Atmospheric Composition Modelling and Assimilation (with focus on aerosols)

Angela Benedetti

With contributions from:

Alessio Bozzo, Francesca Di Giuseppe, Luke Jones, Samuel Rémy, Mark Parrington, Anna-Augusti Panareda, Vincent-Henri Peuch, Sebastien Massart, Antje Inness, Johannes Flemming, Miha Razinger, Martin Suttie, and the CAMS team

OUTLINE

- General introduction to the Copernicus Atmosphere Monitoring System (CAMS)
- Data products and catalogue
- Interesting cases: the Indonesian Fire season of 2015
- Overview of modelling and data assimilation efforts with focus on aerosols
- Impact of aerosols on NWP (medium-range and long-range)
- Summary and future perspectives in aerosol prediction

ECMWF

THE COPERNICUS ATMOSPHERE MONITORING SYSTEM (CAMS)

Atmospheric composition is a pivotal element between human activities and the Earth Environment

emissions

mitigation

aerosol

ozone *PM* *greenhouse gases*

NOx

air quality

climate change

ozone hole

numerical weather prediction

impacts

exposure

adaptation

Atmospheric composition and its changes affect our health and well-being

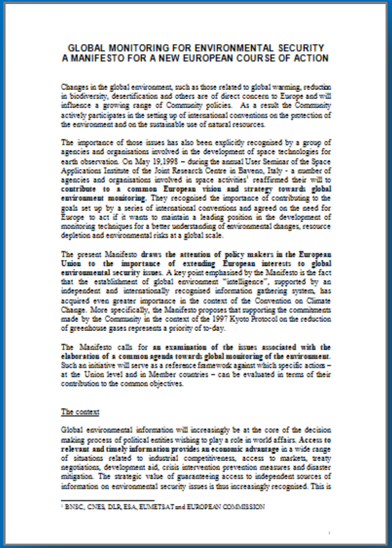
Copernicus

ECMWF

CAMS: A Significant Heritage

- A decade-long series of R&D projects and an internationally respected European achievement (GEMS, MACC, -II, -III)
- An equally long experience in engaging with users and potential users in Europe and across the world (PROMOTE, MACC, -II, -III)

Strategy



GLOBAL MONITORING FOR ENVIRONMENTAL SECURITY
A MANIFESTO FOR A NEW EUROPEAN COURSE OF ACTION

Changes in the global environment, such as those related to global warming, reduction in biodiversity, desertification and others are of direct concern to Europe and will influence a growing range of Community policies. As a result the Community actively participates in the setting up of international conventions on the protection of the environment and on the sustainable use of natural resources.

The importance of those issues has also been explicitly recognised by a group of agencies and organisations involved in the development of space technologies for earth observation. On May 19,1998 – during the annual User Seminar of the Space Applications Institute of the Joint Research Centre in Baveno, Italy - a number of agencies and organisations involved in space activities[1] reaffirmed their will to **contribute to a common European vision and strategy towards global environment monitoring**. They recognised the importance of contributing to the goals set up by a series of international conventions and agreed on the need for Europe to act if it wants to maintain a leading position in the development of monitoring techniques for a better understanding of environmental changes, resource depletion and environmental risks at a global scale.

The present Manifesto **draws the attention of policy makers in the European Union to the importance of extending European interests to global environmental security issues**. A key point emphasised by the Manifesto is the fact that the establishment of global environment "intelligence", supported by an independent and internationally recognised information gathering system, has acquired even greater importance in the context of the Convention on Climate Change. More specifically, the Manifesto proposes that supporting the commitments made by the Community in the context of the 1997 Kyoto Protocol on the reduction of greenhouse gases represents a priority of to-day.

The Manifesto calls for **an examination of the issues associated with the elaboration of a common agenda towards global monitoring of the environment**. Such an initiative will serve as a reference framework against which specific actions – at the Union level and in Member countries – can be evaluated in terms of their contribution to the common objectives.

The context

Global environmental information will increasingly be at the core of the decision making process of political entities wishing to play a role in world affairs. **Access to relevant and timely information provides an economic advantage** in a wide range of situations related to industrial competitiveness, access to markets, treaty negotiations, development aid, crisis intervention prevention measures and disaster mitigation. The strategic value of guaranteeing access to independent sources of information on environmental security issues is thus increasingly recognised. This is

[1] BNSC, CNES, DLR, ESA, EUMETSAT and EUROPEAN COMMISSION

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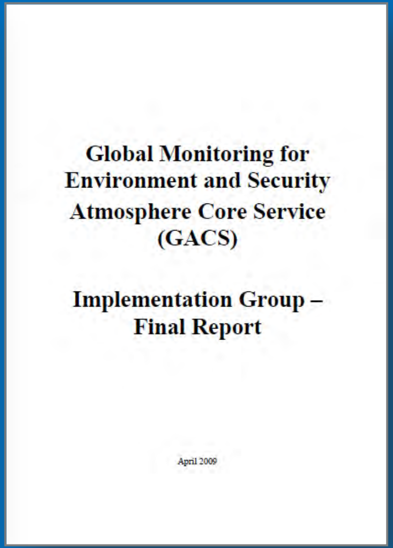
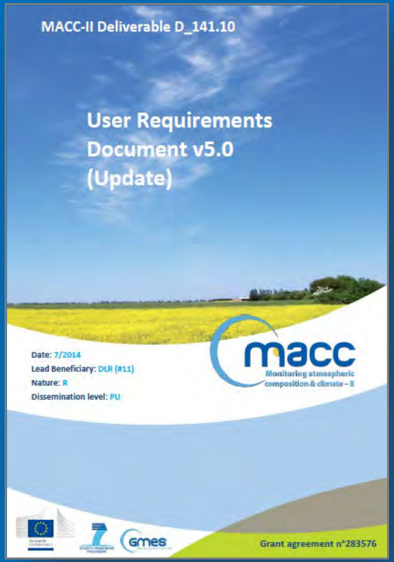
Socio-economic impact

Experts



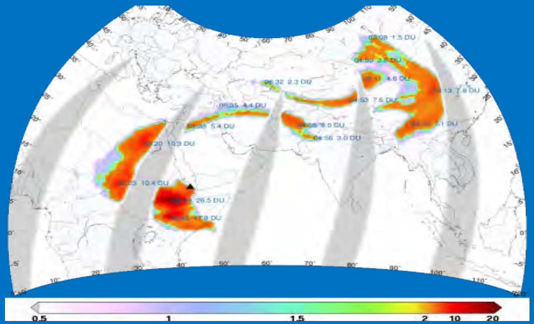
Users

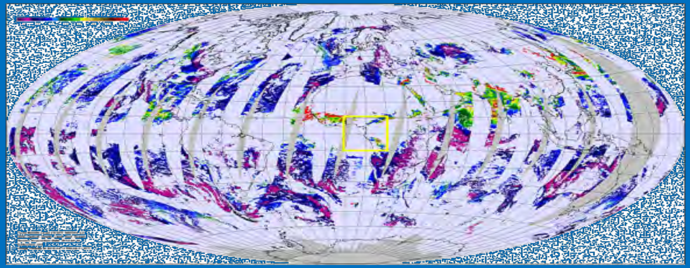


opernicus

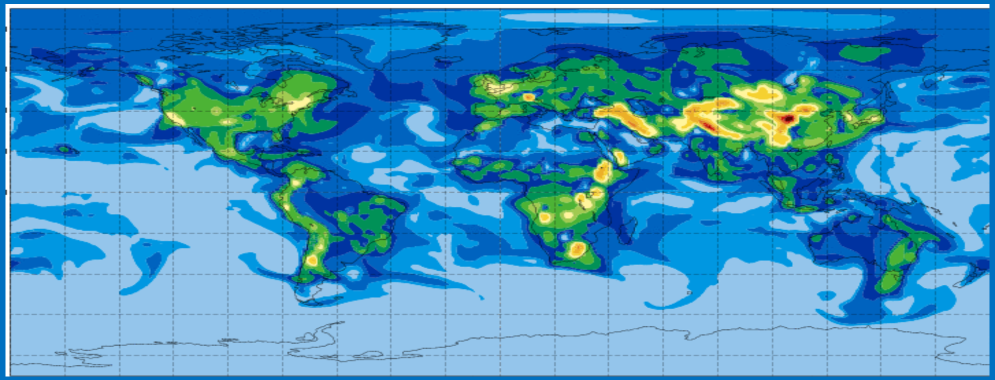
ECMWF

From Earth Observation to policy-quality products

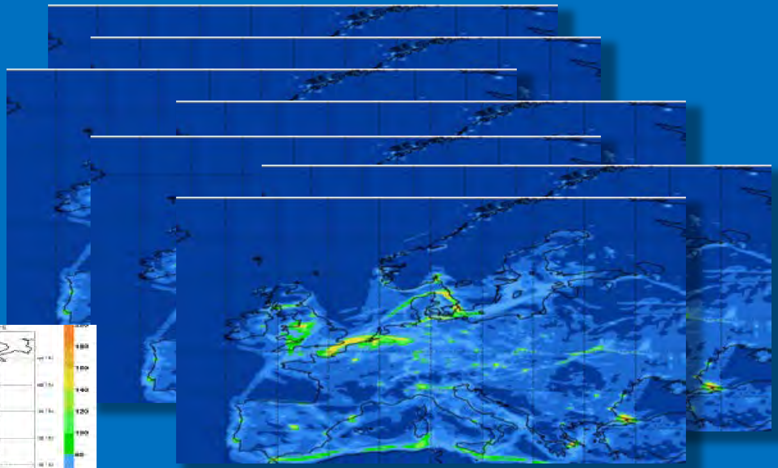




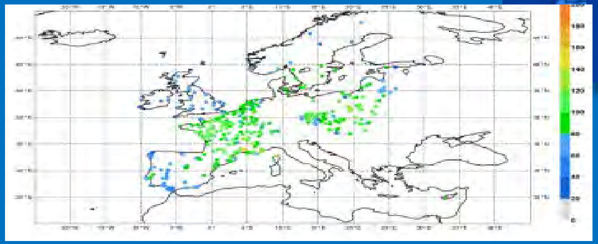
Over 70 EO instruments are assimilated in the global system

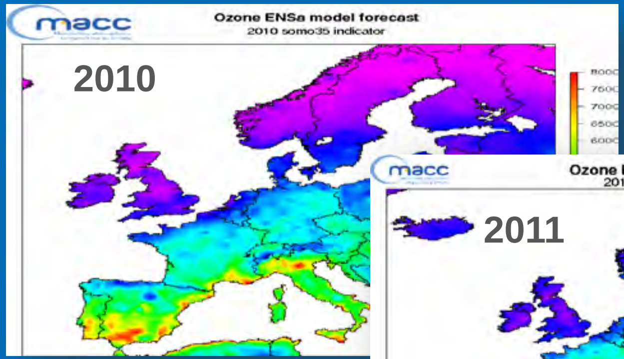


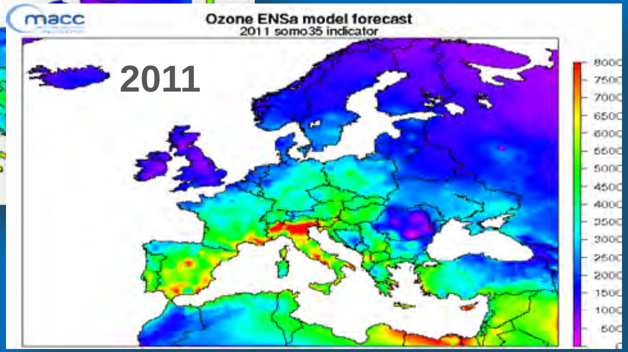
Boundary conditions feed an <u>ensemble</u> of high-resolution European AQ systems (in order to assess uncertainties)



More data are assimilated (in particular in situ) and used for extensive validation







Policy-relevant (here health indicator for ozone) products are delivered. They are “maps with no gaps”, which observations alone don’t provide and are essential to assess impacts.

CAMS Portfolio

AIR QUALITY AND ATMOSPHERIC COMPOSITION

European air quality analyses, forecasts and assessments in support of reporting and policy making, pollen forecasts, global transport of constituents/pollutants.

CLIMATE FORCING

Distributions of aerosol components and their radiative impacts, other radiative forcings.

OZONE LAYER AND UV

Monitoring and forecasting of the ozone layer / hole, UV index, UV radiation (crops, ecosystems).

SOLAR RADIATION

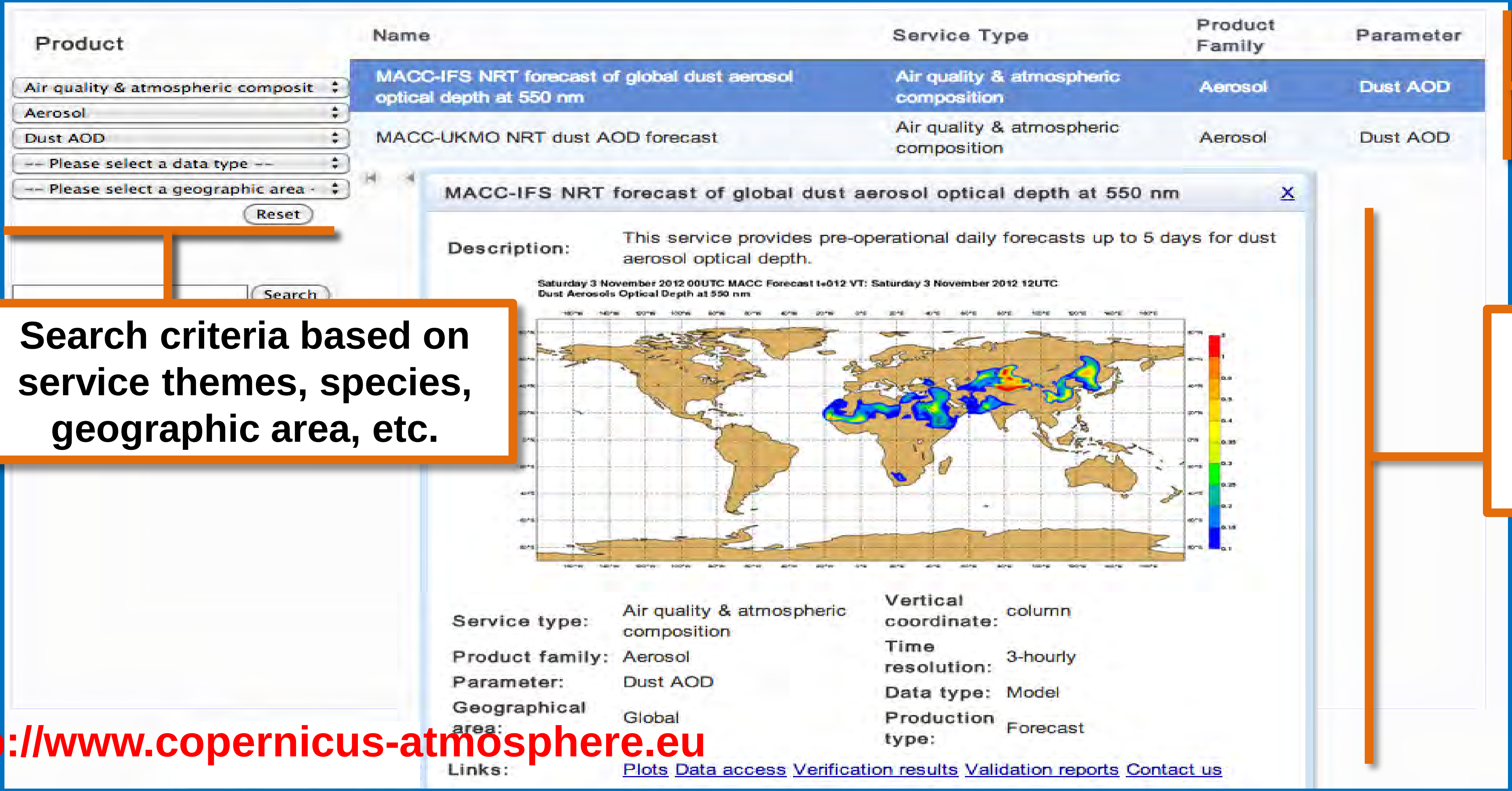
Estimates of solar irradiance at surface, improved potential yield assessments for solar plants.

EMISSIONS AND SURFACE FLUXES

Estimates of human emissions globally and in Europe (high-resolution), emissions by wildfires, surface fluxes of CO_2, CH_4 and N_2O.

http://www.copernicus-atmosphere.eu

CAMS online catalogue search (open data policy)



Products found

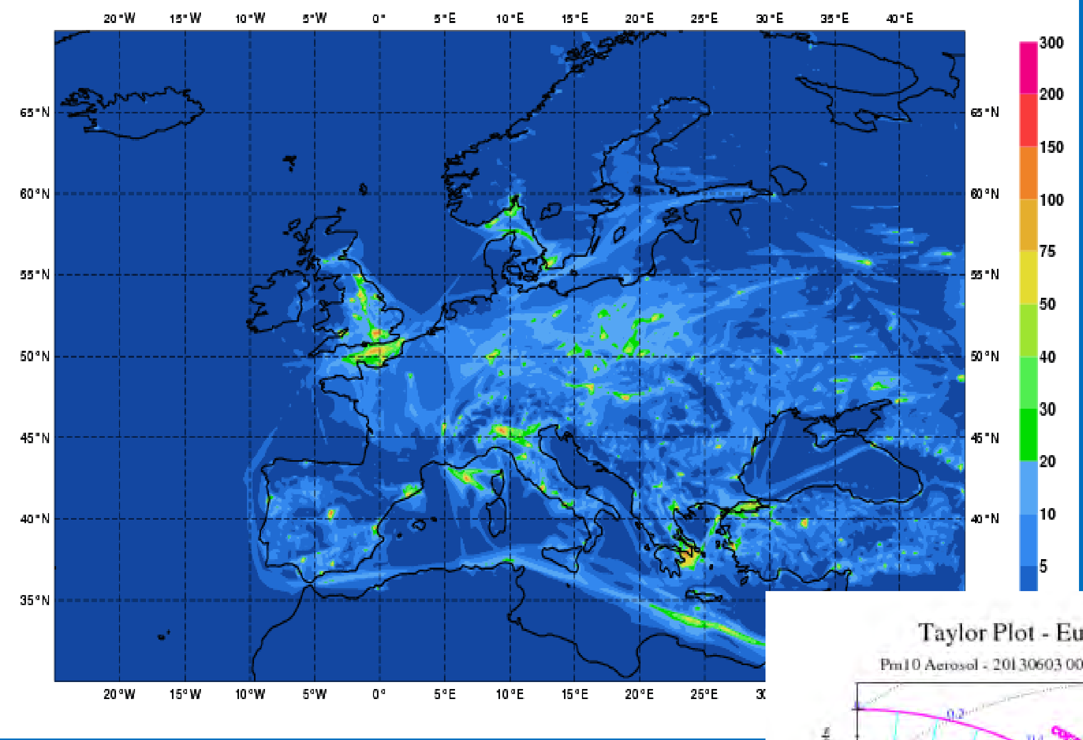
Search criteria based on service themes, species, geographic area, etc.

Pop-up window with product description and links to plots, data, and validation

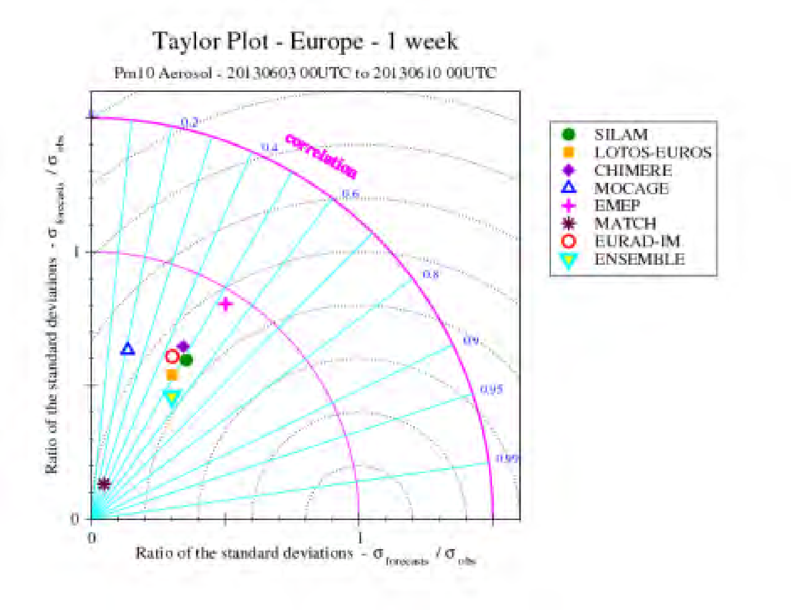
http://www.copernicus-atmosphere.eu

FORECAST PRODUCTS

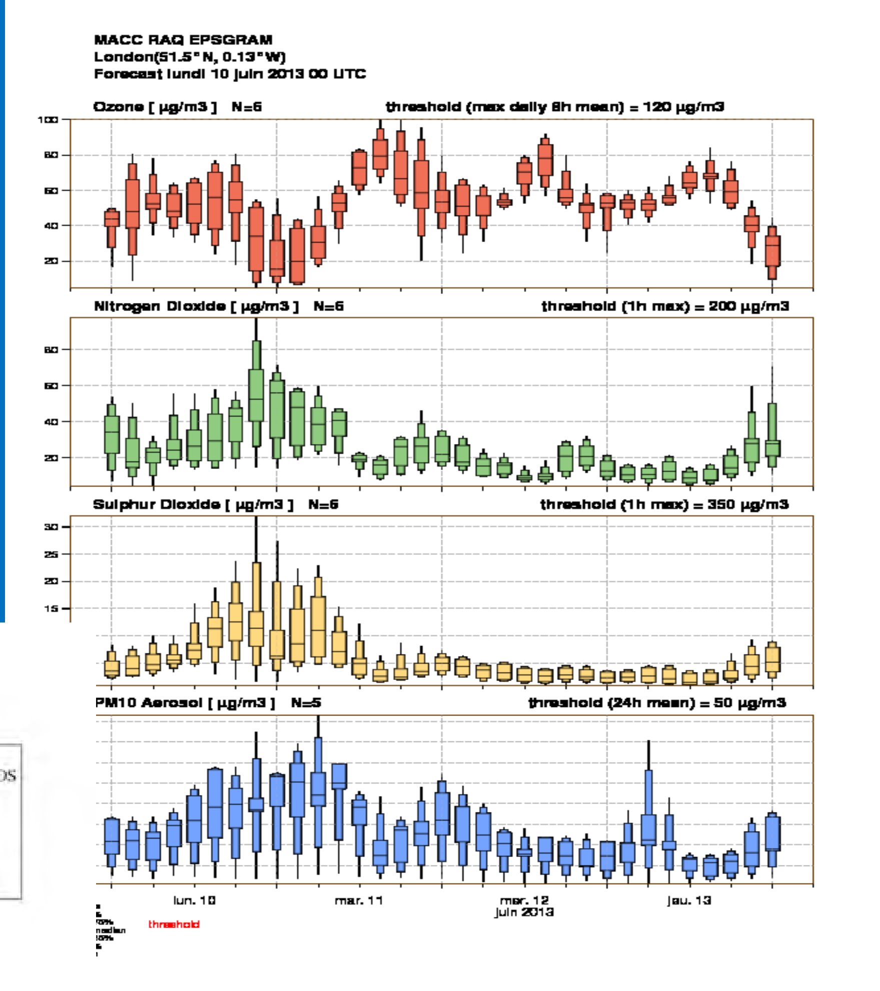
NO2, Europe-wide, ~15 km, hourly +96h



Global and European maps of major pollutants

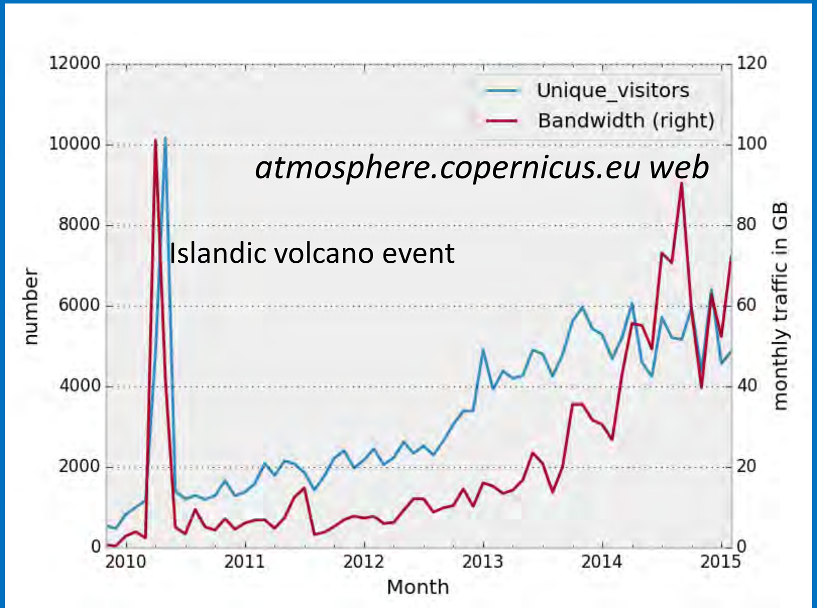


NRT / on-line evaluation

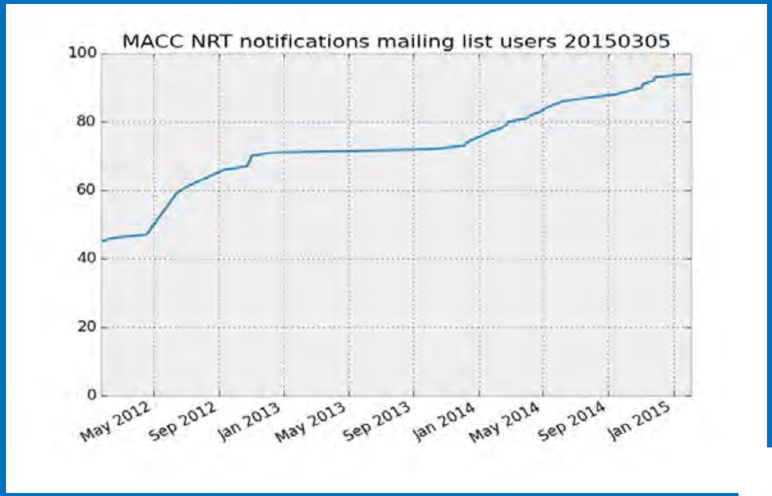


Multi-model spread as a measure of forecast uncertainty

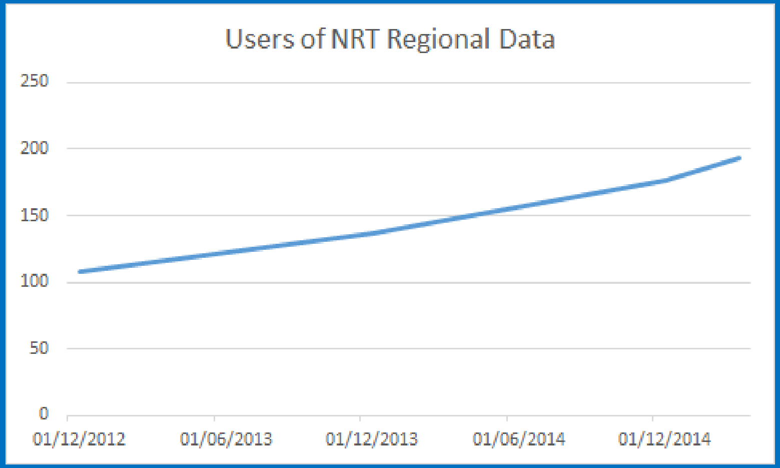
GROWING CAMS AUDIENCES (3000+ USERS)



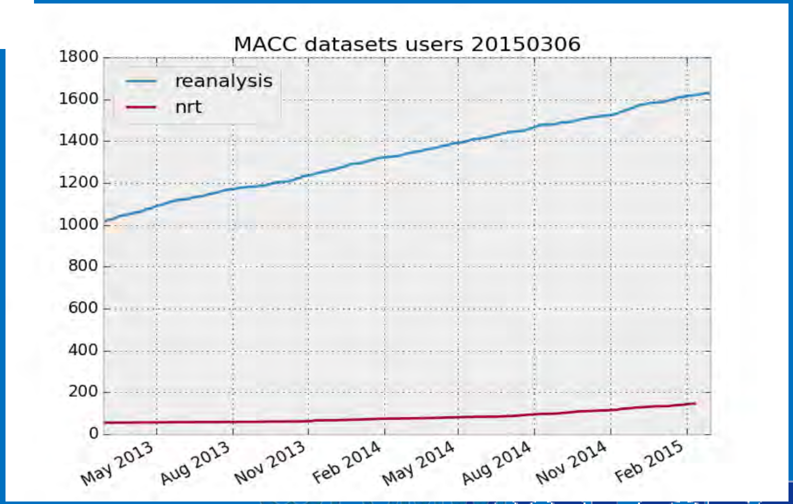
Daily time-critical users of Global Services



Daily time-critical users of Regional Services



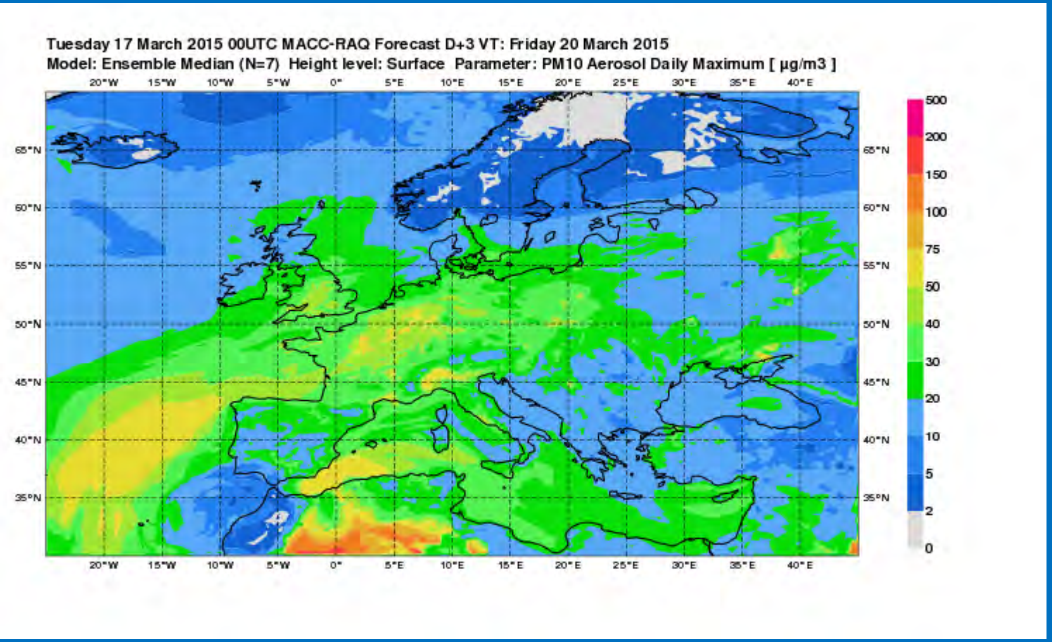
Users of the global re-analysis



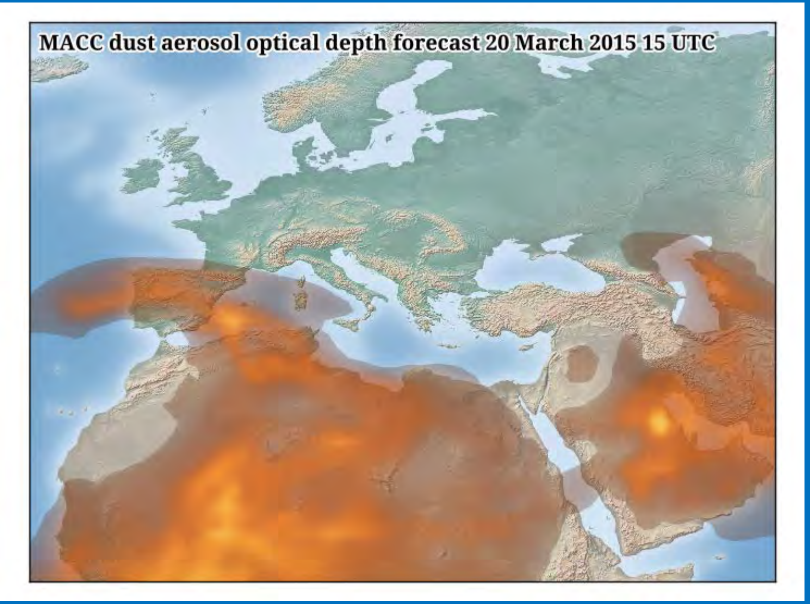
Service	Number of Users/ Requests for data
Global NRT Analyses & Forecasts	~225 users
Regional NRT Analyses & Forecasts	155 users
Global Reanalysis	1600 users
GHG flux inversions	40 users
Solar Radiation	~1000 requests/year
Global ftp	~ 40 users
Emissions, fire	1773 users (716 institutes)

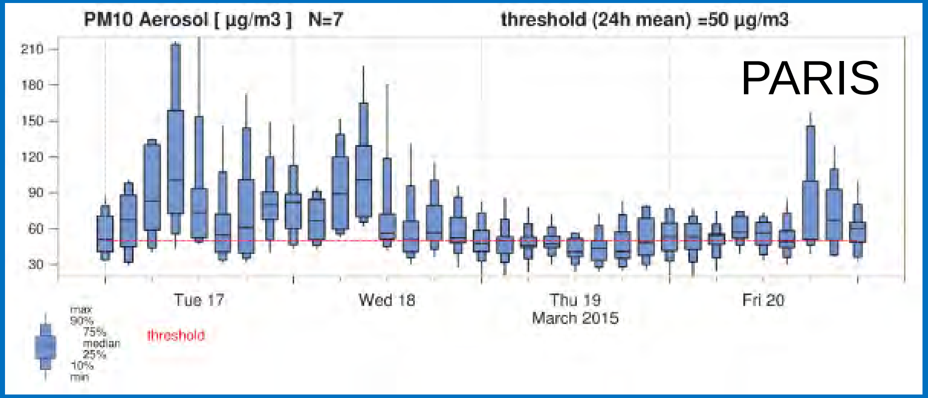
RECENT EPISODES

Poor air quality over Western Europe (March 2015)

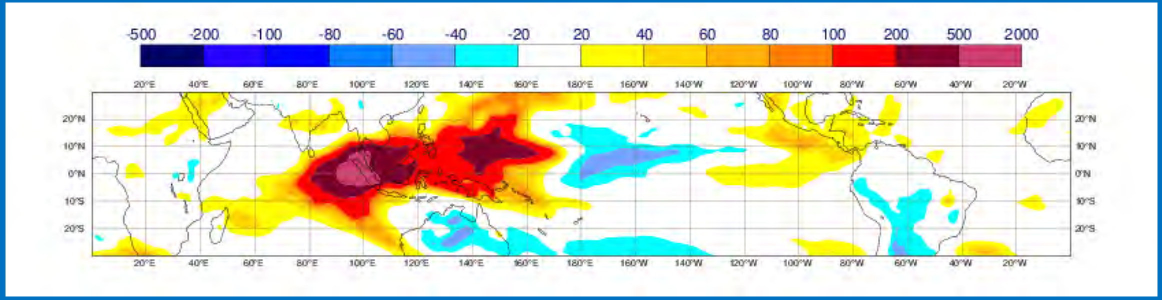


Dust advection from the Sahara (March 2015)





Indonesian fires –large biomass burning AOD anomaly (Aug-Sep-Oct 2015)



INDONESIAN FIRES (AUG-OCT 2015)

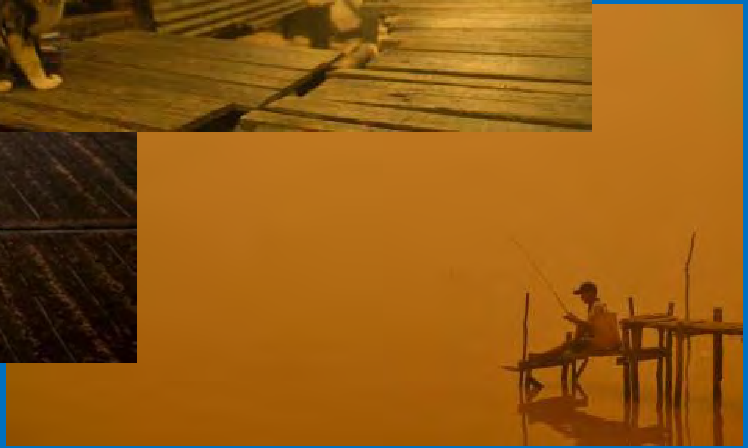

theguardian ≡ all

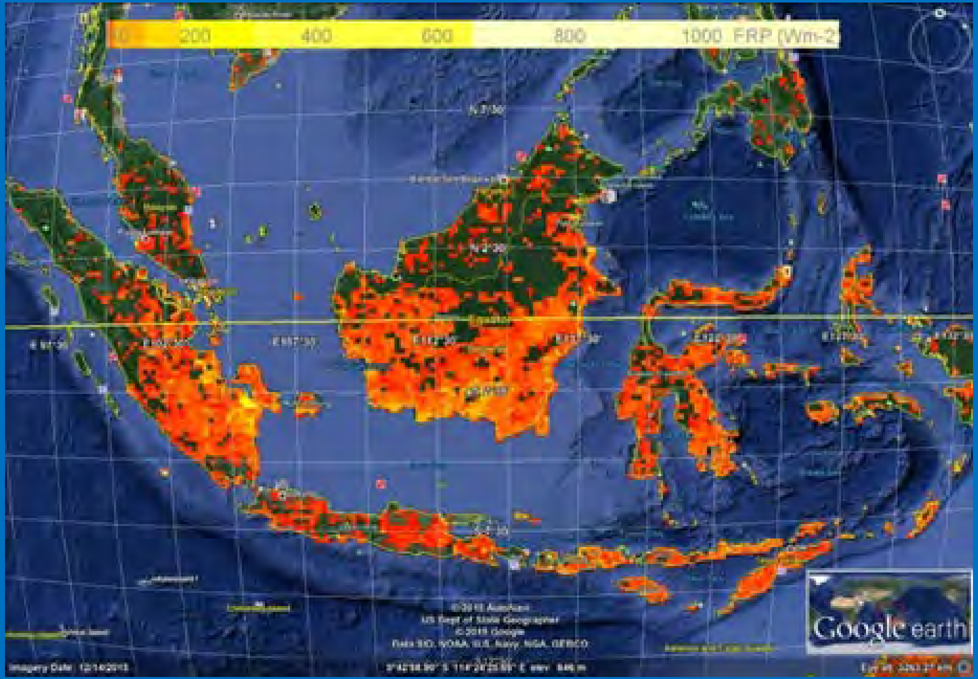
Deforestation

Indonesia forest fires: how the year's worst environmental disaster unfolded - interactive

As world leaders gather in Paris to discuss the global response to climate change, we assess the impact of the widespread forest fires in Indonesia. Set to clear land for paper and palm oil production, the fires have not only destroyed forest and peatland, but also severely affected public health and released massive amounts of carbon

Tuesday 1 December 2015 14.05 GMT

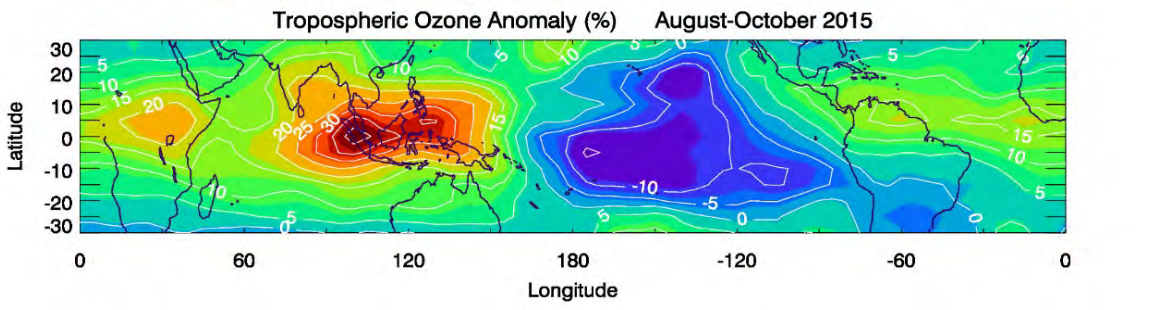




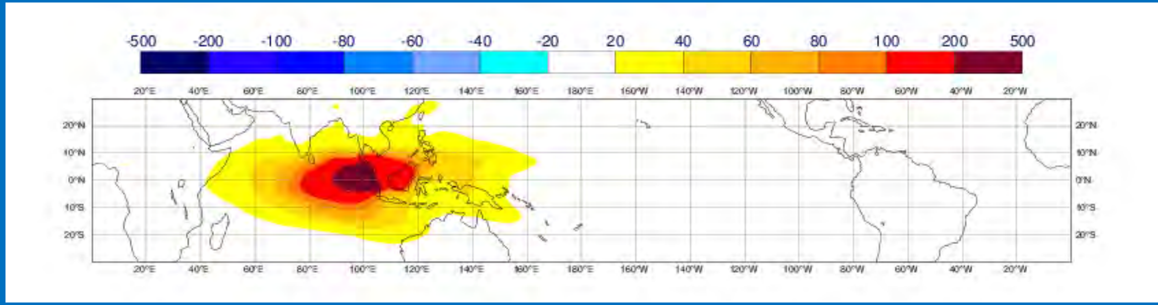
Fire Radiative Power (W/m2) accumulated over Indonesia during the 2015 fire season (Aug-Oct). Credits: Francesca Di Giuseppe

INDONESIAN FIRES
(AUG-OCT 2015)

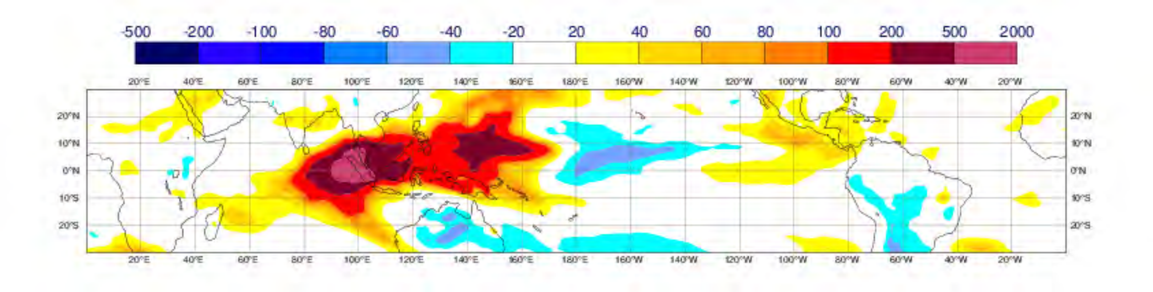
O3 anomaly: 30-40 %

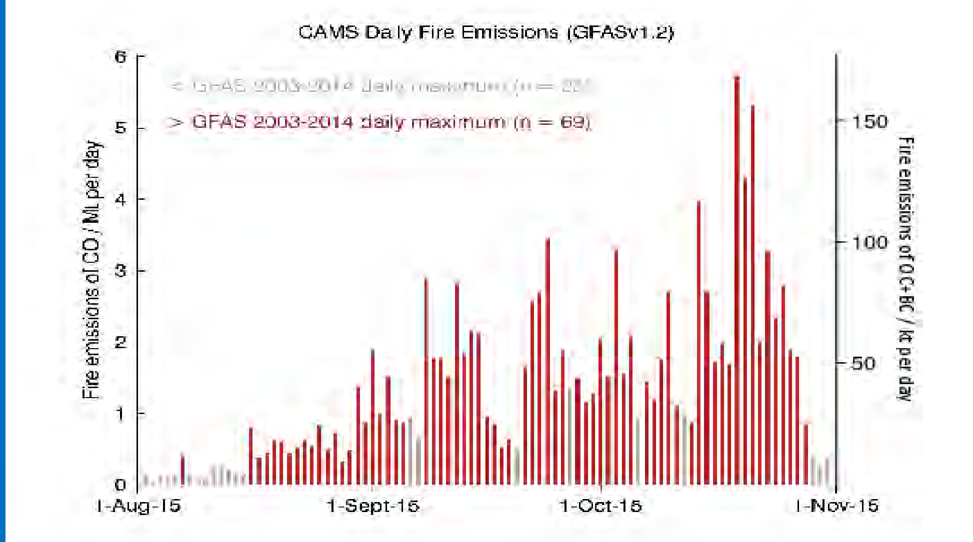


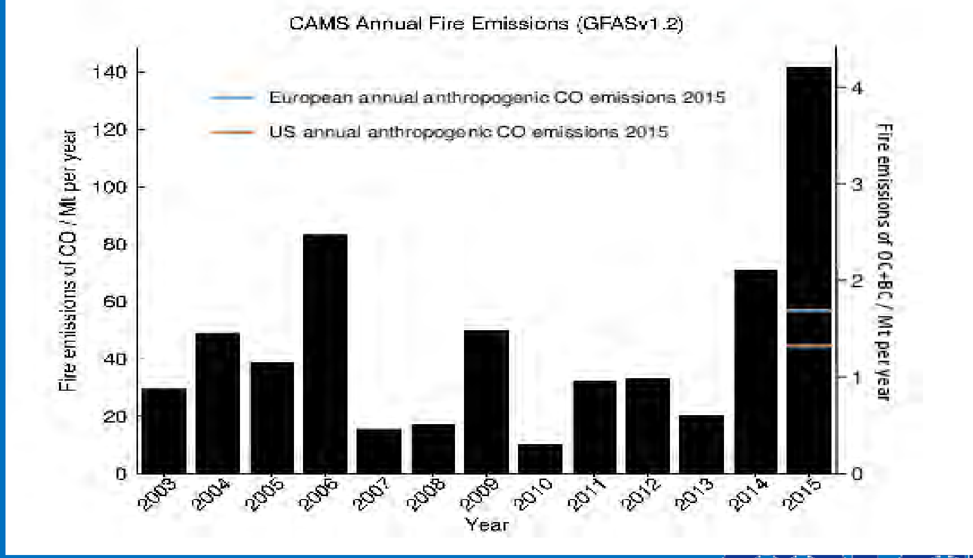
CO anomaly: up to 500%



Biomass burning AOD anomaly: up to 2000%







Benedetti et al, 2106 to appear in State of Climate, BAMS.
Credits: Antje Inness, Mark Parrington (ECMWF), Gerry Ziemke (NASA)

AEROSOL MODELLING AND ASSIMILATION

CAMS aerosol forecasts

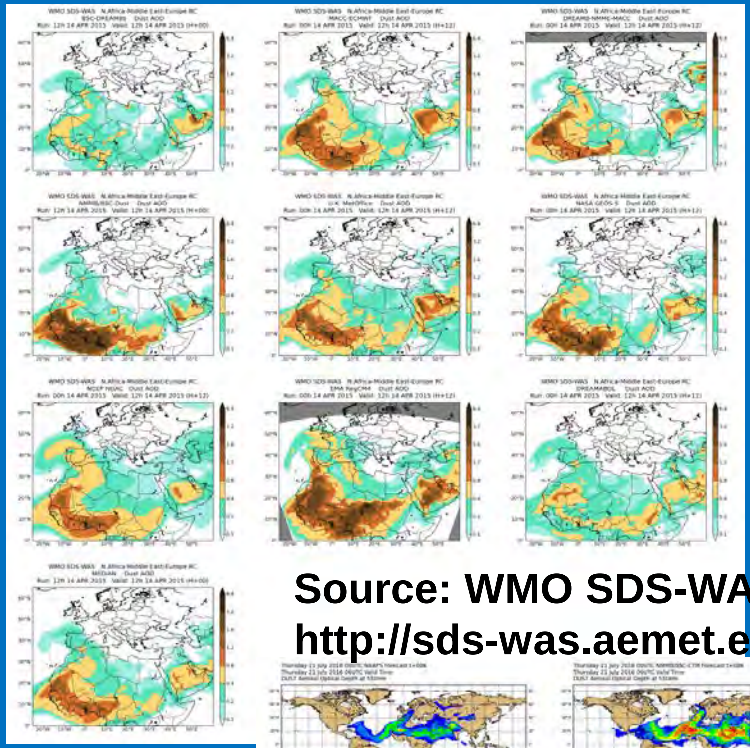
- Built on the ECMWF NWP system with additional prognostic aerosol variables (sea salt, desert dust, organic matter, black carbon, sulphates)
- Aerosol data used as input in the aerosol analysis:

  - NASA/MODIS Terra and Aqua Aerosol Optical Depth at 550 nm

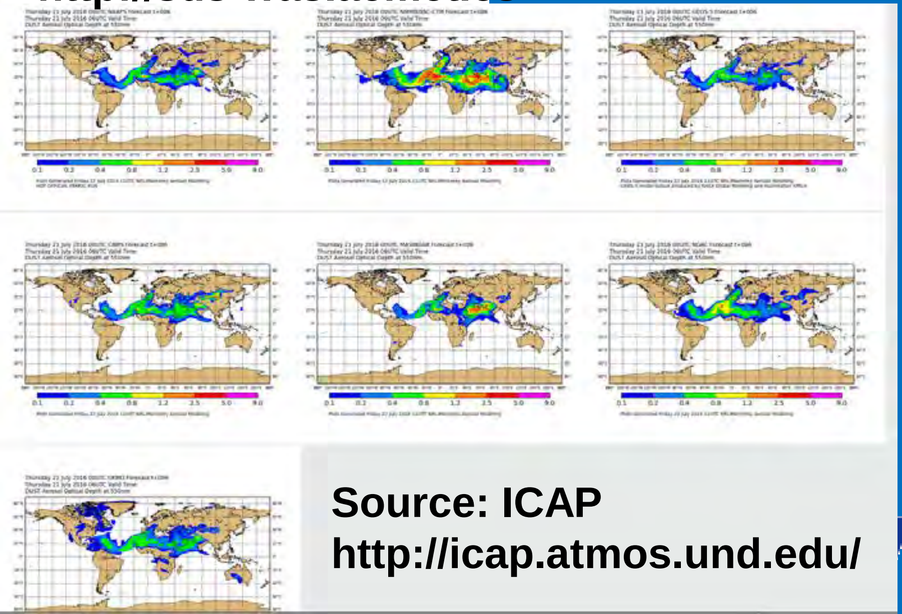
  - EUMETSAT's PMAP AOD (monitoring)

  - NASA/CALIOP CALIPSO Aerosol Backscatter (experimental)

  - AATSR, SEVIRI, VIIRS (experimental)
- Verification based on AERONET Aerosol Optical Depth (and now also Angstrom exponent)
- Part of multi-model ensemble efforts such as the International Cooperative for Aerosol Prediction (ICAP) and the WMO Sand and Dust Storm Warning and Assessment System (SDS-WAS) North-African-Middle-East-Europe and Asian nodes.

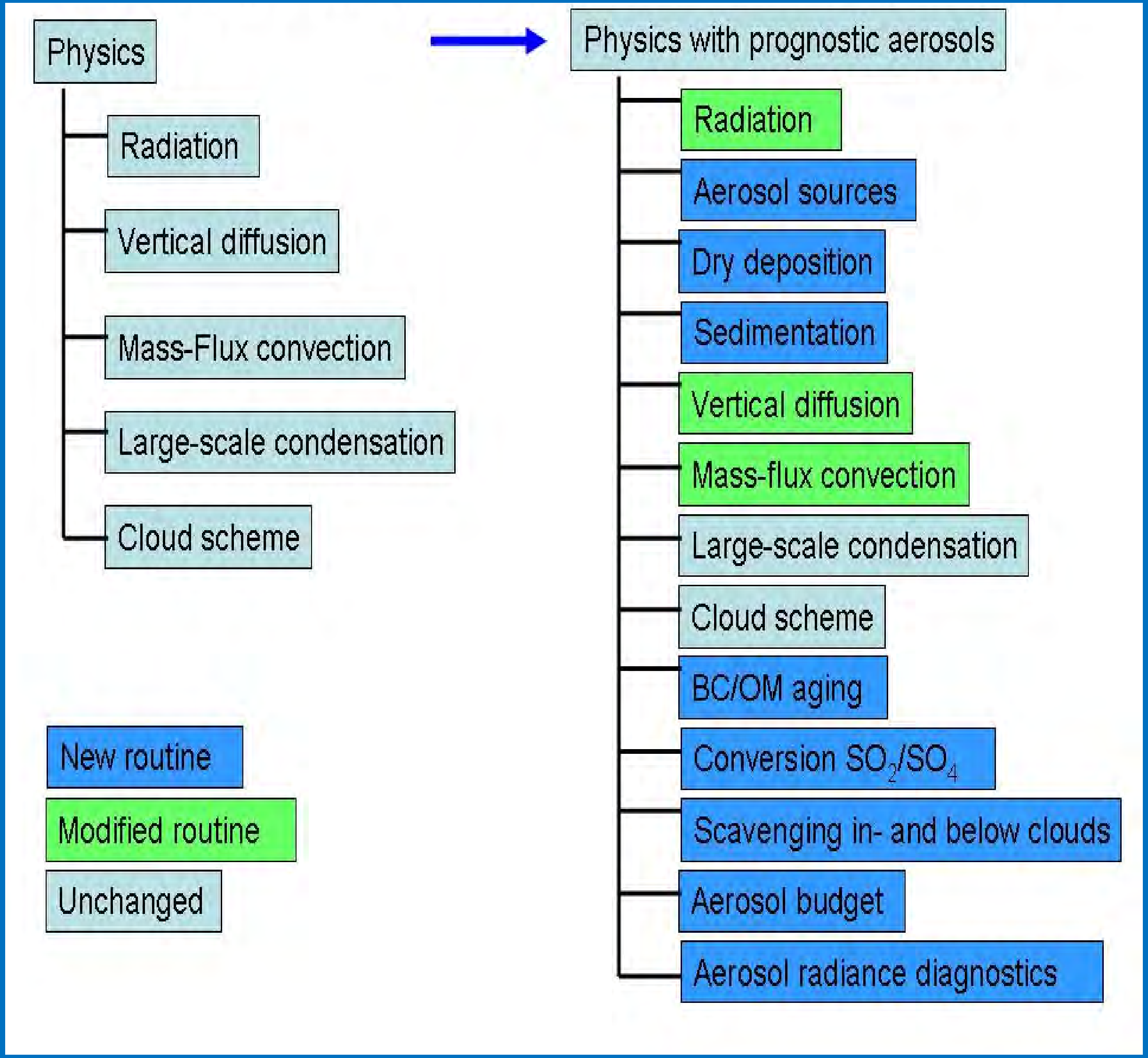


Source: WMO SDS-WAS
http://sds-was.aemet.es



Source: ICAP
http://icap.atmos.und.edu/

Aerosols in the ECMWF IFS (C-IFS)



12 aerosol-related prognostic variables:

* 3 bins of sea-salt (0.03 – 0.5 – 0.9 – 20 µm)
* 3 bins of dust (0.03 – 0.55 – 0.9 – 20 µm)
* Black carbon (hydrophilic and –phobic)
* Organic carbon (hydrophilic and –phobic)
* SO_2 -> SO_4

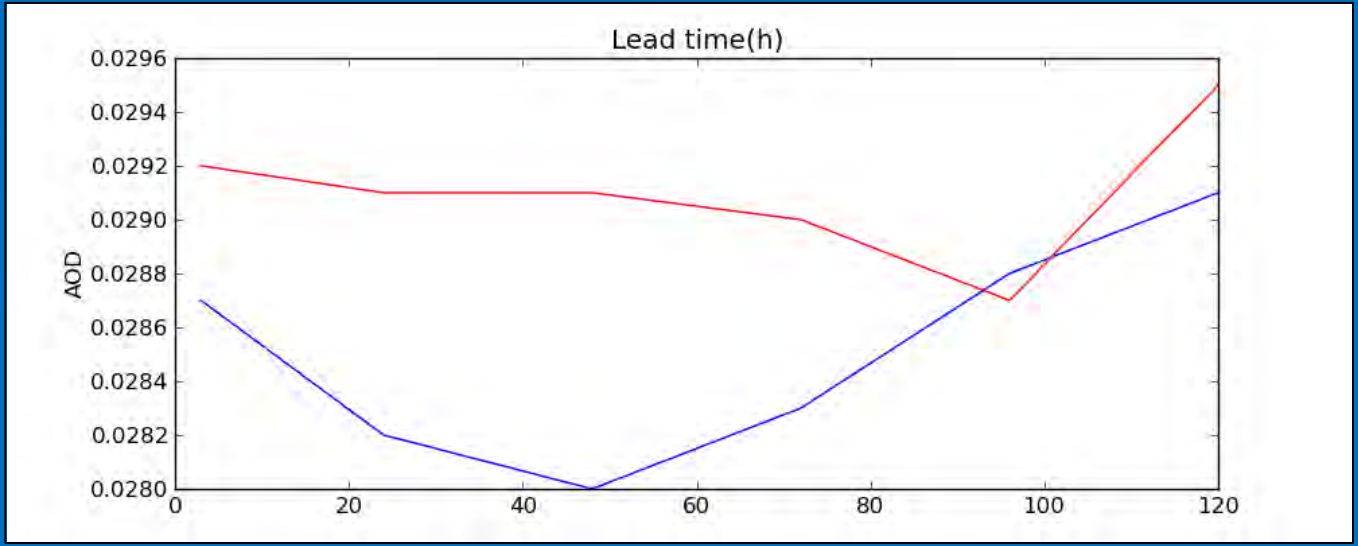
Physical processes include:

• emission sources (some of which updated in NRT, i.e.fires),
• horizontal and vertical advection by dynamics
• vertical advection by vertical diffusion and convection
• aerosol specific parameterizations for dry deposition, sedimentation, wet deposition by large-scale and convective precipitation, and hygroscopicity (SS, OM, BC, SU)

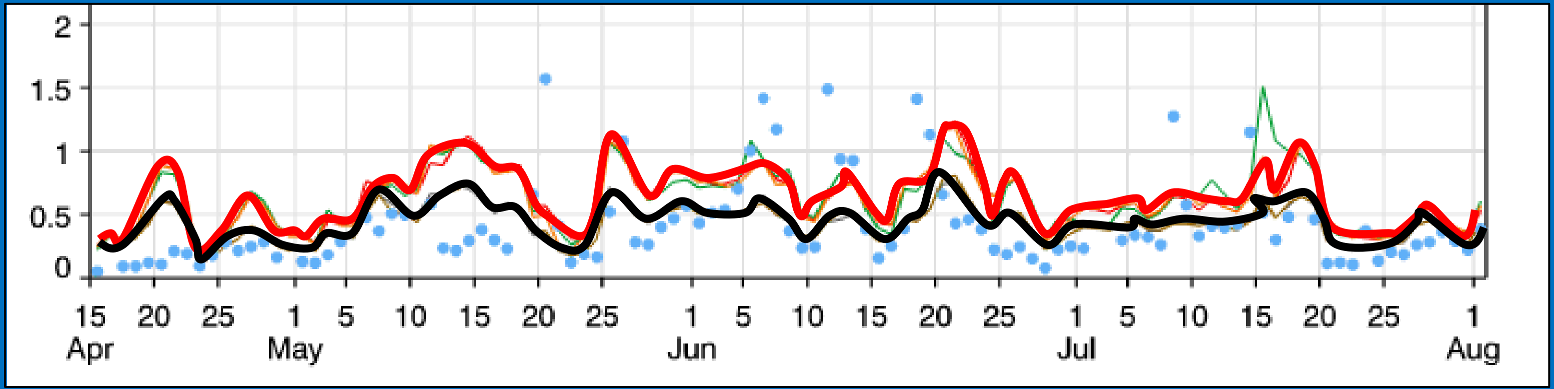
Morcrette et al. 2009, *JGR*, **114**, doi:10.1029/2008JD011235

Recent developments: Dust emissions

- Overestimation of dust AOD : the **average among the models participating in AEROCOMS is 0.023**
- Compared to the literature and other models, the amount of larger particles in dust emissions is too low.
- => decrease of the amount of small particles in the emissions, increase the amount of larger particles



Global dust AOD for May 2014 as a function of lead time, with (red) and without (blue) data assimilation



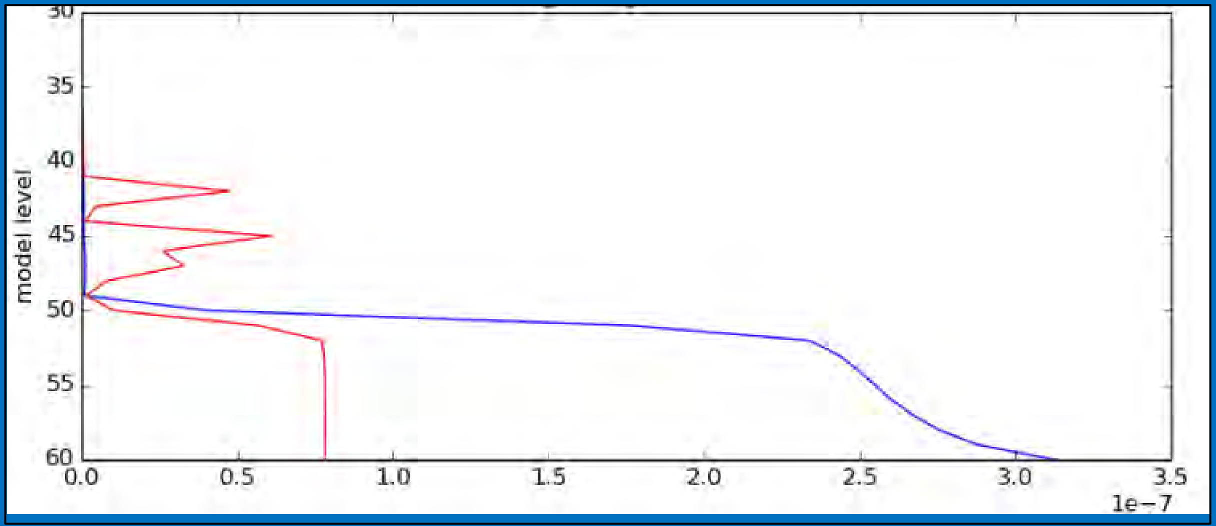
AOD at the AERONET station of Tamanrasset (Algeria), from 15/4/2014 to 1/8/2014. Observations (blue), old emissions (red) and new emissions (black)

- Better balance between the model and observations after the introduction of new emissions

Credits: Samuel Rémy

Recent developments: Injection heights for biomass burning aerosol emissions

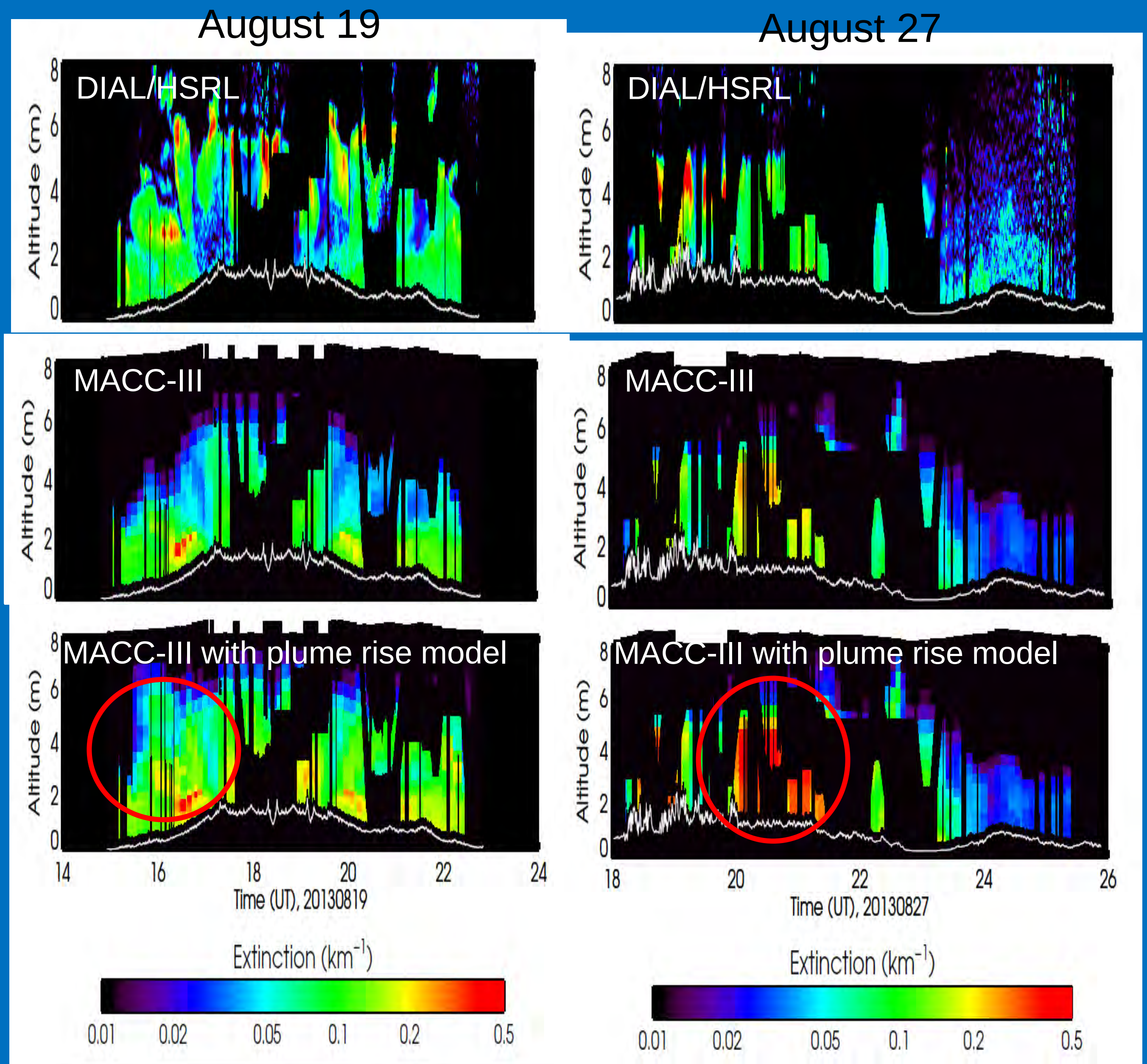
- Biomass burning emissions are currently emitted at the surface.
- Injection heights for biomass burning emissions are routinely produced by GFASv1.2., using a Plume Rise Model (Freitas et al, 2007, Paugam et al., 2015), and Sofiev's parameterization (Sofiev et al. 2012)
- Use of these injection heights was implemented in CIFS for aerosols, chemical species, greenhouse gases



Profile of OM mixing ratio over Canada (52N, 77.5W) on July 6, 2013
Blue, emissions of OM at surface, red, emissions at the injection height given by the PRM

Credits: Samuel Rémy

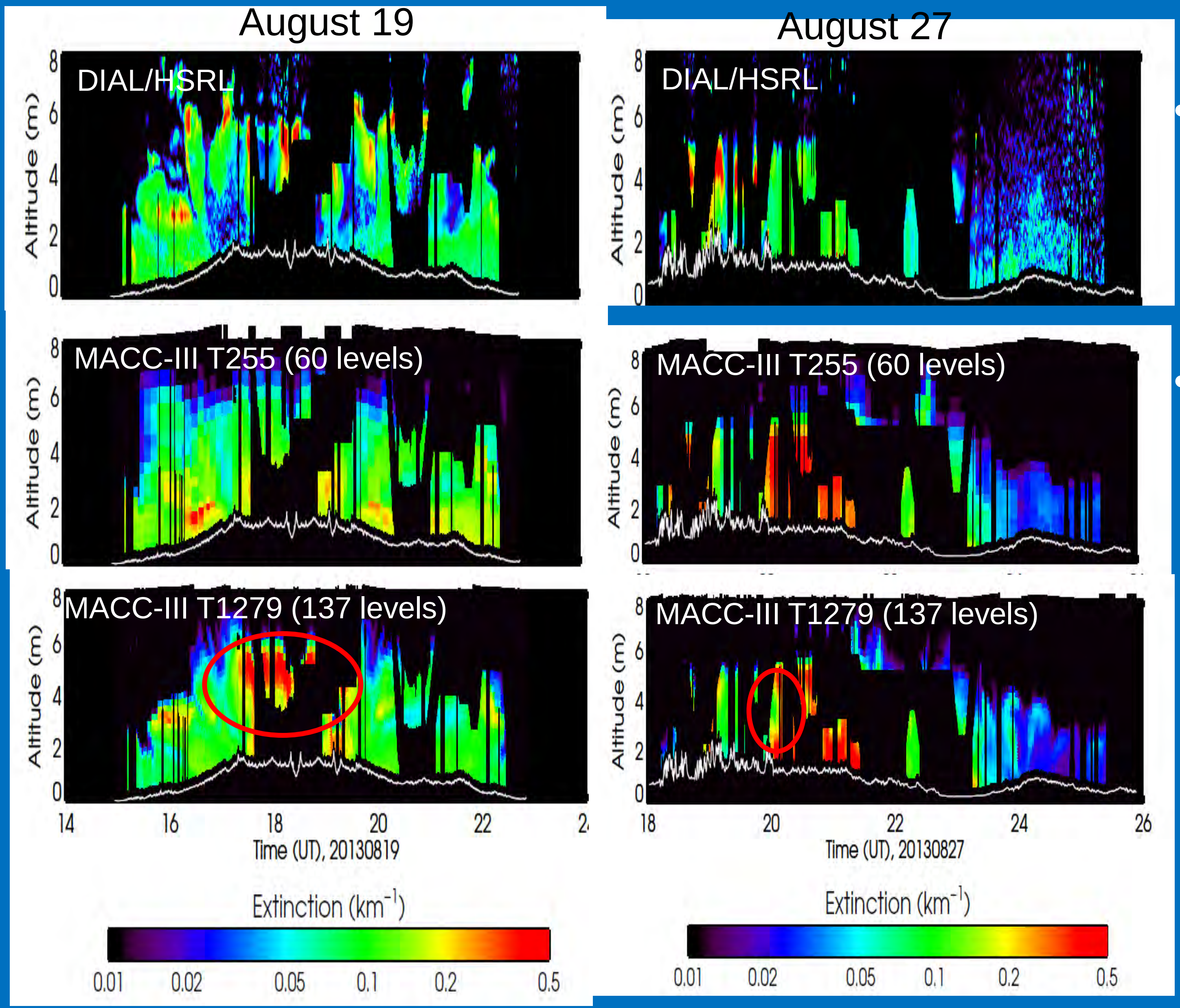
Evaluating the impacts of smoke injection heights computed from plume rise model



- Injection heights for smoke emissions are estimated using a Plume rise model (Paugam et al., 2015, based on Freitas et al., 2007)
- This plume rise model uses MODIS FRP and modelled atmospheric profiles with a shallow convection scheme to represent detrainment from fire plumes
- Initial comparisons show that both aerosol extinction and AOT increase throughout the profile, not necessarily at smoke height shown in DIAL/HSRL profile

Credits: Rich Ferrare and Sharon Burton (NASA Langley)

Evaluating the impact of higher model resolution



- Model resolution increased from T255 (80 km) with 60 vertical levels to T1279 (16 km) with 137 vertical levels
- Higher resolution represents smoke altitude better than assimilating MODIS AOT or using plume rise model

Credits: Rich Ferrare and Sharon Burton (NASA Langley)

Future: GLOMAP aerosol in C-IFS

Aerosol mass as "components" in internally mixed modes

Sulphate, sodium, black carbon, organic carbon, dust
Ammonium, nitrate, chloride

Also emit sea-spray as sodium chloride & sodium sulphate.
Account for sea-salt-SO4 as well as usual nss-SO4.

MONOTER

OH, NO_3, O_3

SEC_ORG

H_2SO_4

OH

SO_2

OH, NO_3

DMS

NH_3

HNO_3

HCl

Insoluble Aitken N_5
BC OC

insoluble accum N_6
DU

insoluble coarse N_7
DU

Soluble nucln N_1
SO4 OC
NH4 NO3

soluble Aitken N_2
SO4 OC
BC
NH4 NO3

soluble accum N_3
SO4 OC
BC Na DU
NH4 NO3 Cl

soluble coarse N_4
SO4 OC
BC Na DU
NH4 NO3 Cl

component mass conc.

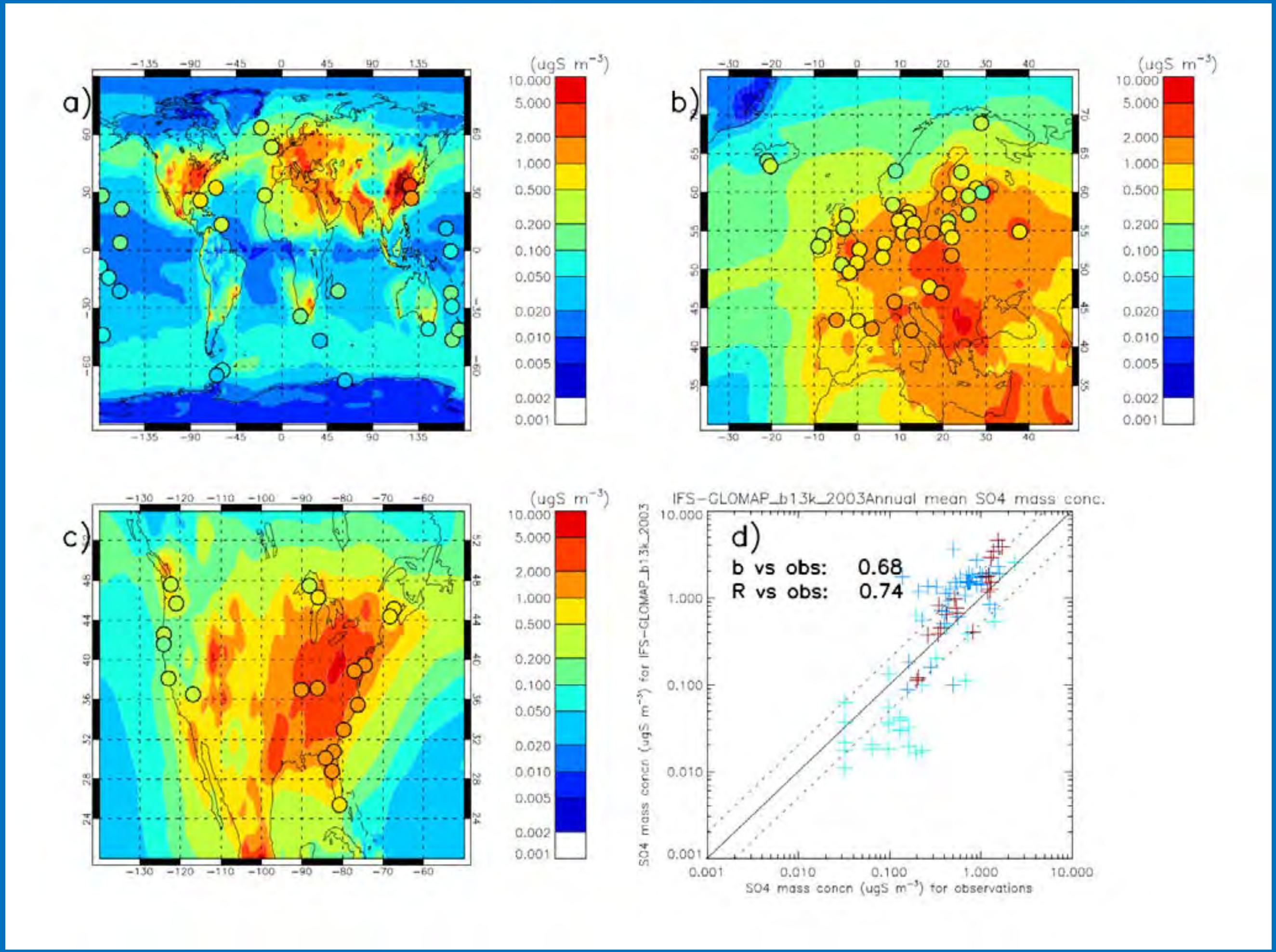
29 mass
7 number

Transported tracers=36

ECMWF

Credits: Graham Mann (University of Leeds)

Evaluation suite for assessing IFS- GLOMAP (also in UM, TOMCAT)

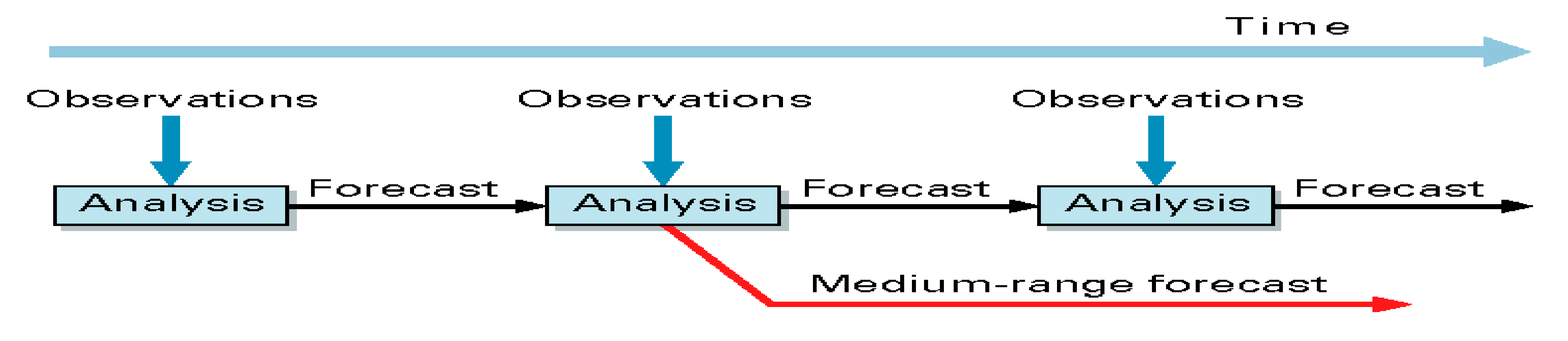


Credits: Graham Mann, Sandip Dhomse (Uni Leeds)

Sulphate mass evaluation against EMEP, IMPROVE, U. Miami obs datasets for reference IFS-GLOMAP run

- GLOMAP evaluation strategy involves assessing a range of aerosol metric against observations. As well as aerosol optical depth speciated mass, size-resolved number concentrations are used.

The ECMWF 4D-Var



- The observations are used to correct errors in the short forecast from the previous analysis time. This is done by a careful 4-dimensional interpolation in space and time of the available observations.
- Every 12 hours we assimilate 4 – 8,000,000 observations to correct the initial conditions on the 100,000,000 variables that define the model's virtual atmosphere (winds, temperature, humidity, surface pressure, ozone and surface variables for the standard operational configuration).
- Additional variables are included in the control vector for the MACC NRT analysis and forecast (reactive gases and aerosols).

The aerosol analysis

- Integrated in the ECMWF incremental 4D-Var
- Control variable is formulated in terms of the total aerosol mixing ratio.
- Increments in total mass are repartitioned into the single species according to their fractional contribution to the total.
- Background error statistics have been computed using forecasts errors as in the NMC method (48h-24h forecast differences).
- Assimilated observations are the MODIS Aerosol Optical Depths (AODs) at 550 nm over land and ocean, including Deep Blue over bright surfaces. Observation errors are prescribed fixed values.
- A global variational bias correction with constant and surface wind predictors for MODIS data is implemented in the current near-real time run.

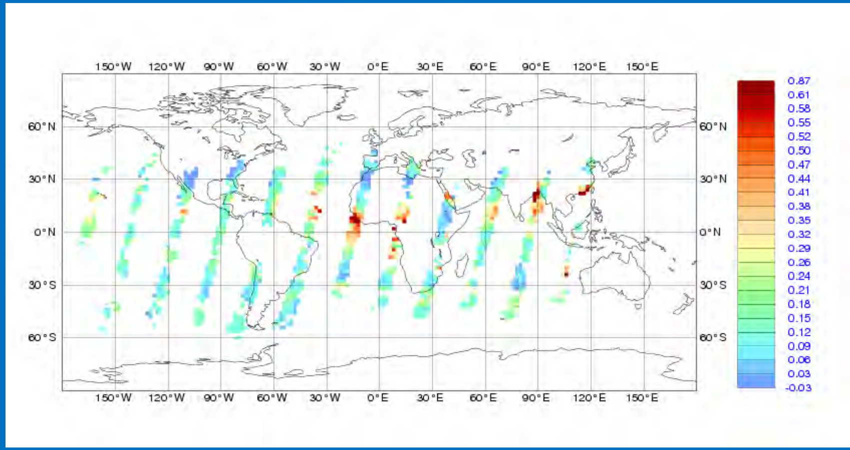
Benedetti et al. 2009, *JGR* ,**114**, doi:10.1029/2008JD011115

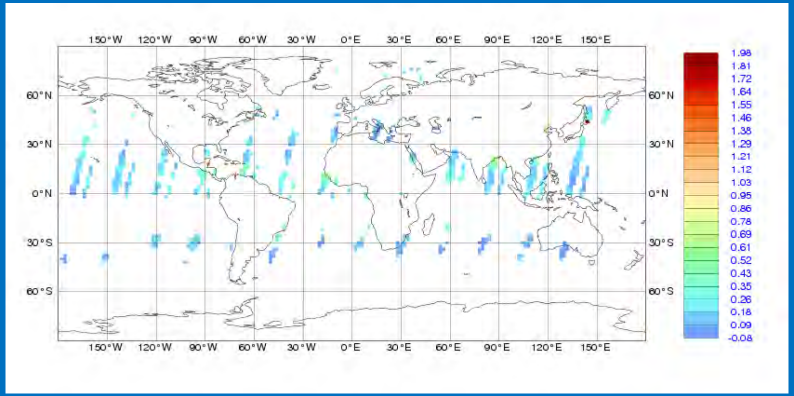
ECMWF

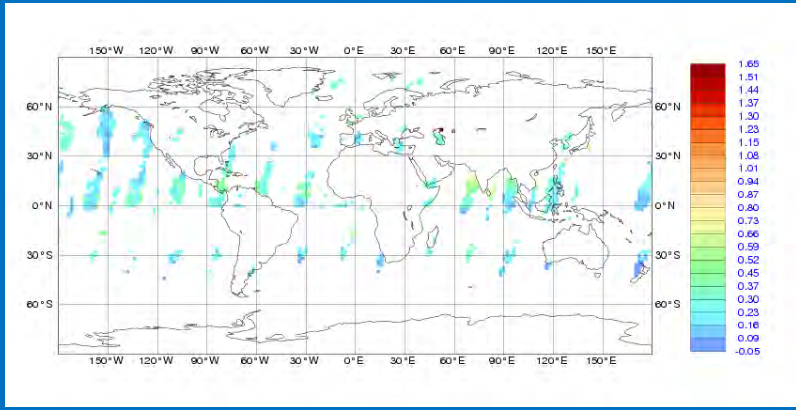
Aerosol Optical Depth coverage from various sensors/products

AATSR: data over deserts
but narrow swath & one
Instrument. Can be replaced by
SLSTR on Sentinel-3

PMAP: for now, only data over ocean were tested at ECMWF.
Two platforms (more resilient), multi-sensor (more points of failure).

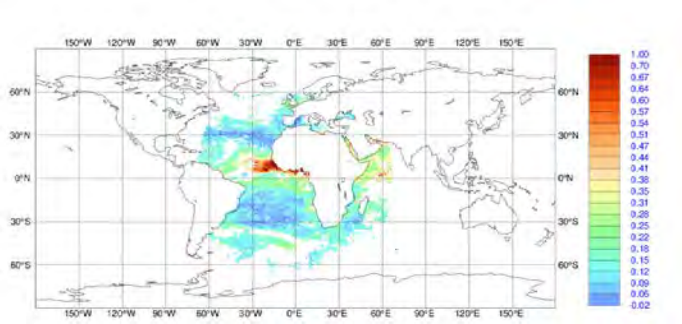


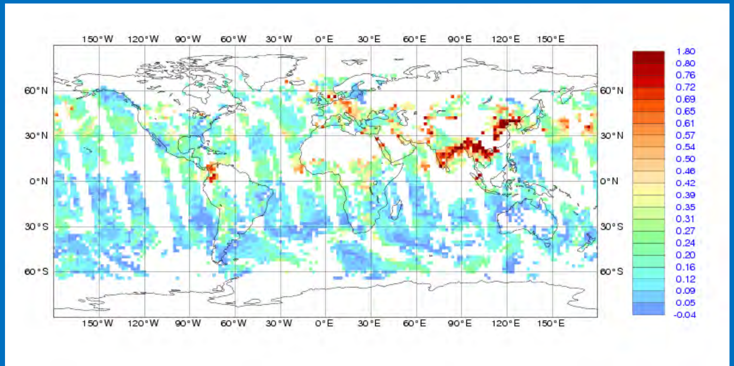


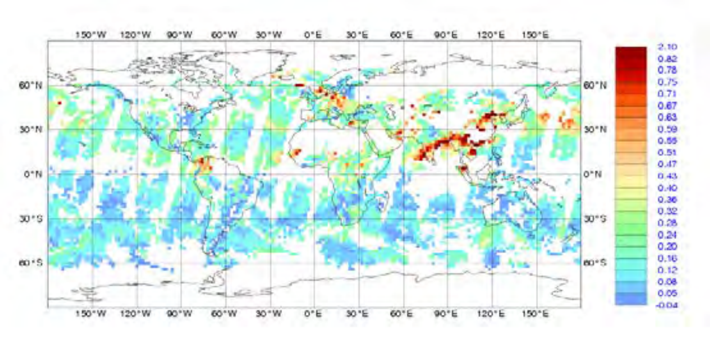


SEVIRI: geo-stationary, high
data volume, partial coverage

MODIS: two platforms, global coverage. Ageing.
Data also over bright surfaces when Deep Blue is used.



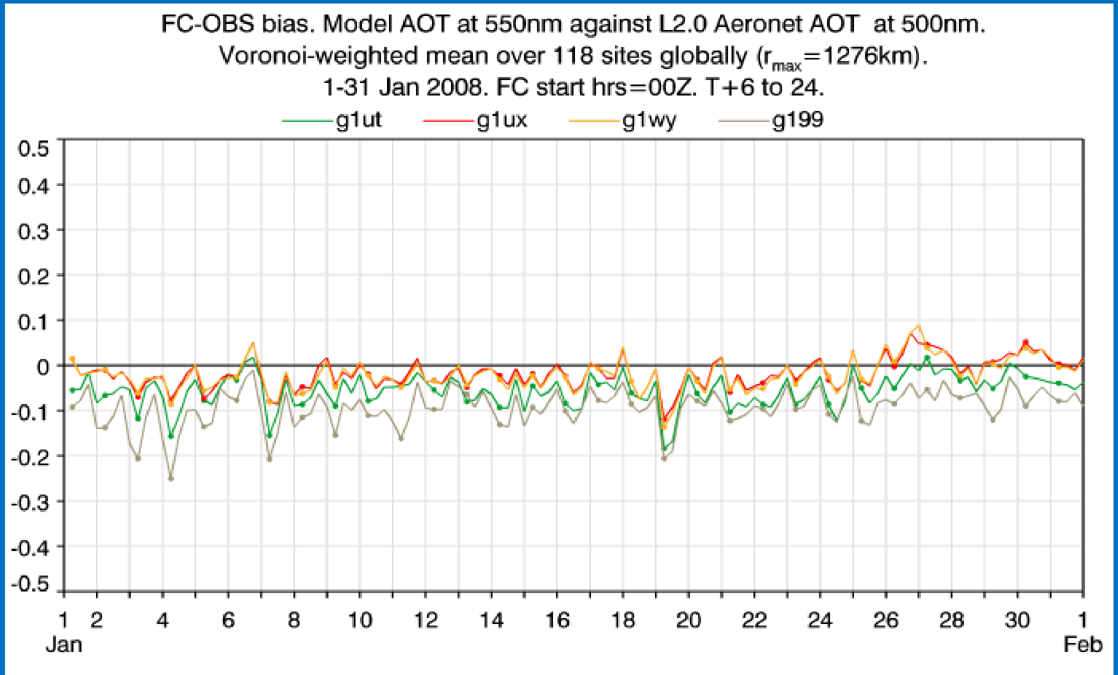


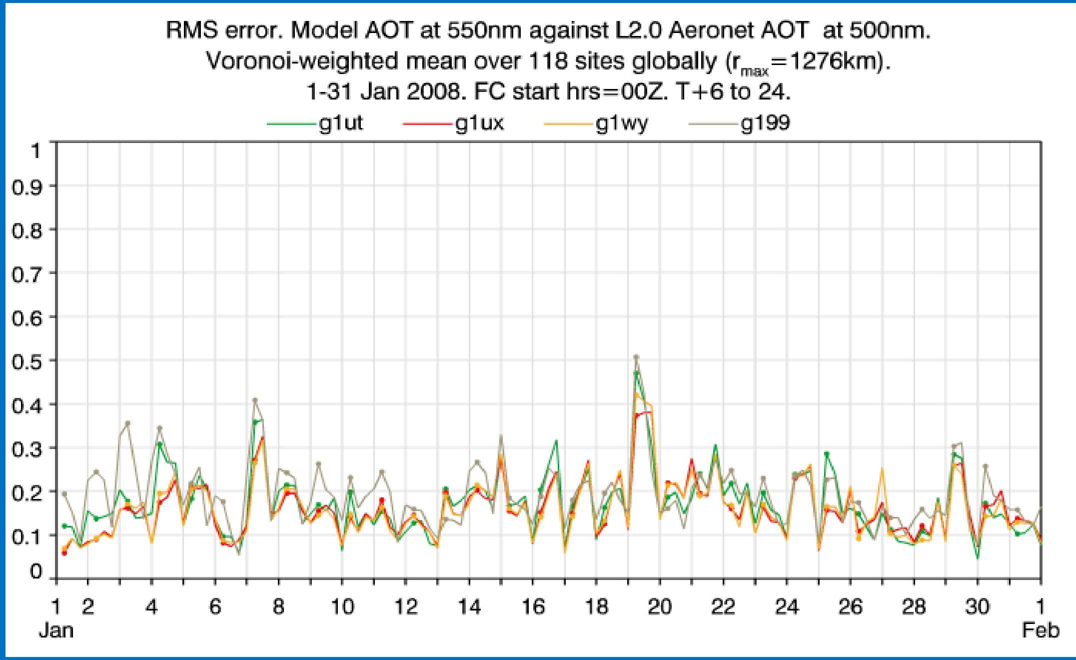


AATSR Aerosol Optical Depth data

AATSR data from FMI were used in a special **Climate Change Initiative** reanalysis for 2008

- Adds value to forecast-only run as shown by comparison with AERONET data
- Less impact than MODIS in the analysis due to coverage
- Data from **Sentinel 3 SLSTR** are expected to have a similar impact





Forecast-only run

AATSR-only run

MODIS-only run

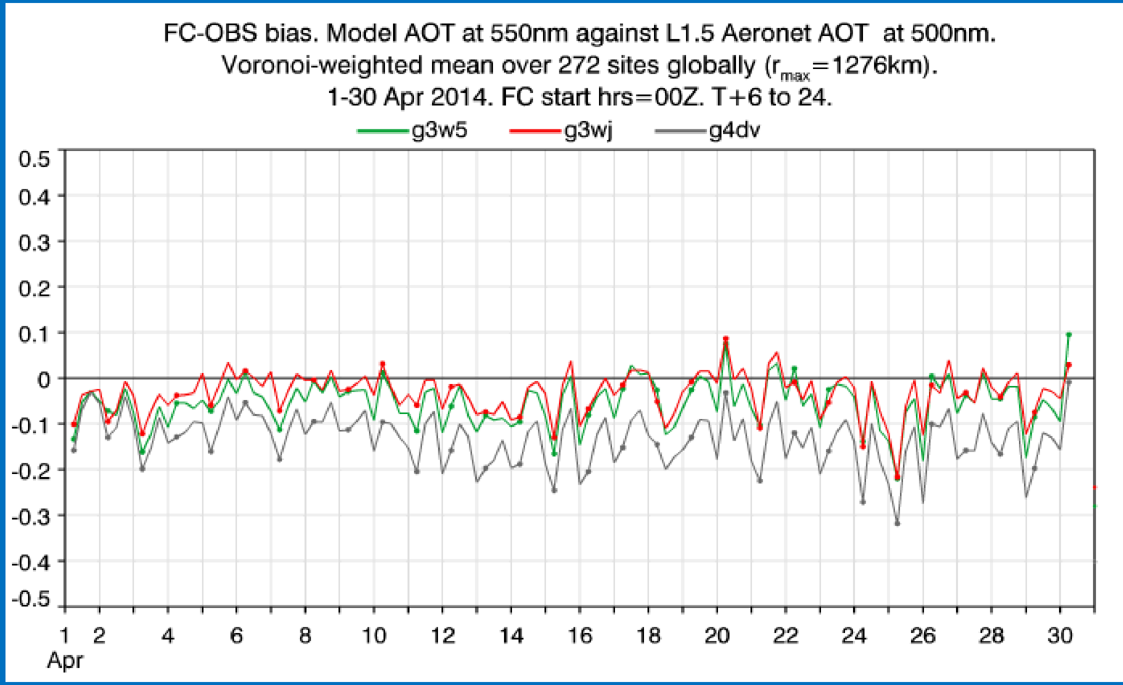
MODIS and AATSR run

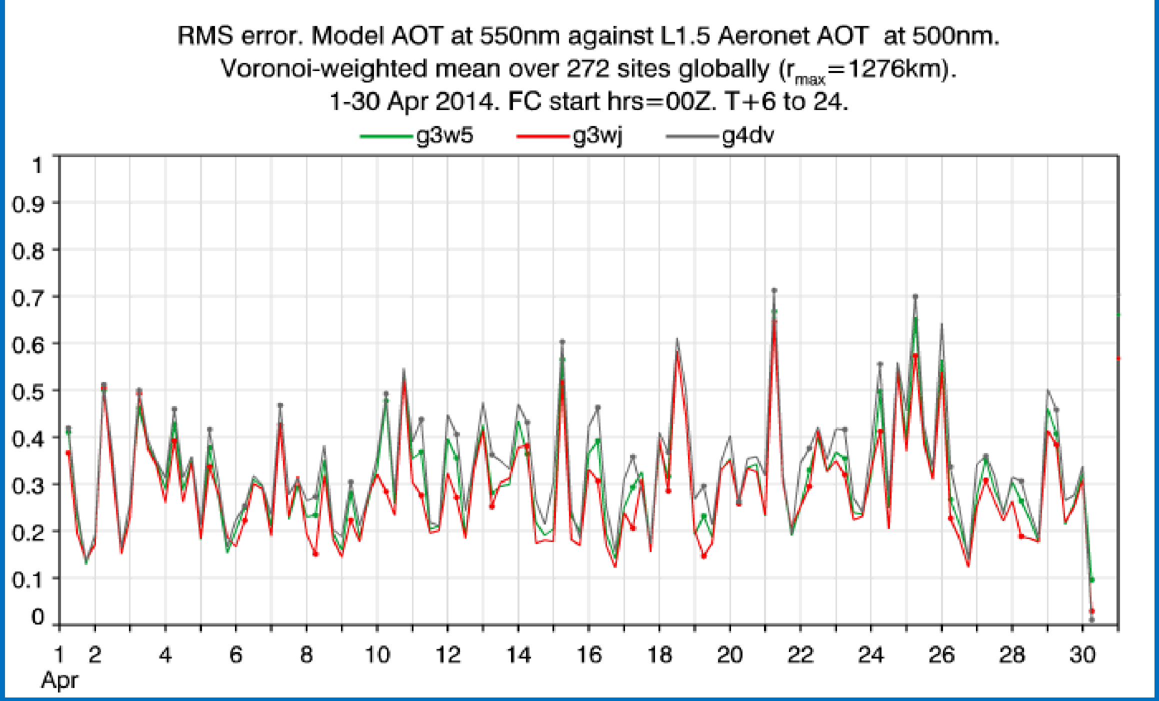
- Other experiments also showed a positive impact of the AATSR data

PMAP Aerosol Optical Depth

Produced pre-operationally by **EUMETSAT** based on GOME2, AVHRR and IASI data. Similarly to AATSR data:

- Adds value to forecast-only run as shown by comparison with AERONET data
- Impact comparable to MODIS due to global coverage





Forecast-only run

PMAP-only run

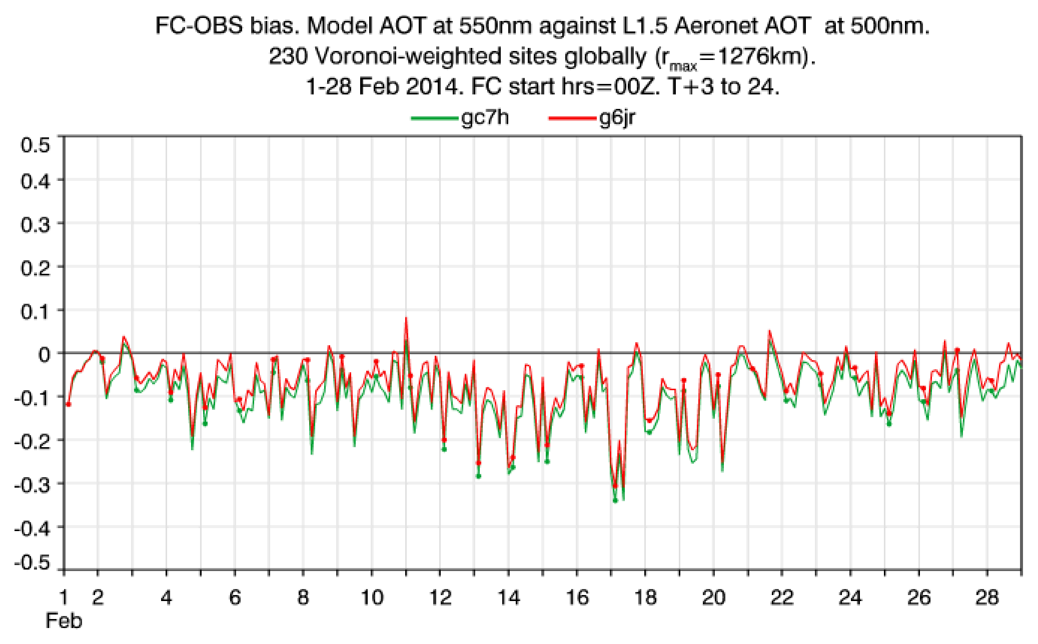
MODIS-only run

- Monitoring of PMAP has started recently
- Assimilation will follow

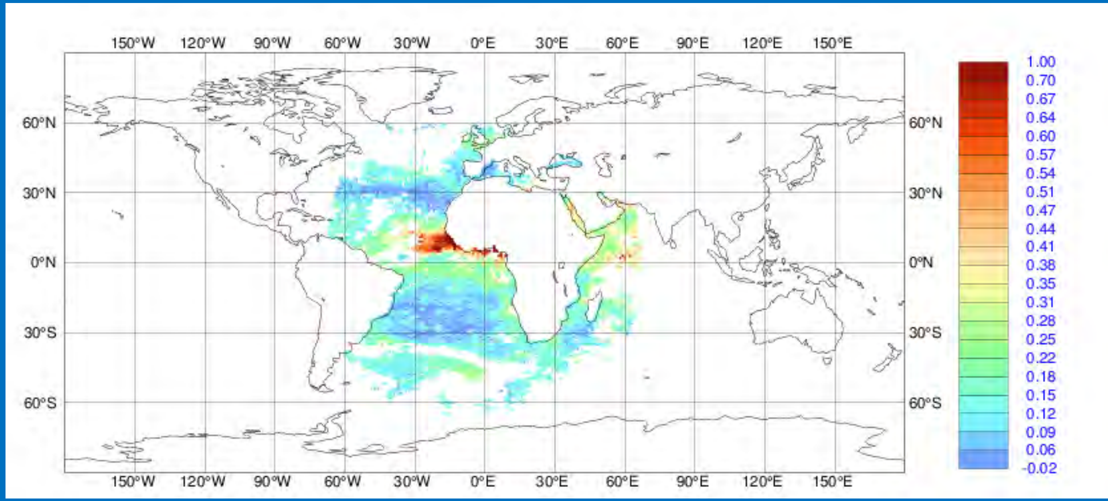
ECMWF

SEVIRI Aerosol Optical Depth (ocean-only)

- Produced in NRT at **ICARE** http://www.icare.univ-lille1.fr/msg/
- Based on an algorithm by Thieuleux et al., 2005
- Small but detectable impact on global bias (negligible in RMS)
- European/African coverage
- Of interest for European regional data assimilation
- Huge data volume (thinning needed)
- Other products under consideration



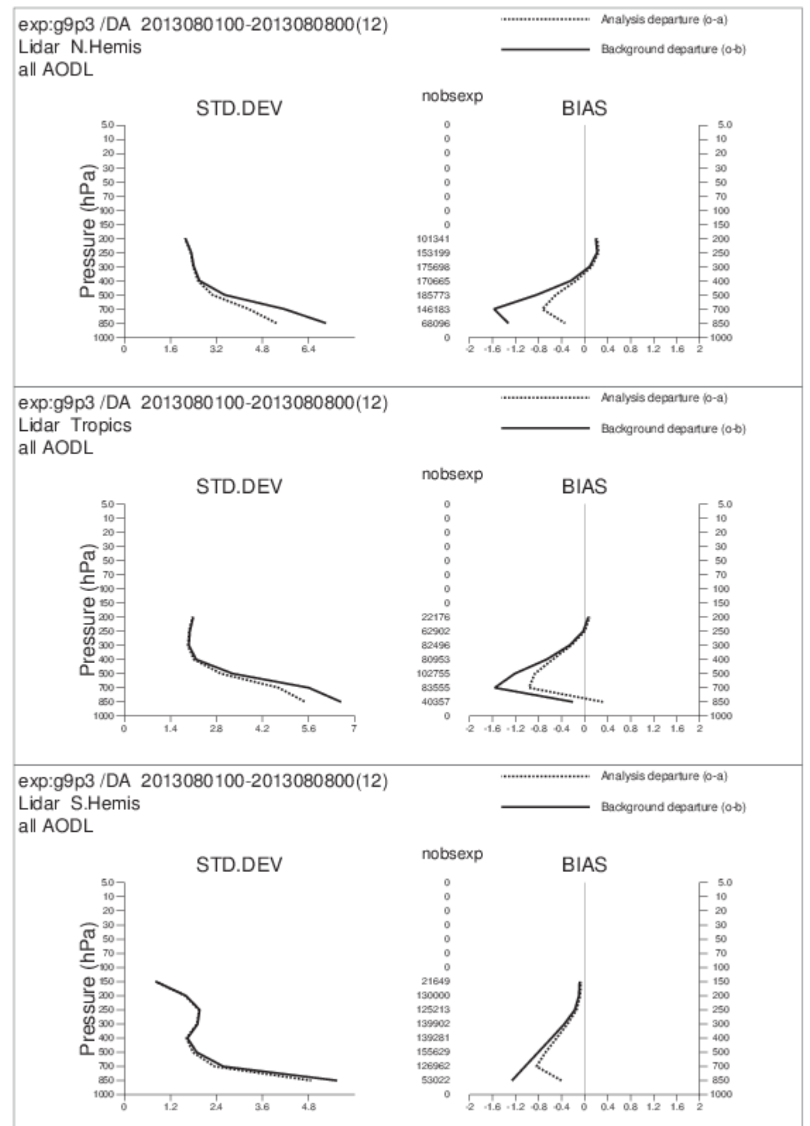
Data coverage over 24h



SEVIRI + MODIS run

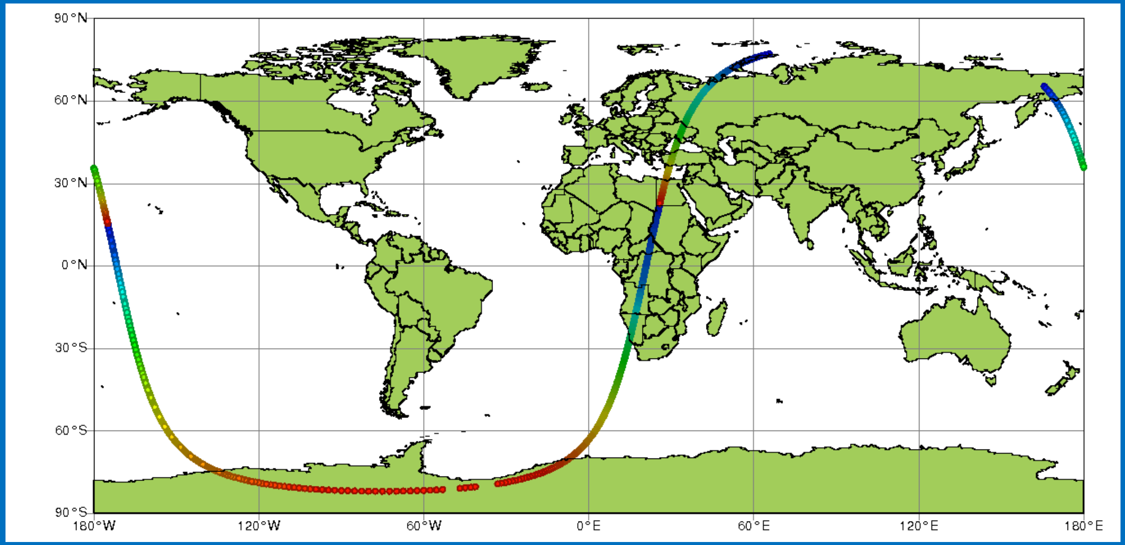
MODIS-only run

Assimilation of lidar signal



Lidar backscatter x 1e7 (sr m)-1

CALIOP level 1.5 sample orbit August 18, 2010



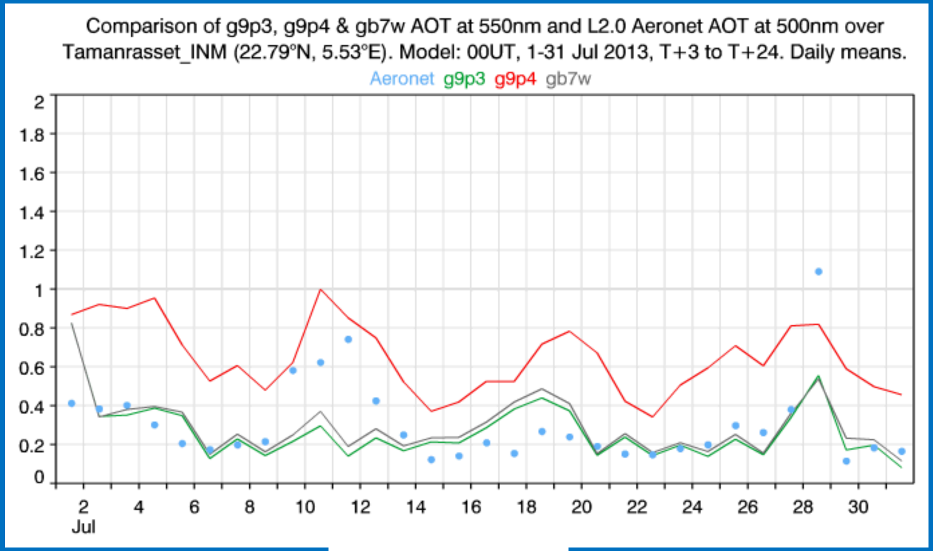
- Expedited product (courtesy of CALIPSO team at NASA Langley: David Winker, Chip Trepte, Jason Tackett)
- Average attenuated backscatter at 20 km, cloud-cleared at 1 km.
- 345 vertical levels corresponding to 60 m resolution (averaged to 300 m before assimilation)

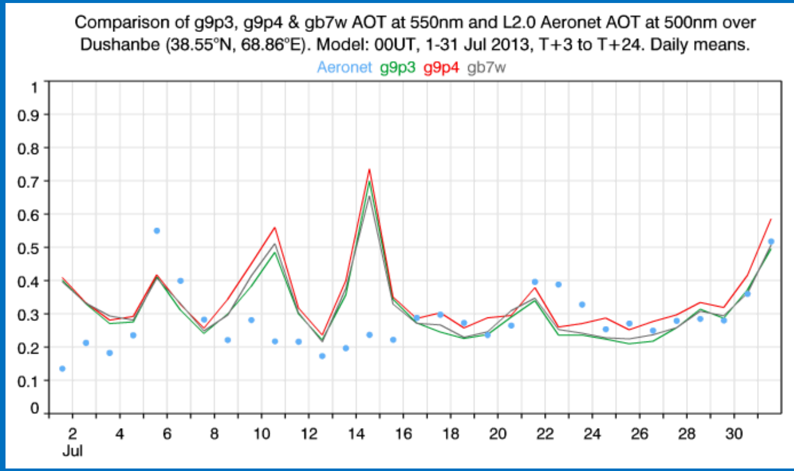
ECMWF

Data: all operational data plus MODIS AOD and CALIOP Level 1.5 backscatter

Verification of lidar assimilation experiments

AERONET verification shows good performance of lidar assimilation locally or at least not worse than the MODIS Dark Target-only run….

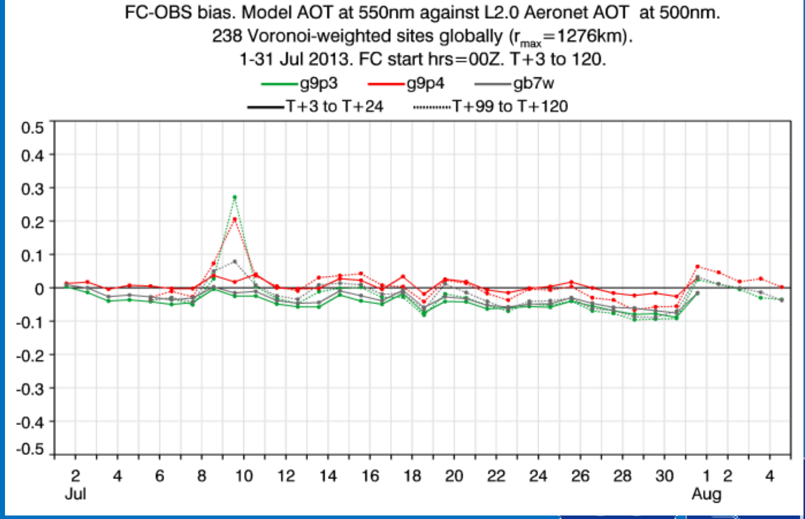




MODIS only

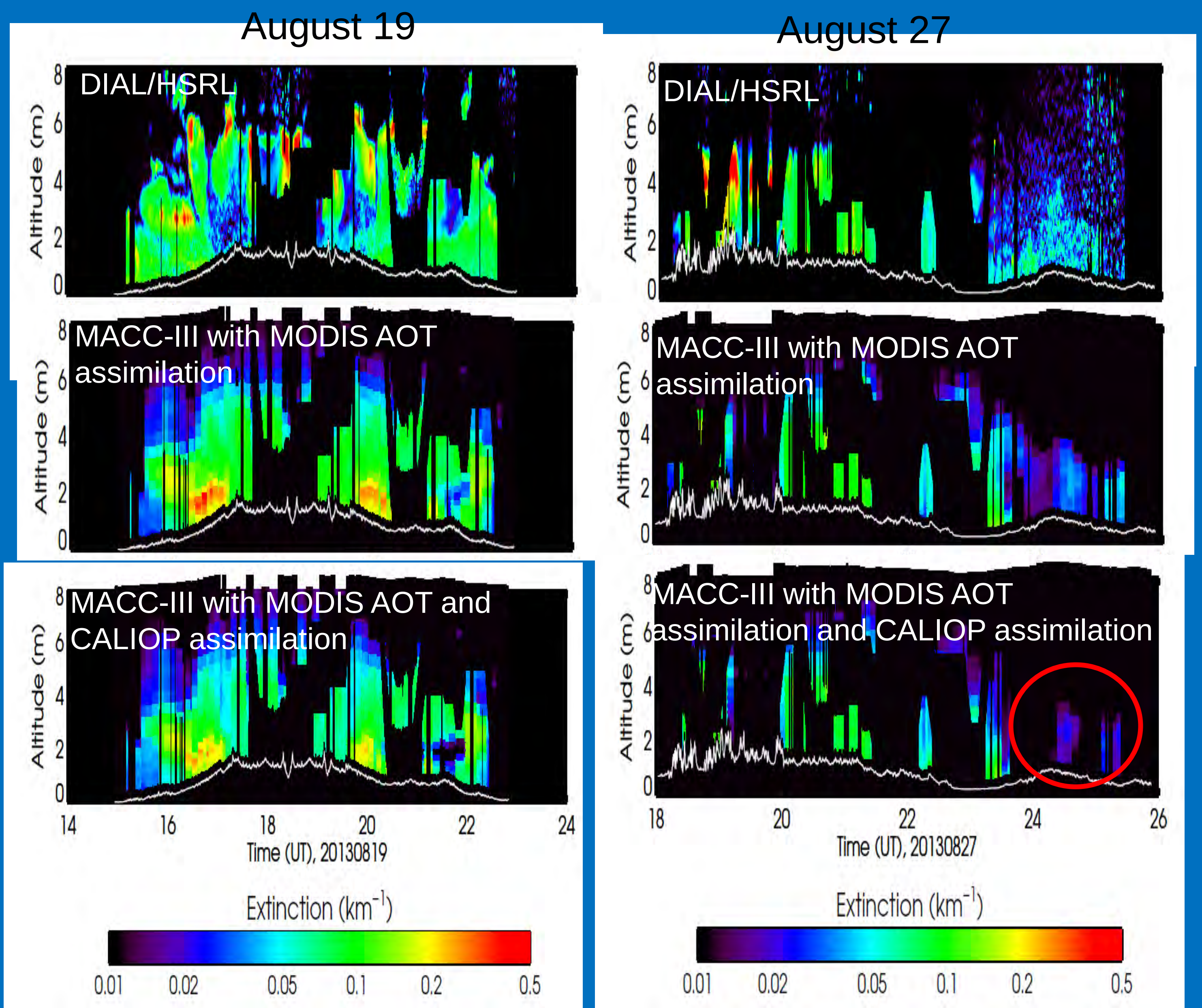
CALIOP+ MODIS

CALIOP + MODIS (both bias corrected)



…but globally the MODIS-only run is still slightly on the lead.

Evaluation of the impacts of CALIOP profile assimilation

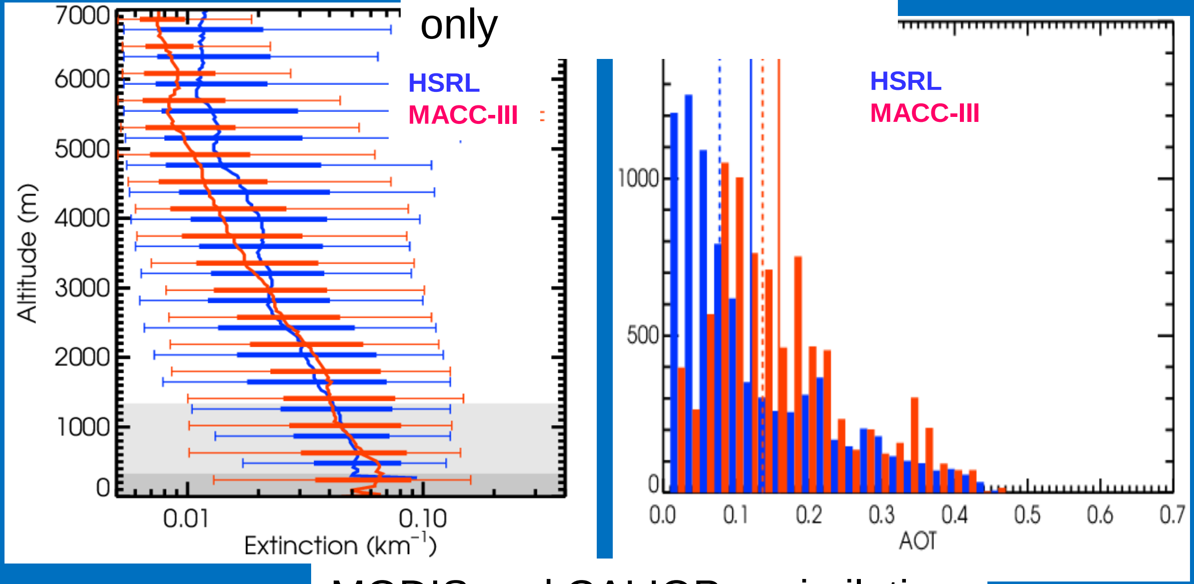


- Assimilation of CALIOP profiles slightly reduces extinction profiles in some locations; largest extinction values remain near surface
- Depending on location, these reductions can improve or worsen agreement with HSRL

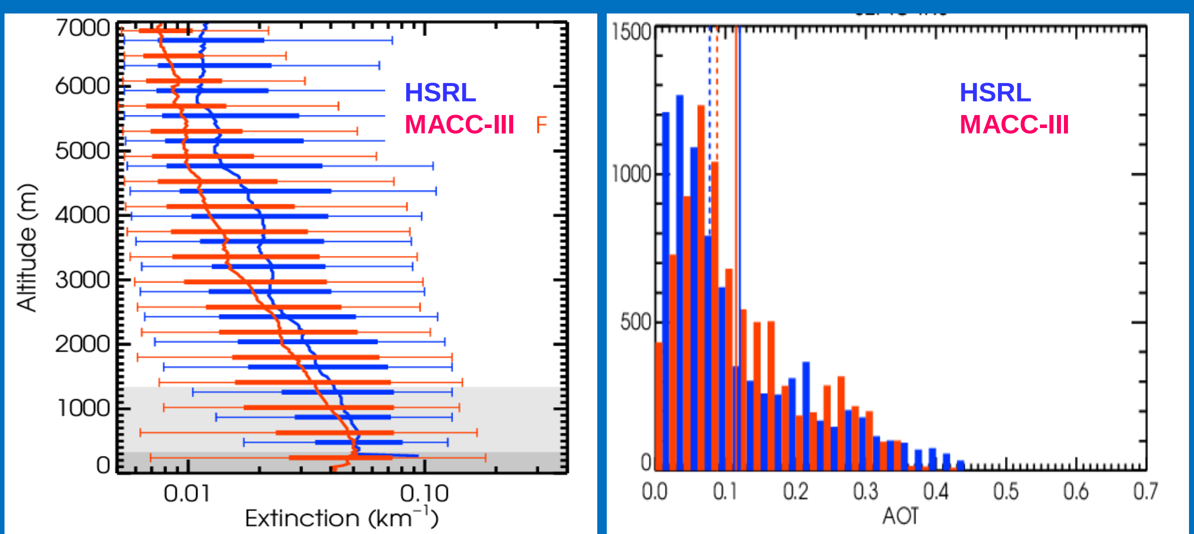
Credits: Rich Ferrare and Sharon Burton (NASA Langley)

Comparison of Median Profiles with and without CALIOP assimilation

MODIS assimilation only



MODIS and CALIOP assimilation

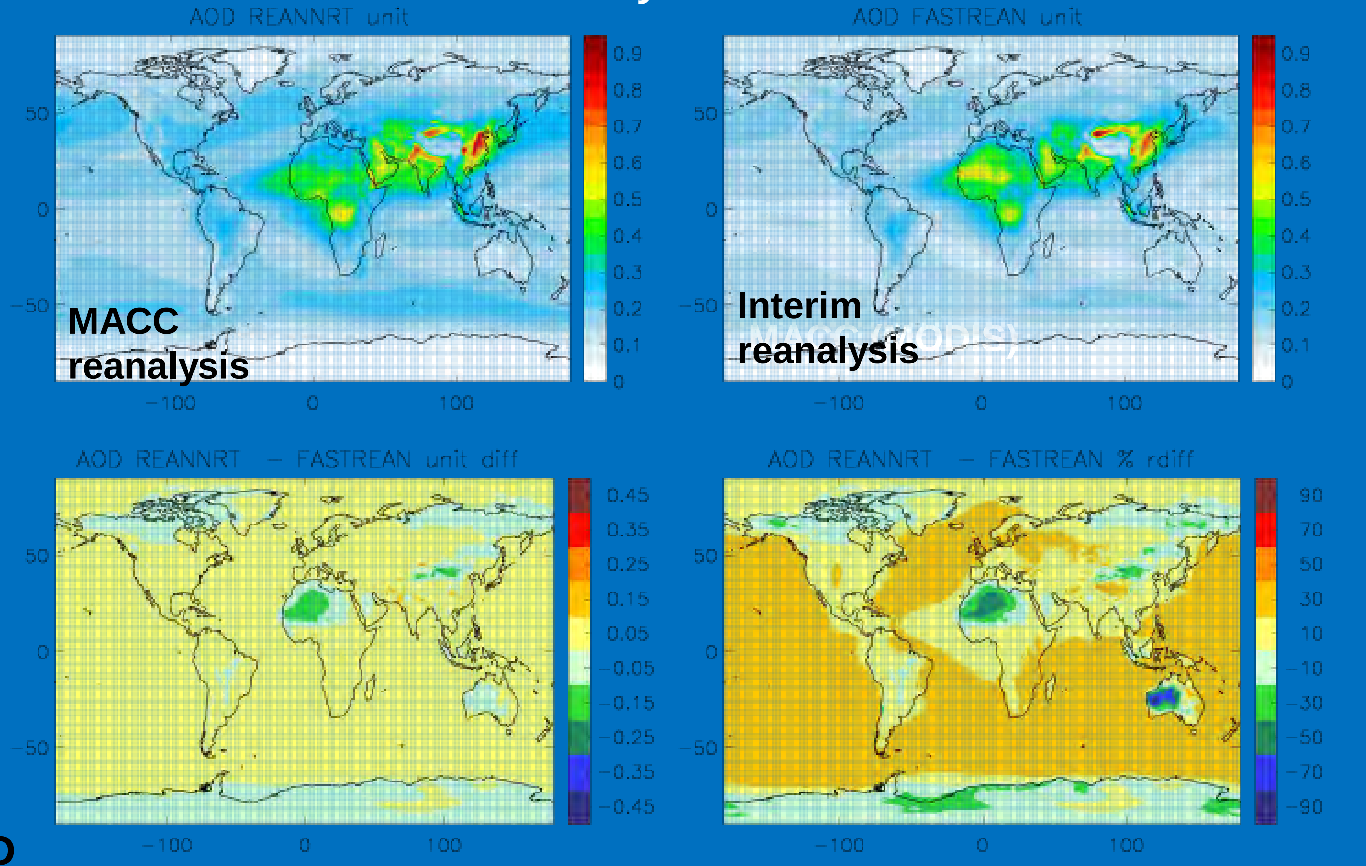


- Median profiles in good agreement with MODIS AOT assimilation
- Adding CALIOP:
  - produces relatively minor effects on median profiles
  - tends to lower the AOT with respect to runs that assimilate only MODIS AOT
  - gives a slightly better agreement with HSRL

Credits: Rich Ferrare and Sharon Burton (NASA Langley)

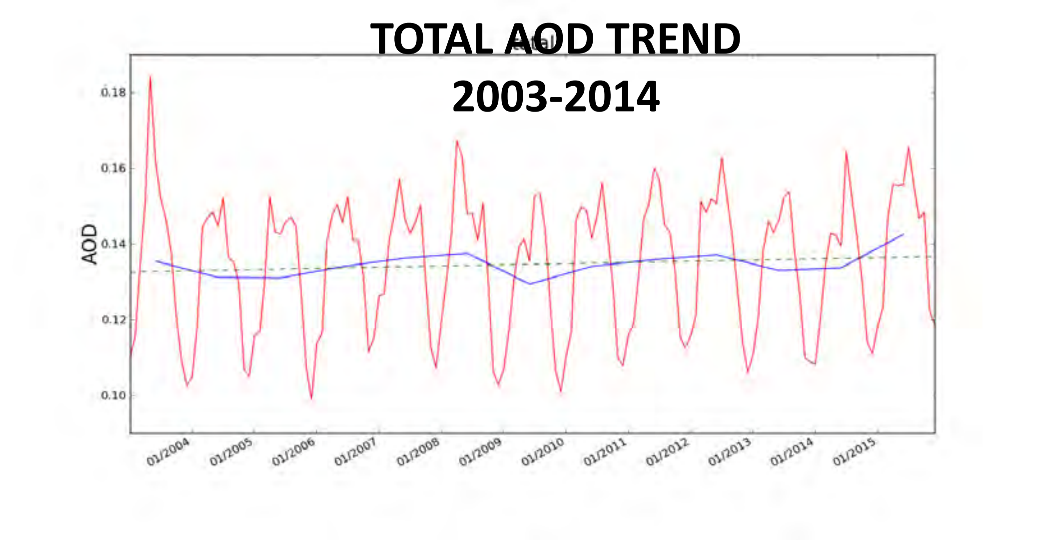
CAMS REANALYSIS RUNS

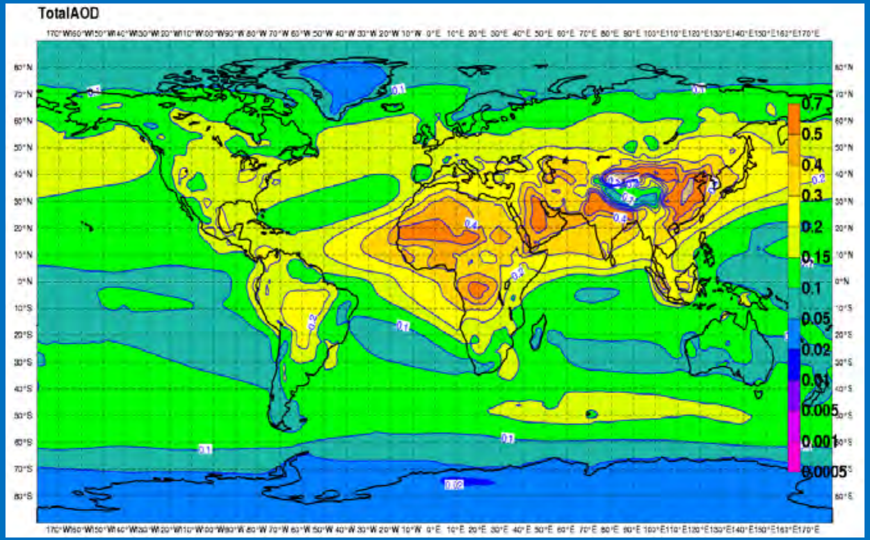
- New “interim” reanalysis from 2003-2015 has been run in parallel mode (literally) for fast turnaround
- Overall good performance
- Used for contribution to the State of Climate (BAMS, in publication)
- Substantial differences with MACC reanalysis



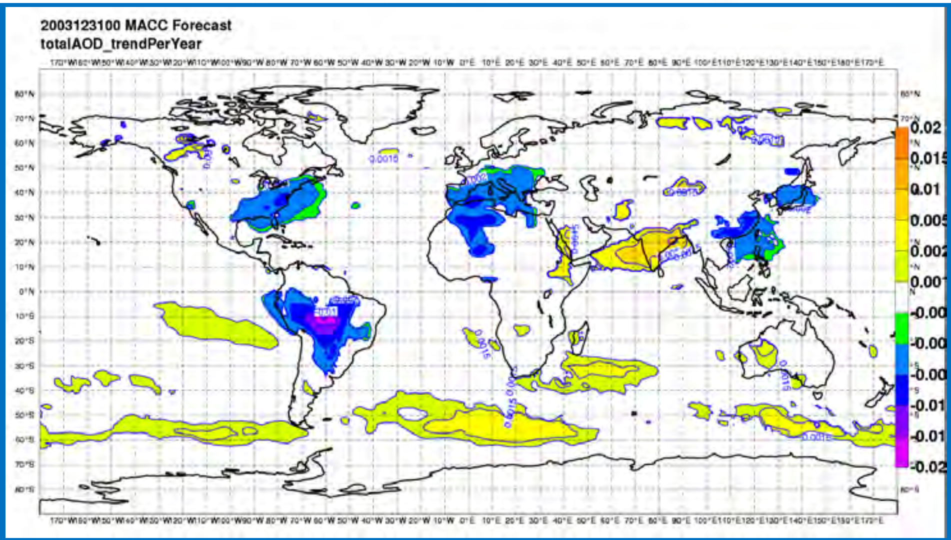
Flemming et al 2016, APCD

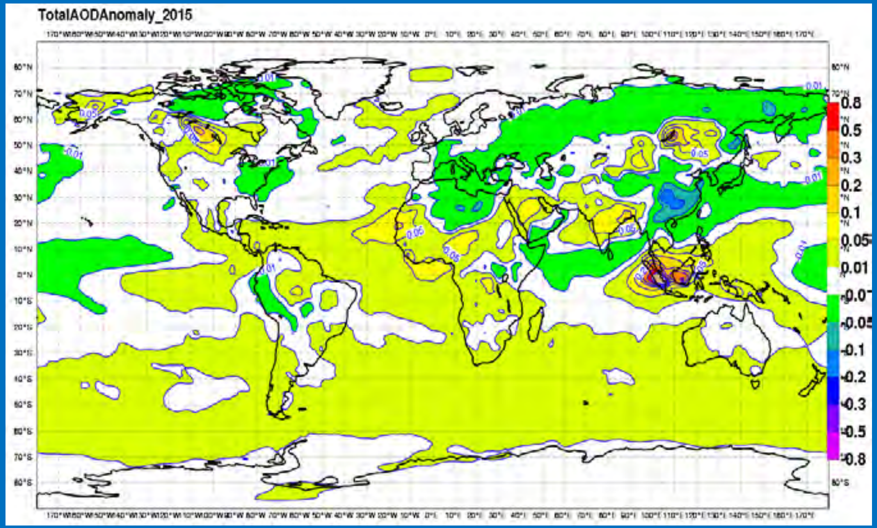
REANALYSIS RUNS: BAMS STATE OF CLIMATE 2015





TOTAL AOD
2003-2014





AOD ANOMALY
2015

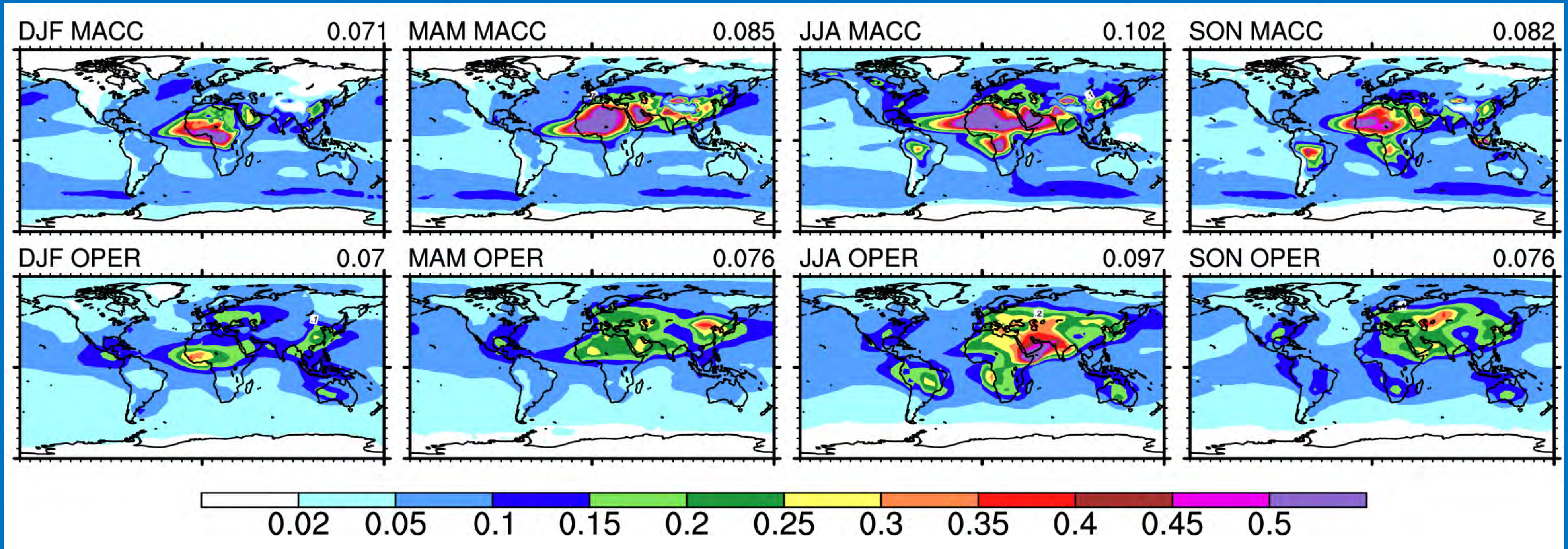
Rémy et al, 2016: [Global climate] Aerosols [in "State of the Climate in 2015"].
To appear in Bull. Amer. Meteor. Soc.

ECMWF

AEROSOL IMPACTS ON NUMERICAL WEATHER PREDICTION

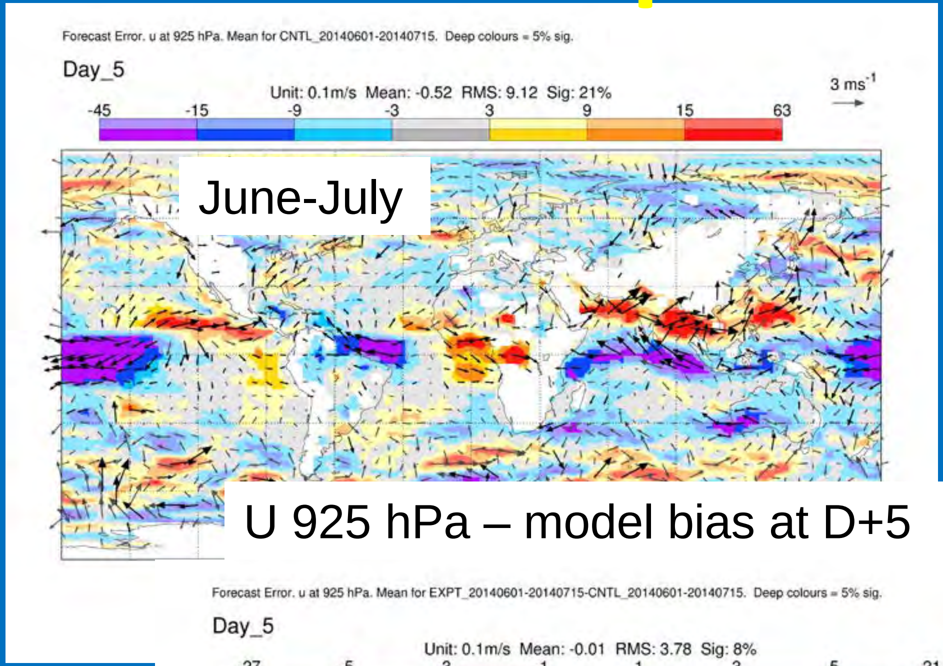
Climatological AOD 550nm distribution MACC vs Tegen et al 1997 (OPER)

Credits: Alessio Bozzo

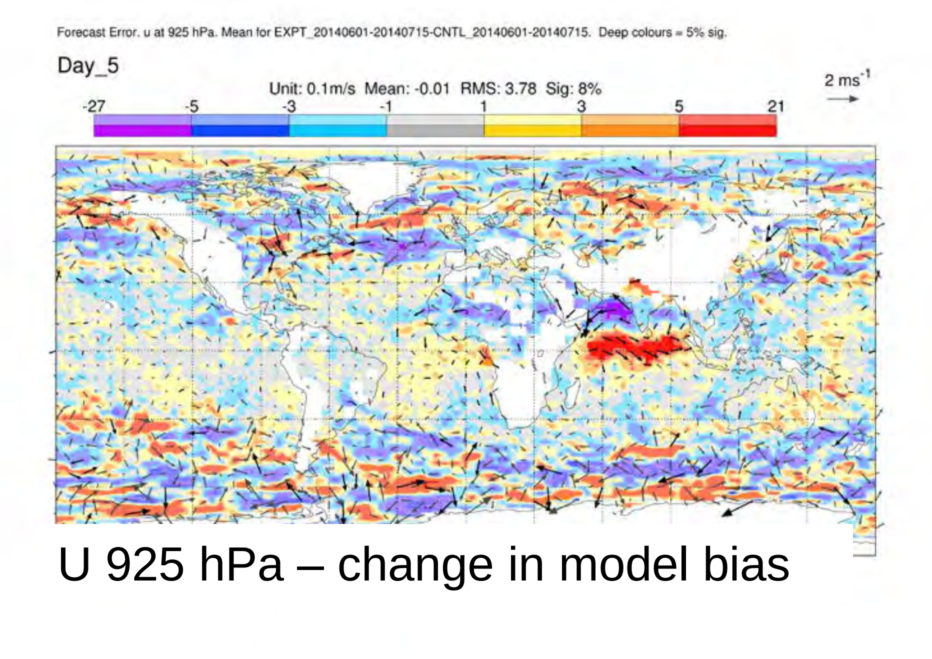


- MACC run (2003-2012): sources of biomass burning from GFAS, sulphate aerosol precursor from EDGAR 4.1, prognostic for sea salt and dust, revised dust model
- Optical properties recomputed for RRTM spectral bands and for each aerosol type/size bin. Mass mixing ratio as input to radiation
- Vertical distribution following an exponential decay with scale height derived from the MACC model for each aerosol type. Monthly varying for dust.

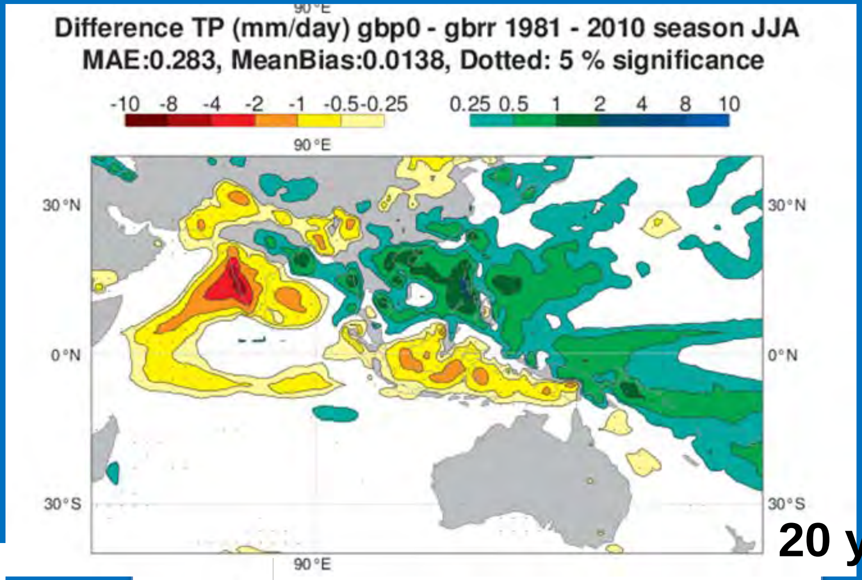
Impacts on FC errors



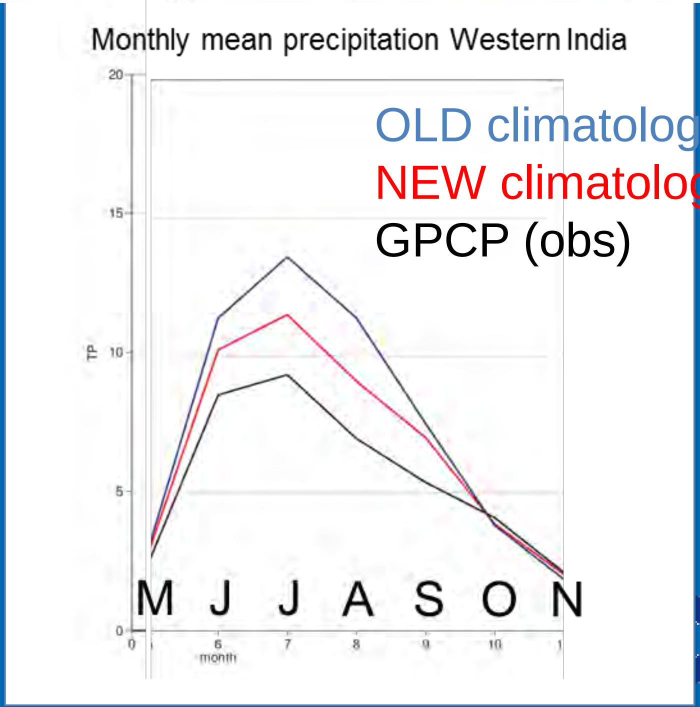
U 925 hPa – model bias at D+5



U 925 hPa – change in model bias



20 year run



Credits: Alessio Bozzo, Linus Magnusson

ECMWF

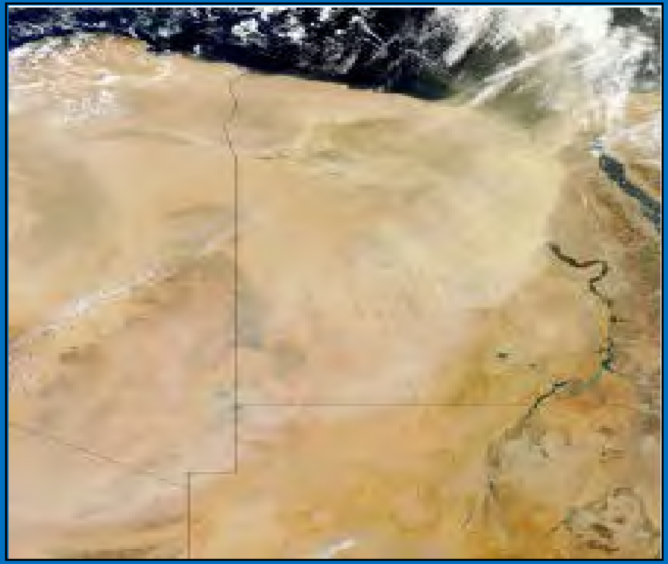
WMO Working Group on Numerical Experimentation (WGNE)

This inter-comparison aims to evaluate the impact of aerosols on Numerical Weather Prediction

Three situations were proposed :

- Dust storm over Egypt on 18th of April 2012
- Extreme pollution over Beijing, 12-16th of January 2013
- Extreme biomass burning over Brazil in September 2012 during the SAMBBA field campaign

Participants : Météo-France, Met-Office, JMA, ECMWF, NOAA, NASA, CPTEC (Brazil)



MODIS imagery, 18/4/2012

Beijing , 14/1/2013

Credits: Samuel Rémy

Dust case of April 2012 – Impact on temperature, winds and dust production

Table 2. 2m temperature, RMSE of REF_ASSIM and TOTAL_ASSIM for forecast times 0, 12, 24, 36 and 48h, average for the period of 10th to 25th of April 2012. Stations considered are Hurguada, Luxor, Kosseir, Siwa, Wadi el Natroon, Cairo, Port Said and Ras Sedr in Egypt, and Ben Gurion airport close to Tel Aviv in Israel.

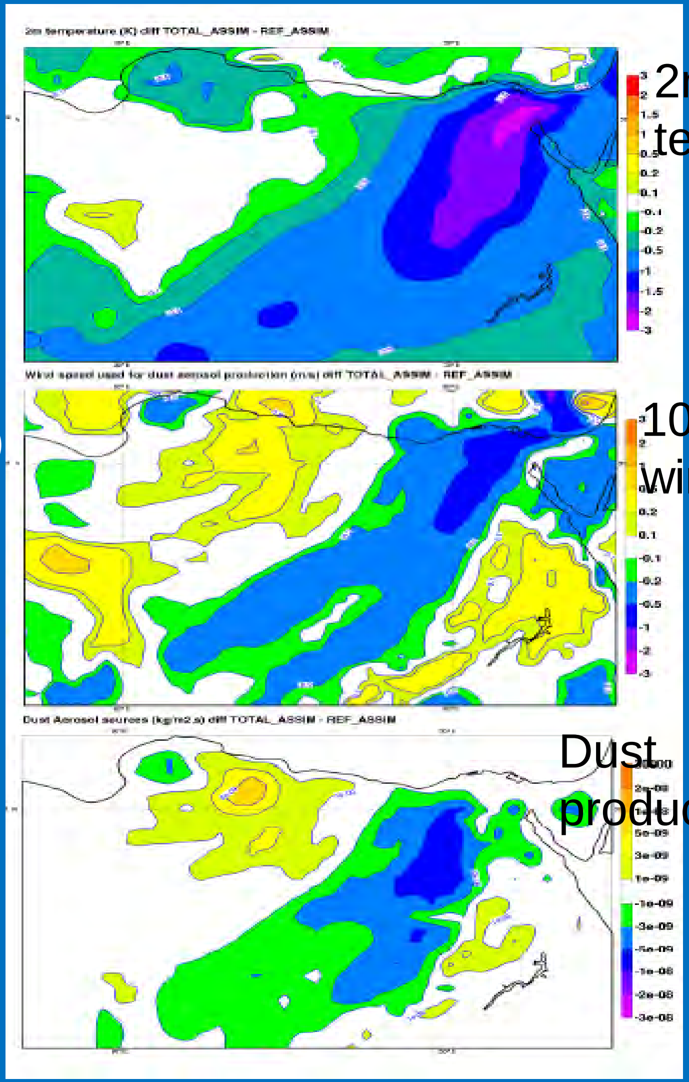
Forecast time	0h	12h	24h	36h	48h
REF_ASSIM	1.46	1.48	1.5	1.62	1.53
TOTAL_ASSIM	1.32	1.49	1.43	1.6	1.58

Table 3. 2m temperature, bias of REF_ASSIM and TOTAL_ASSIM for forecast times 0, 12, 24, 36 and 48h, average for the period of 10th to 25th of April 2012 over the same selection of weather stations as table 2.

Forecast time	0h	12h	24h	36h	48h
REF_ASSIM	-0.87	-0.05	-0.73	0.48	-0.47
TOTAL_ASSIM	-0.65	-0.18	-0.58	0.2	0.26

Difference between run with interactive aerosols (TOTAL_ASSIM) and reference run (REF_ASSIM) 36 hour forecast (valid on April 18th at 12UTC)

- Reduced 2m temperature
- Increased surface winds
- Increased dust production

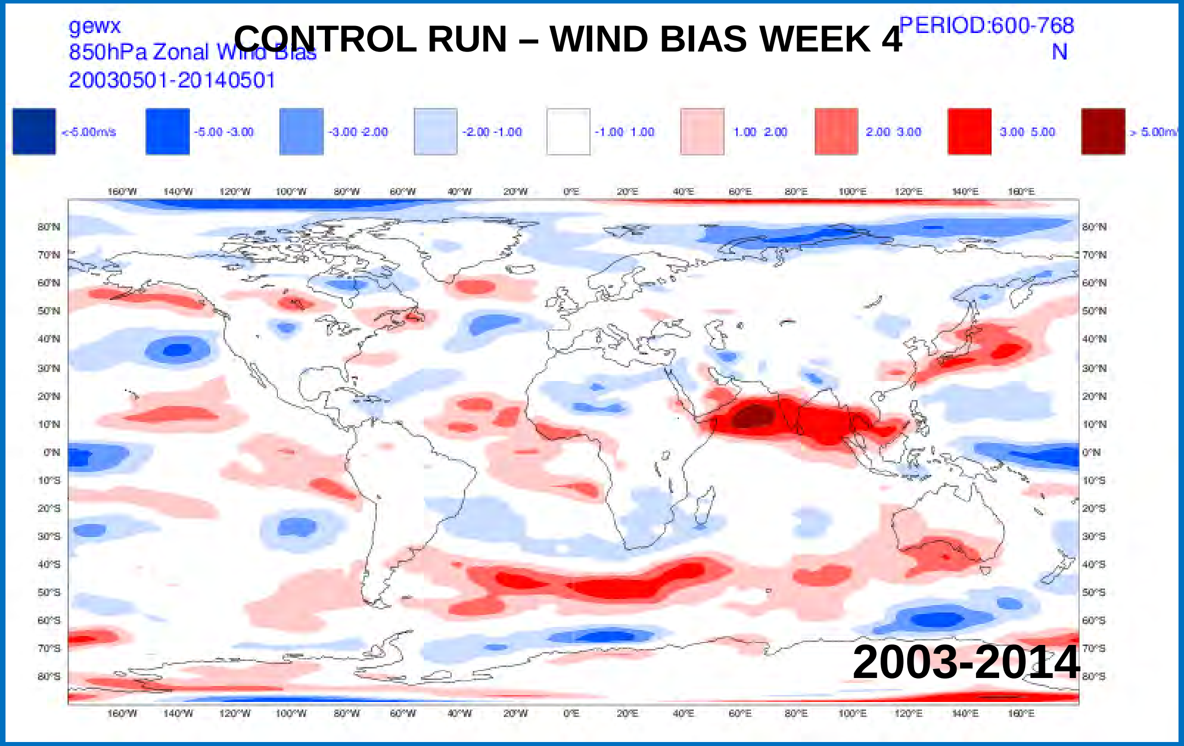


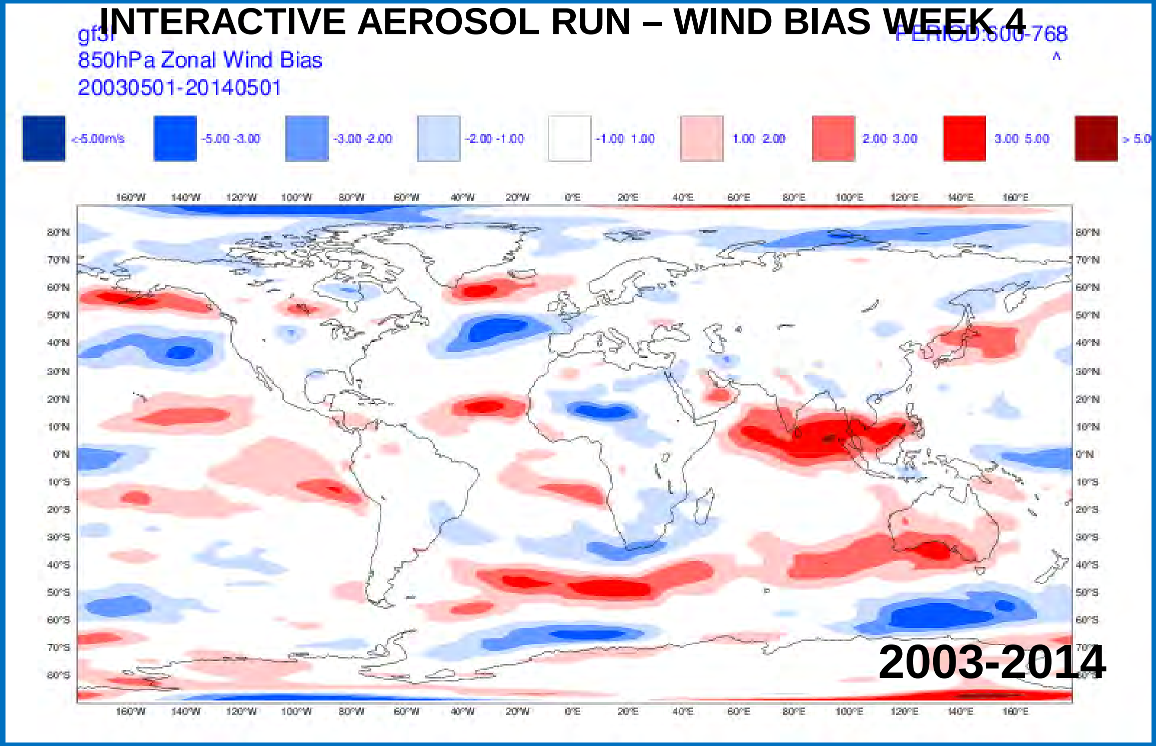
Rémy et al, 2015, ACP, doi:10.5194/acp-15-12909-2015

ECMWF

Aerosol impacts on monthly forecasts (I)

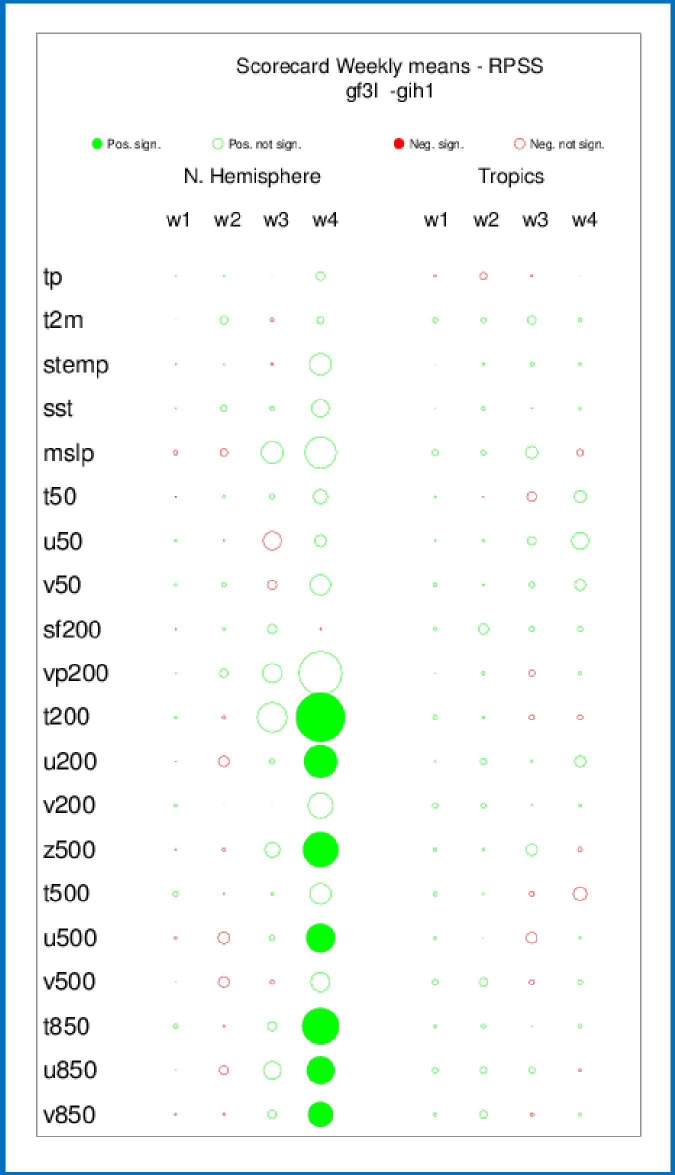
- Preliminary results confirm the positive impact (reduction in bias) of the interactive aerosols on meteorological fields (winds and precipitation)
- More prominent (positive) impact over the Indian Ocean and to a lesser extent in other areas
- Aerosol fields will be evaluated too by comparing with the MACC/CAMS reanalysis (BONUS: aerosol seasonal prediction!)

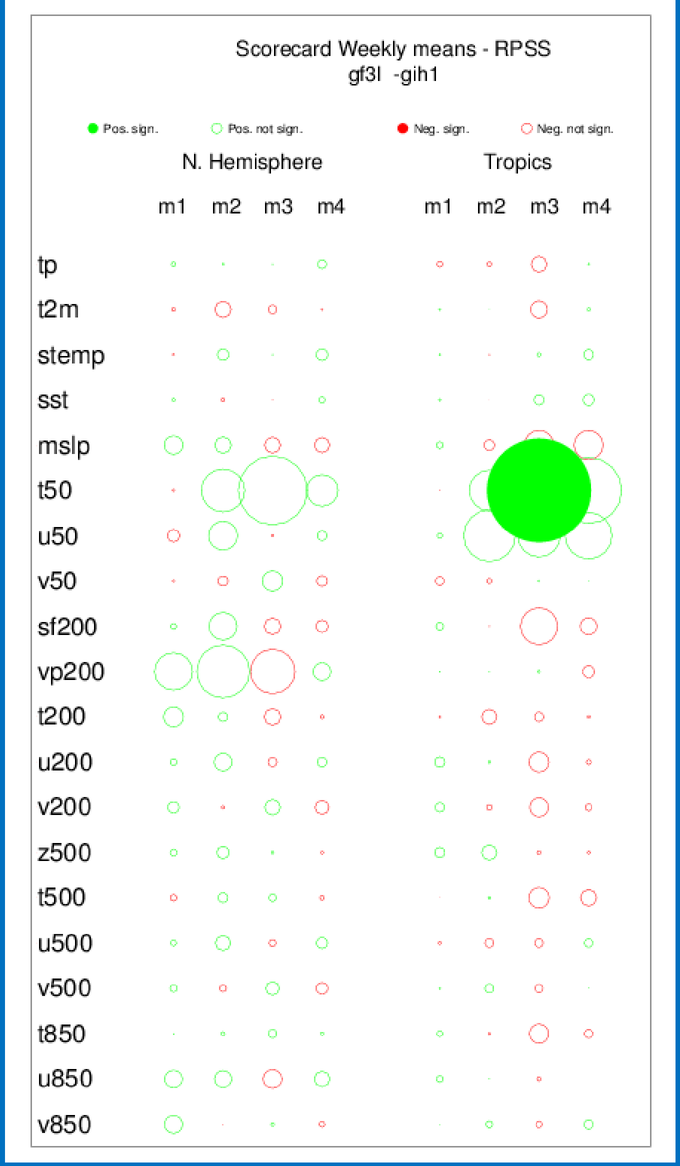




In collaboration with: Fréderic Vitart (ECMWF)

Aerosol impacts on monthly forecasts (II)





- Scorecards measures performance of interactive aerosol experiment with respect to the control run for several parameters.
- Green circles indicate positive impact
- Solid circles indicate significant Impact
- Temperature and winds greatly improved at week 4 in the interactive aerosol run!
- Upper-level temperature also improved on the seasonal scale (month 2-3)

Summary and future perspectives

- CAMS offers many services related to atmospheric composition from daily forecasts to reanalysis runs both at the global and at the regional (European) level

- Model developments have been carried out for the past 10 years during precursors projects. They are now part of the ECMWF's Integrated Forecasting System

- Several datasets are routinely assimilated and more are in the pipeline (Copernicus Sentinel satellites)

- The impact of interactive aerosols on Numerical Weather Prediction is being investigated at different time ranges and promises interesting results