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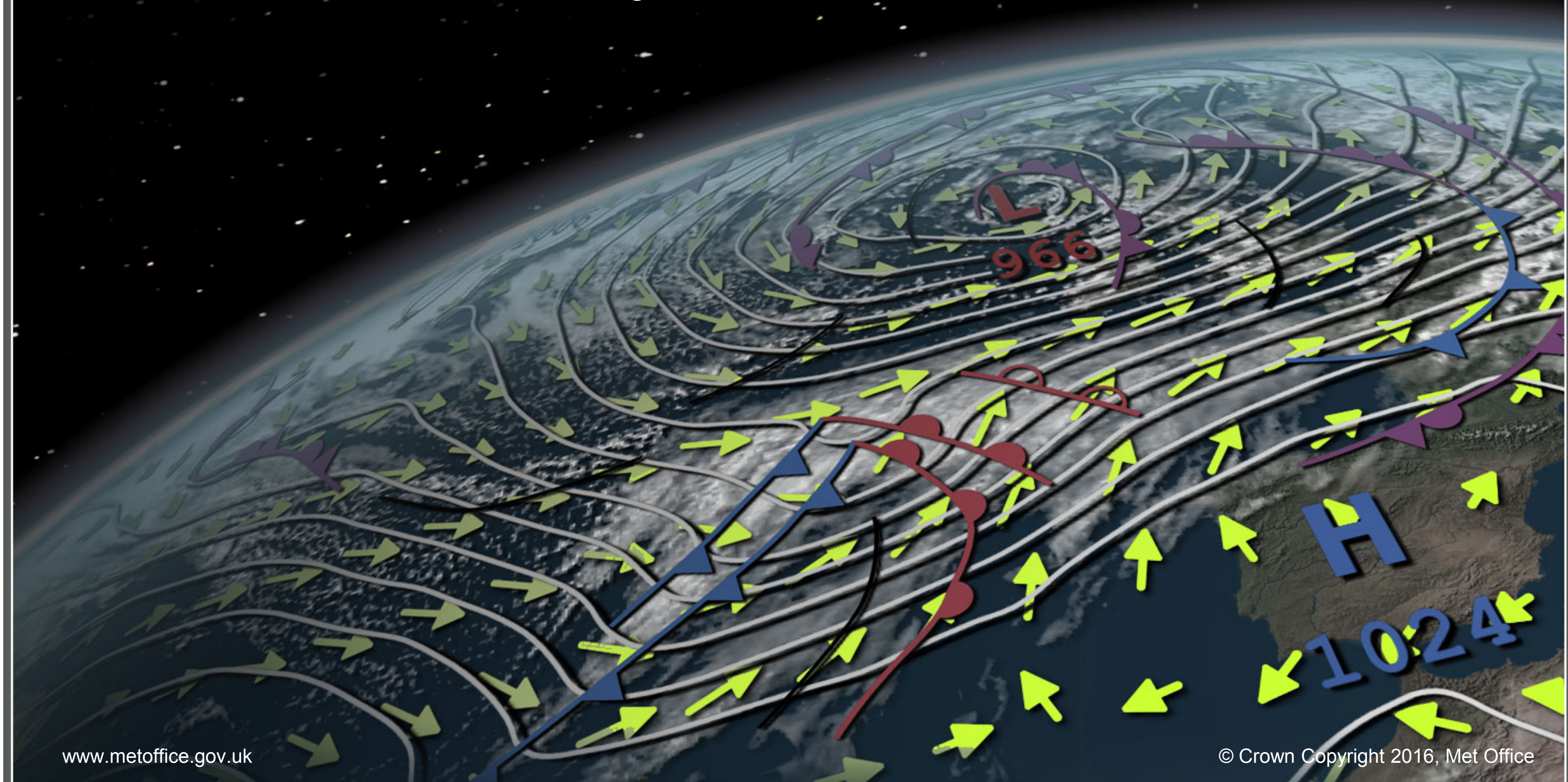
Aerosol impacts on weather

Jane Mulcahy

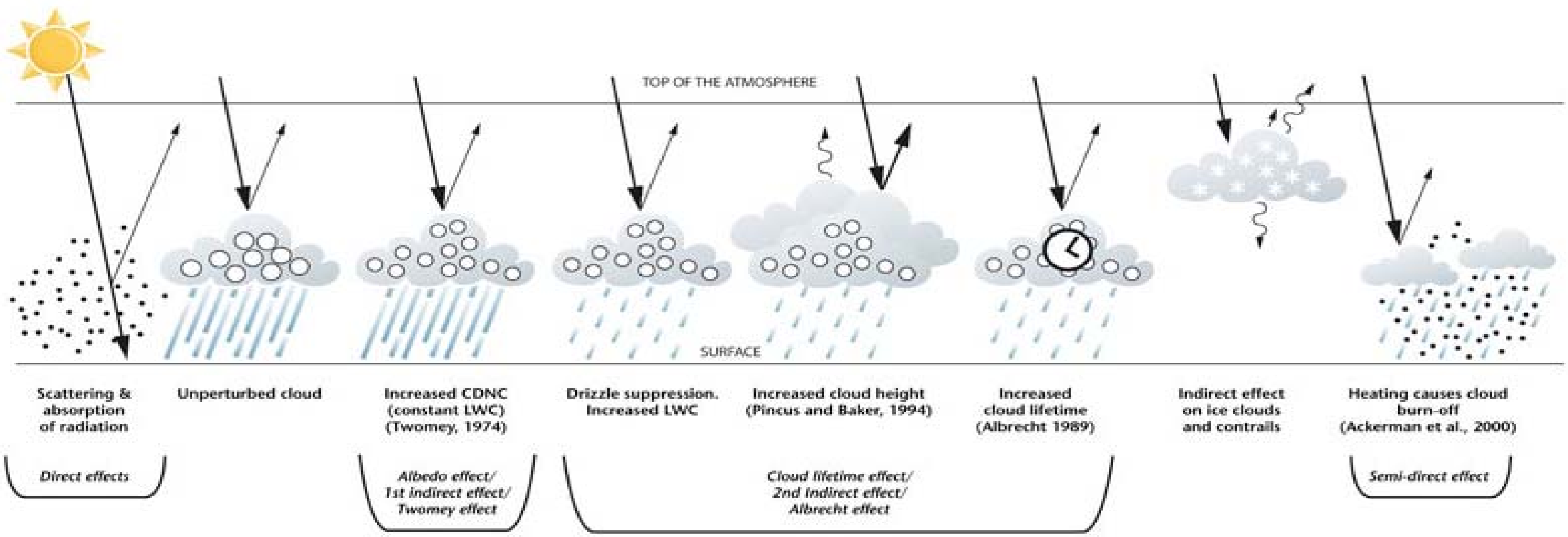
9th ICAP meeting, Lille, France, 26-29th June 2017



Overview

- Motivation
- Increasing aerosol complexity examples:
  - Global impacts in Met Office NWP model
  - Regional significant aerosol episodes: Biomass burning in SAMBBA
- Role of aerosol complexity
- Summary

Aerosol-cloud-radiation interactions



Adapted from Haywood & Boucher (2000)

Aerosols and climate

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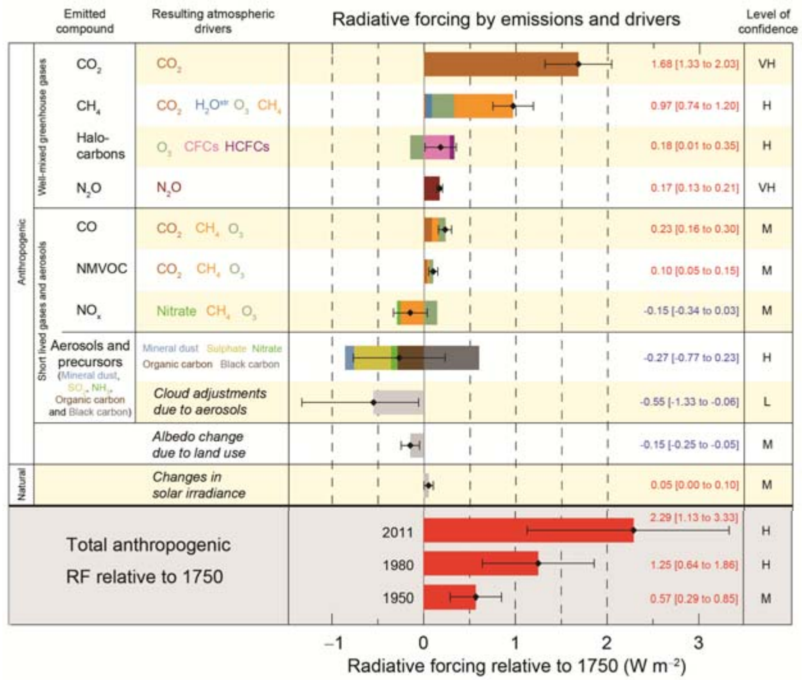
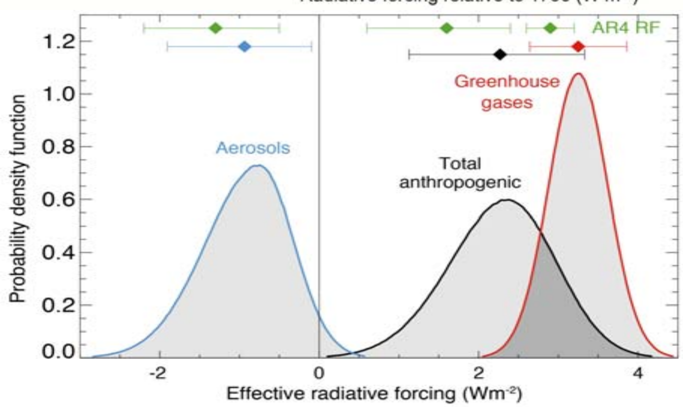
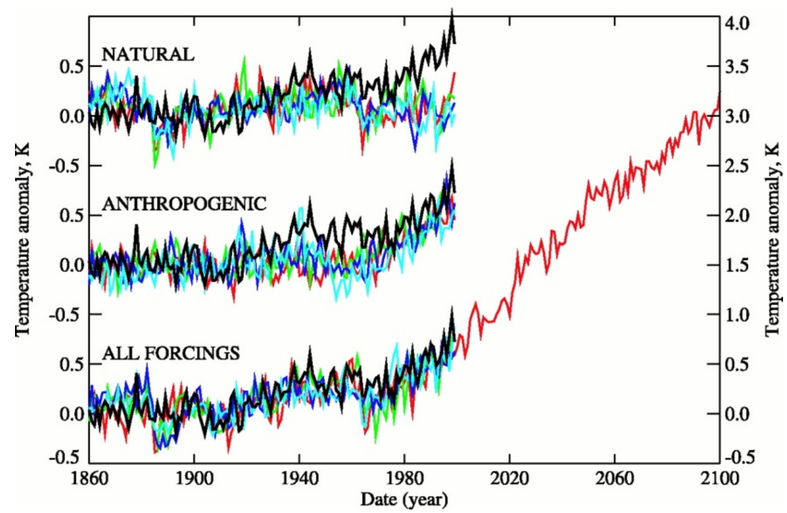




Source: IPCC, AR5, 2013



Source: Stott et al. Science 2000; 290, 2133

Aerosols required to simulate observed temperature anomalies from pre-industrial.

Aerosols play an important role in determining the total anthropogenic forcing on climate but magnitude of aerosol forcing remains highly uncertain

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Aerosols and air quality

Daily Air Quality Index

The new bandings for the Daily Air quality Index are detailed in Table 1.

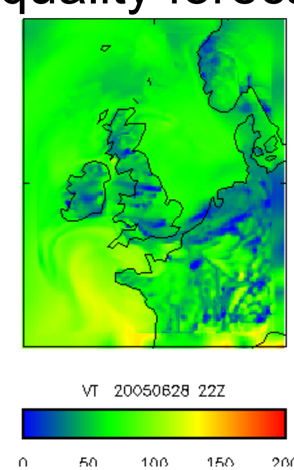
Band	Index	Ozone Running 8 hourly mean μgm⁻³	Nitrogen Dioxide hourly mean μgm⁻³	Sulphur Dioxide 15 minute mean μgm⁻³	$PM_{2.5}$ Particles 24 hour mean μgm⁻³	PM_{10} Particles 24 hour mean μgm⁻³
LOW						
	1	0-33	0-66	0-88	0-11	0-16
	2	34-65	67-133	89-176	12-23	17-33
	3	66-99	134-199	177-265	24-34	34-49
MODERATE						
	4	100-120	200-267	266-354	35-41	50-58
	5	121-140	268-334	355-442	42-46	59-66
	6	141-159	335-399	443-531	47-52	67-74
HIGH						
	7	160-187	400-467	532-708	53-58	75-83
	8	188-213	468-534	709-886	59-64	84-91
	9	214-239	535-599	887-1063	65-69	92-99
VERY HIGH						
	10	240 or more	600 or more	1064 or more	70 or more	100 or more

Table 1: Daily Air Quality Index bands

Over 9,000 deaths due to air pollution exposure in London in 2010

Over 3 million premature deaths in 2012 according to WHO

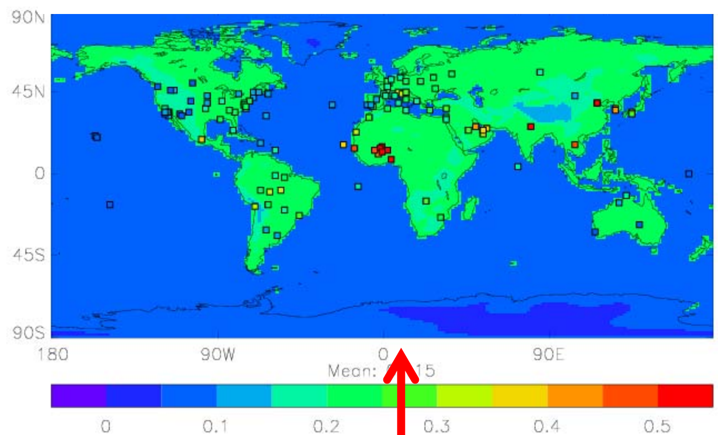
Increasing importance of air quality forecasting



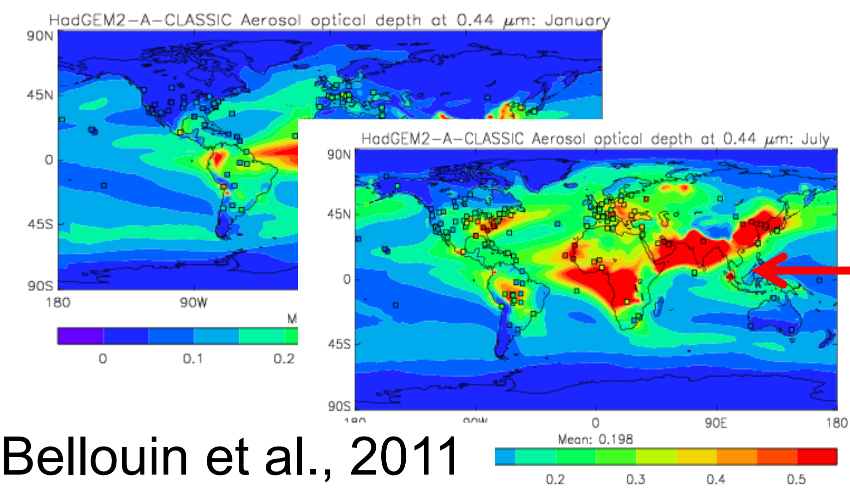
Aerosol and weather

How are aerosols representationed in operational NWP models?

Cusack et al., 1998

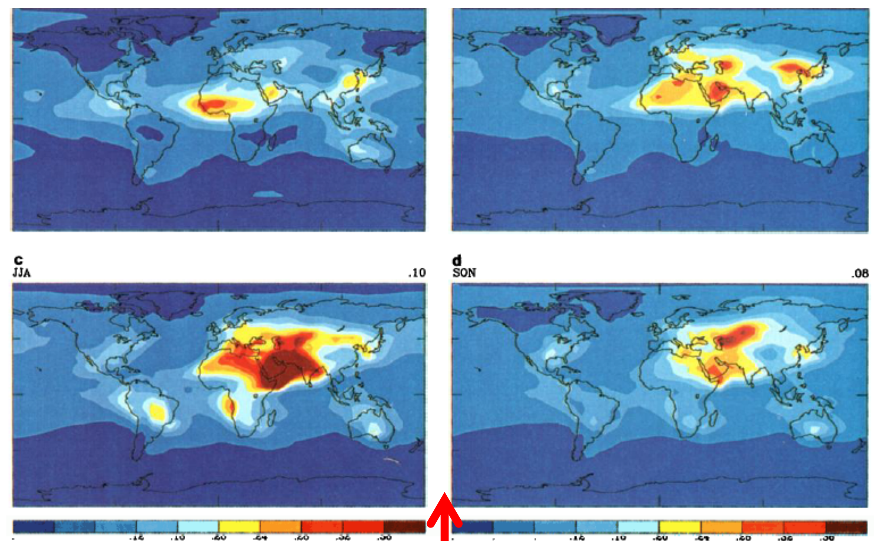


Fixed aerosol properties land/ocean



Bellouin et al., 2011

Tegen et al., 1997

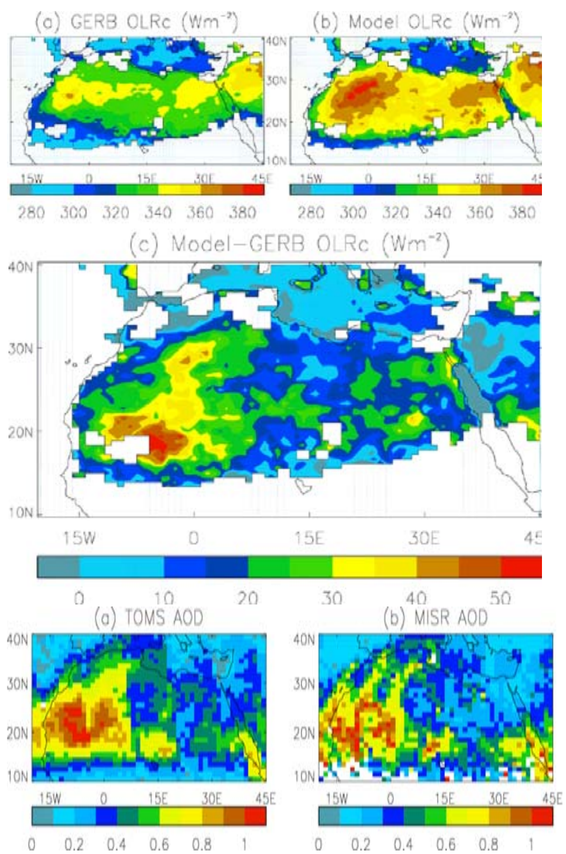


Updated aerosol climatologies:

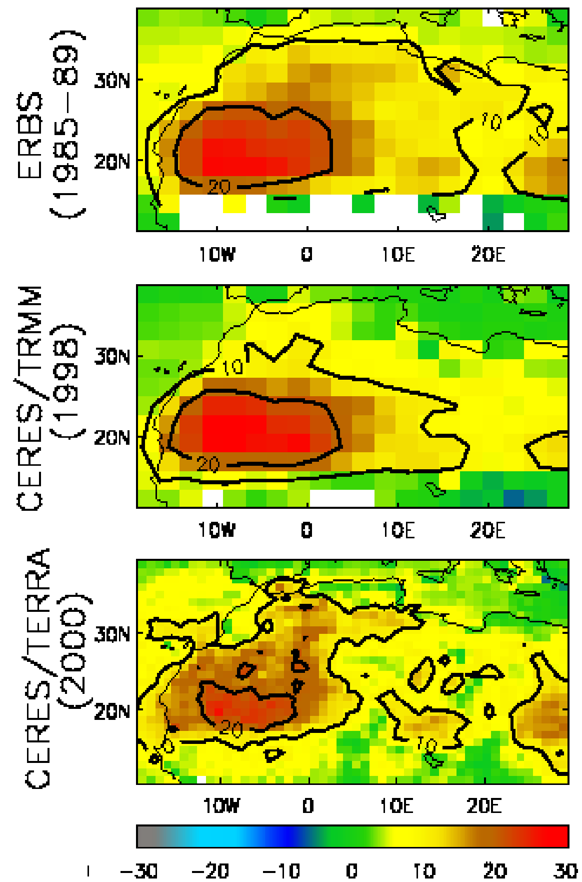
- Monthly/seasonal
- Information on aerosol speciation and life cycle
- 3D fields
- Direct aerosol effect only

Aerosols and weather

OLR biases over West Africa



MetUM bias (Haywood et al., 2005)



AMIP3 ensemble Clear-sky OLR bias (courtesy of R. Allan, Uni. Reading)

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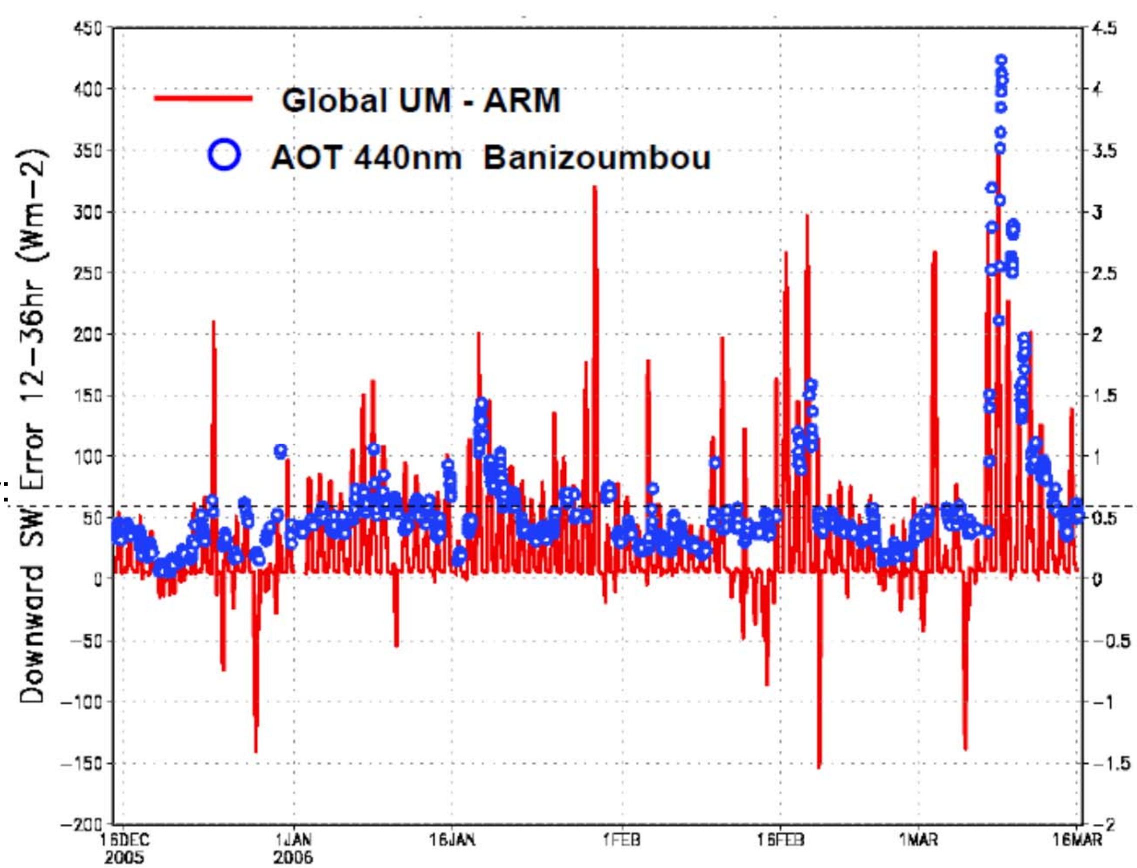
Aerosols and weather

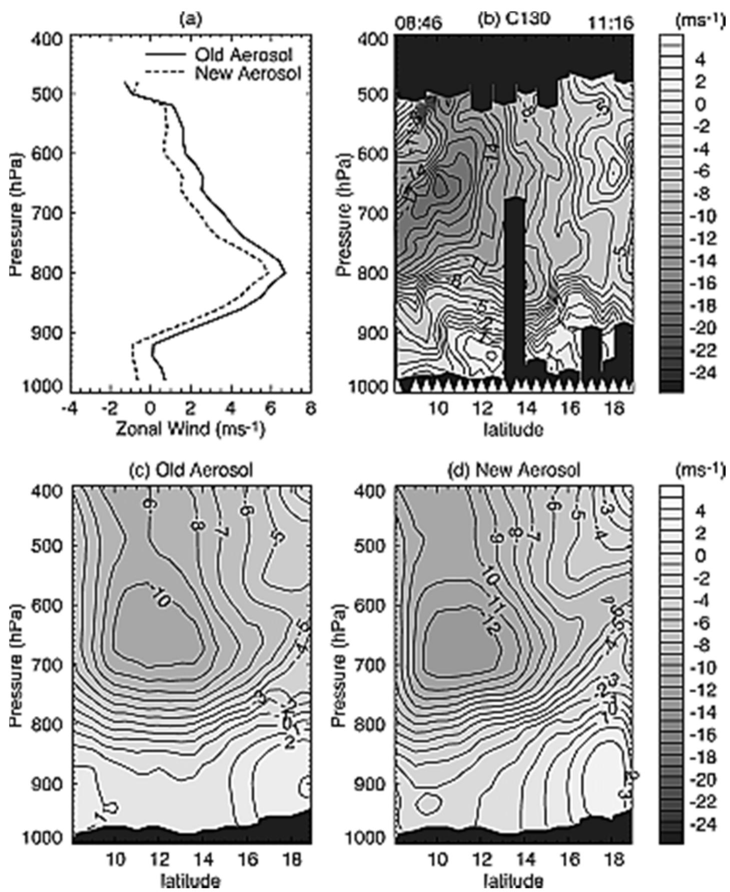
Surface SW biases over West Africa (Milton et al. 2008)

Mean error:
56 Wm^{-2}

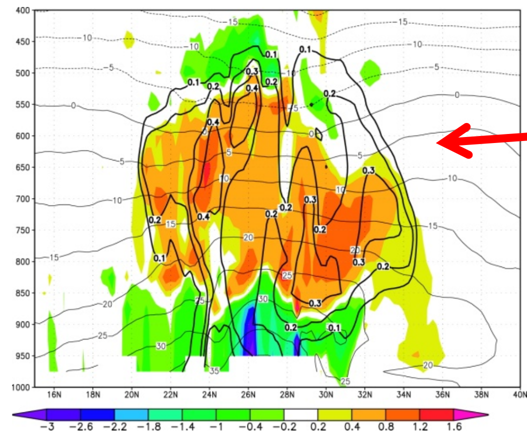


Aerosols and weather

Improving simulation of African Easterly Jet

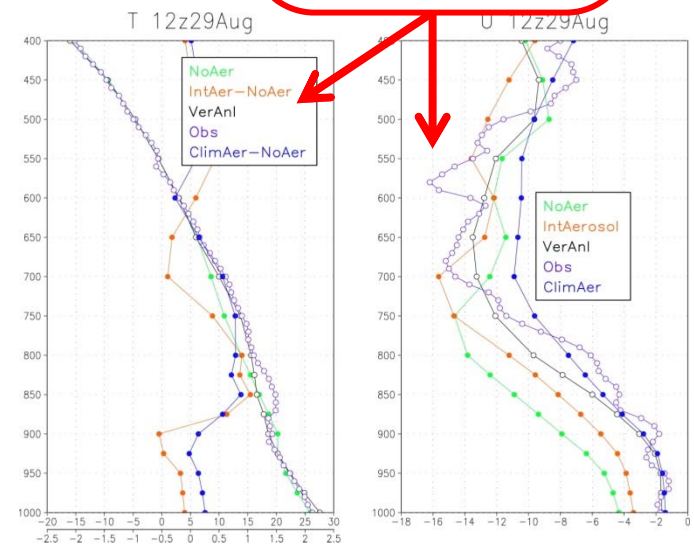


Tompkins et al. (2005), GRL, doi:10.1029/2004GL022189



Impact of interactive aerosol on temperature structure

Improves temperature and zonal wind profiles



Reale et al, Wea. Forecasting,2011

Impact of increasing aerosol complexity in MetUM

Mulcahy et al., ACP, 2014

Key motivations:

- Does inclusion of more complex on-line interactive aerosol representations in weather forecast models improve the predictive skill of the model?
- What level of complexity is required?
- Does the benefit (if any) outweigh the increased cost of implementing such schemes?

Impact of increasing aerosol complexity

Experimental design

Mulcahy et al. ACP, 2014

Tests (hierarchy approach):

Direct Effect	Indirect effects	Aerosol init.
Cusack (1998)	Land/sea split (*as op)*	N/A
CLASSIC clims (*op*)	Land/sea split (*op*)	N/A
Prognostic CLASSIC	Land/sea split (*as op)*	Spun up/run free
Prognostic CLASSIC	Prognostic CLASSIC	Spun up/run free
Prognostic CLASSIC	Prognostic CLASSIC	Initialised from MACC

- Experiments conducted in operational-like NWP model, 4D-VAR for met (not aerosol)
- N320 (~40km) forecasts using 4D-Var DA
- Bulk mass aerosol scheme CLASSIC (Bellouin et al. 2011)
- Period simulated June-July 2009

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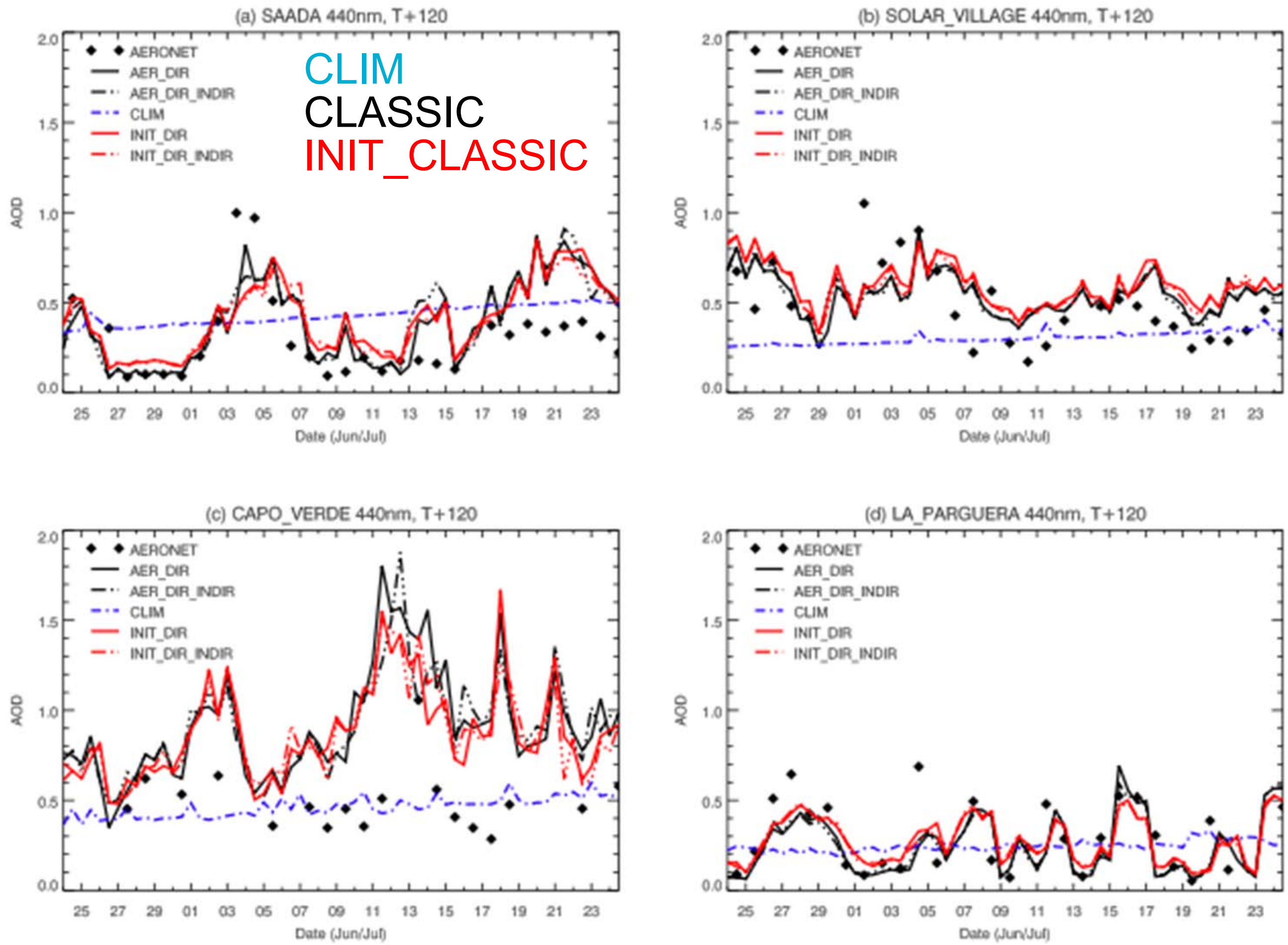
Impact of aerosol complexity

Aerosol simulations (dust regions)

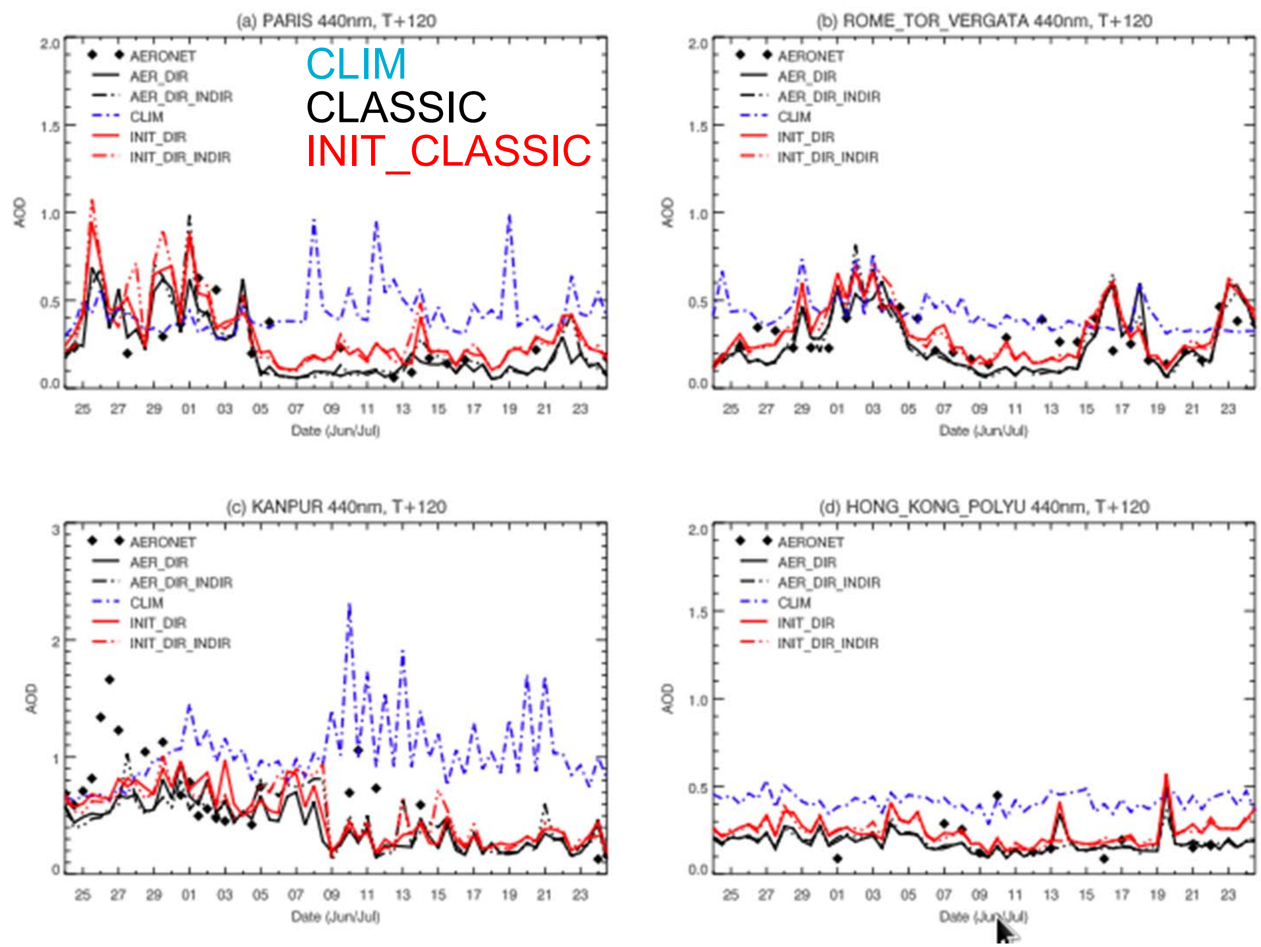
Mulcahy et al., ACP, 2014



Impact of aerosol complexity

Aerosol simulations (anthropogenic regions)

Mulcahy et al., ACP, 2014

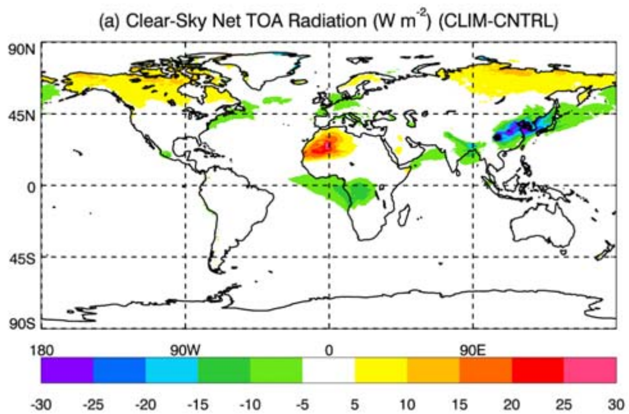


Impact of aerosol complexity

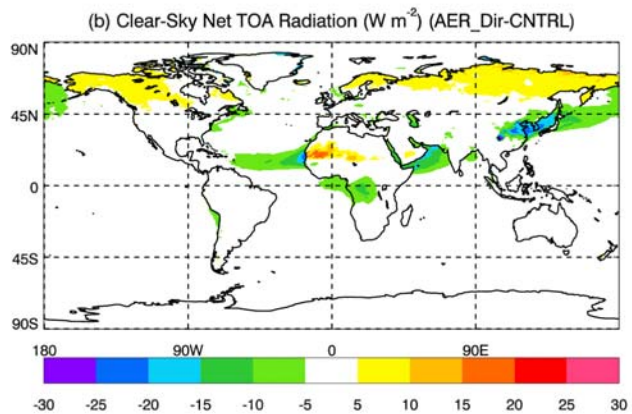
Aerosol-radiation impacts on net clear-sky TOA radiation

Mulcahy et al., ACP, 2014

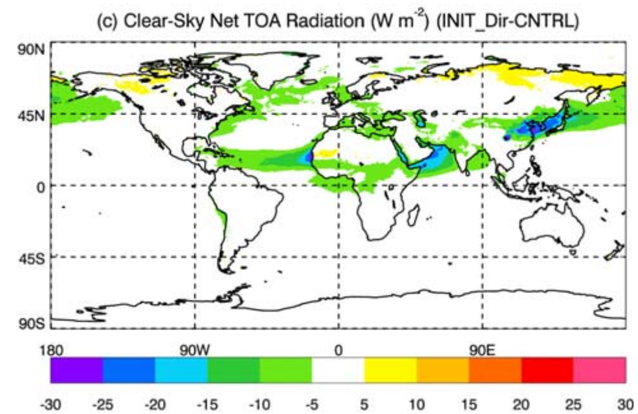
Impact of monthly varying climatologies



Direct aerosol effect from prognostic aerosols



Direct aerosol effect from DA initialised prognostic aerosols

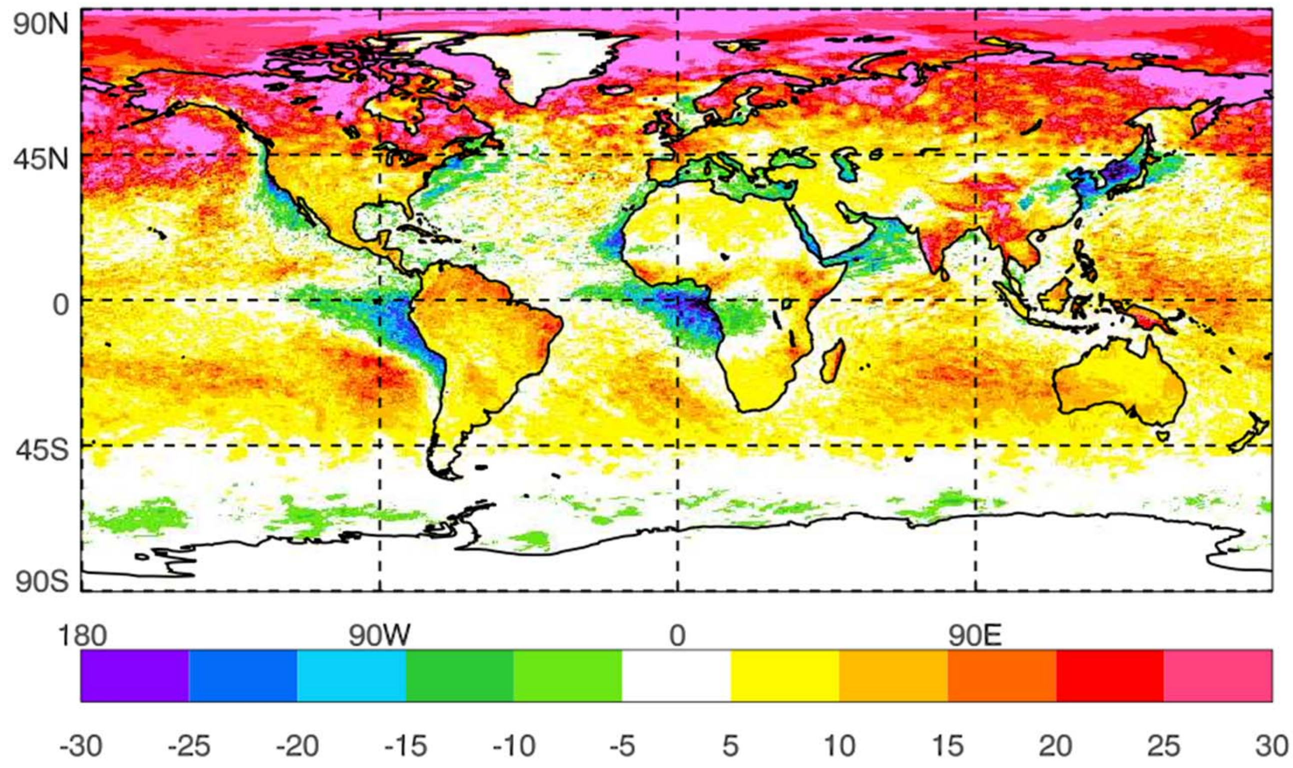


Impacts of aerosol complexity

Aerosol-cloud interactions

Mulcahy et al., ACP, 2014

Impact of prognostic aerosols on Surface SW (T+120)

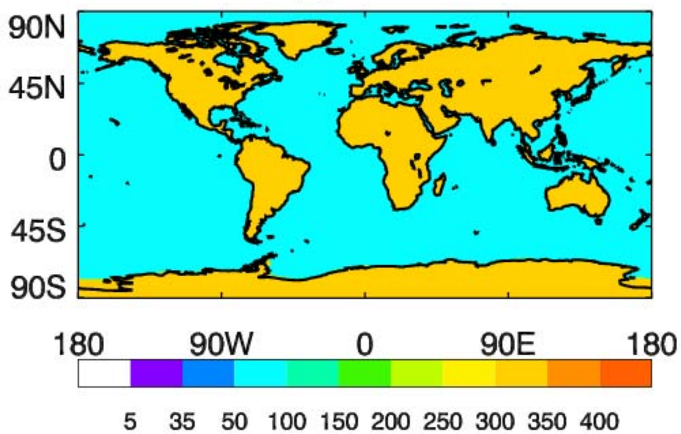


Impact of aerosol complexity

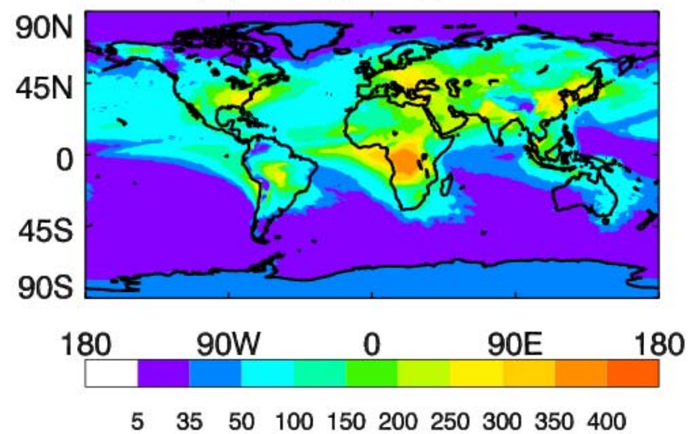
Aerosol-cloud interaction assumptions

Mulcahy et al., ACP, 2014

Potential CDNC in direct effect only expts



Potential CDNC from direct & indirect effect only expts



CDNC assumes a land/sea split distribution:

Nd = 300 cm^{-3} (land)

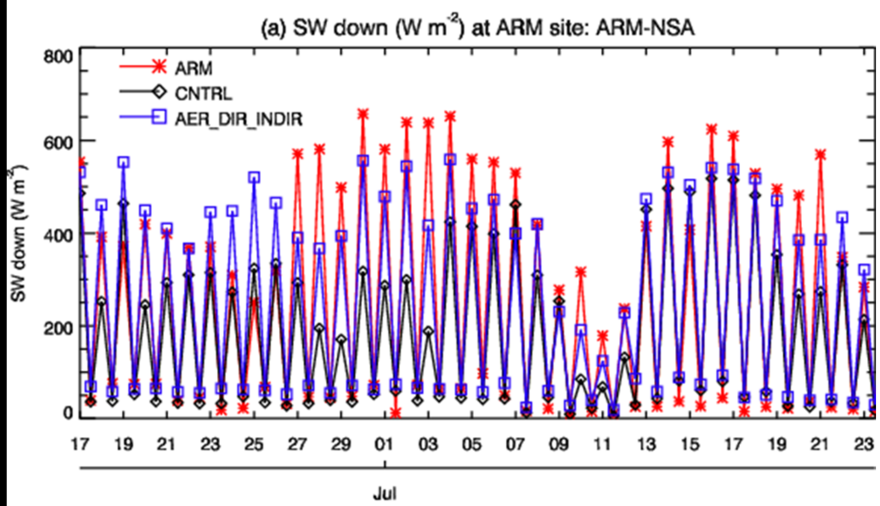
Nd = 100 cm^{-3}(ocean)

CDNC diagnosed from Jones et al. (2001):

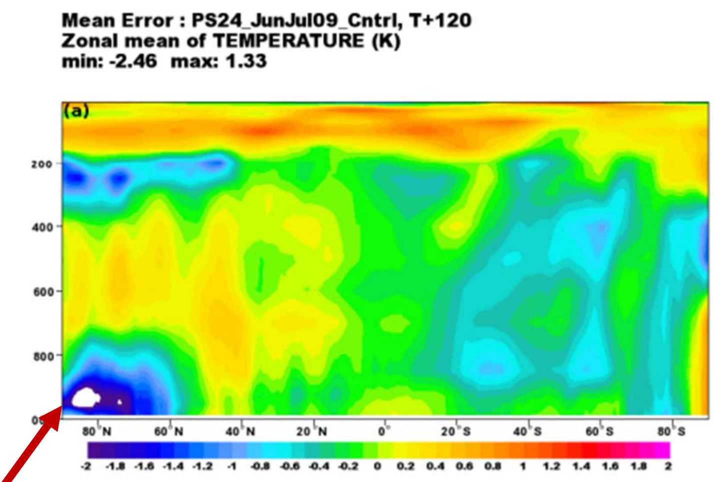
$$N_d = 375x10^6\left(1.0 - \exp\left(-2.5x10^{-9} CNN\right)\right)$$

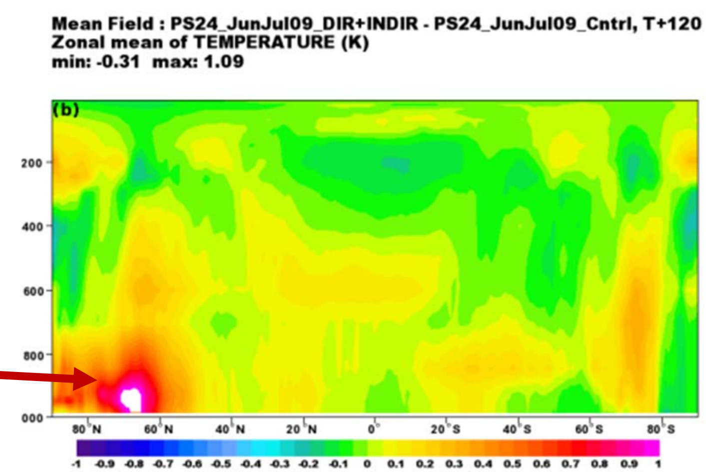
Impact of aerosol complexity

On model biases



- Improvements in radiation biases in North Slope Alaska
- Improvements in day 5 temperature forecasts in high latitudes.
- Control has largest errors near surface at high latitude
- Much warmer in test with prognstic aerosol as fewer CCN means less bright cloud





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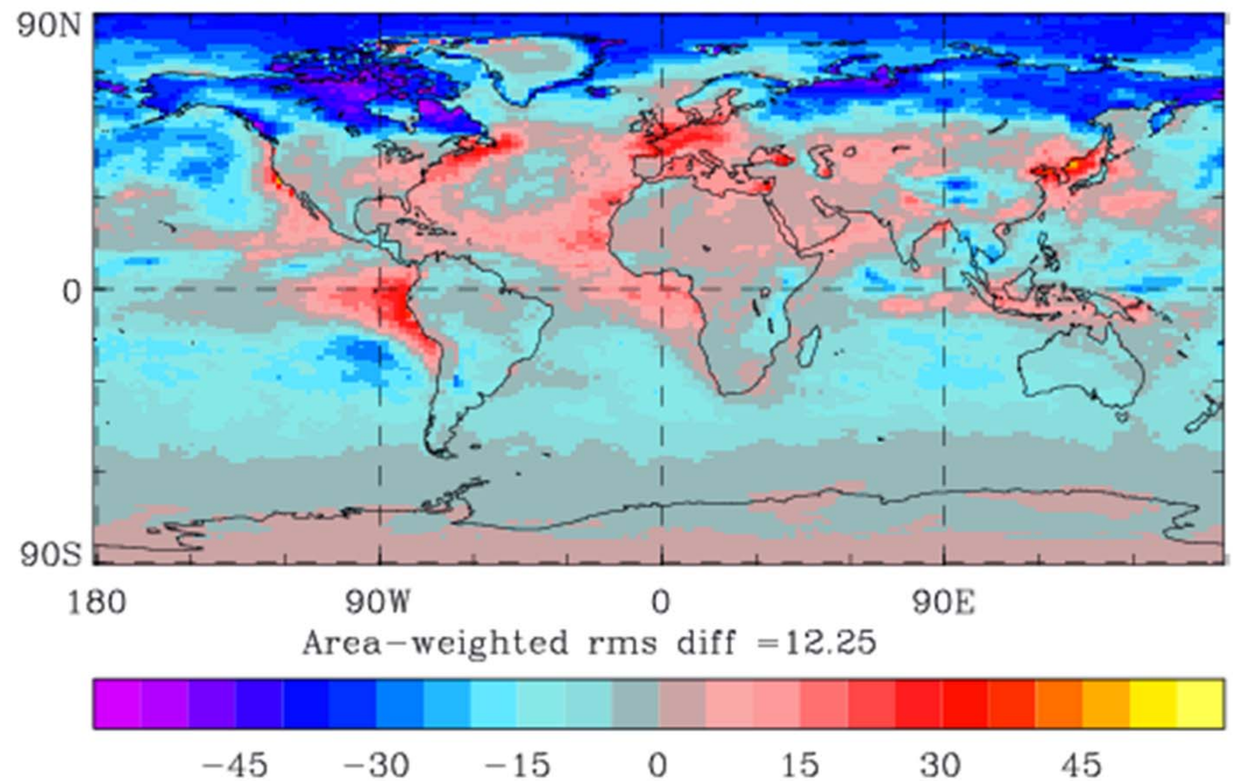
Impact of aerosol complexity

Reverse experiment: Including NWP climatologies in CLASSIC climate simulation - *Tom Riddick*

Impact on JJA surface SW



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Impact of aerosol complexity

Climate model w/ climatology for indirect effect

James Manners, Tom Riddick, Jonathan Wilkinson

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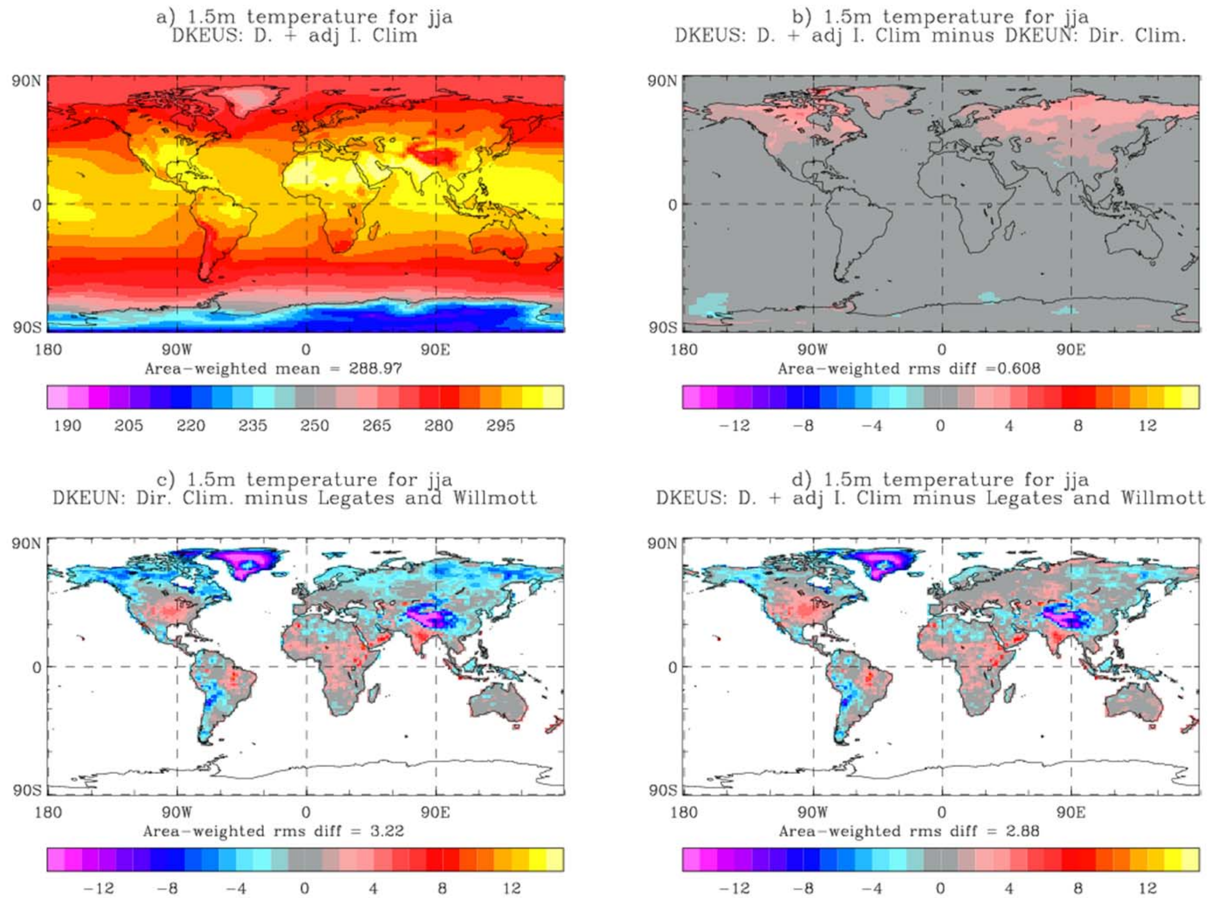
Impact of adding climatological indirect aerosol effects on 20 year mean JJA $T_{1.5m}$ error:



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Impact of aerosol complexity

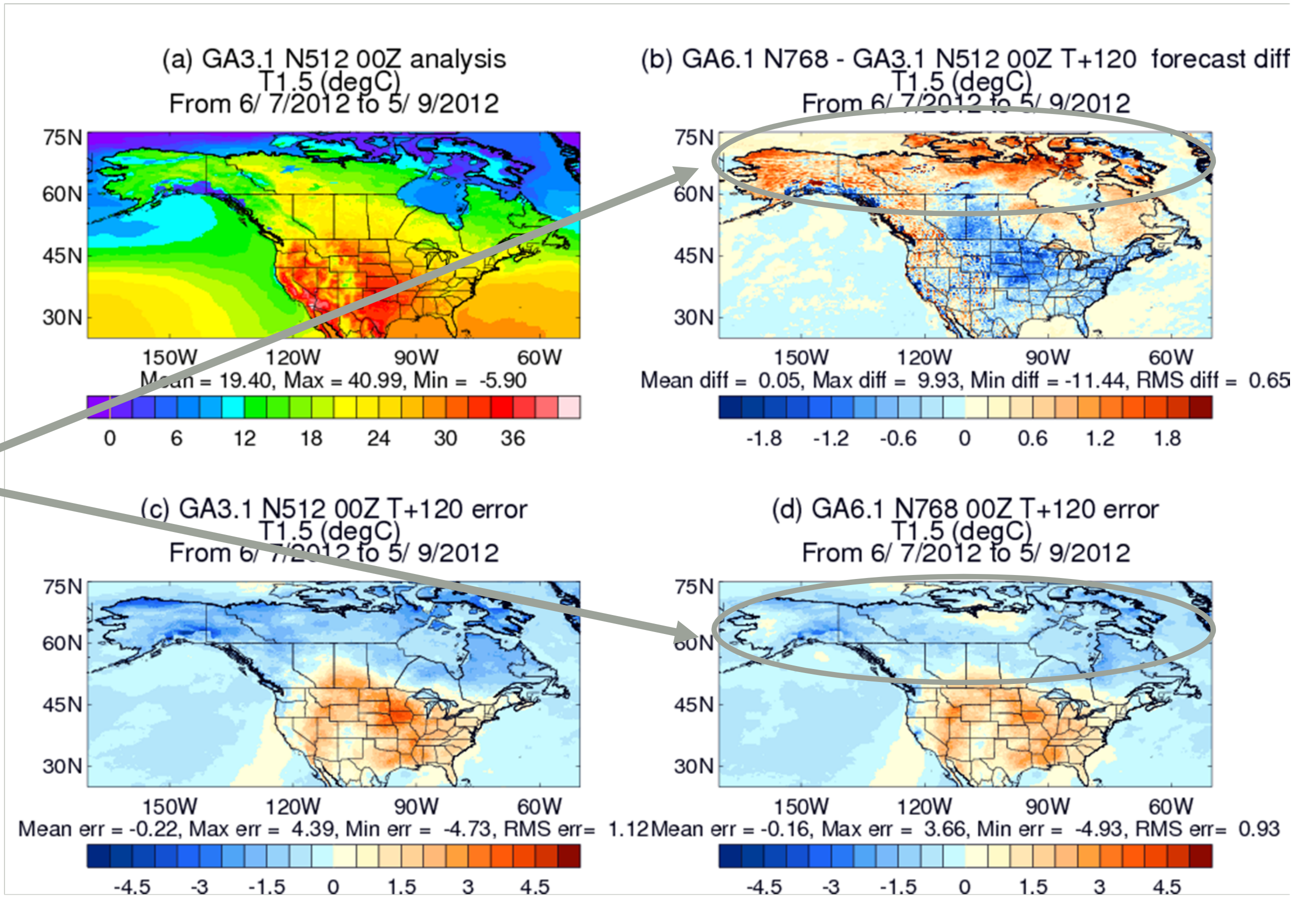
An example of seamless model development

Tom Riddick

Impact on operational implementation (alongside other model changes)

High latitude improvements from aerosol climatologies

Lower latitude improvements from other changes



Impact of aerosol complexity

Lessons learnt

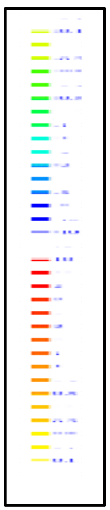
- Running experiments with additional complexity teach you *both* about the potential benefits of complexity *and* the short-comings of your less complex approach
- Highlighting here the important role for inclusion of aerosol-cloud interactions in NWP models (most operational models still don't do this)
- Adopting a *traceable* approach (e.g. to reproduce the mean behaviour of the fully complex scheme) may go a long way to achieving the benefits of the full scheme

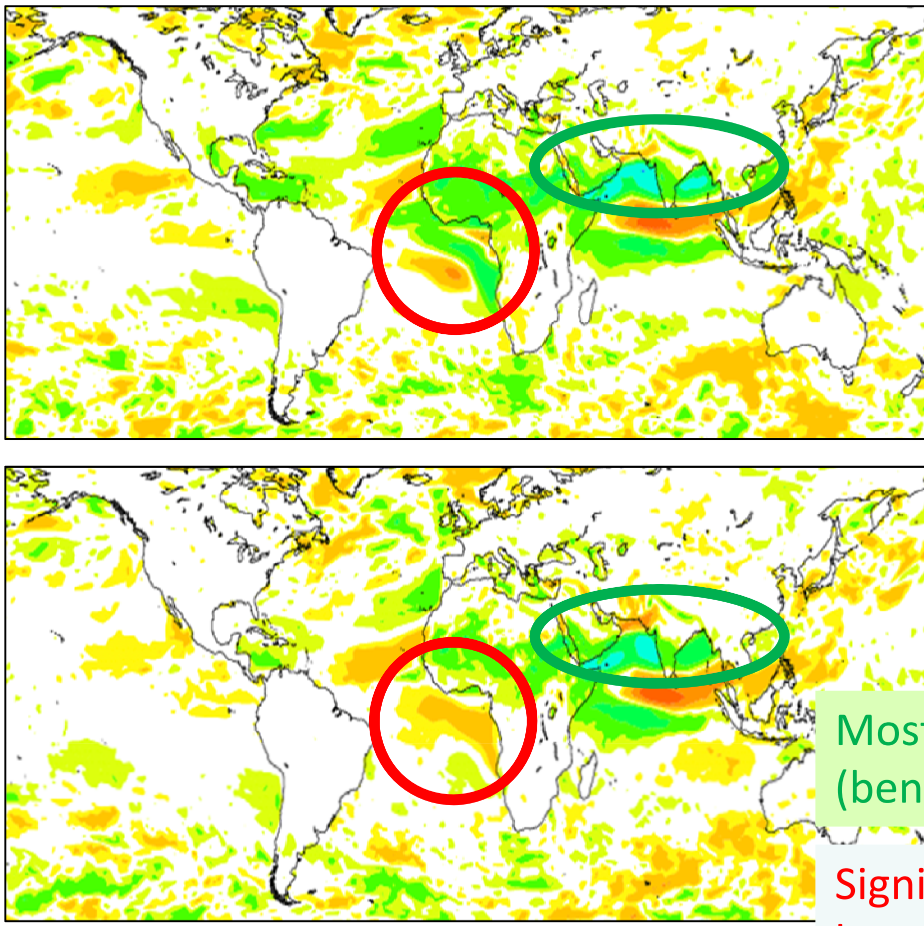
Aerosol impacts in ECMWF IFS

Benefits of an improved climatology

Jean-Jacques Morcrette

10m wind difference





{MACC full prognostic aerosol – REF Oper clim (Tegen et al.)}

{MACC clim – REF Oper clim}

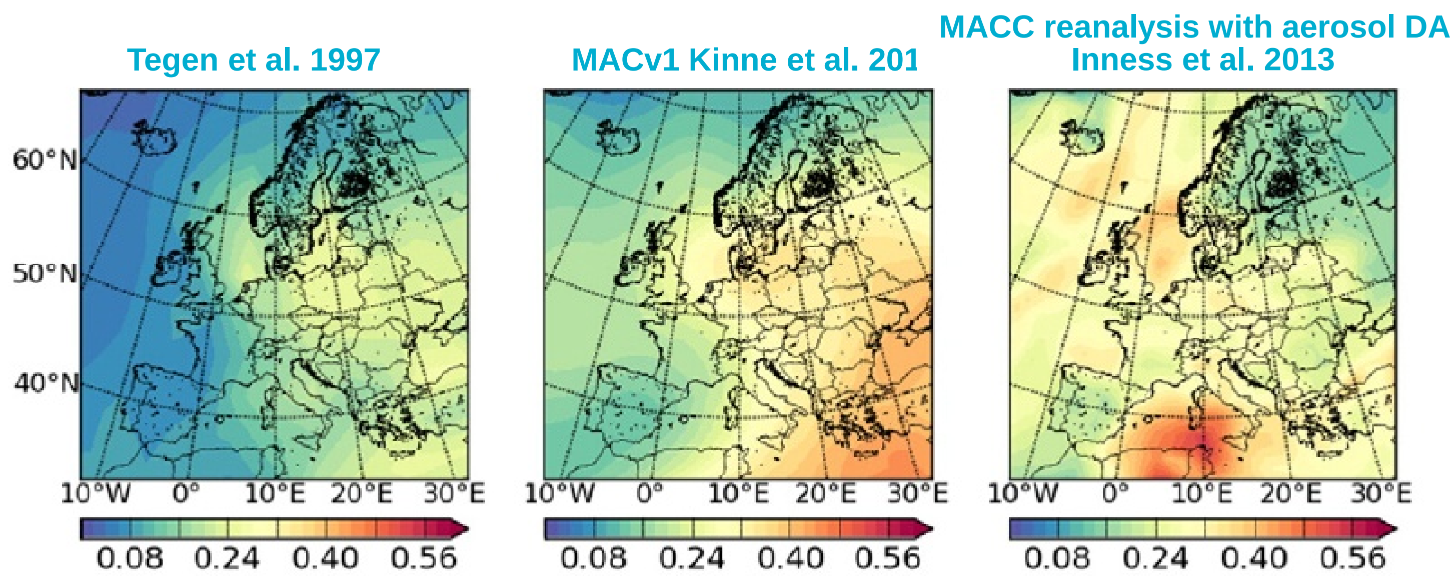
Most global patterns captured including (beneficial) deceleration of Somali jet

Significant differences in some aerosol hot spots with high variability

Aerosol impacts in HIRLAM

Evaluated the impact of different climatological aerosol representations – direct effect only *Toll et al.(2016)*

AOD from climatology:



General improvement with inclusion of aerosol in bias and rmse across a range of met parameters in particular downwelling SW (GHI), specific humidity.

Smaller benefits between choice of climatology but MACC (highest temporal resolution of aerosol information) generally performs better

Table 1

RMSEs and biases for a range of meteorological parameters for CNTRLEXP, TEGEXP, MACv1EXP and MACCEXP. RMSE and bias are calculated at 6-h intervals and averaged over the full forecast length (up to +96 h). Clear sky conditions both in the model and observations are chosen for GHI.

Experiment name	CNTRLEXP	TEGEXP	MACv1EXP	MACCEXP
MSLP bias (hPa)	0.90	0.77	0.80	0.71
MSLP RMSE (hPa)	1.63	1.53	1.56	1.50
2 m temperature bias (°C)	−1.01	−1.03	−1.04	−1.03
2 m temperature RMSE (°C)	2.92	2.93	2.94	2.93
2 m specific humidity bias (g/kg)	0.16	0.13	0.10	0.12
2 m specific humidity RMSE (g/kg)	1.09	1.08	1.07	1.08
Cloud cover bias (octas)	0.50	0.43	0.41	0.42
Cloud cover RMSE (octas)	2.70	2.69	2.68	2.69
12 h precipitation bias (mm/12 h)	0.25	0.21	0.19	0.19
12 h precipitation RMSE (mm/12 h)	2.41	2.40	2.38	2.39
GHI bias (W/m^2)	15.07	1.49	−5.30	−2.79
GHI RMSE (W/m^2)	16.54	8.07	10.20	8.32

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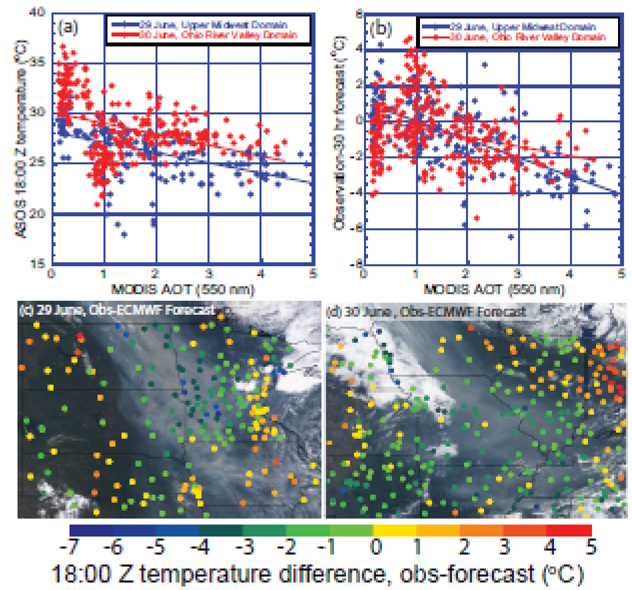
High impact regional aerosol events

Eg: dust storms or biomass burning plumes from forest fires

Zhang et al., ACP 2016

- Smoke event over Mid-west USA, June 2015
- Strong surface temperature gradient between regions to the west of main plume and under the plume.
- Smoke aerosol induced strong surface cooling efficiency of -1.5deg/τ_{550}
- Operational models:

  -0.25 to -1.0 deg/ τ_{550}



Models over-predict surface temperatures under the plume by up to 7deg

SAMBBA biomass burning aerosol

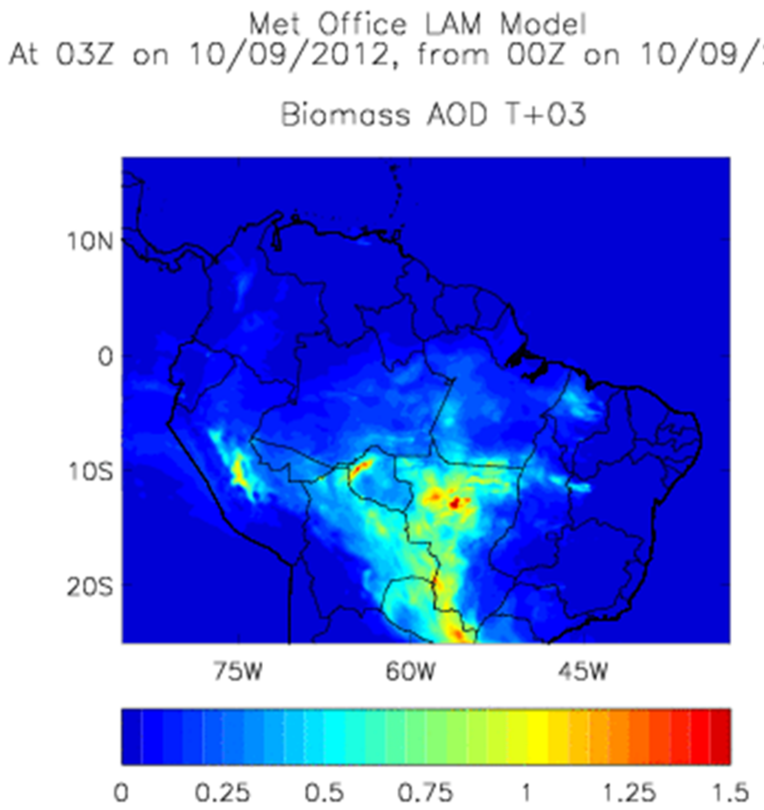
Kolusu et al., ACP, 2015

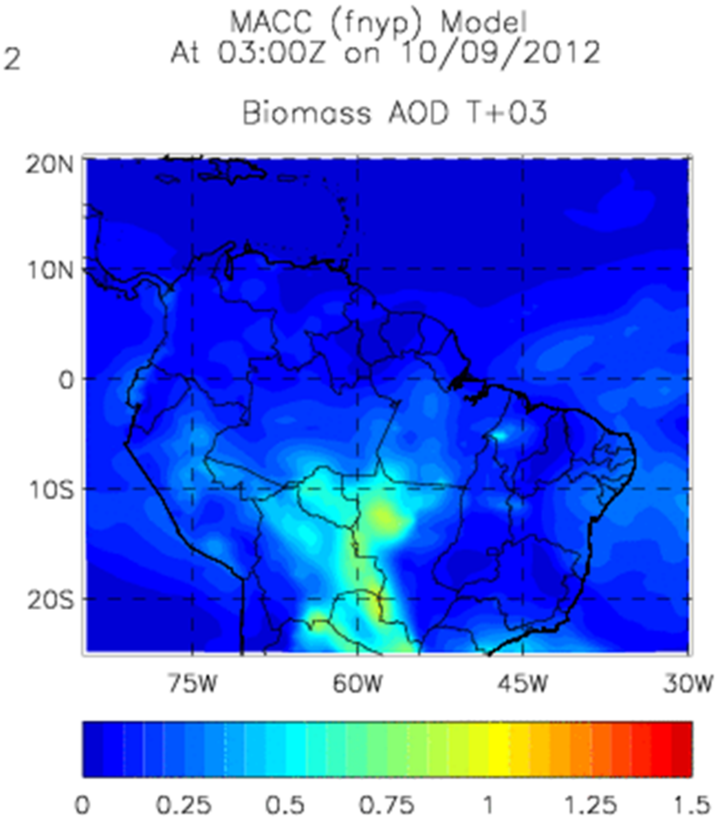
- Extensive field campaign conducted over Amazonia from 14th Sept – 3rd Oct 2012.
- Aimed to characterize the impacts of biomass burning aerosol on air quality, NWP and climate.
- Ran a 12km Limited Area Model with prognostic BBA from CLASSIC to help with flight planning
- After the campaign, investigated the impact of the direct aerosol effect

Credit: Will Morgan, Uni of Manchester

Comparison against MACC

The MACC aerosol forecasting system assimilates AOD using MODIS total AOD at 550nm.





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SAMBBA

Prognostic vs. climatological BBA AOD

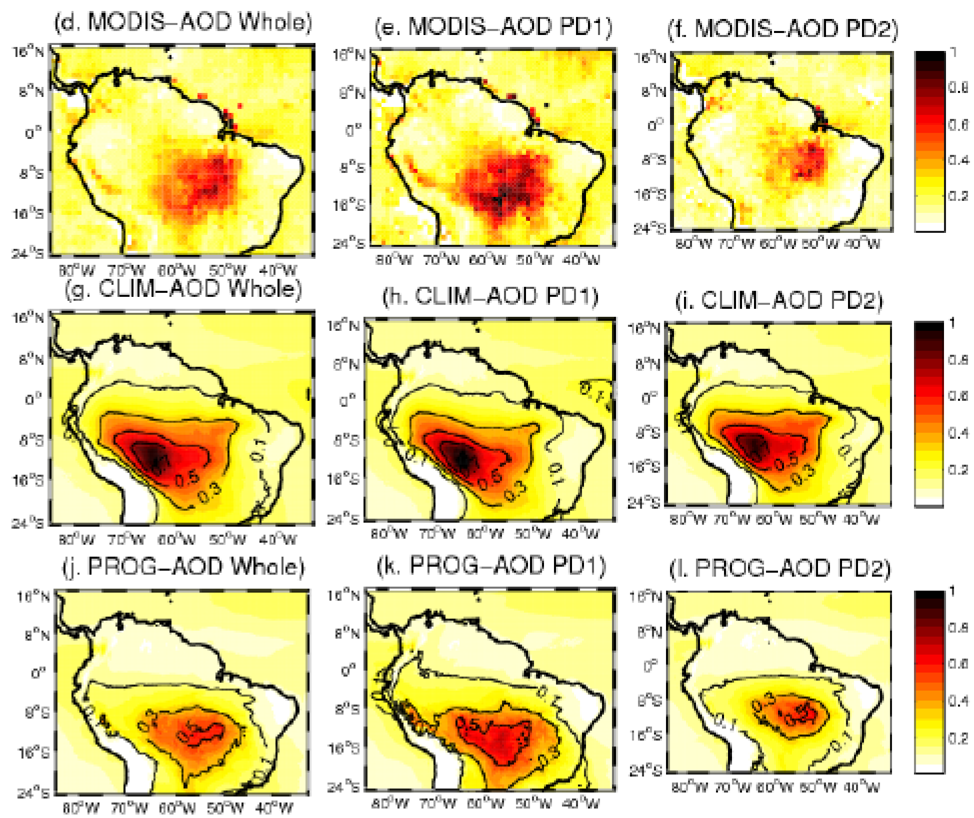
LAM uses daily fire emissions from Global Fire Assimilation System (GFASv1.1)

Prognostic scheme correctly shifts main burning regions to the East

MODIS

Climatology

Prognostic



Kolusu et al., ACP, 2015

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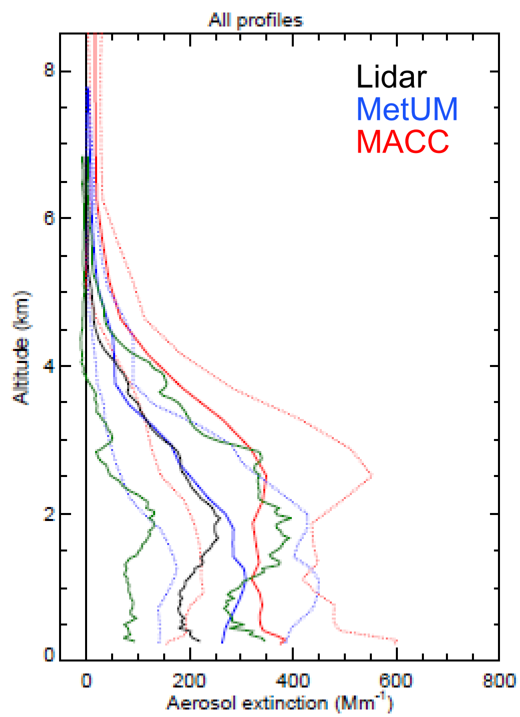
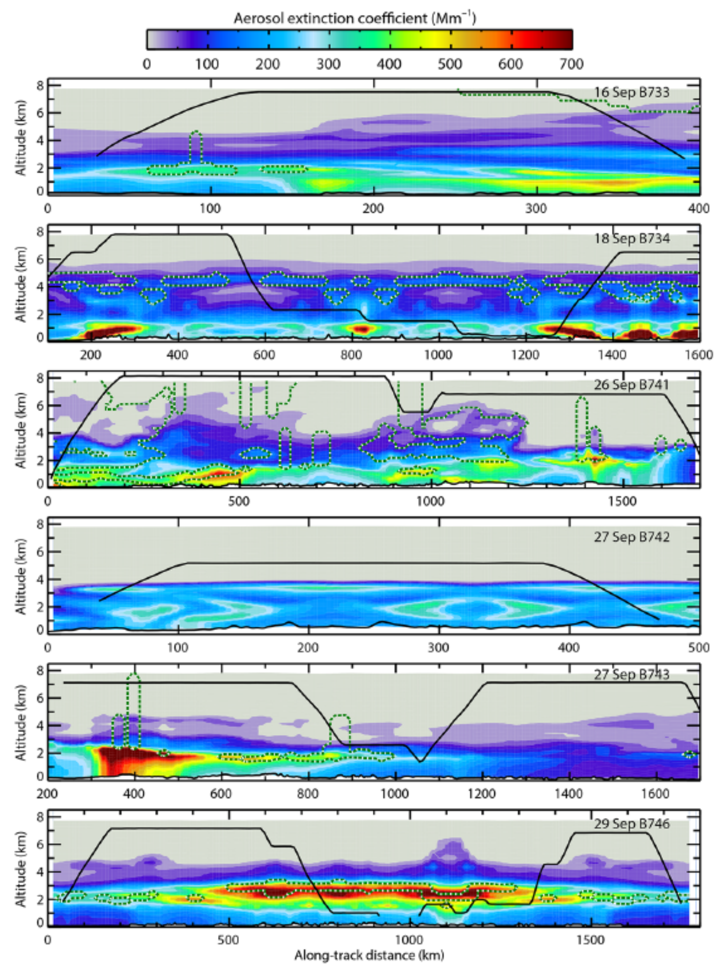
SAMBBA

Simulation of vertical profiles of biomass burning aerosol





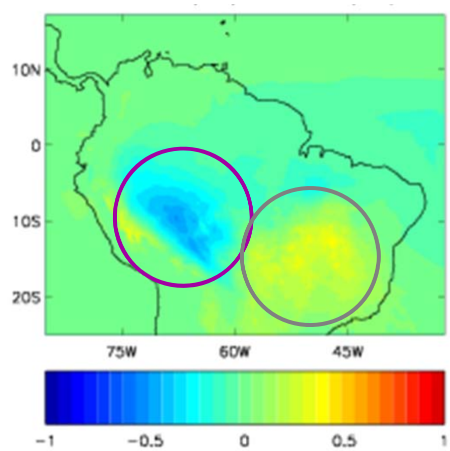
Marenco et al., ACP, 2016

SAMBBA

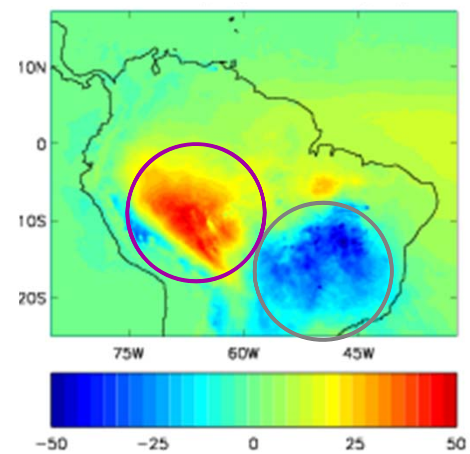
Prognostic vs. Climatology - Impact on radiation

Regional shift in the direct radiative impact of the aerosol

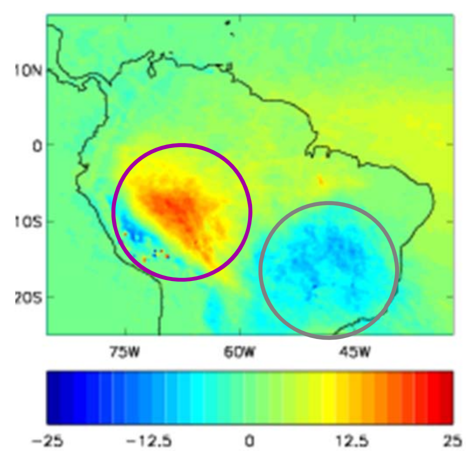
PROG BBA – CLIM
AOD



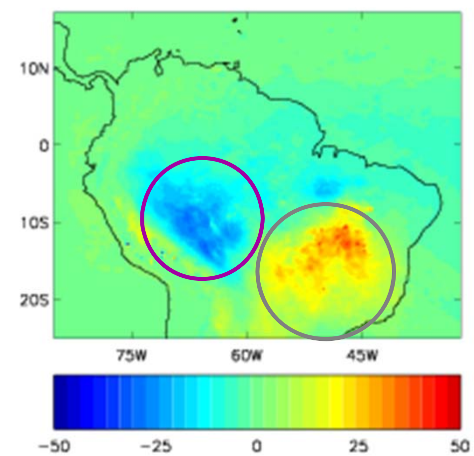
PROG BBA – CLIM
Net surface radiation (W m^{-2})



PROG BBA – CLIM
Net TOA radiation (W m^{-2})



PROG BBA – CLIM
Atm. Divergence (W m^{-2})

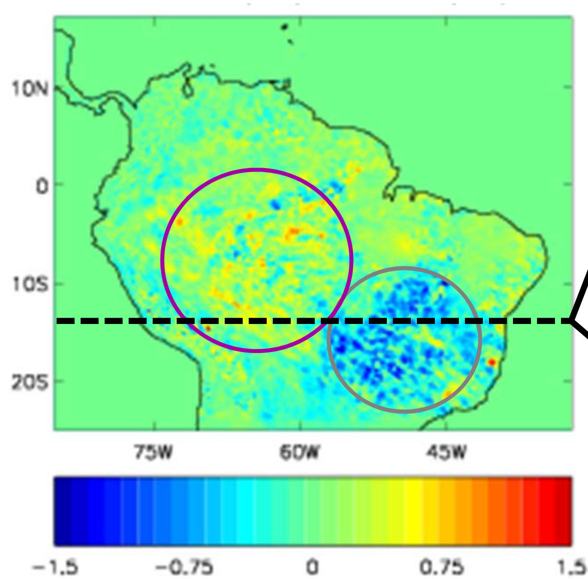


Caroline Dunning

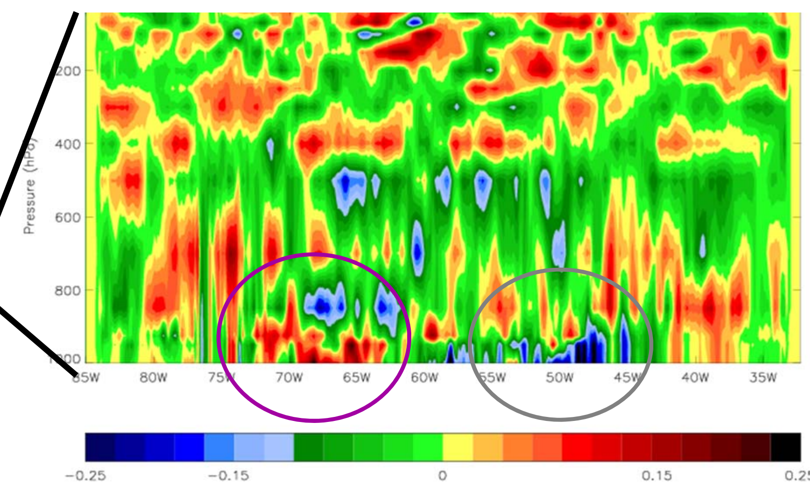
SAMBBA

Prognostic vs. Climatology

Impact on $T_{1.5m}$



Impact on temperature cross section over 10-13S

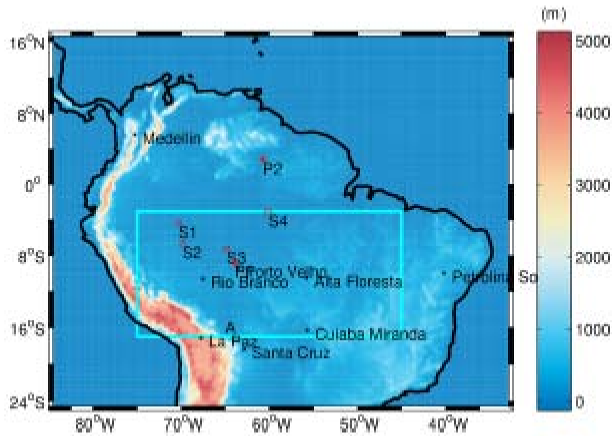


Different aerosol loadings affect both surface temperature and the vertical temperature profile, via scattering and absorption.

Caroline Dunning

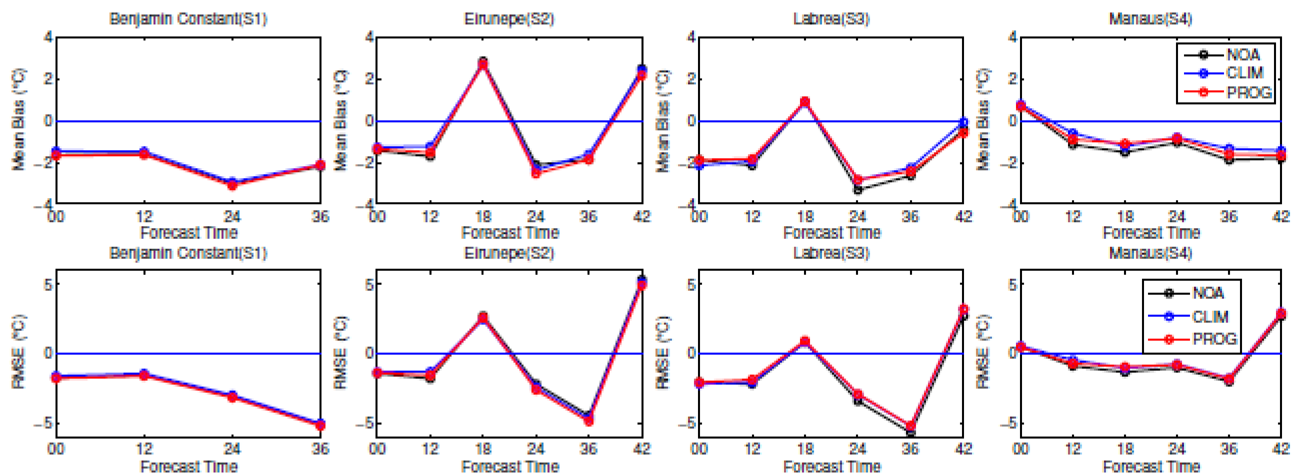
SAMBBA

Implications for temperature biases



Small and significant improvements in 2m temperature bias and rmse relative to No Aerosol run.

Differences not significant relative to aerosol climatology.



Kolusu et al., ACP, 2015

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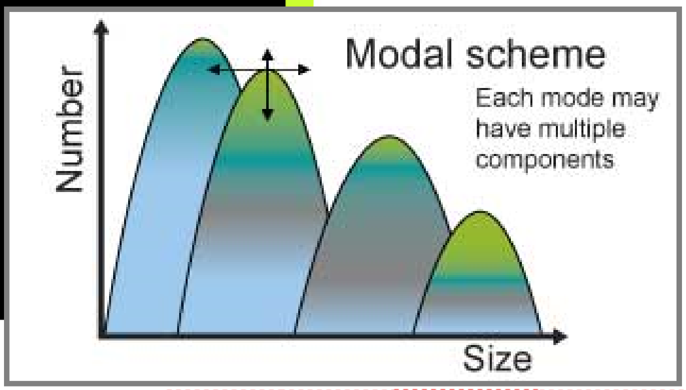
SAMBBA summary

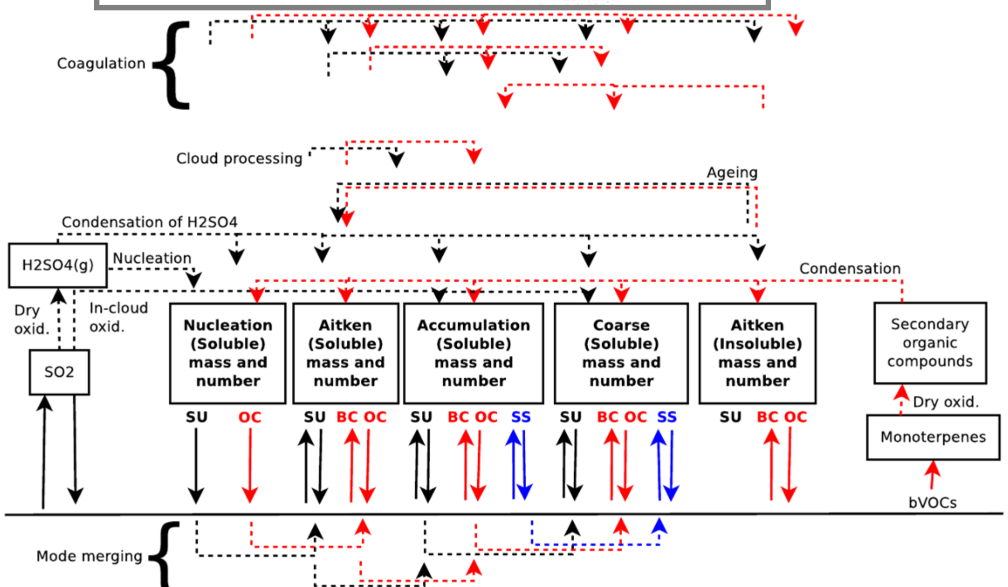
- Successful NRT forecasts of biomass burning aerosol produced for the first time to support flight planning
- Demonstrated skill in aerosol simulations: good evaluation of aerosol optical properties
- Direct effect of BBA: significant impact on radiation, some but small improvement in met biases/fields

How complex is complex?

Further increasing aerosol complexity and complexity of cloud-radiation interactions

UKESM





GLOMAP-mode (Mann et al. 2011)

Included in UKESM / HadGEM3 climate model from GA7 config

Online calculation of aerosol optical properties (RADAER)

Online aerosol activation to cloud droplets (UKCA-Activate, West et al. 2014)

Inconsistent treatment of aerosol between NWP – climate

GLOMAP climatologies currently being developed for NWP

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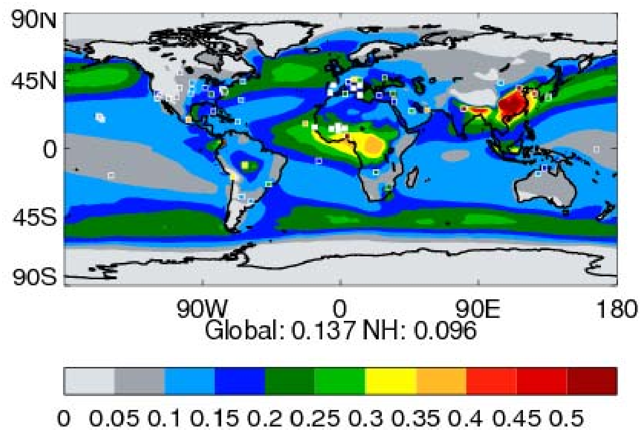
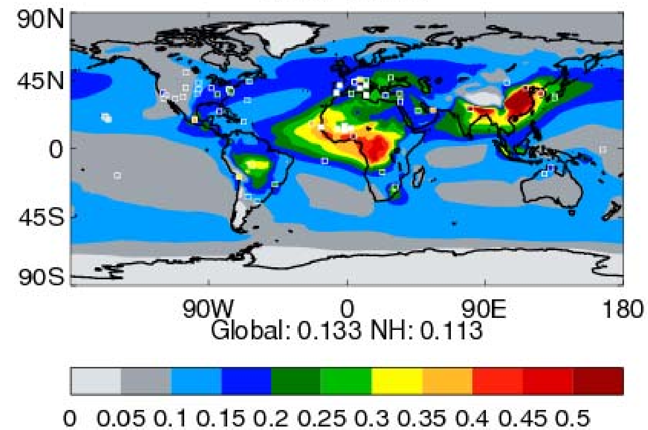
How complex is complex?

CLASSIC vs. GLOMAP-mode Annual mean AOD (550nm)

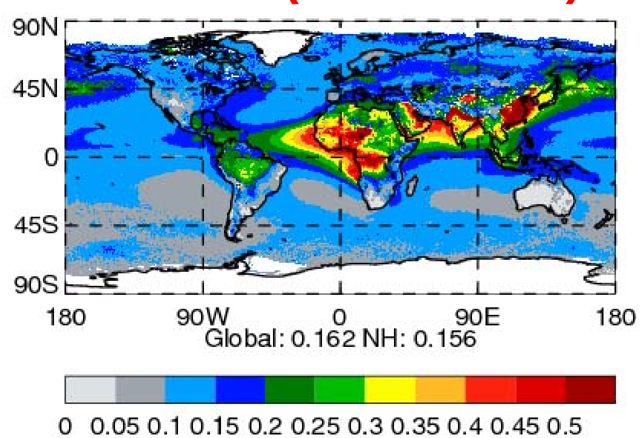
HadGEM3 GA6
CLASSIC



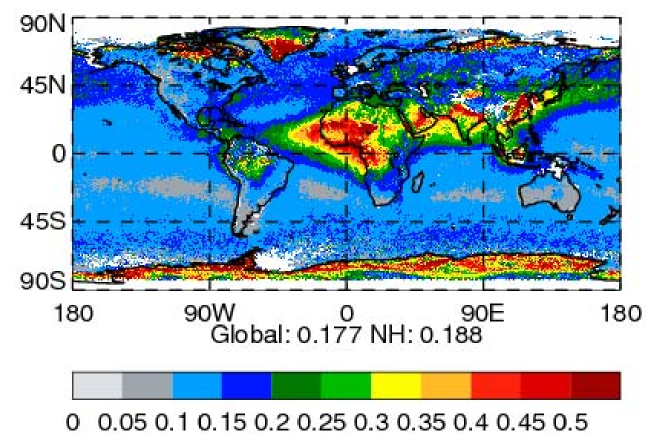
HadGEM3 GA7
GLOMAP-Mode



MODIS (2003 – 2012)



MISR (2002 – 2006)



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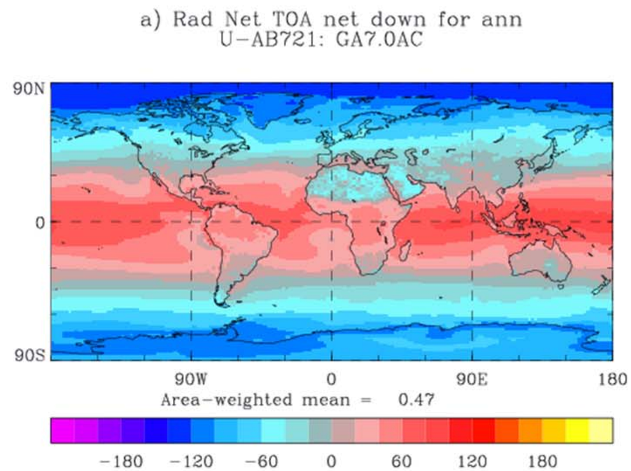
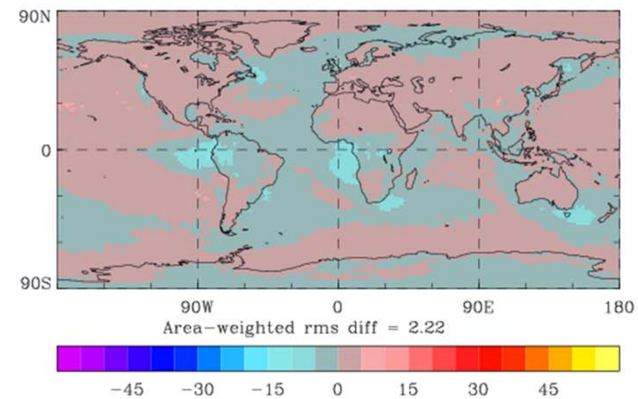
How complex is complex?

GLOMAP-mode vs. CLASSIC climatologies

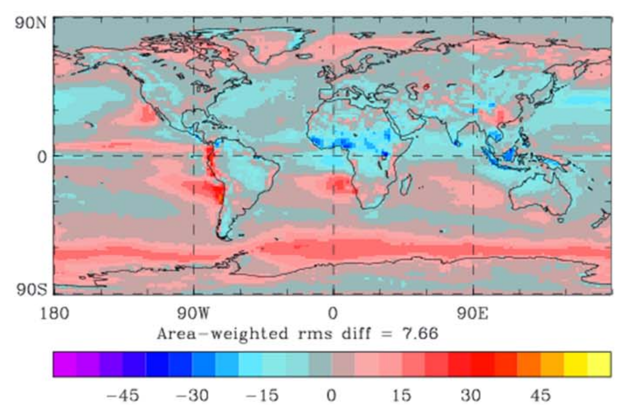
Impact on net TOA radiation



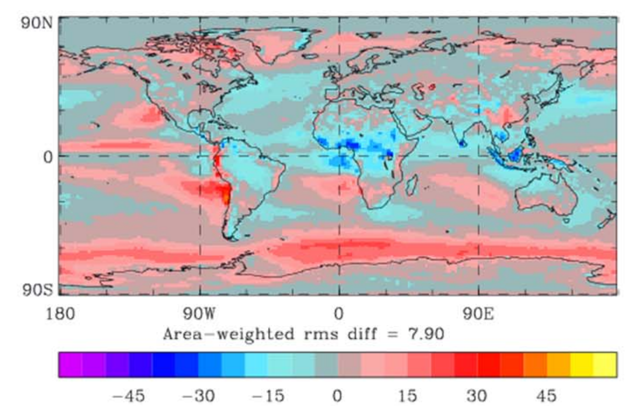
CLASSIC CLIM - GLOMAP-mode



GLOMAP-mode - CERES EBAF



CLASSIC CLIM - CERES EBAF



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Conclusions

Take away messages

- It is clear online aerosol simulations are better able to capture the day-to-day and seasonal variability of global aerosol distributions compared to climatologies used in many operational NWP models.
- Allows us to develop global environmental prediction systems – ICAP MME is a really nice example of this.
- Online interactive aerosols clearly improve the radiation budget of the model.
- Impact on global forecast skill overall is small, although regionally larger.
- Cost-benefit analysis: benefit of interactive online aerosols < benefit of increasing resolution or ensemble member size (for instance)
- Studies do highlight shortcomings in our “simplified” approach for aerosols in operational NWP model which can be addressed (cheap).
- Complexity : will the development of more complex aerosol microphysical models and improved parameterizations of aerosol-cloud interactions (multi-moment cloud microphysics) will allow us to re-address the benefit of interactive aerosols.
- Ripe area of research with lots of potential – as all of todays talks will undoubtedly show.

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Thank you

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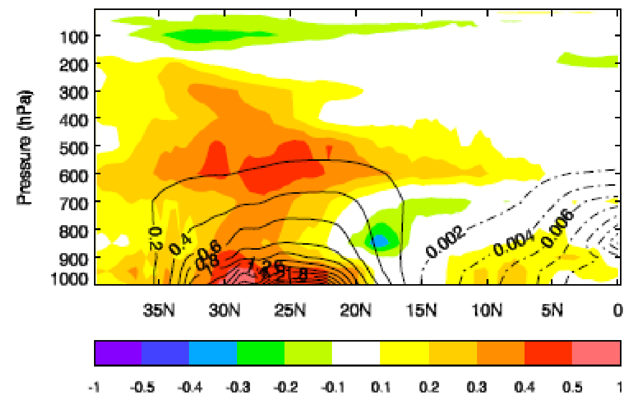
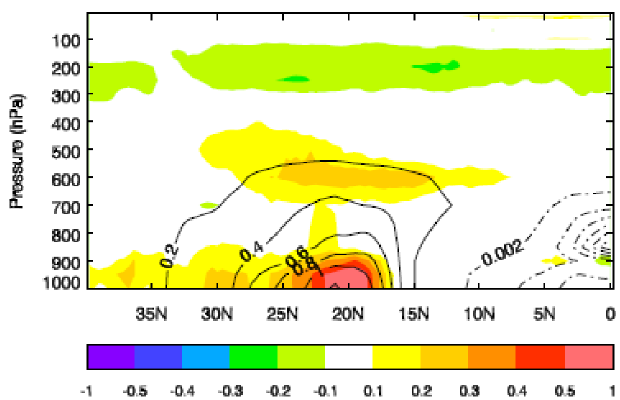
Impact of aerosol complexity

From aerosol-radiation interactions

Impact of monthly varying climatologies



Direct aerosol effect from prognostic aerosols



Direct aerosol effect from DA initialised prognostic aerosols