Dust aerosol data assimilation and forecasting: operational and research aspects

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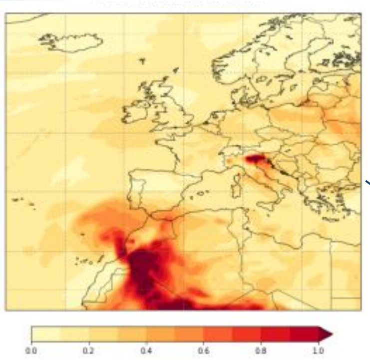
With thanks to Antje Inness (ECMWF)

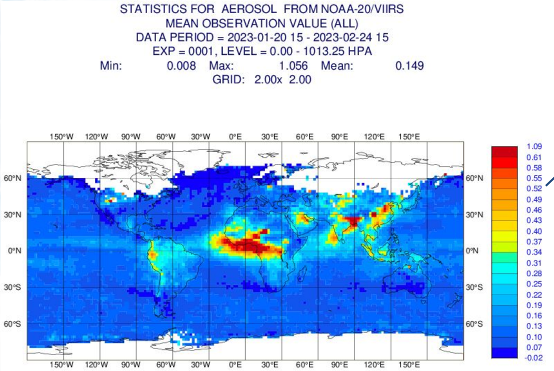
Copernicus Europe's eyes on Earth ECMWF Atmosphere Monitoring Service atmosphere.copernicus.eu

Atmosphere
Monitoring

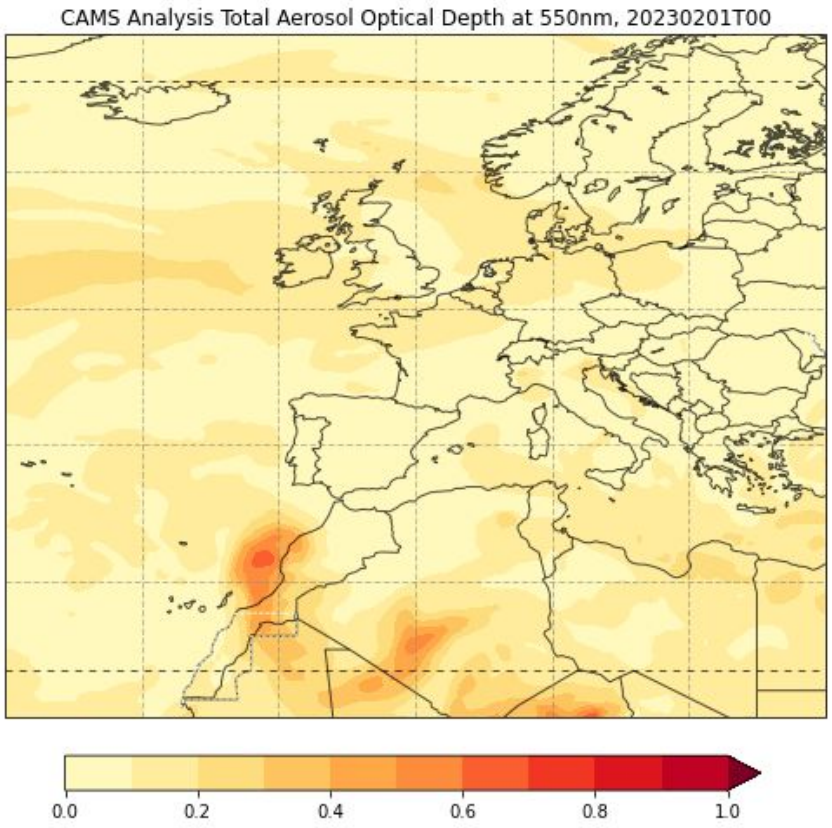
Model information



Observation information



Forecast



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Outline

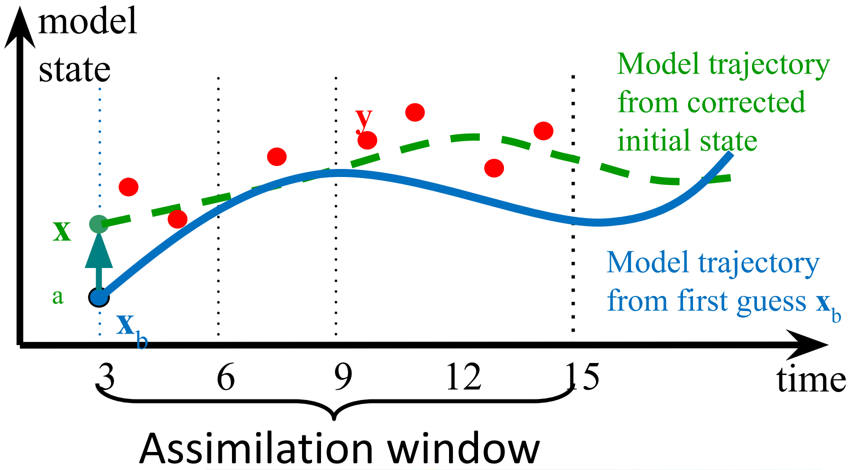
1. Data assimilation methodology for atmospheric composition
2. Operational aerosol analysis and forecasts with focus on dust
3. Reanalysis
4. Research aspects
5. Summary

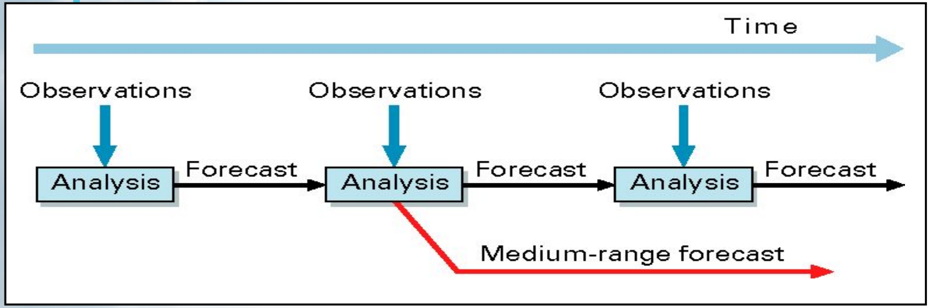
With thanks to the ECMWF CAMS team and the VIS IR team

1. Data Assimilation Methodology for atmospheric composition

Variational Data assimilation

- NWP definition: Combining data and model in an 'optimal' way to produce the best possible initial conditions for a numerical forecast
- Optimal in a statistical sense: minimize error and/or maximize probability of the analysis better matching observations
- CAMS uses ECMWF's 4-dimensional variational data assimilation system (4D-VAR)
- For atmospheric composition DA parameters other than IC might be of interest





Data assimilation methodology

Data assimilation for atmospheric composition is in principle no different from NWP data assimilation

$$J(x) = (x - x_b)^T B^{-1} (x - x_b) + \sum_{i=0}^{n} (y_i - H_i[x_i])^T R_i^{-1} (y_i - H_i[x_i])$$

The ‘optimal’ initial condition equates to minimising the value of this cost function by changing the value of the control vector x

The challenge is the size of the control vector and related background error covariance matrix

x: control vector
x_b: model background (short forecast)
B: Background error covariance matrix
y: Observations
H[x]: Model equivalent of observations
R: Observation error covariance matrix

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Control variables

NWP
vorticity divergence temperature surface pressure (logarithm) specific humidity
Atmospheric Composition
ozone carbon monoxide nitrogen dioxide formaldehyde sulphur dioxide
carbon dioxide methane
aerosol mixing ratio

~13 variables in the CAMS control vector
- 137 model levels
- 348,528 grid points at each model level

Total: 620,728,368 variables just in the full control vector at one point in time

B matrix: 620,728,368^2 = 8.85 x 10^17

Data assimilation methodology

Atmosphere Monitoring

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The challenge is the size of the control vector and related background error covariance matrix

Two main ways of managing this: Ensemble methods and Variational approaches

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x_b: model background (short forecast)
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Incremental 4D-var

$d_i = y_i - \mathcal{H}_i x_b(t_i)$

$$J(\delta\mathbf{x}) = \underbrace{\frac{1}{2}\delta\mathbf{x}^{\mathrm{T}}\mathbf{B}^{-1}\delta\mathbf{x}}_{J_b \text{ Background term}} + \underbrace{\frac{1}{2}\sum_{i=0}^{n}(\mathbf{H}_i\delta\mathbf{x}(t_i)-\mathbf{d}_i)^{\mathrm{T}}\mathbf{R}_i^{-1}(\mathbf{H}_i\delta\mathbf{x}(t_i)-\mathbf{d}_i)}_{J_o \text{ Observation term}}$$

We calculate the gradient of the cost function to find its minimum:

$$\text{Min } J \iff \nabla_{\delta\mathbf{x}_0}J = \mathbf{B}^{-1}\,\delta x_0 + \sum_{i=0}^{n} \underbrace{\boldsymbol{M}'^{T}\,\boldsymbol{H}_i^{T}}_{\text{Adjoint}}\boldsymbol{R}_i^{-1}(\underbrace{\boldsymbol{H}_i\boldsymbol{M}'_i}_{\text{Tangent linear}}[\delta x_0] - d_i) = 0$$

Tangent linear

Adjoint

- δx: low resolution increment at initial time
- $\delta x(t_i)$: incr evolved according to TL model from initial time to time index i
- $d_i = y_i - \mathcal{H}_i x_b(t_i)$: Innovation vector, $x_b(t_i)$ background propagated using full model
- R_i: Obs error covariance matrix at time index i
- B: Background error covariance matrix
- y_i: Observation vector at time index i
- $H_i[x]$: TL model equivalent of observations
- $\mathcal{H}_i[x]$: Full model equivalent of observations

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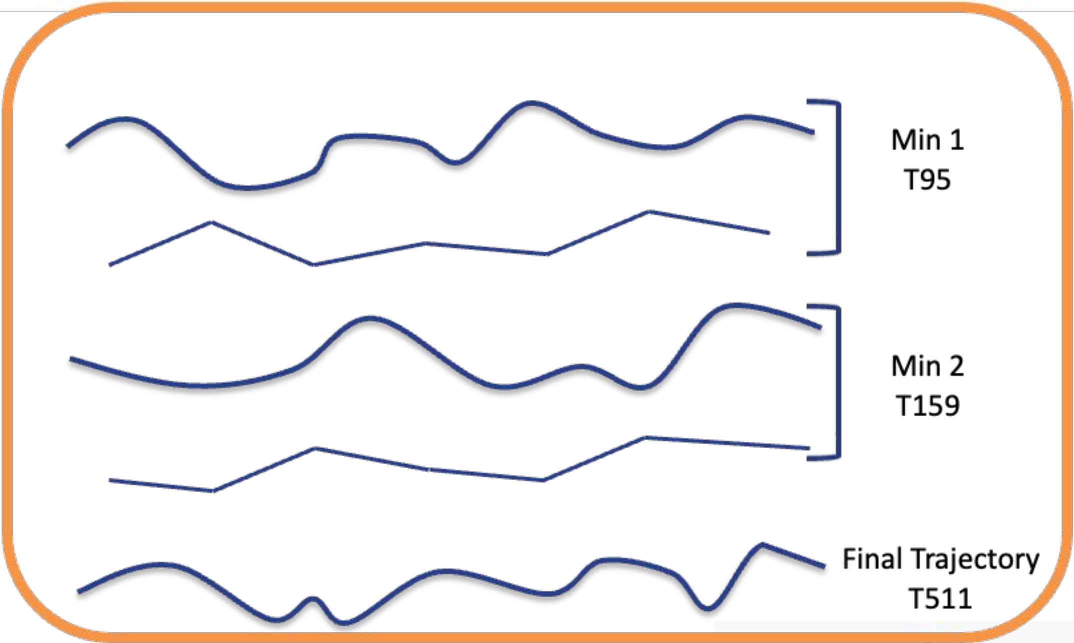
Incremental 4D-var

$$J(\delta\mathbf{x}) = \frac{1}{2}\delta\mathbf{x}^{\mathrm{T}}\mathbf{B}^{-1}\delta\mathbf{x} + \frac{1}{2}\sum_{i=0}^{n}(\mathbf{H}_i\delta\mathbf{x}(t_i) - \mathbf{d}_i)^{\mathrm{T}}\mathbf{R}_i^{-1}(\mathbf{H}_i\delta\mathbf{x}(t_i) - \mathbf{d}_i)$$



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Incremental 4D-var

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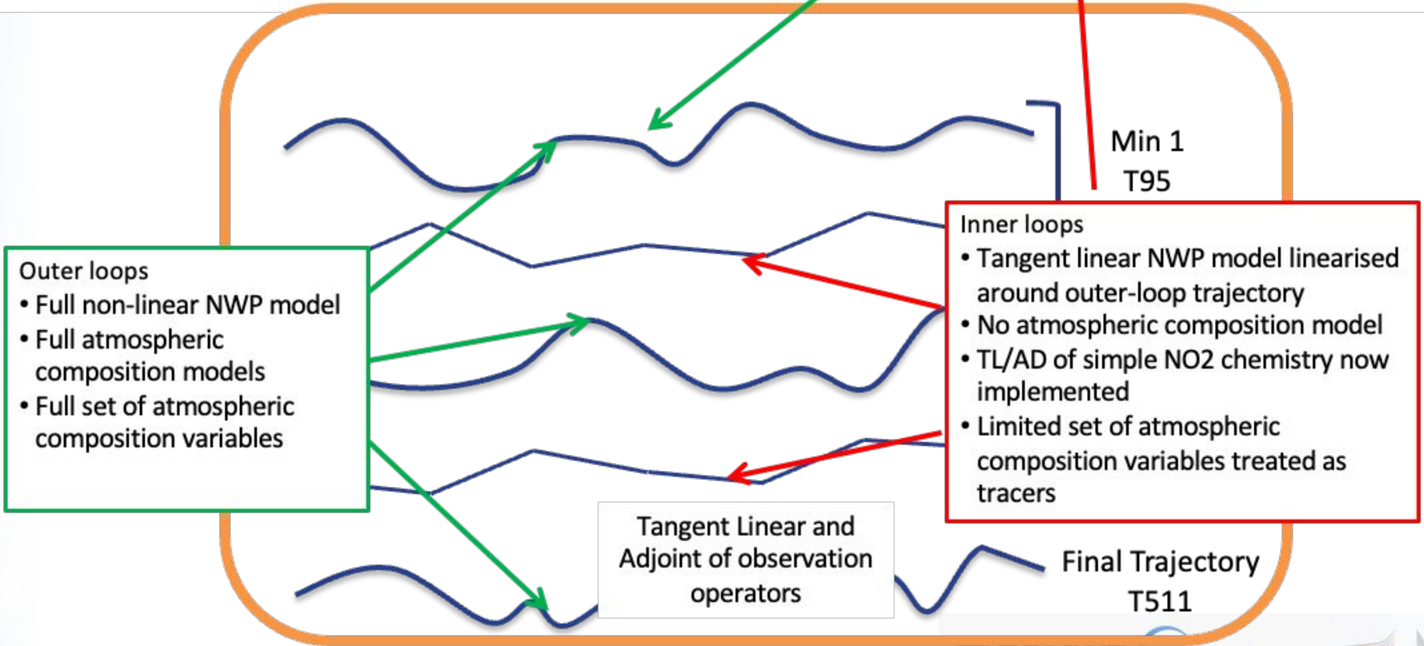
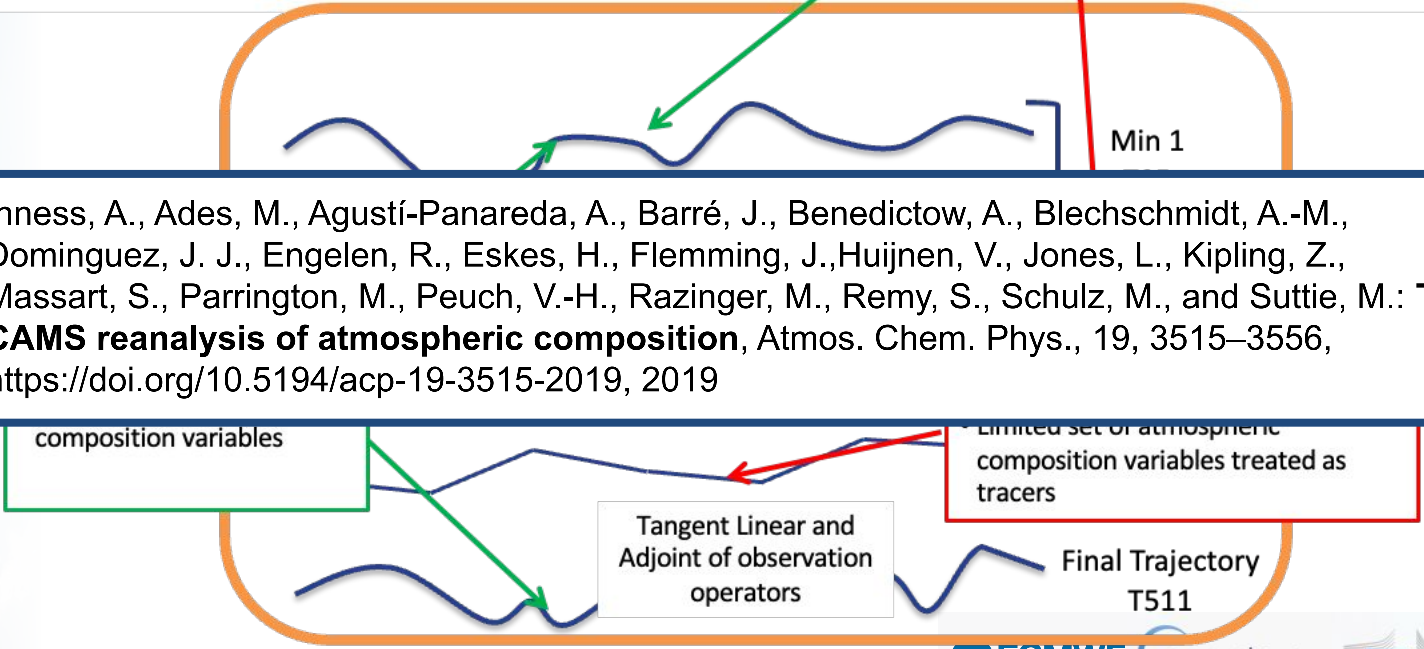


Incremental 4D-var

$$J(\delta\mathbf{x}) = \frac{1}{2}\delta\mathbf{x}^{\mathrm{T}}\mathbf{B}^{-1}\delta\mathbf{x} + \frac{1}{2}\sum_{i=0}^{n}(\mathbf{H}_i\delta\mathbf{x}(t_i) - \mathbf{d}_i)^{\mathrm{T}}\mathbf{R}_i^{-1}(\mathbf{H}_i\delta\mathbf{x}(t_i) - \mathbf{d}_i)$$



Inness, A., Ades, M., Agustí-Panareda, A., Barré, J., Benedictow, A., Blechschmidt, A.-M., Dominguez, J. J., Engelen, R., Eskes, H., Flemming, J.,Huijnen, V., Jones, L., Kipling, Z., Massart, S., Parrington, M., Peuch, V.-H., Razinger, M., Remy, S., Schulz, M., and Suttie, M.: **The CAMS reanalysis of atmospheric composition**, Atmos. Chem. Phys., 19, 3515–3556, https://doi.org/10.5194/acp-19-3515-2019, 2019

2. Operational aerosol analysis and forecasts with focus on dust

Copernicus Atmosphere Monitoring Service

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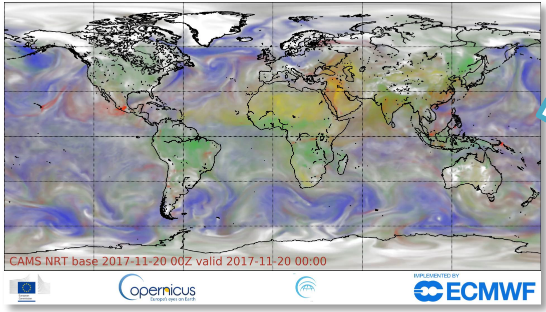
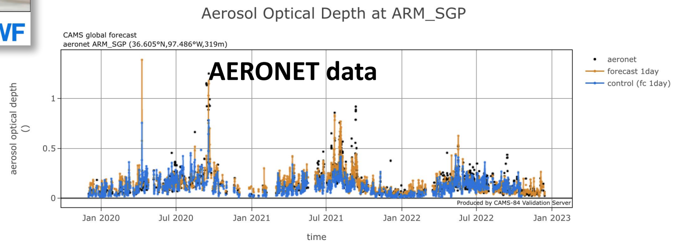
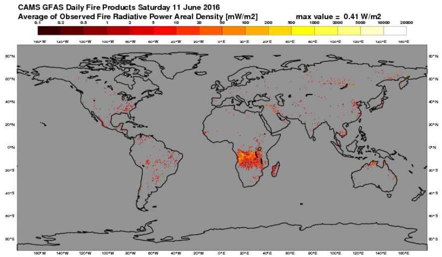
Satellite data are used in the ECMWF's Integrated Forecast System to initialize the model

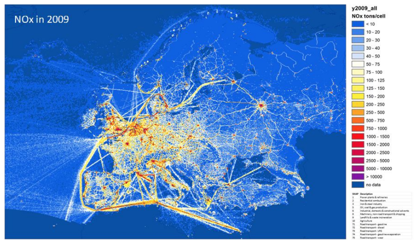
Credits: CAMS team



Ground-based observations are used to verify the model prediction







Fire from FRP (GFAS, Global Fire Assimilation System) and anthropogenic emissions from established inventories are inputs to the model

The CAMS/ECMWF model is based on:

- ECMWF 4D-var and meteorology
- Integrated chemistry and aerosol representation (IFS-COMPO)
- Integrated natural biosphere model

https://atmosphere.copernicus.eu/

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Impact of data assimilation(DA) on forecasts

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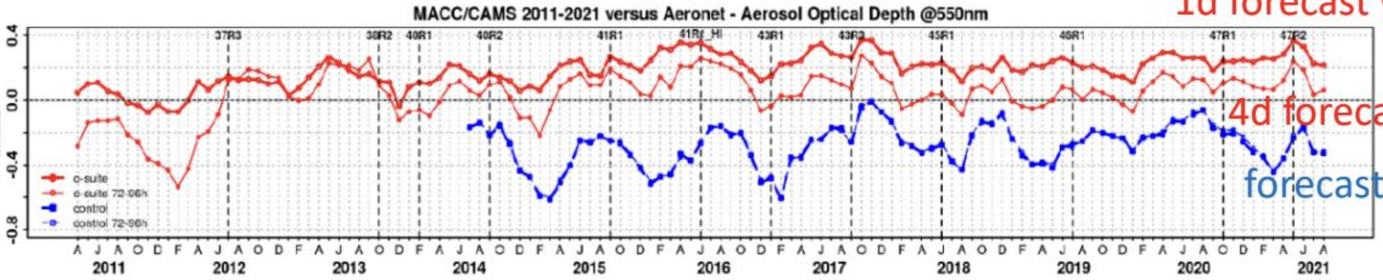
CAMS AOD forecast bias against AERONET



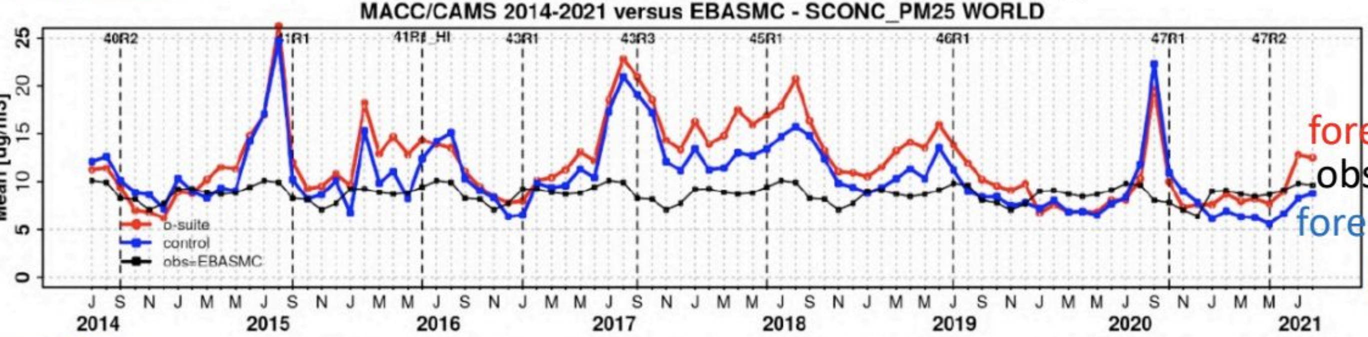
1d forecast with DA

4d forecast with DA

forecast without DA

Positive impact on AOD

MS PM2.5 forecast compared to EMEP and IMPROVE ground observations



Mixed result for PM2.5

forecast with DA

observations

forecast without DA

Credit: CAMS validation report (CAMS84_2018SC3_D1.1.1_JJA2021)

Observations used in CAMS

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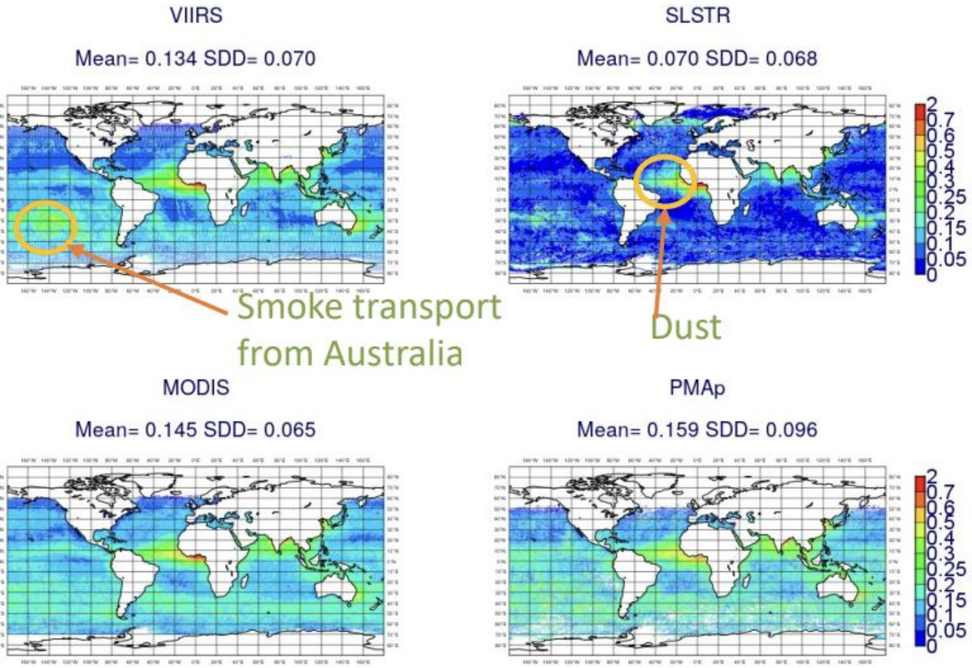
$$J(x) = (x - x_b)^T B^{-1} (x - x_b) + \underbrace{\sum_{i=0}^{n} (y_i - H_i[x_i])^T R_i^{-1} (y_i - H_i[x_i])}_{\text{Observation constraint}}$$



- Assimilated observations are AOD at 550 nm from:
  - VIIRS (NOAA-20 and NPP) over land and ocean
  - MODIS (Aqua and Terra) over land and ocean
  - PMAp (Metop-BC) over ocean
- Assimilation tests with SLSTR AOD ongoing

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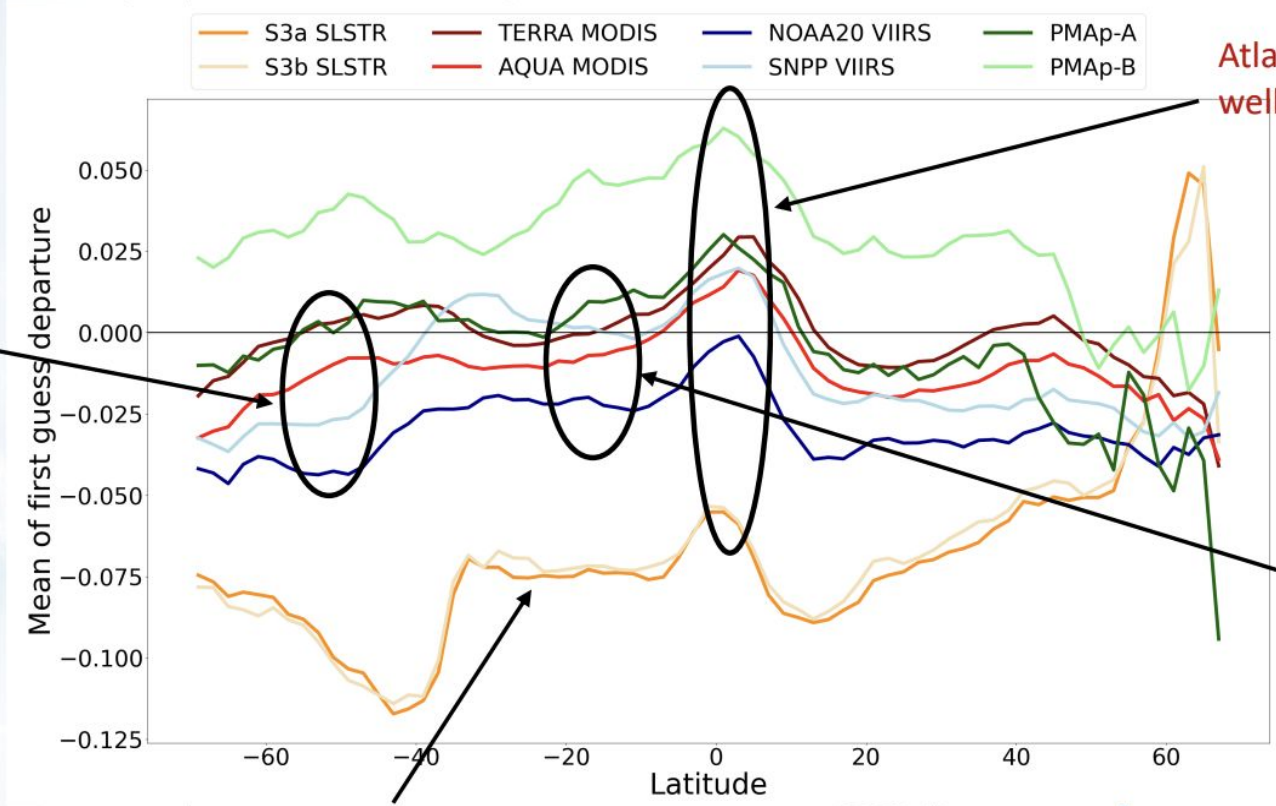
Latitude cross section of **first guess departure** over ocean



Atlantic dust outbreak well captured

Large diversity, in South ocean (wind, clouds)

- SNPP>NOAA20
- TERRA>AQUA

Radiometric uncertainties in level 1

SLSTR shows lower global AOD over ocean

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Ocean (Dec 2019-Feb 2020)

Garrigues et al., ACP, 2022

Atmosphere Monitoring

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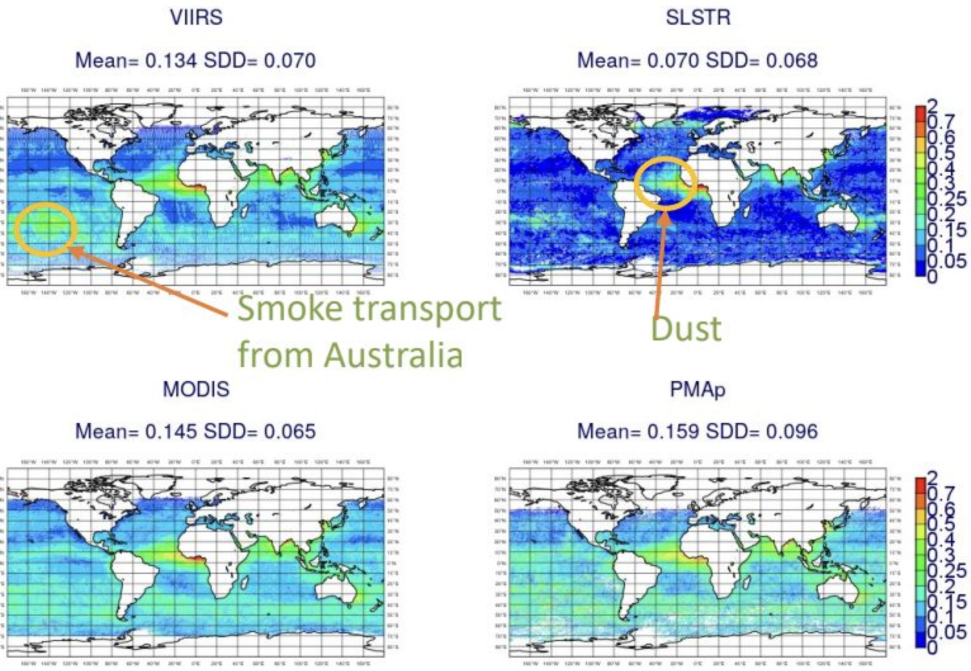

- **AOD observations** - no information on vertical profile of the aerosols or the speciation

Atmosphere Monitoring

Model and control vector

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Greenhouse Gas Module

CHTESSEL
Photosynthesis & ecosystem respiration model
Diagnoses the gross primary production of CO2 by plants and release of CO2 by soil

CH4 comes from prescribed emissions and climatological loss

Control variables

NWP
vorticity divergence temperature surface pressure (logarithm) specific humidity
Atmospheric Composition
ozone carbon monoxide nitrogen dioxide formaldehyde sulphur dioxide
carbon dioxide methane
aerosol mixing ratio

Chemical Module

TM5 (CB05)
57 species, 131 reactions
Photolysis, dry and wet deposition

Aerosol bin scheme

14 aerosol-related prognostic variables:
3 bins sea-salt, 3 bins dust, Black carbon, Organic matter, Sulphate, 2 bins Nitrate, Ammonium

Emissions, dry and wet deposition, sedimentation

All modules are included in ECMWF's Integrated Forecast System

Atmosphere Monitoring

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Atmospheric Composition

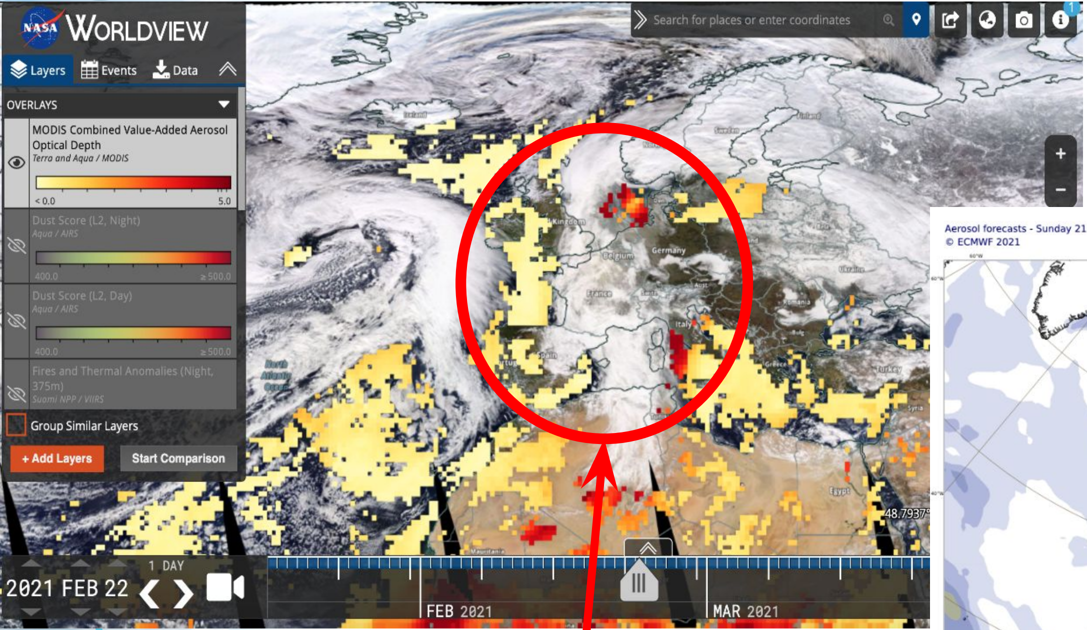
ozone
carbon monoxide
nitrogen dioxide
formaldehyde
sulphur dioxide

carbon dioxide
methane

aerosol mixing ratio

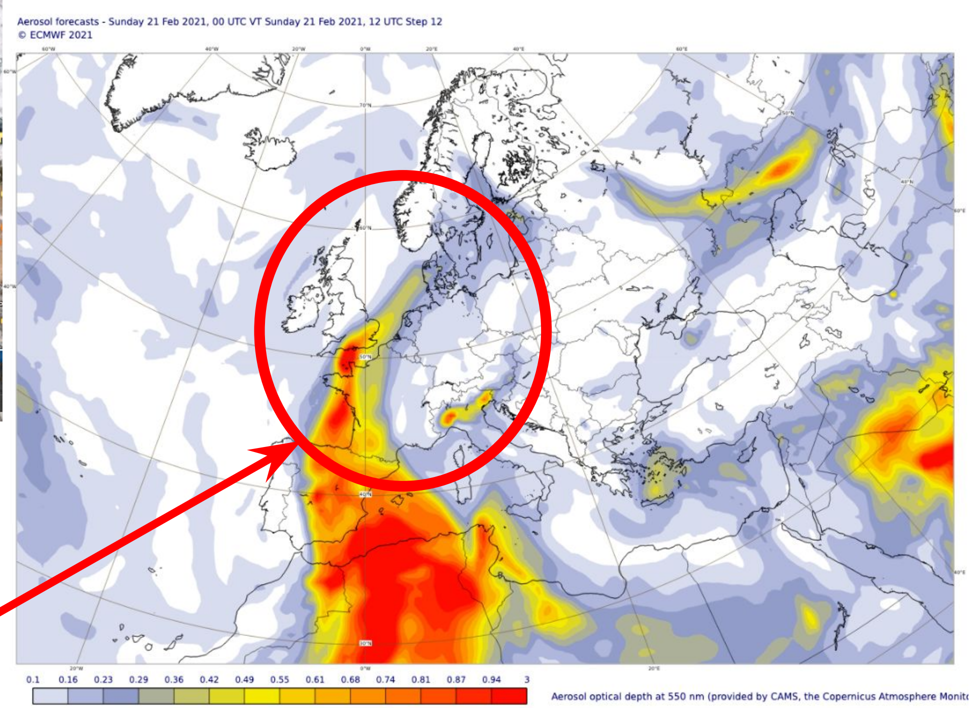
- Control variable is formulated in terms of the total aerosol mixing ratio.
- Analysis increments are repartitioned into the species according to their fractional contribution to the total aerosol mixing ratio.
- The repartitioning of the total aerosol mixing ratio increment into the different bins is difficult

Dust storm February 2021



NASA Worldview – MODIS Aqua and Terra AOD 550nm observations for 20210222

CAMS Total AOD at 550nm 12hr forecast valid at 20210222 12hr

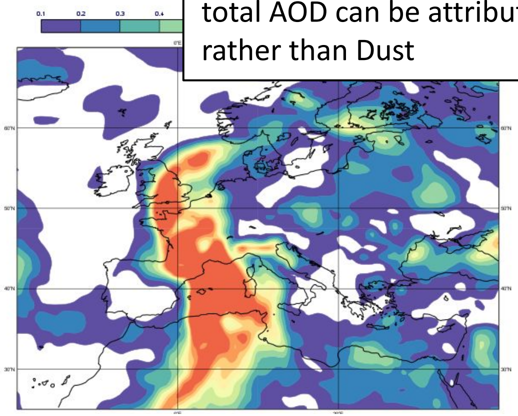


The CAMS forecast does a good job of forecasting the AOD plume from Africa over Northern Europe

Dust test case February 2021

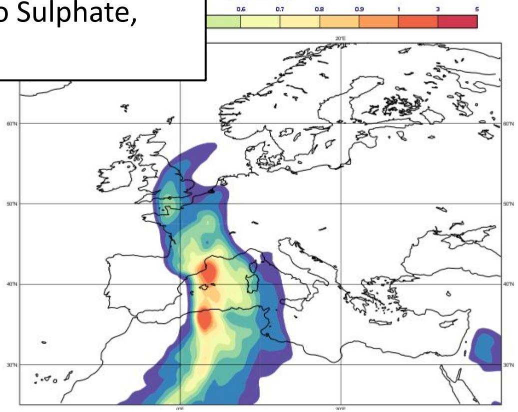
Credit: Melanie Ades

Closer examination shows that some of this total AOD can be attributed to Sulphate, rather than Dust

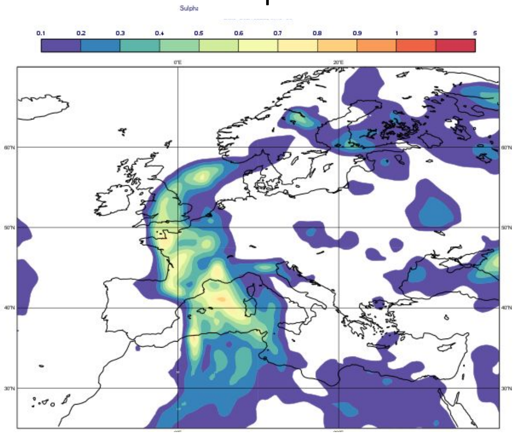


Total AOD at 550nm: 20210222 03hr

Dust

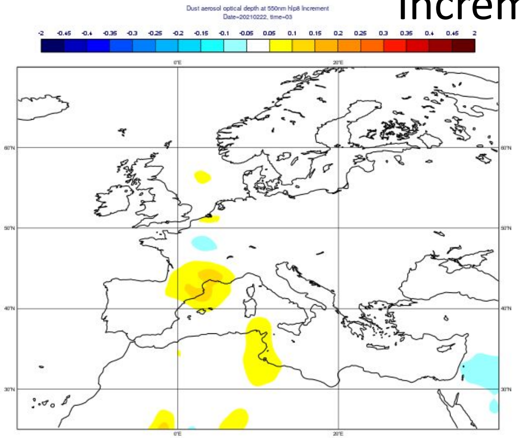


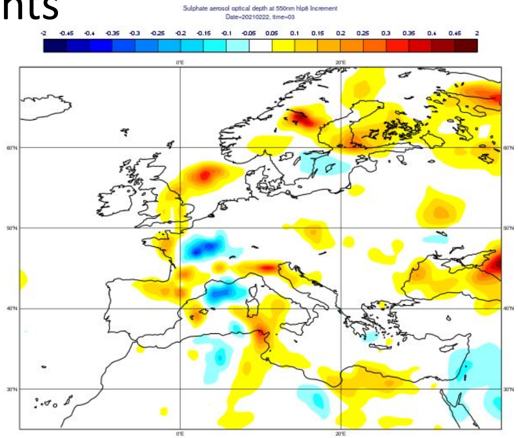
Sulphate



AOD at 550nm

Increments





AOD incr at 550nm

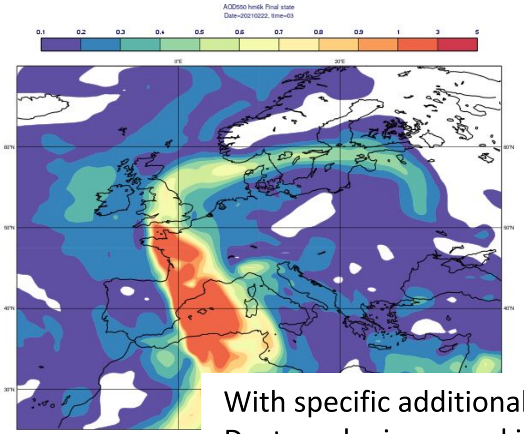
- AOD increments are attributed to the different species according to their proportion in the nonlinear forecast.
- If there is no dust in the forecast in a specific location then the increment will be given to whatever species are there – in this case Sulphate

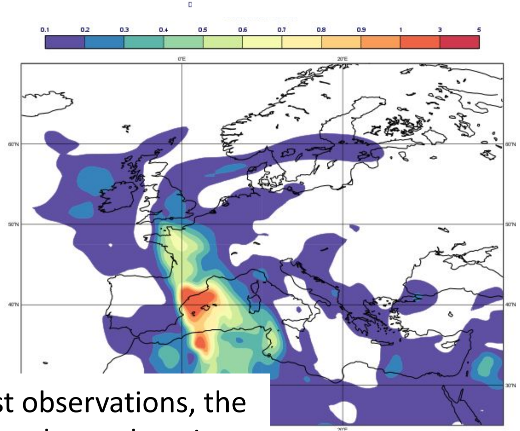
Dust test case February 2021

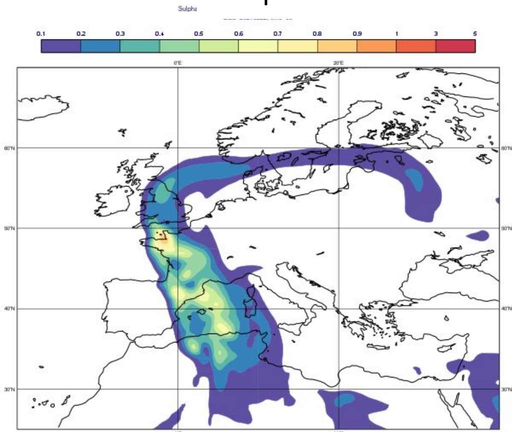
Credit: Melanie Ades

Dust

Sulphate

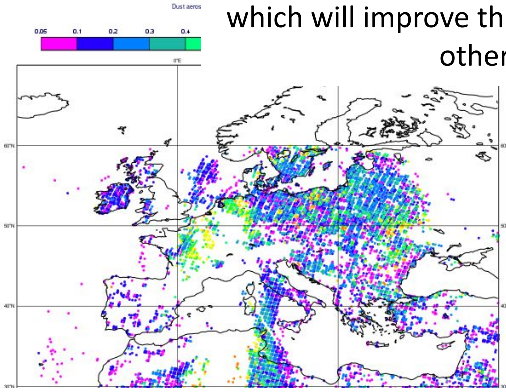




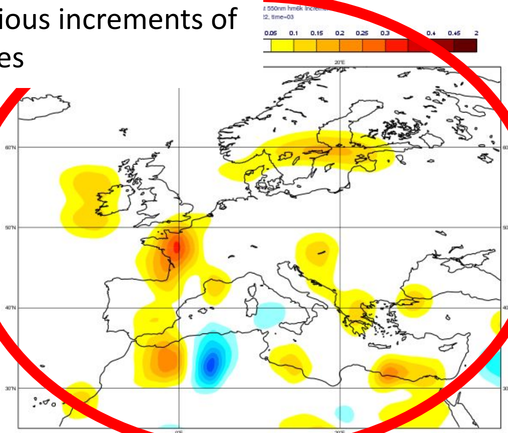


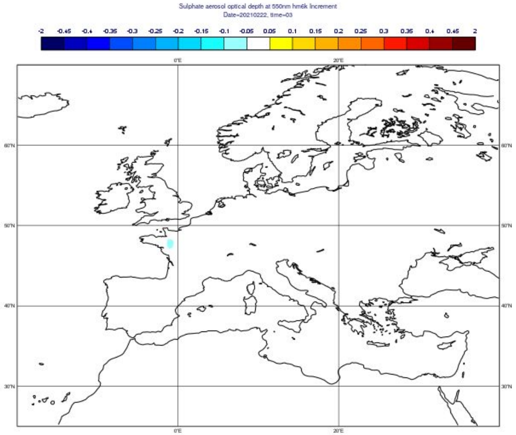
AOD at 550nm

With specific additional Dust observations, the Dust can be increased in the relevant locations which will improve the spurious increments of other species



LMD IASI 10um obs 20210222 12hr





AOD incr at 550nm

3. Reanalysis

CAMS global reanalysis 2003 – 2022 (updated every 6 months)

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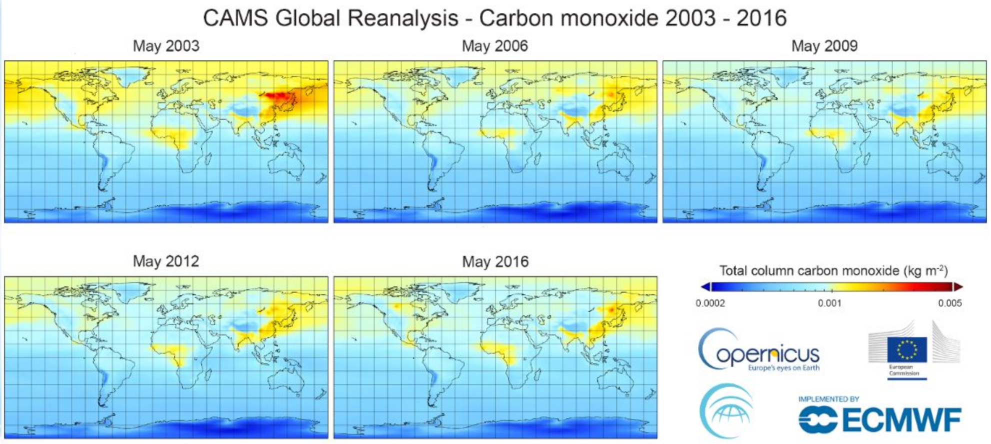


Reanalysis
Using a combination of observations and computer models to recreate historical climate conditions.

DATA DESCRIPTION	
Data type	Gridded
Horizontal coverage	Global
Horizontal resolution	0.75°x0.75°
Vertical coverage	Surface, total column, model levels and pressure levels.
Vertical resolution	60 model levels. Pressure levels: 1000, 950, 925, 900, 850,
Temporal coverage	2003 to 2020
Temporal resolution	3-hourly
File format	GRIB (optional conversion to netCDF)
Versions	Only one version
Update frequency	Twice a year with 4-6 month delay

CAMS global reanalysis (CAMSRA, eac4)

- 2003 –2022, with new years being added
- Aerosols, chemical pollutants, CO_2 & CH_4
- 80 km spatial resolution
- Inness et al. (2019): https://doi.org/10.5194/acp-19-3515-2019
- Wagner et al. (2021): https://doi.org/10.1525/elementa.2020.00171
- atmosphere.copernicus.eu/eqa-reports-global-services
- Available from ADS https://atmosphere.copernicus.eu/data

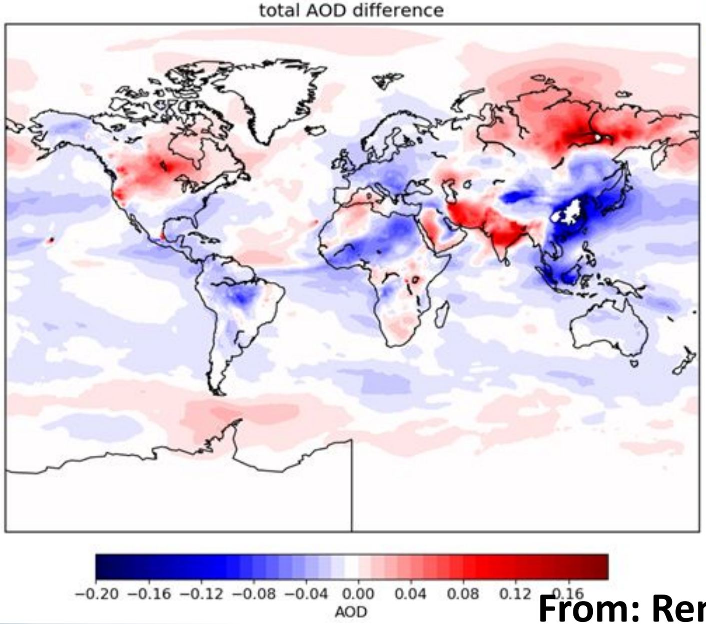
- CB05 tropospheric chemistry
- Cariolle-Déqué scheme for stratospheric ozone
- Interactive prognostic O3 and AER

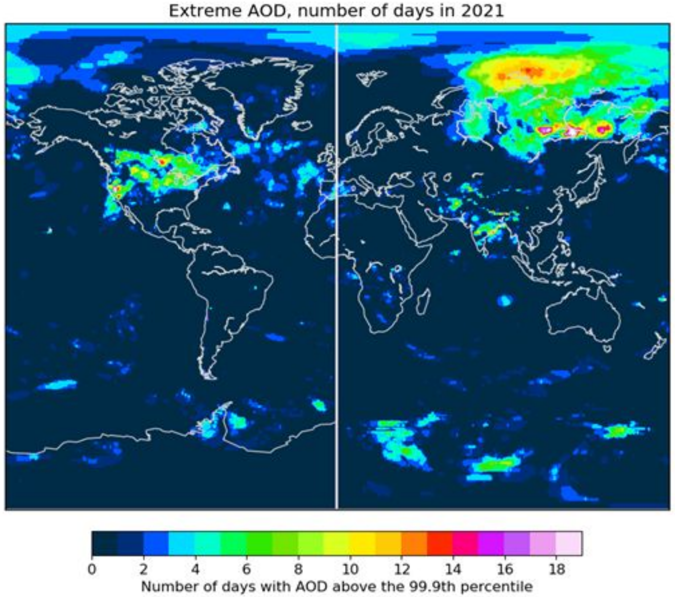
Commission

Aerosol anomalies and extremes in 2021

Atmosp[...]
Monit[...]

Aerosol Optical Depth anomalies calculated against the 2003-2020 annual means from the CAMS reanalysis





Number of days in 2021 with extremely high AOD (extreme being defined as above the local 2003–2020 99.9th percentile).

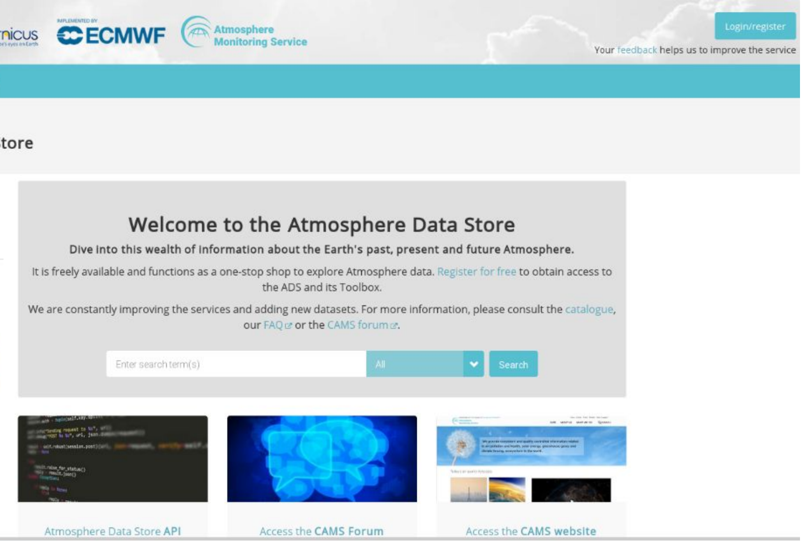
The exceptional fires over parts of Siberia, U.S. and Canada, as well as their downstream plumes over the Arctic ocean and Eastern U.S. are clearly visible.

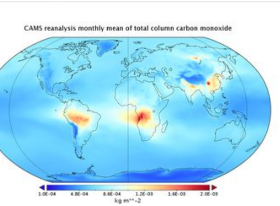
From: Remy et al, Aerosols, BAMS State of Climate in 2021

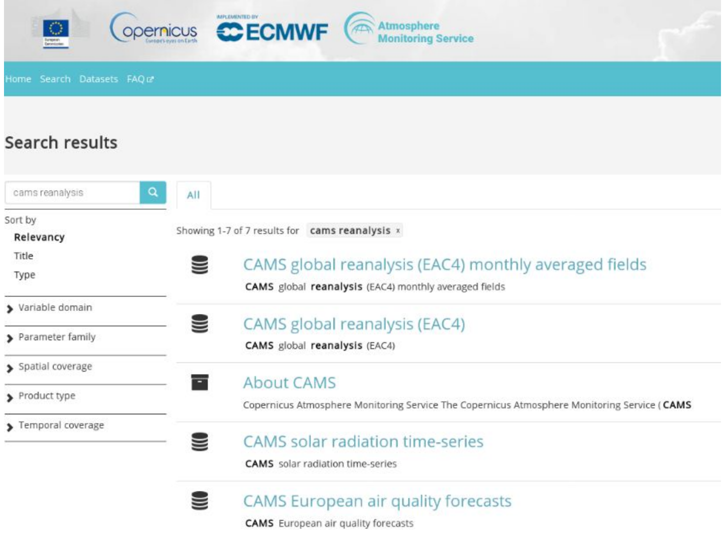
The Atmosphere Data Store (ADS)

Atmosphere Monitoring

All CAMS data are freely available https://atmosphere.copernicus.eu/data







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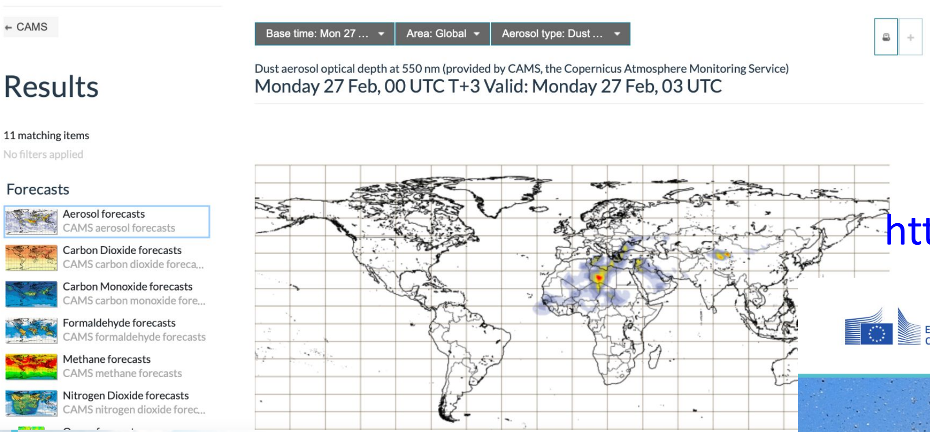
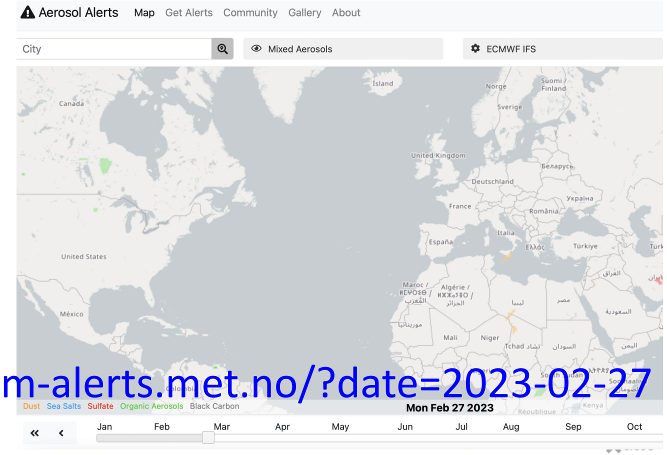
CAMS charts and news bulletins

Aerosol forecasts

https://atmosphere.copernicus.eu/charts/cams





https://aerocom-alerts.met.no/?date=2023-02-27

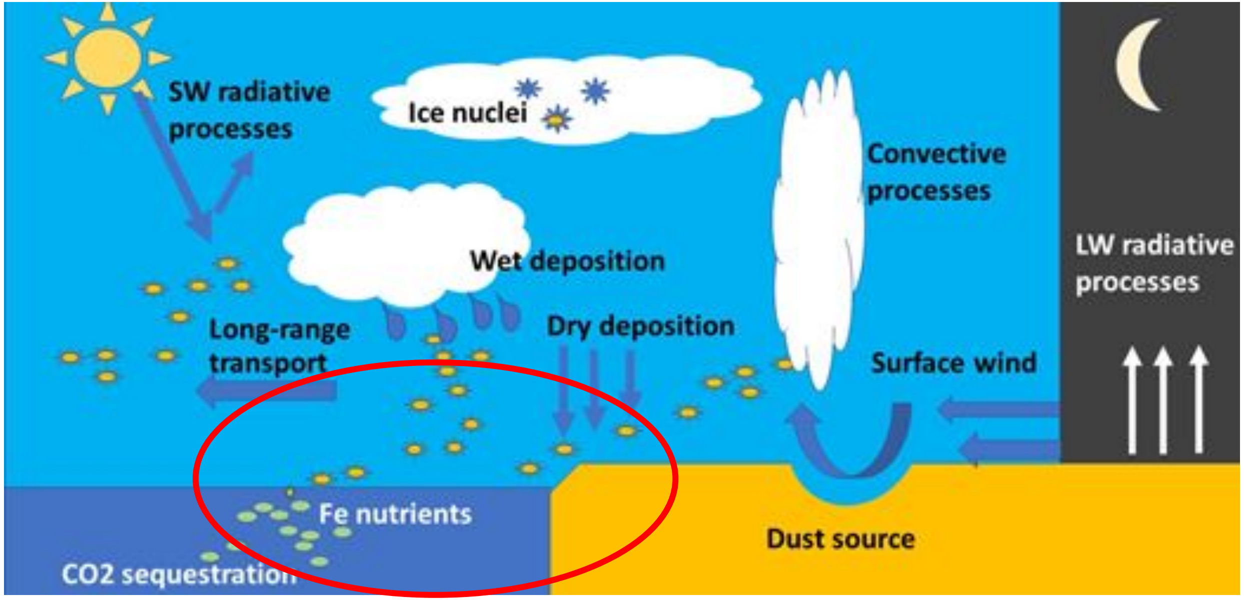
https://atmosphere.copernicus.eu/cams-monitors-first-saharan-dust-episodes-europe-2023

4. Research aspects

4D-ATLANTIC
Dust & Ocean Modelling and Observing Study (DOMOS)

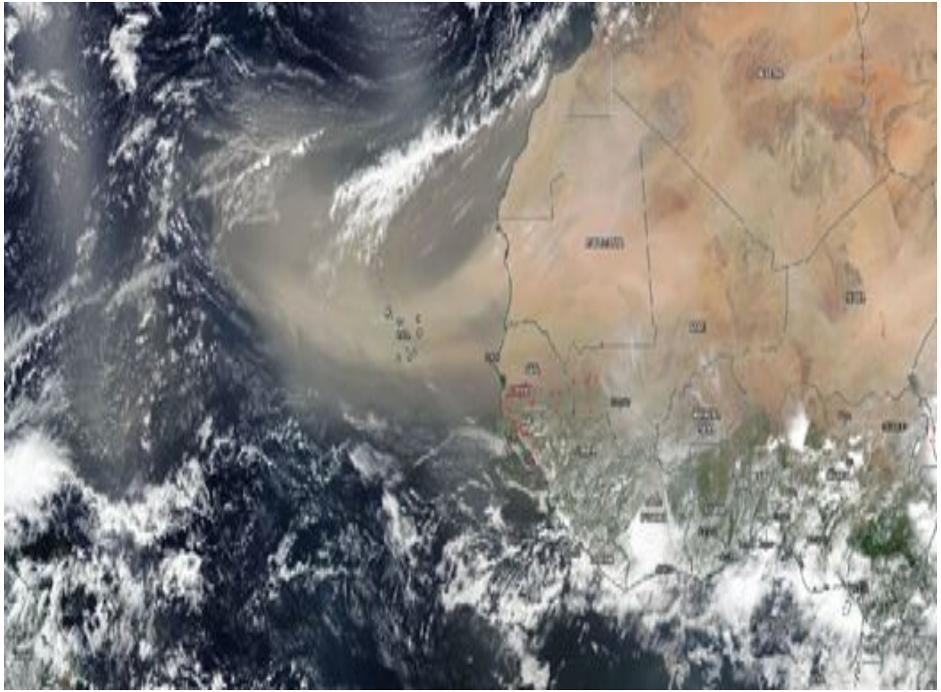
Dust is a key player in the Earth System through its impacts on radiation, clouds and the ocean biogeochemical cycles

DOMOS addresses the dust interactions with the ocean using an **integrated modelling and observing approach**



DOMOS is carried out under a programme of, and funded by, the European Space Agency. The view expressed in this presentation can in no way be taken to reflect the official opinion of the European Space Agency

Science questions



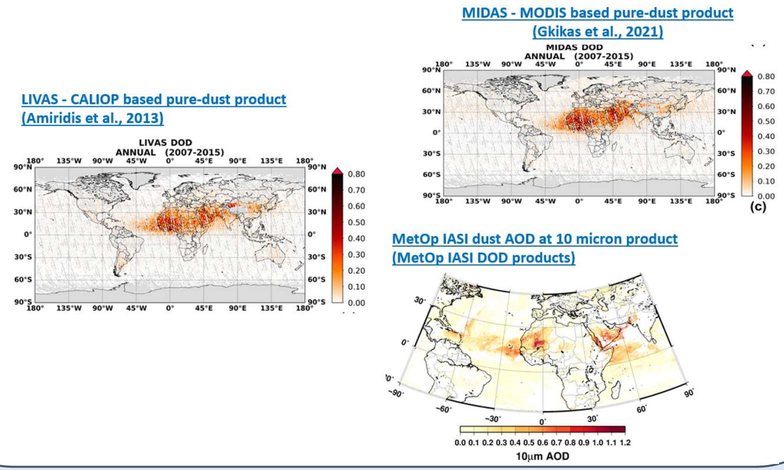
1. To what extent dust deposition over the Atlantic has changed over the last 20 years? Can we identify robust trends in the reanalysis and model datasets and if yes, how can we verify them?

2. What is the contribution of anthropogenic and natural sources of dust compared to biomass burning and anthropogenic aerosols to soluble iron deposition over the Atlantic?

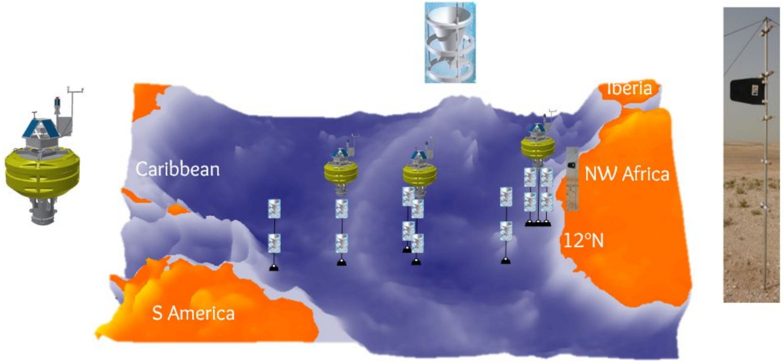
3. What are the impacts of changes in dust deposition on marine biogeochemistry and their potential effects on ecosystems?

DOMOS

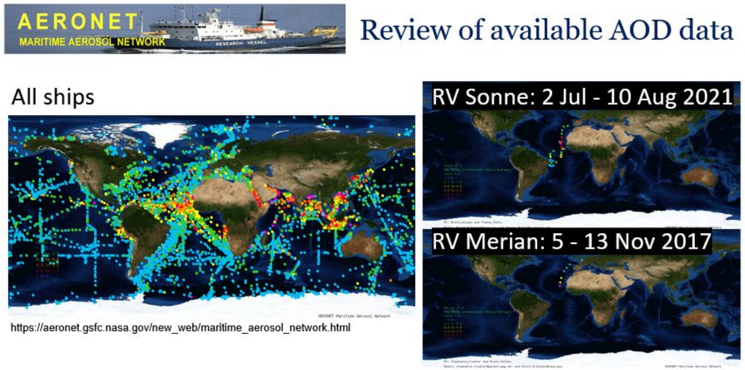
Satellite EO Dust Datasets (NOA)



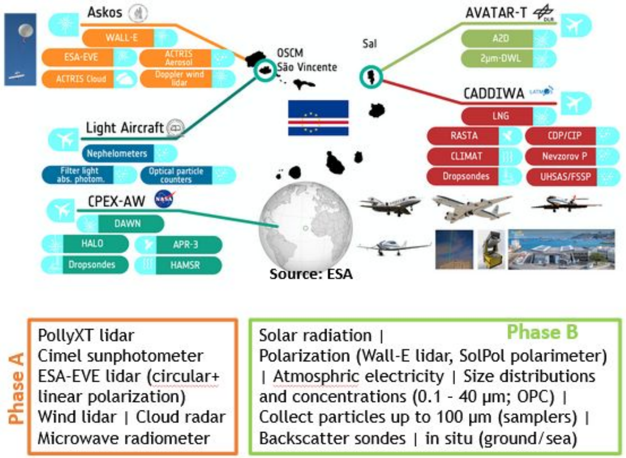
Moored Instruments (NIOZ)



Observations on board vessels (University of Cologne)

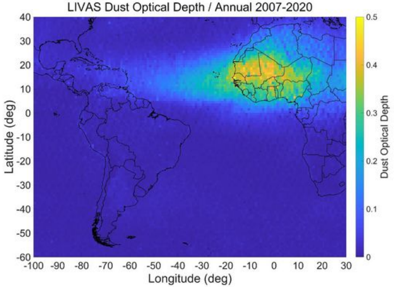


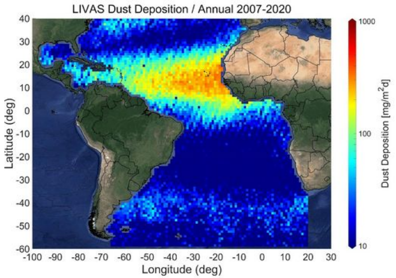
Field campaigns (ASKOS dataset, NOA)



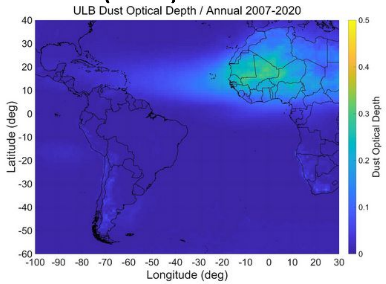
Satellite-derived dust optical depth and deposition products (NOA)- will be publicly released

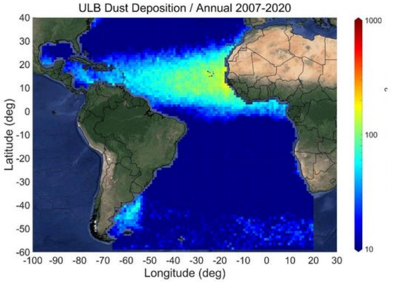
LIVAS (CALIPSO)-derived





ULB (IASI)-derived

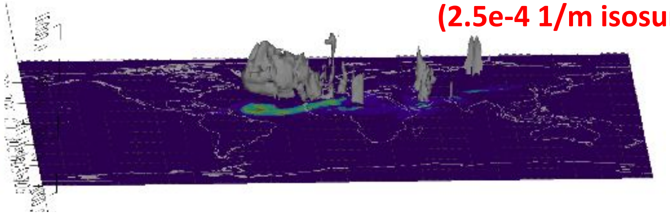




Credits: Manolis Proestakis

LIVAS Dust profile and VIIRS AOD LETKF analysis (BSC)

(2.5e-4 1/m isosurface)

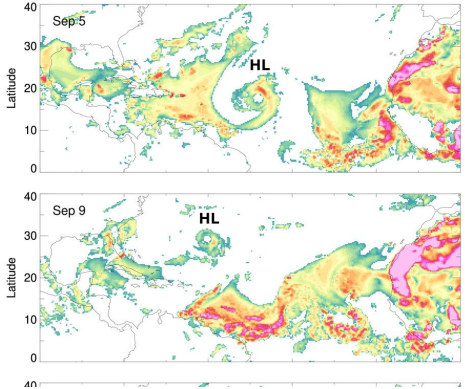


MONARCH analysis of the Godzilla dust event (June 2020)

Credits: Enza Di Tomaso and Jeronimo Escribano

IR Dust AOD 4D-Var analysis (ECMWF)

Credits:
Liam Steele



Dust deposition around hurricane Larry in the CAMS analysis (September 2021)

Dissemination

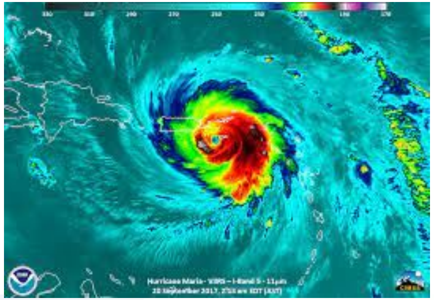
SCIENTIFIC RESULTS

- ✓ Publications
- ✓ Conferences
- ✓ New collaborations

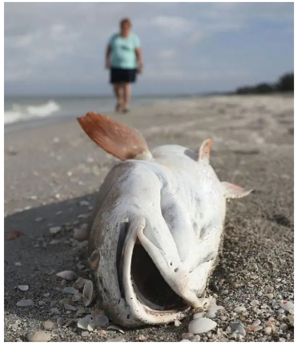
POTENTIAL USER'S APPLICATIONS

- ✓ Risk identification
- ✓ User engagement

Hurricanes prediction



Fisheries



Algae Blooms

CAPACITY BUILDING

- ✓ Training
- ✓ Access data
- ✓ Dissemination - News

esa
European Space Agency

WMO
Barcelona Dust Regional Center

opernicus

- Fill in the Survey to let us know your interest in our project!

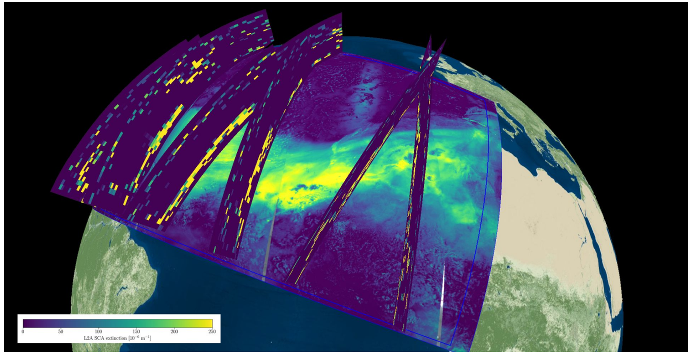
Credits: Sara Basart

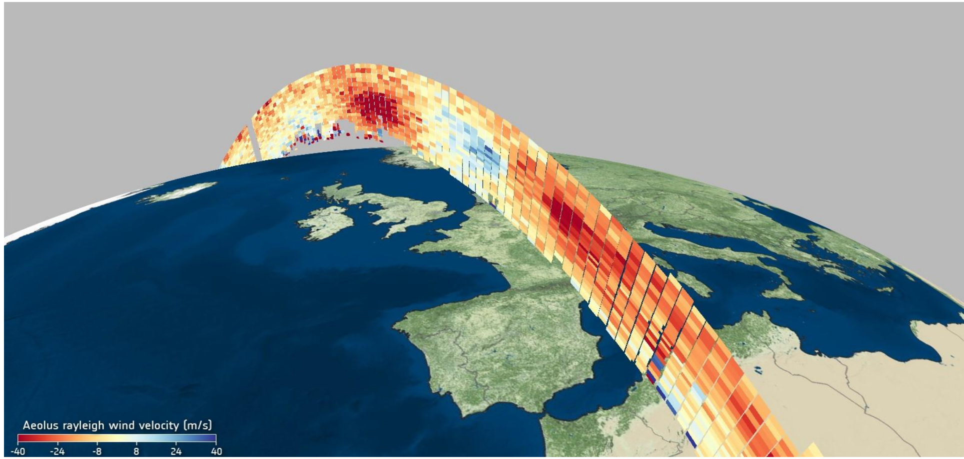
DOMOS

ESA Aeolus Mission

- Launched on 22 August 2018, Aeolus is the first satellite mission to acquire profiles of Earth's wind on a global scale.
- The Aeolus satellite carries a UV Doppler wind lidar (ALADIN) operating at 355 nm to measure winds through the signal backscattered by molecules and particles.

Dust plume seen from Aeolus and S5P





Wind profiles from Aeolus

NRT monitoring of the Aeolus L2A particle backscatter product

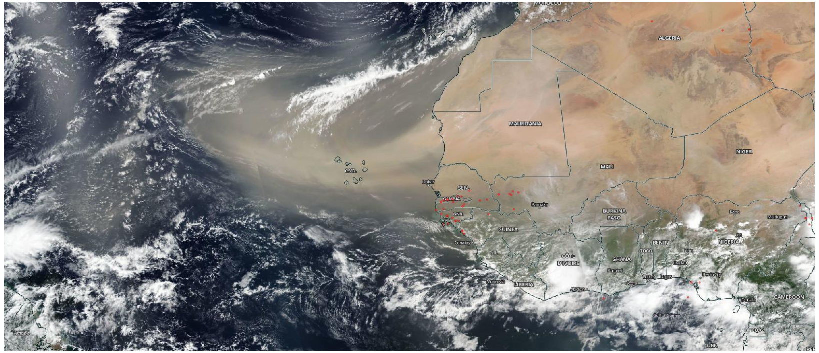
https://www.theguardian.com/science/2018/aug/23/satellite-aeolus-launched-space-map-earth-winds

- The HLOS wind product has been assimilated since January 2020 at ECMWF
- Since January 2022, NRT monitoring of the L2A particle backscatter (spin-off product) has been carried out under ESA funding
- The particle backscatter is processed into IFS-COMPO, and compared with the value calculated by the forward model operator (monitoring).
- Assimilation is also carried out, to measure the effect on the short-range aerosol optical depth (AOD) forecast, compared to the CAMS operational product

Credits: Will McLean (ECMWF)

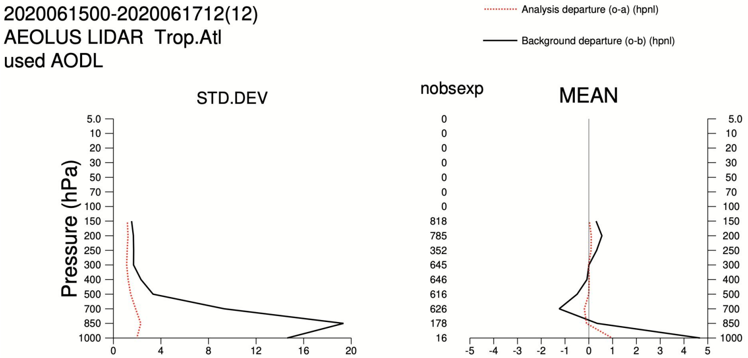
June 2020 “Godzilla” dust event: impact of Aeolus L2A on Aerosol Optical Depth forecast

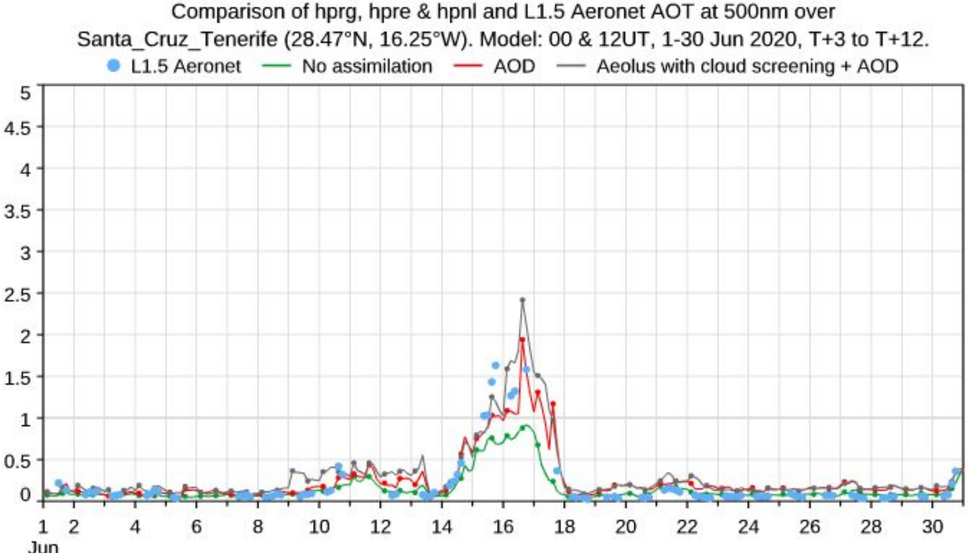
Credits: Will McLean (ECMWF)



NASA Suomi NPP/VIIRS visible image of Saharan dust over the tropical Atlantic region on 17 June 2020 (from NASA Worldview)

Vertical profiles of the Aeolus L2A backscatter over the tropical Atlantic region for June 15-17. The black line shows the first guess departures, clearly showing Aeolus measurements place the plume height differently than the model first guess.





M-RAN

AERONET measurements vs model AOD forecast for June 2020 The red curve is CAMS, and CAMS+Aeolus L2A is the grey. Results with no aerosol assimilation are shown in green.

Atmosphere Monitoring

Summary

- 4D-Var data assimilation methodology
- CAMS operational system, observations used and some of the difficulties of doing data assimilation with respect to dust and aerosols
- Reanalyses and how these can be used, e.g. AOD anomalies
- New research challenges: constraining dust optical depth and dust deposition using novel observations (i.e. lidar profiles, IR dust optical depth, etc).

Atmosphere Monitoring

THANK YOU FOR YOUR ATTENTION!

Any questions?