



Dust forecasts and reanalyses



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Emanuele Emili





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- Mineral dust reanalyses
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Operational dust forecasts

Why mineral dust forecasts?



800+ flights canceled due to Saharan dust storm (*Calima*) in the Canary Islands (Feb 2020)



1,000+ hospitalizations in a single dust storm event (Iraq, May 2022).



Unprecedented collapse in Spain's solar power generation on March 15 2022 (70–80% reduction nationwide).

More on impacts at <https://cost-indust.eu/media-room/resources>



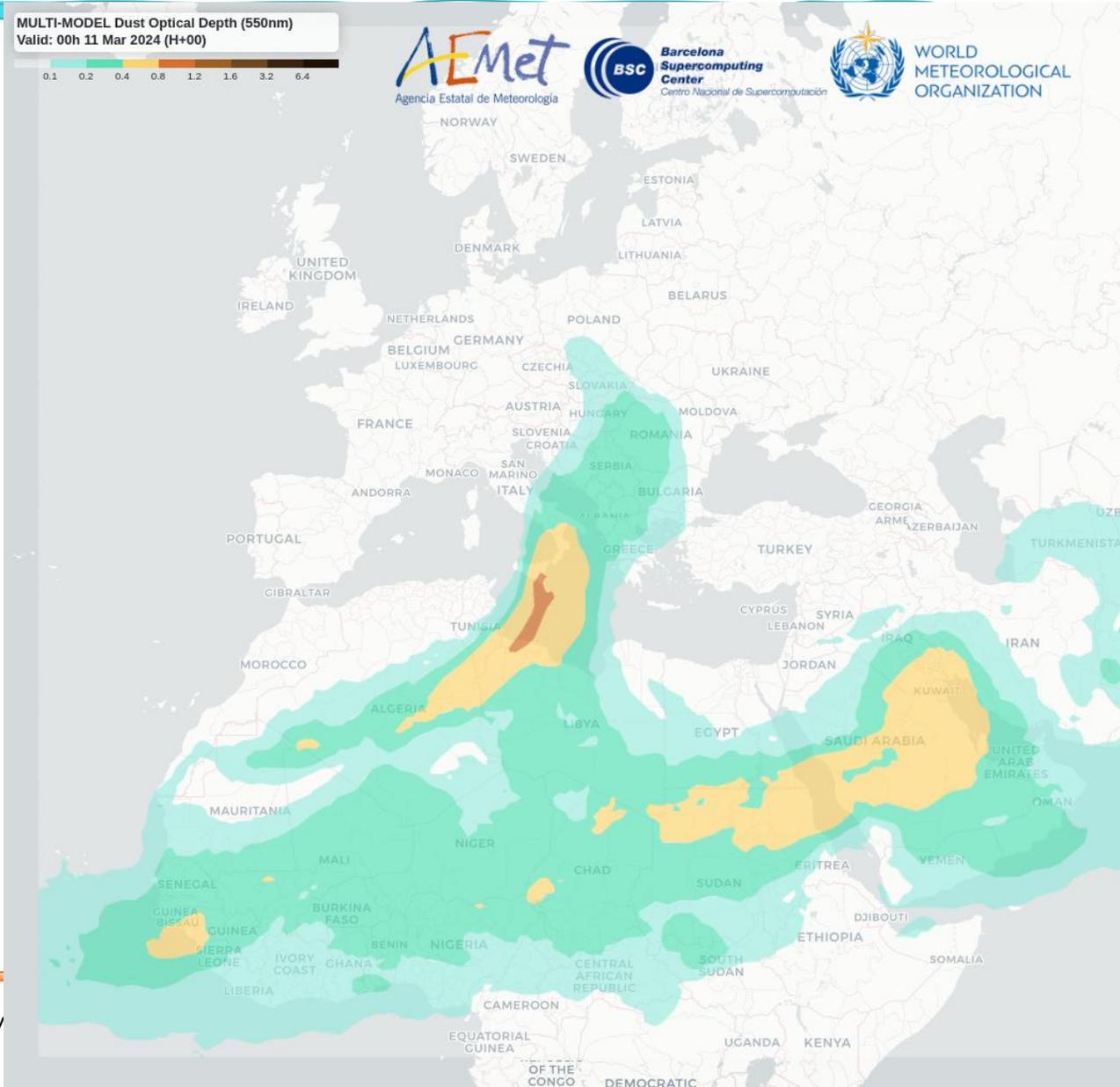
WMO SDS-WAS

WMO Sand and Dust Storm Warning Advisory System (SDS-WAS)

The mission: to enhance the ability of WMO Members to deliver timely and quality sand and dust storm forecasts with a **lead time of 3 days**

Four regional nodes:

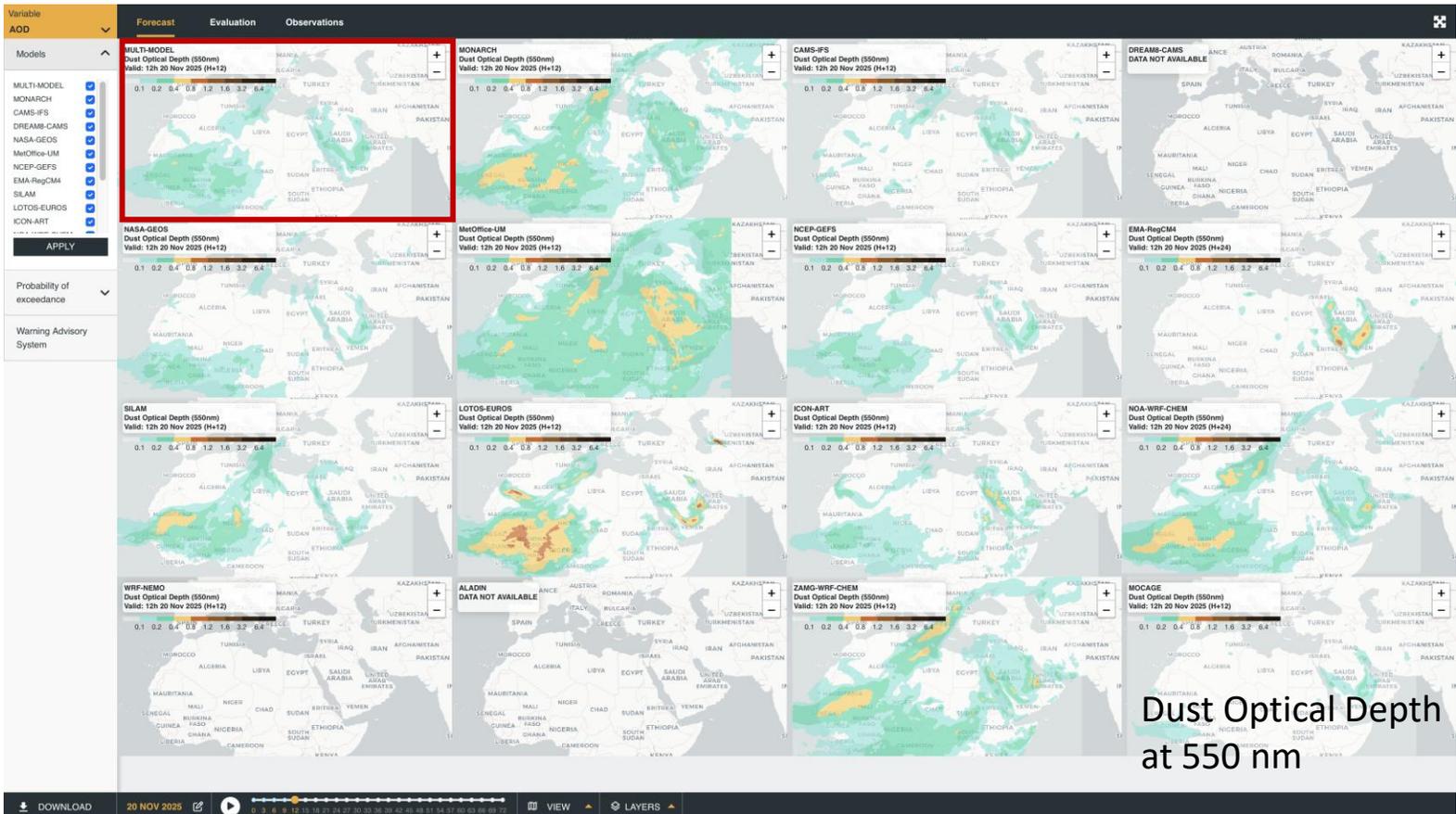
- Asian Regional Node (Beijing, China)
- **North Africa, Middle East and Europe (NAMEE) Regional Node (AEMET and BSC)**
- Pan American Regional Node (Barbados)
- Gulf Cooperation Council (GCC) Regional Node (Jeddah)



BDRC: Multi-model forecasts

Barcelona Dust Regional Center: dust.aemet.es

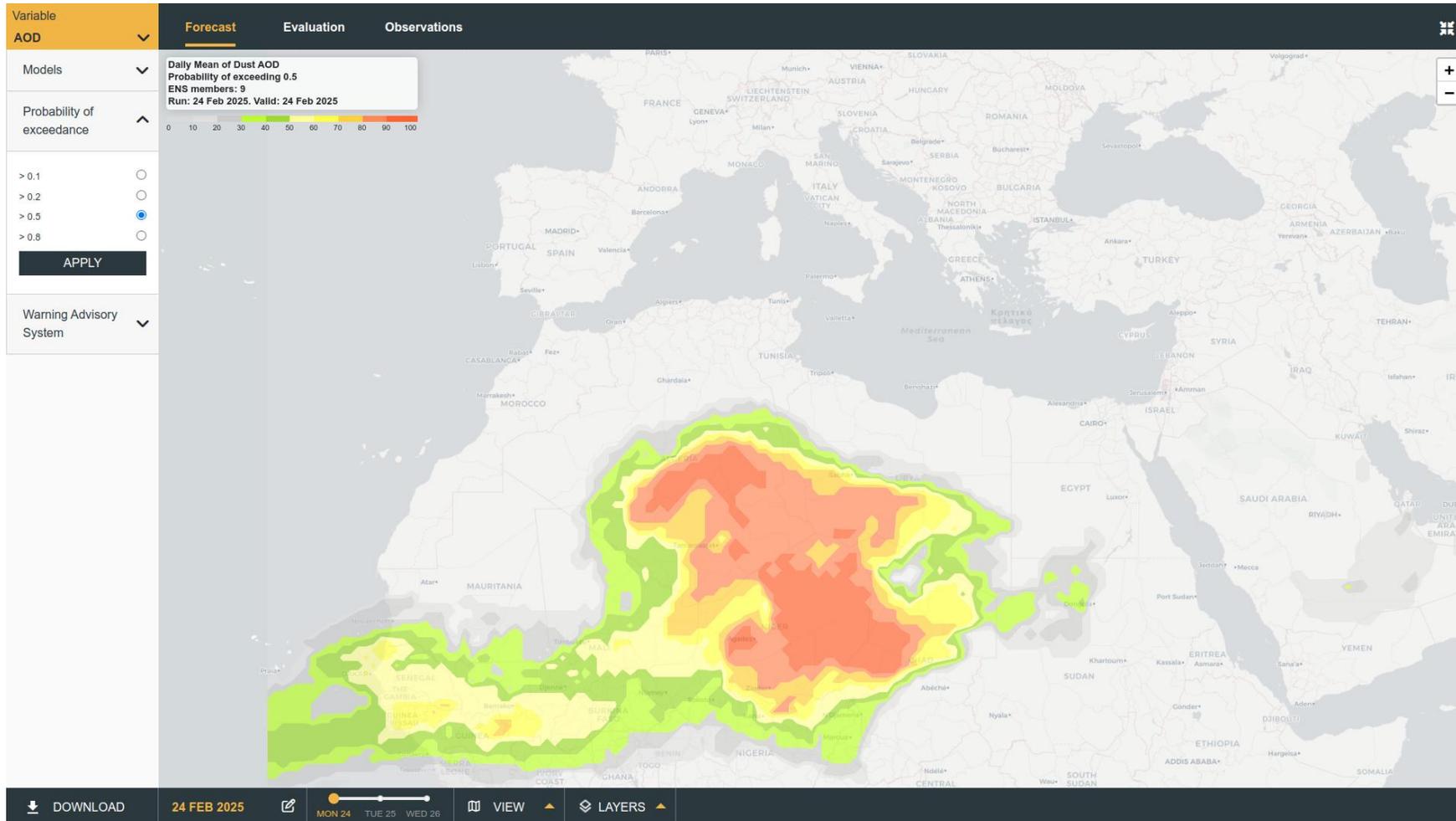
Model	Institution	Contact person	Reference publications	Data Policy	Period available
ALADIN	Météo Algérie	Abdenour Ambar	Termonia et al., 2018 Mokhtari et al., 2012	CCBY 4.0	20190910 - now
BSC-DREAM8b	BSC	Carlos Pérez García-Pando	Nickovic et al., 2001 Pérez et al., 2006 Basart et al., 2012	CCBY 4.0	20100330 - 20220929
CAMS-IFS	ECMWF	Melanie Ades	Rémy et al., 2022	CCBY 4.0	20101012 - now
DREAM8-CAMS	SEEVCCC	Goran Pejanovic	Pejanovic et al., 2010 Nickovic et al., 2016	CCBY 4.0	20111114 - now
EMA RegCM4	EMA	Ashraf Zahey	Zahey et al., 2006	CCBY 4.0	20140504 - now
ICON-ART	DWD	Vanessa Bachmann	Rieger et al., 2015	CCBY 4.0	20190628 - now
LOTOS-EUROS	TNO	Astrid Manders-Groot	Manders et al., 2017	CCBY 4.0	20160928 - now
MetOffice-UM	UK MetOffice	Melissa Brooks	Mulcahy et al., 2014	-	20120522 - now
MOCAGE	MétéoFrance	Vincent Guidard	El Amraoui et al., 2022	CCBY 4.0	20220511 - now
MONARCH	BSC	Carlos Pérez García-Pando	Pérez et al., 2011 Klose et al., 2021	CCBY 4.0	20120214 - now
MULTI-MODEL	AEMET	Ernest Werner	Basart et al., 2019	CCBY 4.0	20120120 - now
NASA-GEOS	NASA	Arlindo da Silva	Colarco et al., 2010	CCBY 4.0	20120701 - now
NCEP-GEFS	NCEP	Jun Wang	Lu et al., 2016	CCBY 4.0	20121008 - now
NOA-WRF-CHEM	NOA	Emmanouil Flaounas	Flaounas et al., 2017	CCBY 4.0	20151001 - now
SILAM	FMI	Mikhail Sofiev	Sofiev et al., 2015	CCBY 4.0	20160314 - now
WRF-NEMO	AUTH	Serafim Kontos	Kontos et al., 2021	CCBY 4.0	20201003 - now
ZAMG-WRF-CHEM	ZAMG	Barbara Scherllin-Pirscher	LeGrand et al., 2019	CCBY 4.0	20220521 - now



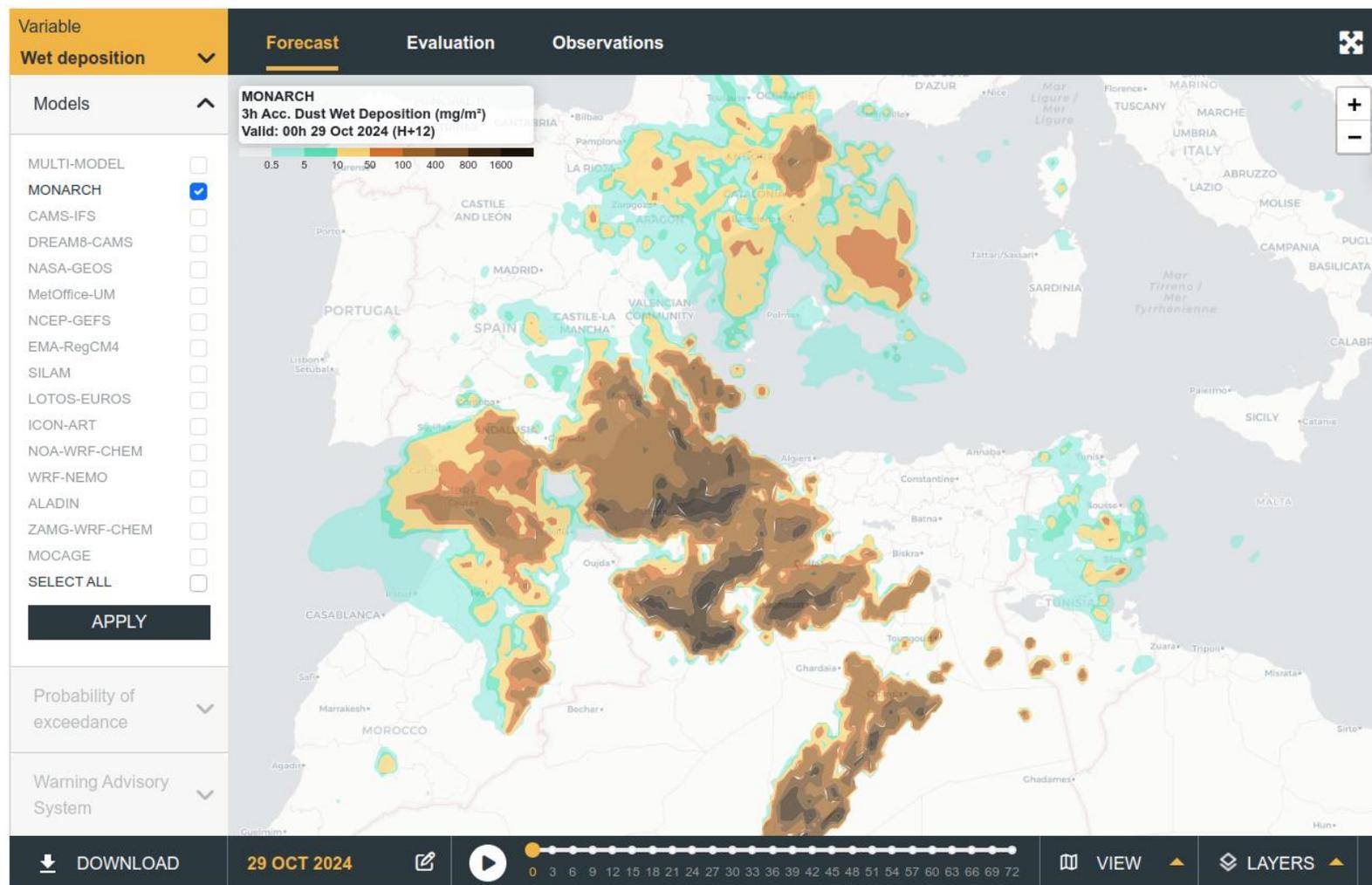
Dust Optical Depth at 550 nm



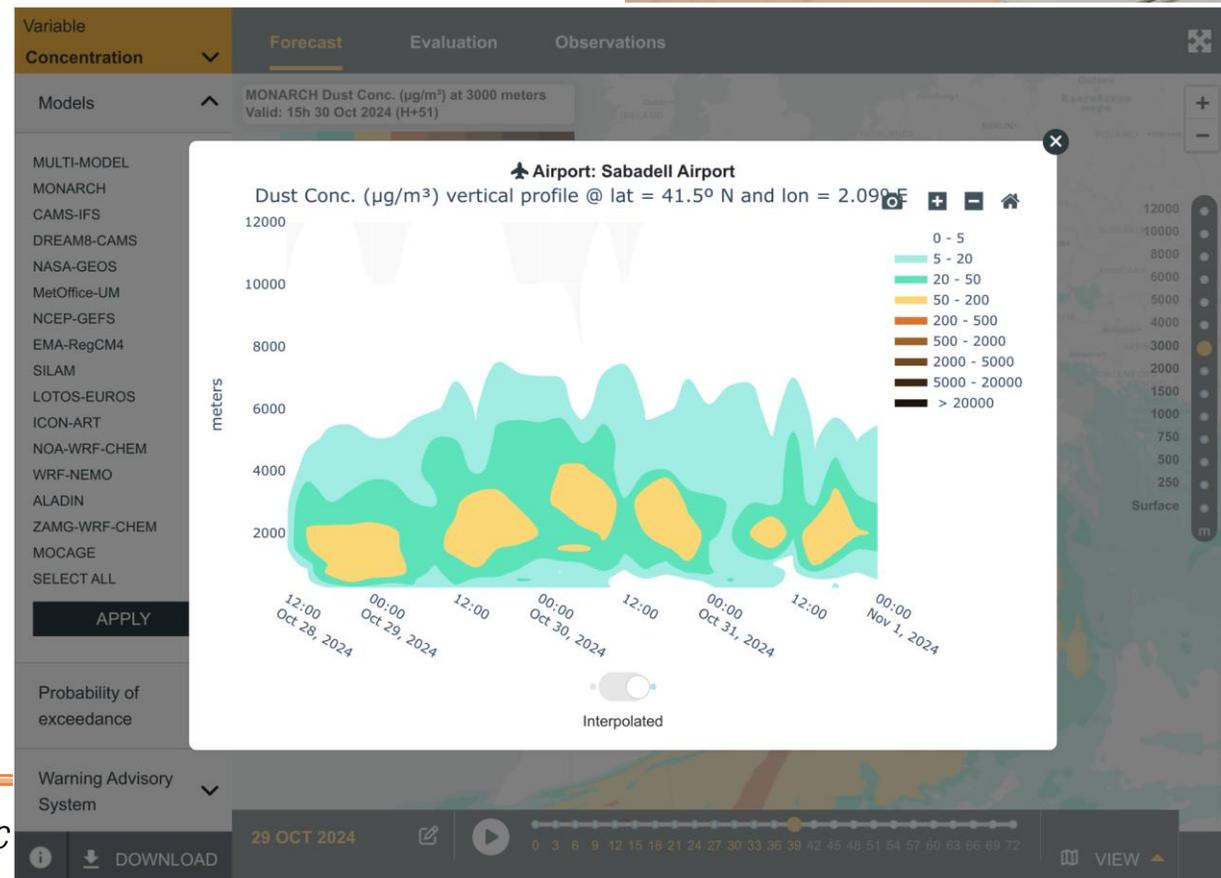
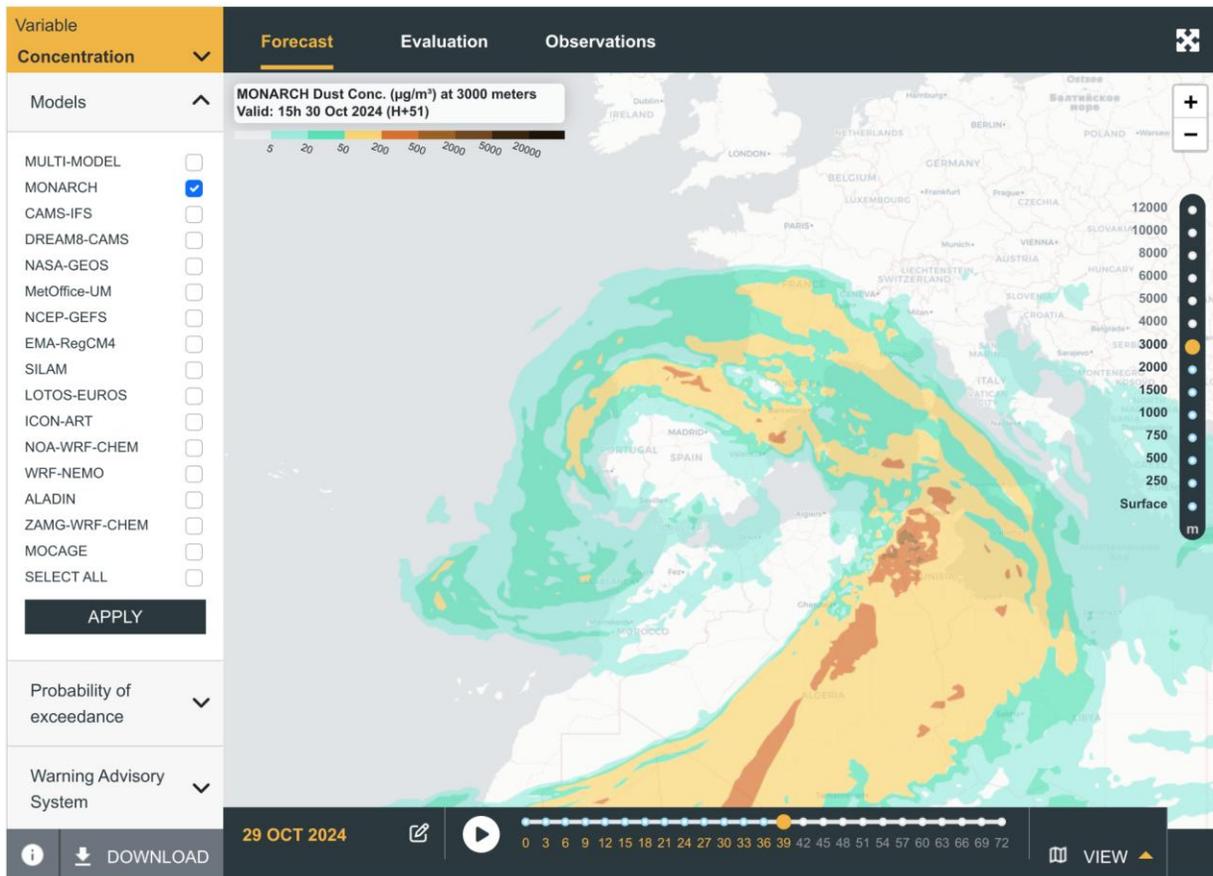
Probabilistic forecast

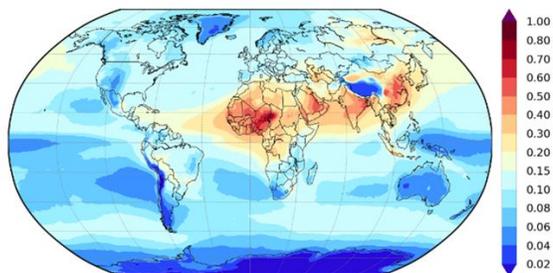


Additional products: deposition

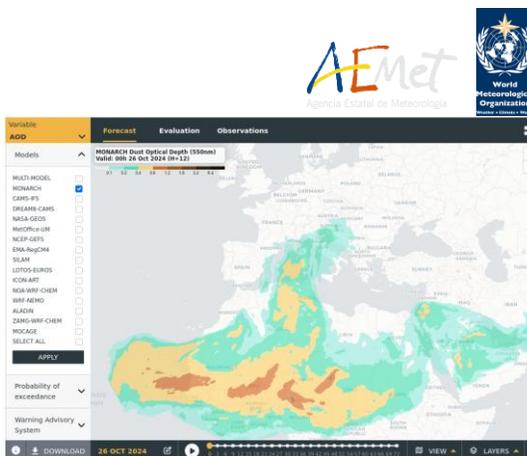


Additional products: vertical layers

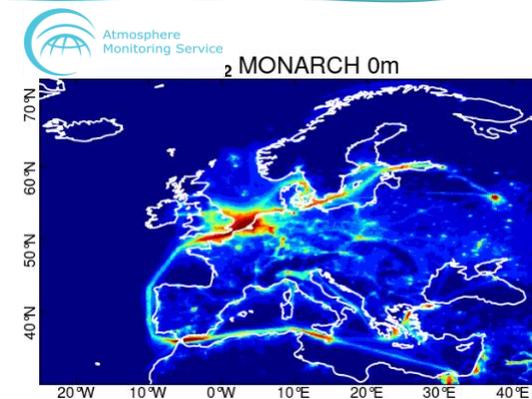




Global aerosols	Configuration
Meteorology	Inline NMMB
Initial condition	GFS 0.5x0.5 deg
Resolution	0.7x0.5 deg
Levels	48
Forecast range	5 days
Output frequency	3 hours
Species	Dust, Sea Salt BC, OC (POA,SOA) Sulfate, Ammonium, Nitrate
Size Bins	8 (dust, salt), 3 nitrate, bulk BC, OA, ammonium, sulfate
Chemistry	CB05 plus chlorine chemistry, Fast-J photolysis
Antho. & Biogenic Emission	CAMS-GLOB-ANTv4.2 (anthro) HTAPv2 (aviation), MEGANv2.04 (biogenic)
Bio. Burn. Emissions	GFAS (daily)



SDS-WAS	Configuration
Meteorology	Inline NMMB
Initial and boundary conditions	GFS 0.5x0.5 deg
Resolution	0.1x0.1 deg
Levels	40
Forecast range	3 days
Output frequency	3 hours
Species	Dust
Size Bins	8
Antho. & Biogenic Emission	NA
Bio. Burn. Emissions	NA

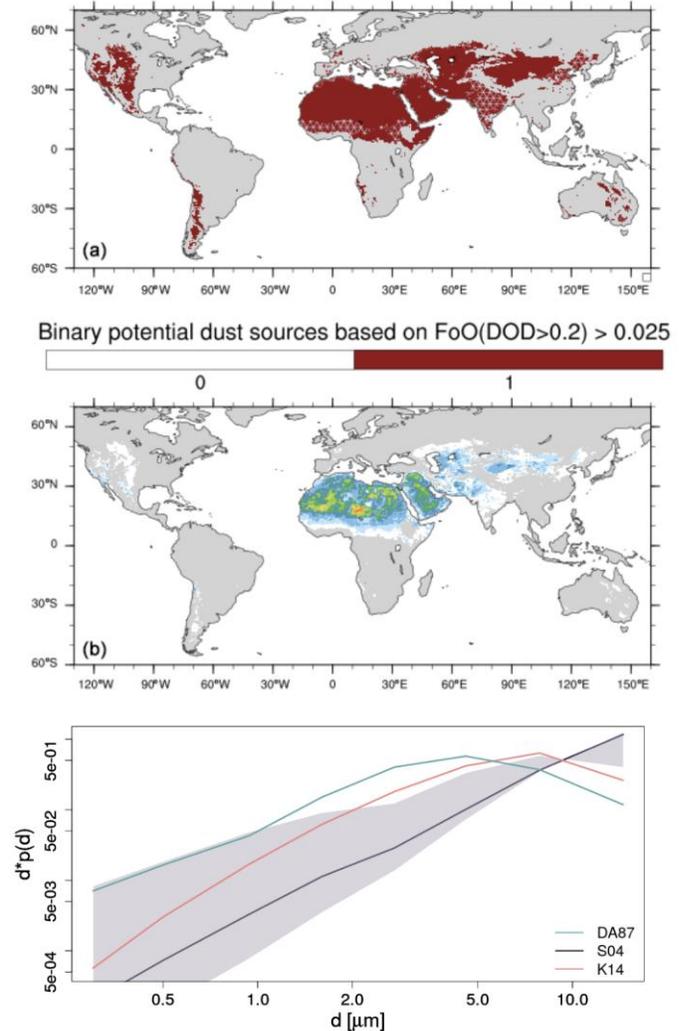


CAMS regional	Configuration
Meteorology	Inline NMMB
Initial and boundary conditions	IFS and CAMS GLOB
Resolution	0.15x0.15 deg
Levels	24
Forecast range	4 days
Output frequency	hourly
Species	Dust, Sea Salt BC, OC (POA,SOA) Sulfate, Ammonium, Nitrate
Size Bins	8 (dust, salt), 3 nitrate, bulk BC, OA, ammonium, sulfate
Chemistry	CB05 plus chlorine chemistry, Fast-J photolysis
Antho. & Biogenic Emission	CAMS-REGv6.1 (anthro), MEGANv2.04 (biogenic)
Bio. Burn. Emissions	GFAS (hourly)

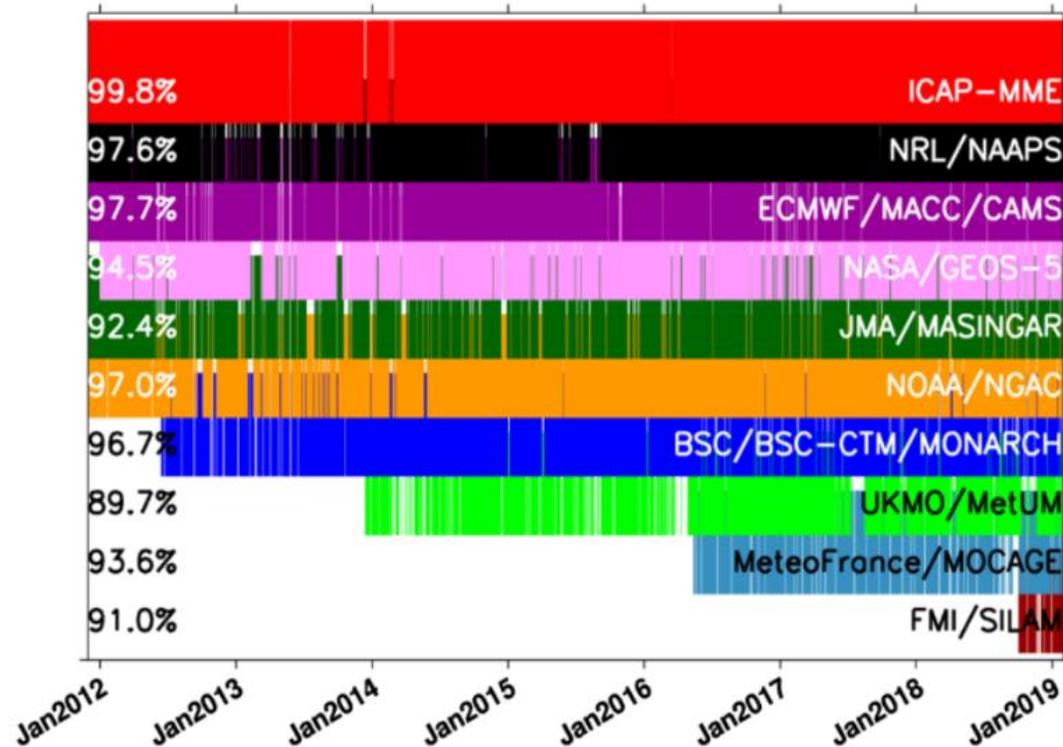
MONARCH dust forecast setup

- 8 dust bins (0.2-20 μm)
- MODIS DB C6 based foO (climatology) derived at 0.1 degrees from Ginoux (2012)
- Standard desert mask based on monthly vegetation fraction Based on MODIS C5 monthly LAI climatology
- Emitted size distribution from Kok (2011)
- GOCART dust emission scheme from Ginoux (2001) updated with friction velocity
- OPAC tri-axial spheroids extinction coefficients
- Online interaction between dust and radiation

Klose et al (2020)



The **International Cooperative for Aerosol Prediction (ICAP)** is a grassroots community of model developers, data providers, and NWP center reps founded in 2010 and focused on global, near real-time aerosol prediction (up to 5 days)



Xian, P. et al. (2019). Current state of the global operational aerosol multi-model ensemble: An update from the International Cooperative for Aerosol Prediction (ICAP) Quarterly Journal of the Royal Meteorological Society <https://dx.doi.org/10.1002/qj.3497>



ICAP models

Courtesy of J. Reid (ICAP 2024)

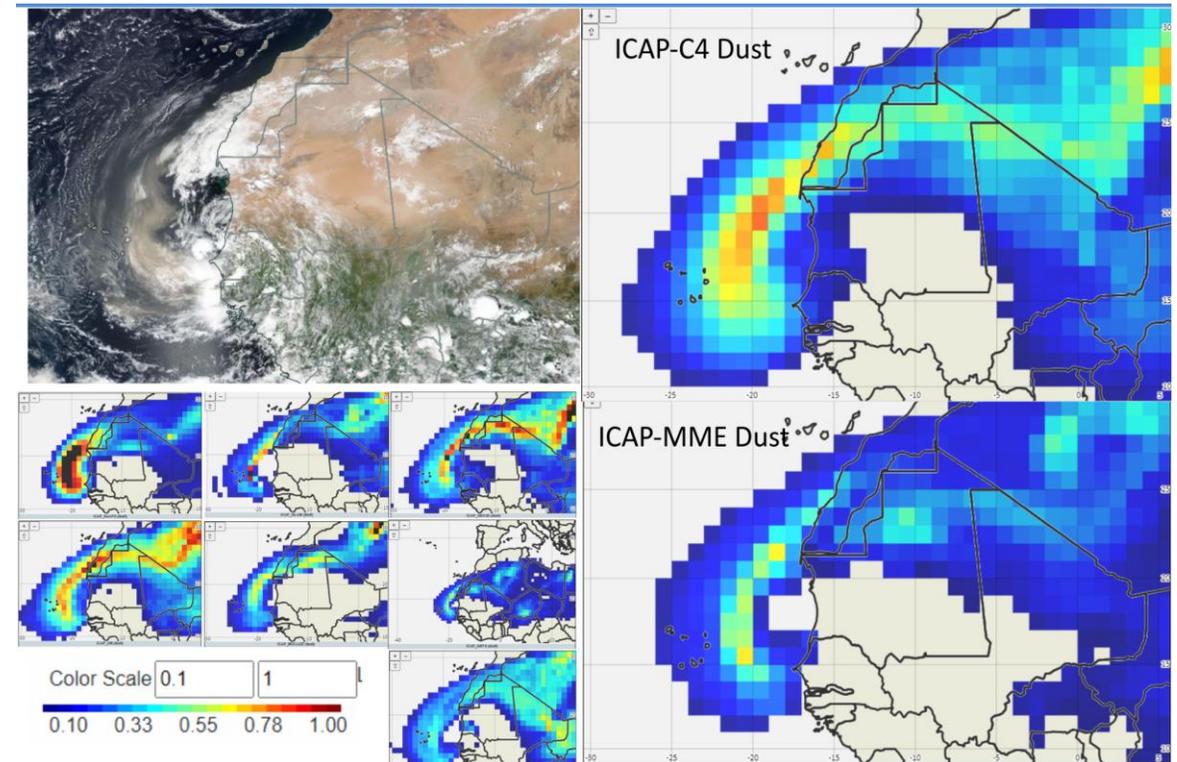
U.S. NAVAL RESEARCH LABORATORY

CURRENT ICAP OPERATIONS: Highlighted are those with reanalysis

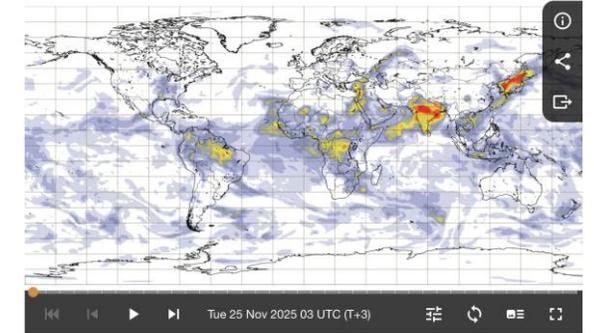
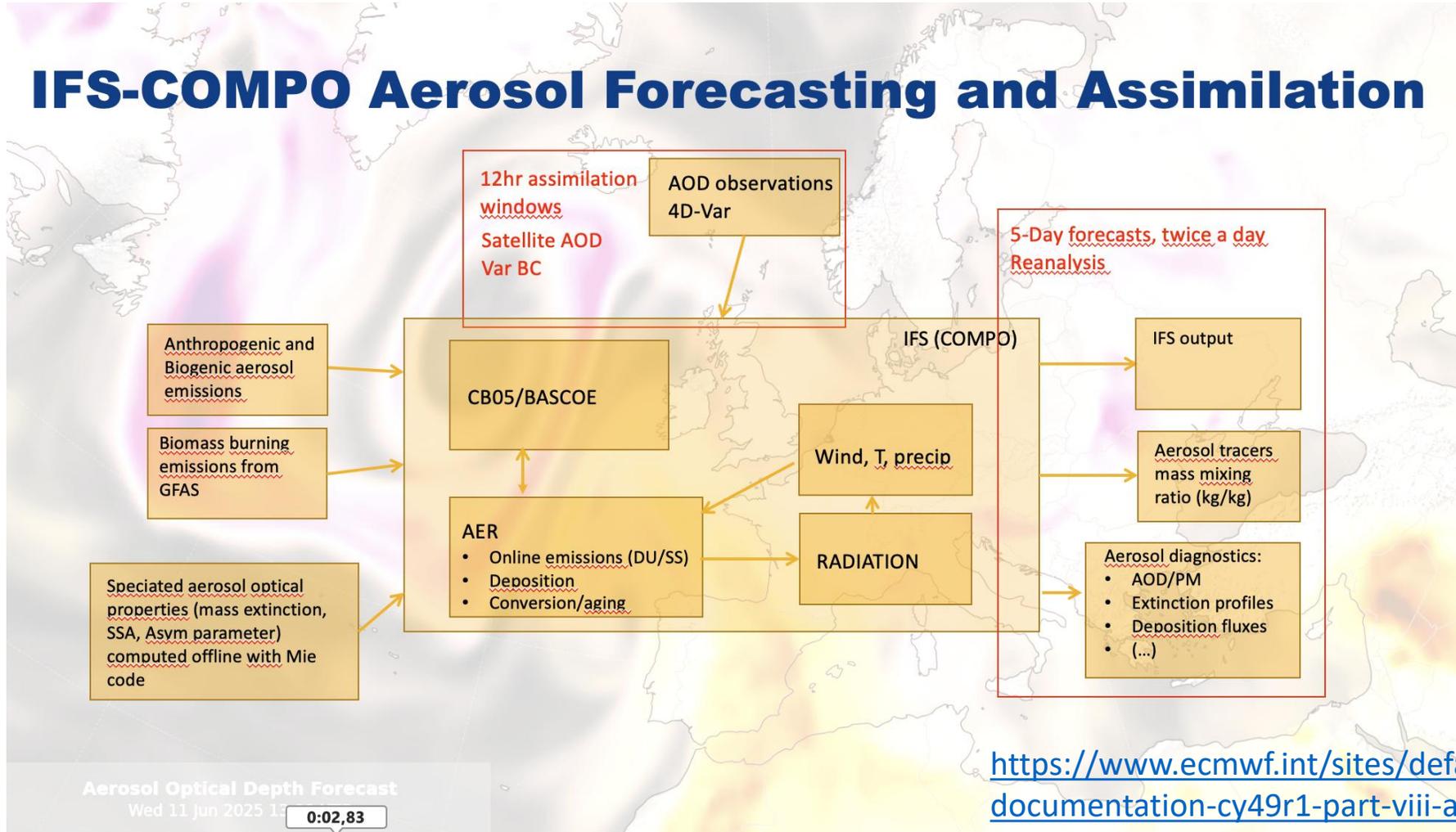
Organization	BSC	Copernicus/ECMWF	JMA	Meteo France	NASA	US Navy	NOAA	FMI	UKMO
Model	MONARCH	CAMS	MASINGAR	MOCAGE	GEOS-5	NAAPS	NGAC/FV3GFS-Chem	SILAM	MetUM
Status	QO	0-24 hrs	QO	O	QO	O	O	O	O
Meteorology	Inline NMMB	Inline IFS	inline AGCM	Offline ARPEGE	Inline GEOS-5	Offline NAVGEM	Inline GFS/FV3GFS	Offline IFS	Inline UM
Resolution	0.7x0.5	0.4x0.4	0.375x0.375	1x1	0.25x0.31	0.33x0.33	1x1/0.25	0.5x05	0.35x0.23
levels	48	137	40	47	72	60	64	60	70
DA	LETKF ^P	4DVar	2DVar LETKF ^P	2018	2DVar +LDE	2DVar 3DVar, EnKF ^P	NA	3Dvar ^P , 4Dvar ^P , EnKF ^P	4DVar
Assimilated Obs	NA	DAQ MODIS DT+DB PMAp	MODIS L3, AHI ^P , CALIOP ^P	NA	Neural Net MODIS	DAQ MODIS, AVHRR ^P , VIIRS ^P , CALIOP ^P	NA	NA	MODIS Dust AOT
Species	Dust, Sea Salt BC, OC (POA,SOA) Sulfate, Nitrate, Ammonium	BC, OC Dust, Sea Salt Sulfate, Nitrate, Ammonium	BC, OC Dust Sea Salt Sulfate	BC, OC Dust Sea Salt Sulfate, Nitrate, Ammonium	BC, OC Dust Sea Salt Sulfate Nitrate	Anthro+bio B. B. Smoke Dust Sea Salt	Dust BC, OC Sea Salt Sulfate	BC, Dust, OC, Sea Salt, Sulfate, Nitrate, B.B. Smoke	Dust
Size Bins	8 (dust, salt), 6 (OM), 2(BC), 3(NI), bulk sulfate and ammonium	3 (dust, salt), bulk for others	10 (dust, salt), bulk for others	6	5 (dust, SS), 2(BC, OC), 3(NI*), bulk sulfate	bulk	5 (dust, SS), 2(BC, OC), bulk sulfate	4 (dust), 5 (SS), 3 (B.B. Smoke), 2 (sulfate), bulk for others	2
Antho. & Biogenic Emission	CAMS-GLOB v4.2 (anthro), MEGANv2.04 (biogenic)	MACCity (anthro), MEGAN (biogenic)	MACCity	MACCity (anthro.) MEGAN-MACC (biogenic)	EDGAR V4.1/4.2, AeroCom Phase II, GEIA	MACCity, BOND, POET	EDGAR V4.1+CEDS AeroCom Phase II, GEIA	MACCity, STEAM, MEGANE, HTAP(Coarse PM)	NA
Bio. Burn. Emissions	GFAS	GFAS	GFAS	GFAS	QFED	FLAMBE	GBBEPxV2	GFAS, IS4FIRES	NA



- **ICAP Consensus:**
 - – Generated at NRL with ~18 hr latency from 0Z
 - – 8 multi species, +1 dust only global model
 - – Have three consensus aggregations: “Core 4-C4” , all models (ICAP-MME), and dust.
 - – Products: Total, fine, coarse, dust, smoke AOD; PM2.5 and PM10
 - – Data available on <https://usgodae.org/pub/outgoing/nrl/ICAP-MME/> Free to use, just please acknowledge NRL and ICAP contributors



IFS-COMPO Aerosol Forecasting and Assimilation



<https://atmosphere.copernicus.eu/global-forecast-plots>

<https://www.ecmwf.int/sites/default/files/elibrary/112024/81630-ifs-documentation-cy49r1-part-viii-atmospheric-composition.pdf>

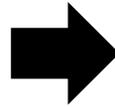
Land & Ocean

EOS-Terra/MODIS

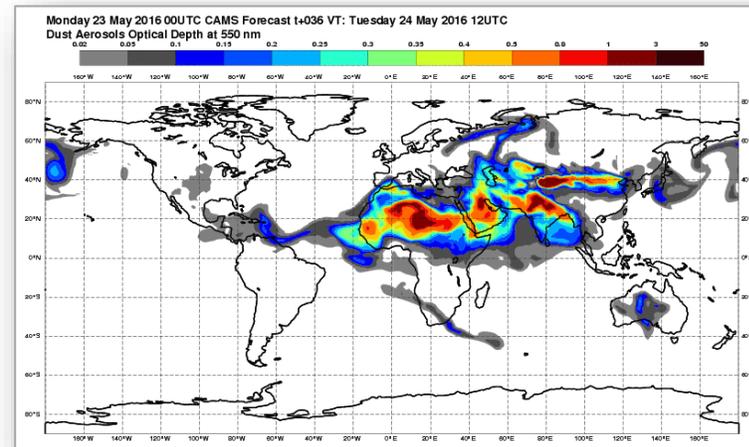
EOS-Aqua/MODIS

S-NPP/VIIRS

NOAA-20/VIIRS



Global CAMS forecasting system



40km Globe (twice daily, d+5)



Ocean only

Metop-C/PMAp

Metop-B/PMAp

Sentinel-3A/SLSTR

Sentinel-3B/SLSTR

<https://www.ecmwf.int/sites/default/files/elibrary/112024/81630-ifs-documentation-cy49r1-part-viii-atmospheric-composition.pdf>



NASA GEOS

Courtesy of P. Colarco (ICAP 2025)



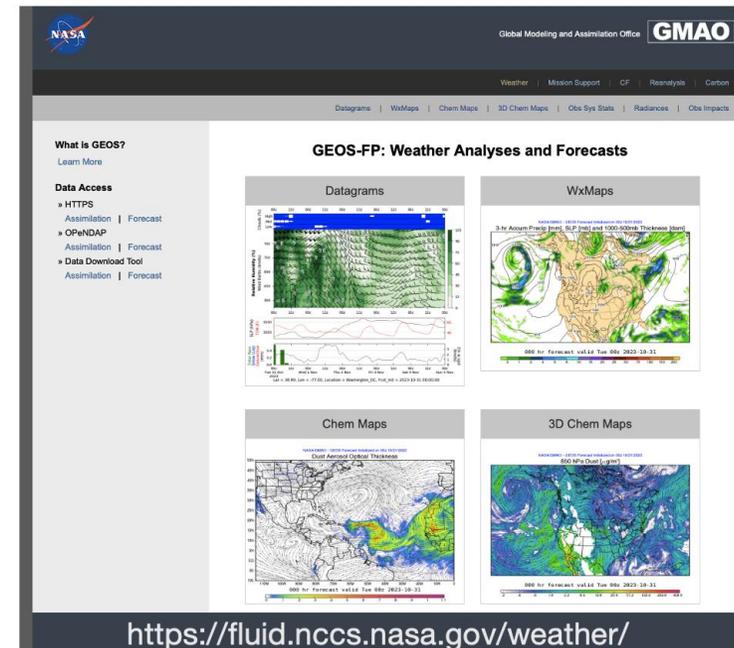
GEOS Products	Purpose	Nominal Resolution	Aerosol DA	Details
GEOS-FP	Weather and aerosol analyses and forecasts	12 km	Y	GOCART
GEOS-CF	Composition forecast with full gas chemistry	25 km	(Y)	GOCART GEOS-Chem
GEOS-S2S	Coupled system for S2S prediction	50 km	(Y)	GOCART
GEOS CCM	Interannual to > decadal aerosols and chemistry	100 km	N	GOCART2G CARMA GMI Chemistry

<https://fluid.nccs.nasa.gov/cf/>





- GEOS near-real time system
- Currently: Version 5.29.5
- ~12 km horizontal, 72 levels to ~80 km
- Legacy GOCART
- Aerosols are inline and radiatively interactive with meteorology
- Assimilation of MODIS NNR and AERONET AOD at 550 nm
- 4x daily forecasts
- This is input to ICAP MME





Ongoing developments



Ongoing developments

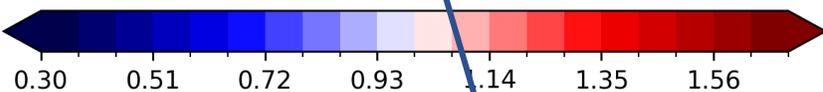
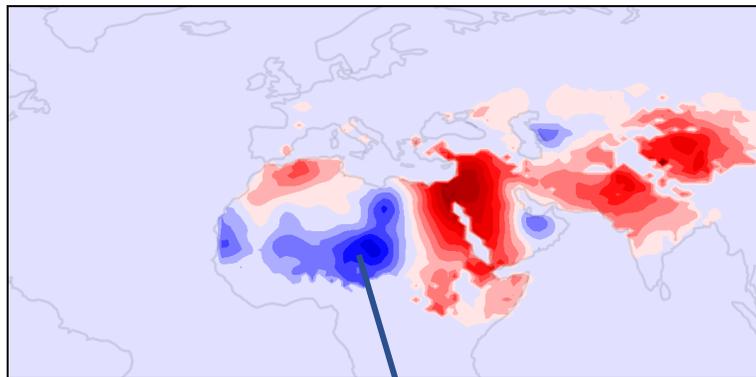
- Transition from MODIS to VIIRS ongoing or already done in most operational centers
- EUMETSAT Sentinels taking over the morning orbit
- Refined particle size distribution, sources function ...
- Infrared (MetOP IASI) and vertically resolved assimilation (EARTHCARE ATLID)



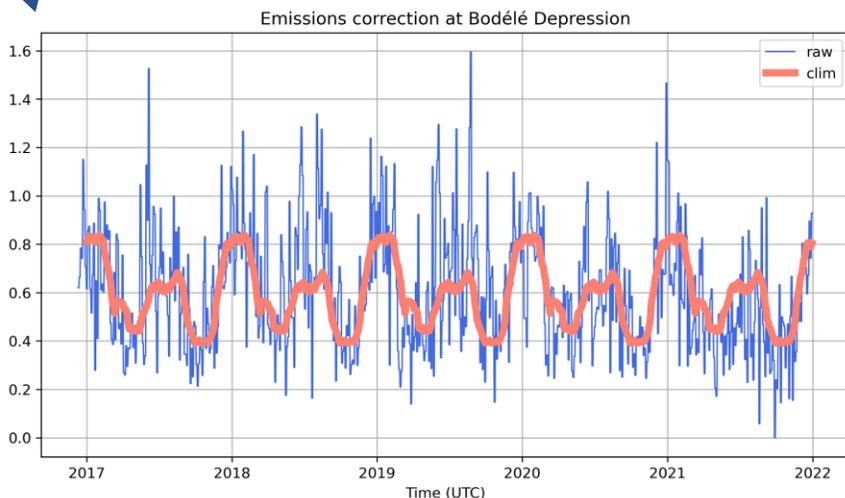
Emissions correction

Oper Forecast (o-suite)
DA Forecast (e-suite)
Satellite emissions

Emissions factors



- Global MONARCH configuration (1x1.4 deg)
- 5 years run (2017-2021)
- Assimilates SUOMI-NPP VIIRS Deep Blue V1 dust flagged AOD
- Ensemble of 100 members
- One emission factor every 3 days

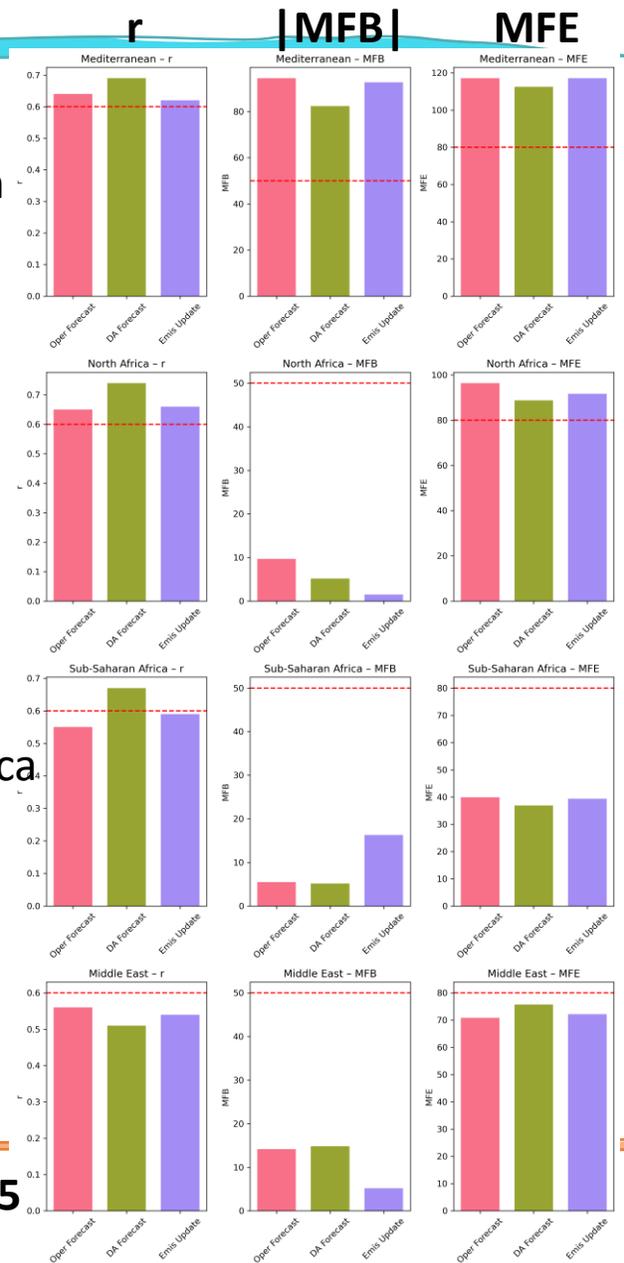


Mediterranean

North Africa

Sub-Saharan Africa

Middle East



October 2024 - March 2025



AIFS for NWP

AIFS - ECMWF'S DATA-DRIVEN FORECASTING SYSTEM

A PREPRINT

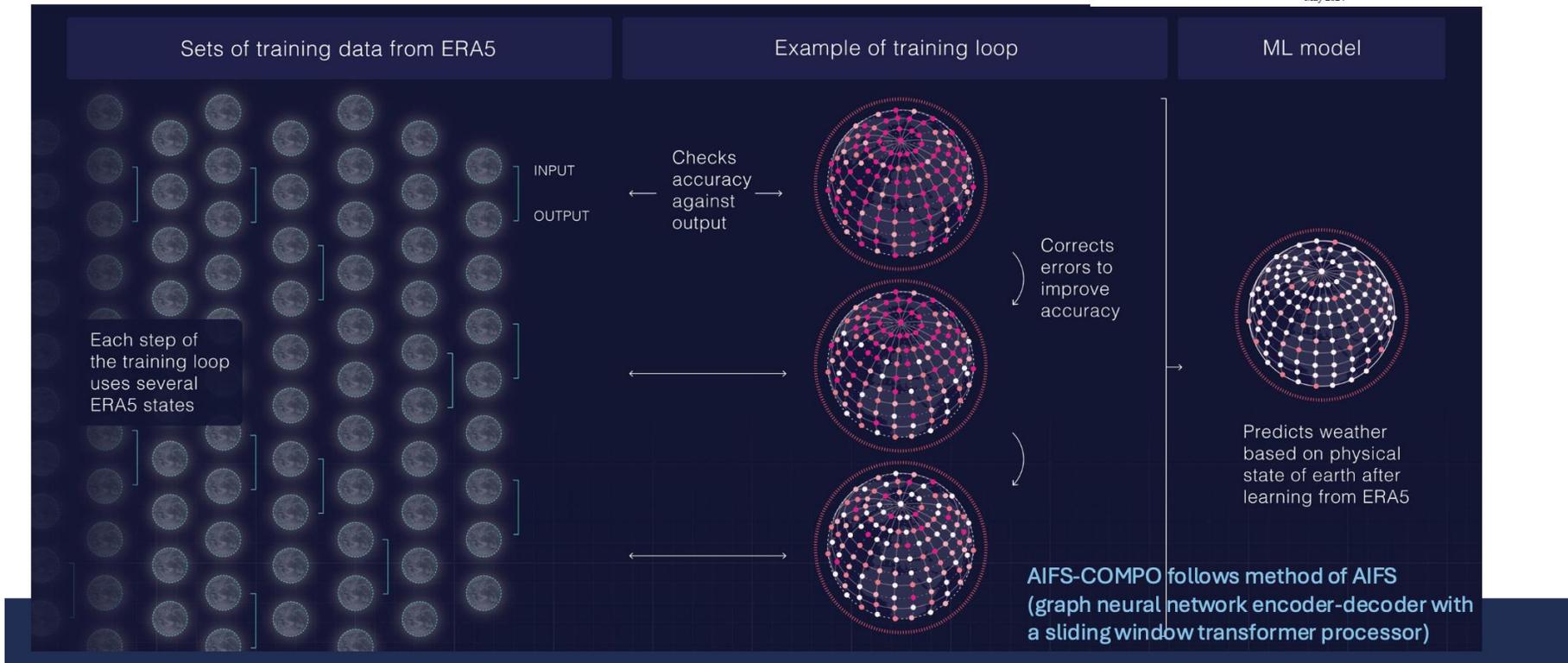
Simon Lang^{*} Mihai Alexe^{*} Matthew Chantry Jesper Dransch Florian Pinault Baudouin Raoult

Mariana C. A. Clare Christian Lessig Michael Maier-Gerber Linus Magnusson

Zied Ben Bouallègue Ana Prieto Nemesio Peter D. Dueben Andrew Brown Florian Pappenberger

Florence Rabier

May 2024



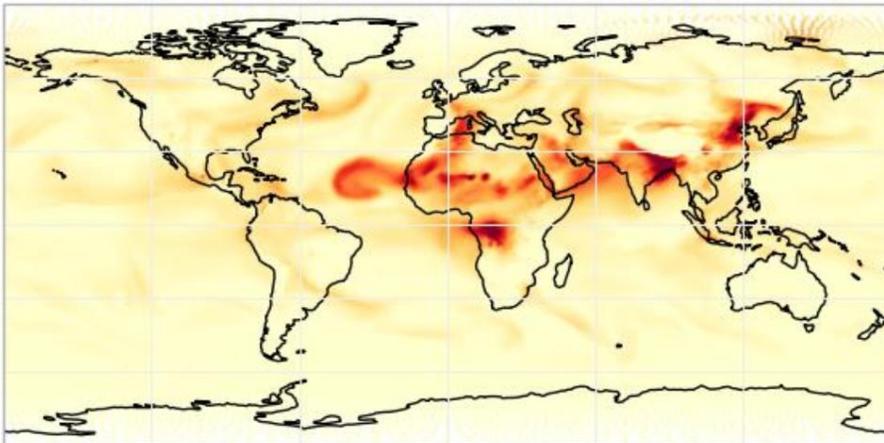


Results: AOD

AIFS-Compo 0.1

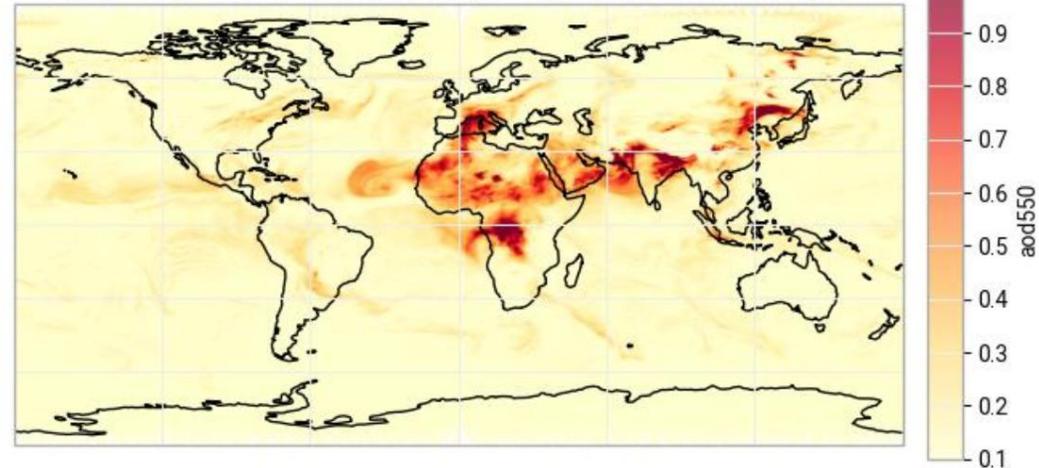
AIFS-Compo

AOD day 3 forecast AIFS-Compo, 20-06-2024T00:00:00



IFS-Compo

AOD day 3 forecast operational, 20-06-2024T00:00:00



Data used

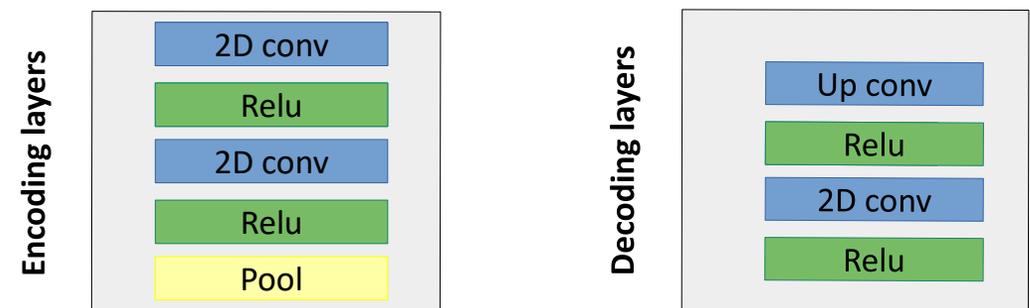
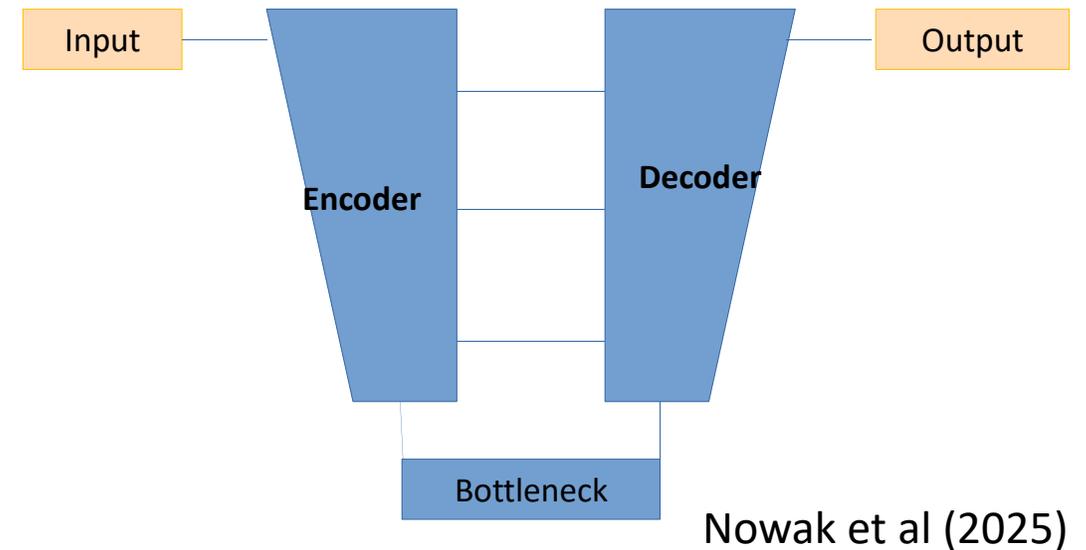
- About 10 years of VIIRS NOAA20 DBv2 550nm AOD L2
- GFS weather forecasts
 - 3 levels (500, 850 & 1000 hPa)
 - Dimensions (UGRD, VGRD, VVEL, T & RH)
- Terrain elevation
- Time encoding

Data split

Total instances 4281

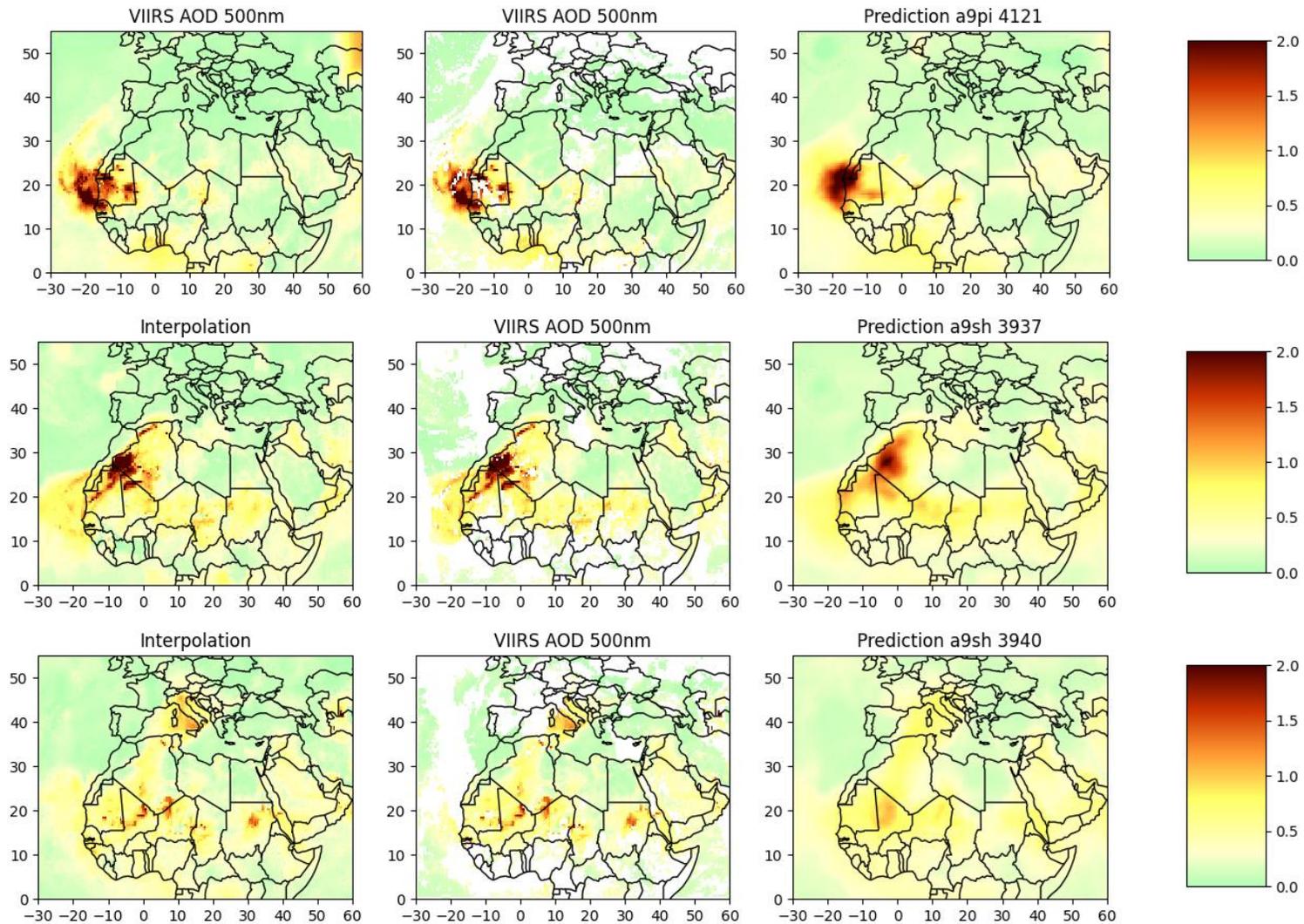
- Training set 70% (2996)
- Validation 20% (848)
- Test set 10% (437)

Network architecture



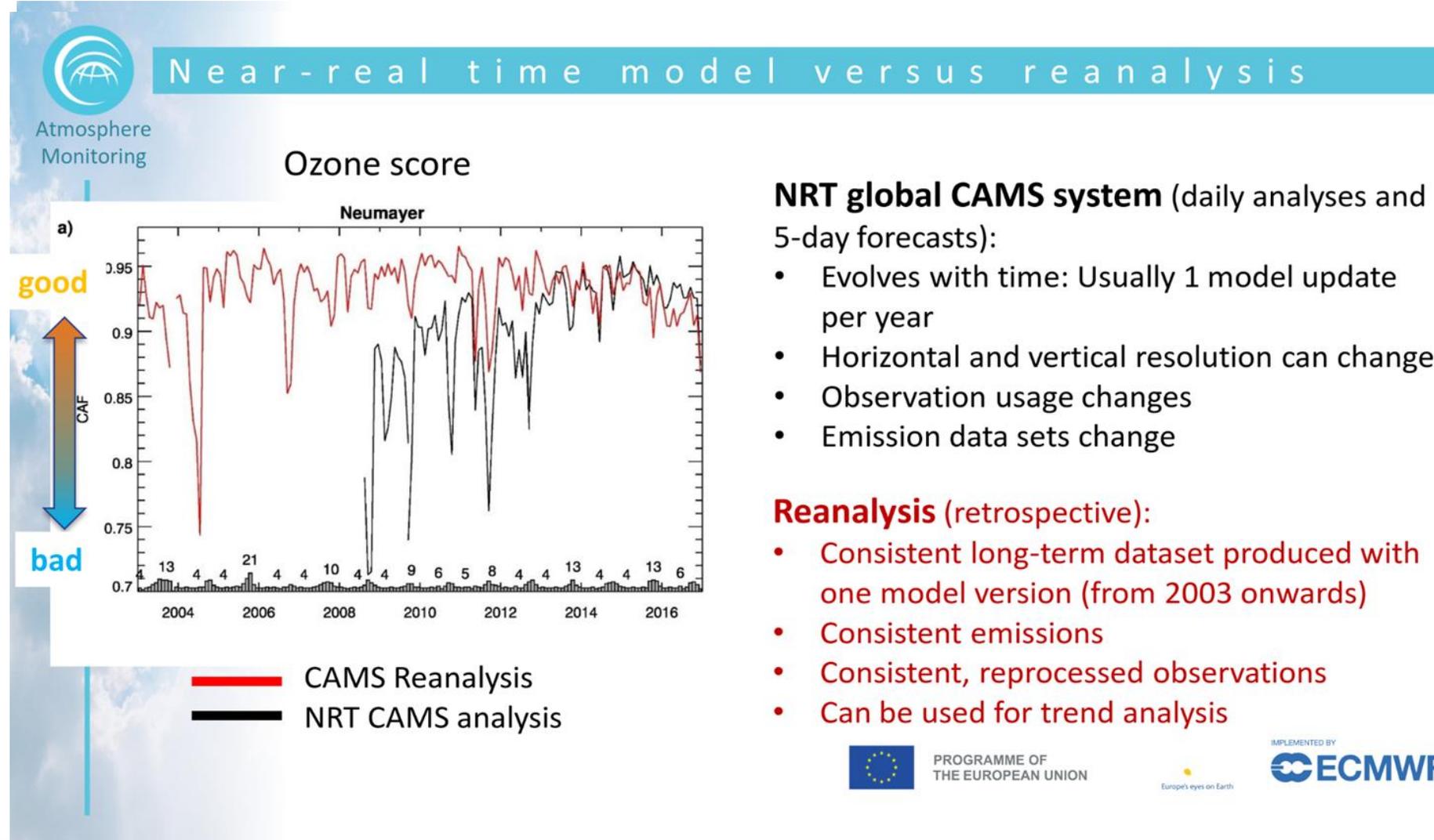
Machine learning forecasting

Courtesy of M. Hortelano





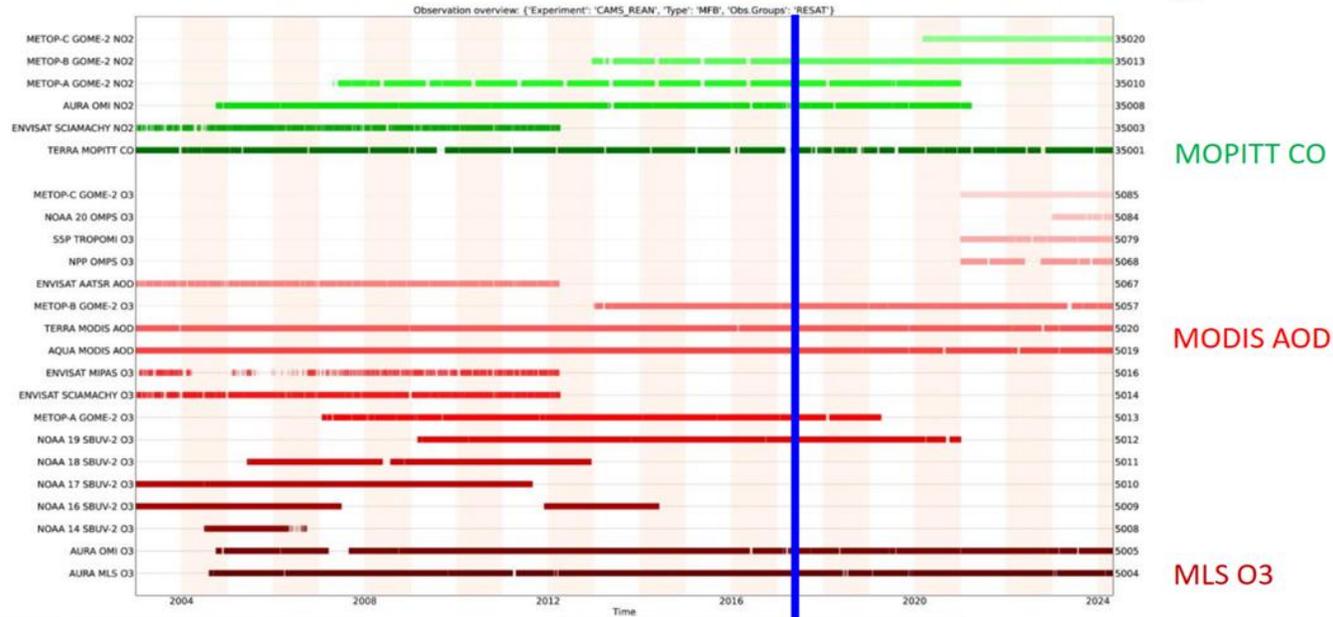
Mineral dust reanalyses





Atmosphere Monitoring

Atmospheric composition data used in EAC4



- Observing system changes with time
 - Change from reprocessed to NRT data once EAC4 had caught up with NRT
 - MLS important for vertical ozone distribution
 - Reliance on MOPITT CO/ MODIS AOD
- End of EAC4 when these die

CAMS reanalysis: Aeroval

Experiments

- IFS
- IFS-NRT
- IFS-EAC4**
- IFS-EGG4
- IFS-ESUITE-Cy48R1

IFS-EAC4: Evaluation of CAMS forecast and reanalysis models

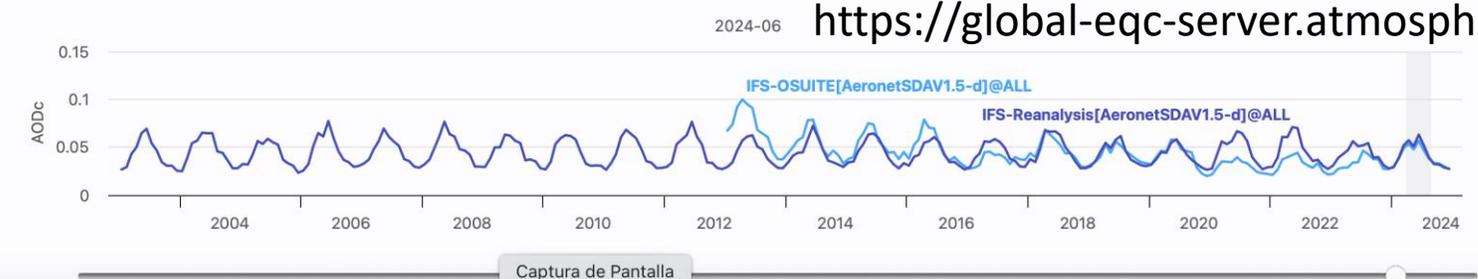
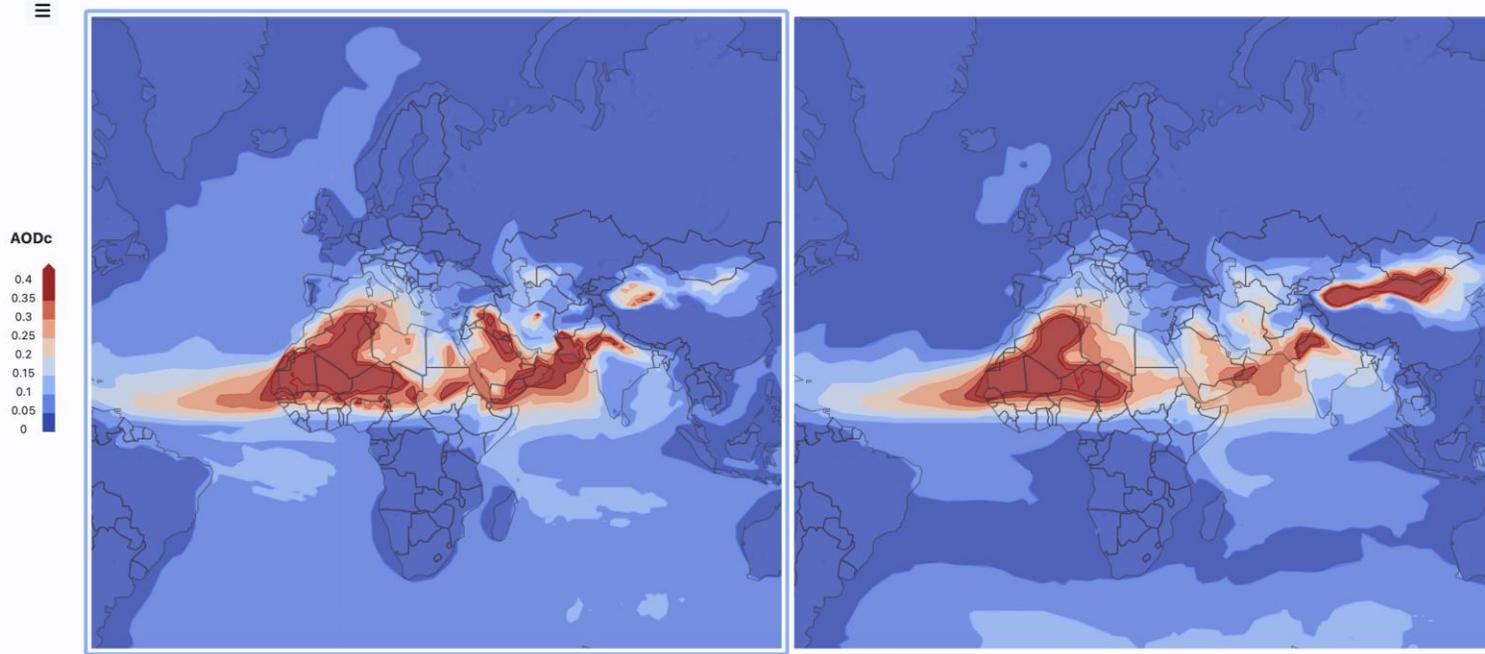
OSUITE, CNTRL, REAN and REAN_CNTRL are evaluated against multiple observation records including AOD from AERONET.

- [CAMS user support](#)
- 🕒 2025-03-04
- 📌 0.23.0

Data Policy

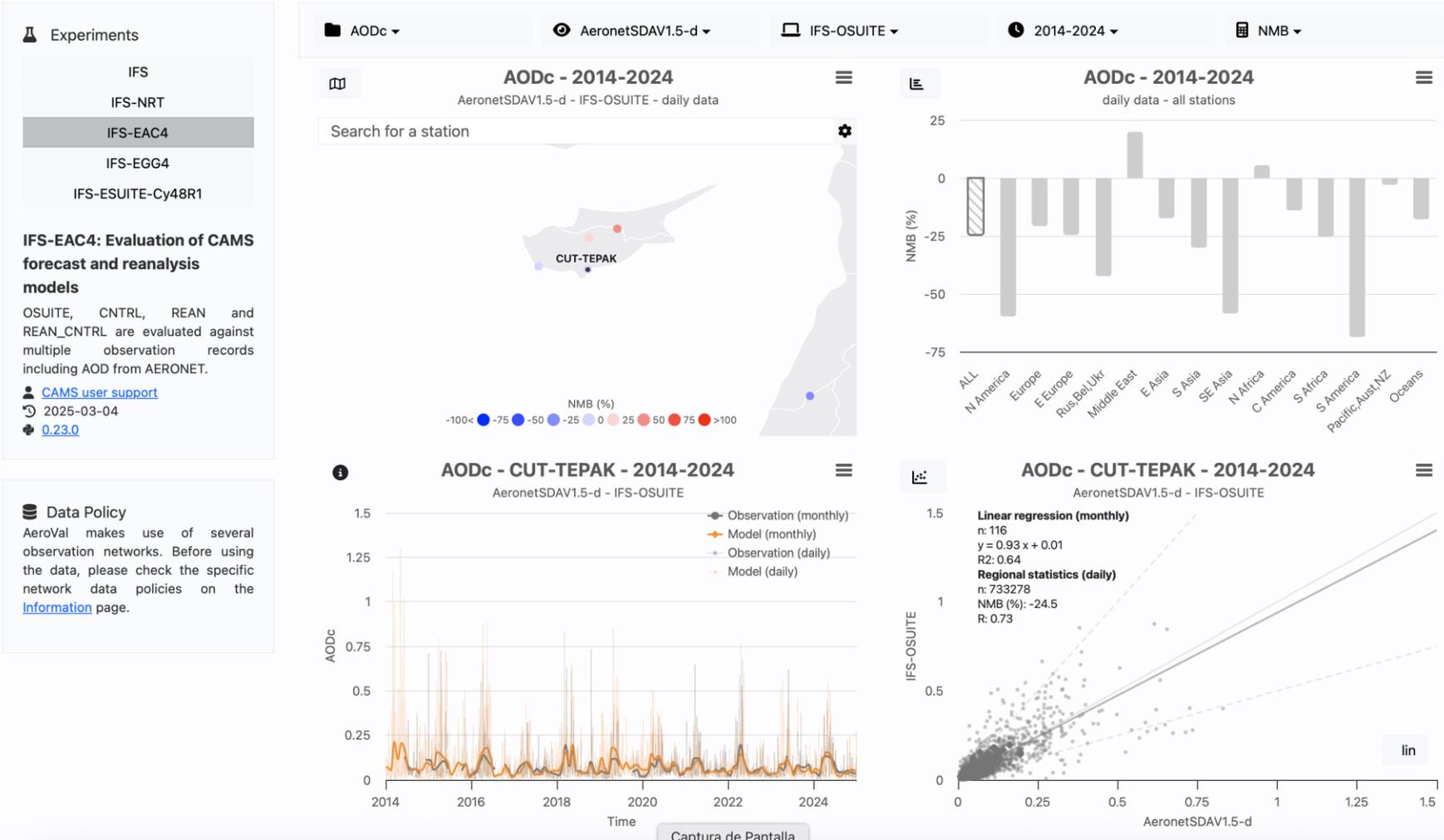
AeroVal makes use of several observation networks. Before using the data, please check the specific network data policies on the [Information](#) page.

📁 AODc
🌐 ALL
📄 IFS-OSUITE
📄 IFS-Reanalysis



<https://global-eq-server.atmosphere.copernicus.eu>

CAMS reanalysis: Aeroval





PROGRAMME OF THE EUROPEAN UNION

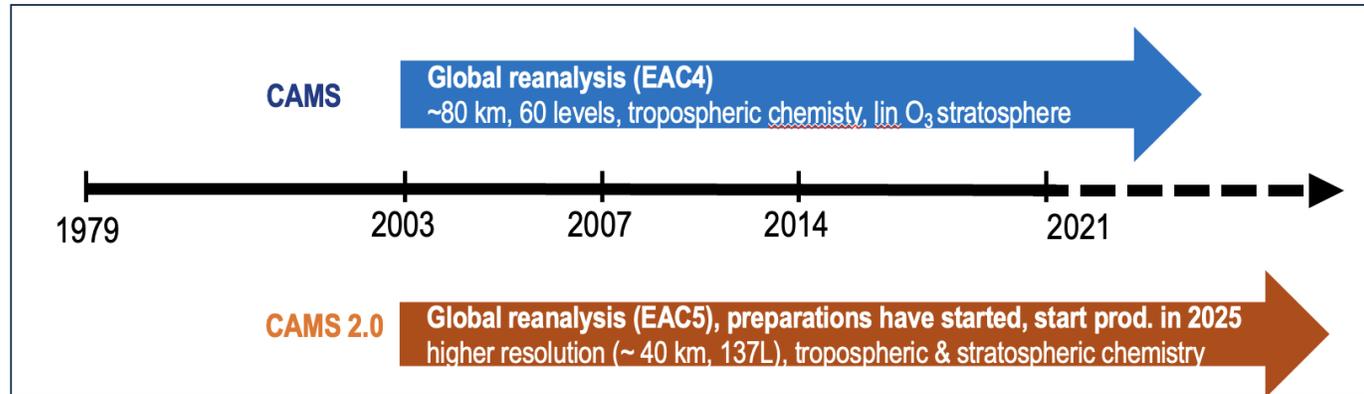


IMPLEMENTED BY



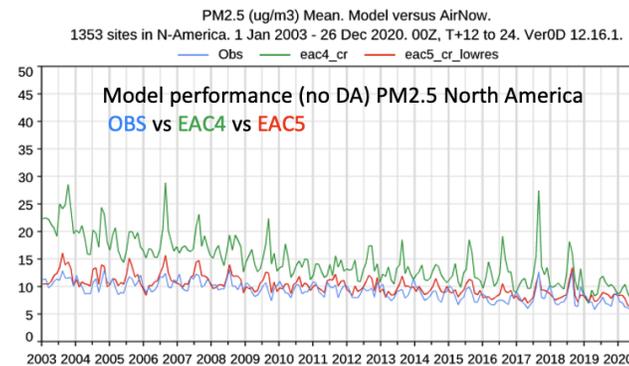
Production period (2026-2028)

A new CAMS reanalysis (EAC5) in prep



Innovations of EAC5 (w.r.t. EAC4)

- Increased resolution (137 vertical levels, 40 km, 1-h output)
- Model updates:
 - BASCOE stratospheric chemistry added
 - Nitrate, Ammonium and SOA added
 - New emissions including online biogenic emissions
 - Many more model updated (Cycle 49r2)
- **New and reprocessed observation (S5P, VIIRS, S3)**



S.Remy



Introduction: MERRA-2 at GES DISC

- Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2)
- Generated by NASA Global Modeling and Assimilation Office (GMAO)
- Archived and curated at NASA GES DISC
- **Total of 100 collections** (95 standard collections, 4 derived climate statistical collections, and 1 value-added collection to be released very soon - monthly PM_{2.5} at country level)
- Model Version: 5.12.4
- Format: NetCDF4
- Temporal Range: 1980-01-01 to Present
- Temporal Resolution: Hourly, 3-Hourly, Daily, Monthly, and Monthly Diurnal
- Spatial Coverage: Global
- Spatial Resolution:
 - 2D: 0.5° × 0.625°
 - 3D: 0.5° × 0.625° × 72 model levels or 0.5° × 0.625° × 42 pressure levels
- **Data Latency: ~ 3 weeks**
- **Users: Over 7000 in 2021**

GMAO Webpage: <https://gmao.gsfc.nasa.gov/reanalysis/>

Data Access Page: <https://disc.gsfc.nasa.gov/datasets?project=MERRA-2>



The details of this presentation can be referred to the ARSET training “[Tools for Analyzing NASA Air Quality Model Output](#)” (Part 1)

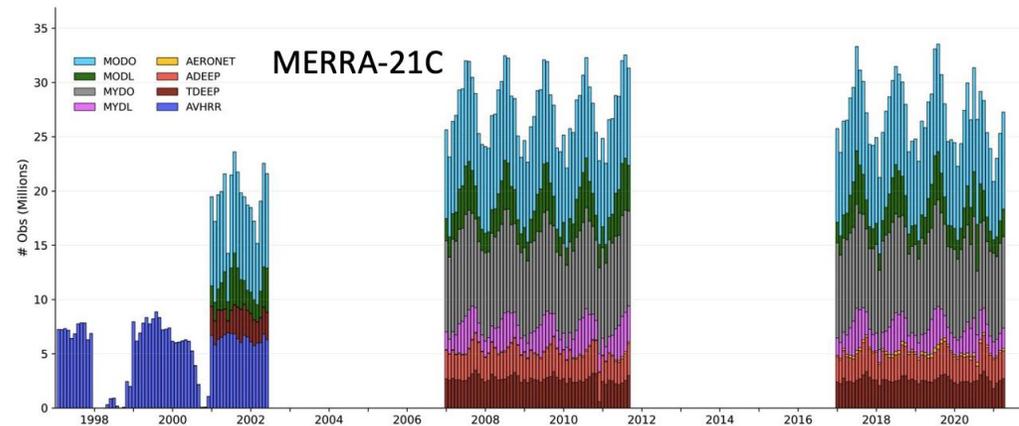
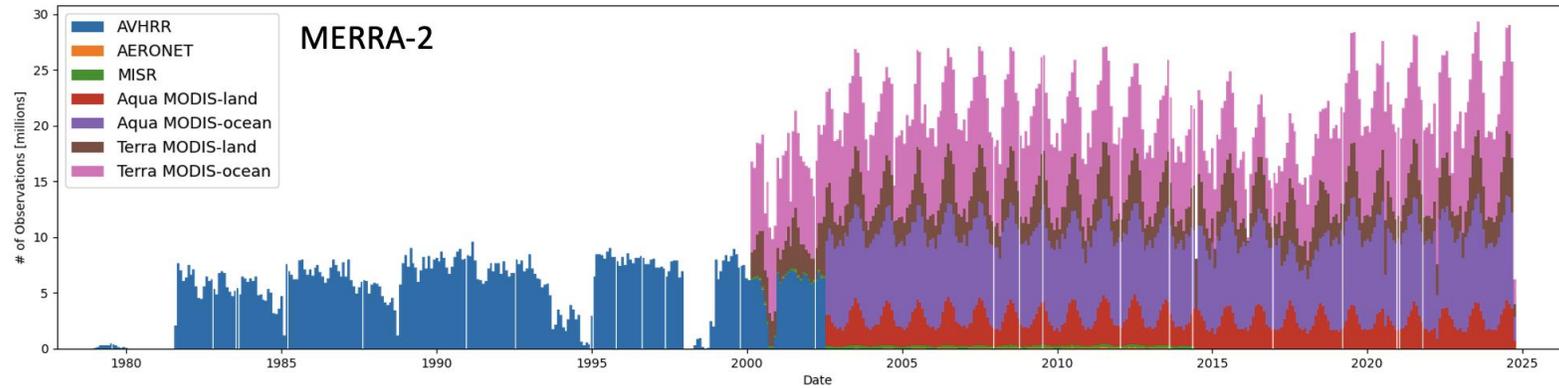


GEOS Products	Purpose	Nominal Resolution	Aerosol DA	Details
MERRA-2	Legacy reanalysis (1980 - present)	50 km	Y	GOCART (no nitrates)
GEOS-IT	NRT analyses for instrument teams (1998 - present)	50 km	Y	GOCART
MERRA-21C	Next generation reanalysis (1998 - present)	25 km	Y	GOCART2G



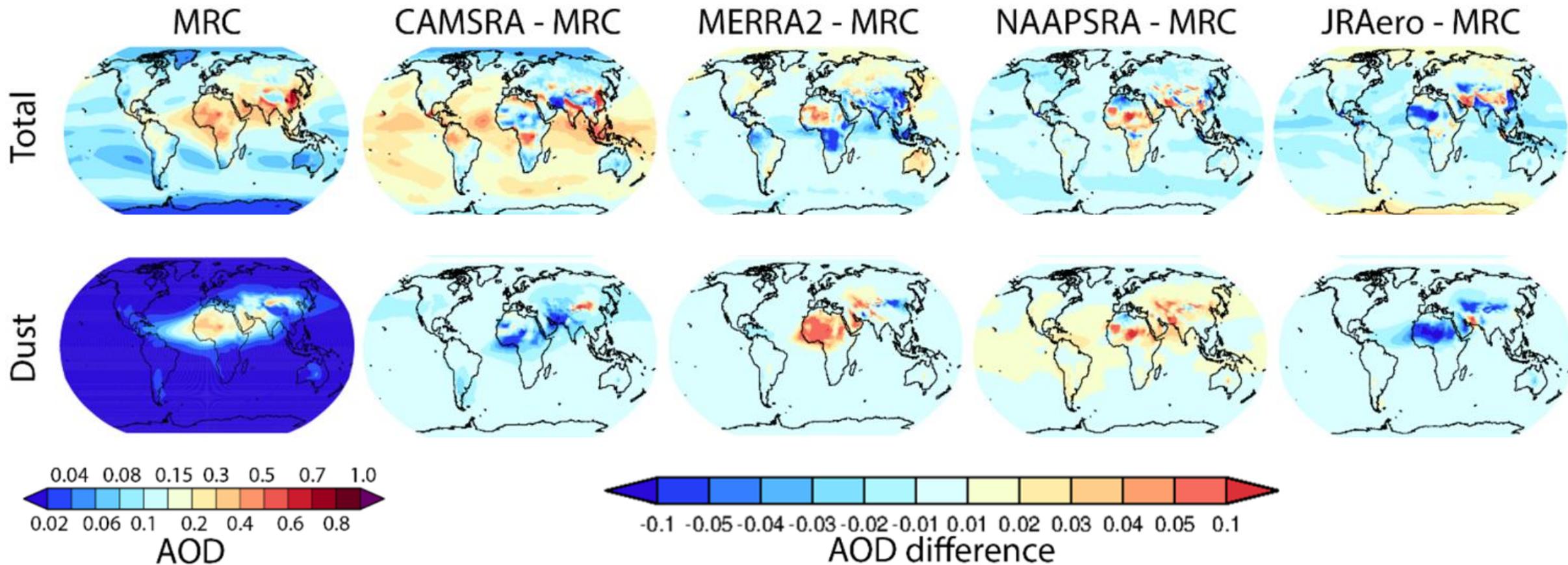
GEOS reanalysis

Courtesy of P. Castellano (ICAP 2025)

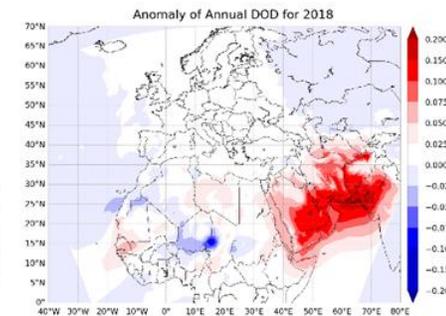
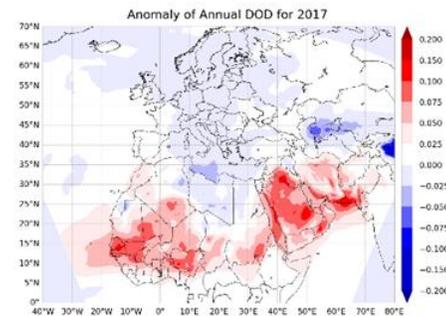
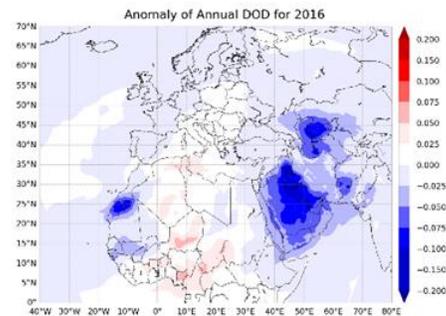
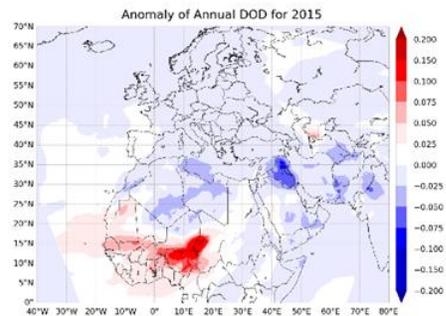
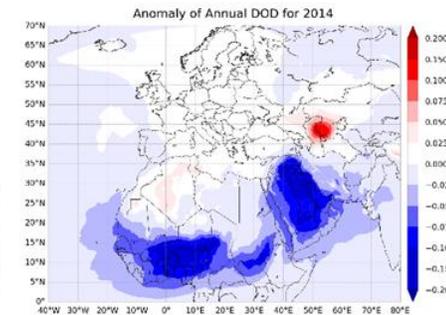
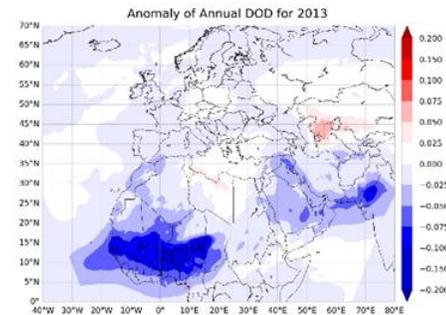
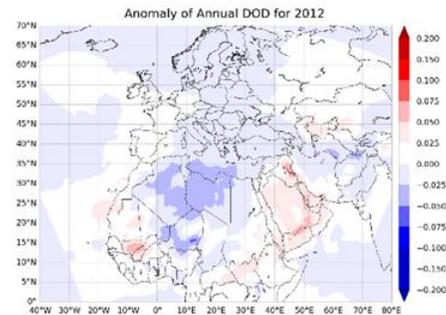
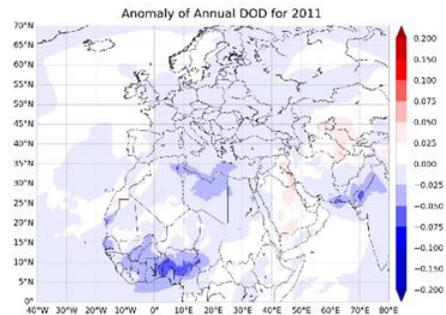
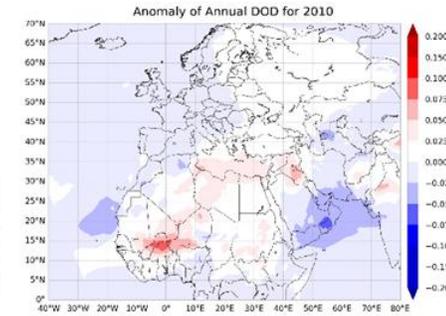
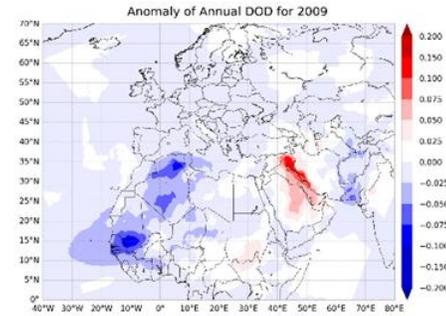
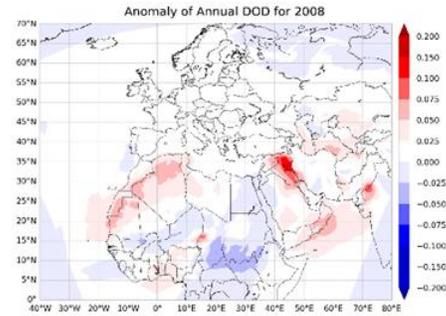
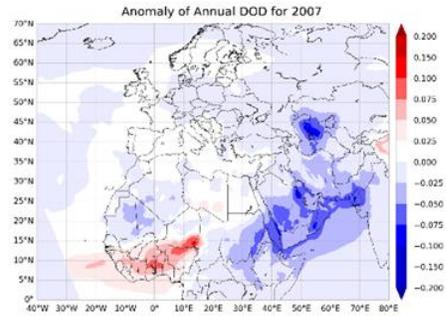
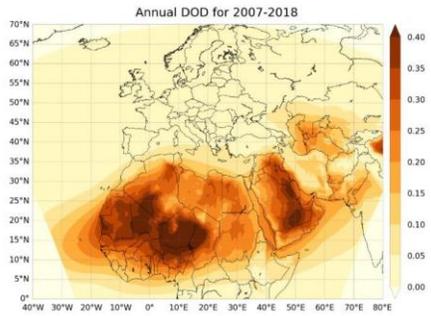


ICAP reanalyses comparison

[Peng et al \(2023\)](#)



MONARCH reanalysis: Dustclim



DOD yearly anomalies

https://earth.bsc.es/thredds_dustclim
Di Tomaso et al (2022)

- 10 km spatial resolution
- assimilation of MODIS Deep Blue C6.0 coarse optical depth (Ginoux, 2012)
- size and vertically resolved dust fields
- direct and global irradiance
- ensemble statistics (first guess and analysis)
- MODIS Deep Blue C6.0 until 2016 -> C6.1 starting from 2017-2018

MONARCH reanalysis: Dustclim

DATA DESCRIPTION	
Geographical domain	Northern Africa, the Middle East and Europe
Horizontal resolution	0.1° latitude × 0.1° longitude
Vertical resolution	15 pressure levels (1000-100 hPa) *
Temporal coverage	1 January 2007 to 31 December 2016 (10 years)
Temporal resolution	3 hours (starting at 3 UTC)
Variable ensemble fields	mean, standard deviation, maximum and median
Grid mapping	rotated latitude longitude
File format	NetCDF

* Data are stored on 15 standard pressure levels (i.e. 1000, 975, 900, 850, 750, 700, 600, 500, 400, 350, 300, 250, 175, 150, 100 hPa). However, model simulations have been run with 40 hybrid pressure-sigma layers (up to 50 hPa top pressure).

VARIABLE	UNITS	DESCRIPTION	SPATIAL DIMENSION	PARTICLE SIZE DESCRIPTION	ANALYSIS AVAIL. *
concdubin1-8	kg m ⁻³	dust concentration	3D	8 bins	yes
dni	W m ⁻²	direct normal irradiance	2D	NA	no
drydu	kg m ⁻² 3 h ⁻¹	accumulated dust dry deposition over the previous 3 hours	2D	8 bins	no
ec550du	m ⁻¹	dust extinction coefficient at 550 nm	3D	total	yes
ghi	W m ⁻²	global horizontal irradiance	2D	NA	no
loaddu	kg m ⁻²	dust load	2D	8 bins	yes
od550du	unitless	dust optical depth at 550 nm	2D	total	yes
od550ducoarse	unitless	coarse dust optical depth at 550 nm	2D	total	yes
sconcdubin1-8	kg m ⁻³	dust surface concentration	2D	8 bins	yes
sec550du	m ⁻¹	dust surface extinction coefficient at 550 nm	2D	total	yes
wetdu	kg m ⁻² 3 h ⁻¹	accumulated dust wet deposition over the previous 3 hours	2D	8 bins	no
z	m	height of pressure level above sea level	3D	NA	no

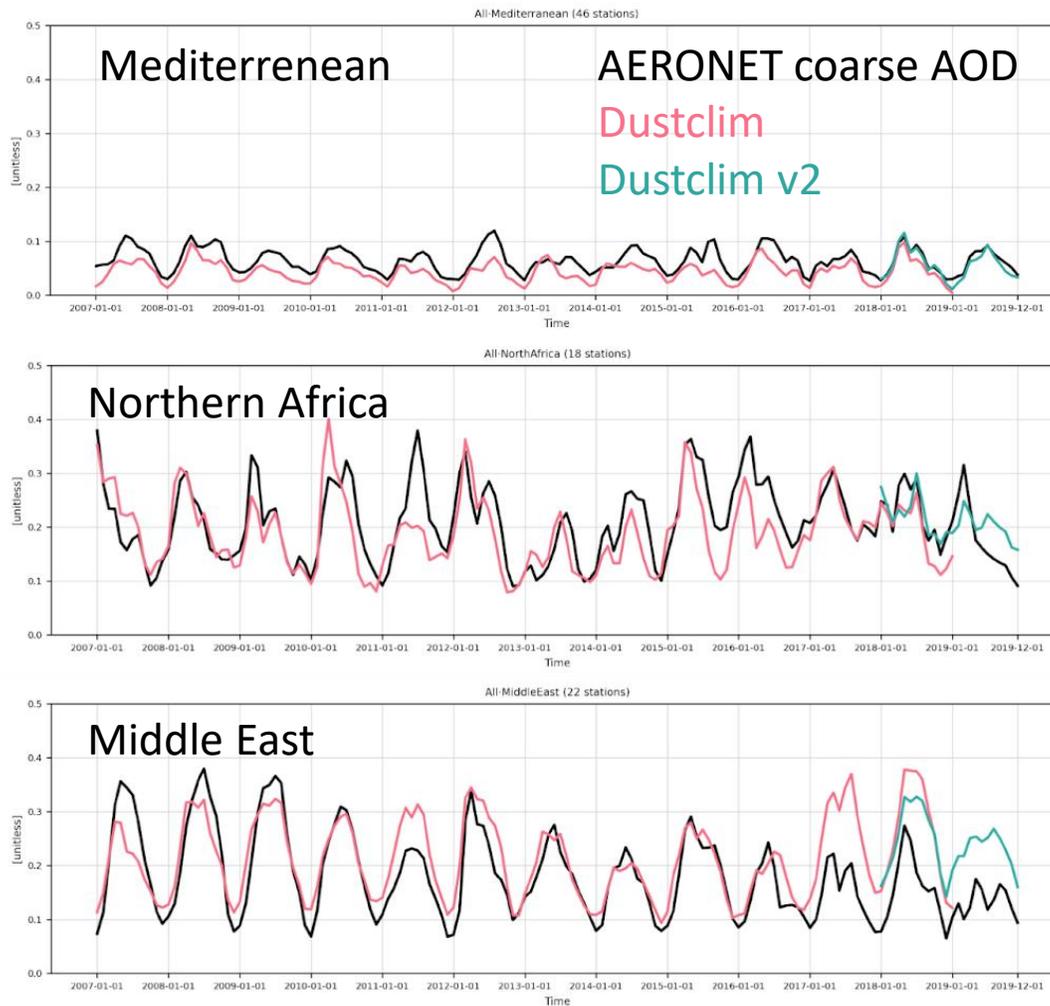
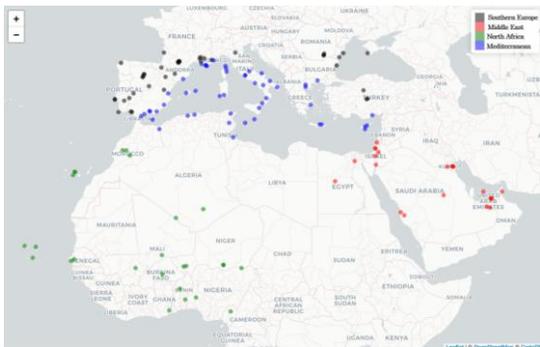
* Model first-guess fields are available for all the variables.



MONARCH v2 reanalysis: DustClim v2

- Model version and data assimilation revised to match current operational forecasts
- ERA-Interim → ERA5 meteorology
- MODIS coarse DOD over land → VIIRS Dust Filtered AOD over land and ocean
- Deterministic control simulation
- Additional fields (emissions, dust radiative effect)
- Preliminary production ongoing for 2018-2019
- Aim is to keep up-to-date production with current day

BSC MONARCH DustClim v2 production





Final remarks

- Many mineral dust forecasts publicly available and easy to access
- Few established forecast centers routinely assimilate satellite observations
- Those that do generally produce as well long-term reanalyses
- Assimilated observations are generally total aerosol optical depth values
- Changes in observational networks / systematic differences between satellite products are important aspects to be considered in reanalyses
- The AI revolution is ongoing



References

To be updated ...





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