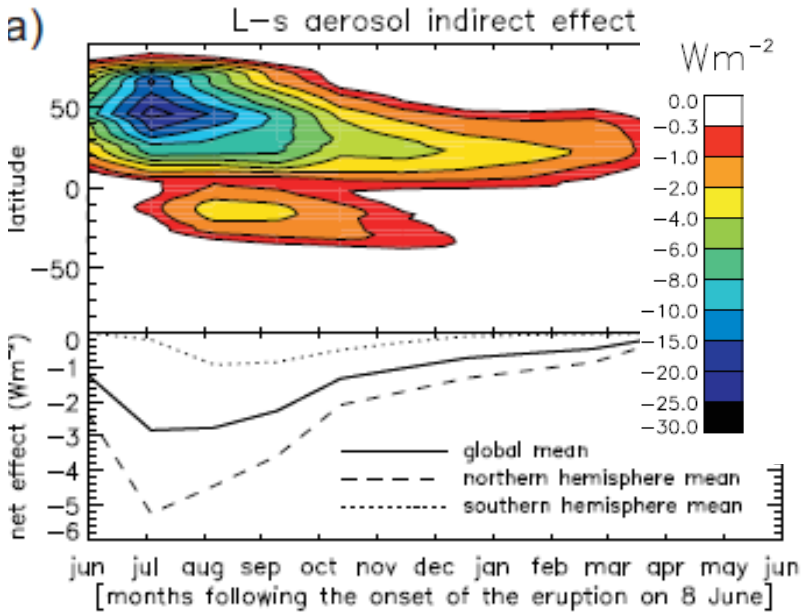
Schmidt et al (2010, ACP)

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

1783 Laki eruption: aerosol indirect climate effects

UNIVERSITY OF LEEDS





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

Schmidt et al (2011, in prep)

Anja Schmidt (Leeds) will soon do Laki simulations in UKCA.

Simulate climate forcing and impact on European climate

UKCA-aerosol applications (2): Strat-geoengineering & Large volcanic eruptions

UNIVERSITY OF LEEDS

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)

• We will apply UKCA in coupled-AO to simulate stratospheric injection of SO_2 and associated climate forcings and response for GeoMIP simulations.

• Also plan to examine climate response to volcanic eruptions in UKCA coupled A-O simulations with CheS + MODE.

-- Examine aerosol-chemistry-climate interactions in fully coupled HadGEM3-AO model with unprecedented level of physical realism

-- UKCA composition-climate model will be world-leading in capability here.

Stratospheric sulphur chemistry now in UKCA

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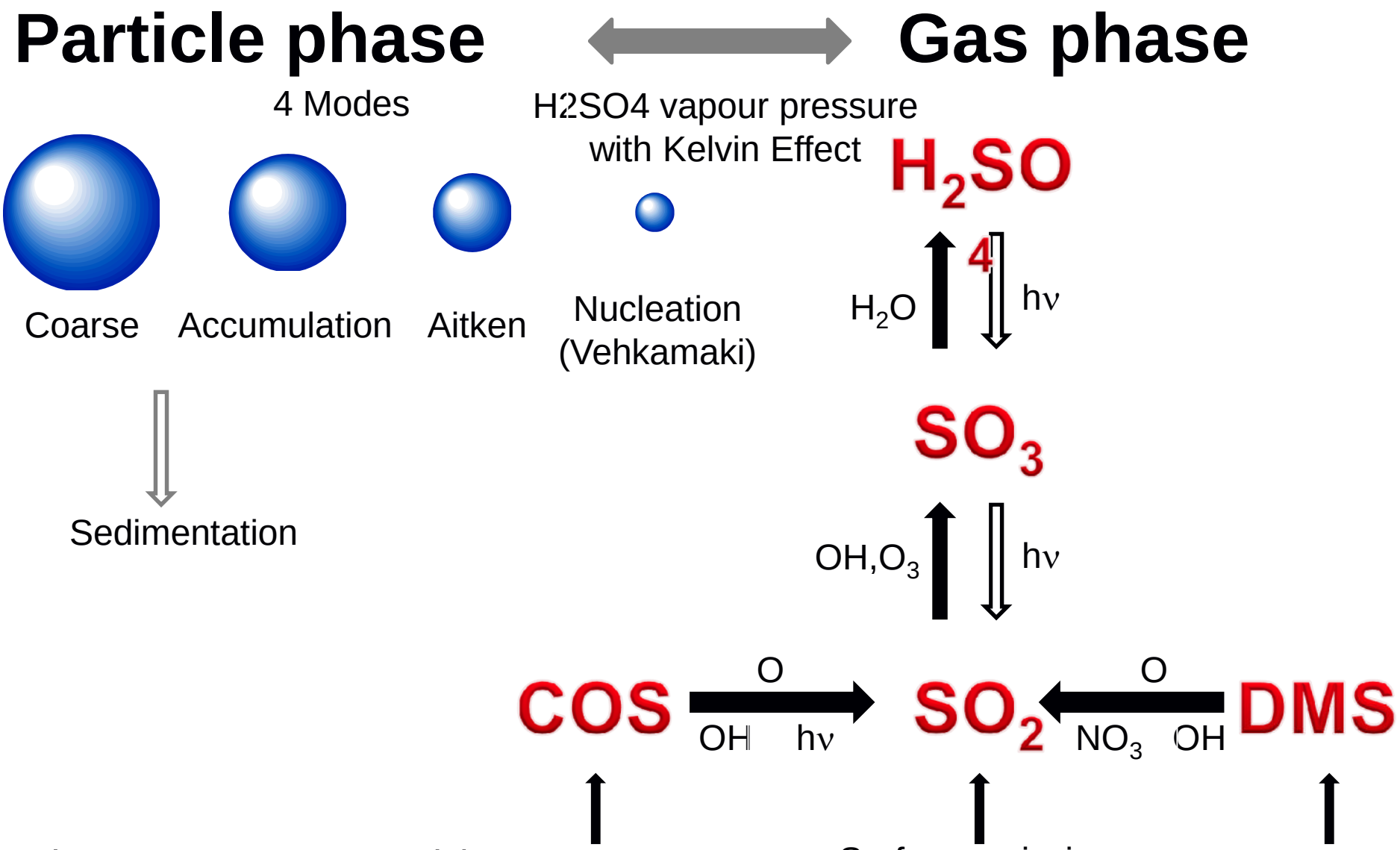


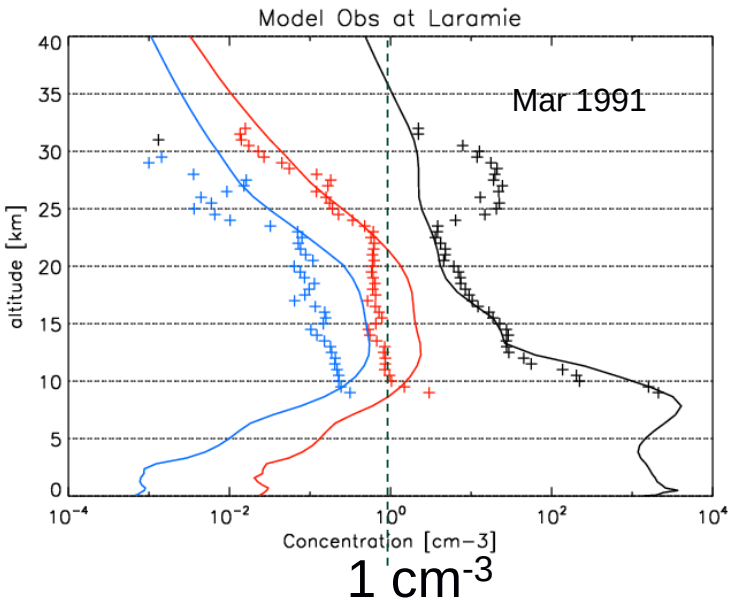
(Kathryn Emmerson, Leeds)

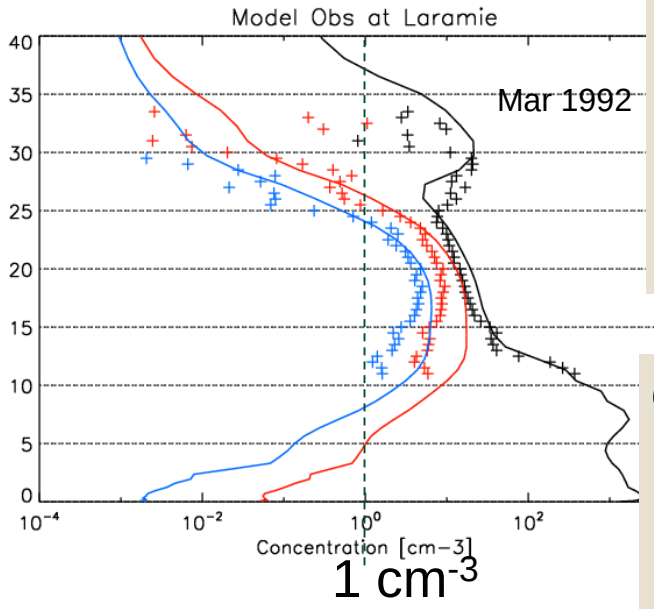
UKCA StratChem + Saerchem + MODE N48L60

UNIVERSITY OF LEEDS

Test UKCA CheS + MODE stratospheric aerosol for Pinatubo eruption.

Inject 20 Tg of SO_2 from tropopause up to 28km in the model 15th Jun 1991.





Model

CN

CN > 150nm

CN > 250nm

Observations

\+ CN

\+ CN > 150nm

\+ CN > 250nm

3 months before Pinatubo

9 months after Pinatubo

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

(Kathryn Emmerson, Leeds)

Evaluate simulated stratospheric aerosol properties

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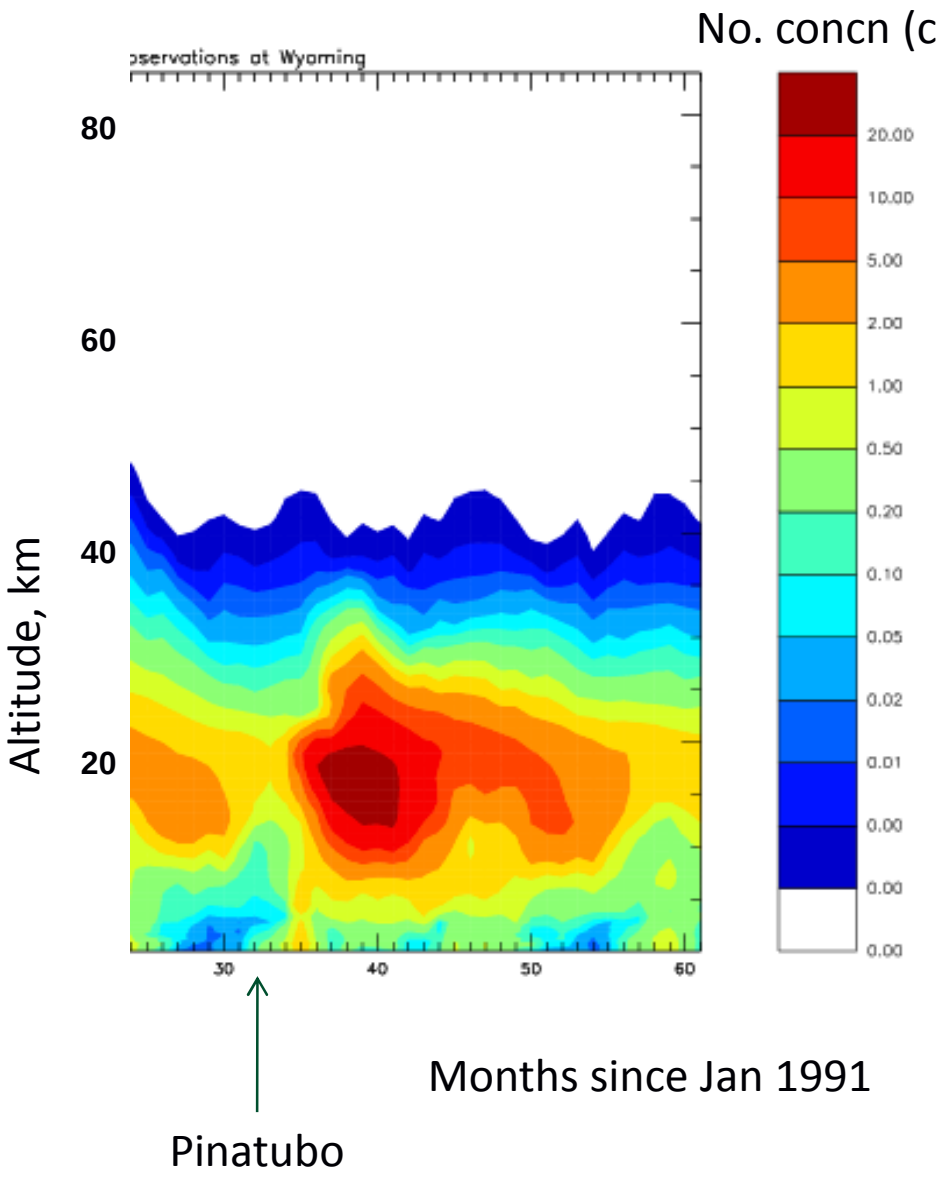
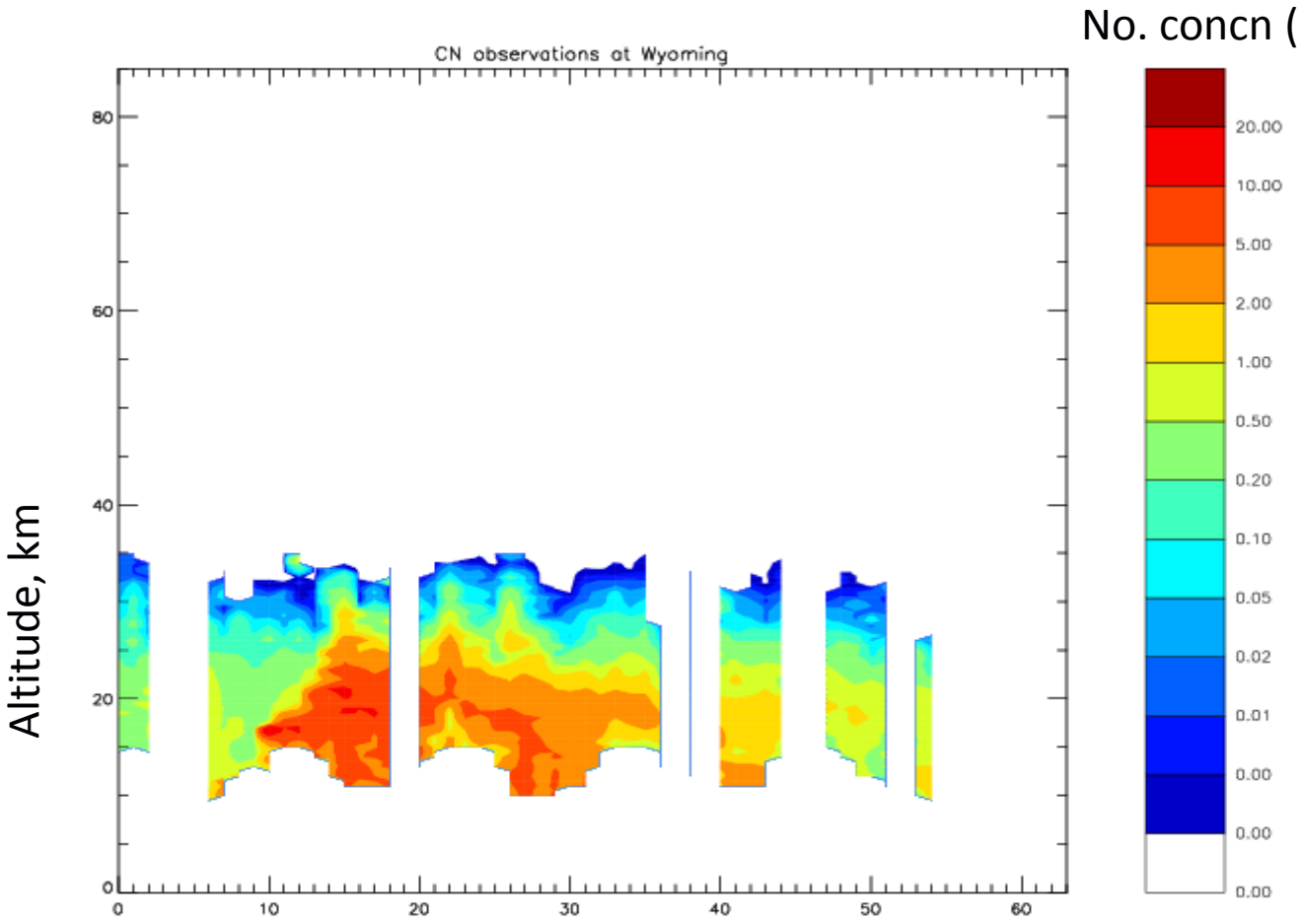


Hovmoller plot of **model number concentration > 150 nm** at Laramie, Wyoming.

Evaluate simulated stratospheric aerosol properties

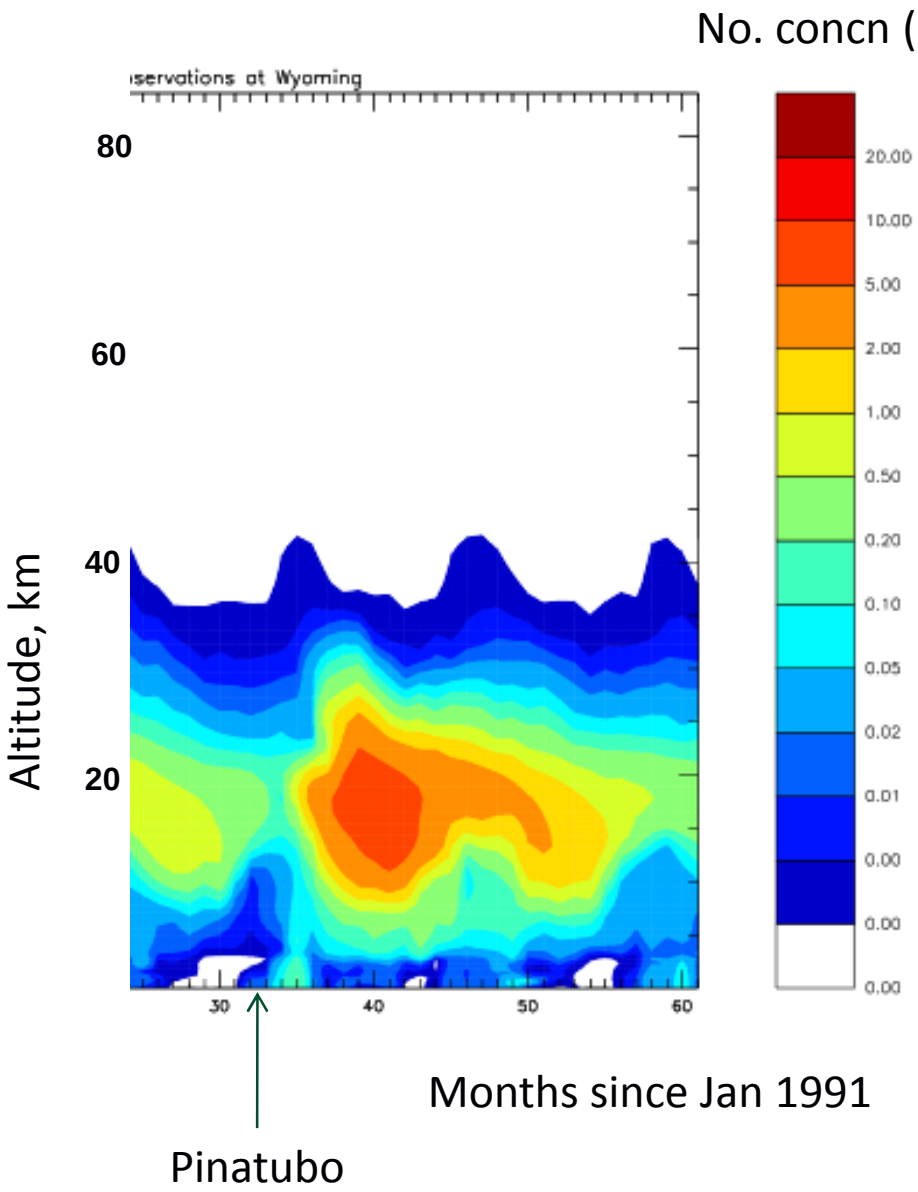
UNIVERSITY OF LEEDS



Hovmoller plot of **observed number concentration > 150 nm** at Laramie, Wyoming.

Evaluate simulated stratospheric aerosol properties

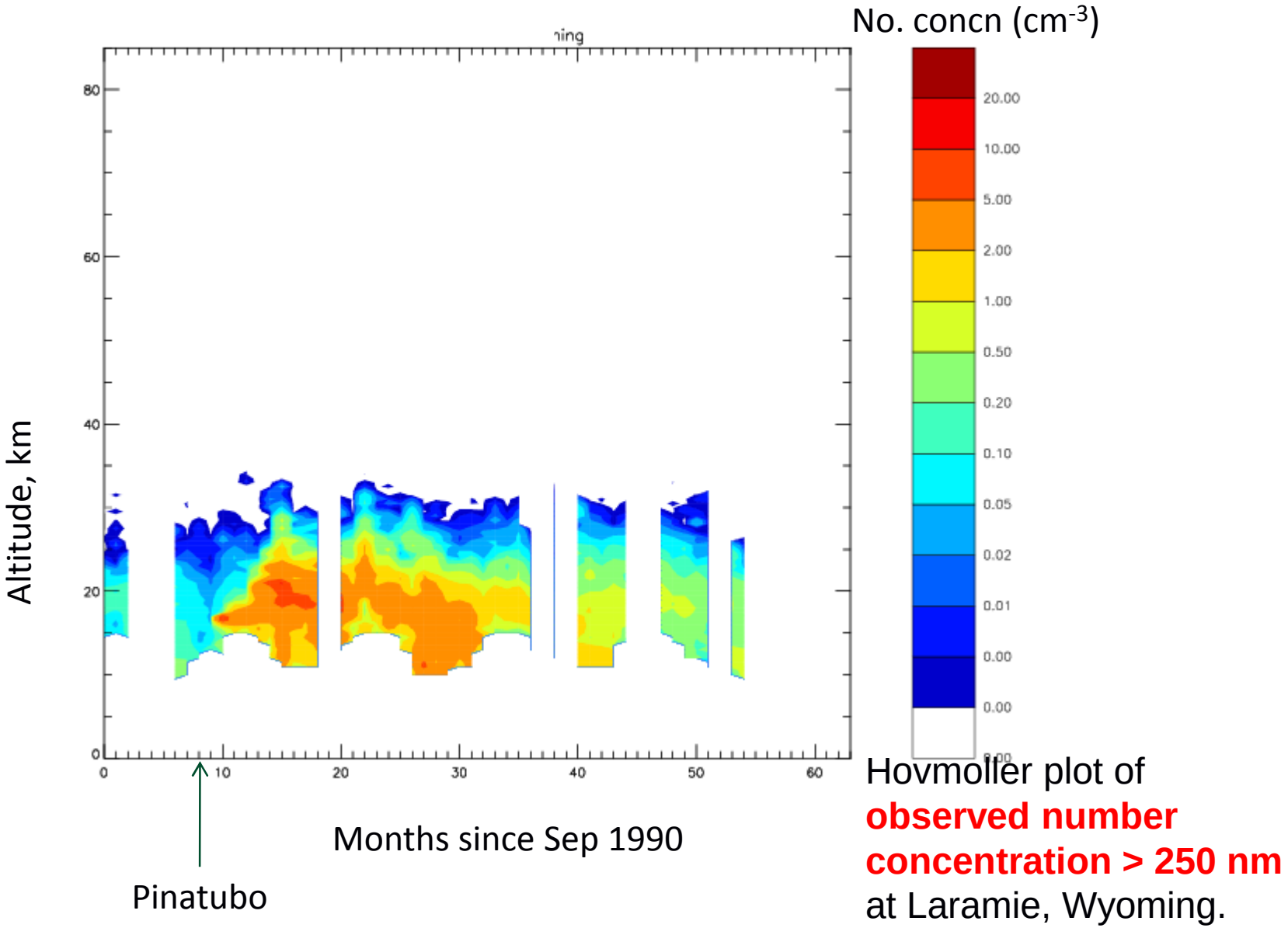
UNIVERSITY OF LEEDS



Hovmoller plot of **model number concentration > 250 nm** at Laramie, Wyoming.

Evaluate simulated stratospheric aerosol properties

UNIVERSITY OF LEEDS



Hovmoller plot of **observed number concentration > 250 nm** at Laramie, Wyoming.

UKCA-aerosol applications (3): Role of natural aerosol in the Earth System

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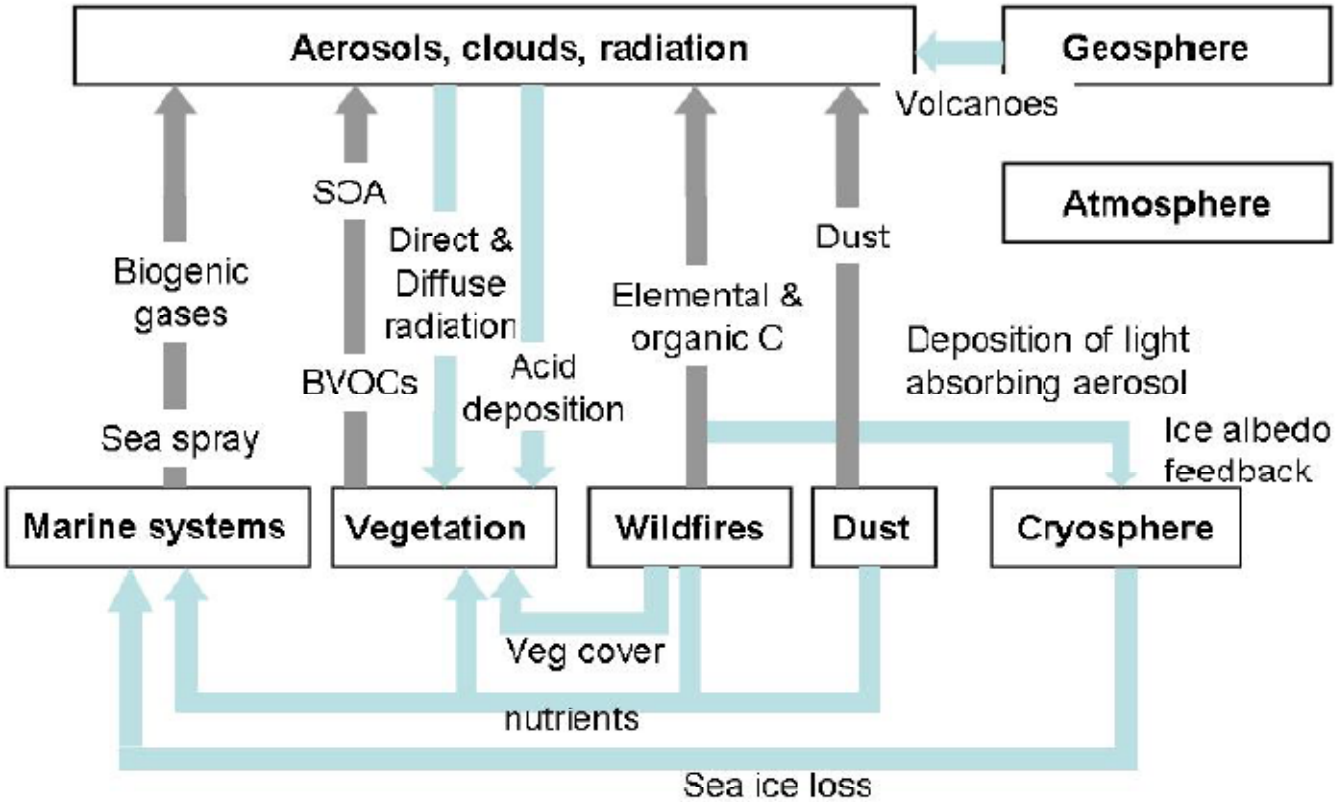
Carslaw et al (2010) review of *Natural aerosol interactions in the Earth System*



Offline CTM simulations have examined the role of these sources.
UKCA chemistry & size-resolved aerosol microphysics allows state-of-the-science studies of these within the HadGEM3-ES AO-GCM.

UKCA experiments on DMS-climate feedbacks

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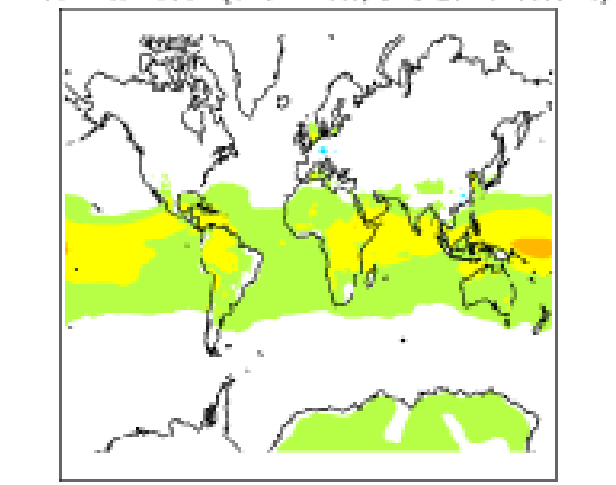
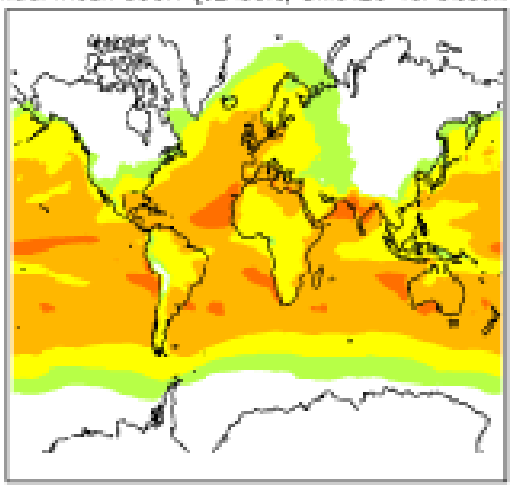
Change in CCN due to 25% increase in DMS emissions

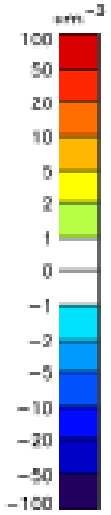
- UKCA-mode predicts a much smaller response of CCN

UM-UKCA-mode



UM-CLASSIC





Matt Woodhouse (Leeds) : from PhD thesis 2010.

CCN sensitivity to DMS in UKCA-UM cf CLASSIC

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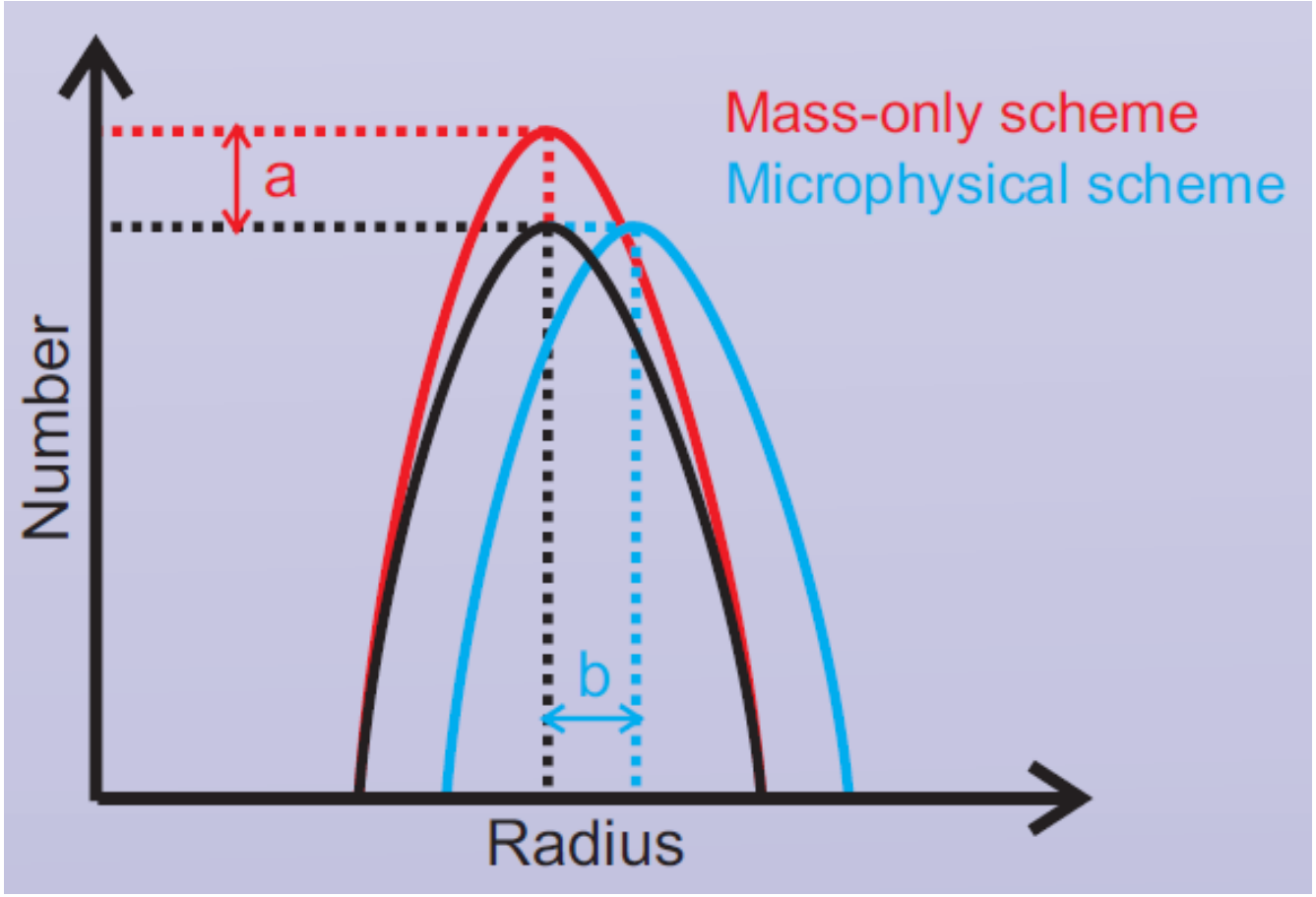

Mass-only schemes cannot represent aerosol growth.

Any process that adds mass automatically increases particle number.

Processes like aqueous sulphate production in clouds introduce bias.

UKCA experiments on DMS-climate feedbacks

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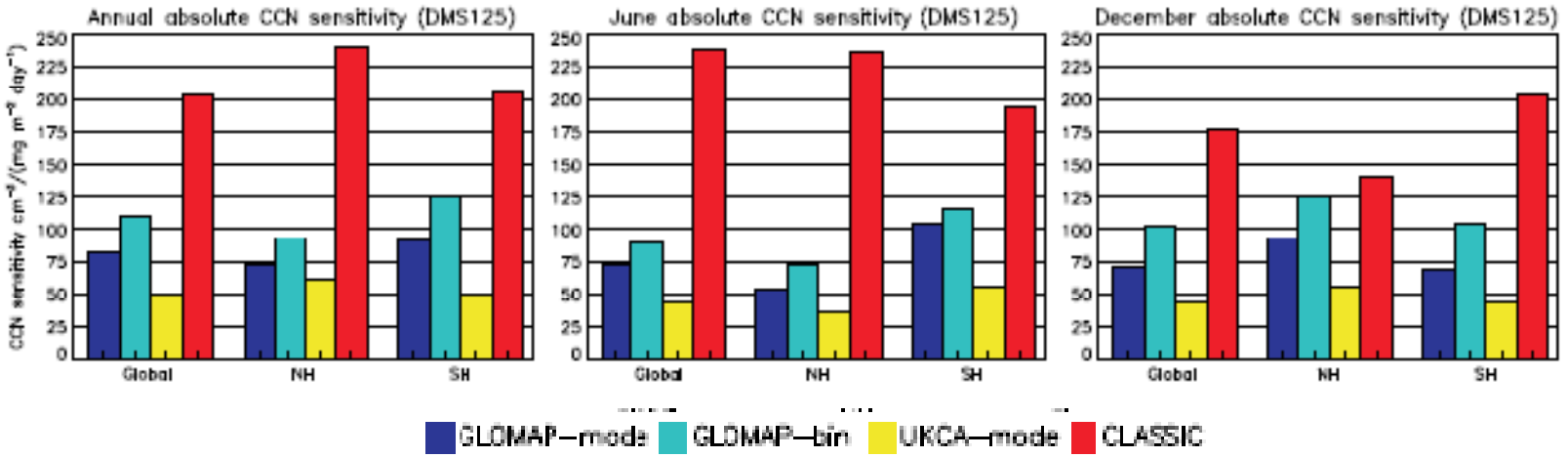

CLASSIC mass-based aerosol scheme (in HadGEM2-ES for IPCC AR5) overestimates CLAW feedback because increase in aerosol mass (e.g. from in-cloud oxidation of SO_2) increases cloud drops

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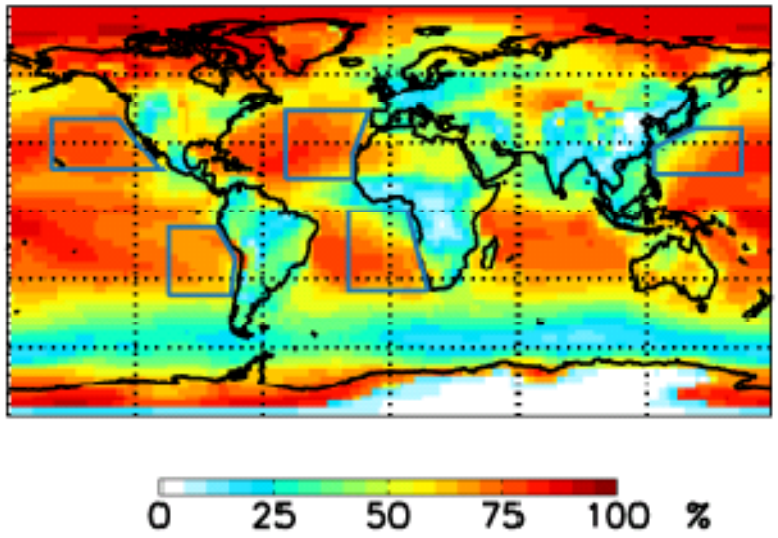
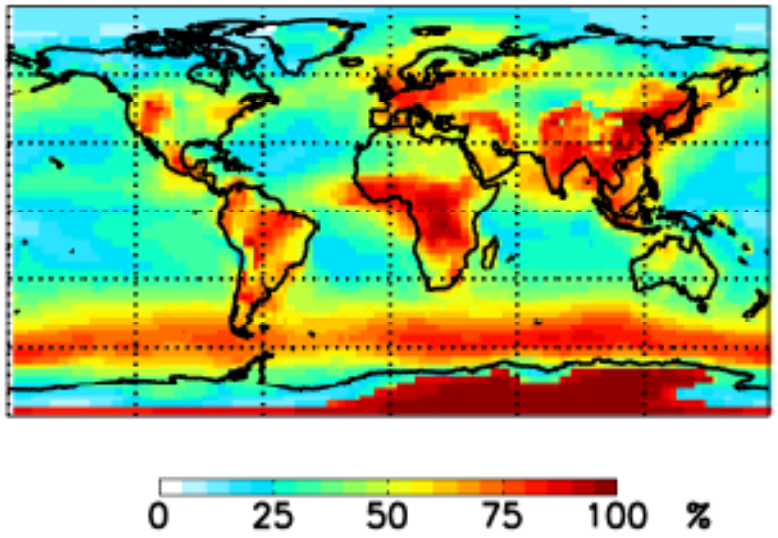
Nucleated particles important for aerosol indirect effects.
Growth to CCN sizes via coagulation and gas to particle transfer.

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.

UKCA-aerosol applications (4): Nucleation in UK climate model

UNIVERSITY OF LEEDS

- Nucleated particles grow from ~3nm to CCN-size by coagulation,condensation
- Most climate models for IPCC climate assesments don't include them.
- Carried out UKCA simulations with present-day and pre-industrial emissions with direct and 1st indirect forcing from MODE.
- Meteorology nudged to ECMWF re-analysis fields.
- UKCA chemistry (StdTrop) plus DMS, SO2, terpene oxidation
- CTRL run includes full UKCA-MODE aerosol microphysics
  Sensitivity run with nucleation switched off
- Isolate role of nucleated particles on aerosol climate forcing

UKCA-aerosol applications (4): Nucleation effects on climate

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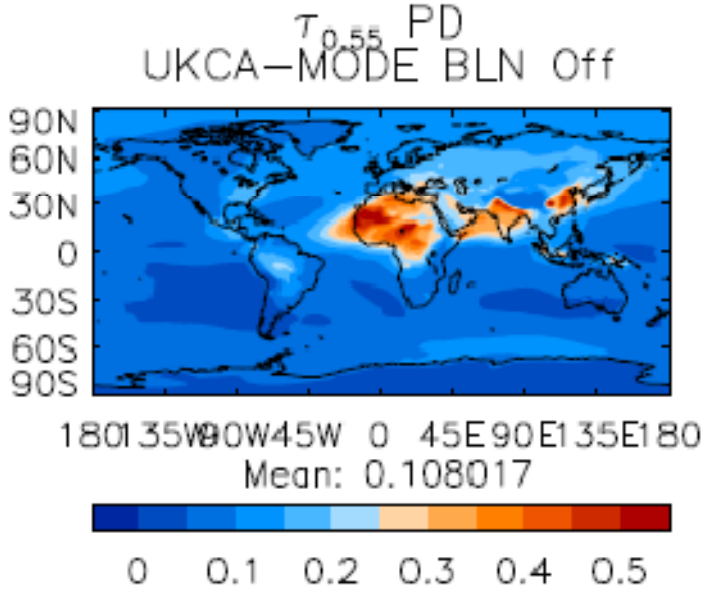

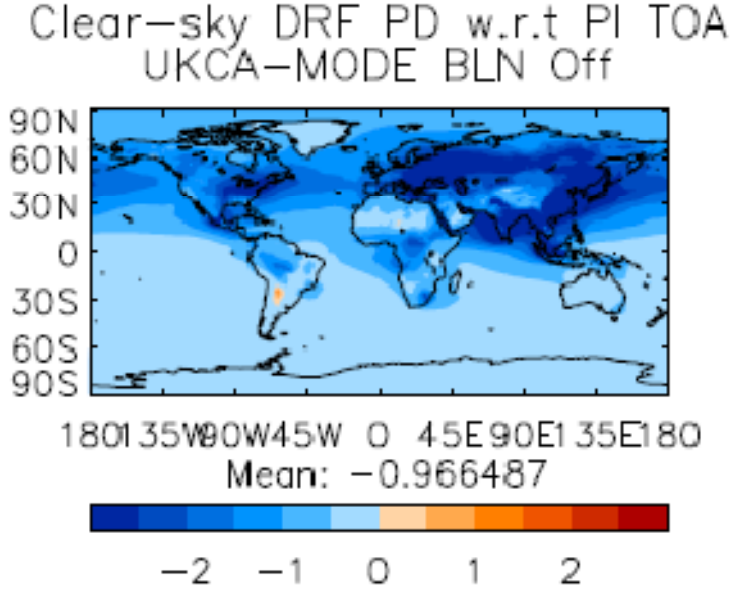

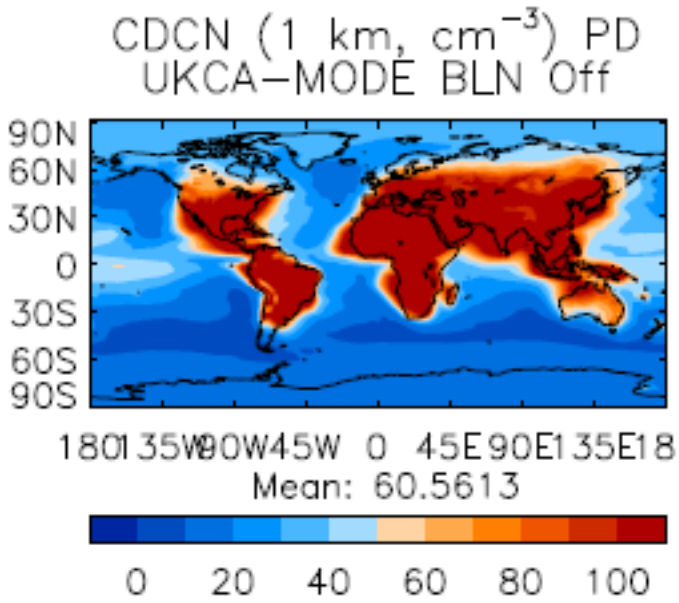

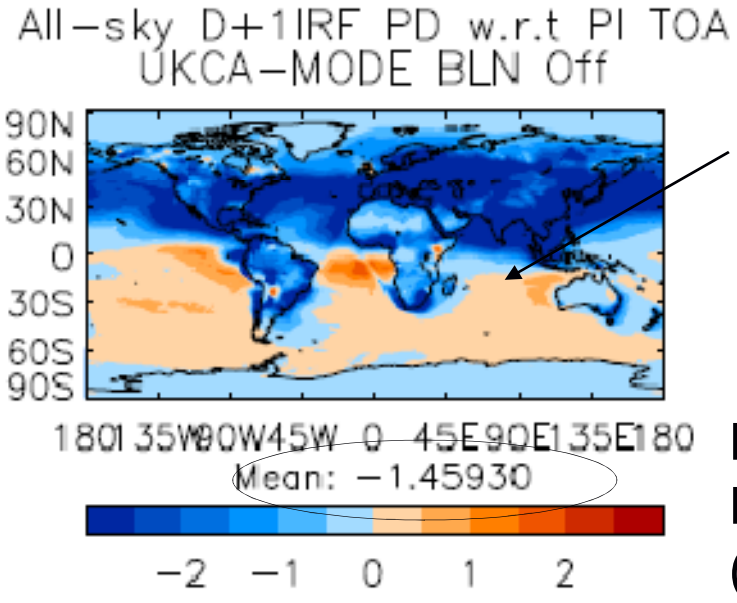

+ve SH marine forcing because CDN higher in pre-ind

Stronger growth in pre-ind'l due to lower surface area density?

Nicolas Bellouin (Met Office)

UKCA-aerosol applications (4): Nucleation effects on climate

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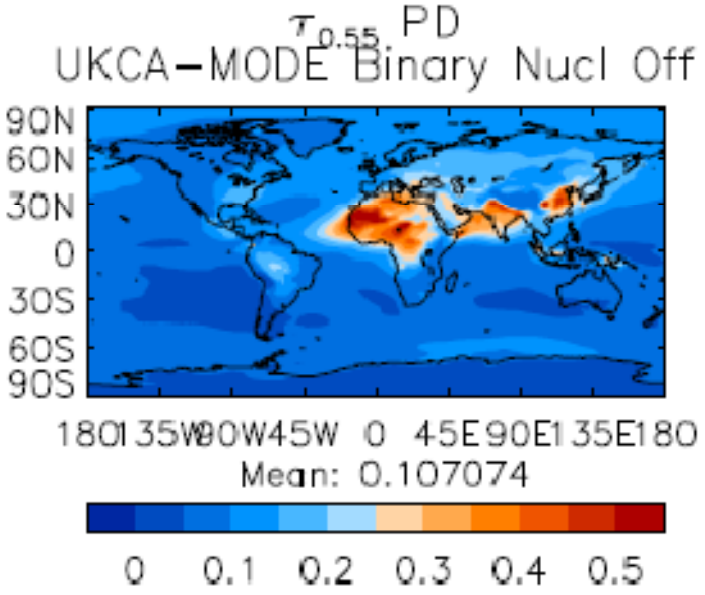

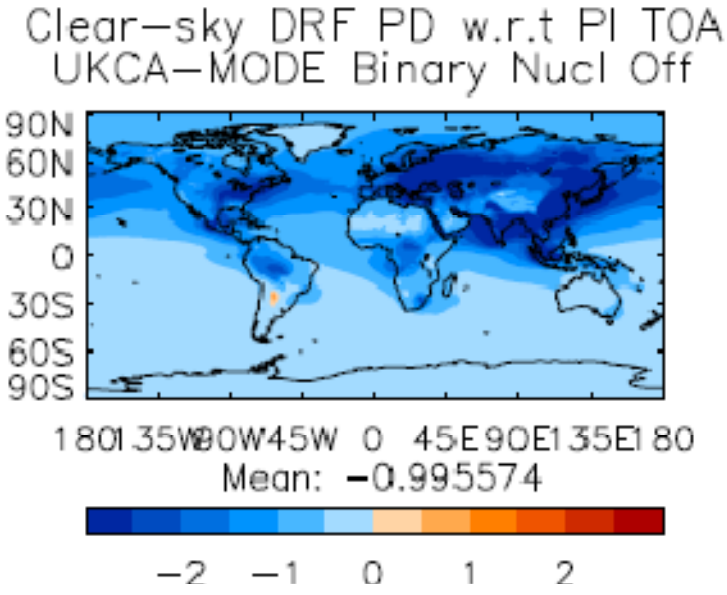

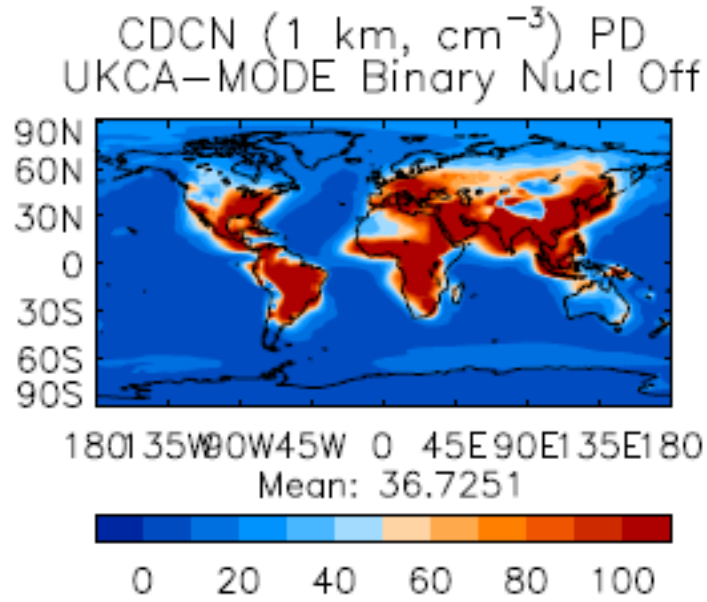

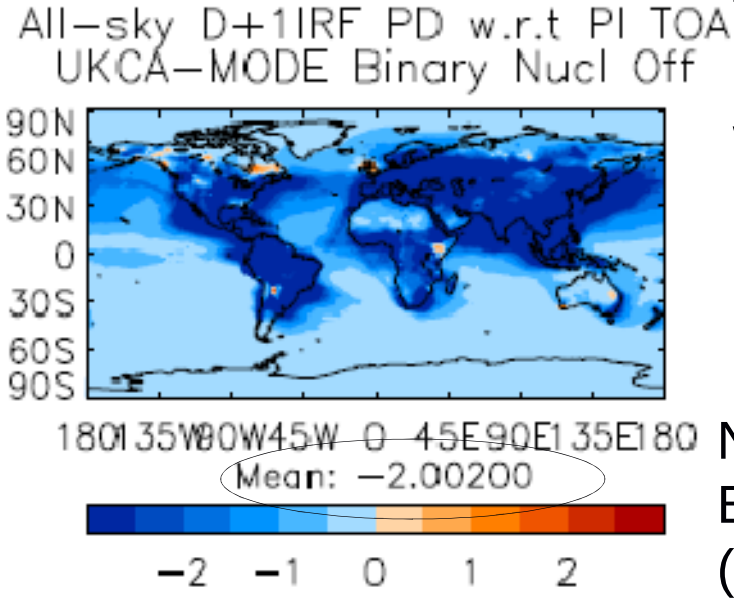

Direct forcing similar with or without nucleation.

But indirect forcing 50% lower when nucleation included.

Nicolas Bellouin (Met Office)

Next: full inorganic composition in UKCA

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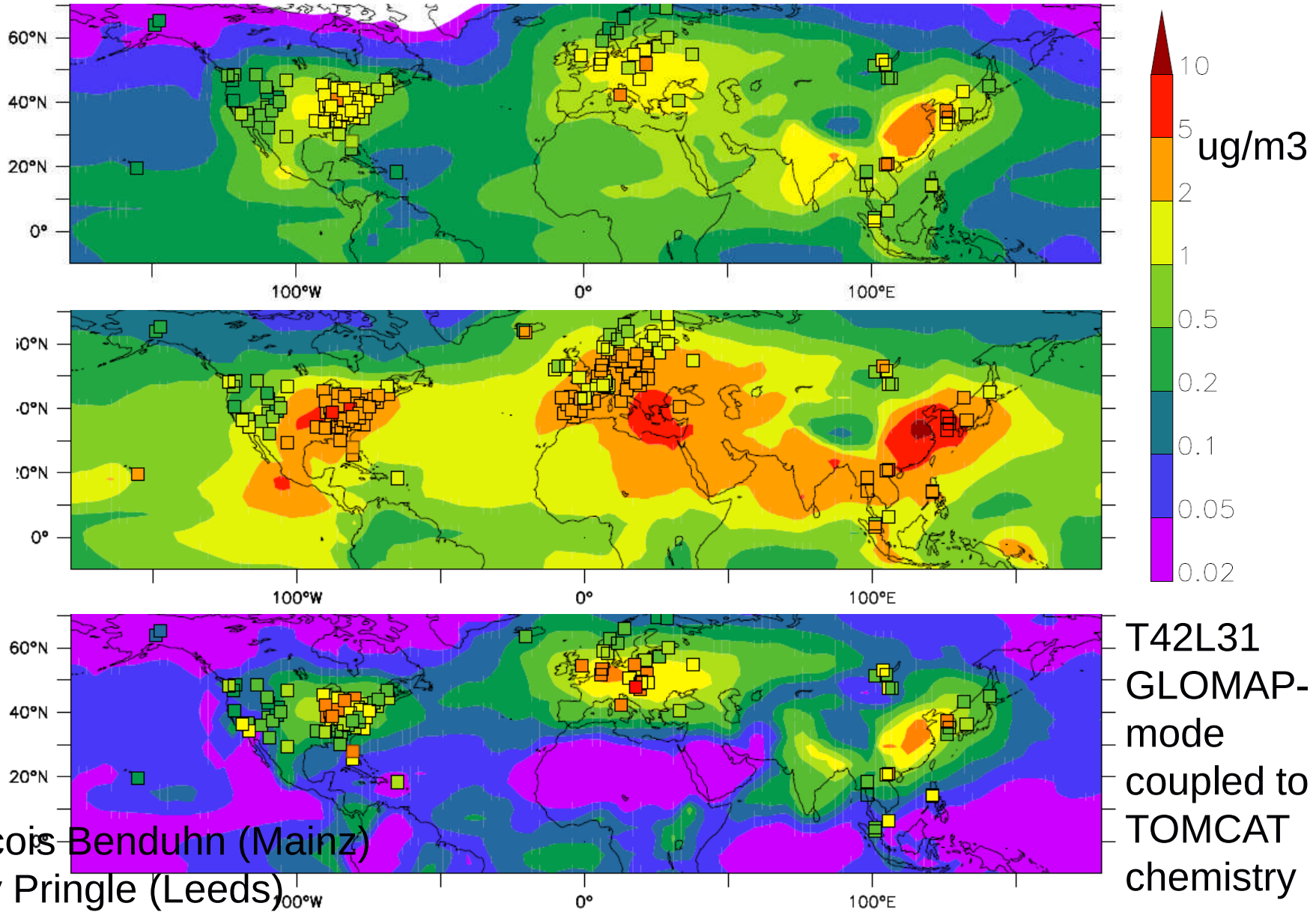

T42L31 GLOMAP-mode coupled to TOMCAT chemistry

Francois Benduhn (Mainz)
Kirsty Pringle (Leeds)

Next: UKCA nested runs
Global → European → UK (or other domains)

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Can now output UKCA tracers from global runs as lateral boundary conditions to initialise limited-area model simulations for regional simulations

Applications for dust forecasting, air-quality, aerosol-cloud interactions, regional composition-climate modelling

Future UKCA aerosol applications

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Air Quality-Climate Interactions

Future model developments will include nitrate aerosol

Can also nest to higher resolution in regional domains to allow detailed studies of changing air quality with climate change

Leading role for UKCA in the EU IP Pan European Gas-Aerosol Interaction Study (PEGASOS)

Aerosol impacts on NWP and aerosol-cloud interactions

Inclusion of dust into operational NWP greatly reduced SW/LW radiation biases.

Building capability to apply UKCA-MODE at convection-permitting resolution.

Also, UKCA-MODE scheme being implemented in ECMWF IFS.

Composition-dynamics interactions

Whole-atmosphere chemistry-aerosol in HadGEM allows simulation of changes in large-scale dynamics from changes in composition and vice versa.

Polar stratospheric clouds in the composition-climate model.

Improved PSCs with mountain-wave parameterization & NAT growth & sedimentation