Evaluation of Earth System Models*

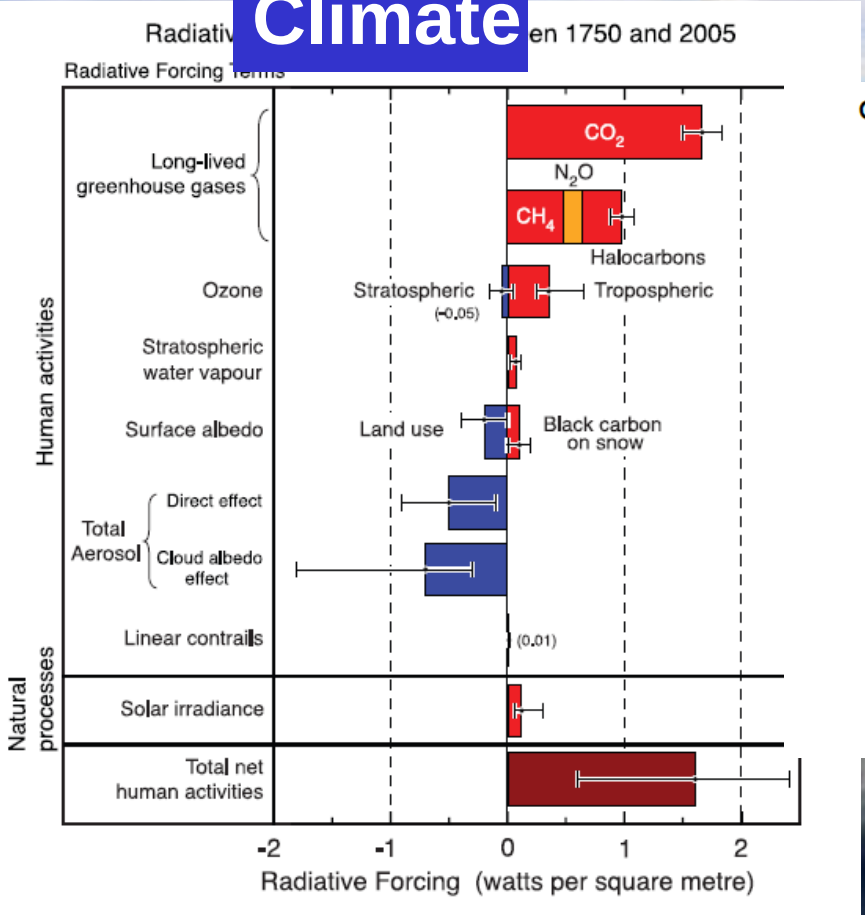
Dominick Spracklen
University of Leeds

Please ask questions as we go along.....there is no such thing as a "stupid question"!

*apologies for heavy bias to the work of my group

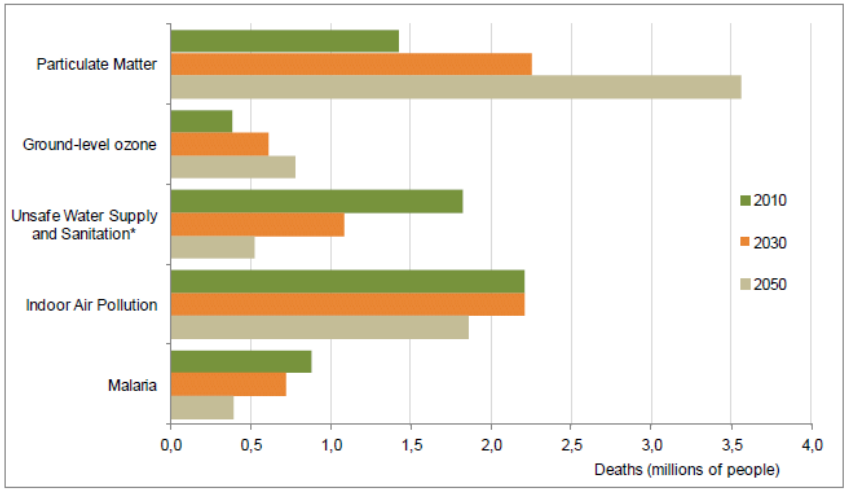
The need for Earth System Models to understand atmospheric composition

Climate



Human Health

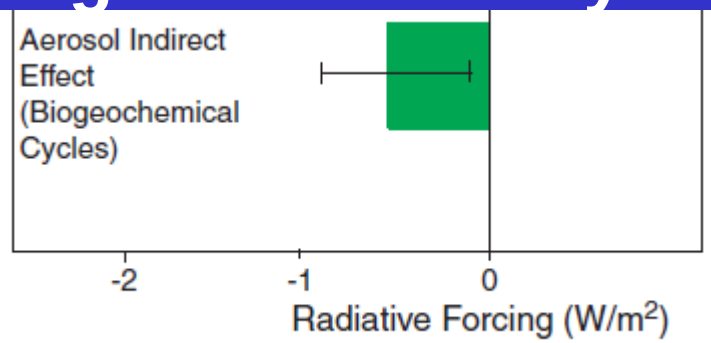
Global premature deaths from selected environmental risks: *Baseline*, 2010 to 2050



Note: * Child mortality only.

Source: *OECD Environmental Outlook Baseline*; output from IMAGE.

Biogeochemical cycles



Some general pointers on model evaluation

UNIVERSITY OF LEEDS

Evaluation rather than ***Validation***

Avoid using model does a “good job”, “model compares well”, “model in reasonable agreement” .....

Where possible make comparisons ***quantitative***

Go beyond model bench marking

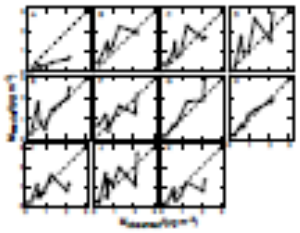
Comparison with observations should help improve our understanding of **processes** in the atmosphere

How do we quantify model-observation agreement? : Metrics

UNIVERSITY OF LEEDS

❑Test of Metrics (Continued) :11 models for nss-SO_4^{2-}

Models	A	B	C	D	E	F	G	H	I	J	K	L	M	N
$\overline{O}$	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
$\overline{M}$	0.35	1.37	1.19	1.34	1.22	1.16	1.19	1.02	0.79	1.23	0.67	0.00	1.96	+∞
N	9	9	9	9	9	9	9	9	9	9	9	9	9	9
r	0.959	0.840	0.737	0.777	0.839	0.769	0.953	0.977	0.609	0.692	0.767	0.00	1.00	0.00
Difference														
B_{MB}	-0.63	0.40	0.21	0.37	0.24	0.18	0.21	0.05	-0.19	0.25	-0.31	-0.98	+0.98	+∞
E_{MAGE}	0.63	0.46	0.42	0.52	0.34	0.42	0.24	0.14	0.42	0.52	0.41	0.98	+0.98	+∞
E_{RMSE}	0.79	0.55	0.52	0.70	0.49	0.48	0.37	0.16	0.58	0.63	0.55	0.98	+0.98	+∞
Relative Difference														
B_{MNB}	-0.65	1.23	0.91	0.38	0.70	1.40	0.34	0.33	0.19	0.75	-0.06	-1.00	+1.00	+∞
E_{MNGE}	0.65	1.26	1.01	0.60	0.80	1.58	0.39	0.39	0.59	0.94	0.52	1.00	+1.00	+∞
B_{NMB}	-0.64	0.41	0.22	0.38	0.25	0.18	0.21	0.05	-0.20	0.26	-0.32	-1.00	+1.00	+∞
E_{NME}	0.64	0.47	0.43	0.53	0.34	0.43	0.25	0.15	0.44	0.53	0.42	1.00	+1.00	+∞
B_{FB}	-1.00	0.53	0.37	0.16	0.30	0.35	0.22	0.16	-0.04	0.30	-0.24	-2.00	+0.67	+∞
E_{FGE}	1.00	0.56	0.48	0.45	0.43	0.56	0.27	0.24	0.47	0.53	0.53	2.00	+0.67	+∞
B_{NMBF}	-1.80	0.41	0.22	0.38	0.25	0.18	0.21	0.05	-0.24	0.26	-0.46	-∞	+1.00	+∞
E_{NMEF}	1.80	0.47	0.43	0.53	0.34	0.43	0.25	0.15	0.54	0.53	0.61	+∞	+1.00	+∞



- Model H: best; Model A: worst
- Models E, G, H: acceptable

If criteria: ±25% (B_{NMBF}), 35% (E_{NMEF})

[slide: courtesy S. Yu]

Difficulties evaluating atmospheric composition in Earth System Models

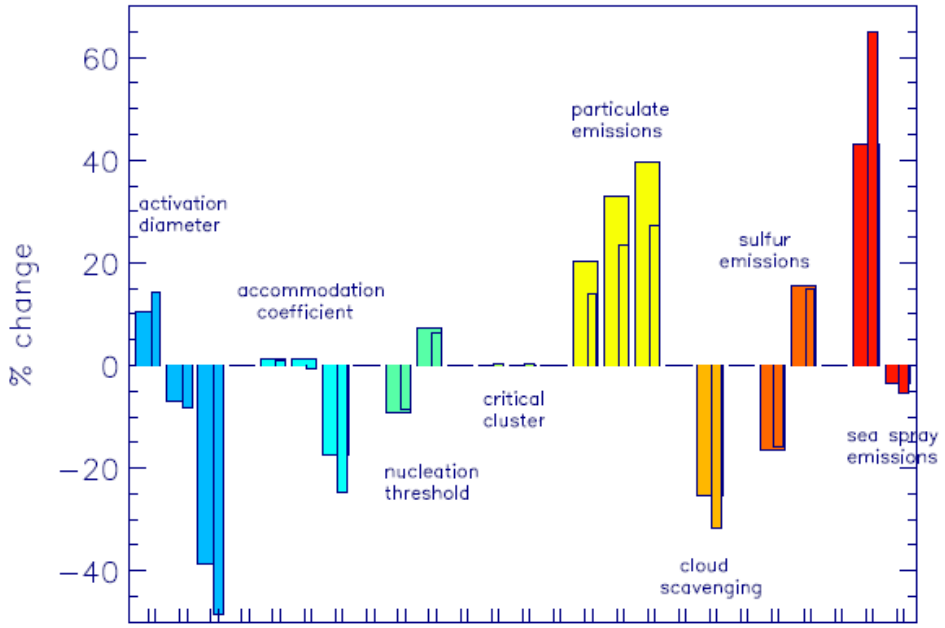
UNIVERSITY OF LEEDS

- Sparse observations (mostly surface or column, some aircraft, satellite)
- Errors in meteorology (GCM: doesn't use 'real' meteorology)
- Resolution
- Sub-grid processes
- Compensating errors (e.g., emissions vs removal)
- Representativeness of observations
  - "Special objectives" of "mission" observations introduces bias
- Temporal processes rarely observed (e.g., nucleation, growth, scavenging)

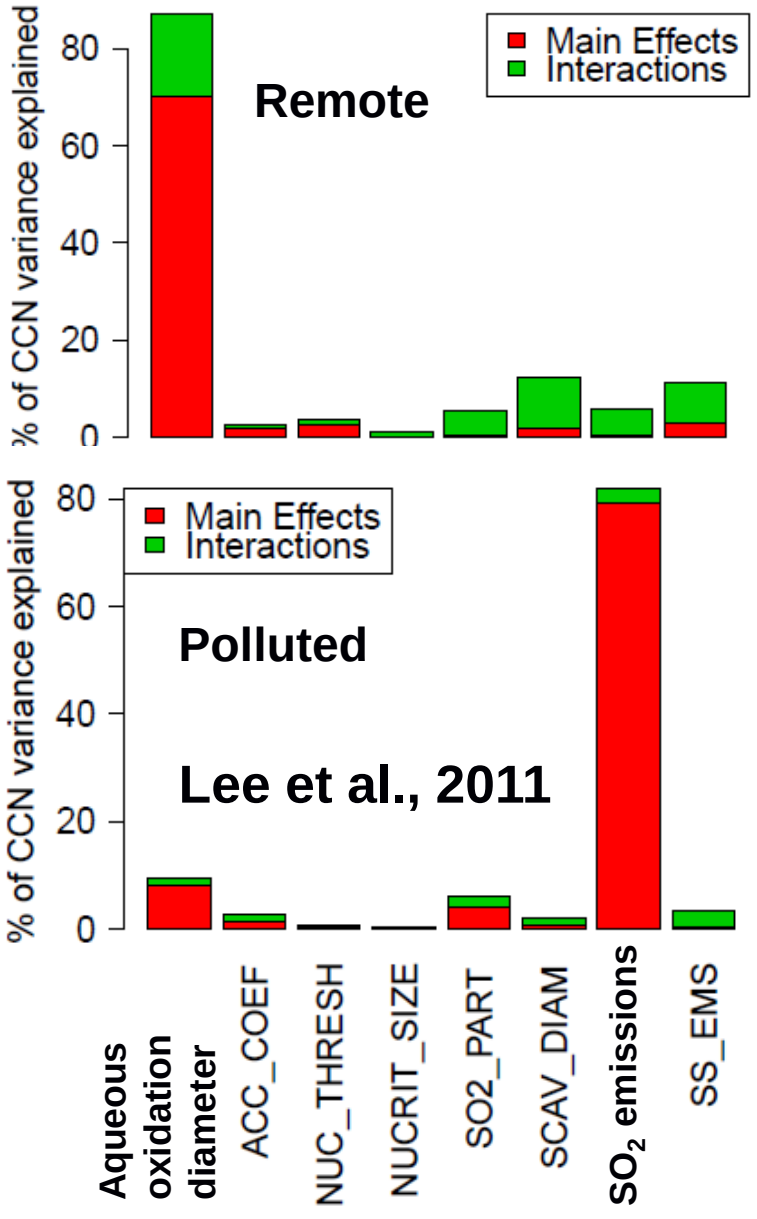
Uncertainty analysis to determine sensitivity of model diagnostics to different processes

UNIVERSITY OF LEEDS

CCN sensitivity

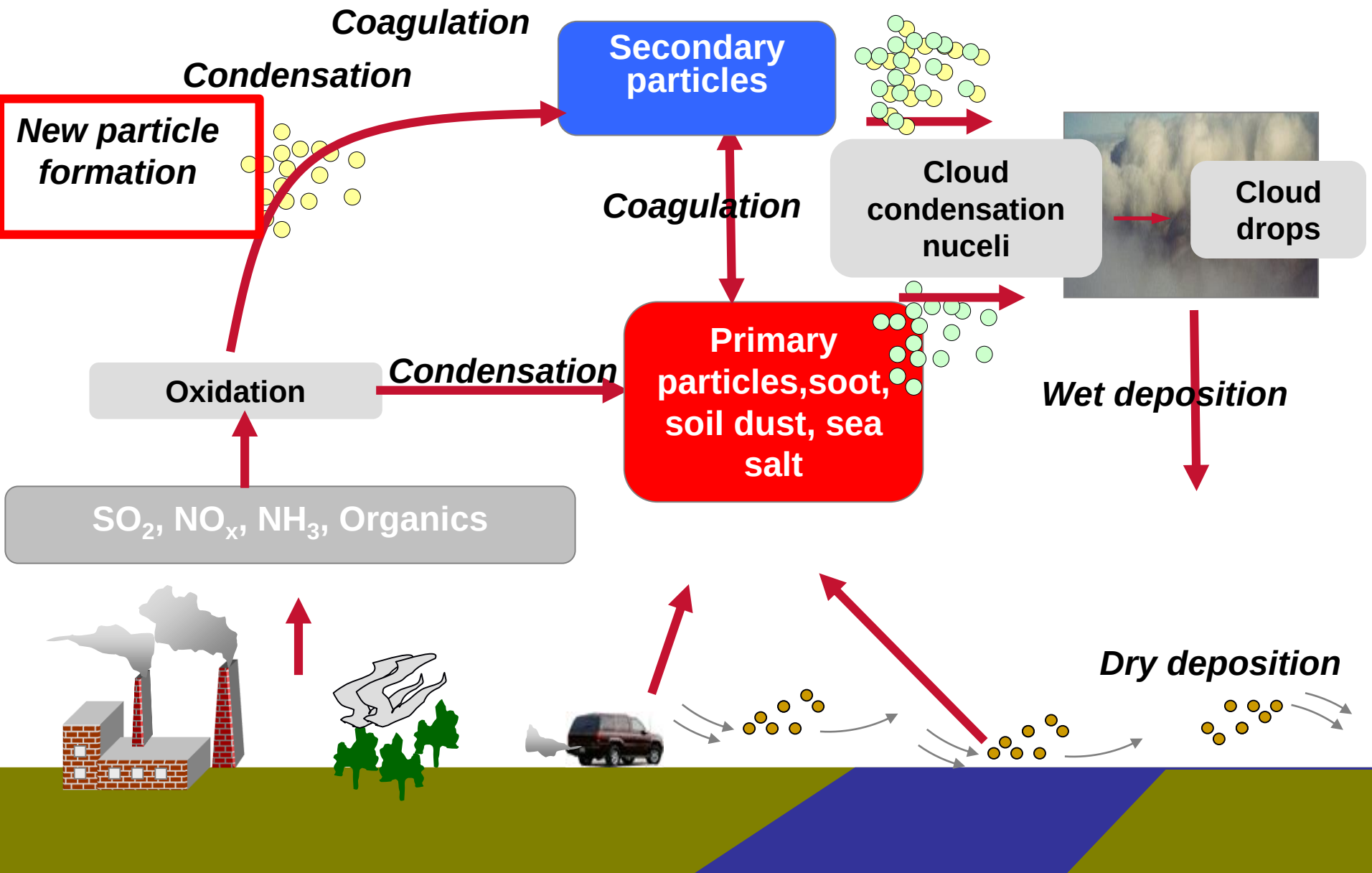


Spracklen et al., 2005

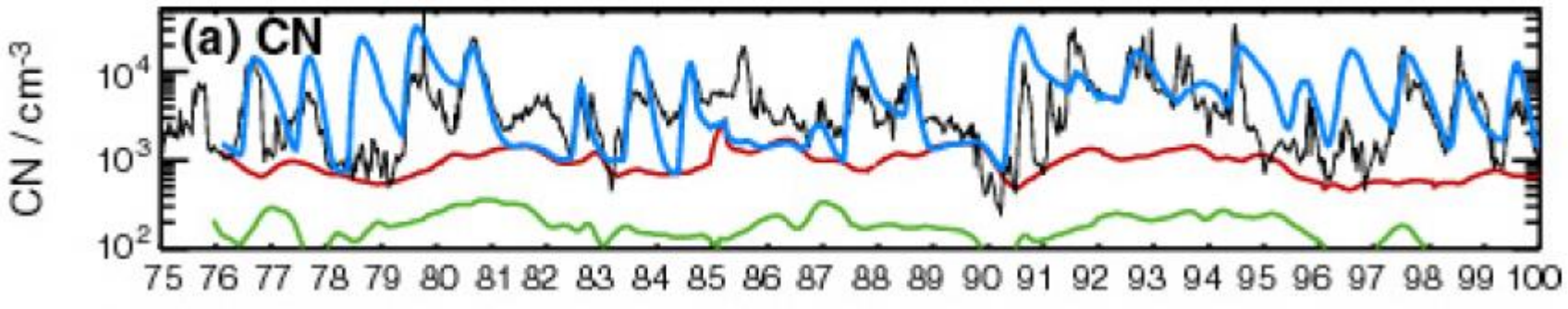


Aerosol sources and processes: New particle formation

UNIVERSITY OF LEEDS



Evaluating particle formation mechanisms in a global model



Observations

Model

- **Binary Homogeneous Nucleation (BHN)**
- **BHN + Primary particle**
- **BHN + Primary particles + Boundary Layer Nucleation (BLN)**

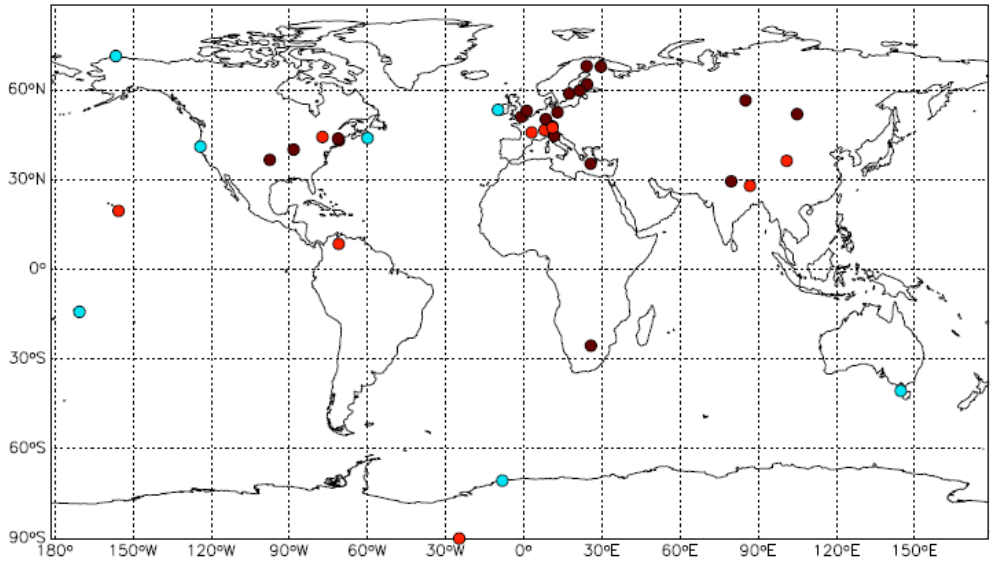
BLN Formation rate of 1 nm particles: $J_1 = A\,[H_2SO_4]$

Spracklen et al., ACP, 2006

UNIVERSITY OF LEEDS

Synthesis of observations of total particle number concentration

Locations of total particle number observations



Crucial importance of those making observations – involve early in analysis and acknowledge with co-authorship when appropriate

Spracklen et al., ACP, 2010

Atmos. Chem. Phys., 10, 4775–4793, 2010
www.atmos-chem-phys.net/10/4775/2010/
doi:10.5194/acp-10-4775-2010

Atmospheric Chemistry and Physics

Explaining global surface aerosol number concentrations in terms of primary emissions and particle formation

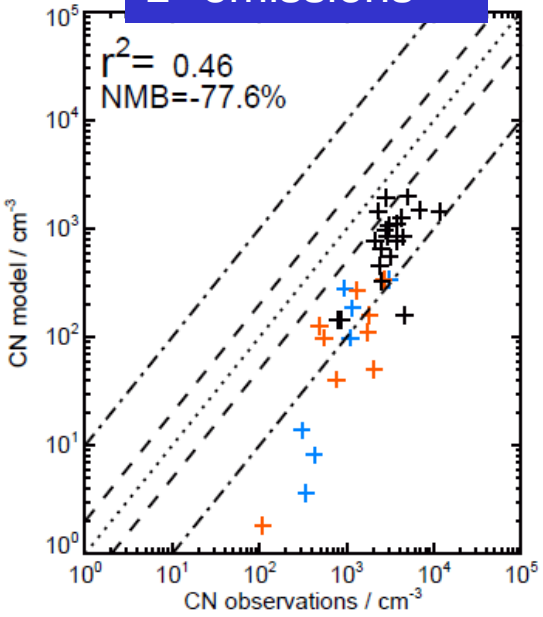
D. V. Spracklen[1], K. S. Carslaw[1], J. Merikanto[1], G. W. Mann[1], C. L. Reddington[1], S. Pickering[1], J. A. Ogren[2], E. Andrews[2], U. Baltensperger[3], E. Weingartner[3], M. Boy[4], M. Kulmala[4], L. Laakso[4], H. Lihavainen[5], N. Kivekäs[5], M. Komppula[5,20], N. Mihalopoulos[6], G. Kouvarakis[6], S. G. Jennings[7], C. O'Dowd[7], W. Birmili[8], A. Wiedensohler[8], R. Weller[9], J. Gras[10], P. Laj[11], K. Sellegri[12], B. Bonn[13], R. Krejci[14], A. Laaksonen[5,15], A. Hamed[15], A. Minikin[16], R. M. Harrison[17], R. Talbot[18], and J. Sun[19]

[1]Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, LS2 9JT, UK
[2]NOAA/ESRL Global Monitoring Division, 325 Broadway R/GMD1, Boulder, Co 80305, USA
[3]Paul Scherrer Institut, Laboratory of Atmospheric Chemistry, 5232 Villigen, Switzerland
[4]Department of Physics, University of Helsinki, 00014 Helsinki, Finland
[5]Climate Change, Finnish Meteorological Institute, P.O. Box 503, 00101, Helsinki, Finland
[6]Department of Chemistry, University of Crete, University campus, P.O. Box 2208, 71003, Voutes, Heraklion, Crete, Greece
[7]Department of Physics, National University of Ireland, Galway, Ireland
[8]Leibniz Institute for Tropospheric Research, Permoserstrasse 15, 04318 Leipzig, Germany
[9]Alfred Wegener Institute, Am Handelshafen 12, 27570 Bremerhaven, Germany
[10]CSIRO Marine and Atmospheric Research, Ctr Australian Weather and Climate Res, Aspendale, Victoria, Australia
[11]Laboratoire de Glaciologie et Géophysique de l'Environnement CNRS/Université Grenoble 1, Grenoble, France
[12]Laboratoire de Météorologie Physique, Université Clermont-Ferrand/ CNRS, Clermont-Ferrand, France
[13]Institute for Atmospheric and Environmental Sciences, J. W. Goethe University, Frankfurt/Main, Germany
[14]Department of Applied Environmental Science (ITM), Stockholm University, 106 91 Stockholm, Sweeden
[15]Department of Physics and Mathematics, University of Eastern Finland, (Kuopio campus), P.O. Box 70211 Kuopio, Finland
[16]Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut fr Physik der Atmosphäre, Oberpfaffenhofen, Germany
[17]National Centre for Atmospheric Science, School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
[18]Climate Change Research Center, University of New Hampshire, Durham, NH 03824 USA
[19]Key Laboratory for Atmospheric Chemistry of CMA, Center for Atmosphere Watch and Services, Chinese Academy of Meteorological Sciences, CMA, Beijing 100081, China
[20]Kuopio Unit, Finnish Meteorological Institute, Kuopio, Finland

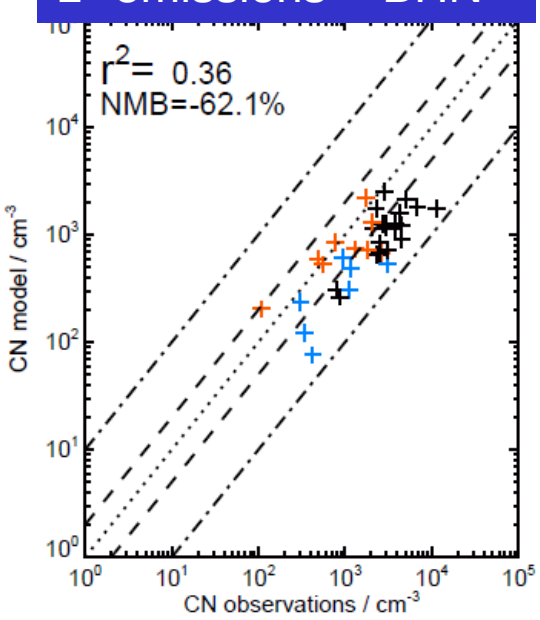
Received: 10 November 2009 – Published in Atmos. Chem. Phys. Discuss.: 10 December 2009
Revised: 3 May 2010 – Accepted: 17 May 2010 – Published: 26 May 2010

Model evaluation to elucidate importance of different processes for total particle number

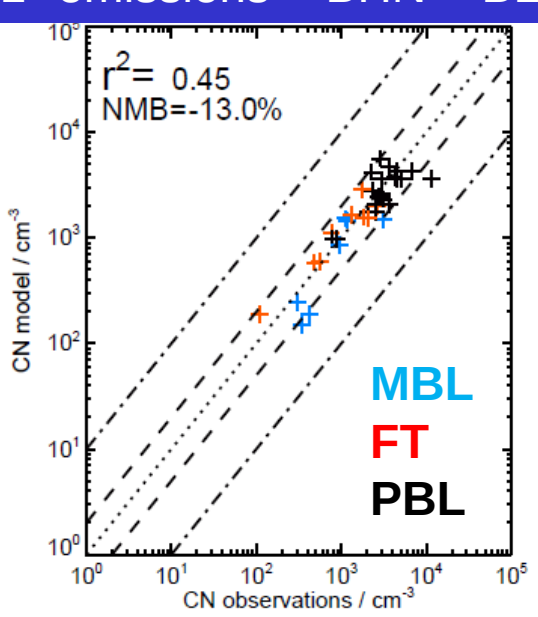
1º emissions



1º emissions + BHN



1º emissions + BHN + BLN



Spracklen et al., ACP, 2010

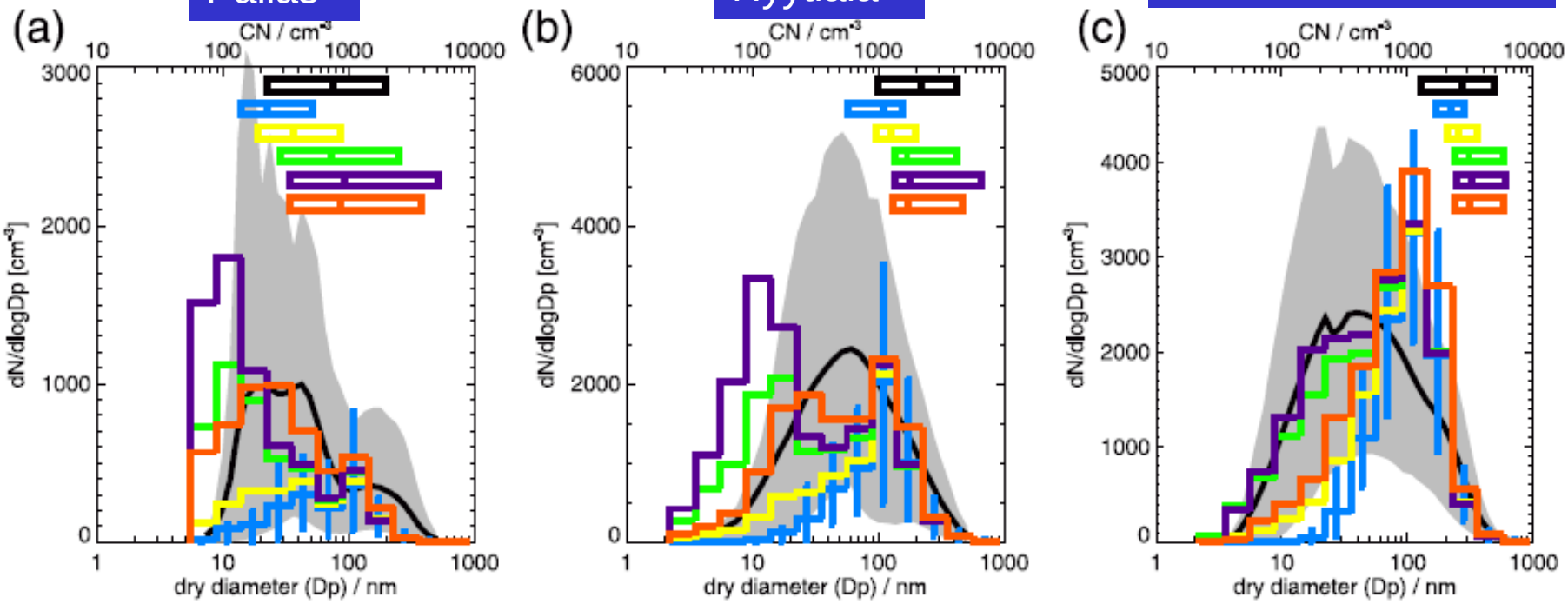
UNIVERSITY OF LEEDS

Particle formation, particle growth and cloud condensation nuclei

Pallas

Hyytiala

Hohenpeissenberg



Observations

BHN

BHN+BLN(A=2e-8s^{-1})

BHN+BLN (A=2e-7s^{-1})

BHN+BLN(A=2e-6s^{-1})

BHN+BLN(A=2e-6s^{-1}) ; SOAx5

BLN

Formation rate of 1 nm particles:

$J_1 = A\,[H_2SO_4]$

Spracklen et al., GRL, 2008

UNIVERSITY OF LEEDS

Use the evaluated model to estimate the importance of particle formation

Careful design of model experiments required

Combinations of model experiments were carried out to obtain the relative contribution from primary particles (PR), upper tropospheric nucleation (UTN), and boundary layer nucleation (BLN) to particle number concentrations:

1. PR: Runs with only primary particles from particulate emissions with and without ultrafine sea-salt. We can calculate the contribution of ultrafine sea-salt to CN and CCN from these runs.

2. PR+UTN: Runs with particulate emissions (without ultrafine sea-salt) and UTN represented with the BHN (Kulmala et al., 1998) nucleation parameterization.

3. PR+UTN+BLN: Runs with particulate emissions (without ultrafine sea-salt), UTN represented with BHN (Kulmala et al., 1998), and BLN represented by the activation nucleation parameterization (Kulmala et al., 2006).

These simulations were carried out by running the model over the full year 2000 with 3-month spin-ups.

Primary particles only

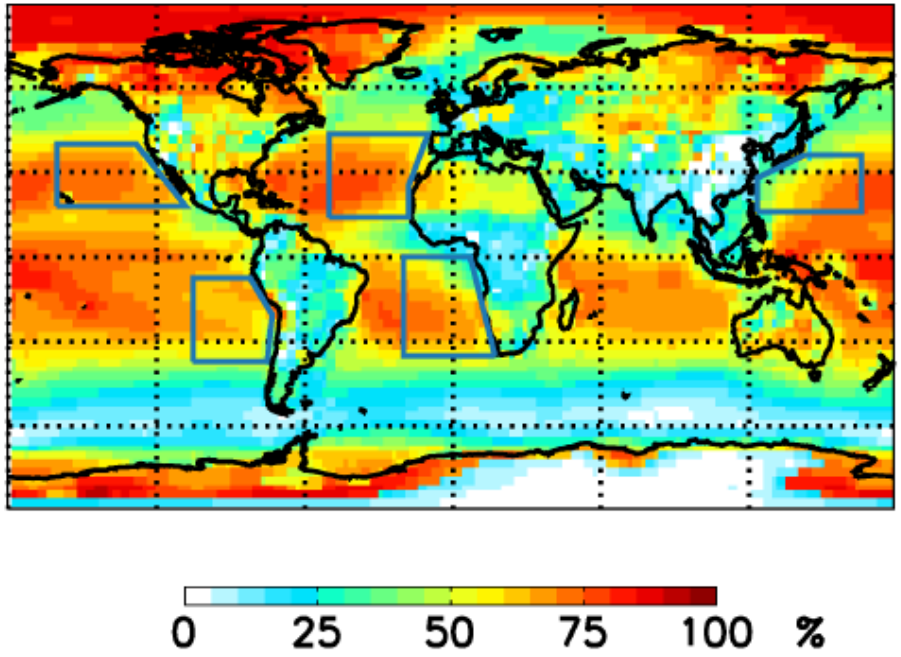
Primary particles + Binary homogeneous nucleation (BHN or UTN)

ALL = Primary particles + BHN + Boundary Layer Nucleation (BLN)

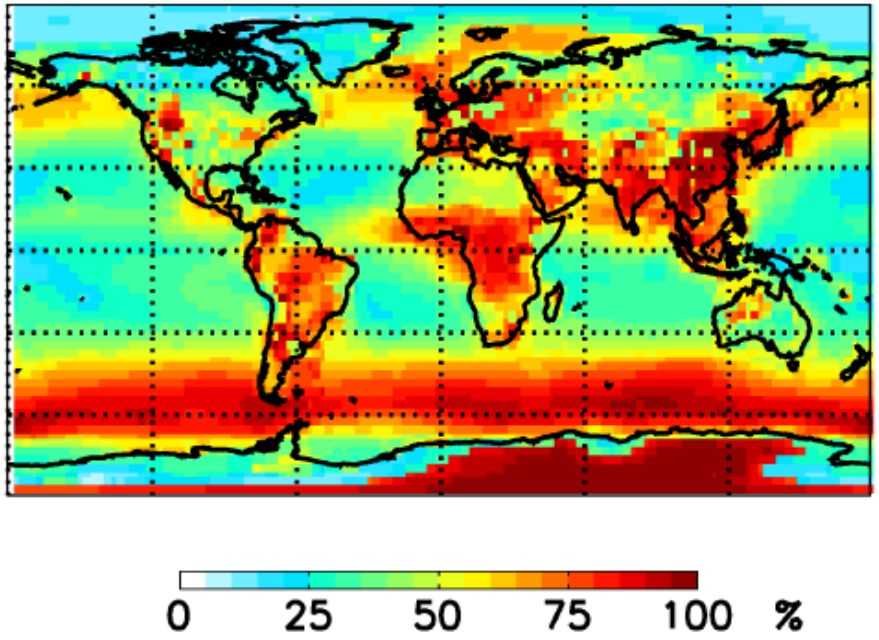
Merikanto et al., ACP, 2009

Particle formation accounts for ~50% of global CCN number

Fraction of CCN from particle formation (gas-to-particle formation)



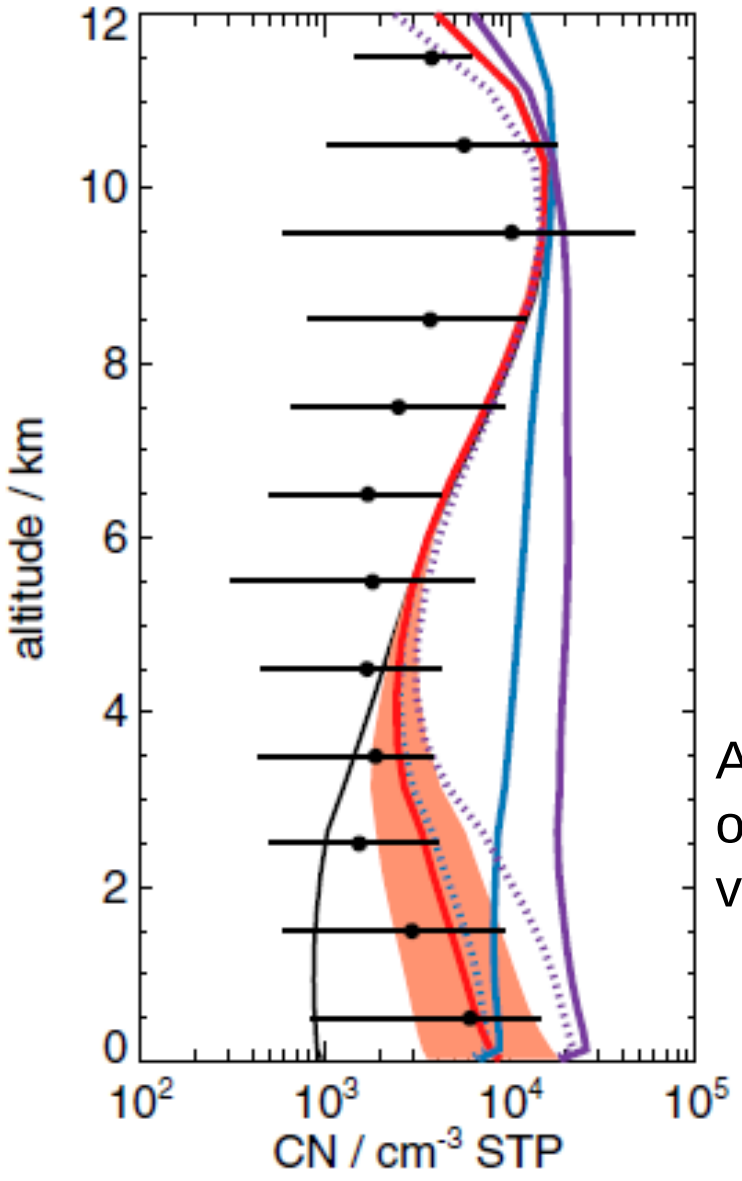
Fraction of CCN from primary particle emissions



Merikanto et al., ACP, 2009

UNIVERSITY OF LEEDS

Evidence from ambient observations for a role of organics in particle formation



Observations

Binary Homogeneous nucleation

$J=A[H_2SO_4]$

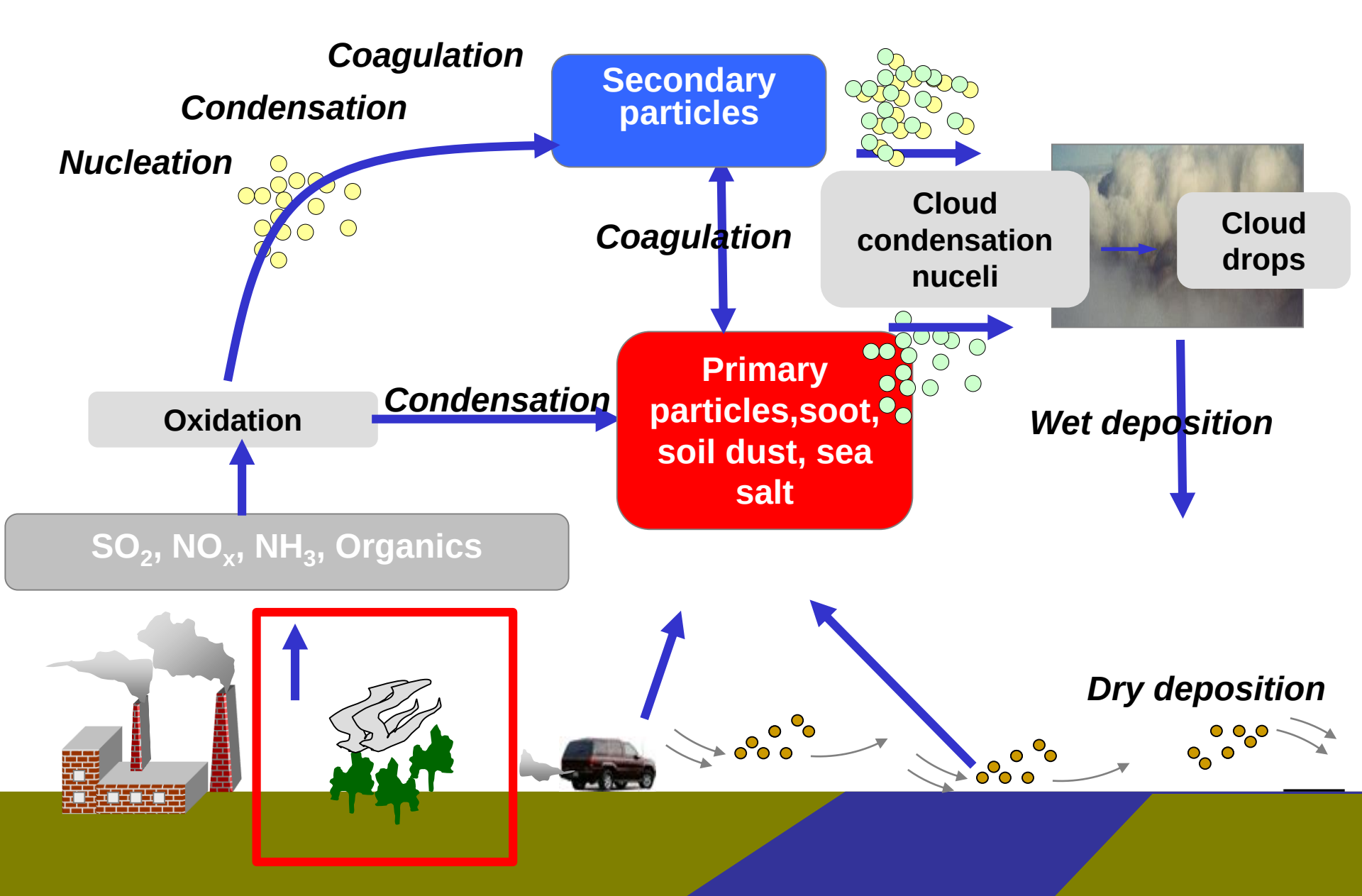
$J=k[H_2SO_4]^2$

$J=k[H_2SO_4][oxorg]$

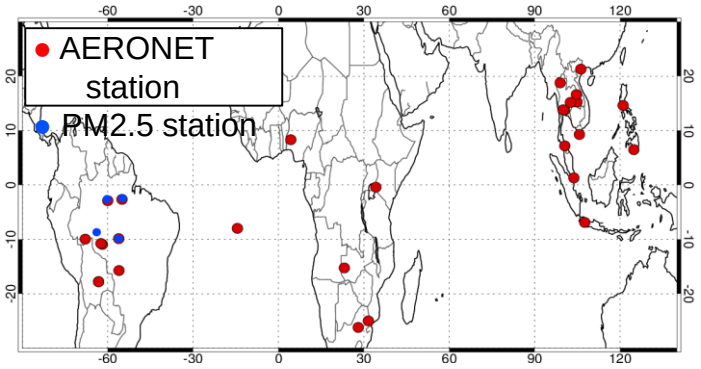
A particle formation mechanism including organics results in better representation of vertical profiles of aerosol number

Metzger et al., PNAS, 2010

Aerosol sources and processes: Biomass burning

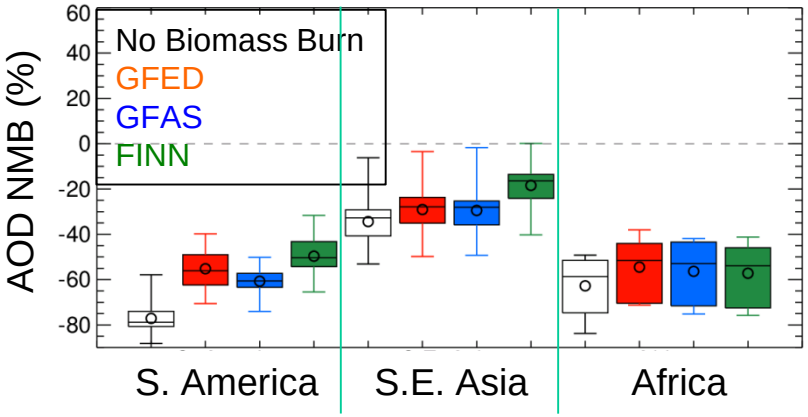


Impacts of tropical biomass burning on surface air quality (PM2.5)

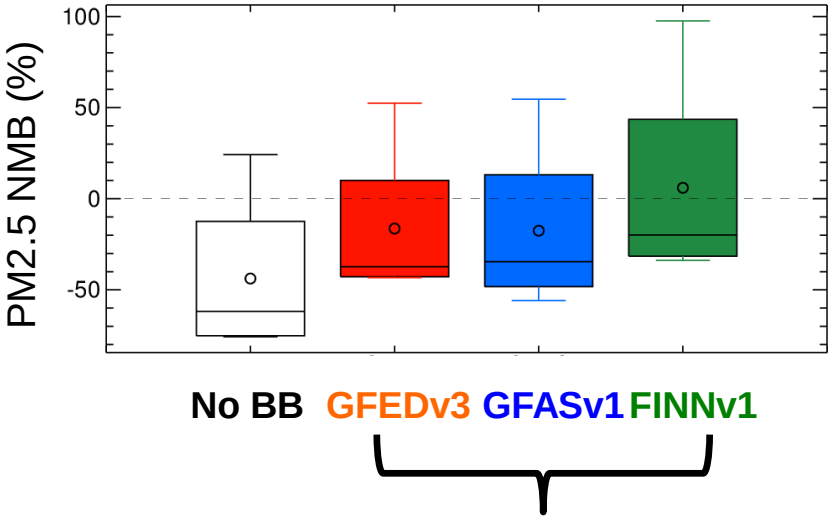


Aerosol optical depth (AOD) underestimated.
Surface PM2.5 in Amazonia is well simulated

Normalised mean bias for AOD at (440 nm)



Normalised mean bias for PM2.5



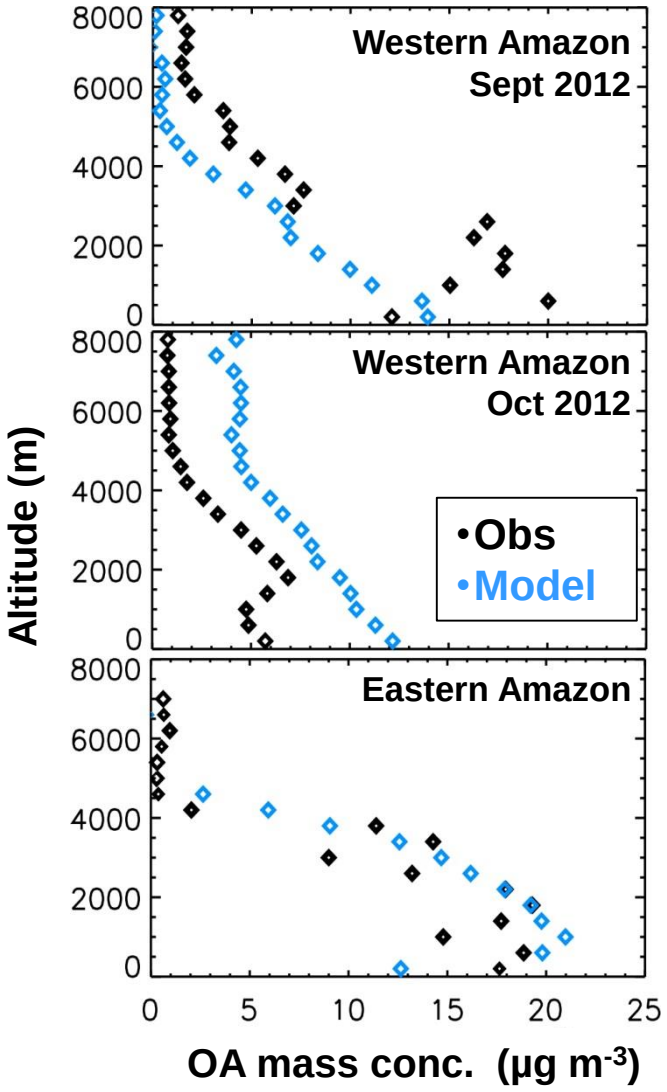
Kaiser et al., 2012; Marlier et al., 2012; Tosca et al., 2013

PM2.5 observations c/o Paulo Artaxo

UNIVERSITY OF LEEDS

Aerosol profiles over the Amazon provide additional evidence of model performance

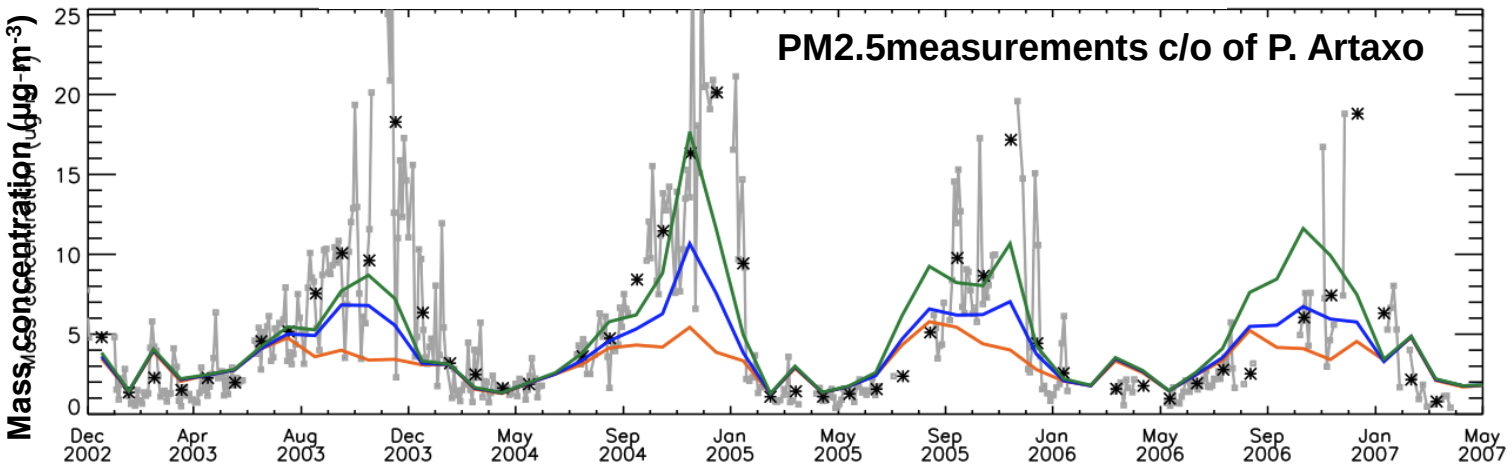
AMS observations during SAMBBA



Observations c/o Will Morgan

Issues with emissions: biomass burning emissions from satellite

Total PM2.5 at Santarem NE Amazon

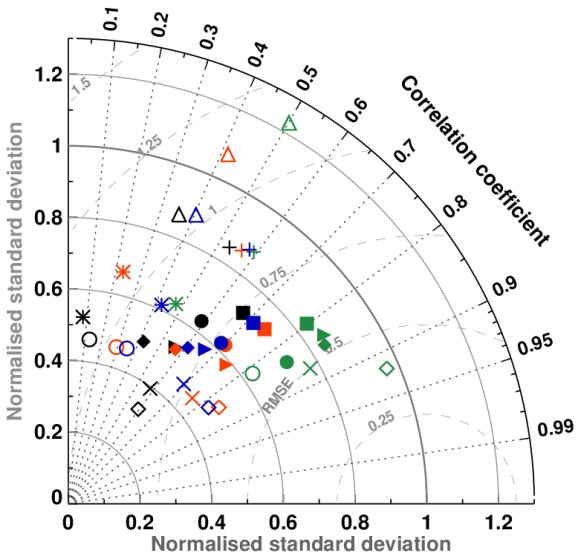


observations (raw data)
observations (monthly mean)

FINN
GFAS
GFED

Aerosol Optical Depth in SE Asia

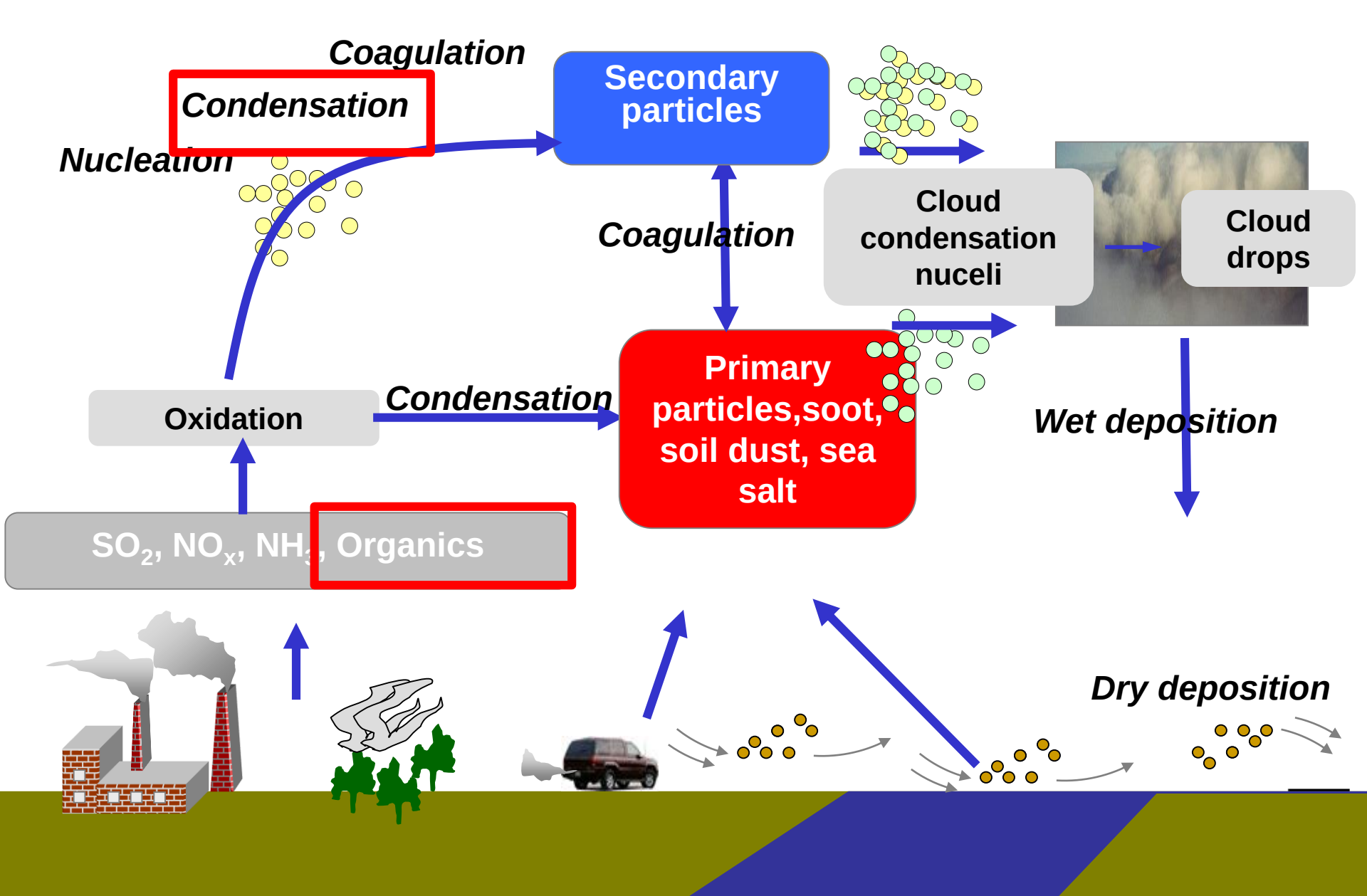
No fire
FINN
GFAS
GFED



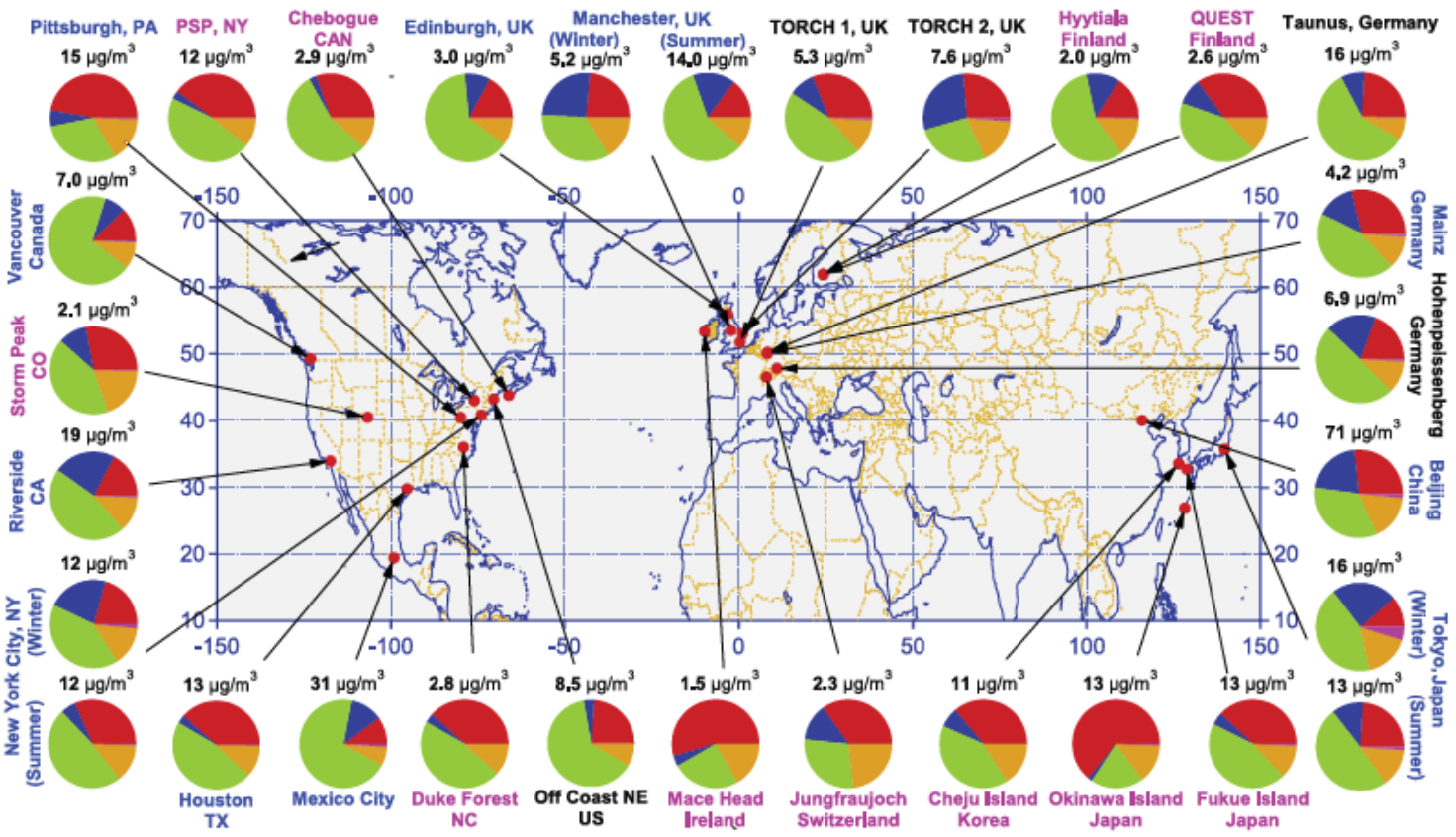
Fire emissions from FINN give better model performance than GFED and GFAS particularly in regions with small fires.

UNIVERSITY OF LEEDS

Aerosol sources and processes: Secondary organic aerosol formation



Organic aerosol is dominant in the atmosphere – but sources are very poorly understood

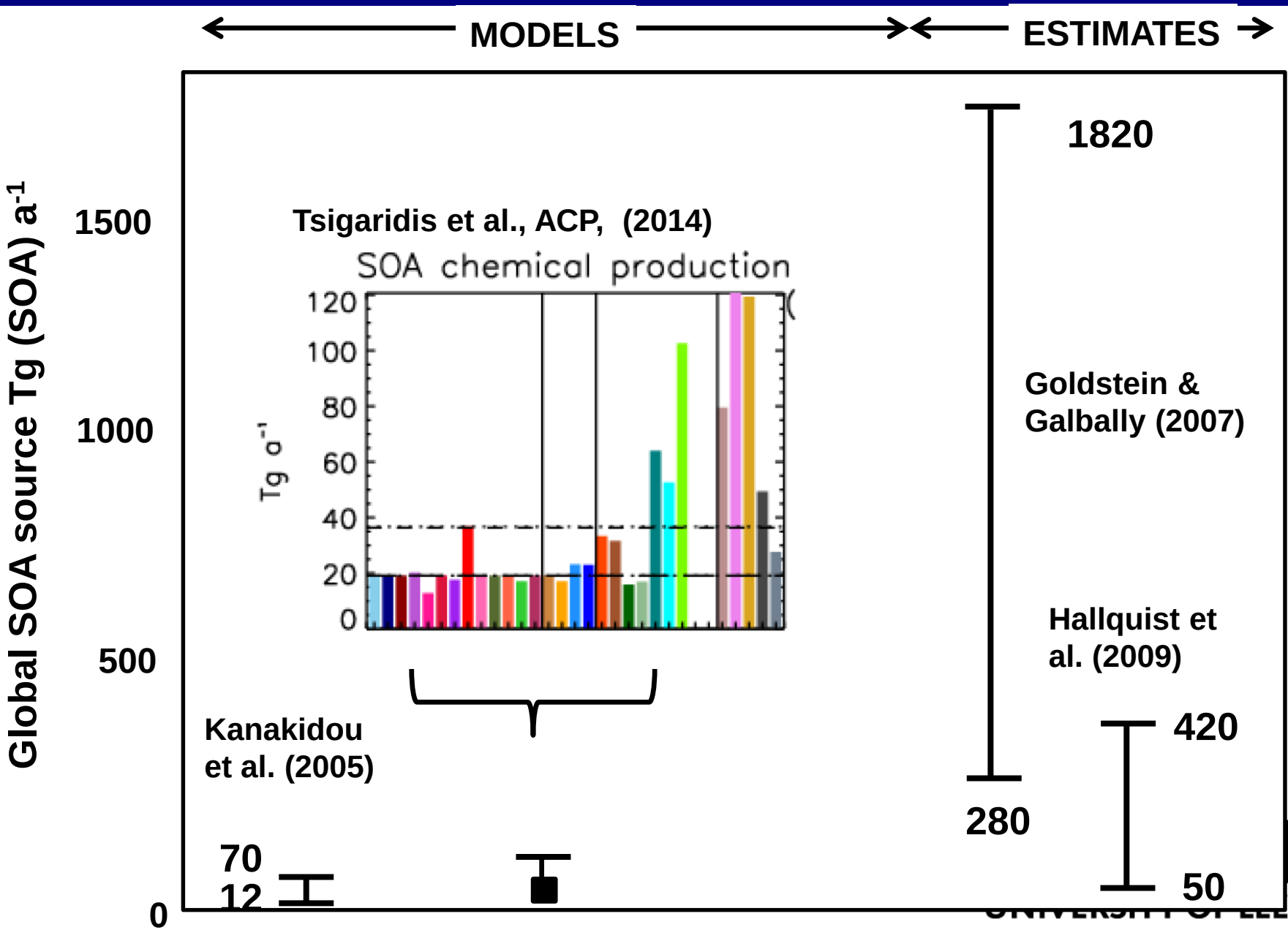


Sulfate **Organics** **Nitrate** **Ammonium**

Zhang et al., GRL, 2007

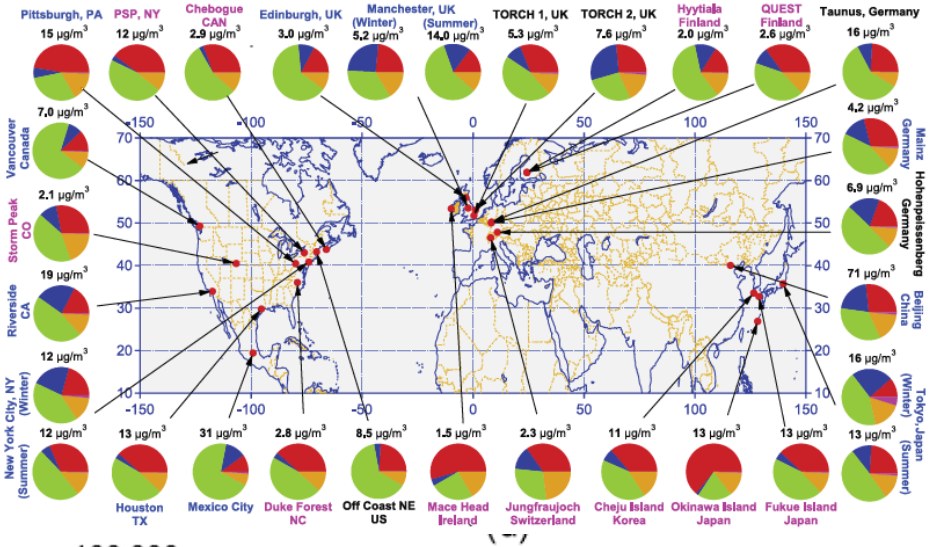
UNIVERSITY OF LEEDS

Global budget of secondary organic aerosol (SOA) is particularly uncertain

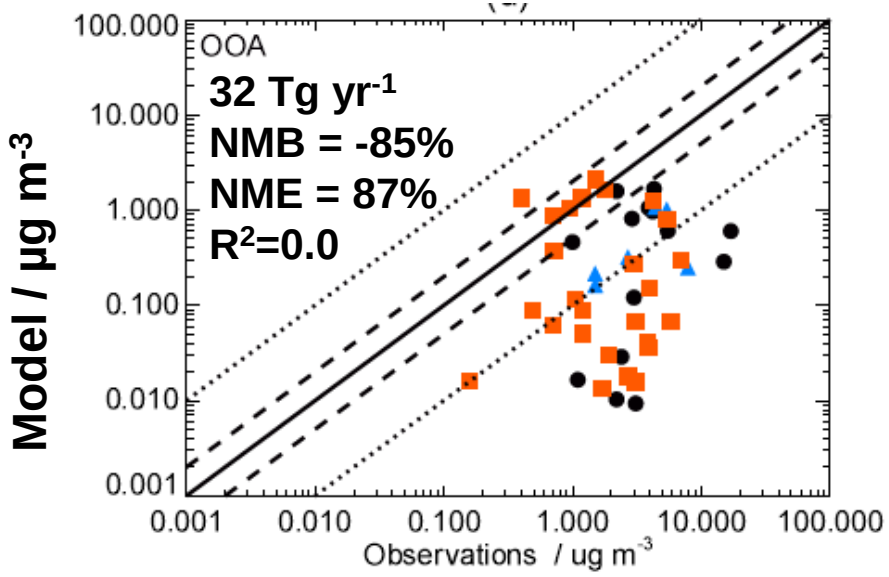


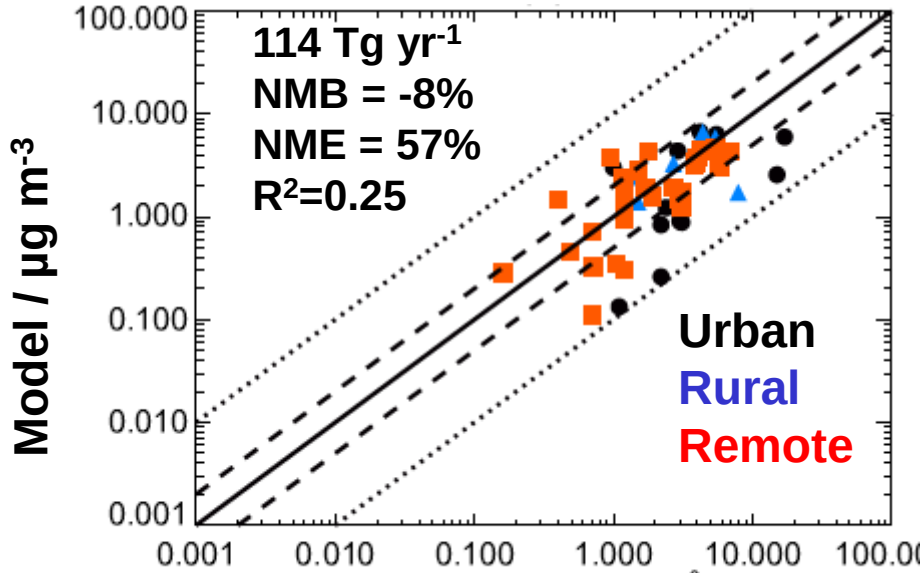
Understanding sources and formation of SOA

AMS observations



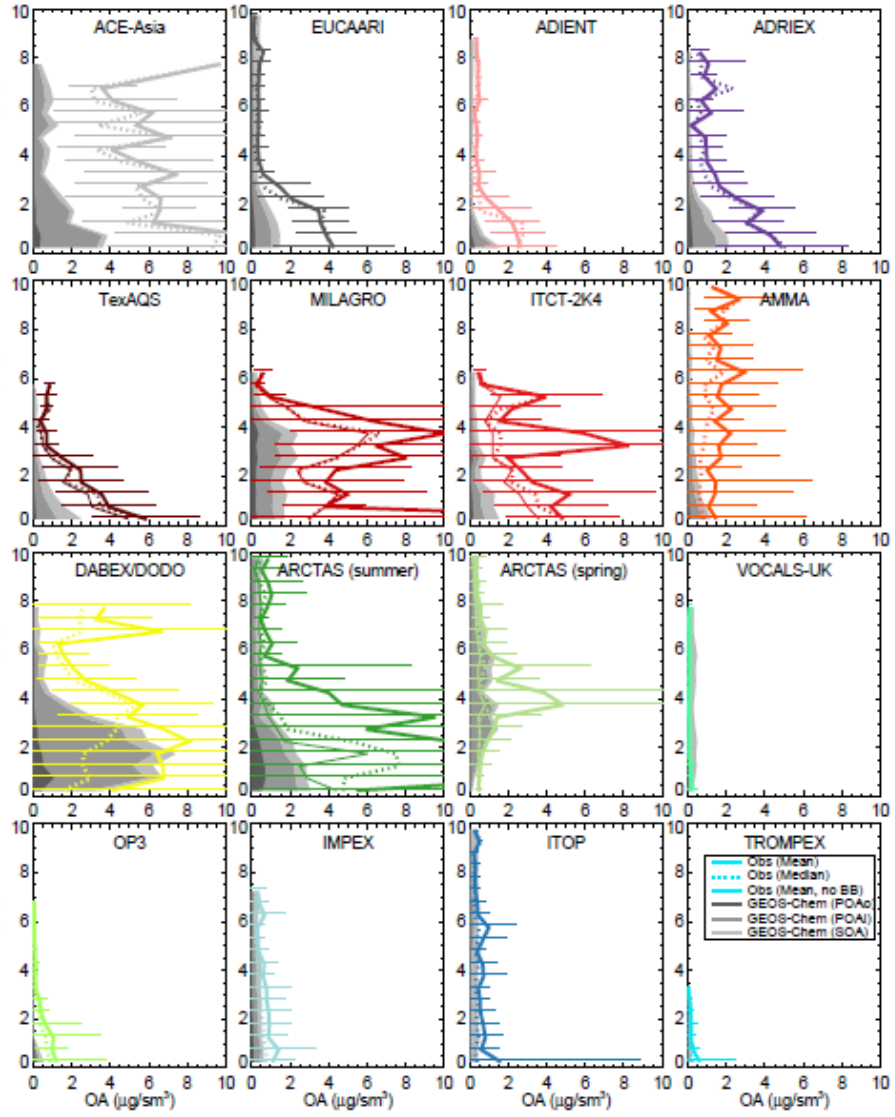
GLOMAP model with ~100 Tg a^{-1}
SOA source matches surface AMS observations



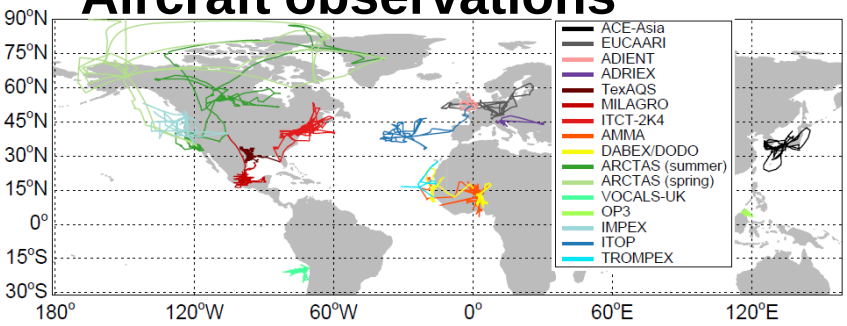


Spracklen et al., ACP, 2011

Using aircraft observations – standard model underestimates organic aerosol



Aircraft observations

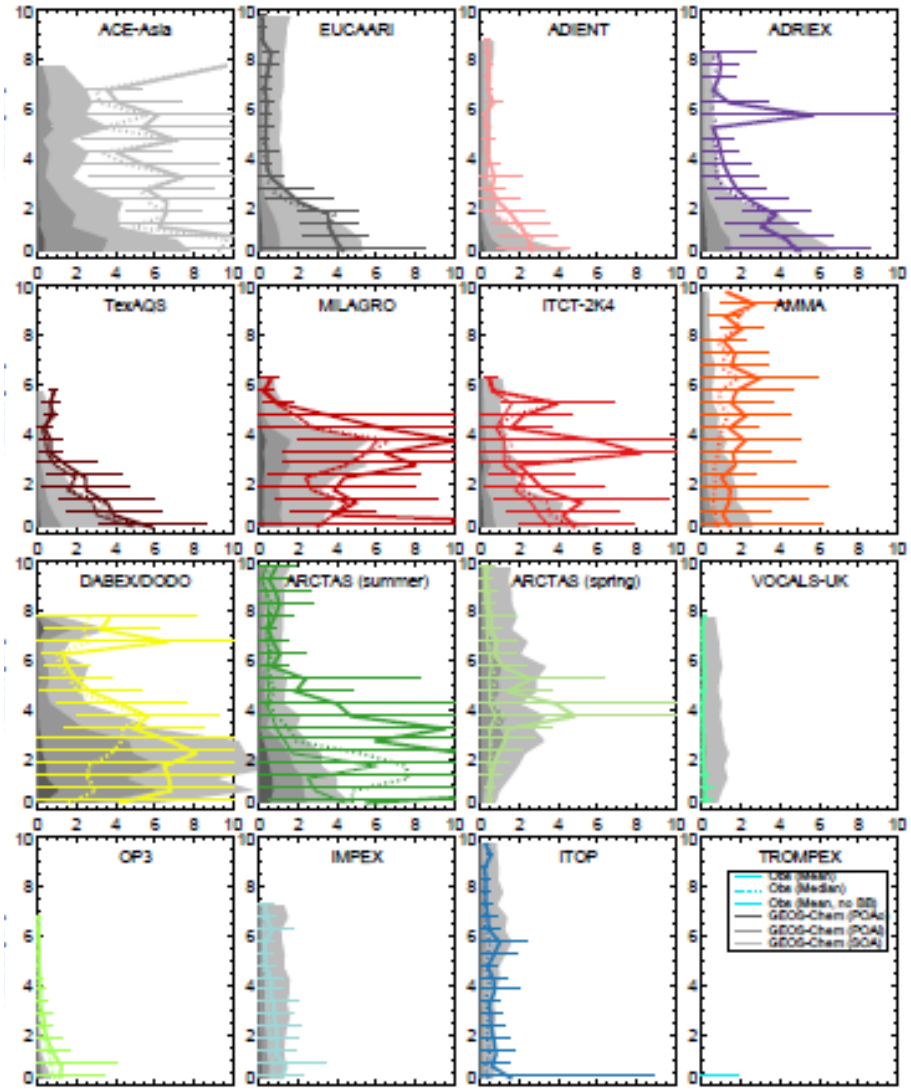


GEOS-CHEM Model
26 Tg SOA a^{-1}

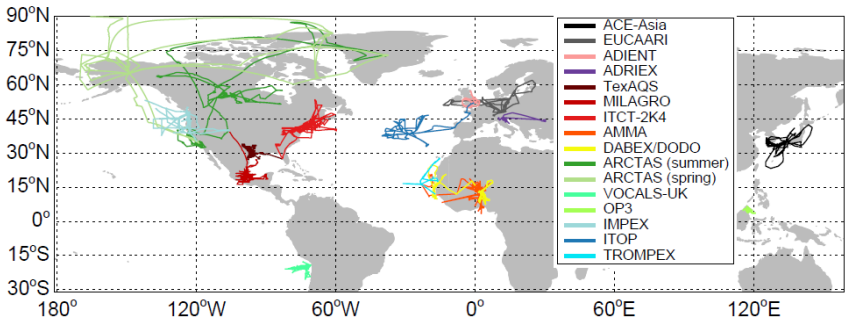
Heald et al., 2011

UNIVERSITY OF LEEDS

Understanding sources and formation of SOA



Aircraft observations



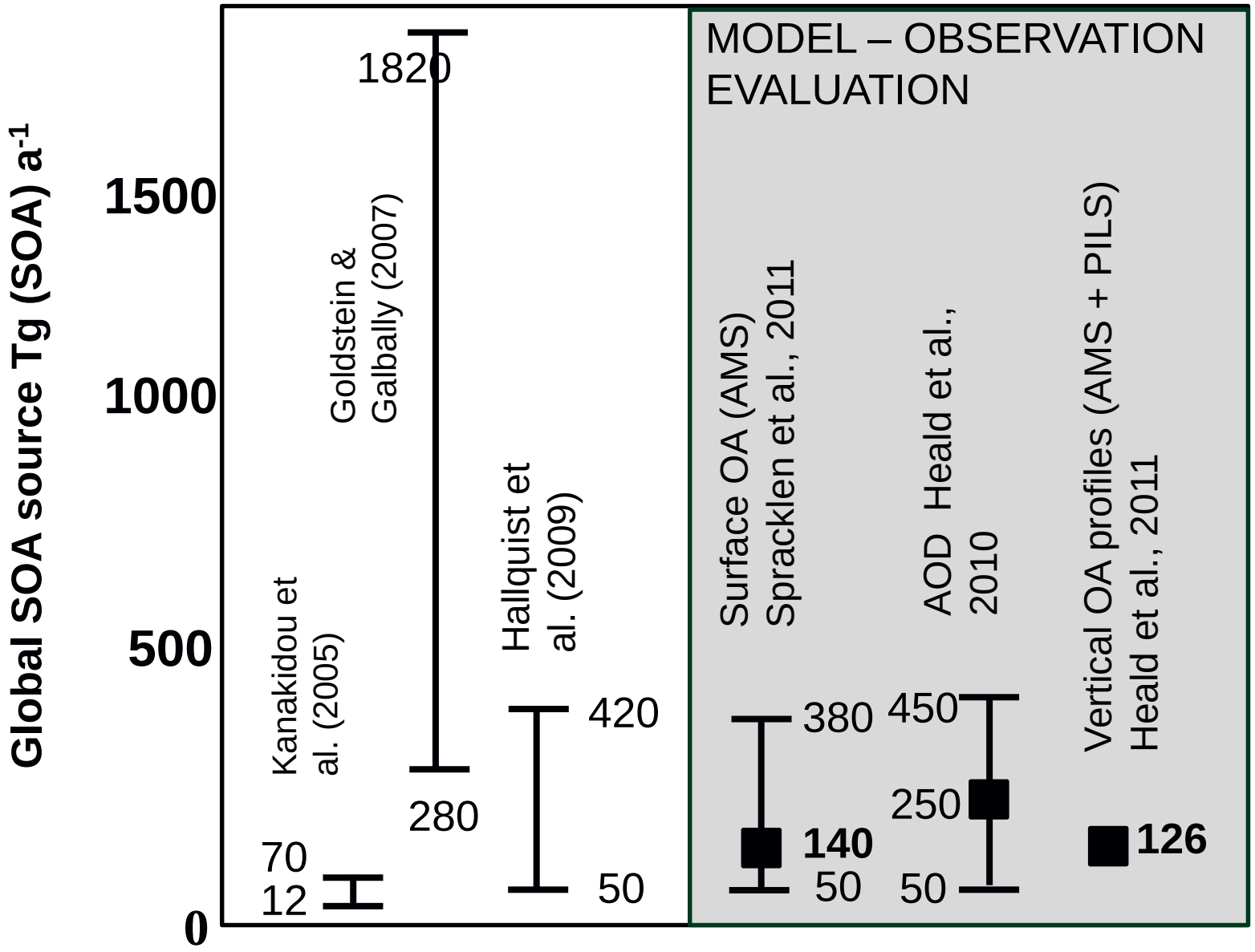
GEOS-CHEM Model
Increased SOA source:
126 Tg SOA a^{-1}

Heald et al., 2011

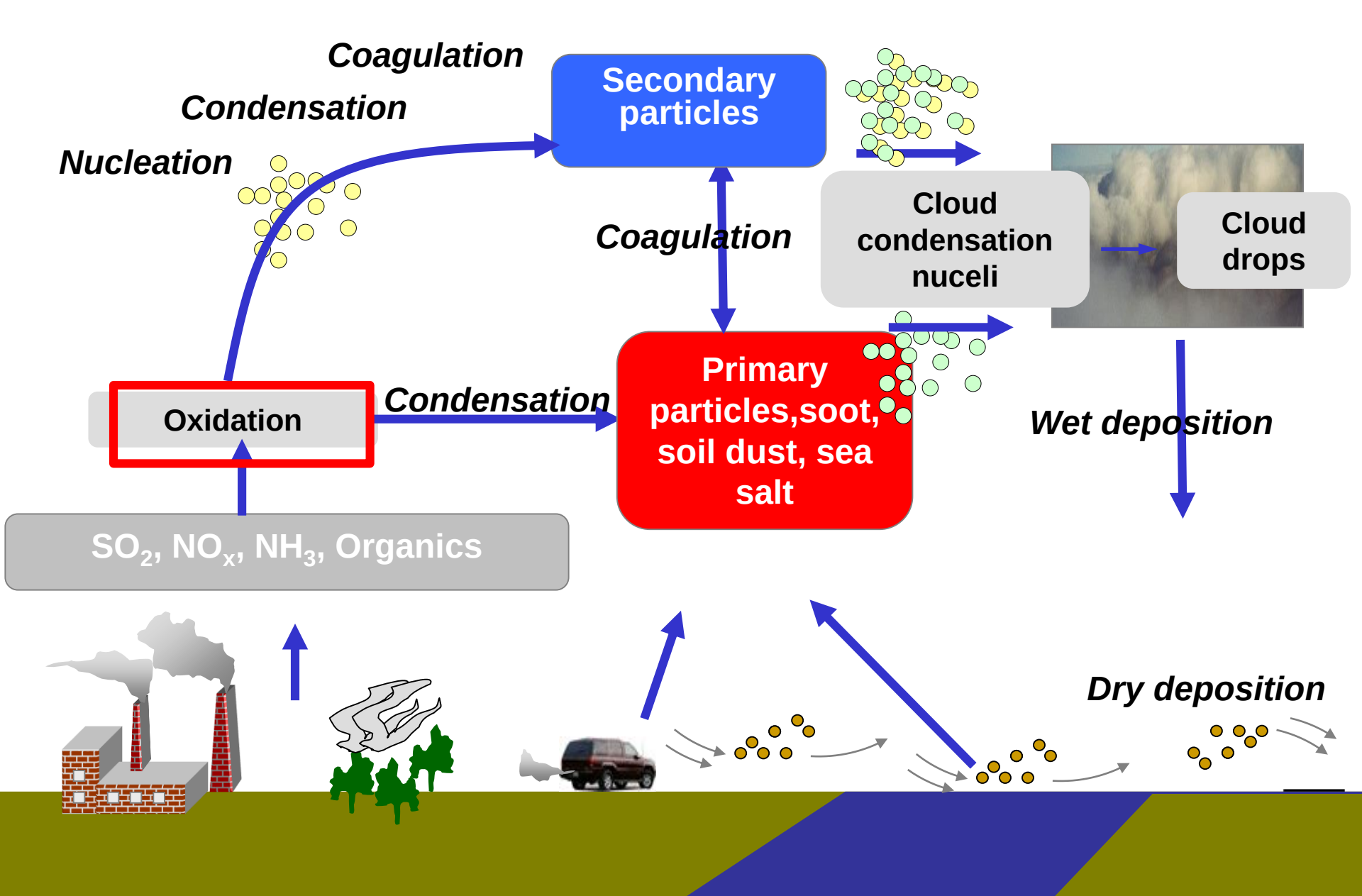
UNIVERSITY OF LEEDS

Model-observation analysis provides improved estimates of SOA budget

UNIVERSITY OF LEEDS



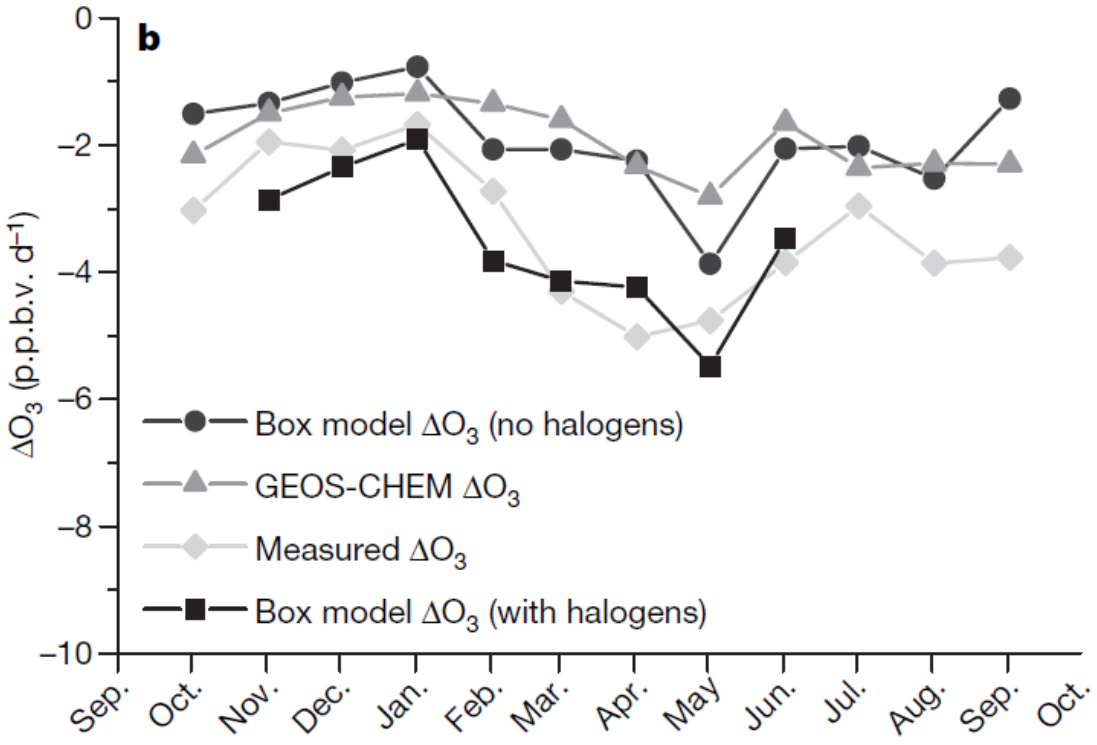
Atmospheric processes: Oxidation



Going beyond evaluation of the model mean.....

UNIVERSITY OF LEEDS

Daytime change in ozone (09:00 - 17:00 UT) Cape Verde

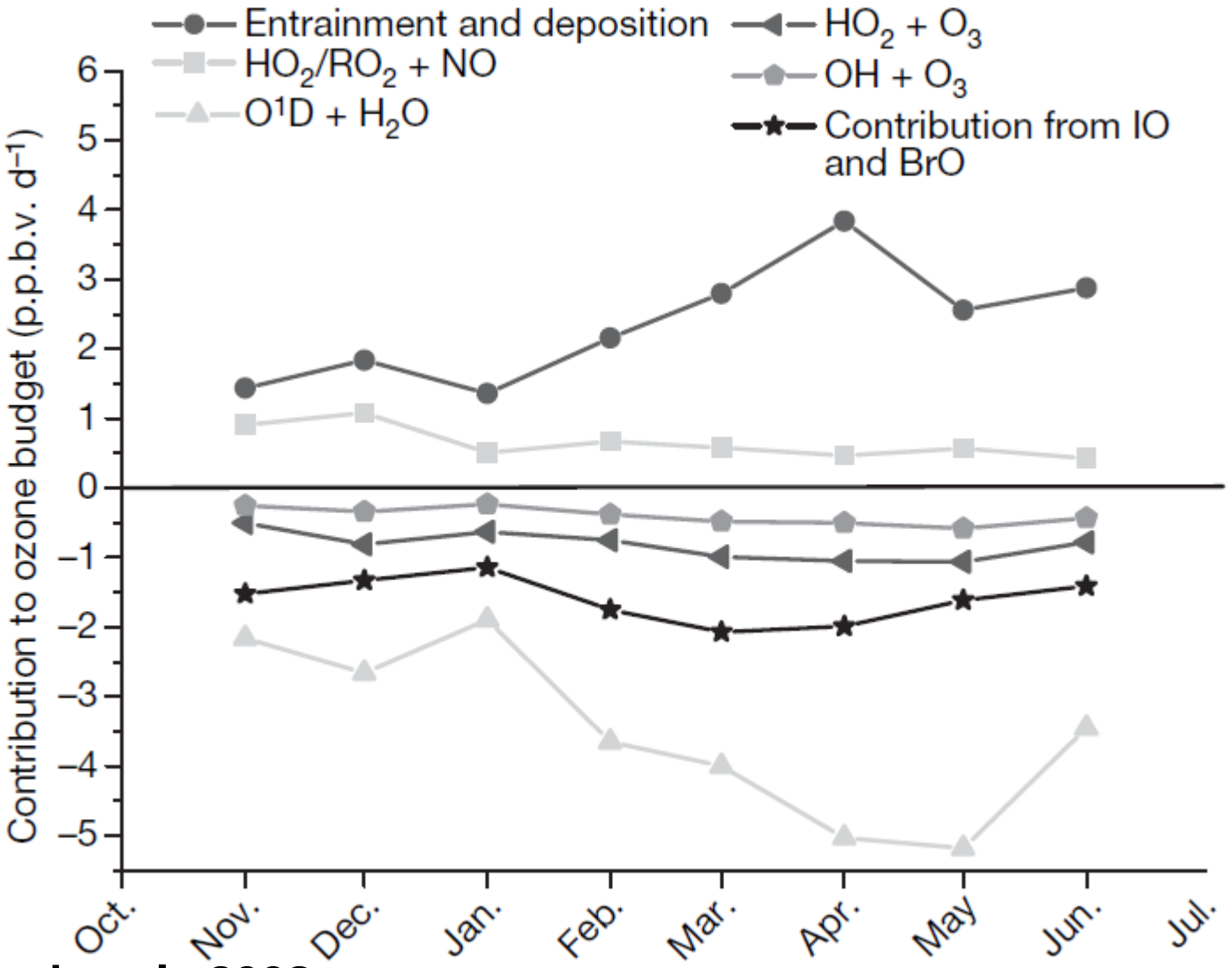


Without halogen chemistry the model underestimates daytime destruction of ozone

Read et al., 2008

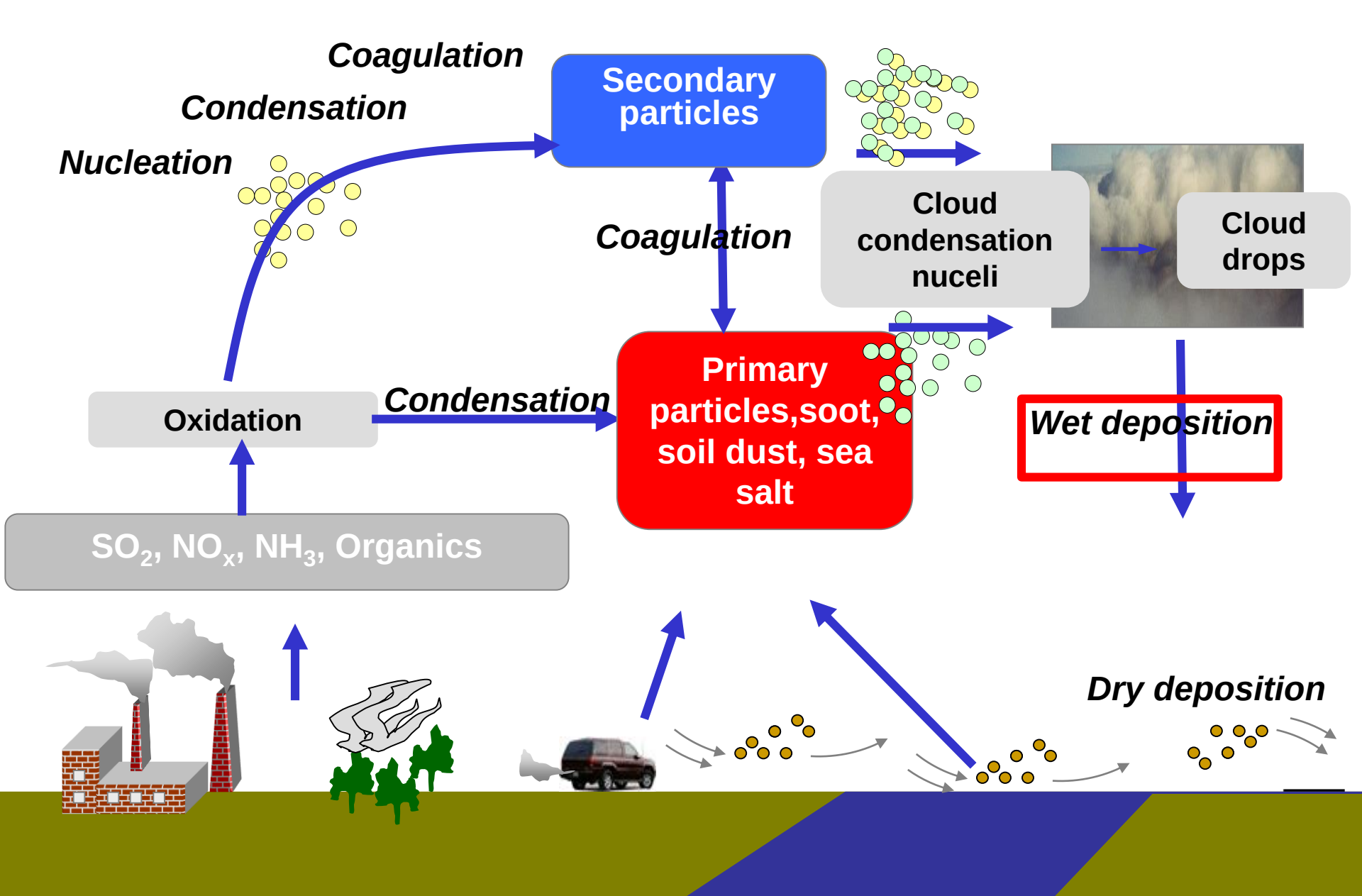
Role of halogens in ozone destruction

UNIVERSITY OF LEEDS



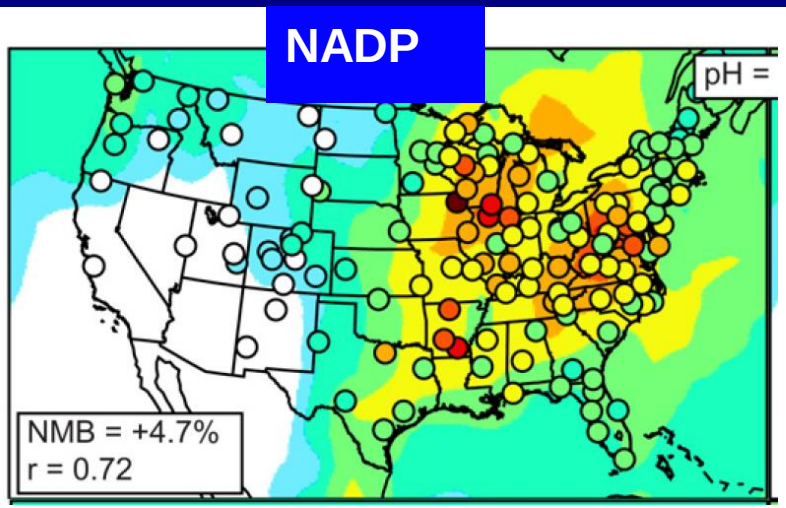
Read et al., 2008

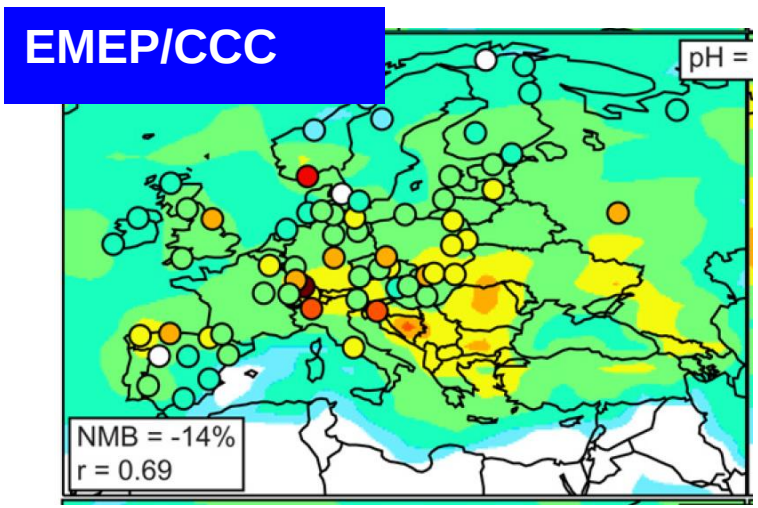
Atmospheric processes: Deposition

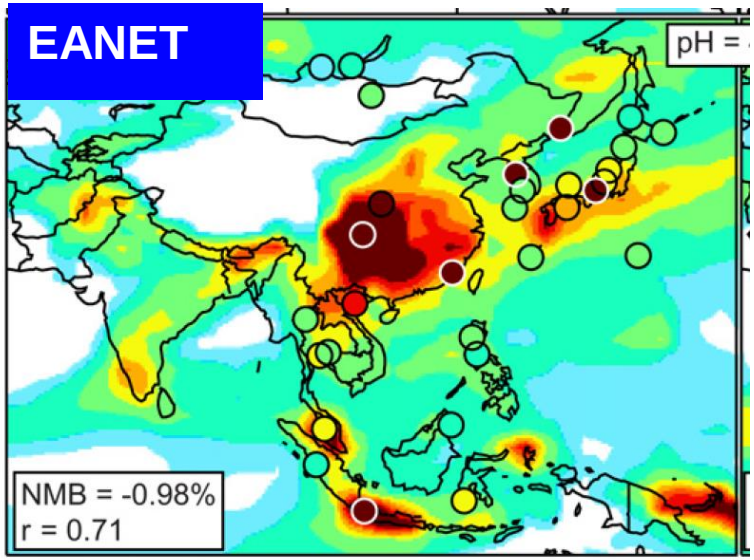


Aerosol deposition

UNIVERSITY OF LEEDS





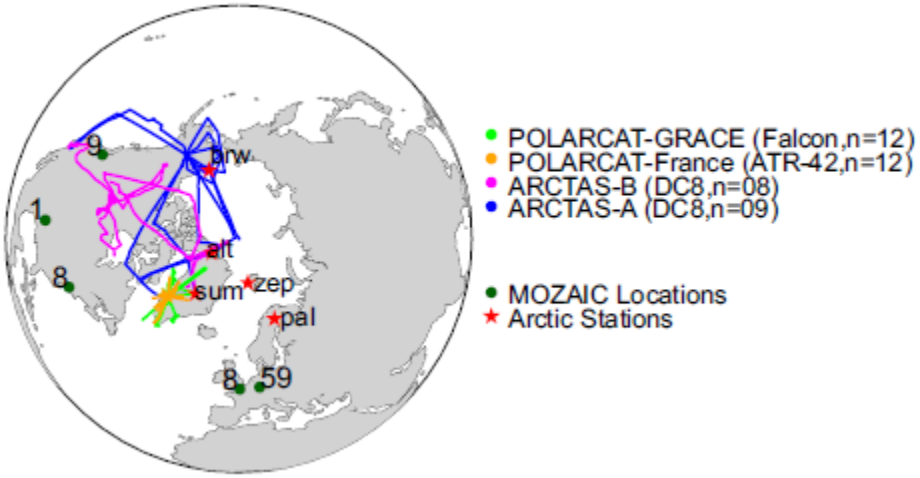


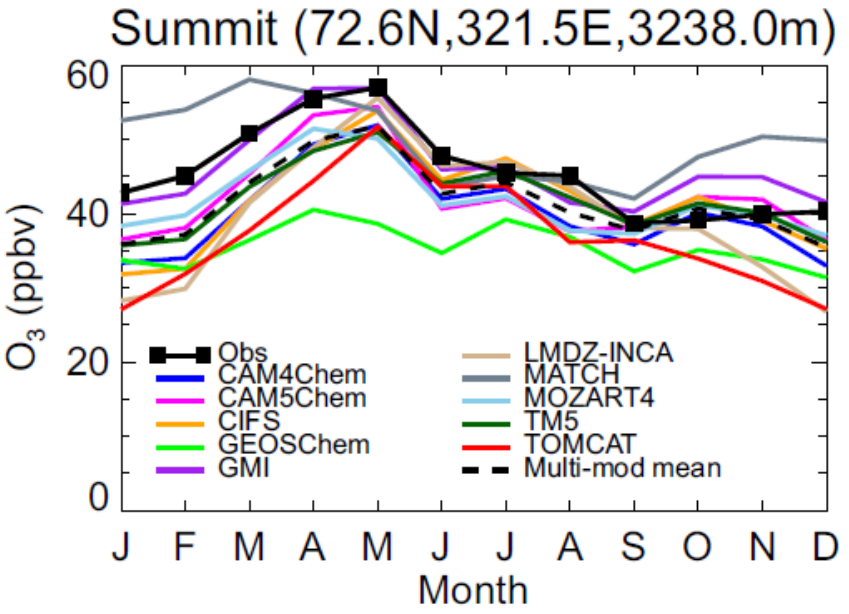
But comparisons can also be interpreted as test of emissions rather than deposition.

Fisher et al., 2011

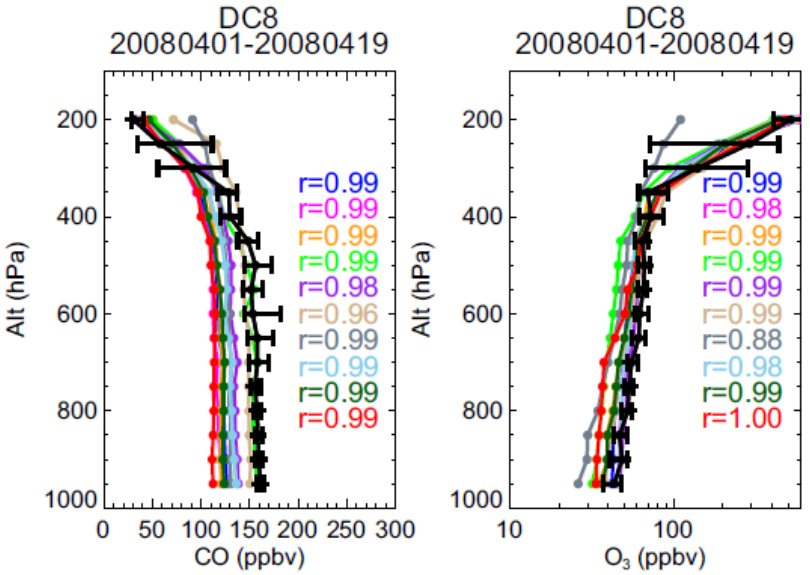
Multi-model evaluation creates additional complexity

UNIVERSITY OF LEEDS





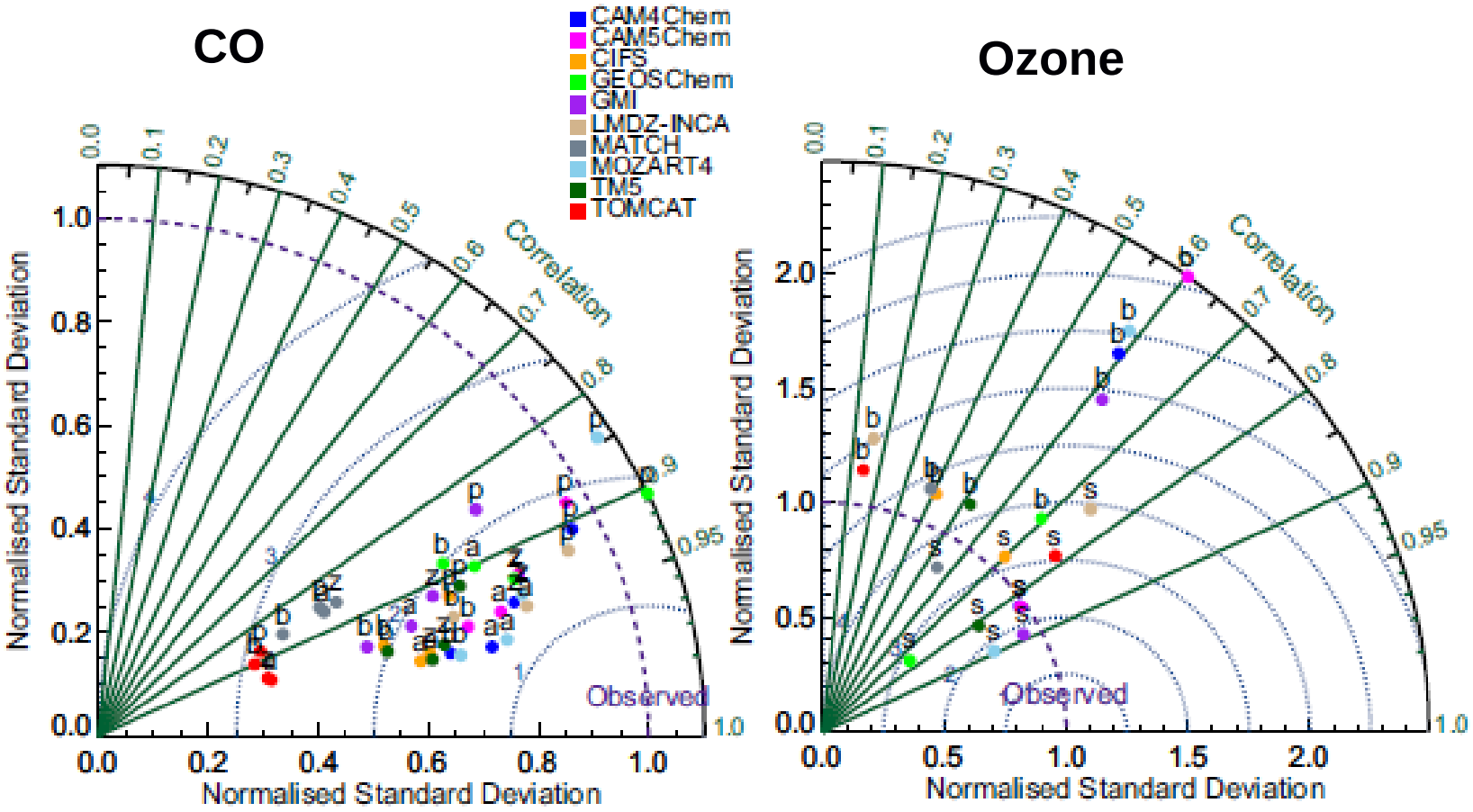
Using observations of atmospheric composition in the Arctic to evaluate a range of chemisty-climate models



Monks et al., ACPD, 2014

Developing methods to synthesise evaluation of multiple models against the same data

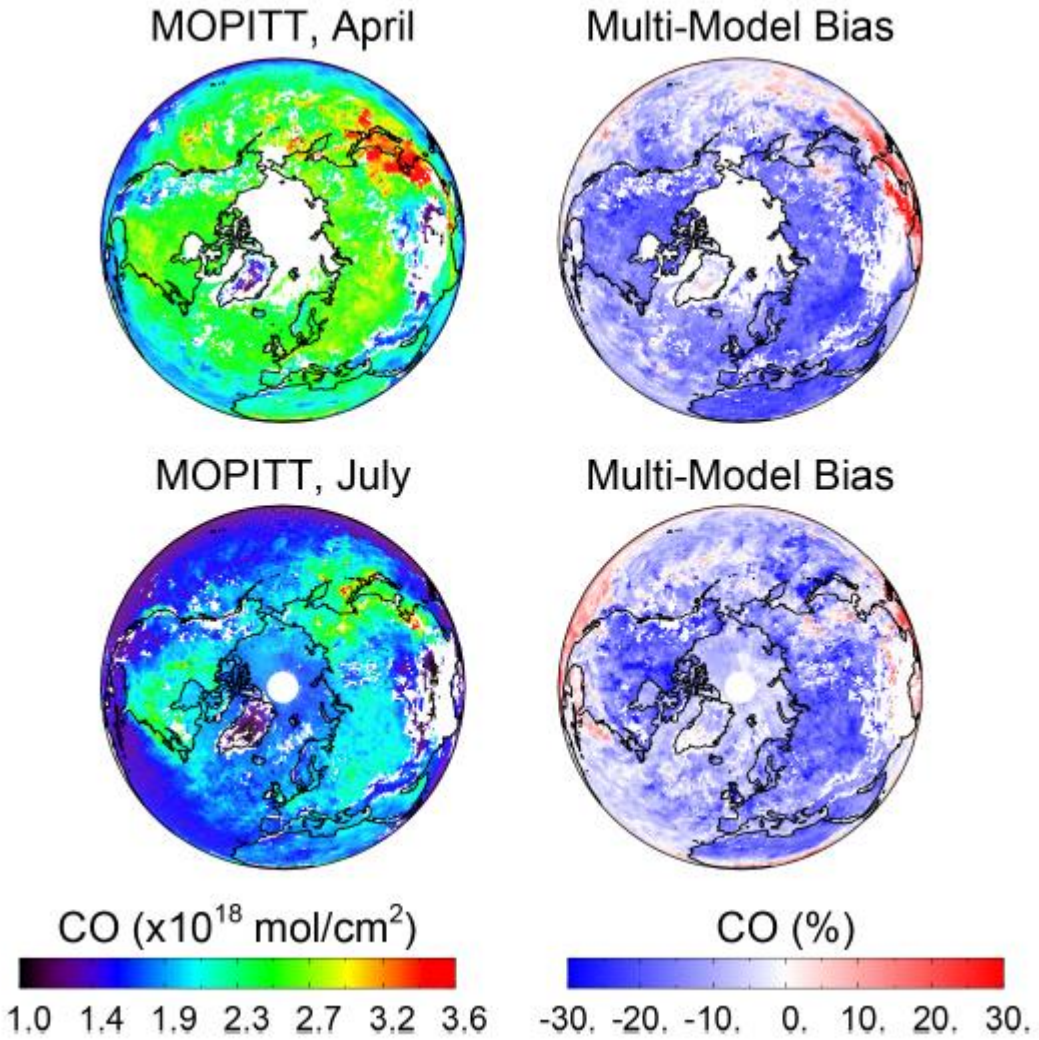
UNIVERSITY OF LEEDS



Monks et al., ACPD, 2014

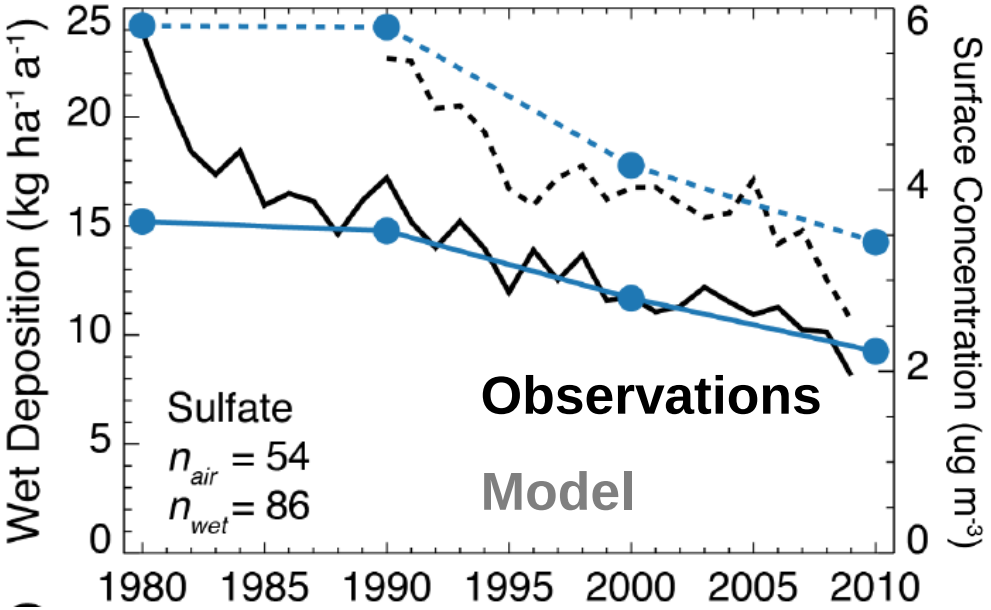
Satellite observations of CO and multi-model bias

UNIVERSITY OF LEEDS

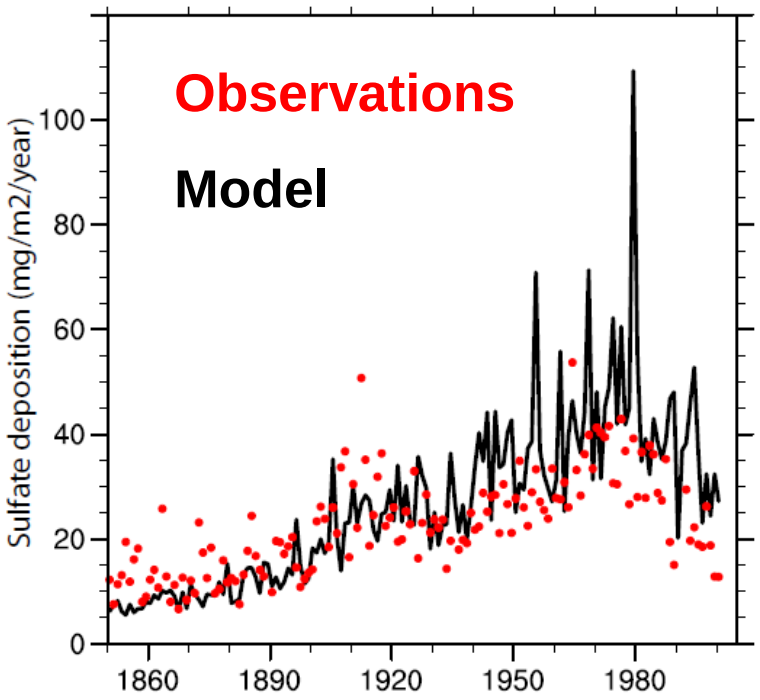


Monks et al., ACPD, 2014

Evaluating “long-term” trends in atmospheric composition



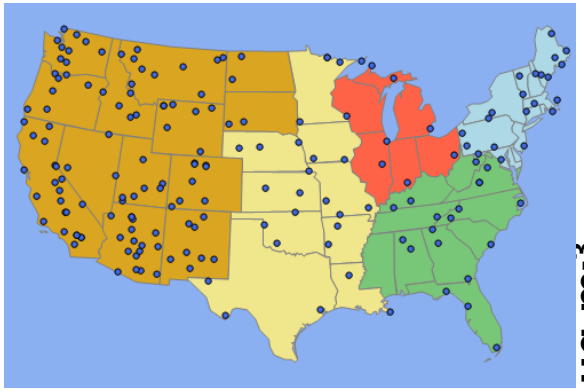
Leibensperger et al., 2012



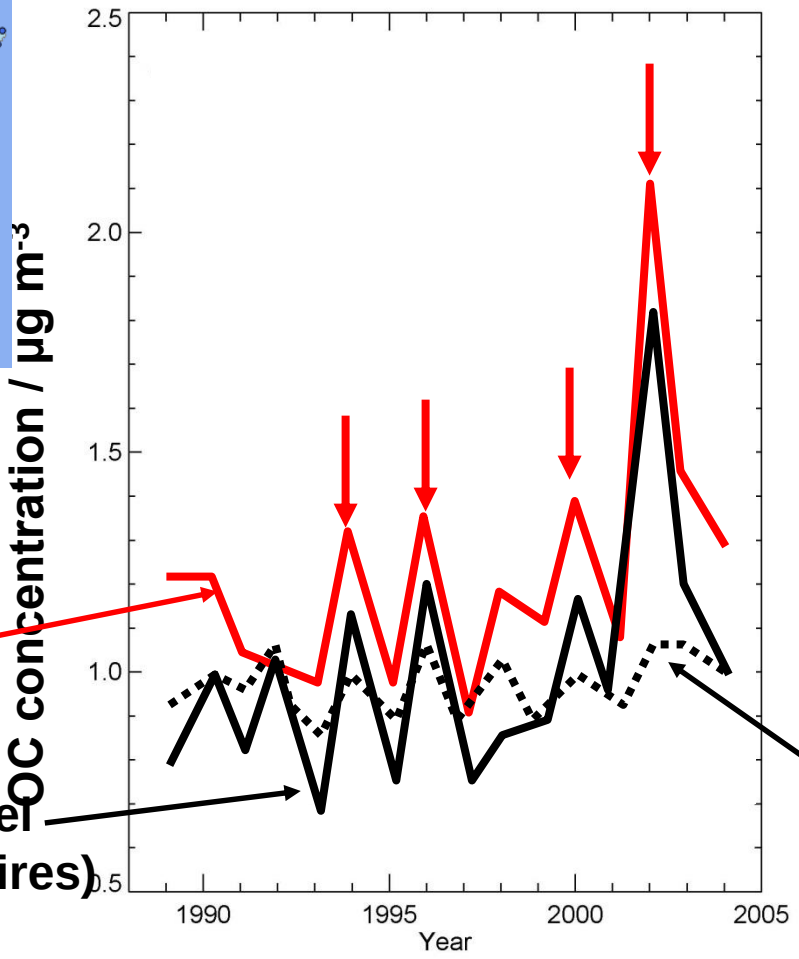
Lamarque et al., 2010

UNIVERSITY OF LEEDS

Exploring processes that contribute to interannual variability of atmospheric composition



Western US regional mean
Jun-Aug organic carbon (OC) aerosol



Observations (IMPROVE)

Global model (Observed fires)

Global model Climatological fires

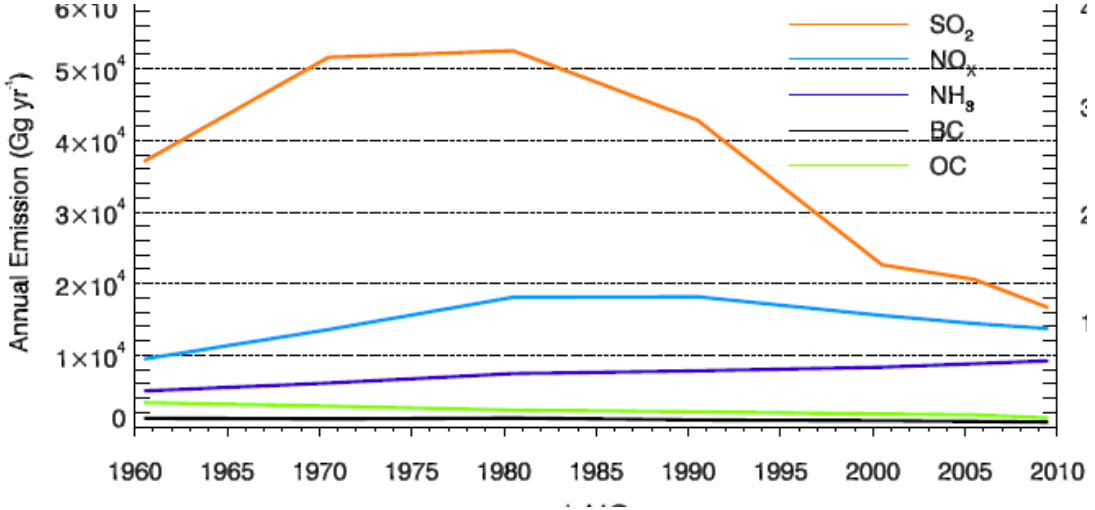
Model captures interannual variability driven by changing emissions

Spracklen et al., GRL. 2007

UNIVERSITY OF LEEDS

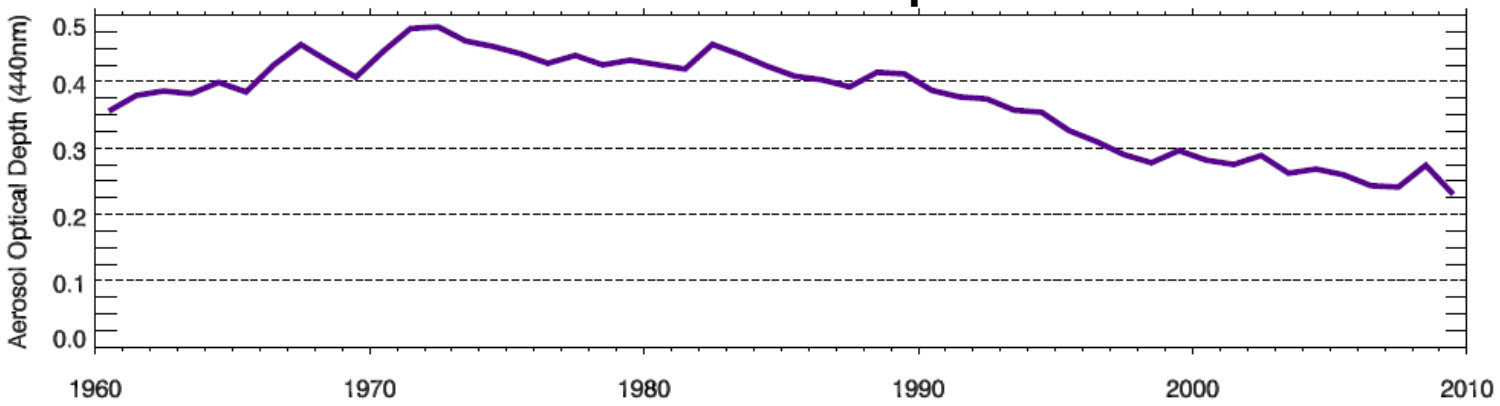
Exploring the impacts of trends in anthropogenic sources of aerosol

European mean anthropogenic emissions (MACCity)



Large changes in anthropogenic pollution sources over last 50 years.

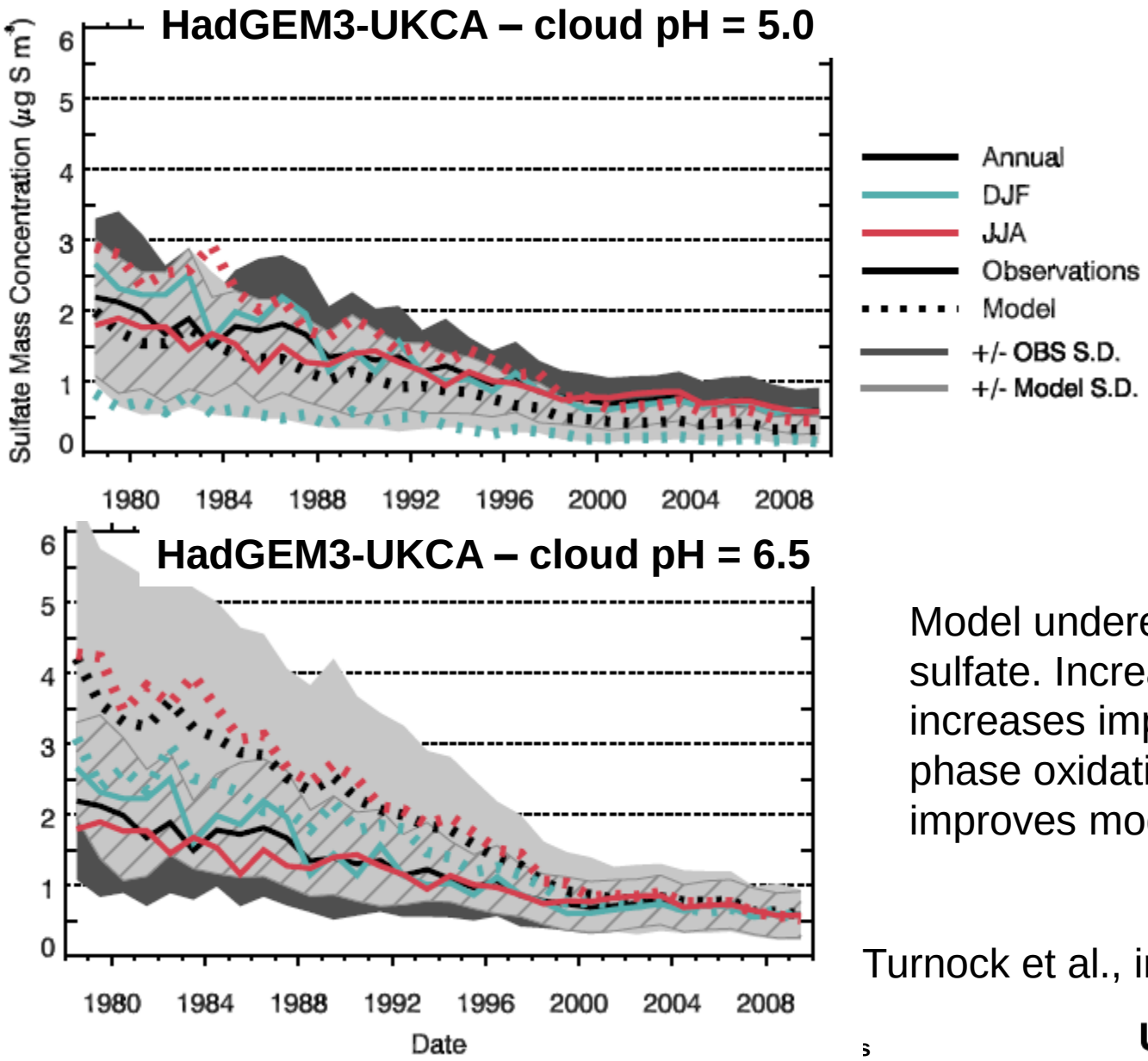
HadGEM3-UKCA simulated European mean AOD



Turnock et al., in prep

UNIVERSITY OF LEEDS

Sulfate aerosol trends over Europe – the importance of cloud pH



Model underestimates wintertime sulfate. Increasing cloud water pH, increases importance of aqeous phase oxidation by ozone and improves model in winter

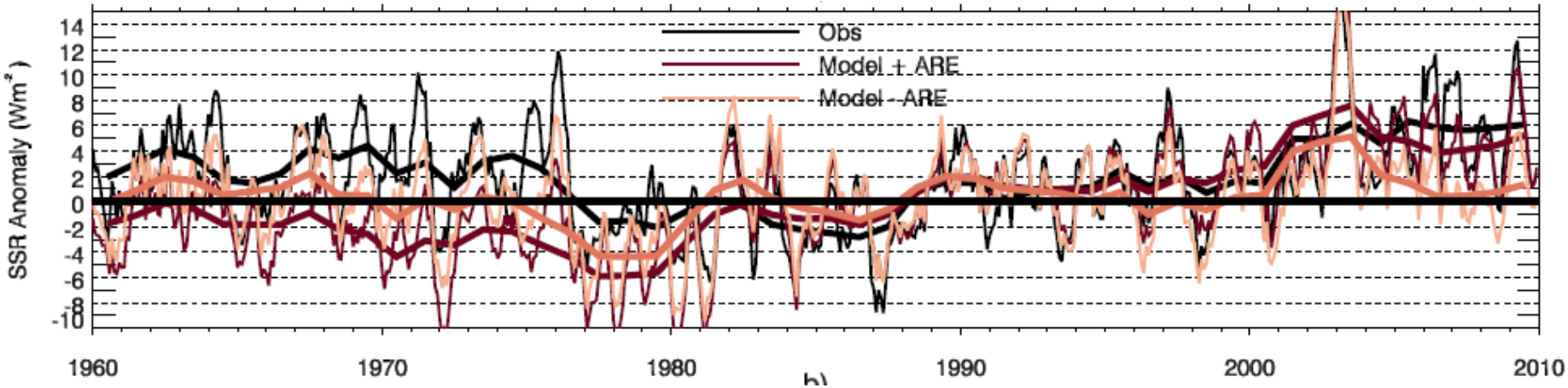
Turnock et al., in prep

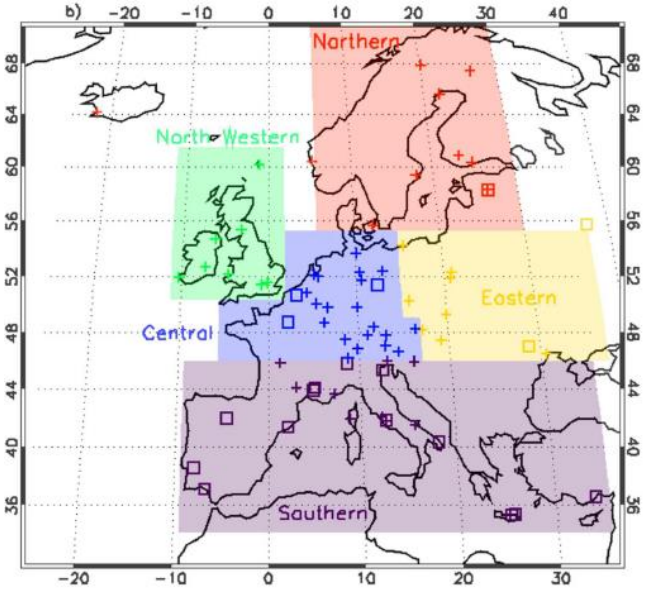
UNIVERSITY OF LEEDS

Trends in surface shortwave radiation

Surface shortwave radiation across Europe

Observations
Model incl. ARE
Model no ARE



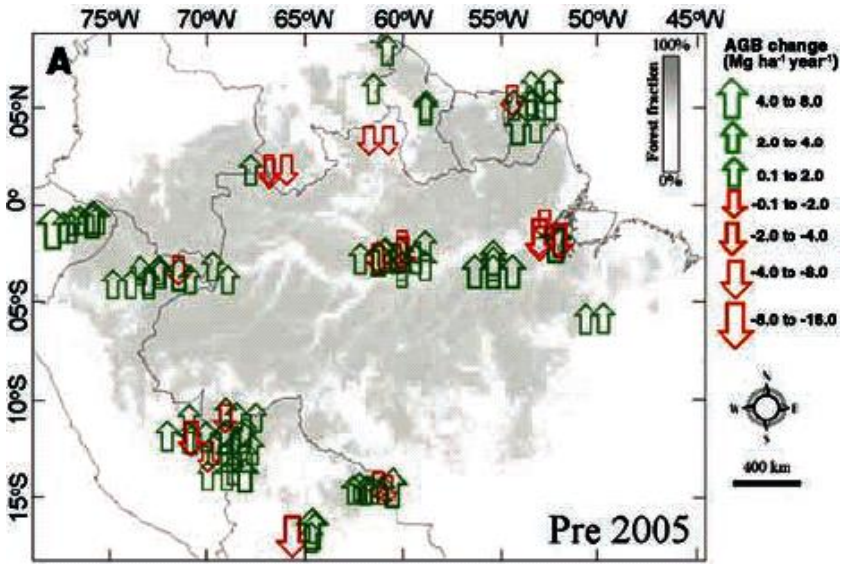


Model with aerosol radiative effects (ARE) captures observed brightening from ~1980 onwards

Re-analysis product impacts model performance before 1980

Turnock et al., in prep

Coupling to the Earth System: impacts of atmospheric composition on ecosystems



Long-term observations of forest biomass in the Amazon show a long-term increase in biomass.

The cause is not known: CO_2, T, aerosol?

Coupling and evaluating model components

Fire emissions GFEDv3

Deforestation emissions

Meteorology

Meteorological data ECMWF

GLOMAP
(Spracklen et al., 2005)
(Mann et al., 2010)

Aerosol model

Clouds, albedo, GHGs

ISCCP, ECMWF

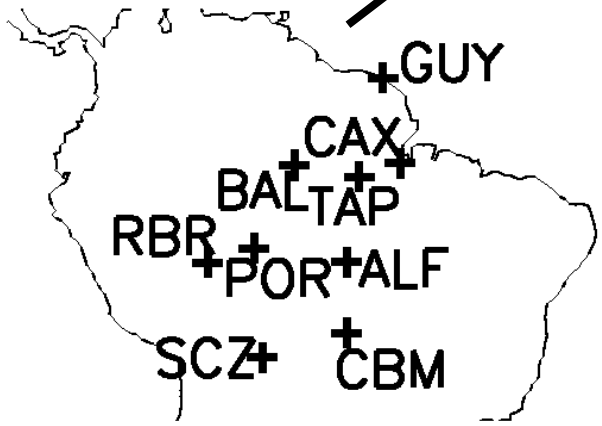
EU WATCH

Meteorology

Radiation model

Edwards-Slingo
(Edwards & Slingo, 1996)
(Rap et al., 2013)

OBSERVATIONS

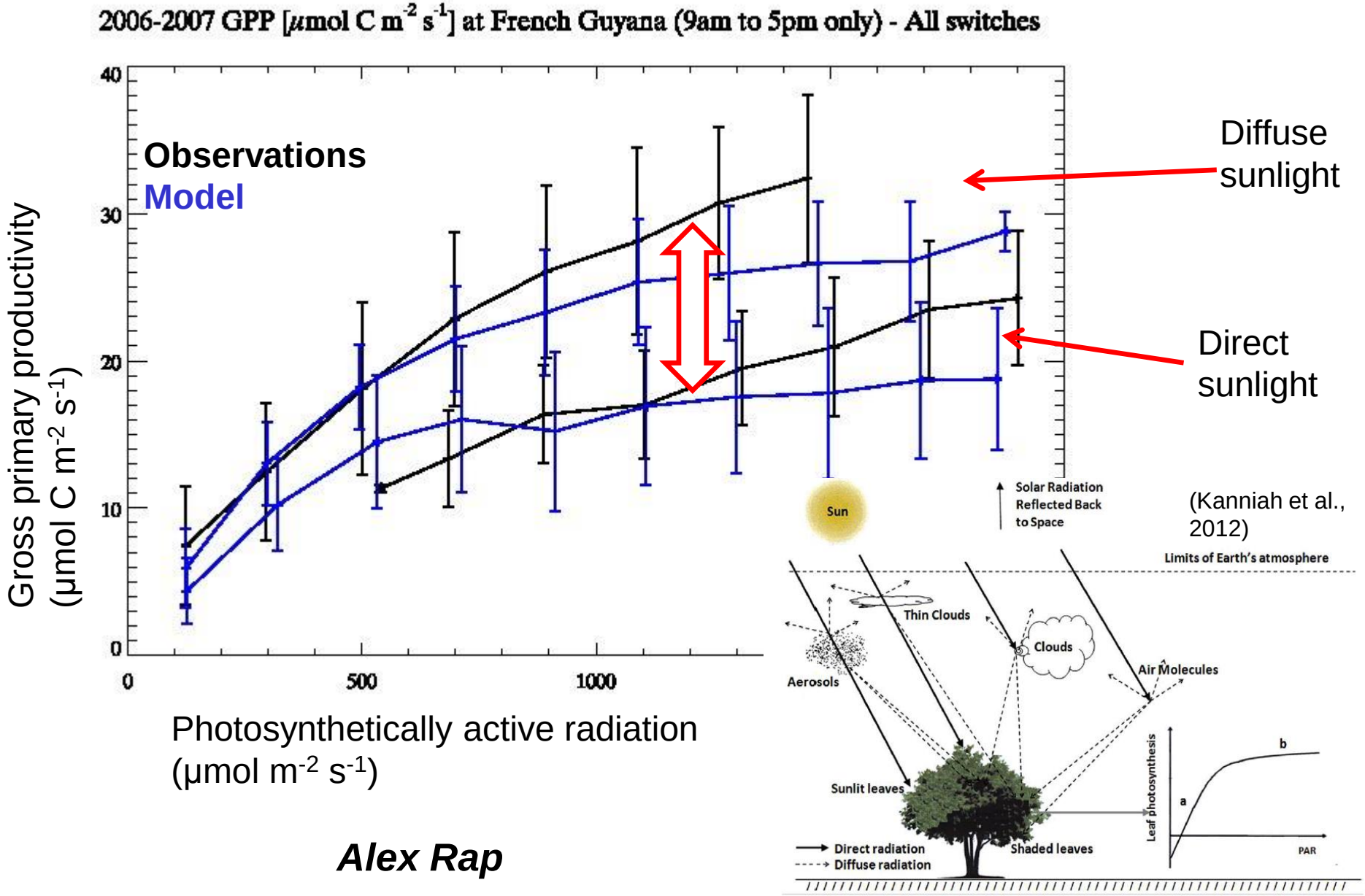


Land-surface model

JULES
(Mercado et al., 2007)
(Best et al., 2011)
(Clark et al., 2011)

UNIVERSITY OF LEEDS

Evaluating the impacts of aerosol on diffuse radiation and photosynthesis



(Kanniah et al., 2012)

Alex Rap

Impact of deforestation fires on forest carbon uptake

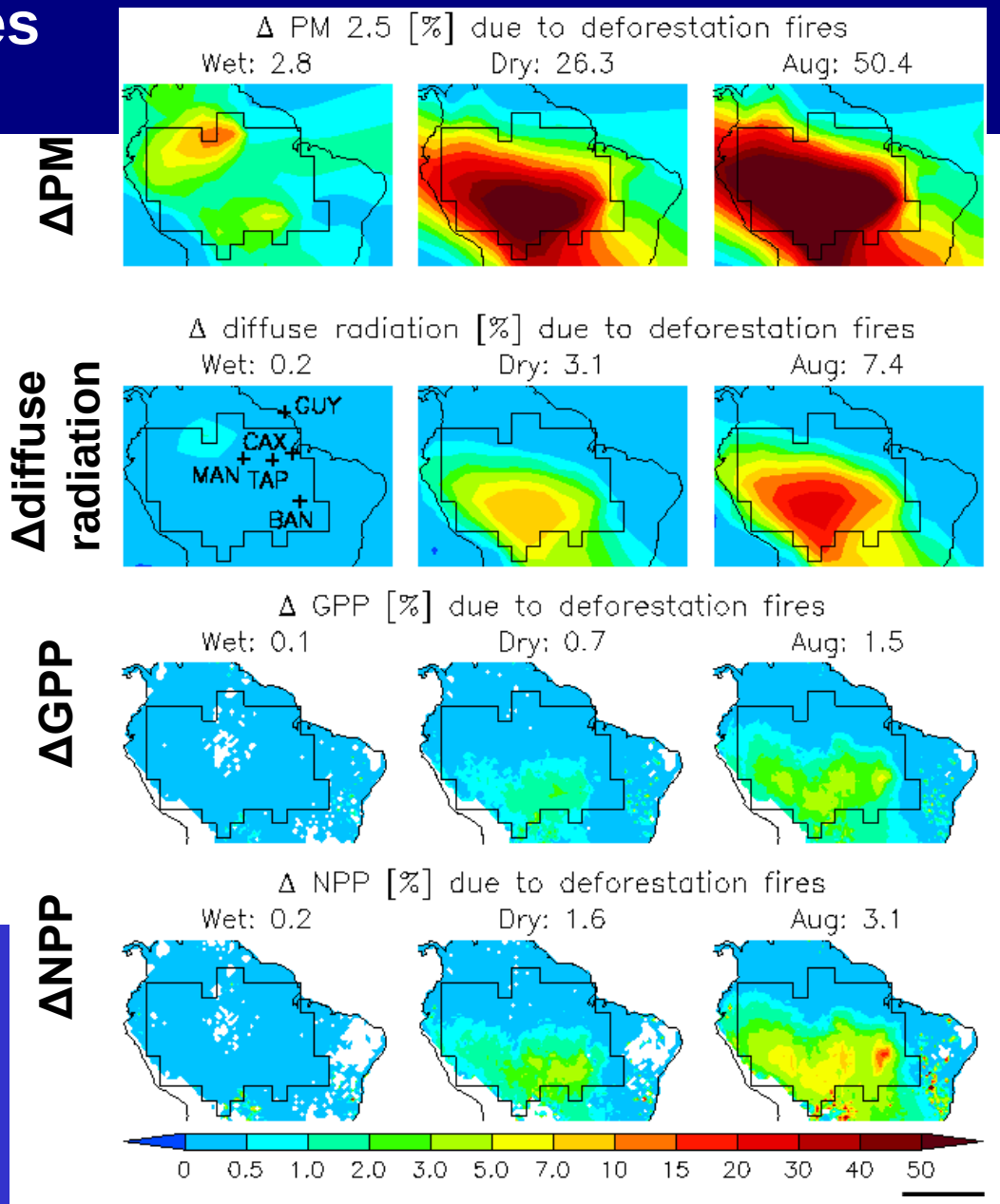
GLOMAP aerosol model

↓

Edwards & Slingo Radiation

↓

JULES Land Surface Model



Rap et al. submitted

Diffuse radiation from deforestation fire increases Amazon basin carbon storage by 60 Tg C a^{-1} (100 kg C ha^{-1} a^{-1}), accounting for 15% of the observed carbon sink.

Summary

Model evaluation is a critical component of our work.

Model evaluation should be quantitative. Ideally it should inform and improve our understanding of atmospheric processes.

Careful experimental design and model-observation analysis is required.

As more processes are coupled into ESMs – evaluation will become more and more necessary (and difficult)!

We rely on observational data for our science. Involve observational scientists in evaluation from an early stage. Acknowledge the crucial role through co-authorship where appropriate.