Visible aerosol reflectance assimilation in the CAMS system (IFS-COMPO)

Samuel Quesada-Ruiz, Cristina Lupu, Tobias Necker and Angela Benedetti (IR VIS team)

Atmosphere Monitoring

With many thanks to the CAMS colleagues and many others for the help.

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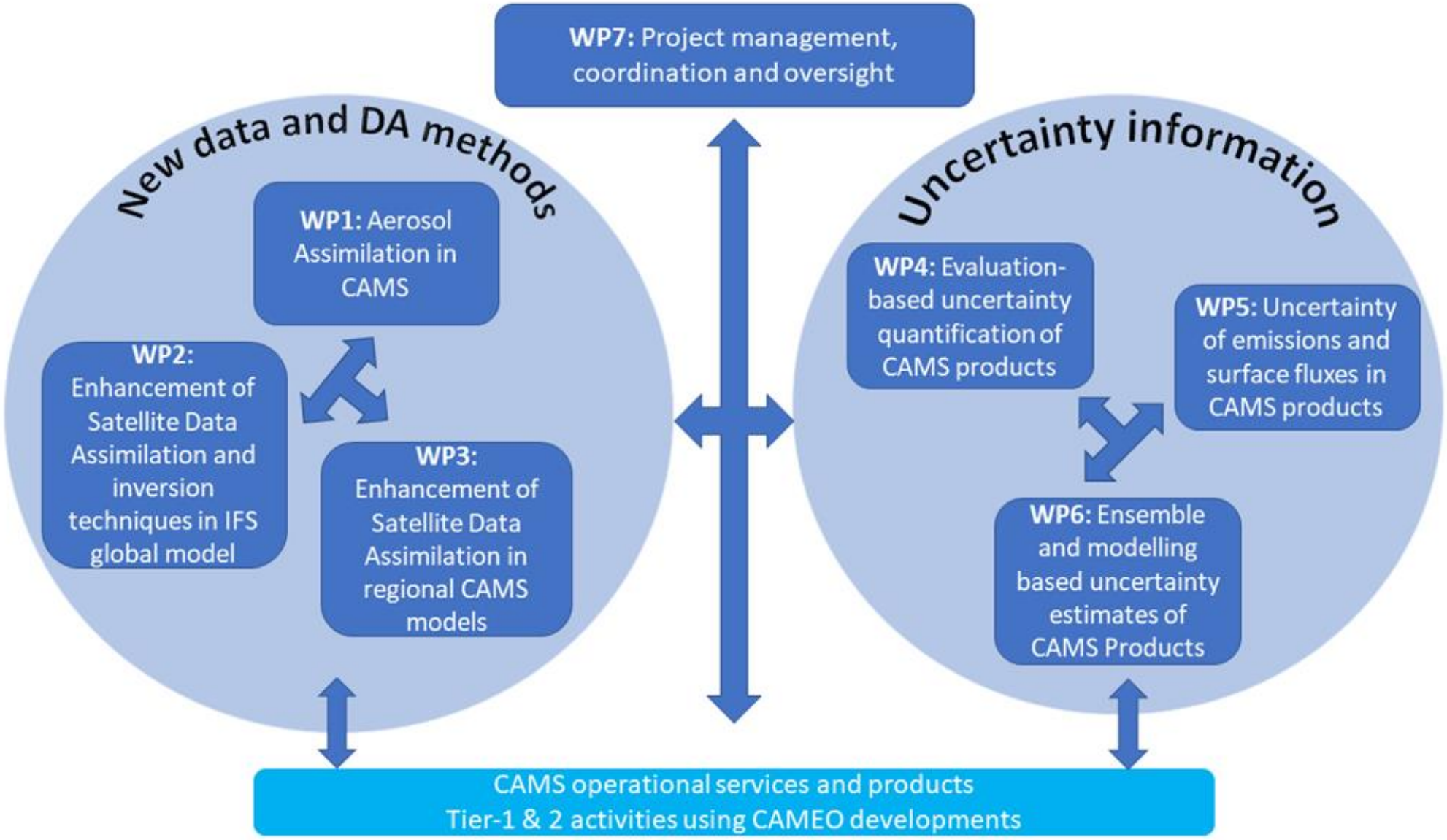
Tobias Necker is funded by the HE CERTAINTY project, under Grant Agreement No 101137680

Copernicus Europe's eyes on Earth | European Commission | ECMWF

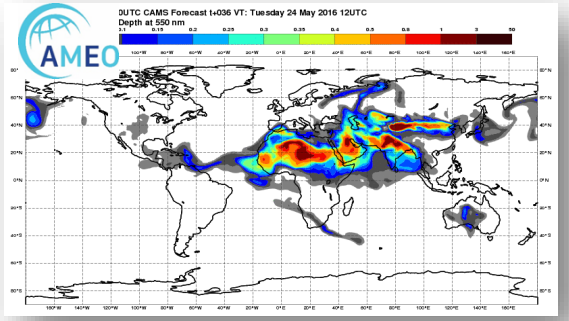
The CAMEO project



CAMEO impact in CAMS

Global
CAMS Emissions

ECMWF
IFS
global,
40x40 km

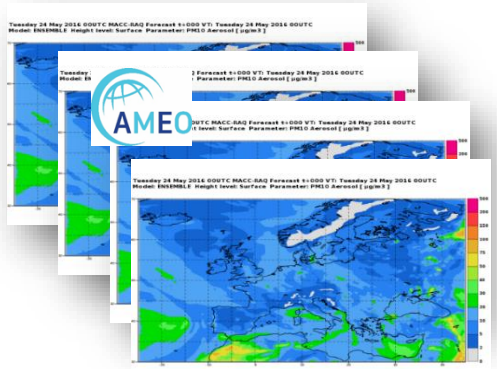


Boundary conditions

GFAS
wildfire emissions

European CAMS
Emissions

11 regional CTMs over
Europe,
10x10 km



Data assimilation

Satellite Observations
(AOD, O_3, CO, HCHO, NO_2, SO_2)

Surface AQ observations

Data assimilation

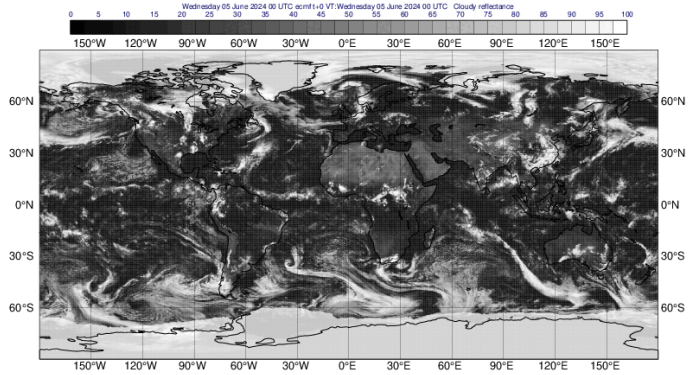
Global and regional Forecast and analysis

Solar Radiation

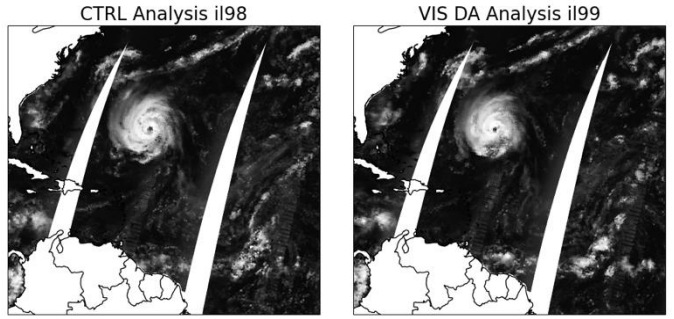
Policy Support

Visible radiances related activities at ECMWF

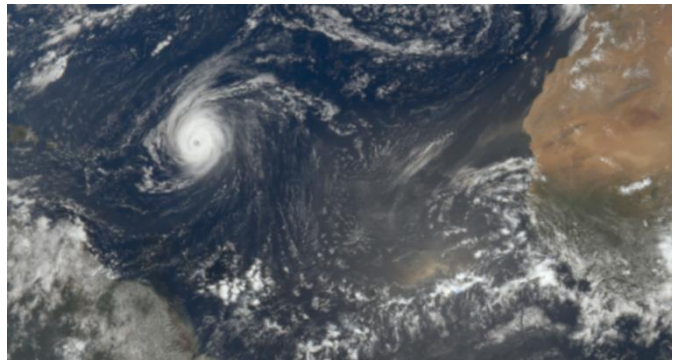
Operational satellite image simulation (global, nadir, VIS/IR)



Cloud visible reflectance monitoring and assimilation in IFS NWP configuration



Aerosol visible reflectance monitoring and assimilation in IFS COMPO configuration



Thanks to Samuel Quesada-Ruiz, Cristina Lupu and Tobias Necker

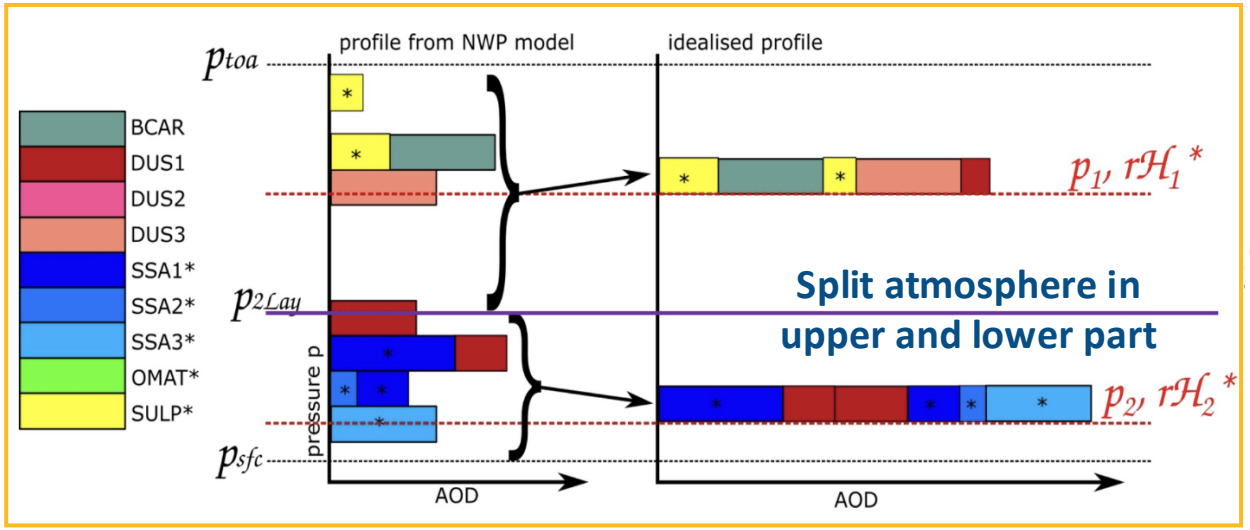
Aerosol visible reflectances observation operator in RTTOV: **MFASIS-Aerosols**

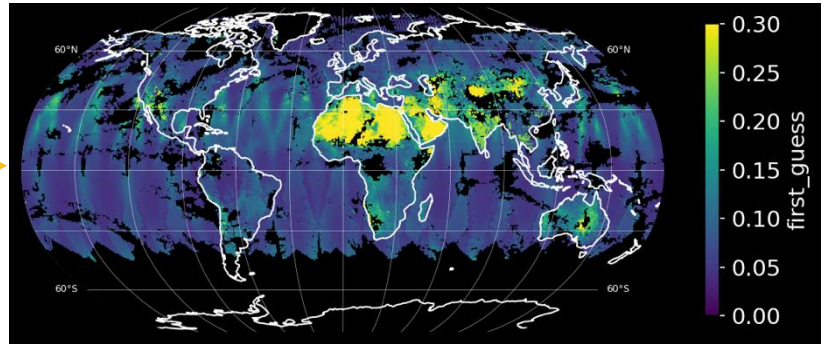
A prototype based on CAMS aerosols

Incl TL & AD

- Can we generate reflectances for arbitrary combinations of many aerosols species with one NN and still have sufficiently small errors? Species A may be above B or vice versa…
- Same strategy as for clouds: **Replace complex aerosol profile by simplified version** with same AOD and approximately same relative humidity and air mass above/below aerosols

IFS COMPO profiles



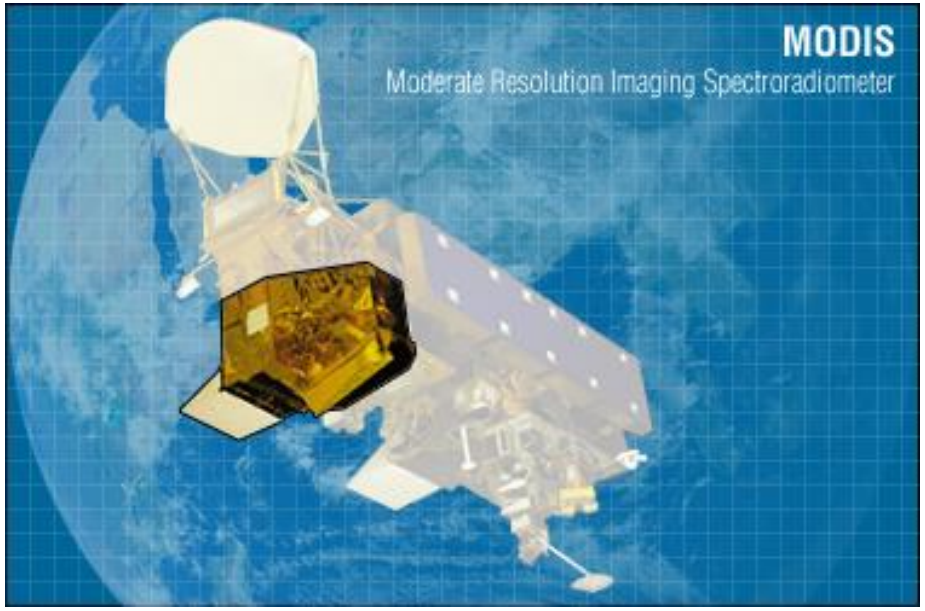


- Prototype with **23 input variables** (incl. AOD in upper and lower layer for 9 CAMS species)

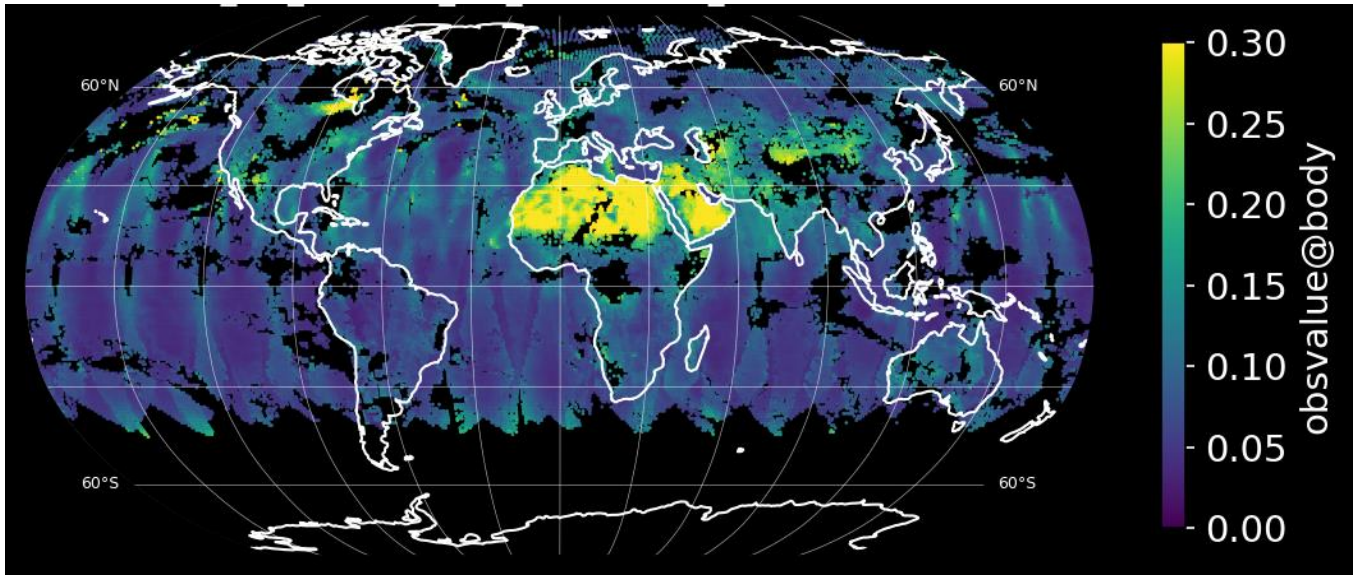
Early integration of NWPSAF MFASIS-Aerosols developments (released with RTTOV-14.1, February 2026)
Thanks to DWD for developing the operator (credits: Leonhard Scheck, Florian Baur et al.)

Visible observations: cloud-cleared L2 **aerosol** visible reflectances onboard LEO

ECMWF aims to exploit aerosol affected visible reflectances from LEO imagers. Currently looking at MODIS on Aqua/Terra, but future work could extend to VIIRS. It would also be beneficial to have similar products developed for other imagers (eg., OLCI, SLSTR, etc.).



https://es.wikipedia.org/wiki/Espectrorradi%C3%B3metro_de_im%C3%A1genes_de_media_resoluci%C3%B3n



655nm visible Level-2 cloud-cleared aerosol reflectance from MODIS Aqua/Terra on 3-4 June 2025

Preparing the IFS for **aerosol** visible reflectances

Build a bespoke data flow for pre-processing the VIS reflectance data:

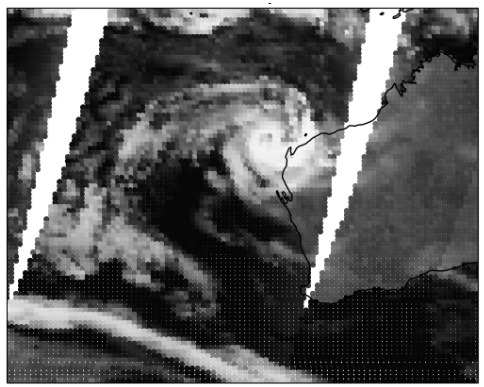
Pre-processing (BUFR format) → Superob → BUFR2ODB Convert to ODB file format

Extract reflectances from the MODIS BUFR corresponding to the channel of interest and convert them to a local BUFR sequence recognised by the IFS (same as for the clouds).

The superobbing calculates an average of all reflectances within a grid box, reducing data volume and accounting for effective model resolution.

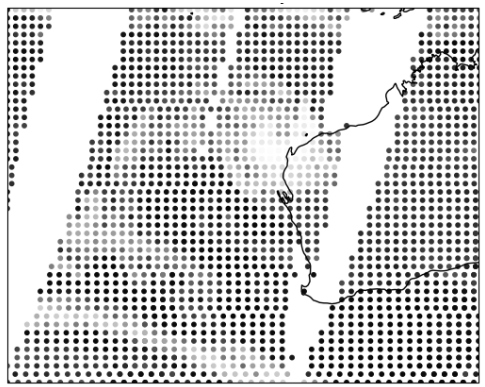
ODB is in-house data storage software to allow the 4D-Var system within IFS to store and access data.

N256 (40km)



TCo1279

N128



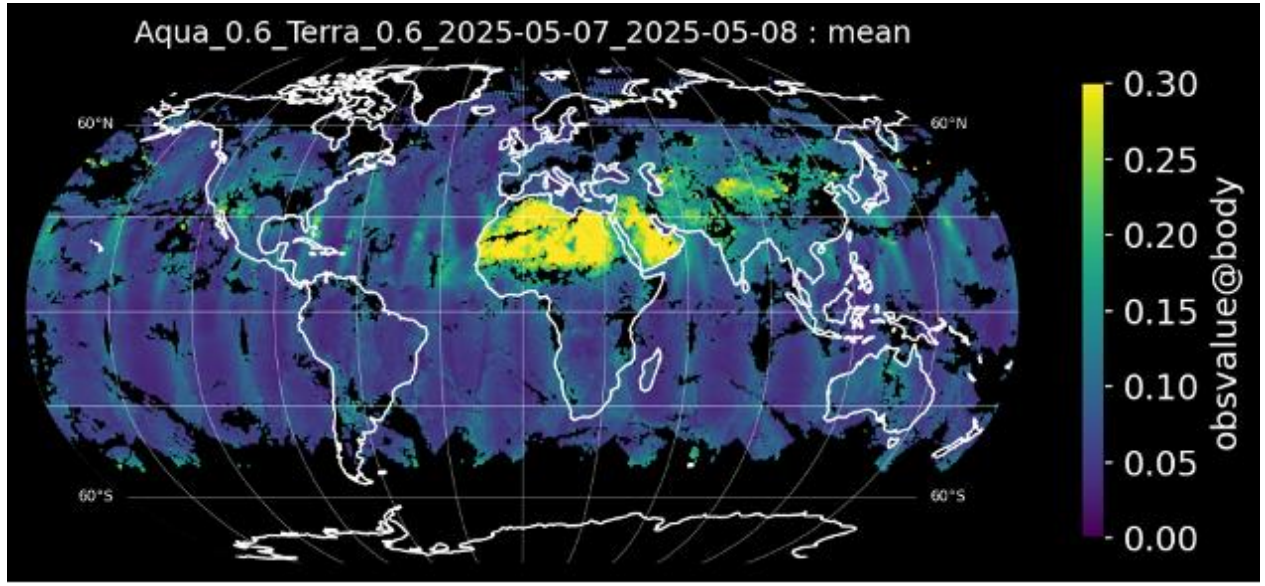
TCo399

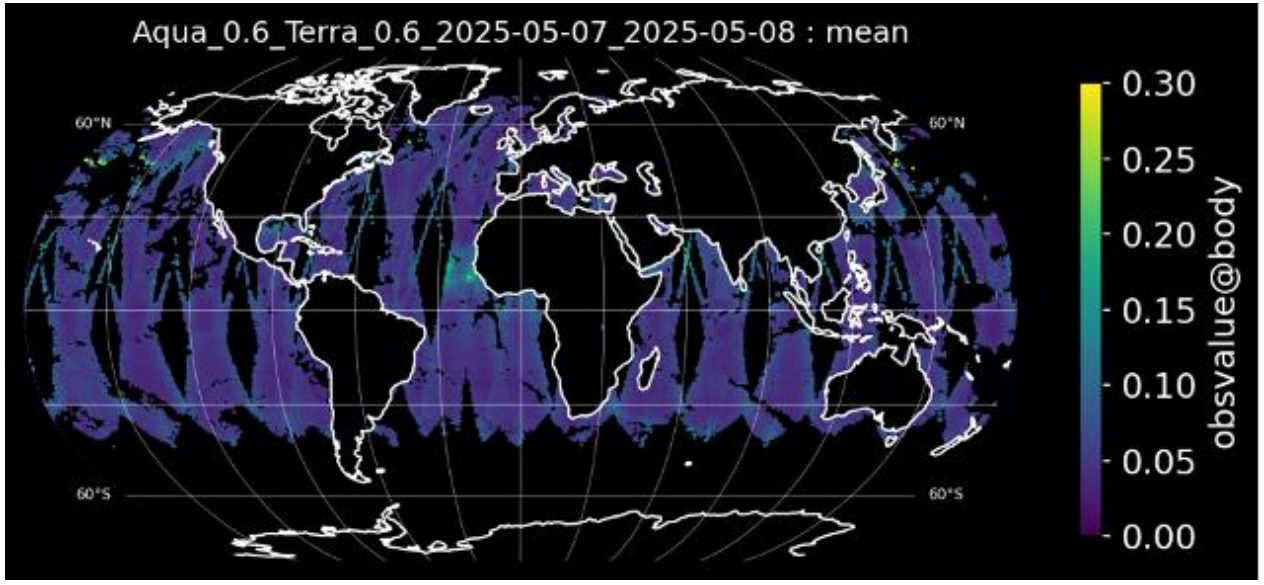
Showcasing the importance of observation screening for visible 665nm

ALL

Ocean only
Sunglint
Sea ice
Large solzen/satzen angles
…

ACTIVE





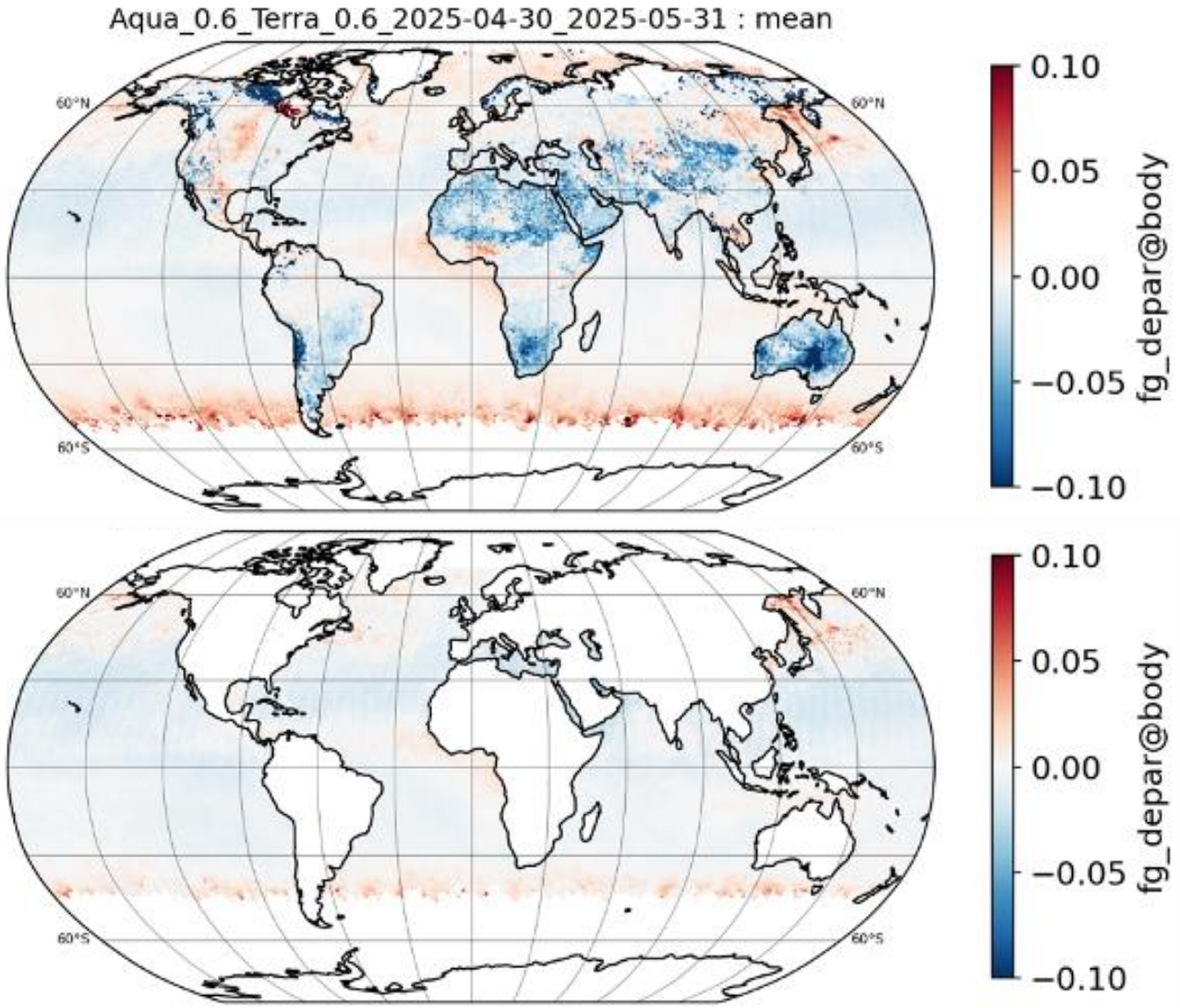
8 May 2025

Visible aerosol reflectance monitoring – First-guess departure maps

ALL

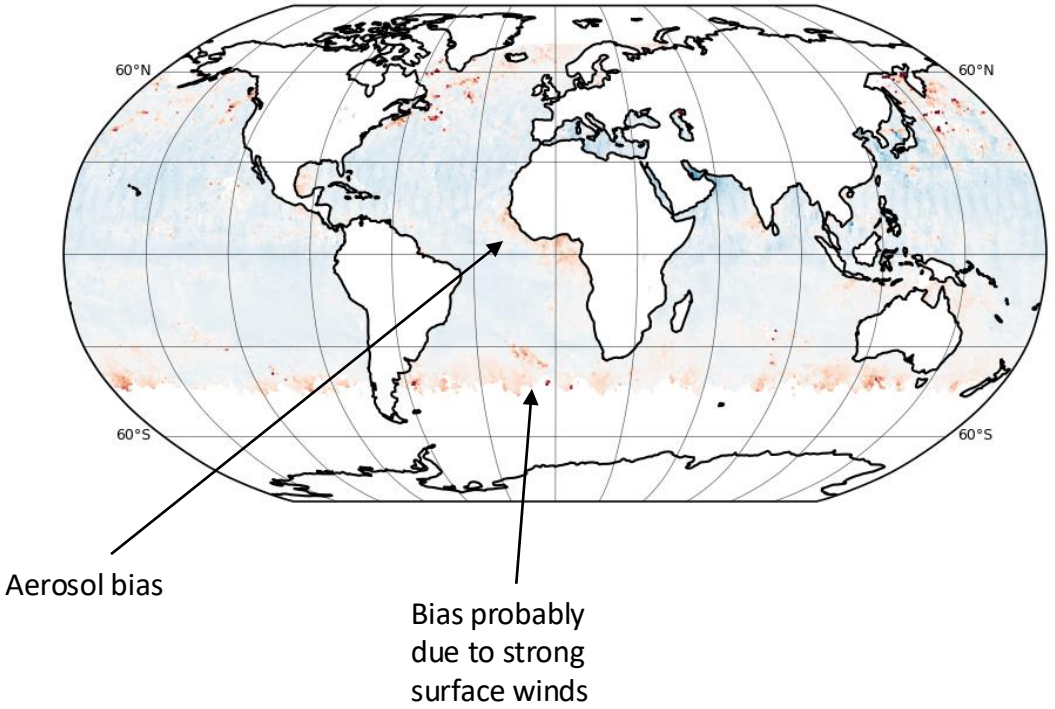
Ocean only
Sunglint
Sea ice
Large solzen/satzen angles
…

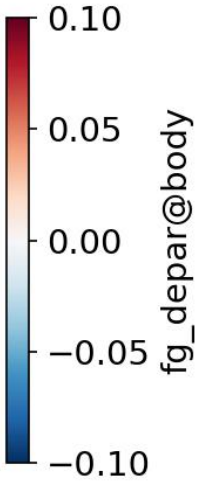
ACTIVE



May 2025

Visible aerosol reflectance monitoring – First-guess departure

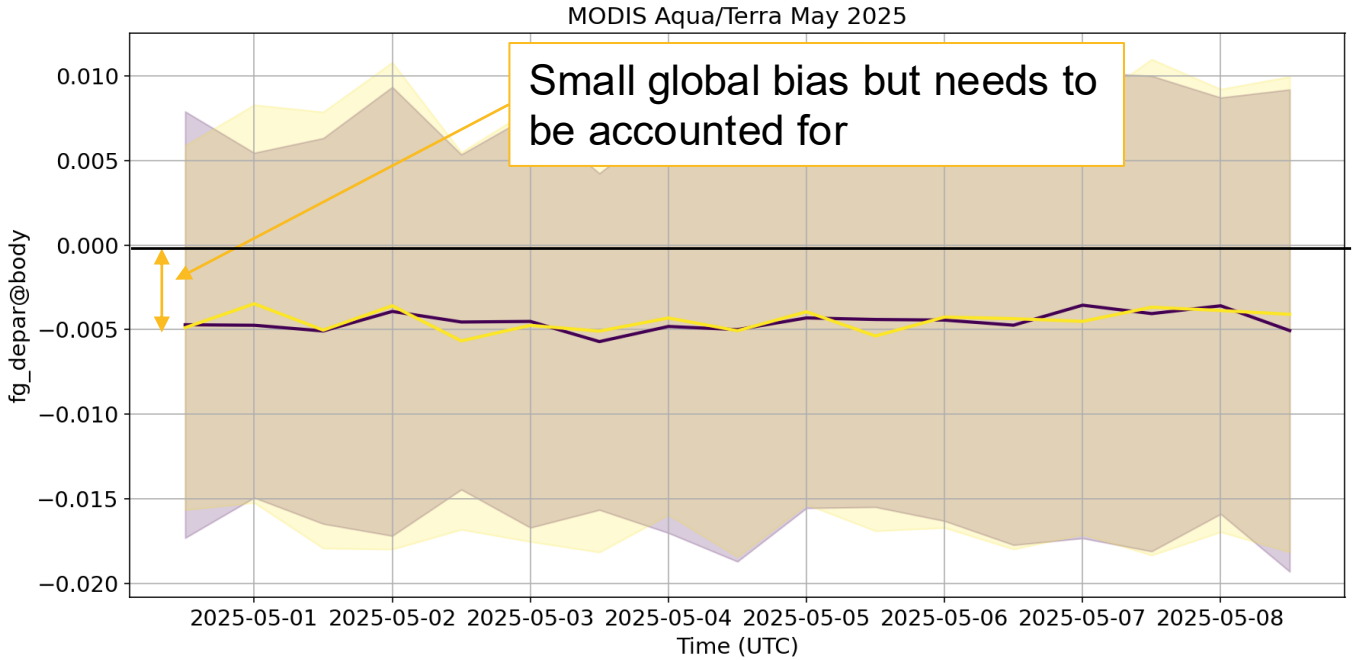




As MODIS MFASIS-Aerosol coefficient was not available at the time of this study the SEVIRI Meteosat-11 aerosol scattering properties file was used as a proxy.

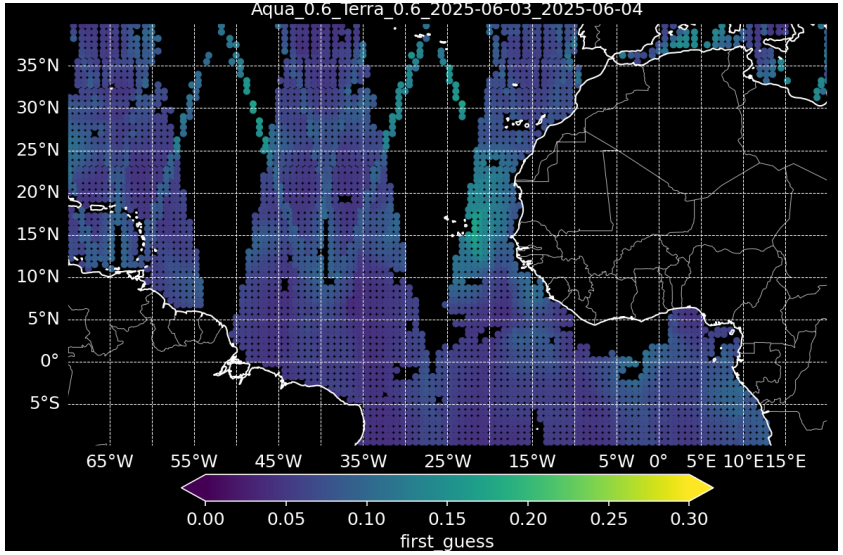
These results should be understood as proof of concept without drawing any final scientific conclusions.

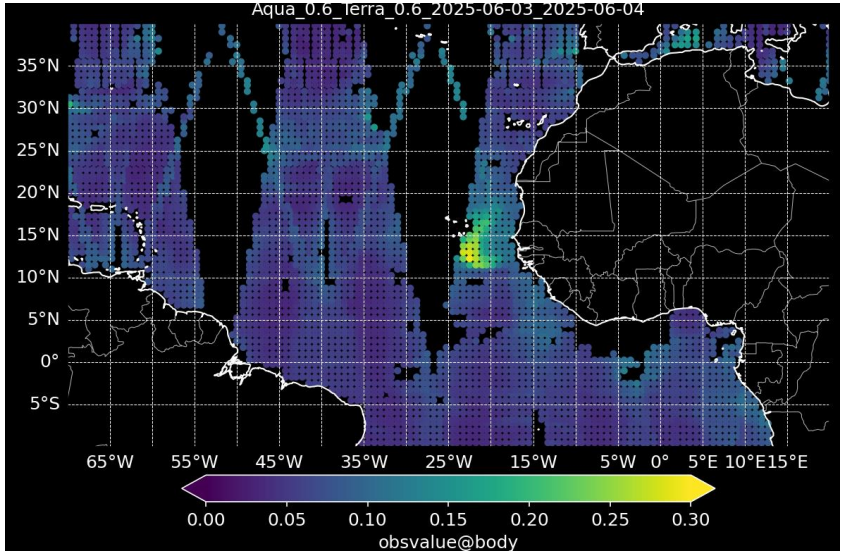
There is a global small negative bias over ocean in the aerosol-clear scenes, together with a larger positive bias in the presence of aerosols.



Aerosol visible assimilation case study – dust event 4 June 2025

First-Guess Simulated Reflectance

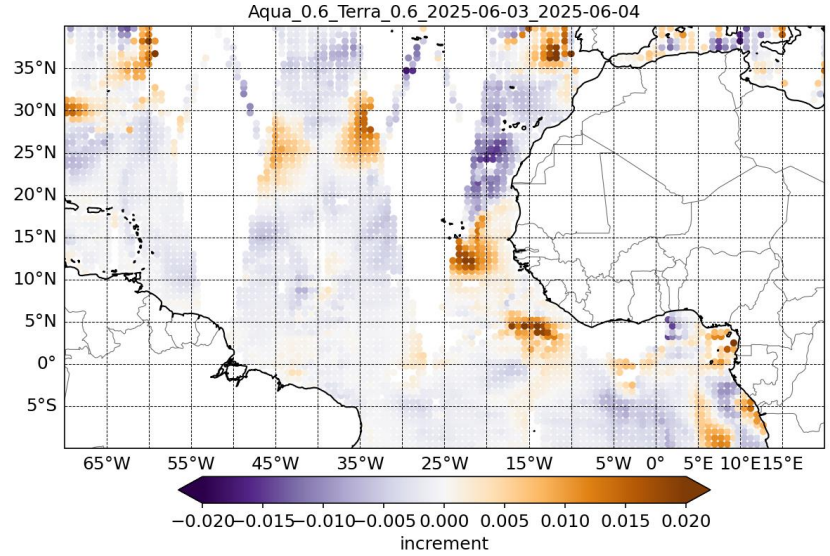


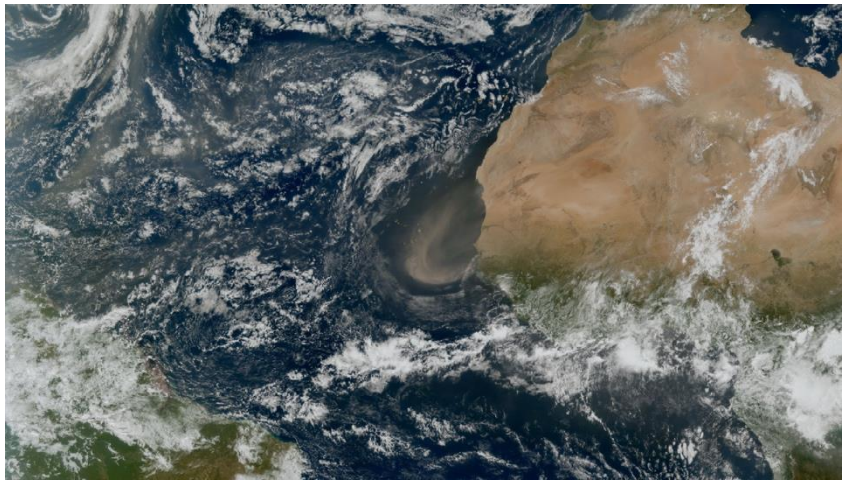


MODIS Observations

Analysis Increment

orange = increase AER
purple = decrease AER



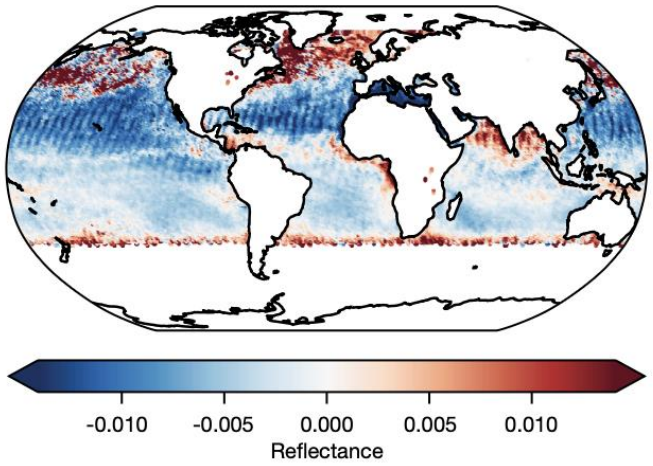


https://www.eumetsat.int/saharan-dust-over-atlantic-ocean

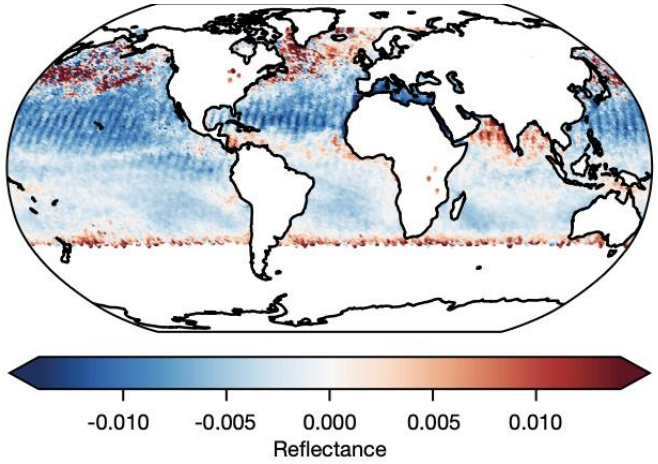
Independent FCI composite observation showing the dust outbreak

Aerosol visible assimilation substantially reduces reflectance departures

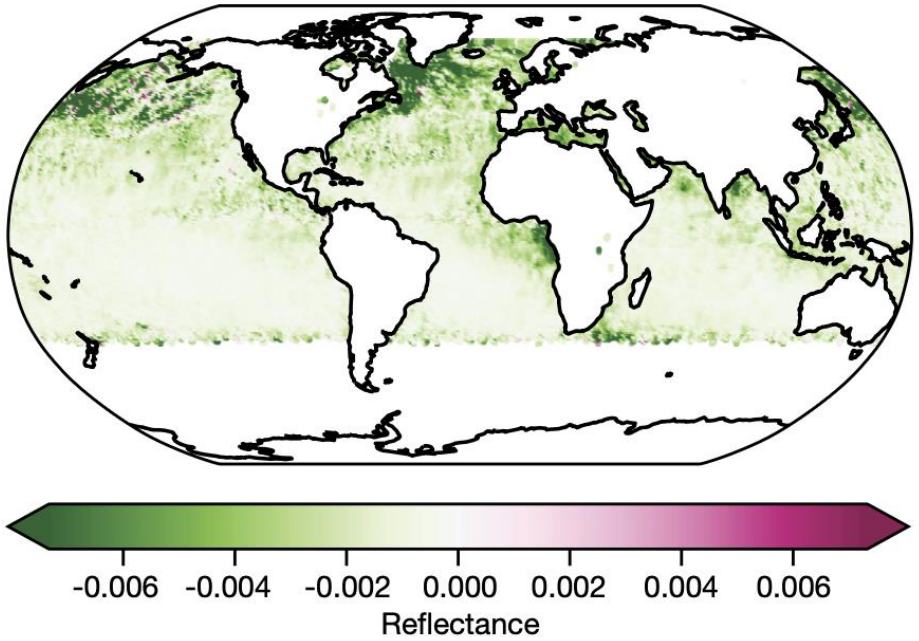
First guess departures



Analysis departures



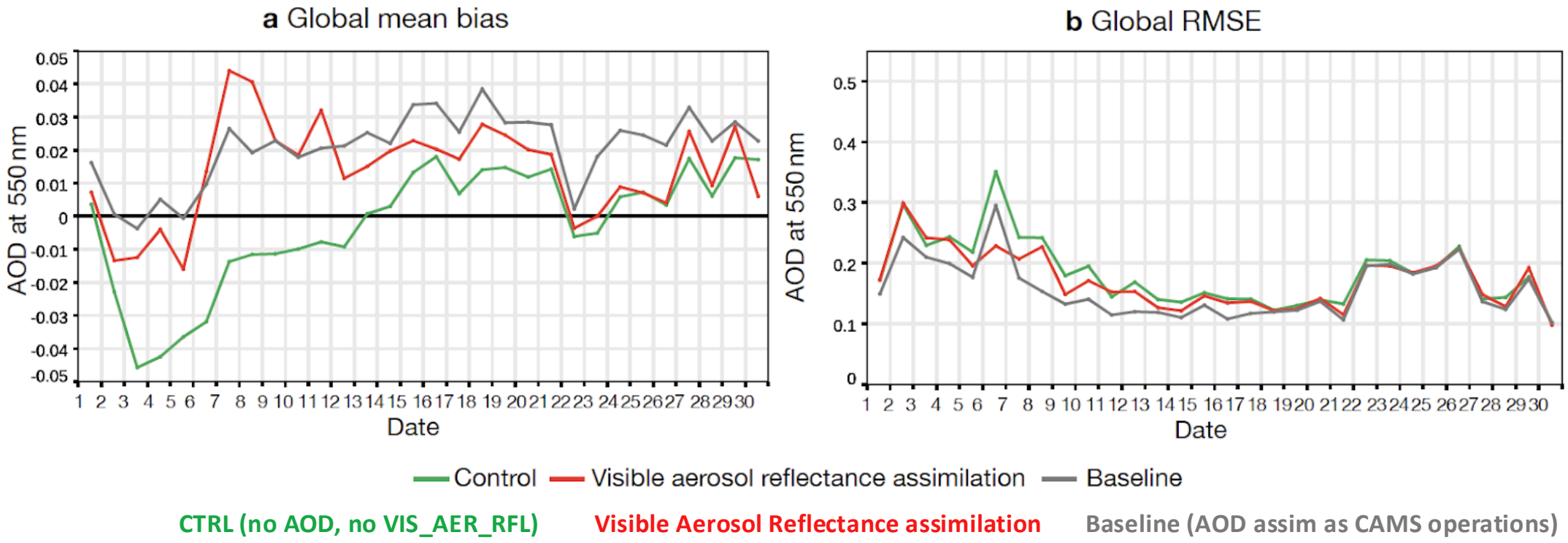
Absolute analysis increments



Monthly mean visible departure statistics (June 2025)

- Assimilation, on average reduces differences between observation and model
- A significant reduction can be seen in the Gulf of Guinea, north Atlantic and the W-coast of Africa.

Verification against AERONET (in AOD space)



CTRL (no AOD, no VIS_AER_RFL) **Visible Aerosol Reflectance assimilation** **Baseline (AOD assim as CAMS operations)**

June 2025

Summary and outlook: aerosol visible reflectance assimilation at ECMWF

- **Substantial technical developments to enable** cloud visible reflectance monitoring and assimilation in **IFS NWP**
- First demonstration of direct **aerosol visible reflectance monitoring** and **assimilation** using RTTOV MFASIS-Aerosol in **IFS-COMPO**

- Scientific evaluation using the appropriate MFASIS-Aerosol coefficient file is ongoing
  - Expand from 9 to 16 species to better align with current CAMS configuration
  - Explore the use of other sensors like VIIRS, OLCI, SLSTR, etc. (requires L2 cloud-cleared reflectances)
- Extend to **additional visible channels** (beyond 0.6µm) for monitoring and assimilation
- Extend promising initial assimilation trials and refine assimilation system (e.g., QC, biases correction, error assumptions)

Aeolus and EarthCARE aerosol lidar assimilation in the CAMS system (IFS-COMPO)

Kirsti Salonen, Will McLean, Michael Rennie, Mark Fielding and Angela Benedetti

Atmosphere Monitoring

With many thanks to the CAMS colleagues and many others for the help.

This research has been funded by ESA via the Aeolus and EarthCARE Data Innovation and Science Cluster contracts and the Horizon Europe CERTAINTY project, under Grant Agreement No 10113768

Why lidar backscatter observations?

- Currently, Aerosol Optical Depth (AOD) products from MODIS, PMAp and VIIRS are assimilated into IFS-COMPO
  - AOD is column integrated data, it does not provide vertical profiling information

- Lidars like ALADIN (Aeolus) and ATLID (EarthCARE) provide particle backscatter at different altitudes
  - Worth to note: Aeolus measures co-polar circularly polarized backscatter while the forward model in IFS is for total backscatter.

- Assimilating this information into IFS-COMPO can better place the altitude of aerosol and cloud in a column of atmosphere.

- So far, the focus has been on assimilating aerosol information from lidar backscatter in clear sky. However, in the future the aim is to use total extinction, i.e. aerosol and cloud information jointly.

Assessing the quality of Aeolus 4th reprocessed B16 L2A data in the IFS system

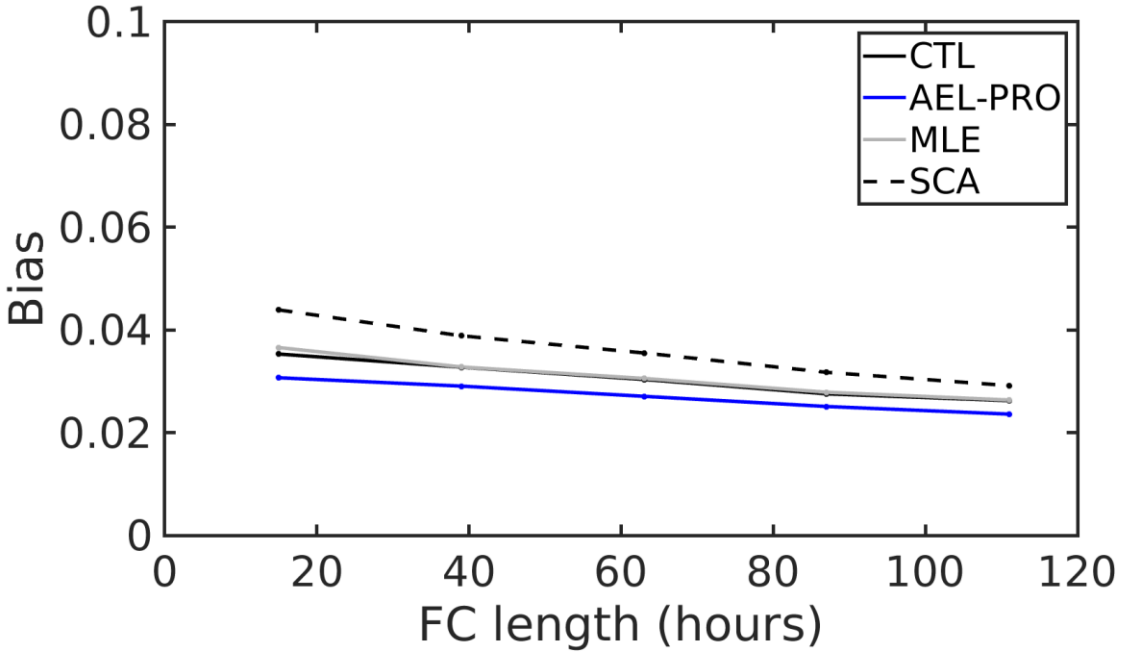
- Overall, the extended assimilation experiments cover now nearly 20 months:
  - 4.9.2018 – 17.6.2019 FM-A 1st period
  - 1.7-31.12.2019 for FM-B, main focus is on these results in the presentation
  - 28.11.2022 – 15.3.2023 for FM-A 2nd period
- Three different products included to the comparison
  - SCA mid bin (standard correct algorithm; original Aeolus L2A algorithm)
  - MLE (physically constrained maximum-likelihood estimation, improved product from SCA)
  - AEL-PRO with classification information giving guidance if signals is aerosol or cloud (adapted from algorithms developed for Earthcare ATLID).
- Aeolus L2A data used with
  - Observation values limited to: 10^{-7} … 10^{-5} $m^{-1}sr^{-1}$
  - Observation error: 3 x error estimate provided with the observations, error values limited to: 10^{-9} … 10^{-5} $m^{-1}sr^{-1}$
  - Observation is rejected if model background has cloud fraction over 1%

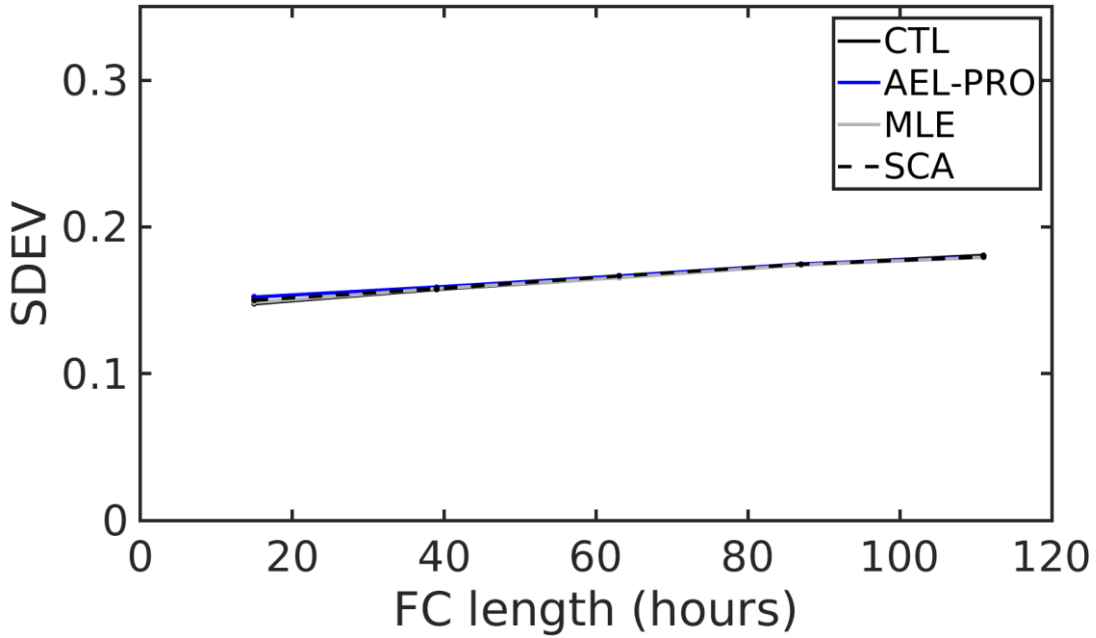
Thanks to Kirsti Salonen and Will McLean

Global impact shows reduction in bias when assimilating AEL-PRO product

- In terms of bias:
  - Assimilation of the AEL-PRO improves the bias against Aeronet AOD observations for all forecast lengths.
  - Impact from the MLE product is rather neutral
  - Assimilation of SCA mid-bin increases the bias
- Globally the impact on standard deviation is neutral from all products.

Verified against Aeronet AOD observations, 1.7-31.12.2019

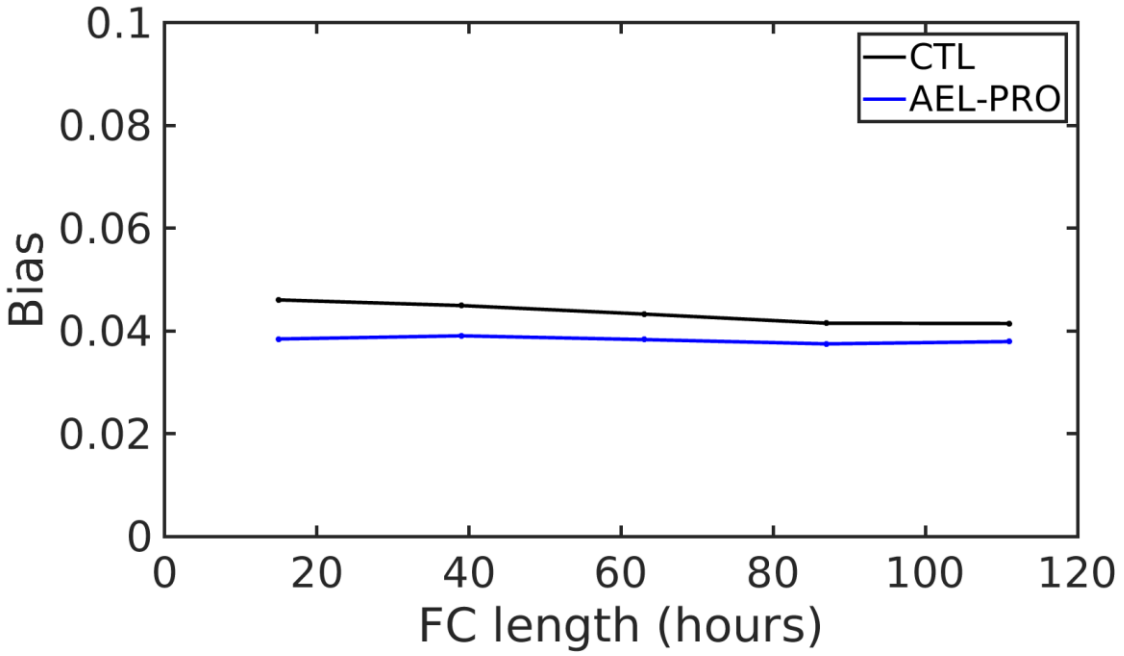


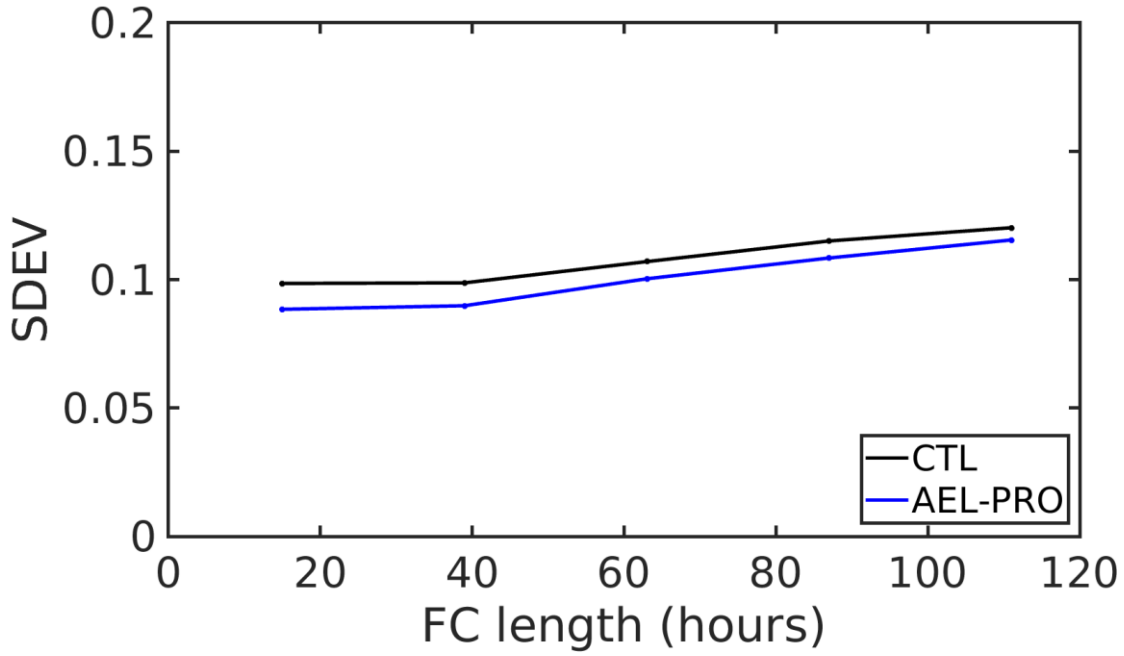


Over Europe forecast improvements are seen both in terms of bias and sdev for all forecast lengths

- The experiment where AEL-PRO with feature mask is actively assimilated improves the forecast scores for all fc lengths.

Verified against Aeronet AOD observations over Europe, 1.7-31.12.2019

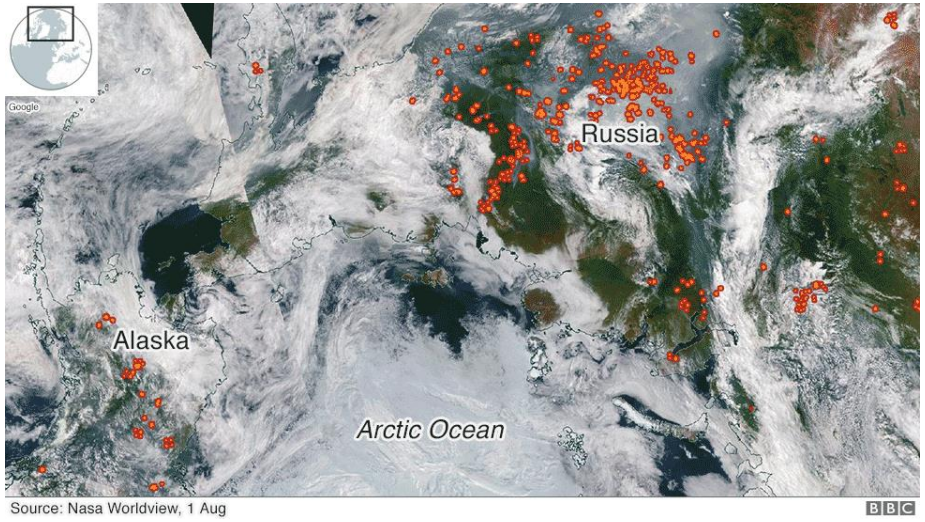




Where do the improvements originate from?

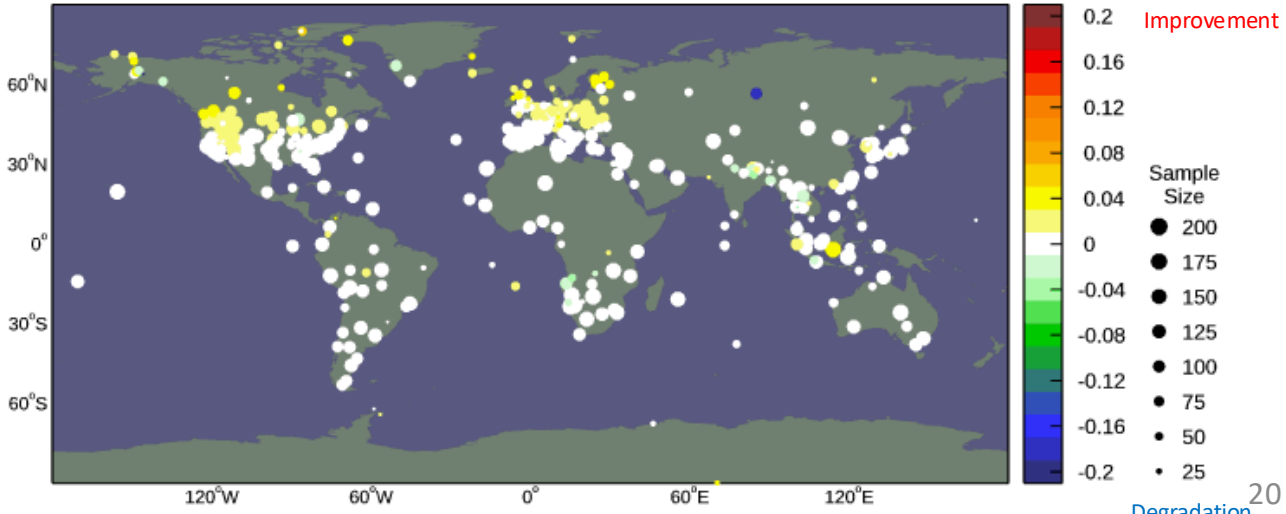
- Summer 2019 was characterised with strong wild fires over northern hemisphere high latitudes.
- Verification of the AEL-PRO experiment against Aeronet AOD observations indicates decreased RMS error difference over the regions were wild fires occured.

Snapshot of the wild fire analysis on 1st August 2019



https://www.bbc.co.uk/news/world-europe-49125391

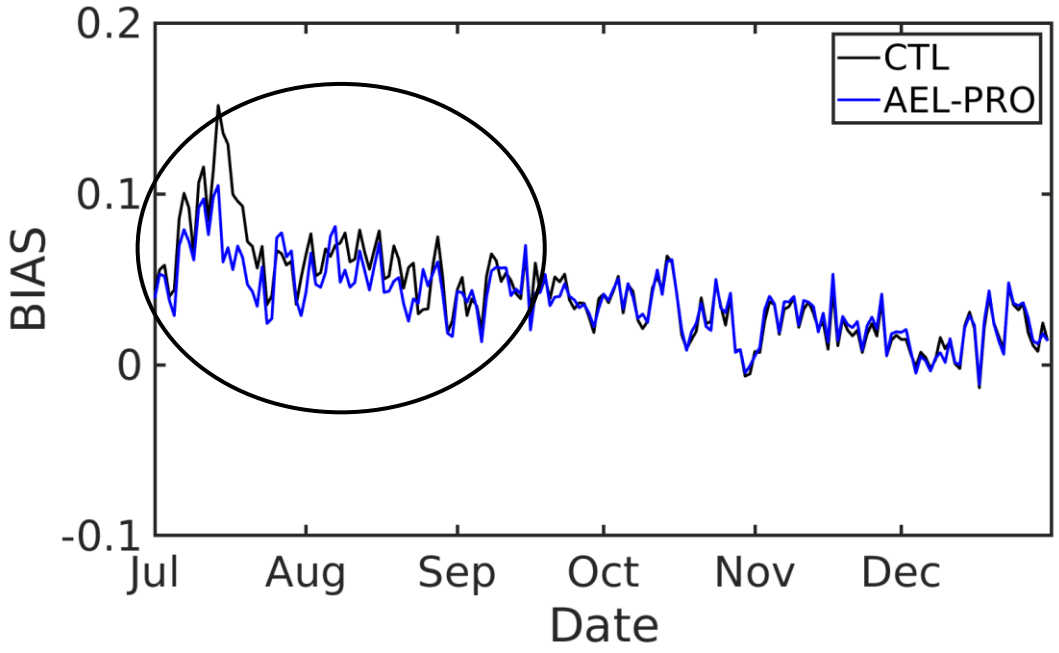
RMS error difference CTL – AEL-PRO FM, July – December 2019

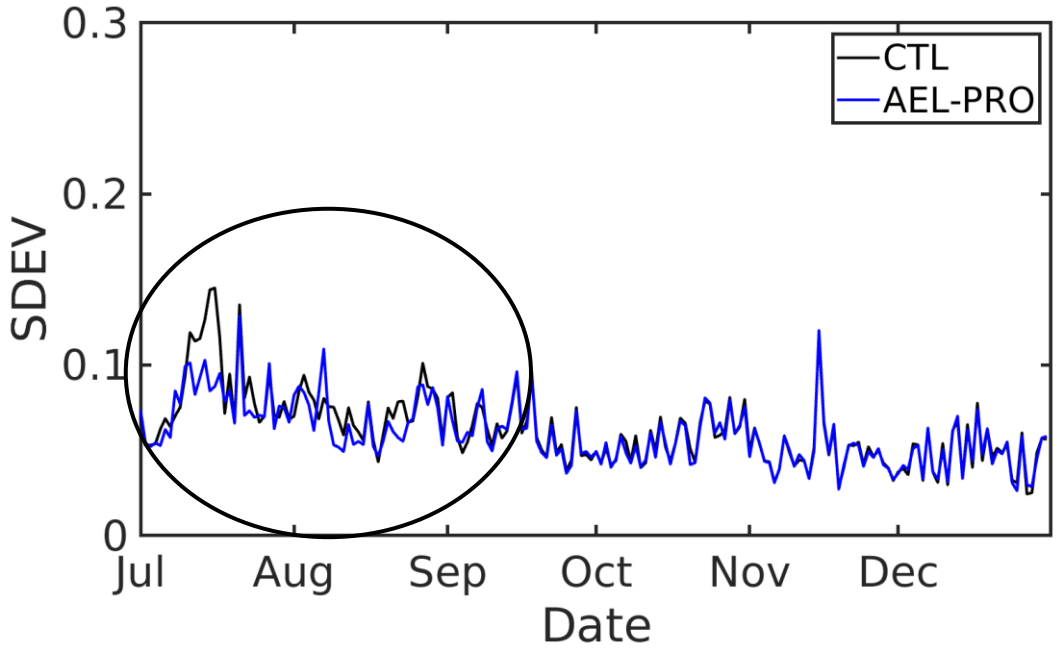


Time series confirm that the improvements co-incide with the wild fires

- Both bias and SDEV are decreased for July – September period over Europe when verified against Aeronet observations.
- Similar improvements are seen also over North America.

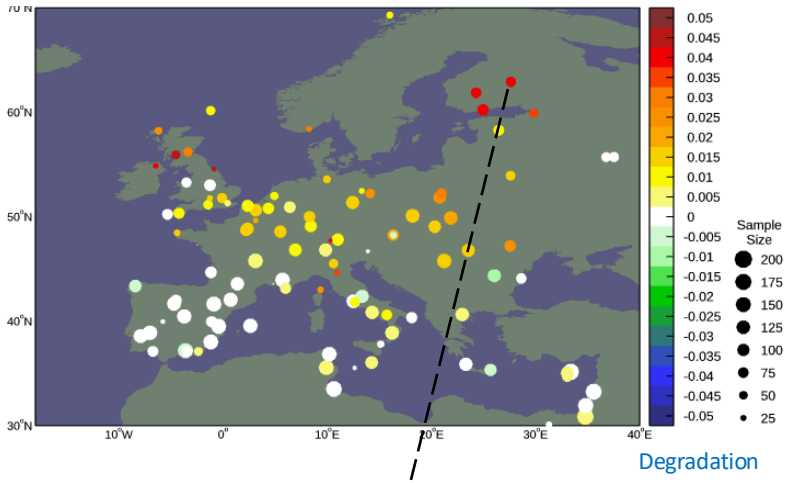
Verified against Aeronet AOD observations over Europe, 1.7-31.12.2019



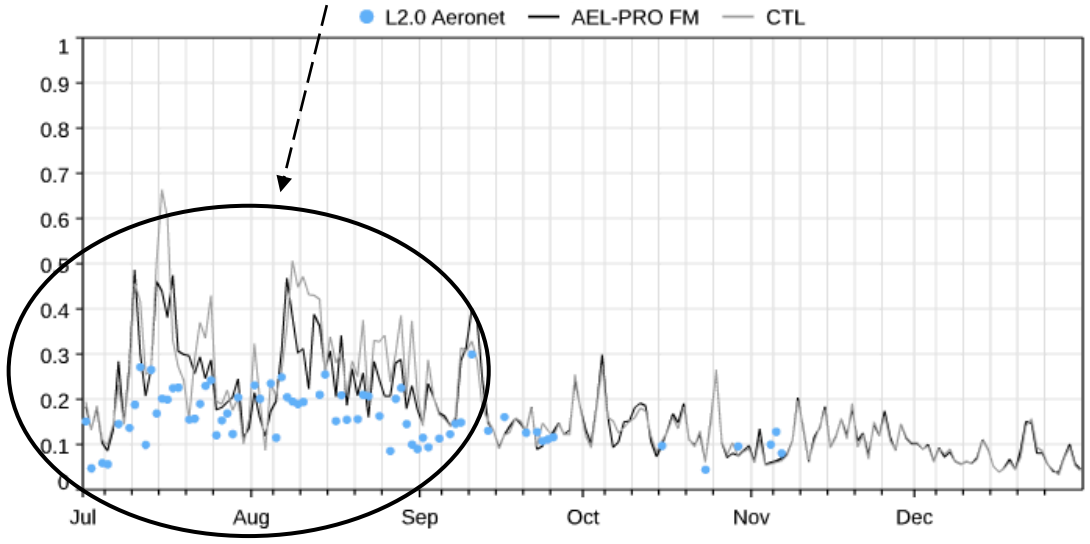


Timeseries from selected locations show that AEL-PRO experiment is closer to the Aeronet observations than the CTL during the wildfire period

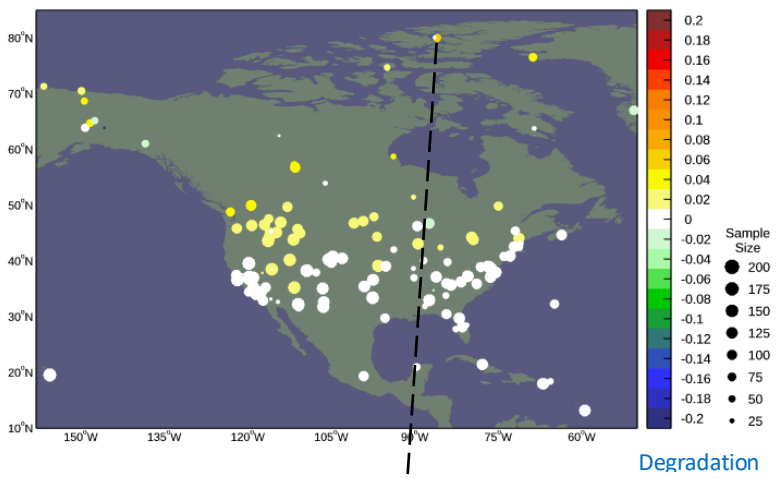
RMS error diff (CTL – AEL-PRO FM)



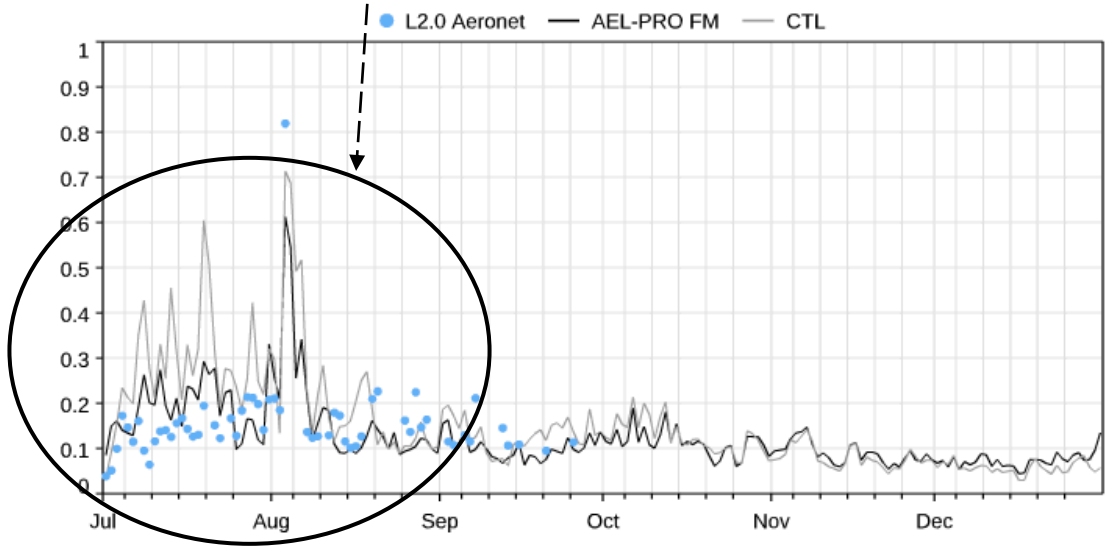
Kuopio, Finland



RMS error diff (CTL – AEL-PRO FM)

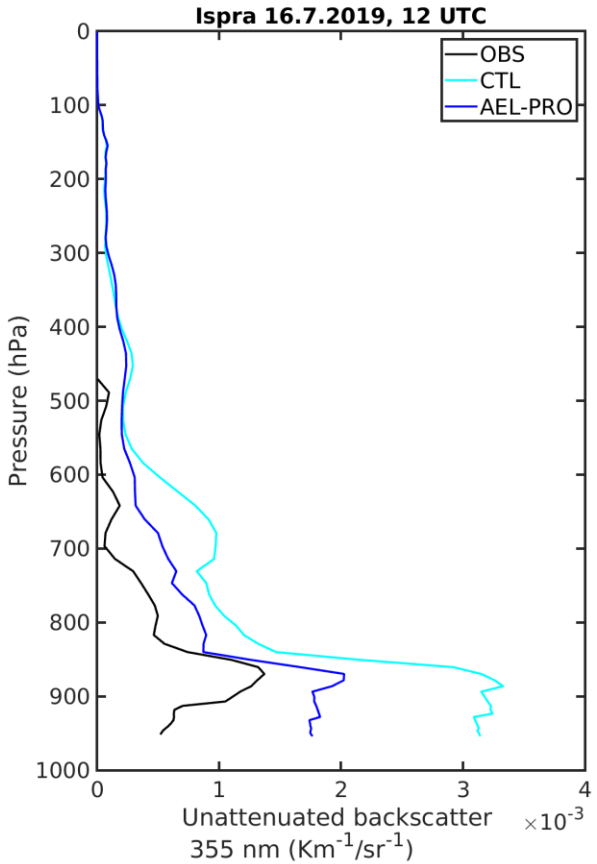


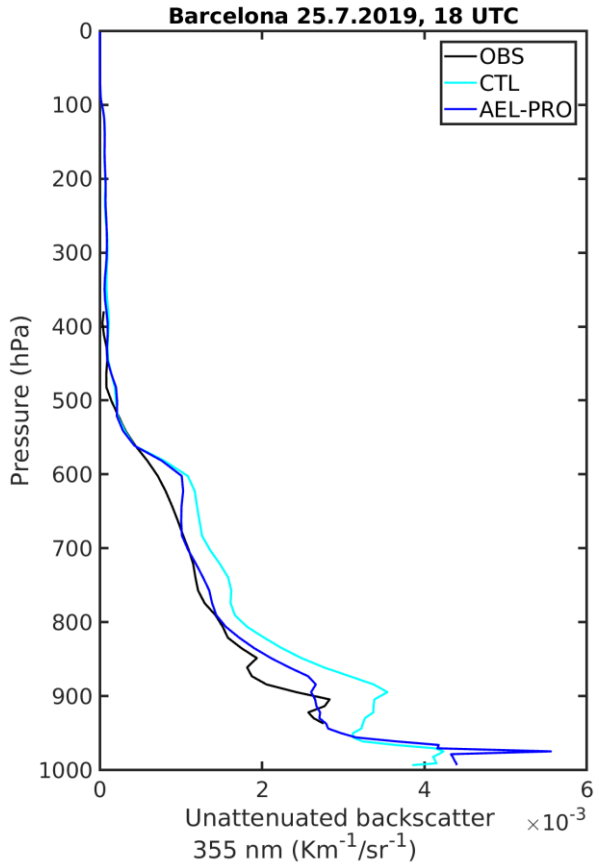
Opal, Canada

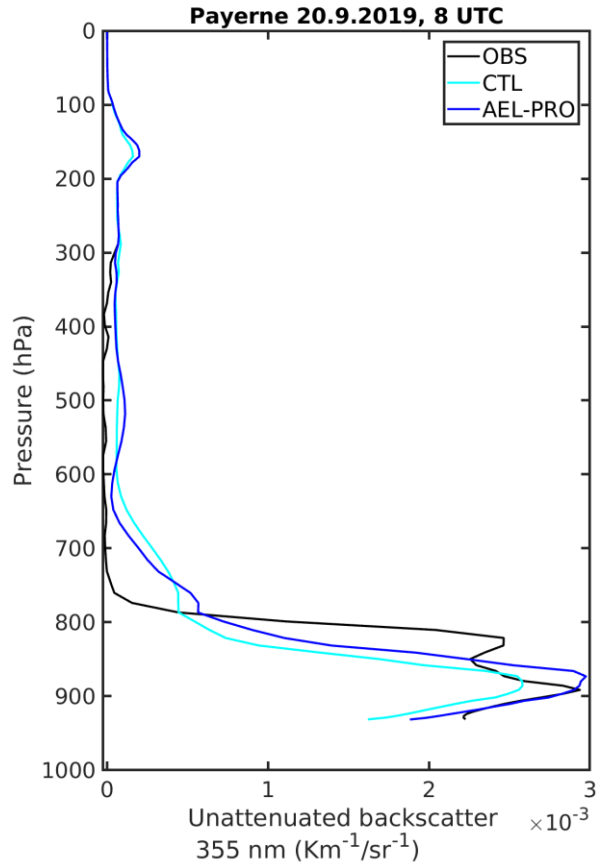


Examples of comparisons to EARLINET lidar profiles

- Assimilation of the Aeolus lidar backscatter profiles is making changes to the model aerosol distributions.



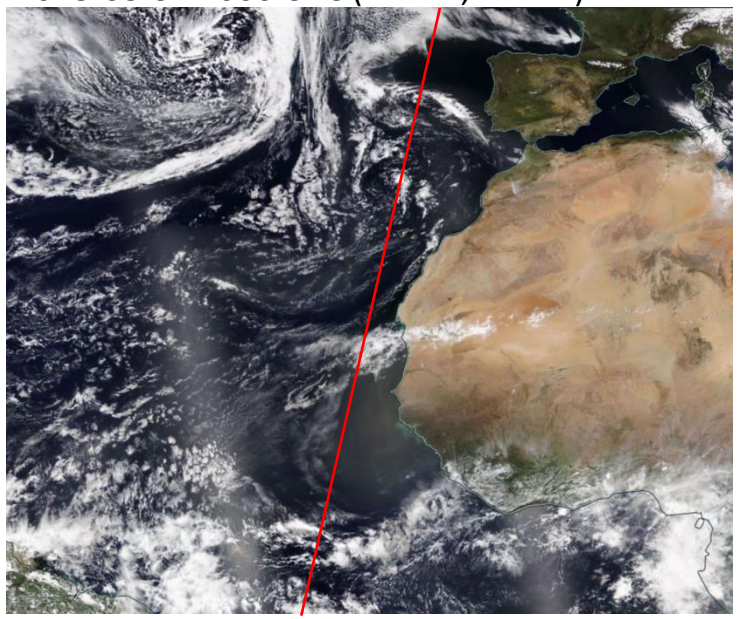


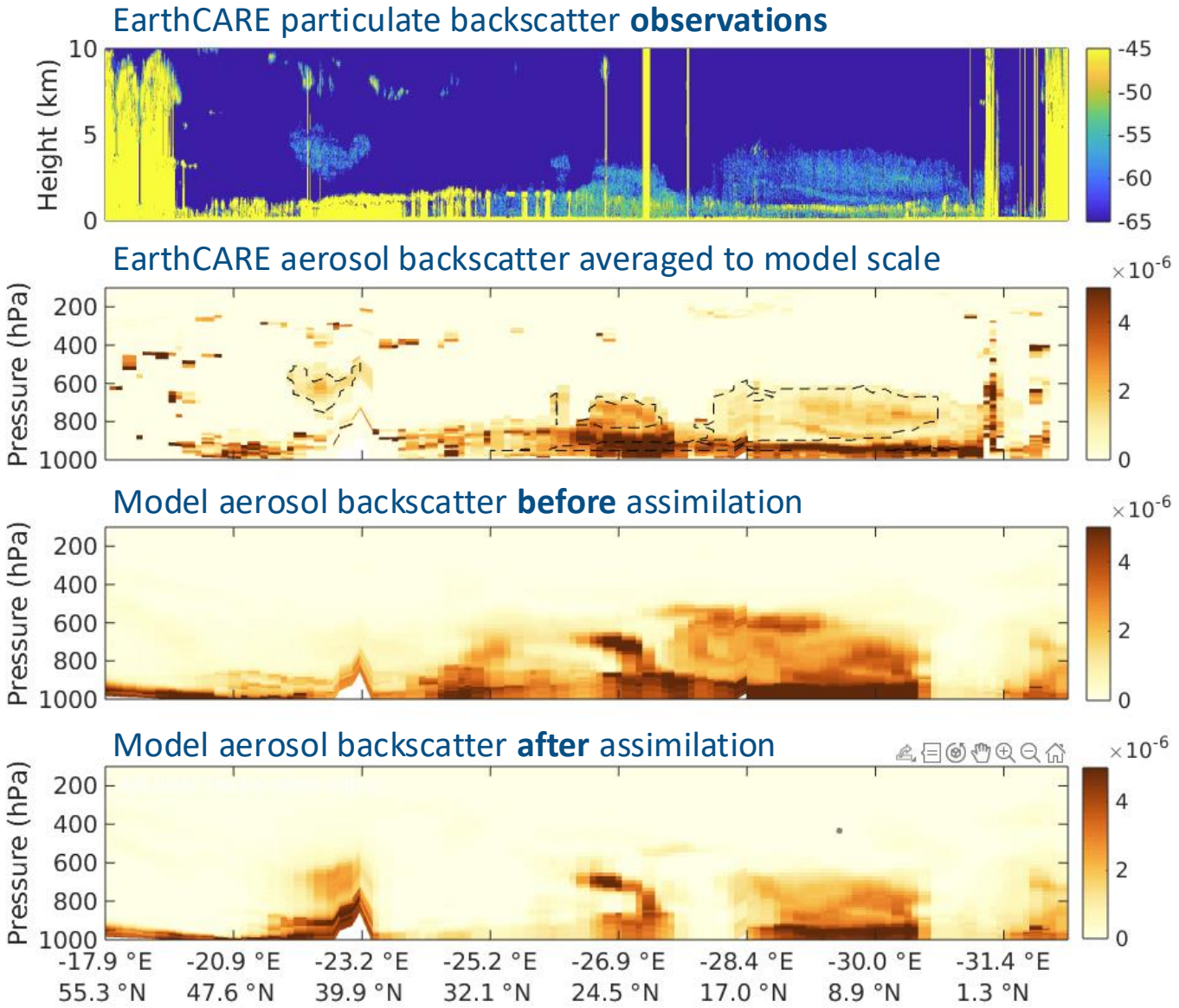


EarthCARE

- ATLID **aerosol backscatter** provides a new vertical constraint on aerosol profiles for atmospheric composition models in both day and night.
- As part of the ESA-funded EarthCARE DISC, feasibility studies are being performed for assimilation of L2 aerosol products.

2025-03-31 1600 UTC (4772D, 4772E)

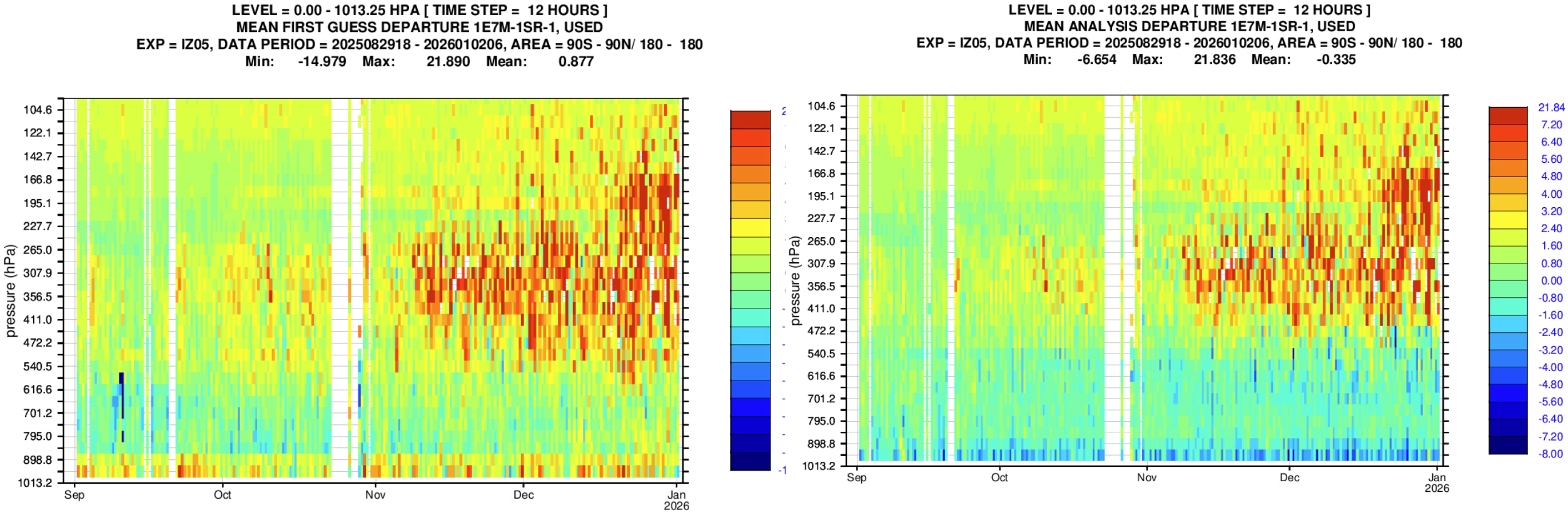




Thanks to Will McLean and Mark Fielding

First guess and analysis departures for lidar backscatter

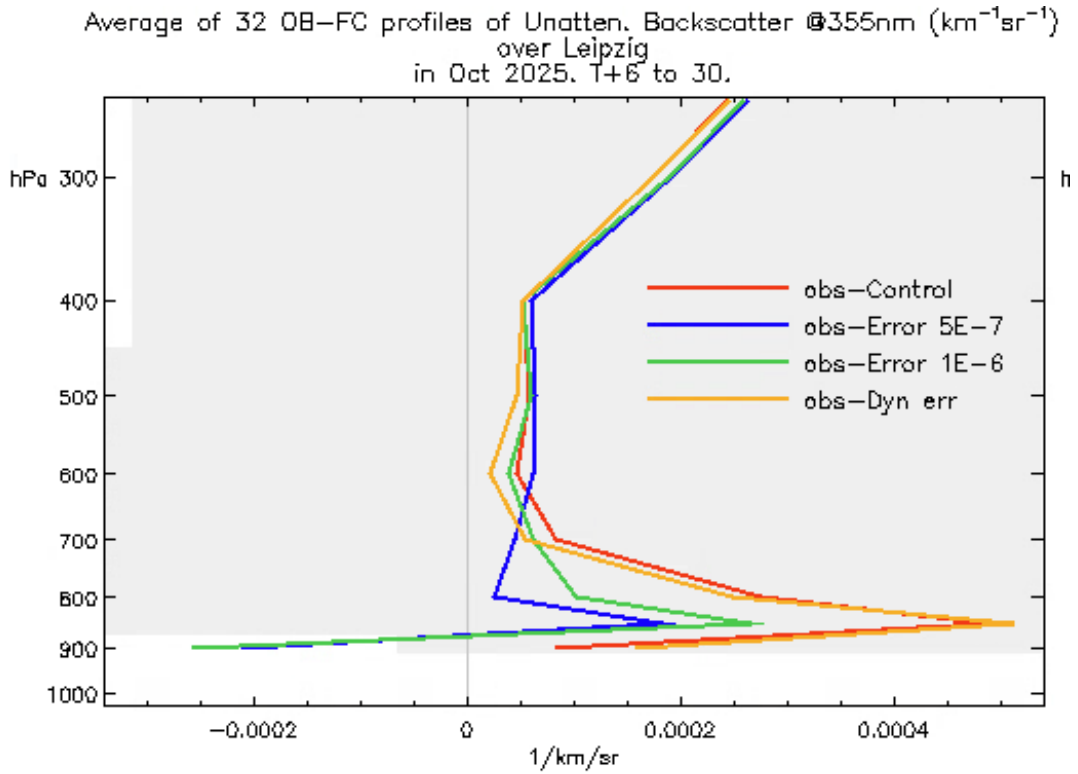
O-B and O-A Sept 01 – Dec 31 2025
(for exp with 5E-7m-1sr-1 as error)



- Sharp increase in first-guess departures starting in mid-November due to a change in processing
- Analysis departures (O-A) are generally smaller indicating that the assimilation draws to the observations

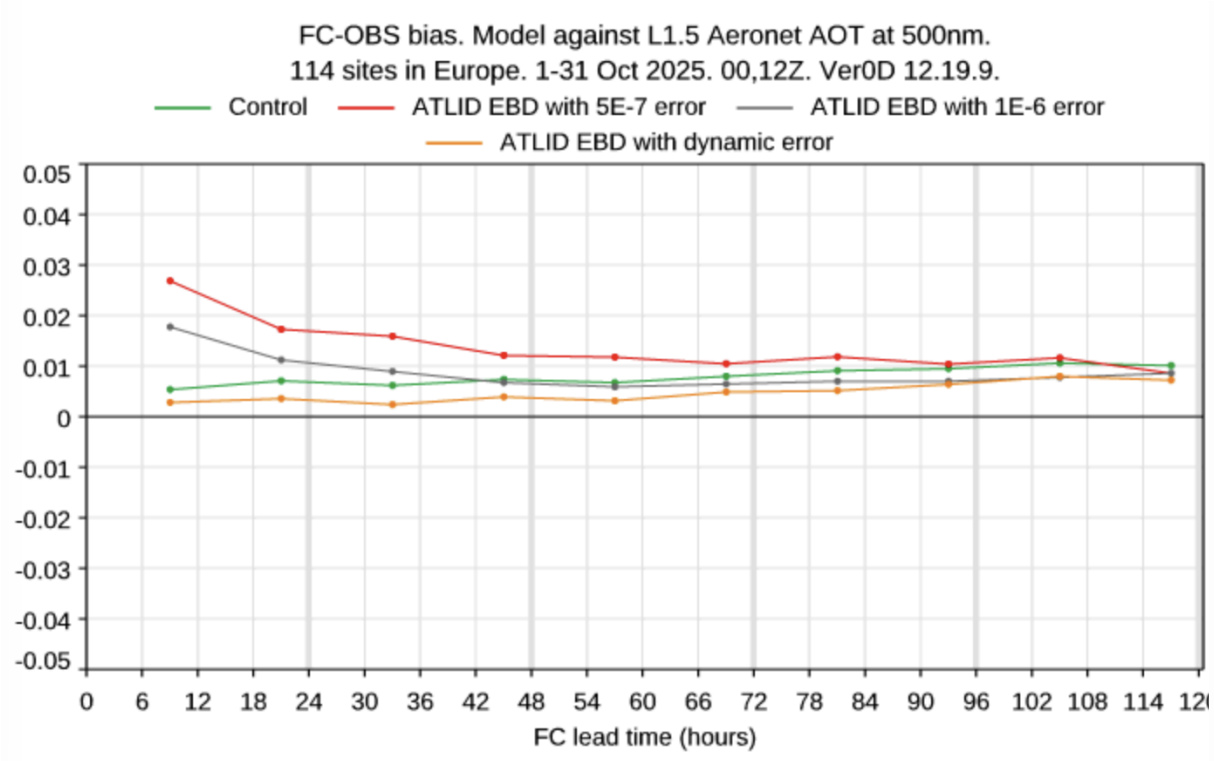
Comparisons with independent lidar observations

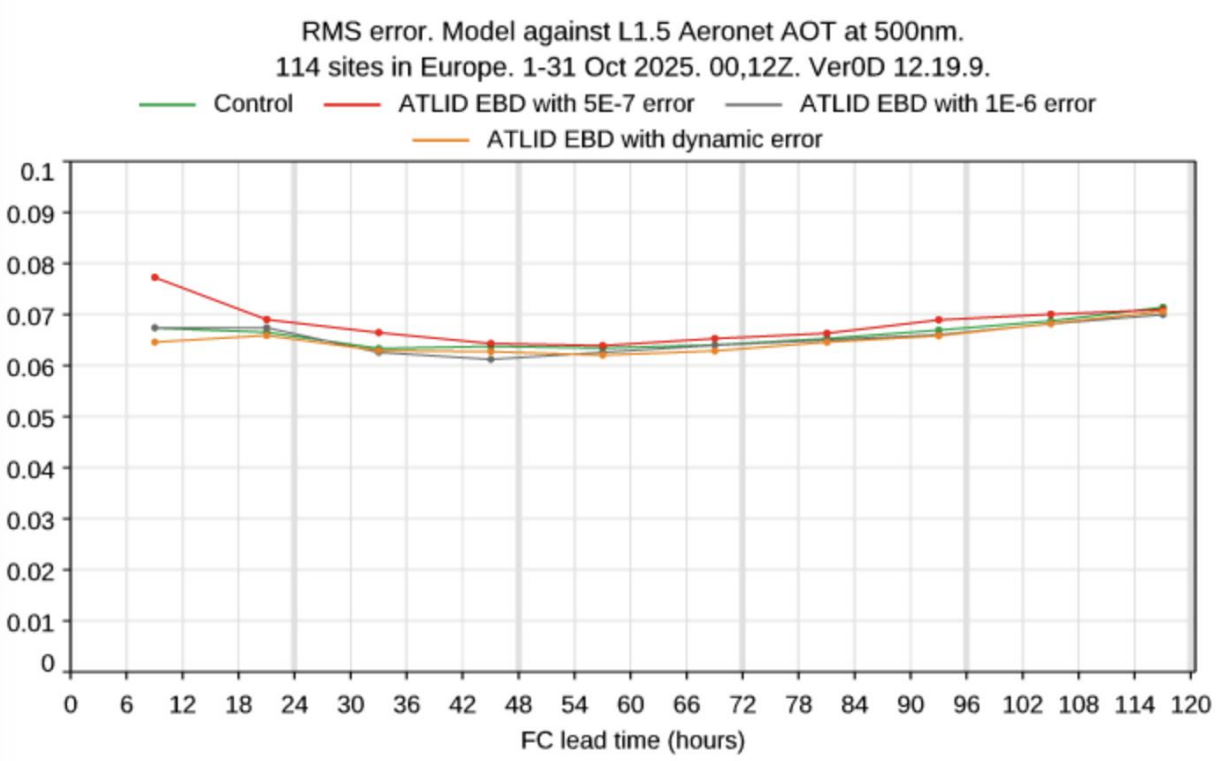
$$'Dynamic\ error' = \frac{1}{4}\beta\ + 5 \times 10^{-7}\ \ (m\ sr)^{-1}$$



- Strong sensitivity to error assumptions
- Reduction in bias with respect to the ground-based observations at higher and middle altitudes using the dynamic error
- Opposite behaviour at lower levels

Verification against AERONET AOD at 500 nm five-day forecast range, Oct 2025 for Europe



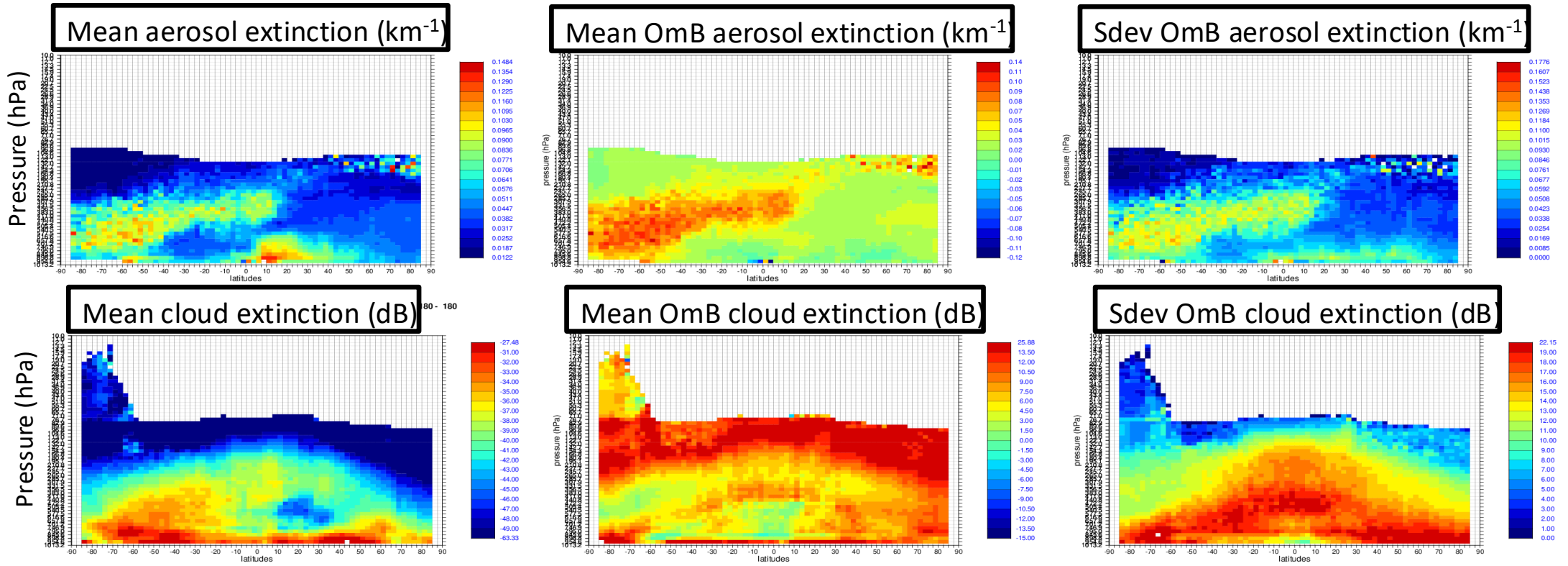


- Assimilating ATLID aerosols using a constant observation error introduces a positive bias in AOD
- Using the dynamic error reduces the forecast bias and standard deviation to slightly less than the control for some times, particularly out to 3 days.

$$\text{`}Dynamic\ error\text{'} = \frac{1}{4}\beta\ + 5 \times 10^{-7}\ \ (msr)^{-1}$$

Towards joint assimilation of cloud and aerosol extinction

- Monitoring statistics indicate strong cloud contamination in aerosol extinction
- Great motivation to aspire to the assimilation of cloud and aerosol information jointly.
- Statistics of observation minus model background (OmB) cover April – May 2025. Cloud extinction is converted to dB.



ECMWF Kirsti Salonen is funded by the EU HE CERTAINTY project, under Grant Agreement No 101137680

Summary and outlook: lidar data assimilation

- **Substantial technical developments** enabling use of lidar observations in the aerosol analysis (both backscatter and extinction).
- Assimilation of lidar backscatter from Aeolus AEL_PRO algorithm showed promising results particularly over Europe.
- Assimilation of EarthCARE ATLID backscatter data shows a similar behavior, but the observations errors in 4D-Var are still being refined.
- More optimal L2 EarthCARE aerosol products will be looked at.
- Joint cloud and aerosol assimilation is also being investigated.

- The expected lifetime of EarthCARE is now 10 years, making the investment in assimilating the aerosol lidar backscatter in operational aerosol forecast systems worthwhile.