Use of satellite data for Environmental Monitoring

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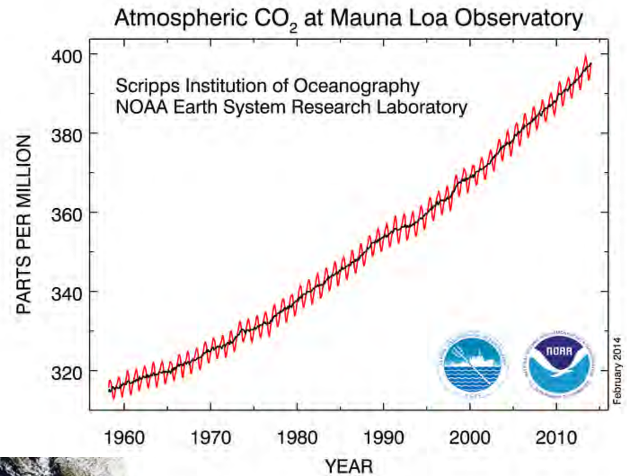
Based on a lecture by: Antje Inness

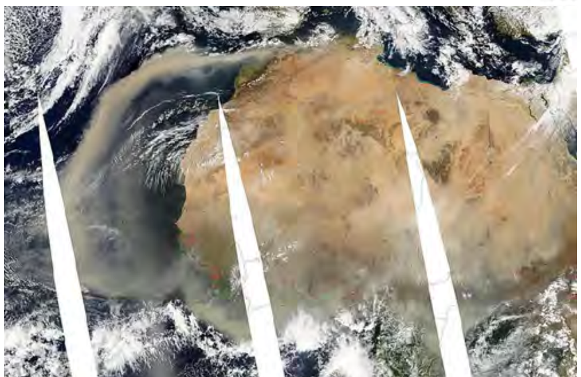
Contributions from: Richard Engelen, Johannes Flemming, Sebastien Massart

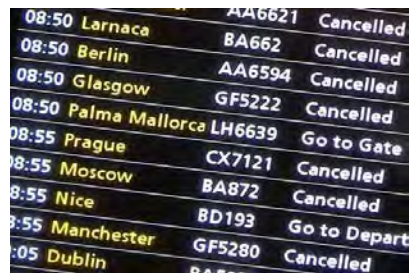
Outline

1. **Introduction**
2. **Challenges for atmospheric composition DA**
3. **Observations of atmospheric composition**
4. **Atmospheric composition assimilation**
5. **Concluding remarks**

Atmospheric composition







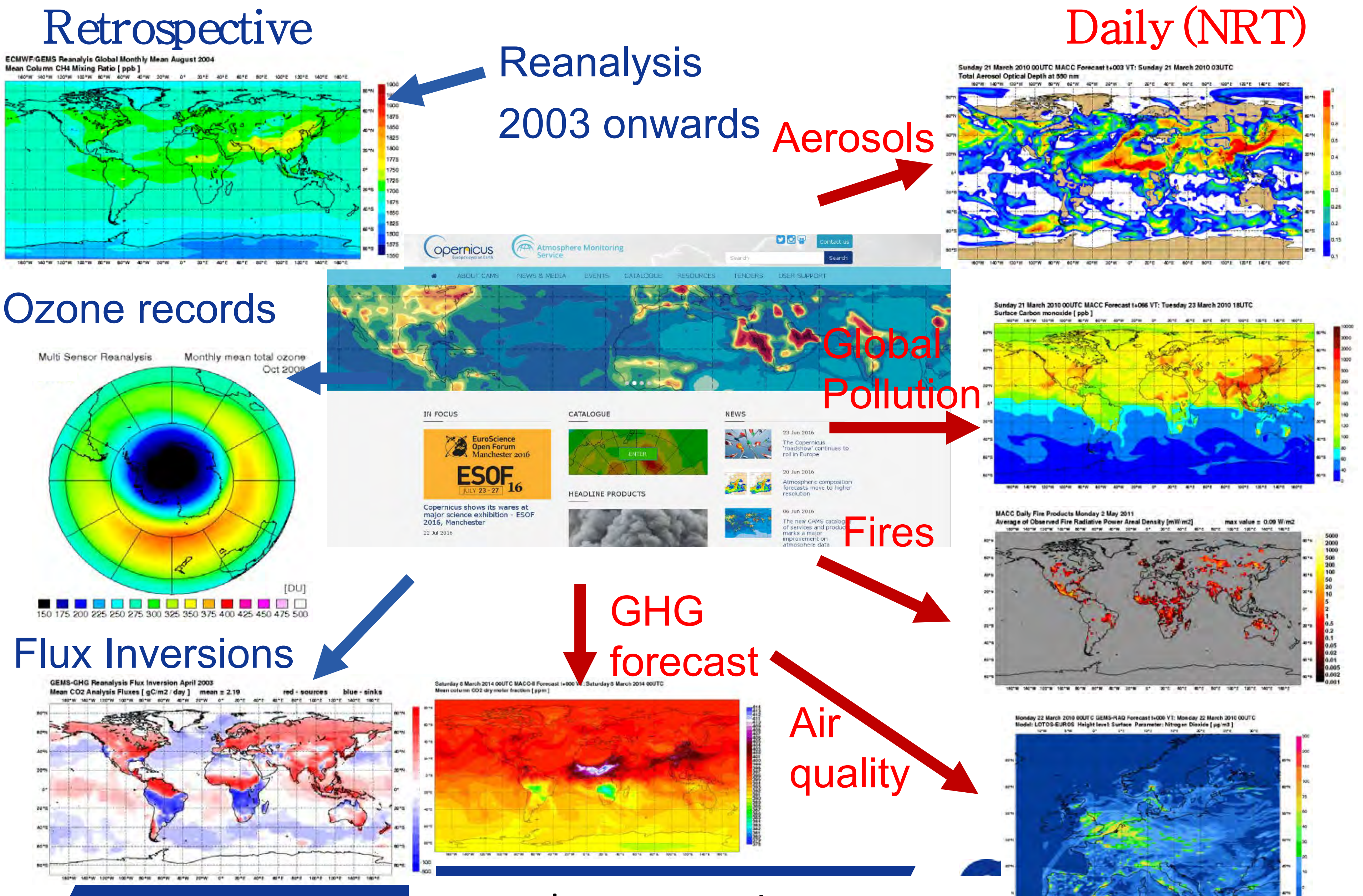
Scientific Motivation

- Environmental and health concern (29,000 premature deaths due to pollution in UK per year)
- Important to provide air quality forecasts
- Expertise in data assimilation and atmospheric modelling
- Not fundamentally different from meteorological DA but several new challenges
- Interaction of atmospheric composition (AC) and NWP
  - Feedback on dynamics via radiation scheme
  - Precipitation and clouds
  - Satellite data observations influenced by aerosols (and trace gases)
  - Hydrocarbon (Methane) oxidation is water vapour source
  - Assimilation of AC data can have impact on wind field

Composition-IFS (C-IFS)

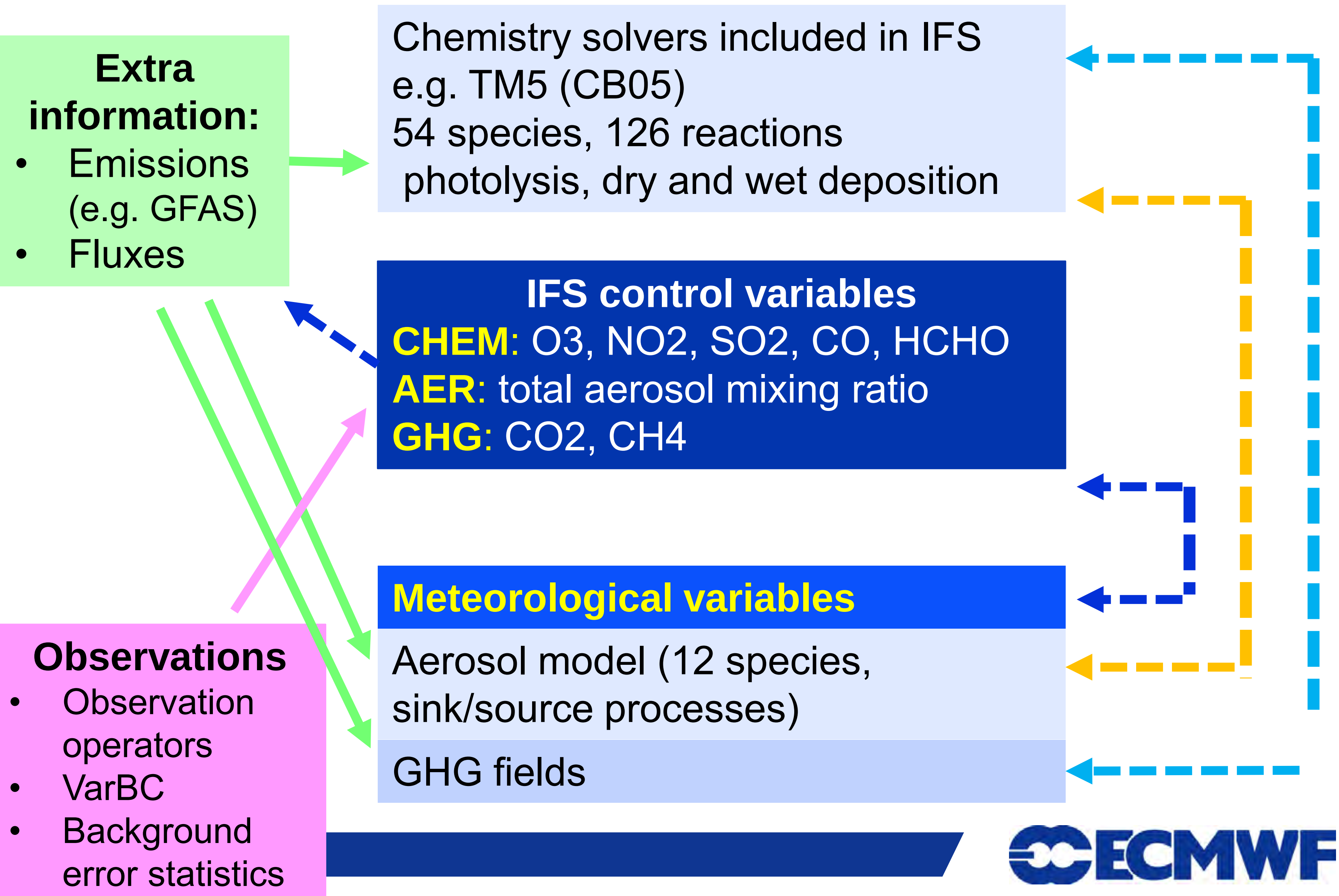
- Over the last decade IFS has been extended with modules for atmospheric composition (aerosols, reactive gases, greenhouse gases)
- GEMS -> MACC -> CAMS (Copernicus Atmosphere Monitoring Service) projects
- At first a “Coupled System”, now composition fully integrated into IFS
- Data assimilation of AC data to provide best possible IC for subsequent forecasts
- AC benefits from online integration and high temporal availability of meteorological fields
- C-IFS provides daily analyses and 5-day forecasts of atmospheric composition in NRT

CAMS Service Provision



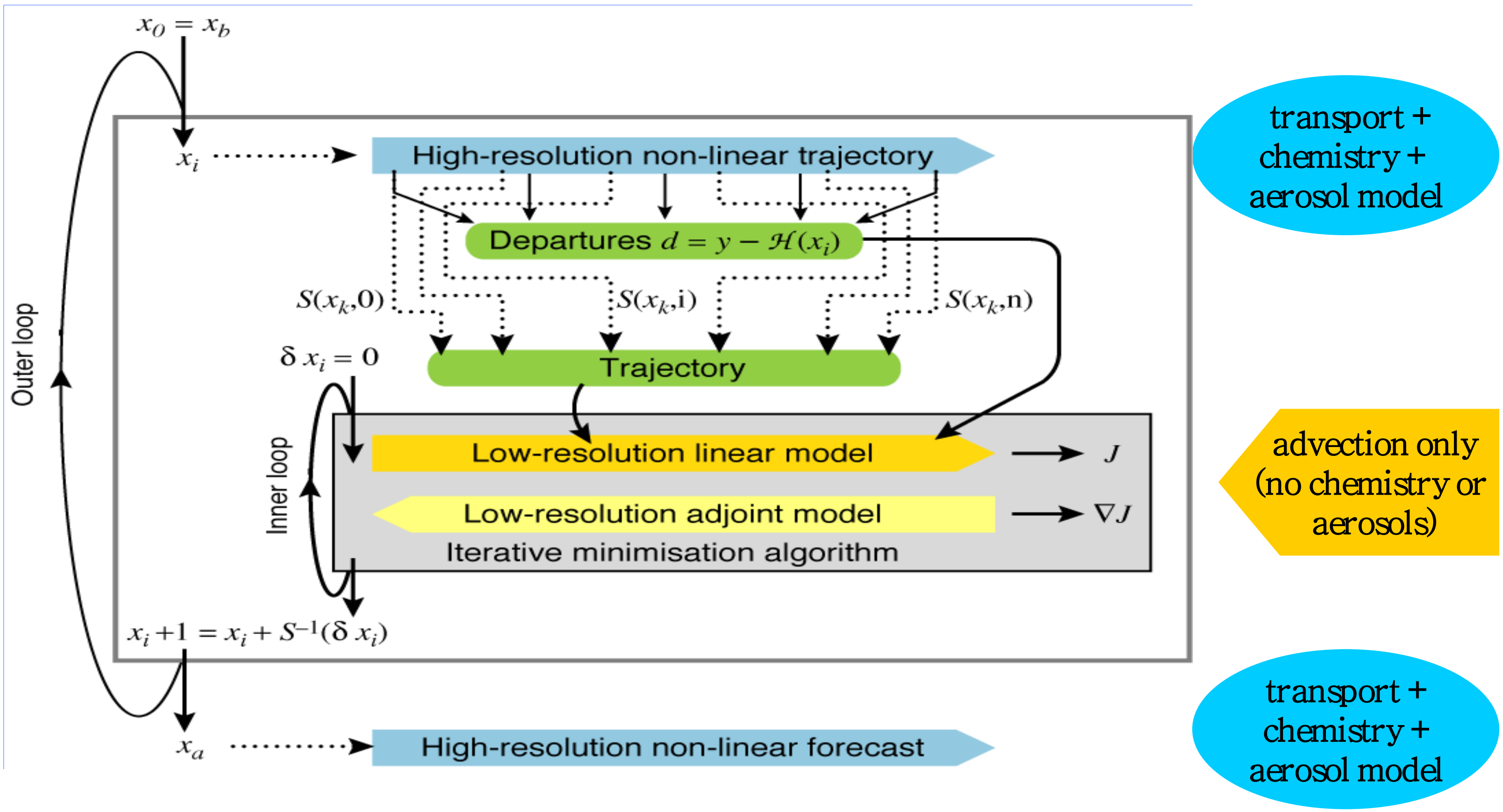
atmosphere.copernicus.eu

CAMS data assimilation system



ECMWF

ECMWF CAMS 4D-VAR Data Assimilation Scheme: Assimilation of AC

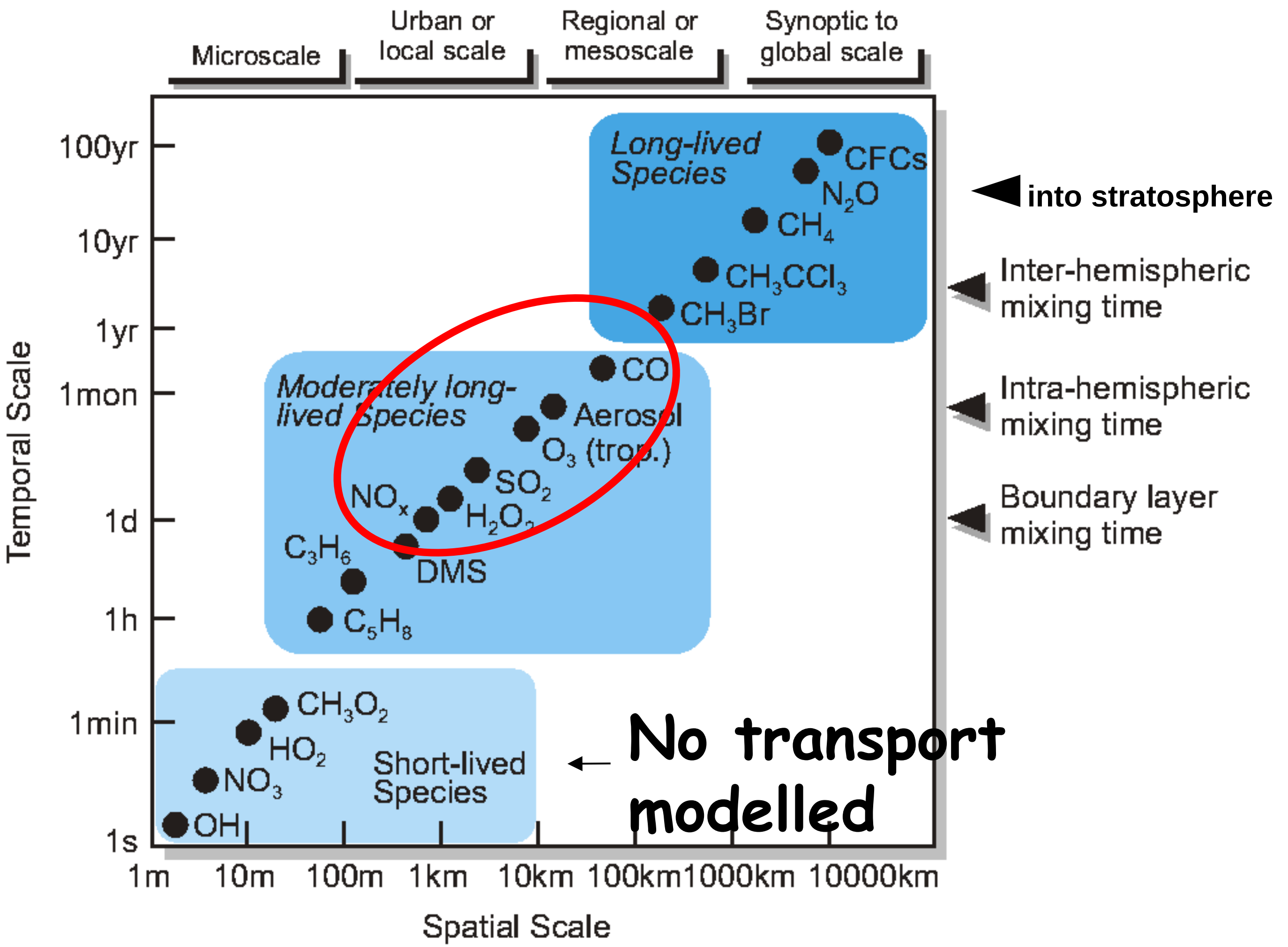


CHALLENGES IN ATMOSPHERIC COMPOSITION DATA ASSIMILATION

Challenges

- Quality of NWP depends predominantly on initial state
- AC modelling depends on initial state (lifetime) and surface fluxes
- Large part of chemical system not sensitive to initial conditions because of chemical equilibrium, but dependent on model parameters (e.g. emissions, deposition, reaction rates,…)
- Data assimilation is challenging for short lived species (e.g. NO2)
- CTMs have larger biases than NWP models
- Most processes take place in boundary layer, which is not well observed from space
- Only a few species (out of 100+) can be observed
- Data availability
- More complex and expensive, e.g. atmospheric chemistry, aerosol physics
- Concentrations vary over several orders of magnitude

Chemical Lifetime vs. Spatial Scale



After Seinfeld and Pandis [1998]

Emission Estimates

- Emissions are one of the major uncertainties in modeling (difficult to measure directly)
- The compilation of emissions inventories is a labour-intensive task based on a wide variety of socio-economic and land use data
- Some emissions can be "modeled" based on wind (sea salt aerosol) or temperature (biogenic emissions)
- Some emissions can be observed indirectly from satellites instruments (Fire radiative power, burnt area, volcanic plumes)
- "Inverse" methods can be used to correct emission estimates using observations and models – in particular for long lived gases such as CO2 (e.g. Chevallier et al. 2014) and Methane (Bergamaschi et al. 2009)
- Emissions can be included in the control vector and adjusted together with concentrations (e.g. Hanea et al. 2004; Elbern et al. 2007; Miyazaki et al. 2012)

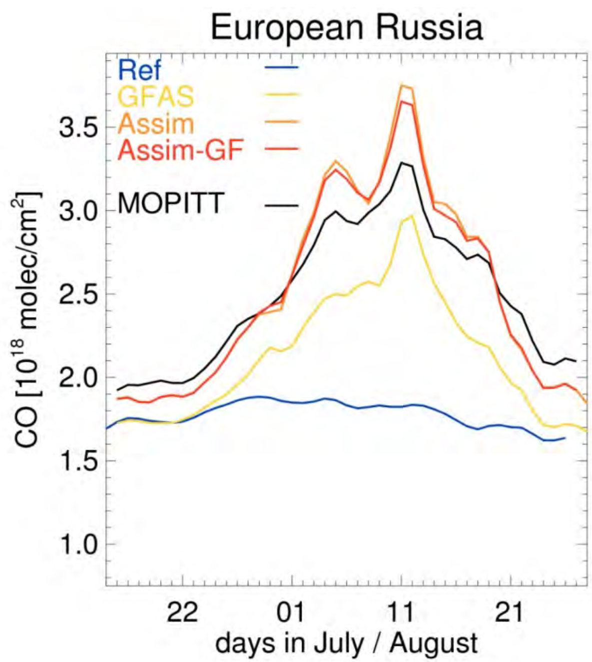
Emission Processes

- Combustion related (CO, NO_x, SO_2, VOC, CO_2)
  - fossil fuel combustion
  - Bio-fuel combustion
  - fires (anthropogenic and wild fires)
- Fluxes from biogeochemical processes (VOC, CH4, CO_2, Pollen):
  - biogenic emissions (plants, soils oceans)
  - agricultural emissions (including fertilisation)
- Fluxes from wind blown dust and sea salt (from spray)
- Volcanic emissions (volcanic ash, SO_2, HBr …)
- In MACC we use **GFAS fire emissions** (Kaiser et al. 2012) and **MACCity anthropogenic emissions** (Granier et al. 2011)
- Biomass burning accounts for ~ 30% of total CO and NO_x emissions, ~10% CH4

Importance of emissions (Russian fires 2010)

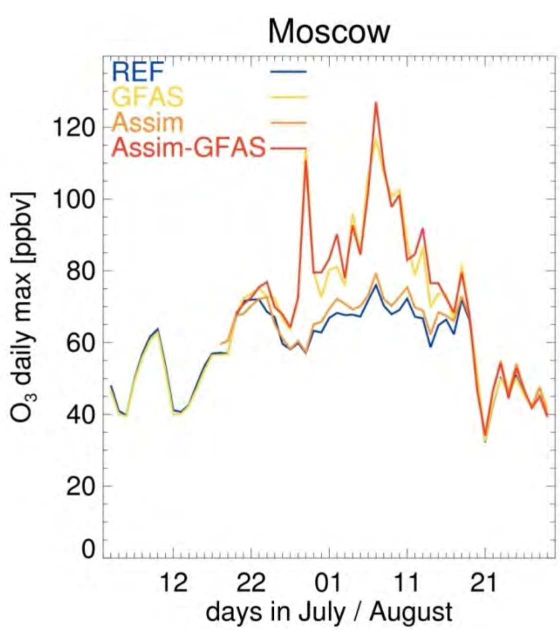
Huijnen et al. 2012 (ACP)

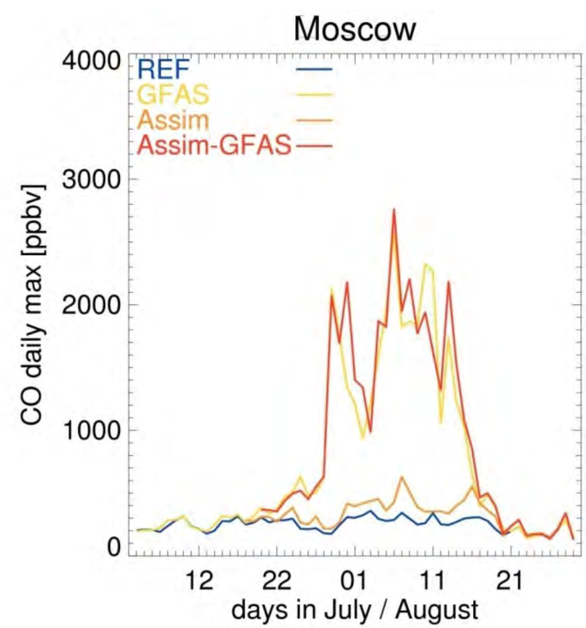
Total column CO



- Assimilation of IASI TCCO leads to improved fit to MOPITT TCCO
- TCCO from **Assim** and **Assim-GFAS** are very similar

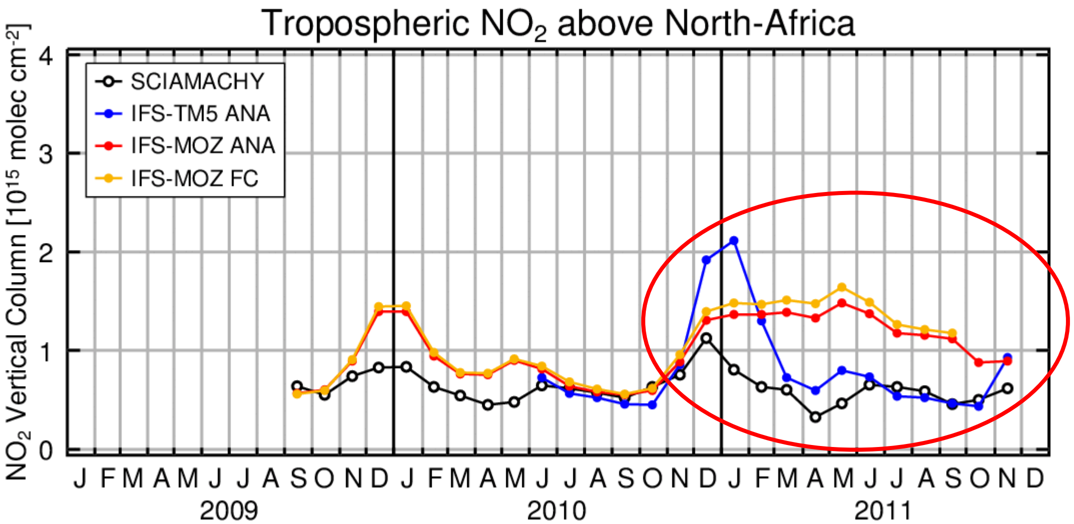
Daily maximum surface O3 and CO

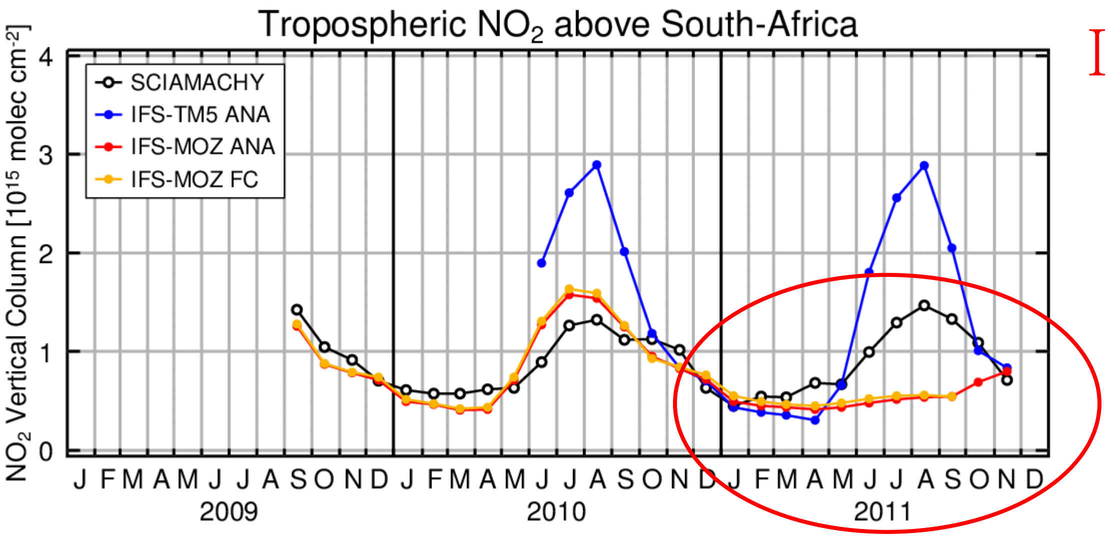




GFAS emissions are needed to get peak in **surface concentrations** in **GFAS** and **Assim-GFAS**

Importance of fire emissions on tropospheric NO2

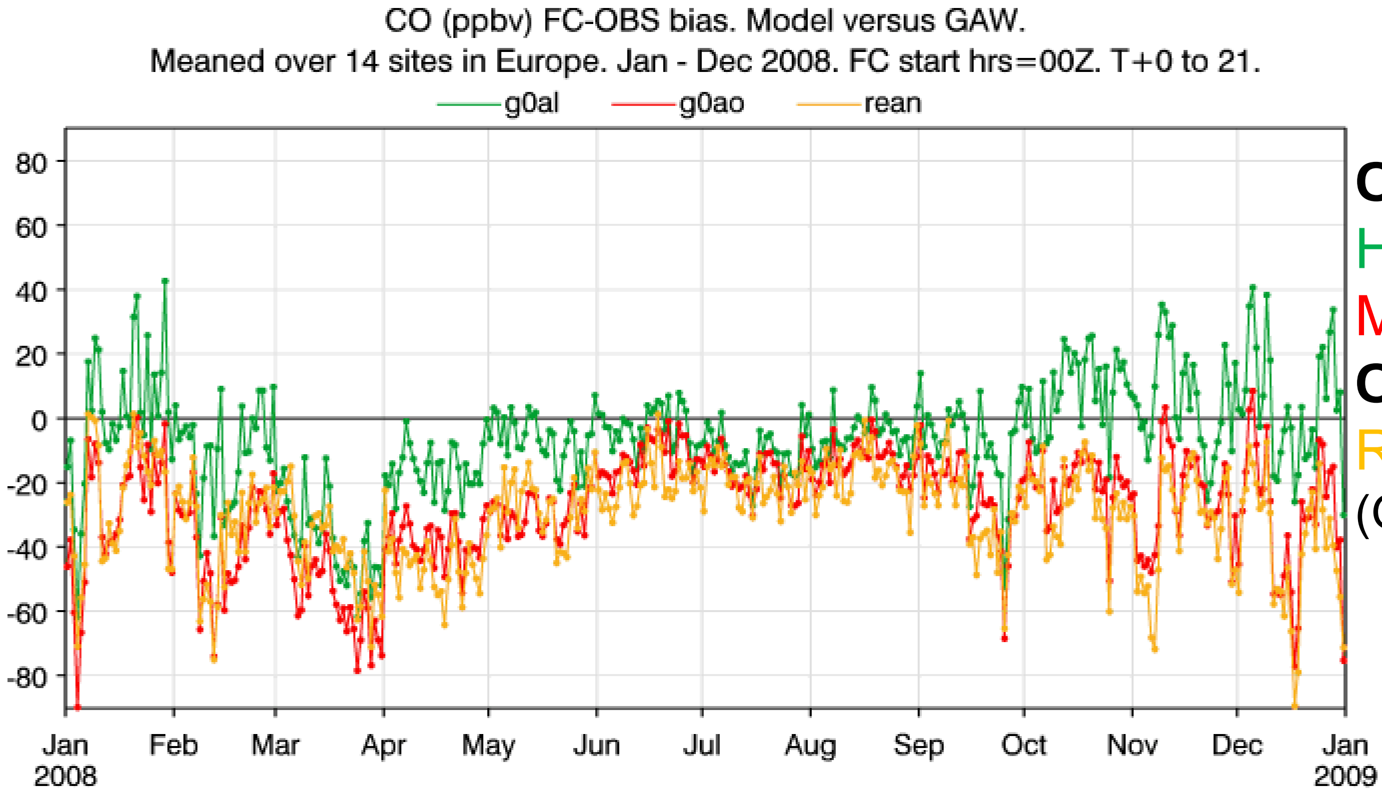




GFAS emissions for January used by mistake in IFS-MOZ during 2011

ECMWF

Impact of anthropogenic emissions: CO Bias - GAW Europa timeseries



C-IFS runs:

HTAP emissions

MACCity emissions

Coupled system:

Reanalysis (MACCity)

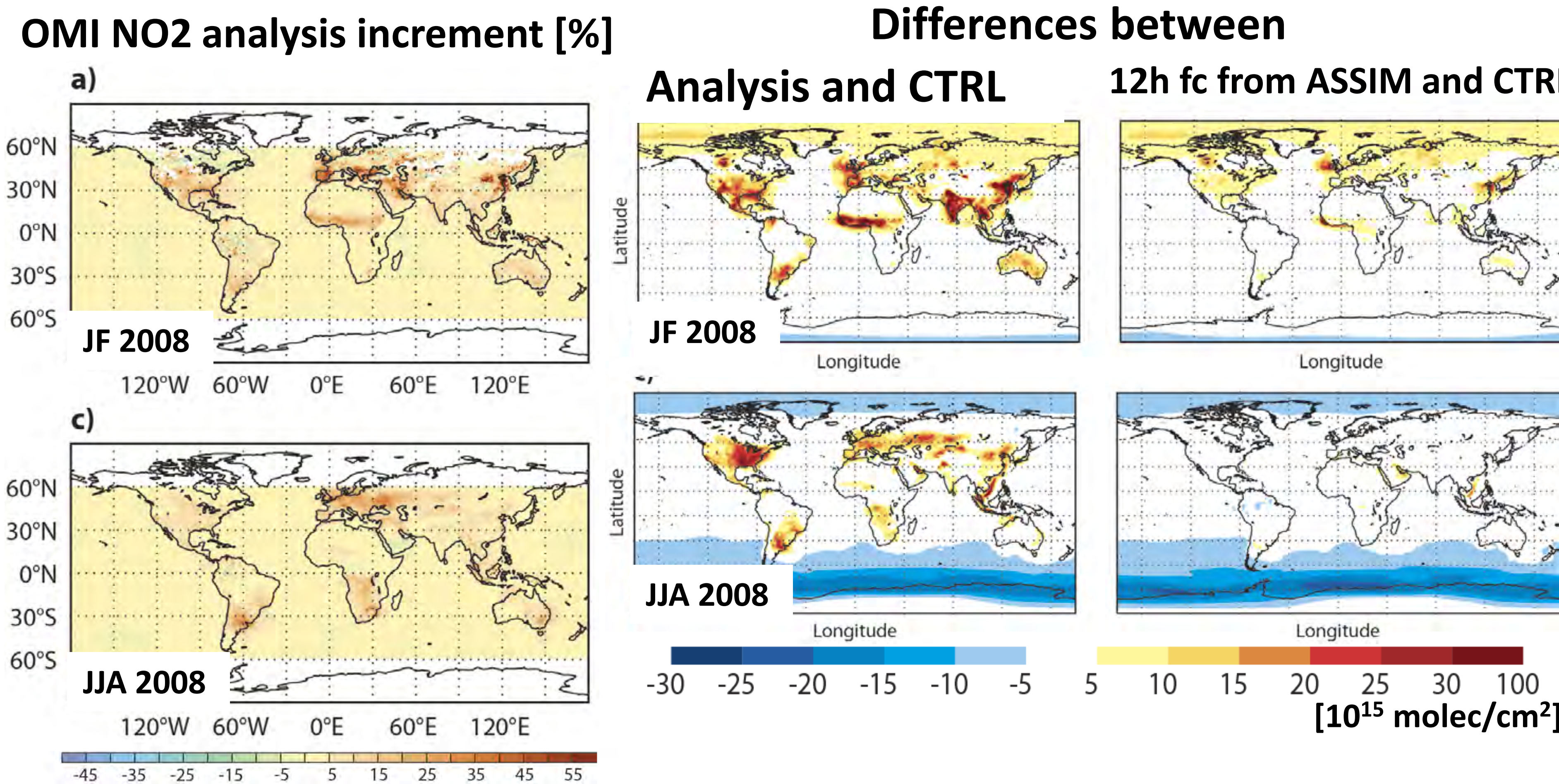
(GFAS used in all runs)

Choice of emissions data set has large impact on surface concentrations

Credits: J. Flemming

ECMWF

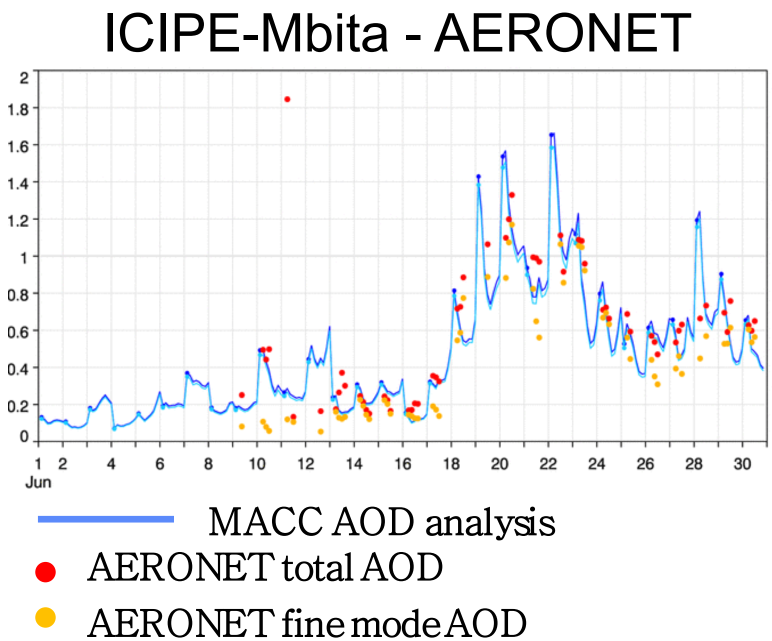
Short lived memory of NO2 assimilation

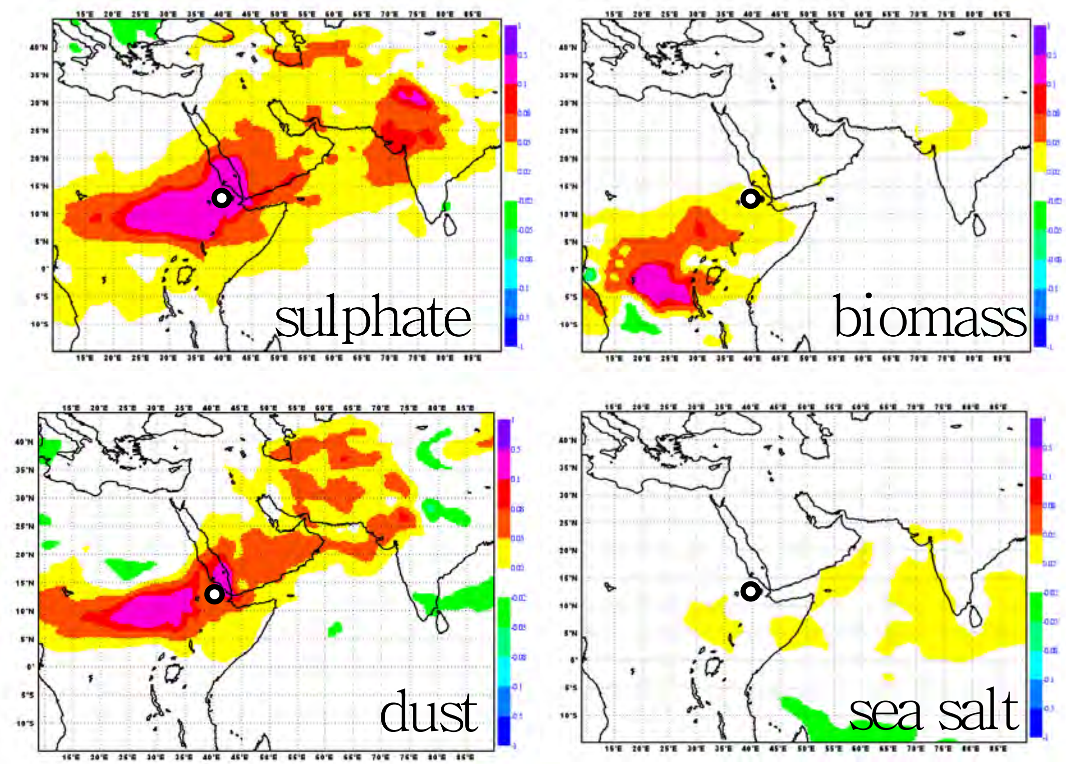


- Large positive increments from OMI NO2 assim
- Large differences between analyses of ASSIM and CTRL
- Impact is lost during subsequent 12h forecast
- It might be more beneficial to adjust emissions (instead of IC)

Under-constrained system for aerosols

Eruption of the Nabro volcano in June 2011 put a lot of fine ash into the stratosphere. This was observed by AERONET stations and the MODIS instrument.

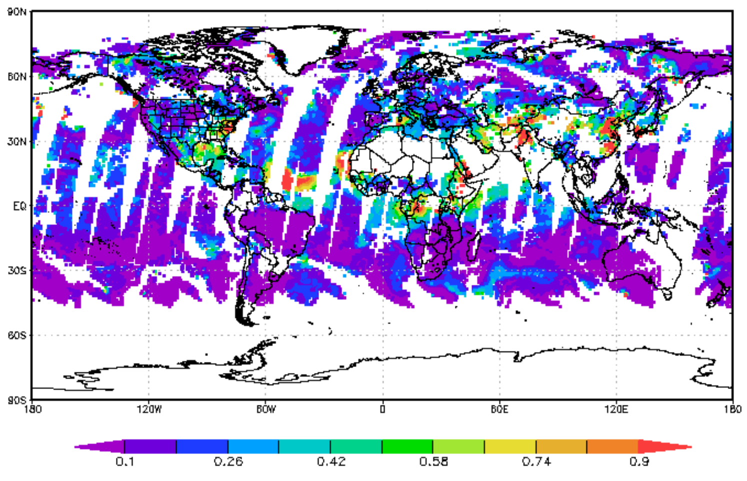


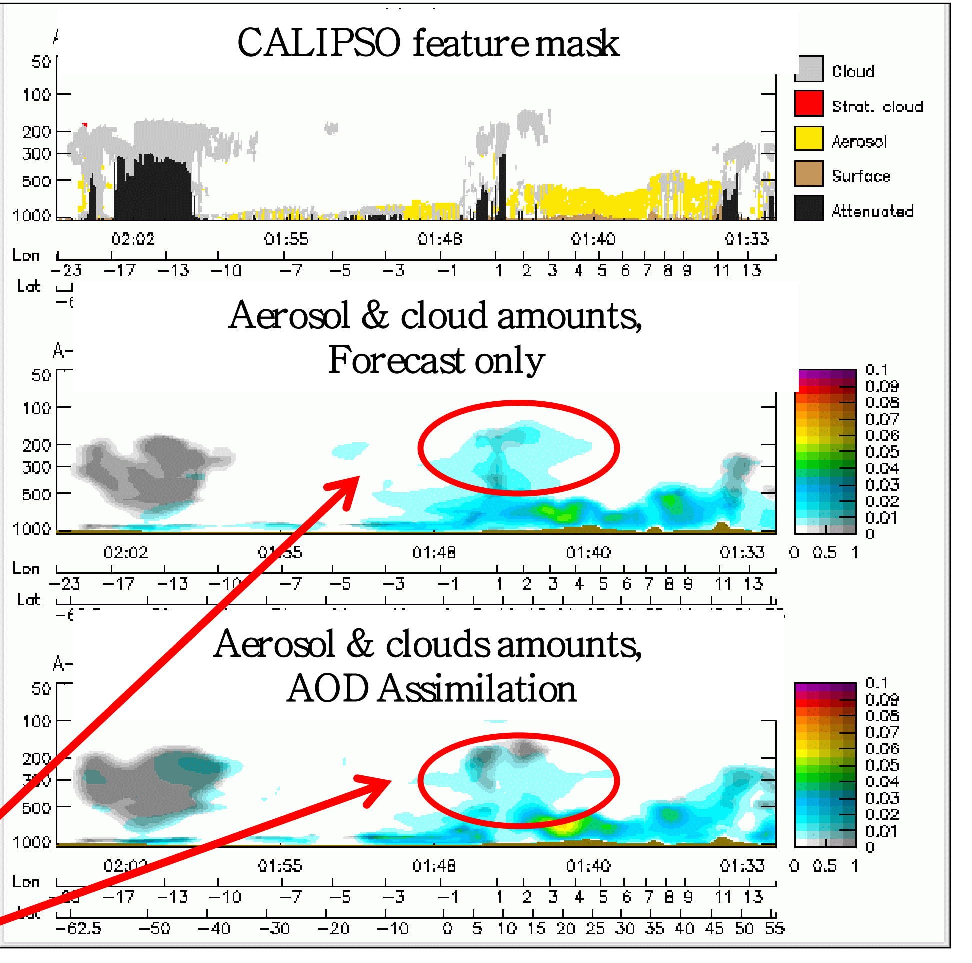


The MACC aerosol model did not contain stratospheric aerosol at this time, so the observed AOD was wrongly attributed to the available aerosol types.

ECMWF

Need for profiling data





- AOD is a column-integrated quantity
- Assimilation of AOD does not modify the vertical profile
- Profile data are needed (lidar)

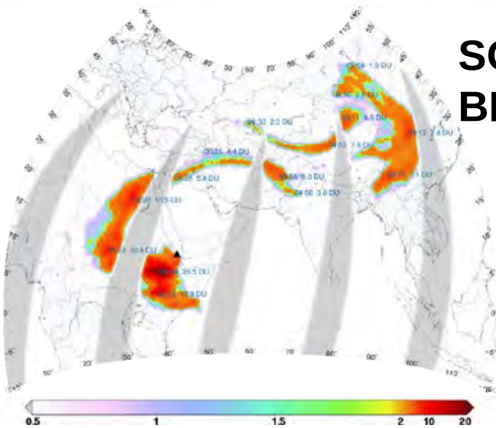
Graphics by Luke Jones

ECMWF

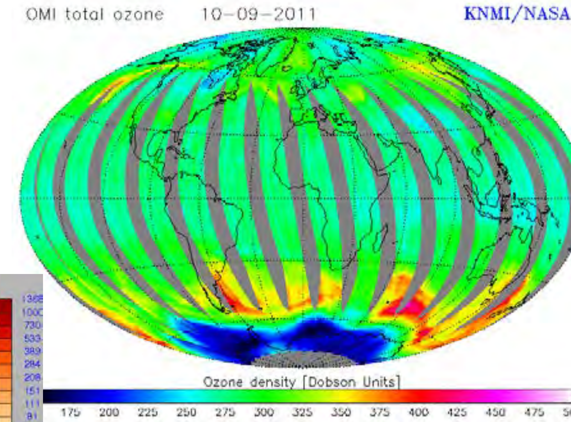
OBSERVATIONS OF ATMOSPHERIC COMPOSITION

Satellite observations

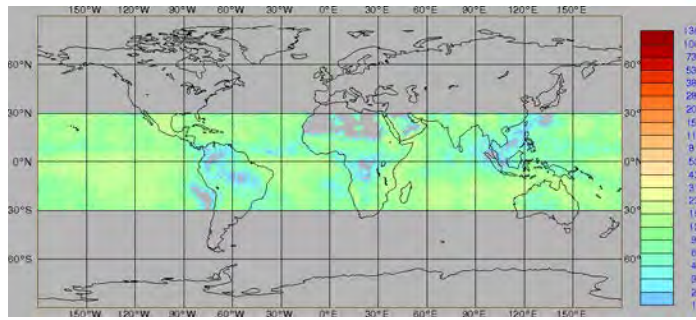
SO_2, GOME-2, SACS, BIRA/DLR/EUMETSAT



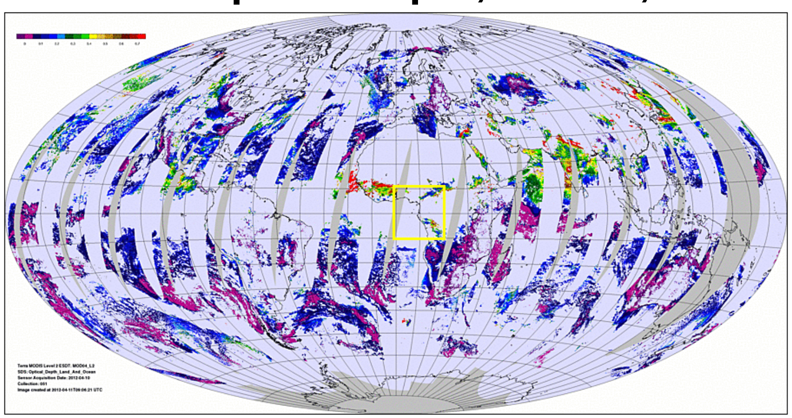
O_3, OMI, KNMI/NASA



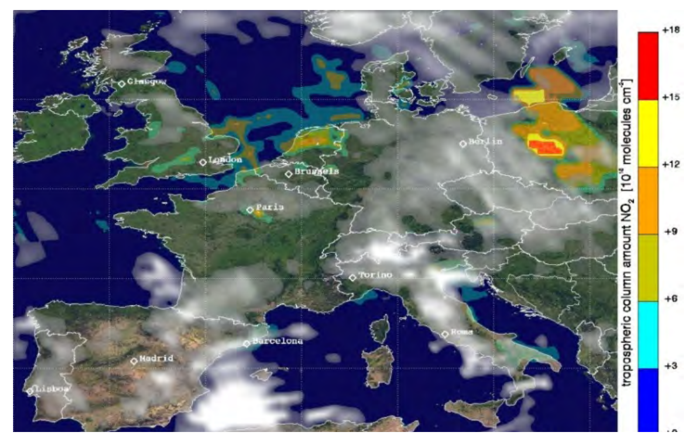
CH_4, IASI, LMD



Aerosol Optical Depth, MODIS, NASA

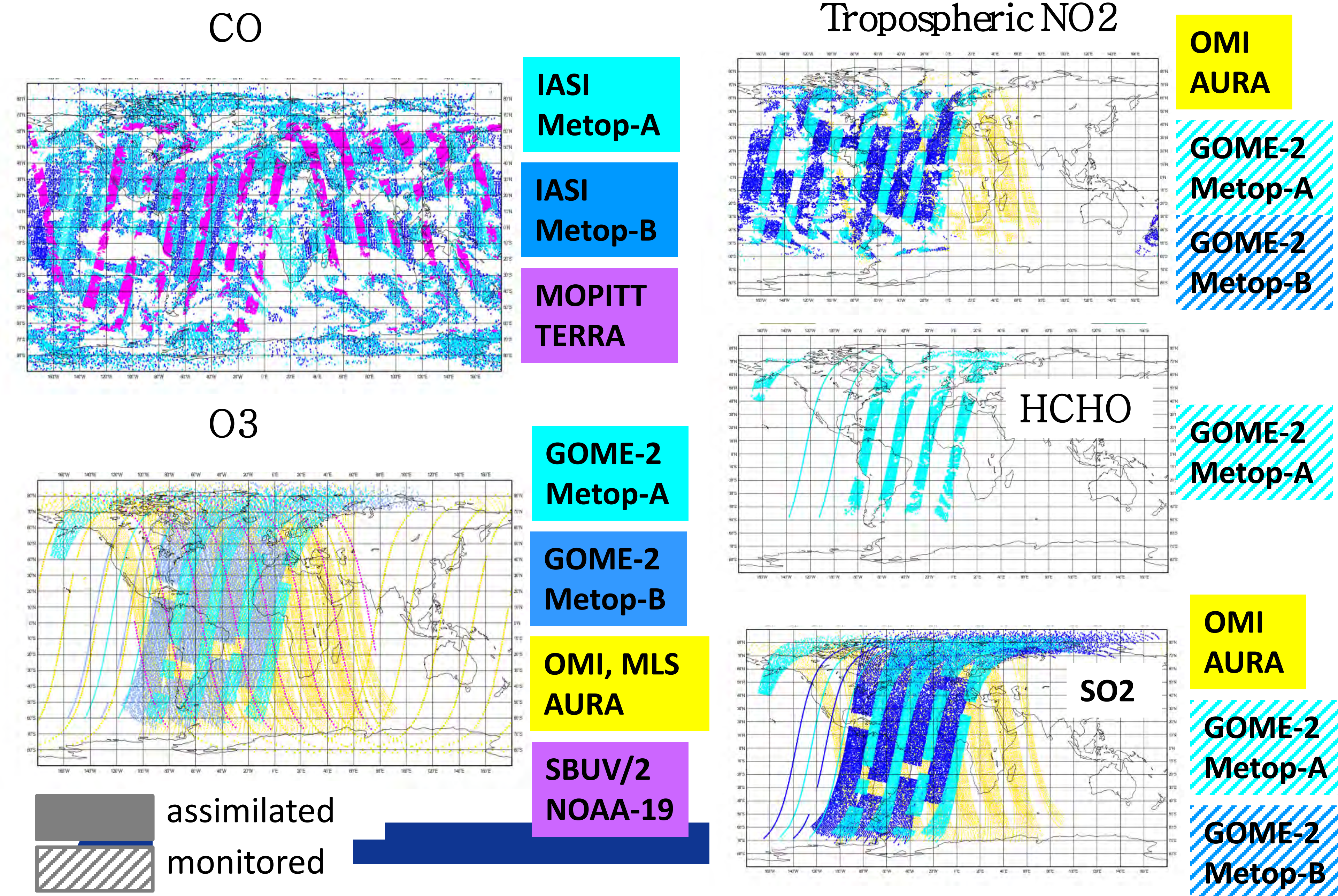


NO_2, OMI, KNMI/NASA



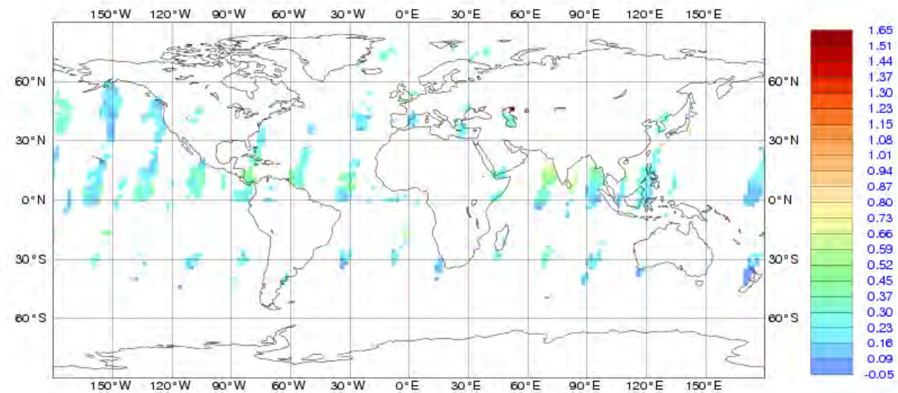
Atmospheric composition observations traditionally come from UV/VIS measurements. This limits the coverage to day-time only. Infrared/microwave are now adding more and more to this spectrum of observations (MOPITT, AIRS, IASI, MLS, MIPAS …)

Reactive gases data availability in MACC NRT system: 20140901, 12z



Aerosol data availability in NRT system (daily)

Aerosol Optical Depth

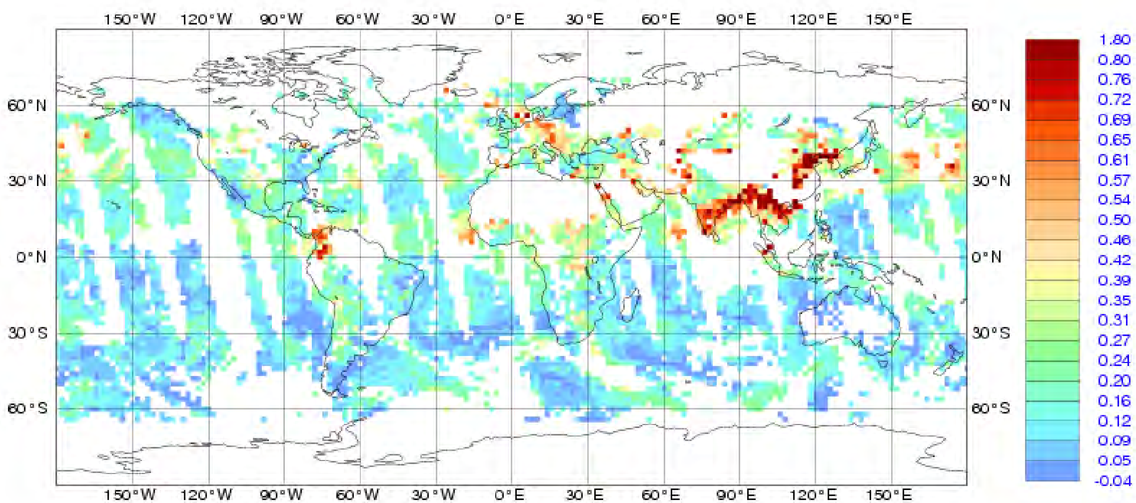


PMAP Metop-A

PMAP Metop-B

MODIS AQUA

MODIS TERRA



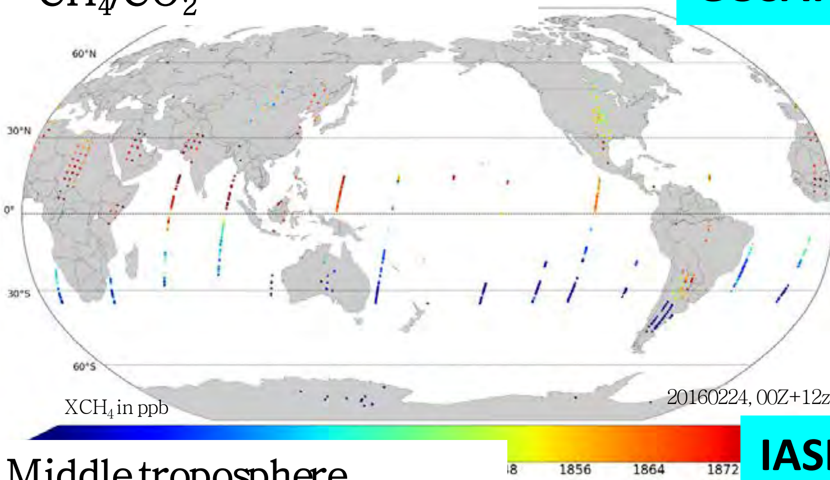
assimilated

monitored

Greenhouse gases data availability in MACC NRT system: 20160224, 0z & 12z

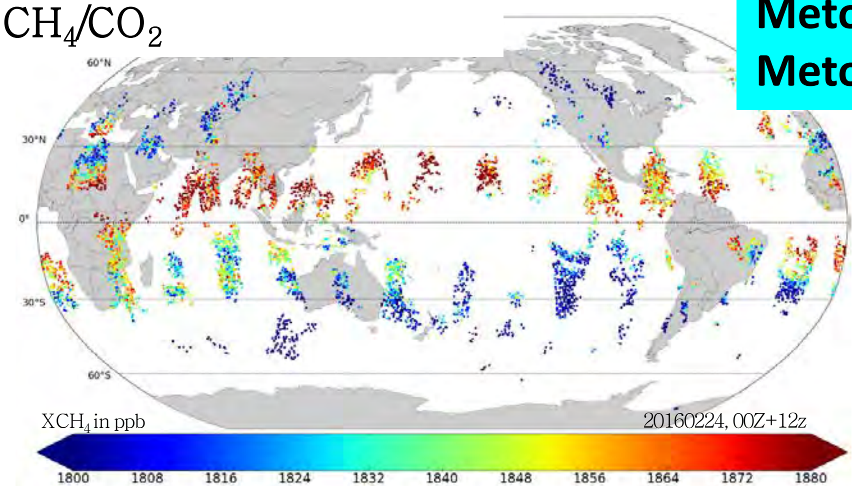
TANSO-FTS GOSAT

Lower troposphere CH_4/CO_2

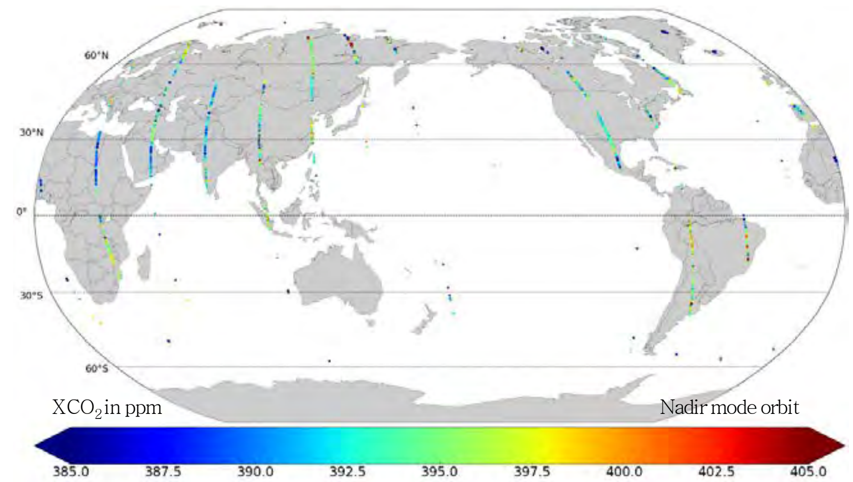


IASI Metop-A Metop-B

Middle troposphere CH_4/CO_2



OCO-2



ECMWF

Issues with Observations

- **AC Satellite retrievals**
  - **Little or no vertical information from satellite observations. Total or partial columns retrieved from radiation measurements. Weak or no signal from boundary layer.**
  - **Fixed overpass times and daylight conditions only (UV-VIS) -> no daily maximum/cycle**
  - **Global coverage in a few days (LEO); often limited to cloud free conditions; fixed overpass time.**
  - **Retrieval errors can be large; small scales not resolved**
  - **We use retrievals for AC: Averaging kernels important**
- **AC in-situ observations**
  - **Sparse (in particular profiles)**
  - **Limited or unknown spatial representativeness**

ATMOSPHERIC COMPOSITION DATA ASSIMILATION

Importance of height resolved observations

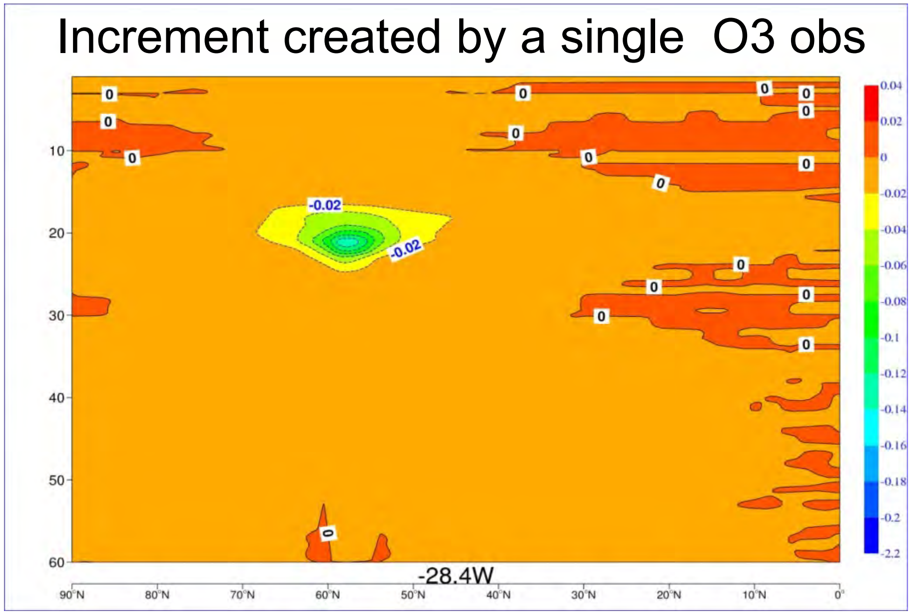
Impact of a single observation in 3D-Var (for model variable at a gridpoint)

$$x_a - x_b = \frac{y - x_b}{\sigma_o^2 + \sigma_b^2} B$$

- x_a: analysis value
- x_b: background value
- y: observation
- σ_o^2: observation variance
- σ_b^2: background covariance
- B: column of background error covariance matrix

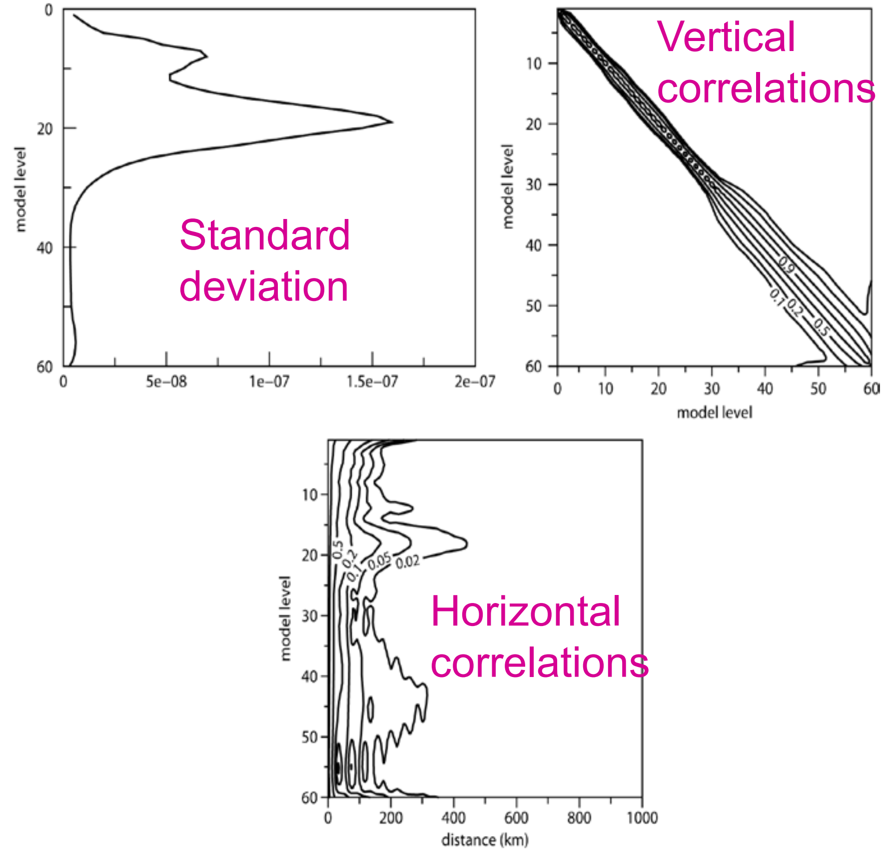
- Analysis increment is proportional to a column of B-matrix
- B-matrix determines how increment is spread out from a single observation to neighbouring gridpoints/ levels

Increment from a single TCO3 observation



Ozone observation of 247 DU, 66 DU lower than background

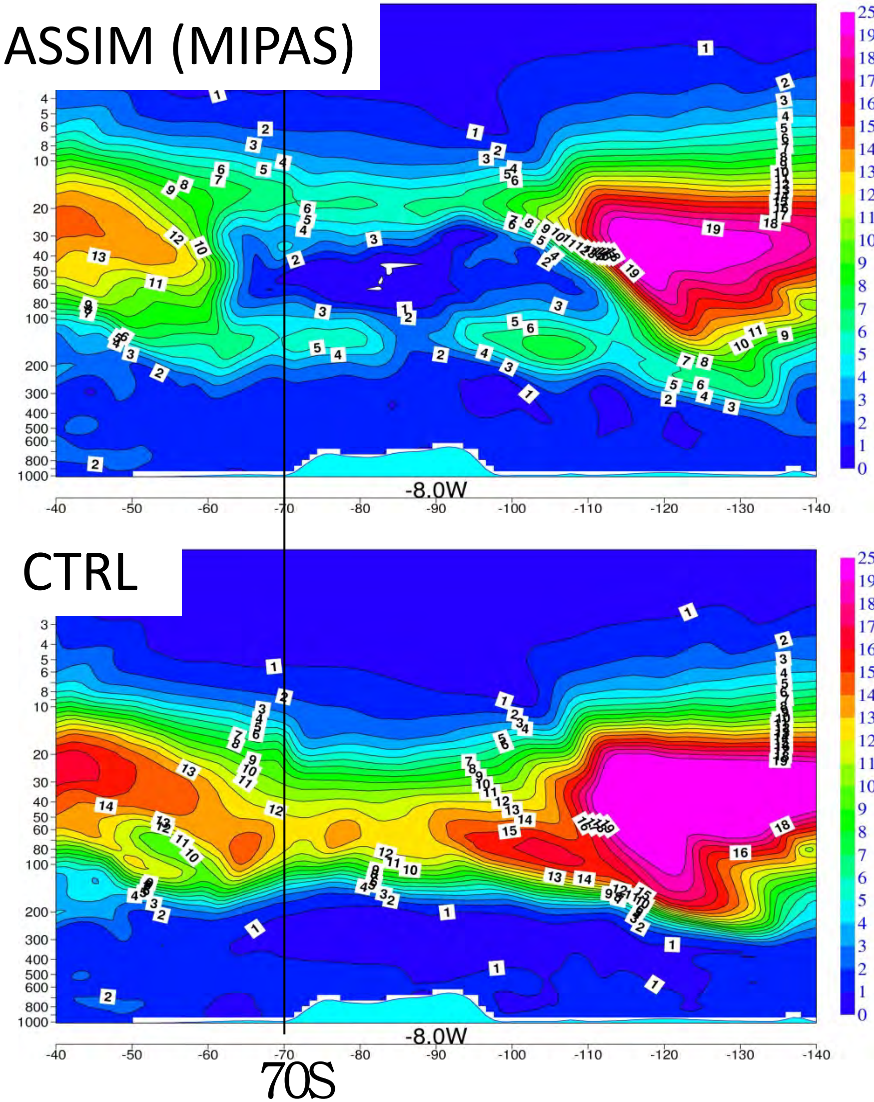
Ozone background errors

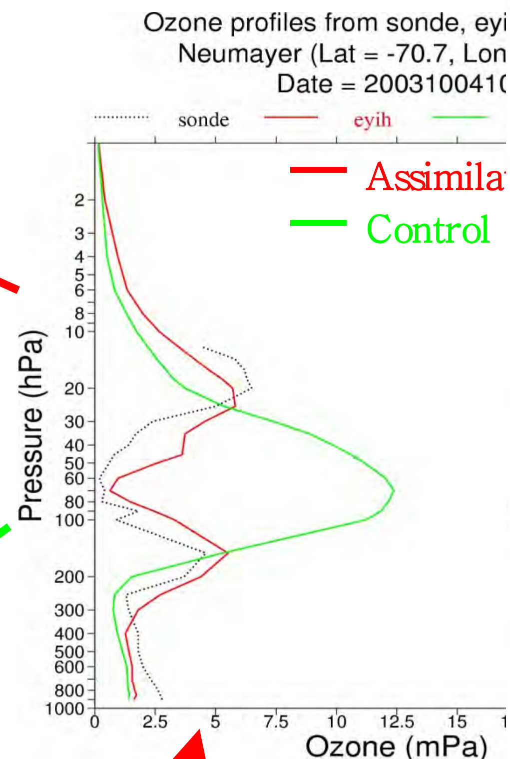


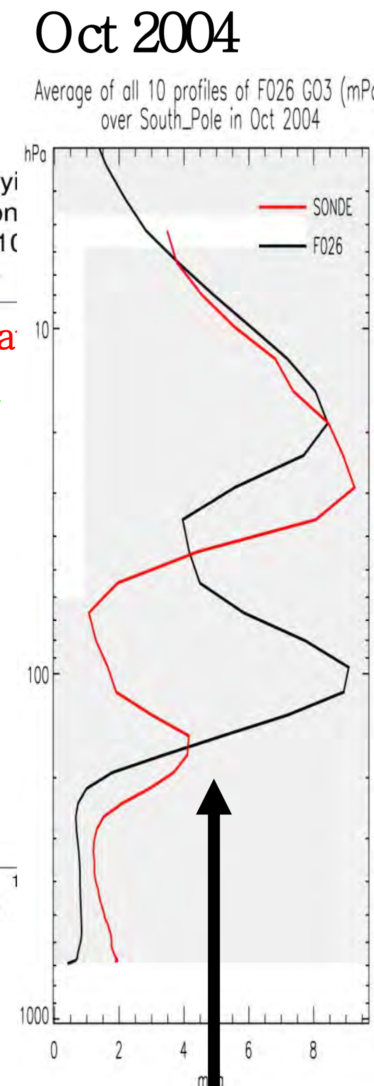
- Maximum impact around L20 (~35 hPa)
- Profile data are important to obtain a good vertical analysis profiles

ECMWF

Ozone hole in GEMS reanalysis: Cross section along 8E over South Pole, 4 Oct 2003







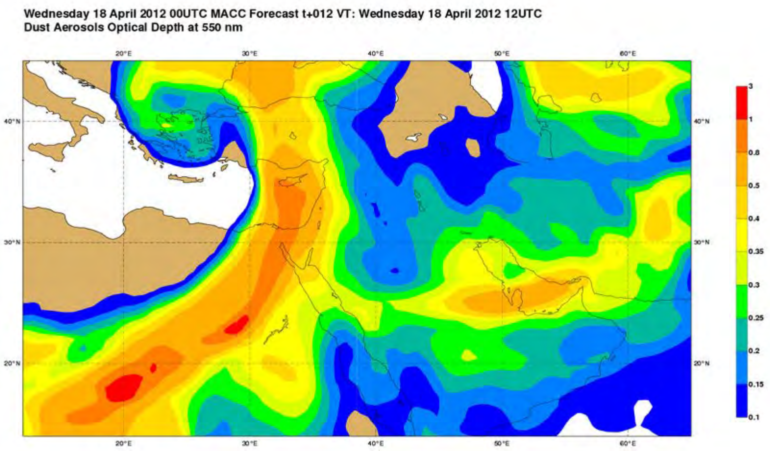
Assimilation **with profile data**

Assimilation **with total column data**

4D-Var assimilation system for aerosols

Aerosol assimilation is difficult because:

- **There are numerous unknowns (depending on the aerosol model) and very little observations to constrain them**
- **The concentrations vary hugely with for instance strong plumes of desert dust in areas with very little background aerosol, which makes it difficult to estimate the background error covariance matrix**



ECMWF

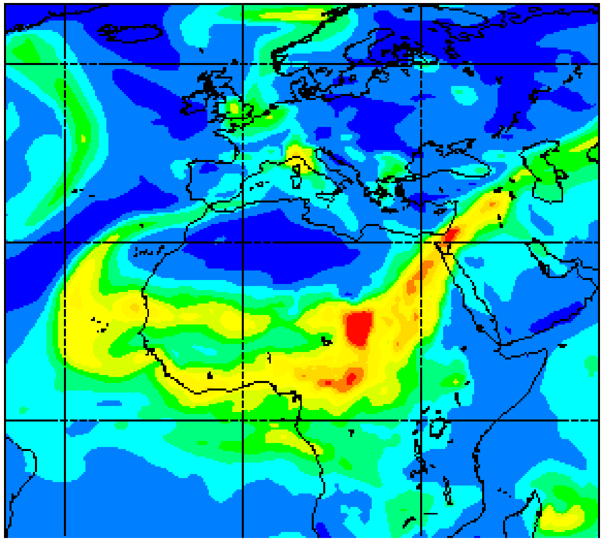
The aerosol prediction system: Analysis

- Assimilated observations are the 550nm MODIS Aerosol Optical Depths (AODs) over land and ocean.
- Control variable is formulated in terms of the total aerosol mixing ratio.
- Analysis increments are repartitioned into the species according to their fractional contribution to the total aerosol mixing ratio.
- Background error statistics were computed using forecasts errors as in the NMC method (48h-24h forecast differences).
- Observation errors are prescribed fixed values.
- Variational bias corrections are applied to total AOD

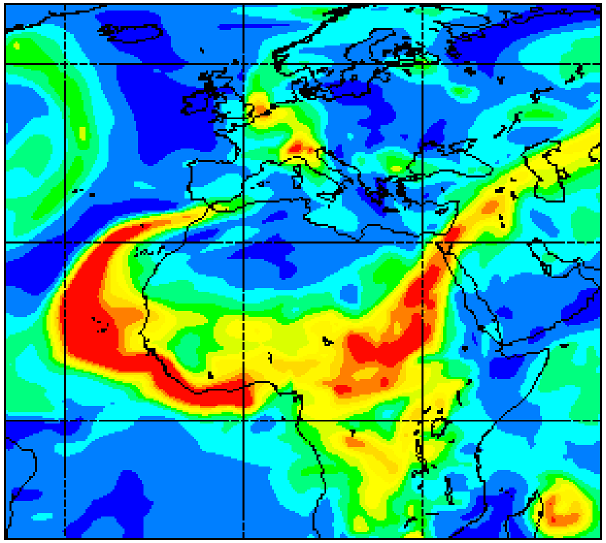
Benedetti et al. 2009, *JGR*, 114, doi:10.1029/2008JD011115

Impact of assimilation for a Saharan dust outbreak

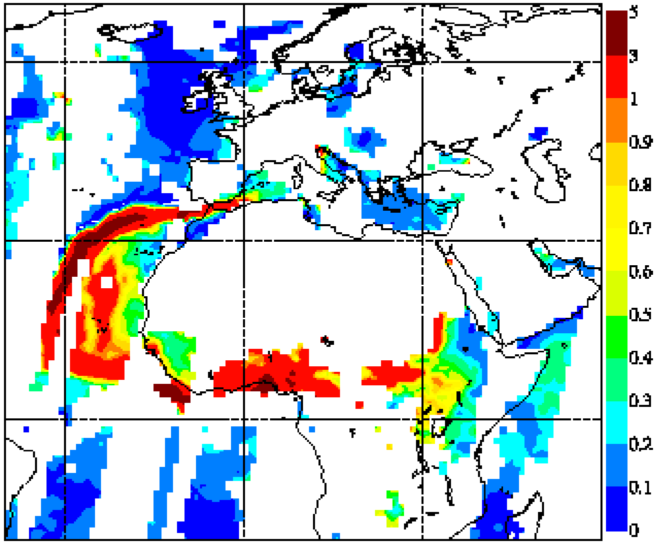
Model simulation



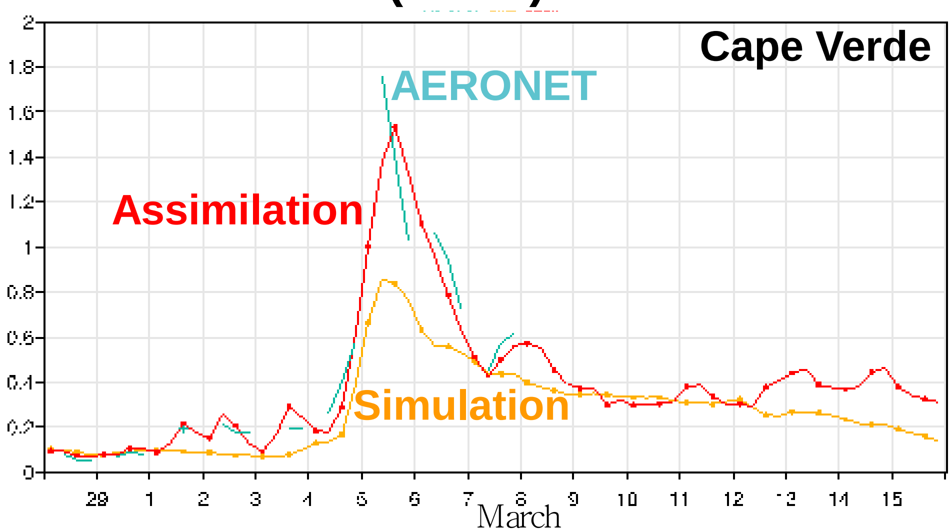
Assimilation

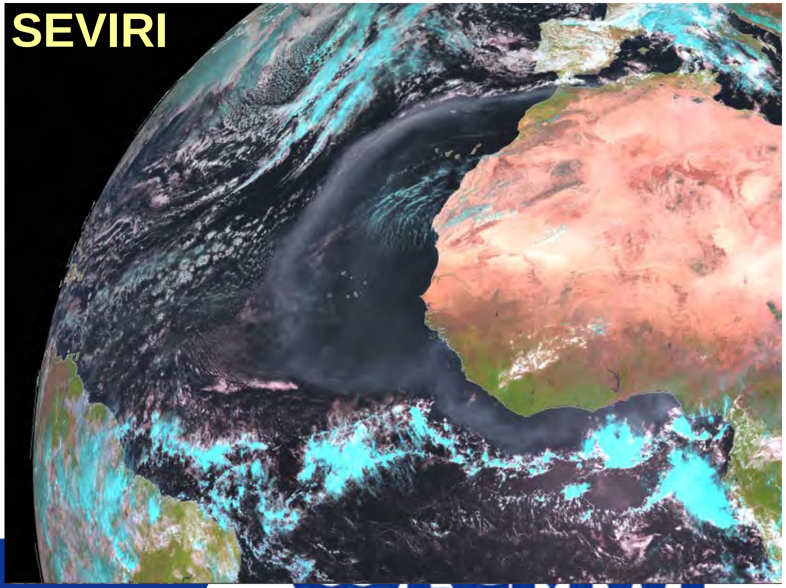


MODIS



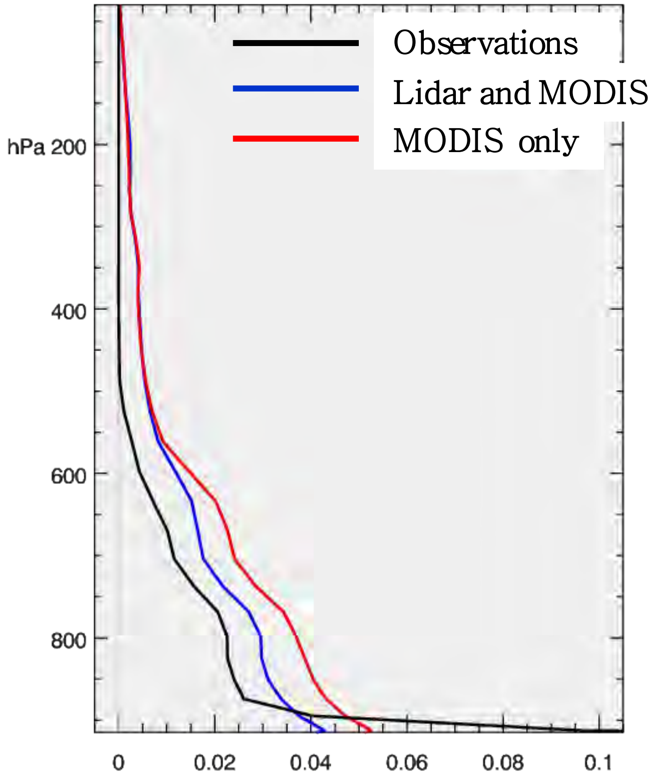
Aerosol optical depth at 550nm (upper) and 670/675nm (lower)



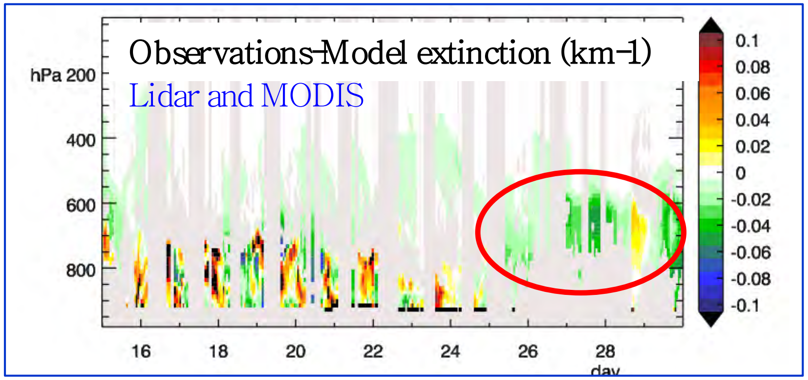


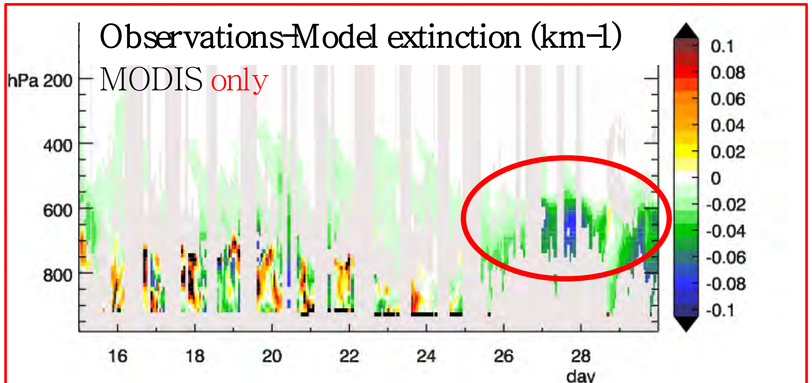
Towards lidar assimilation: Impact of CALIPSO on vertical profiles

- NRT CALIPSO level 1.5 product available since mid-2011
- Mean Attenuated aerosol backscatter at 532 nm (cloud cleared)
- Aimed at operational NWP centres (ECMWF, US Naval Research Lab, JMA,…)
- Developed through close collaboration with NASA LaRC CALIPSOTeam
- Lidar observation operator in place
- CALIPSO data have positive impact on the aerosol extinction profile (in initial tests) but biases still remains



Monthly averaged extinction (km^{-1}) at 532nm at Sede Boker (453 profiles)





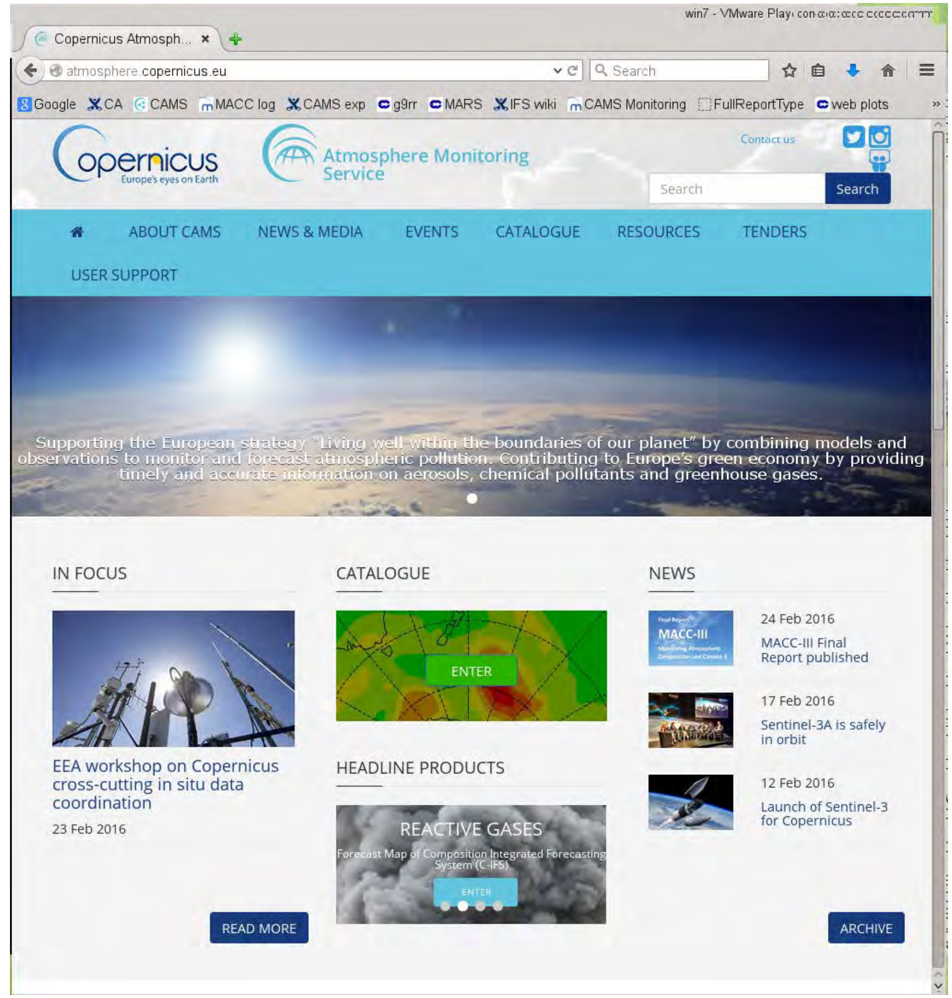
(*) Lidar data are courtesy of Arnon Karnieli. Special thanks to Simone Lolli, Judd Welton and the MPLNET team.

6. Concluding remarks

- The ECMWF's Integrated Forecast System has been extended to include fields of atmospheric composition: Reactive gases, greenhouse gases, aerosols => **Composition-IFS (C-IFS)**
- Modelling of AC needs to include many species with concentrations varying over several orders of magnitude
- AC forecasts benefit from realistic initial conditions (**data assimilation**) but likewise from improved emissions
- Extra challenges for DA of atmospheric composition compared to NWP - but also potential benefits through chemical coupling and impact on NWP
- CAMS system produces useful AC forecast and analyses, freely available from atmosphere.copernicus.eu

More information about the environmental monitoring activities at ECMWF and how to access the data can be found on:

atmosphere.copernicus.eu



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