Progress in assimilating multi-satellite Aerosol Optical Depth (AOD) within the Copernicus Atmosphere Monitoring Service (CAMS) data assimilation (DA) system

Sebastien Garrigues[1], Melanie Ades[1] , Samuel Remy[2], Julien Chimot[3], Johannes Flemming[1], Mark Parrington[1], Antje Inness[1], Zak Kipling[1], Roberto Ribas[1], Richard Engelen[1], Vincent-Henri Peuch[1]

1: ECMWF, Reading, UK
2: HYGEOS, France
3: MetOffice, Exeter, UK
4: EUMETSAT

Atmosphere Monitoring

European Commission | Copernicus Europe's eyes on Earth ECMWF

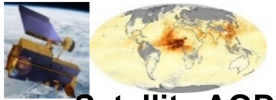
Atmosphere Monitoring

O U T L I N E S

1. Introduction: the CAMS aerosol forecast system
2. Progress in aerosol model developments
3. Multi-satellite AOD monitoring
4. Assimilation of NOAA VIIRS product
5. Assimilation of dust AOD
6. Conclusions

CAMS GLOBAL AEROSOL DATA ASSIMILATION

Atmosphere Monitoring

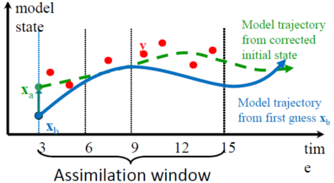


Satellite AOD

MODIS (AQUA, TERRA)

PMAp (METOP A,B,C)

Produce best optimal initial conditions



4D VAR data assimilation

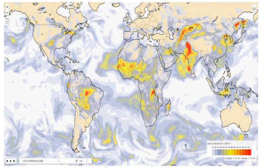
Emission sources:

- satellite-based biomass burning (GFAS)
- emission inventories (anthropogenic, biogenic)

Integrated Forecasting Sytem (IFS)

- ➢ **Atmos. model**
  - Semi-Lagrangian advection model
  - 137 atm levels, ~40 km horizontal resolution
- ➢ **CB05 chemistry model** (Flemming et al., 2015; Huijnen et al, 2019)
- ➢ **Aerosol model** (Remy et al., 2019,2022):
  - Bulk-bin scheme
  - Species: sea salt, dust, organic matter, black carbon, sulfate, nitrate, amomium

- 5 day forecast,
- CAMS reanalysis



AOD, PM2.5, PM10

European Commission

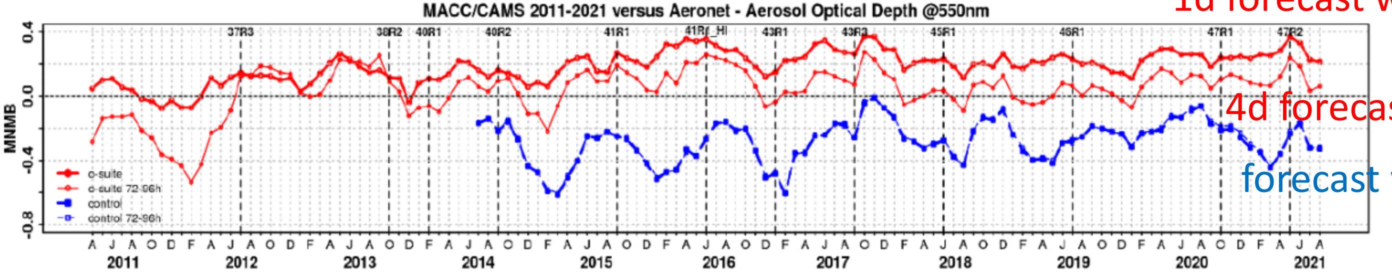
Copernicus Europe's eyes on Earth

ECMWF

Impact of data assimilation(DA) on forecasts

Atmosphere Monitoring

CAMS AOD forecast bias against AERONET



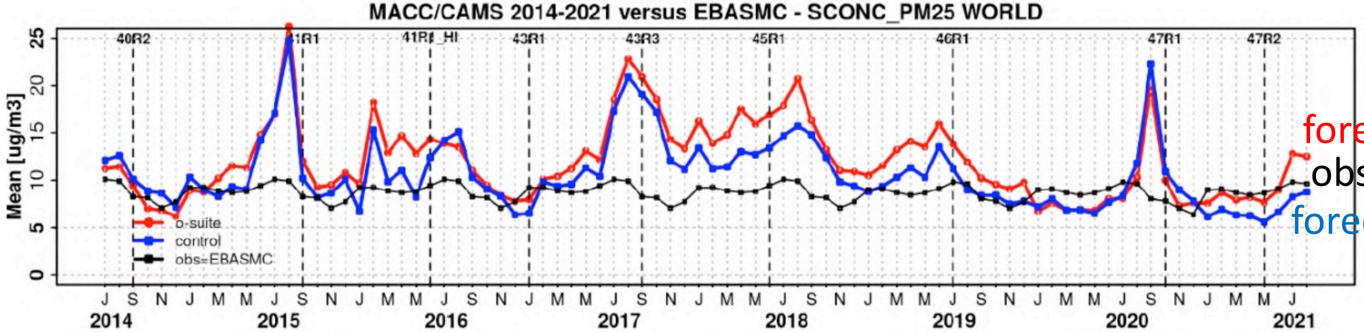
1d forecast with DA

4d forecast with DA

forecast without DA

Positive impact on AOD

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



forecast with DA

observations

forecast without DA

Mixed result for PM2.5

Credit: CAMS validation report (CAMS84_2018SC3_D1.1.1_JJA2021)

Atmosphere Monitoring

O U T L I N E S

1. Introduc

2. Progress in aerosol model developments (S. Remy)

3. Results

4. Conclus

Remy et al., 2019; 2022

European Commission | Copernicus Europe's eyes on Earth ECMWF

Recent updates of the IFS AEROSOL model

- New dry and wet deposition schemes (IFS Cycle 47R3, in operation)
- Secondary organic aerosols (IFS Cycle 48R1, 2023)
- Dust updates (IFS Cycle 48R1,2023)

Results forecast only (no assimilation)

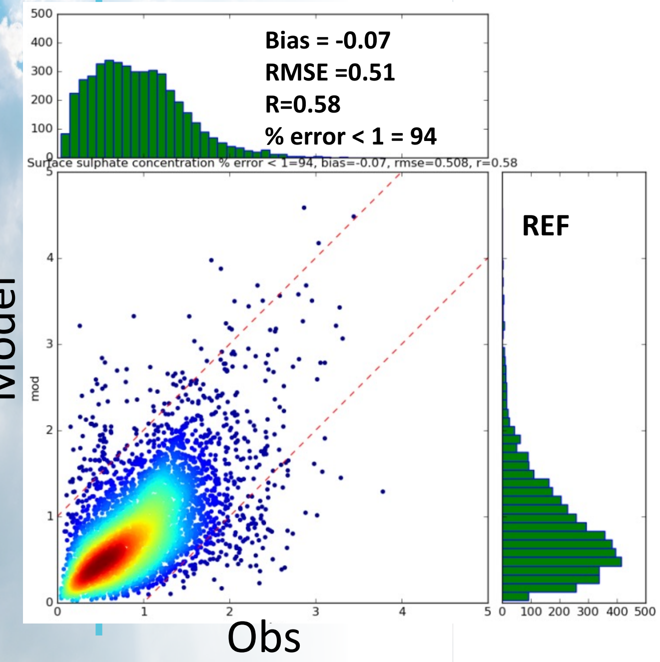
New dry and wet deposition schemes

Atmosphere Monitoring

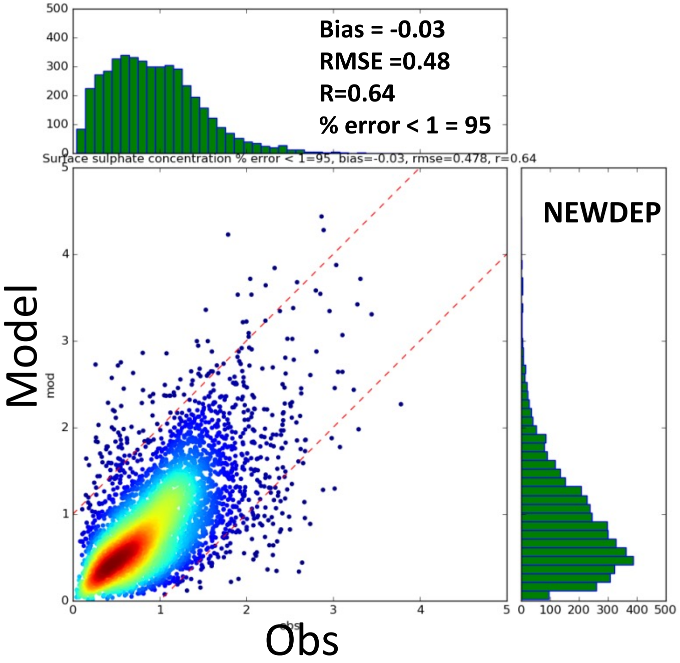
Wet deposition: adaptation and test of the Luo et al. (2019) in-cloud scavenging scheme

Dry deposition: implementation of the Zhang and He (2014) parameterization

2017, Density observation/simulation scatterplot of weekly averaged sulfate concentration at surface from CASTNET, in µg/m³



Improved correlation
Bias reduction



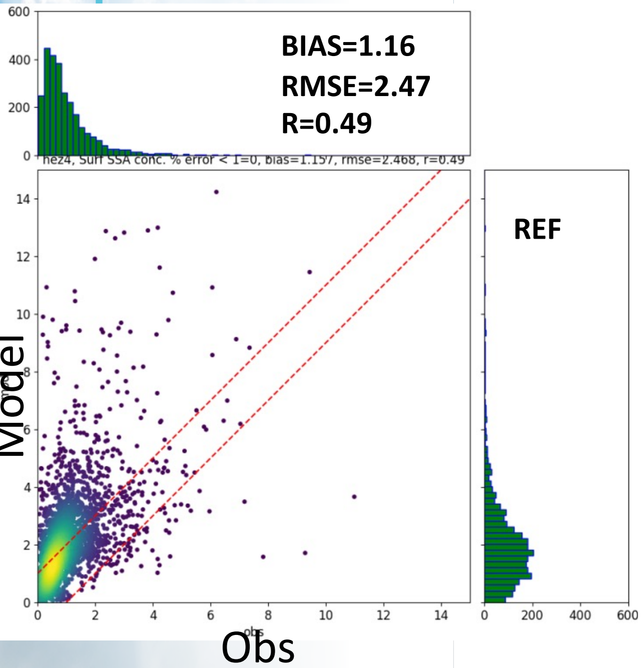
MWF

Secondary Organic Aerosol (SOA)

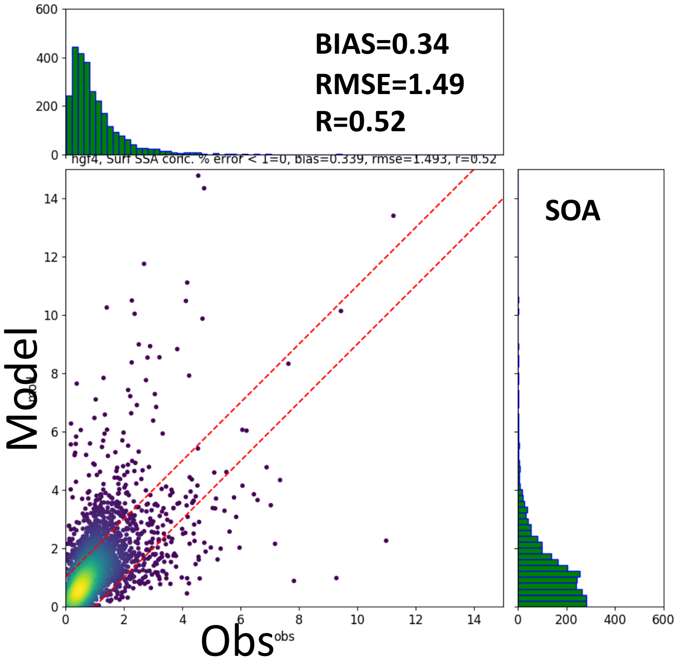
Atmosphere Monitoring

Future architecture: new SOA species, coupled with the global chemistry (IF/CB05)

January-June 2017: density scatterplot of three-day simulated vs observed total organic carbon (primary + secondary) over stations of the IMPROVE network (U.S.) with an altitude < 500m.



Bias reduction



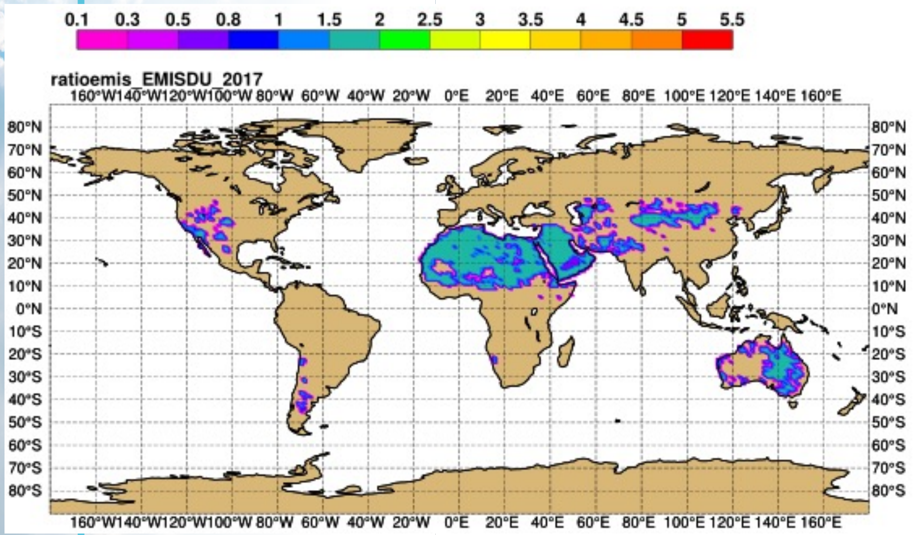
Dust updates

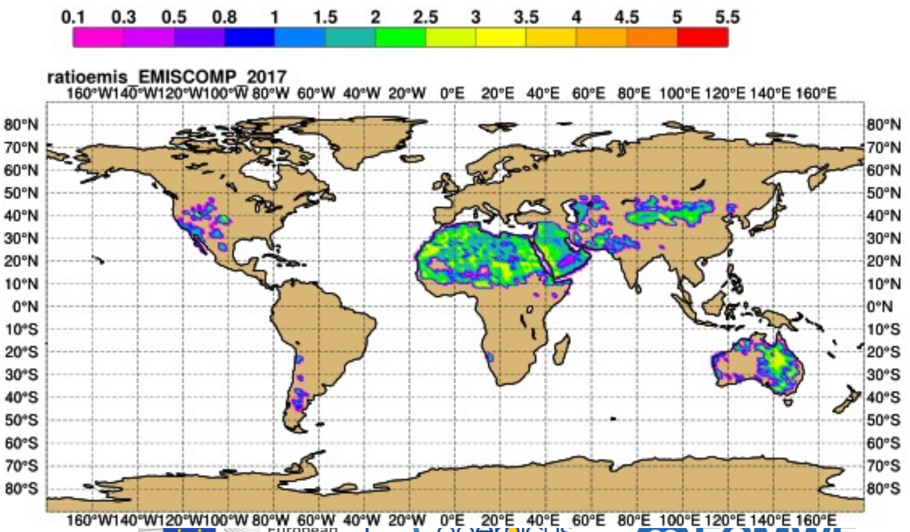
Regional variation of dust size distribution at emissions

Uses information from simulated dust mineralogy

On average, bin1 and bin2 emissions are increased by ~30%, bin3 emissions are reduced by ~1%

2017, ratio in % of dust bin1 + bin2 emissions over total emissions. Reference (left), and with regional variations (right).



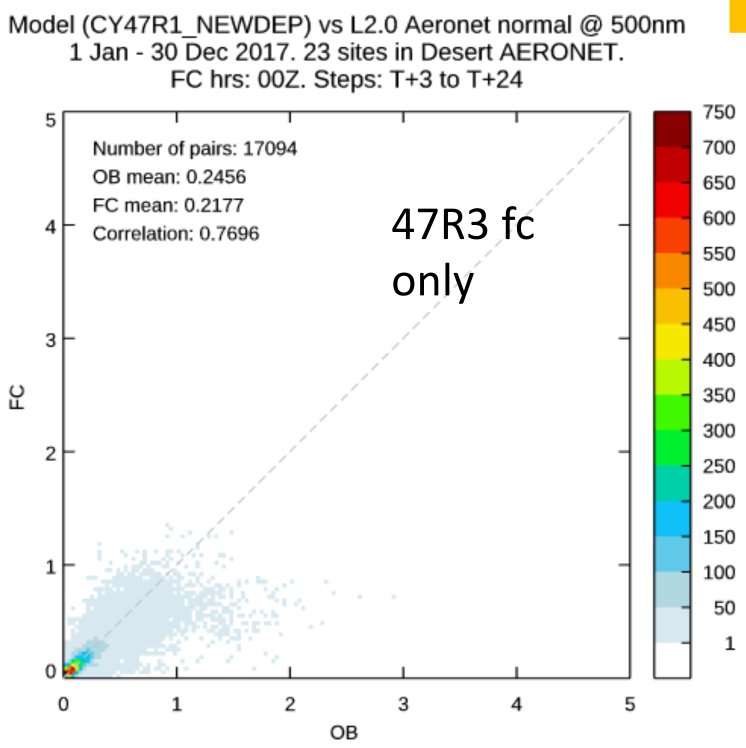


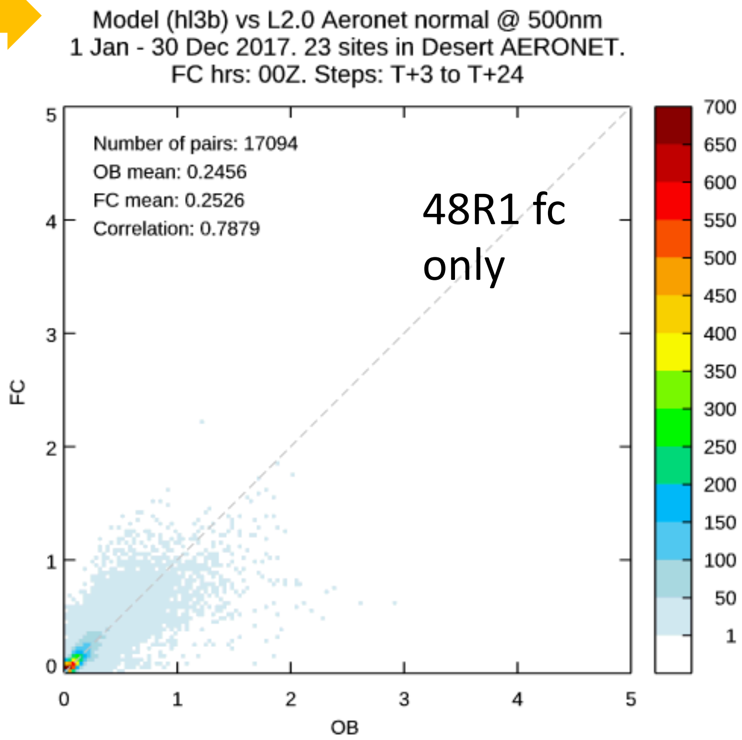
Atmosphere Monitoring

Dust updates - evaluation

Evaluation against a selection of "dusty" AERONET stations (Sahara, Arabic peninsula)

Improvement





Atmosphere
Monitoring

O U T L I N E S

1. Introduc
2. Experim
3. Multi-satellite AOD monitoring (S. Garrigues)
4. Conclus

Garrigues et al., ACP, 2022

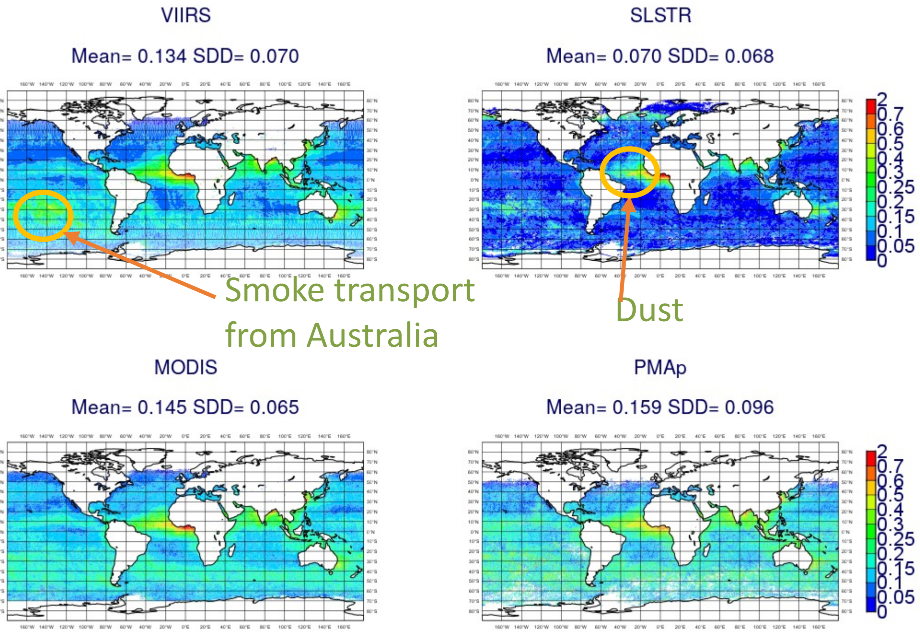
Multi-satellite AOD product intercomparison

Atmosphere Monitoring

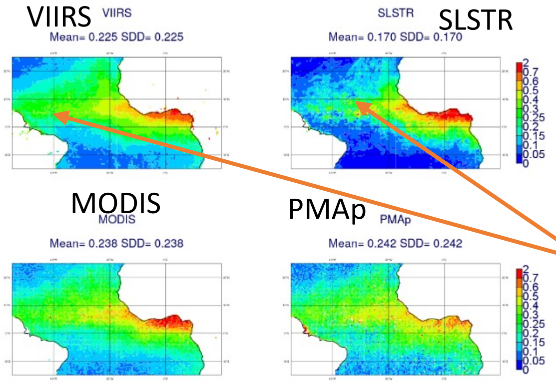
Ocean (Dec 2019-Feb 2020)

Garrigues et al., ACP, 2022

Global



Mid-Atlantic



Differences in spatial representativity related to the more stringent cloud filtering applied to SLSTR

- Good spatial consistency between MODIS and VIIRS
- SLSTR shows lower global AOD over ocean

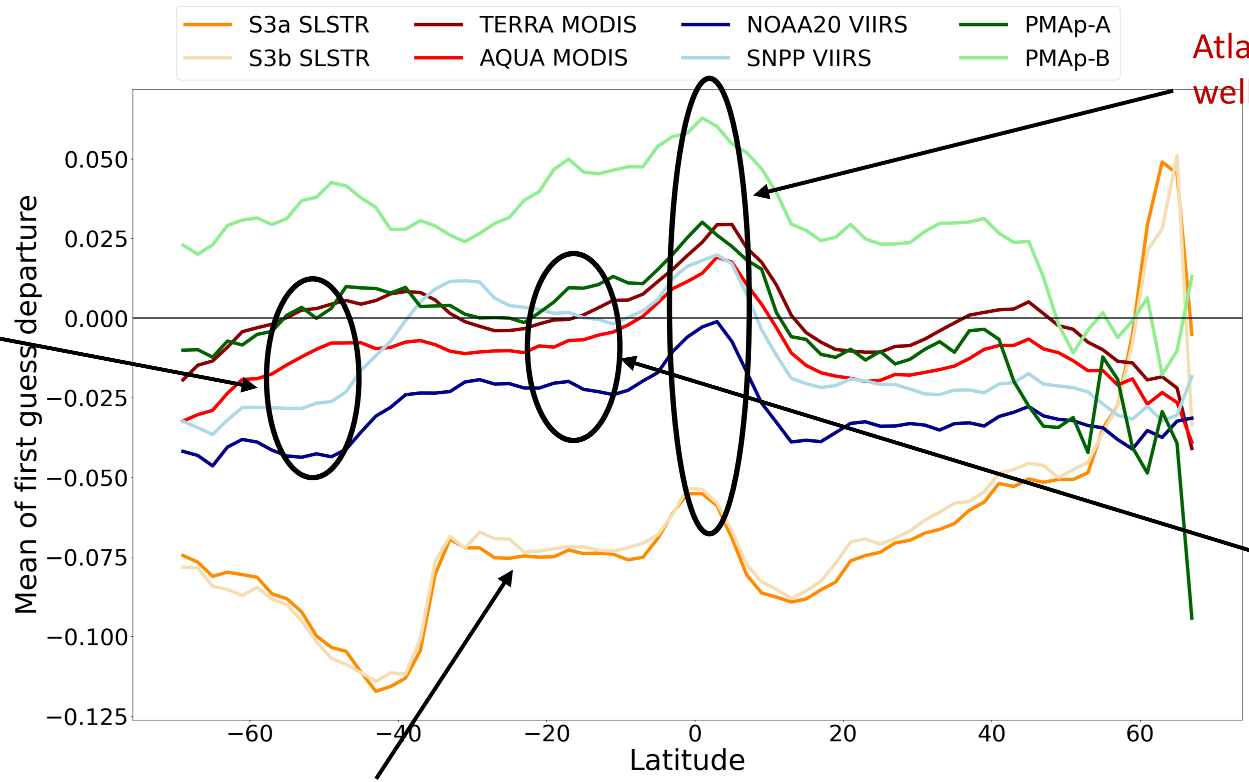
European Commission | Copernicus Europe's eyes on Earth | ECMWF

Atmosphere Monitoring

Multi-satellite AOD product intercomparison

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

Large diversity, in South ocean (wind, clouds)



Atlantic dust outbreak well captured

- SNPP>NOAA20
- TERRA>AQUA

Radiometric uncertainties in level 1

SLSTR shows lower global AOD over ocean

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

Ocean (Dec 2019-Feb 2020)

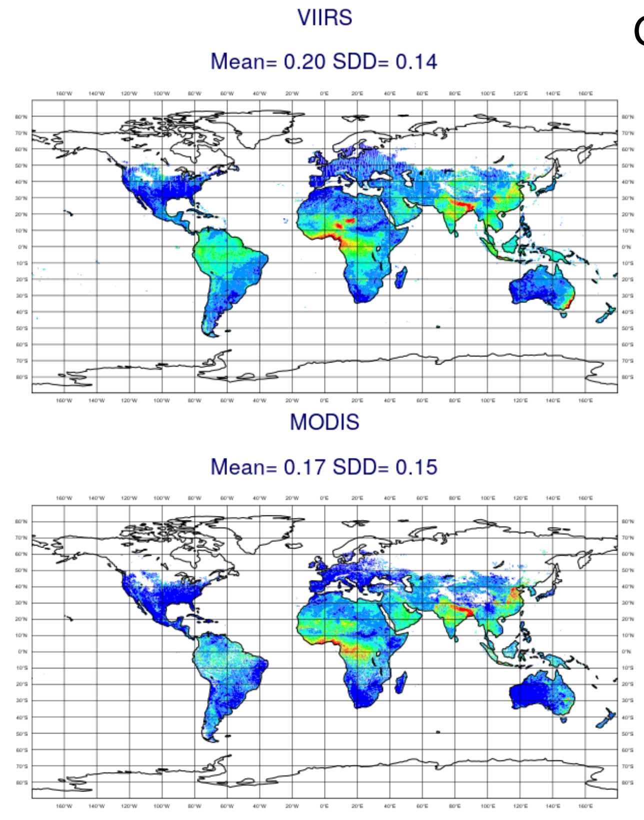
Garrigues et al., ACP, 2022

Multi-satellite AOD product intercomparison

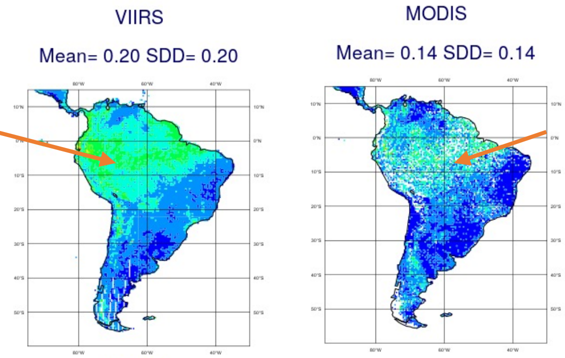
Garrigues et al., ACP, 2022

South America

Land



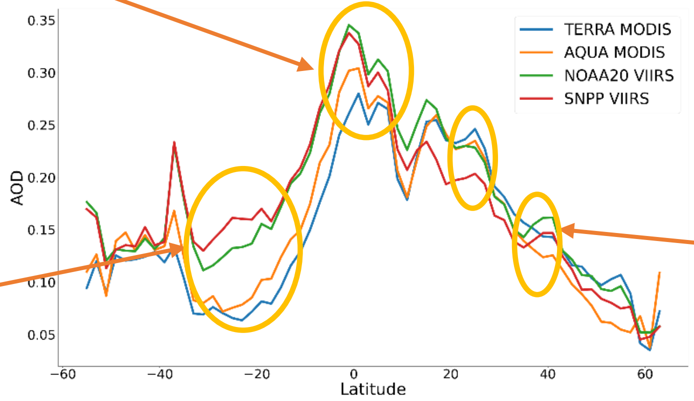
Overall good spatial consistency between VIIRS and MODIS over land



VIIRS: larger AOD over South America

More frequent missing observation

Latitude cross section over land



VIIRS shows larger value at high AOD (biomass burning regions)

Larger diversity in SH

Better consistency in NH

MWF

Atmosphere Monitoring

O U T L I N E S

1. Introduc

2. Experim

3. Assimilation of NOAA VIIRS AOD product (S. Garrigues)

4. Conclusi

Garrigues et al., in preparation

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

Atmosphere Monitoring

Experiment design

- ✓ **AOD retrieval assimilated in CAMS:**
  - ✓ Used in **operational forecast**:
    - MODIS (TERRA, AQUA; C6.1, DT+DB)
    - PMAp (Metop-A,B; v2.1; ocean only)
  - ✓ **Tested product**: VIIRS
    - NOAA EPS product
    - S-NPP, NOAA20
    - 0.750 km spatial resolution=>superobbing at ~40 km resolution
    - v2r1
- ✓ **Simulation period**: 02 June 2020- 30 November 2020 (evaluation on JJA and SON periods)

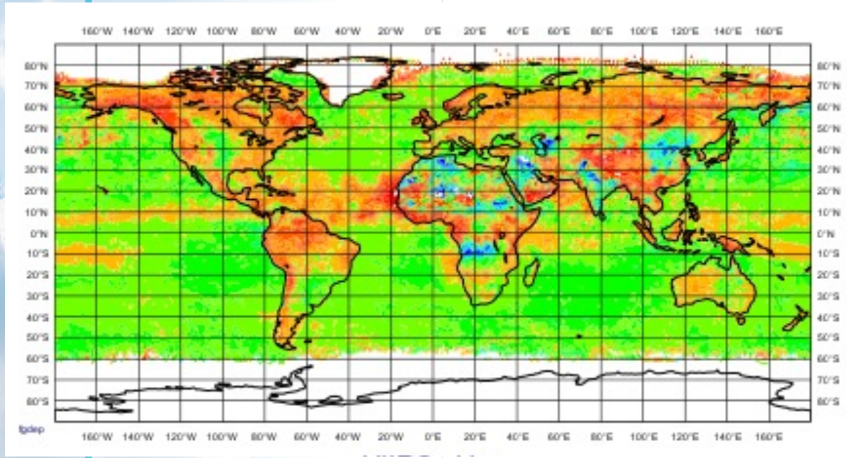
- ✓ **Experiments: impact of assimilating VIIRS**
  - **MODIS+PMAp versus MODIS+PMAp+VIIRS**
  - **MODIS only versus VIIRS only**

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

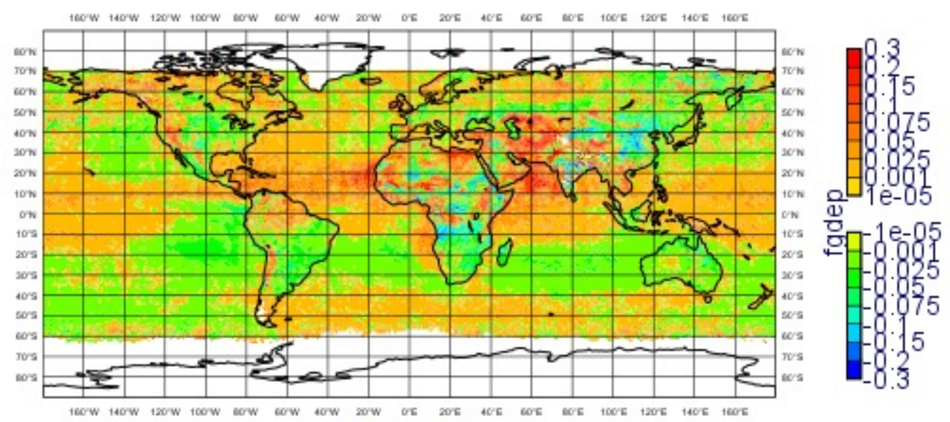
First guess departure (satellite-model)

Temporal average June-August 2020

VIIRS



MODIS

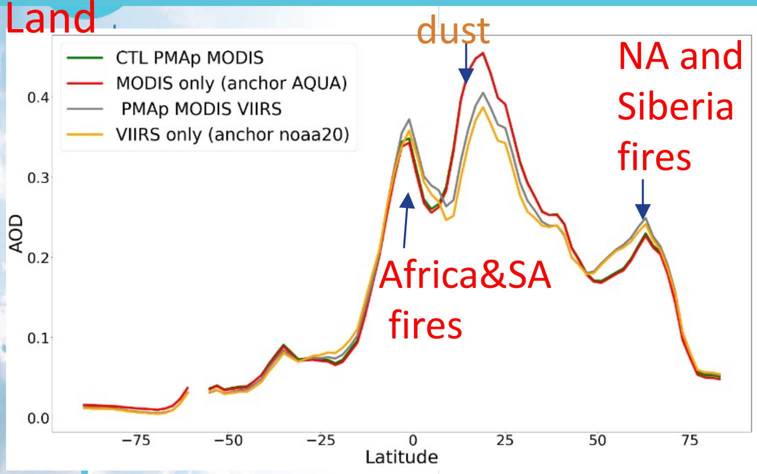


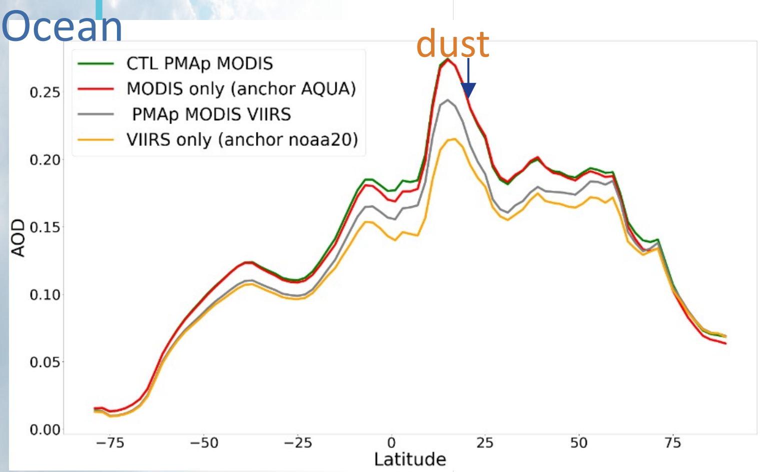
Ocean: VIIRS <model, MODIS > Model

Temporal average June-August 2020

Land: VIIRS > model over dust source and biomass burning regions

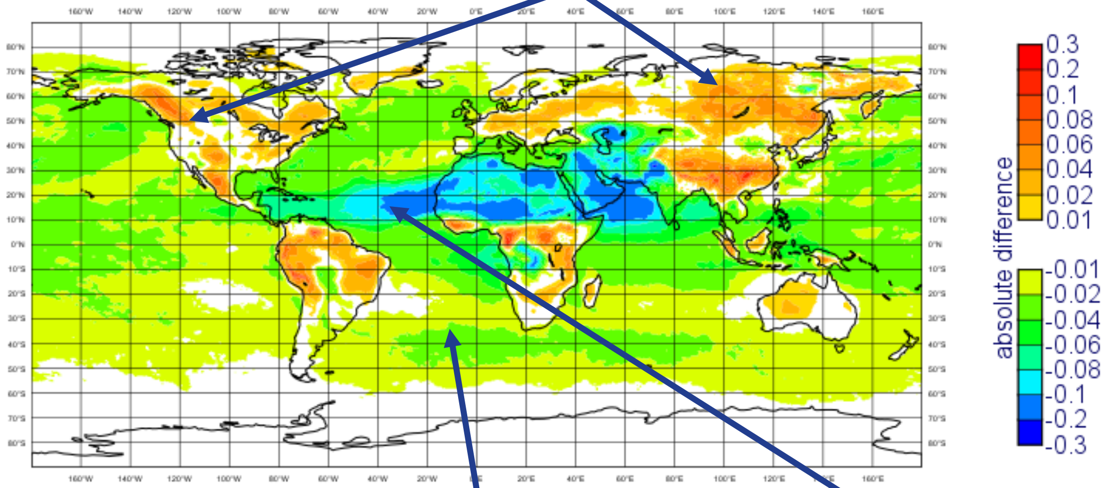
Results: Impact of assimilating VIIRS on analysis





VIIRS Only – MODIS Only analysis

AOD increases over biomass burning regions

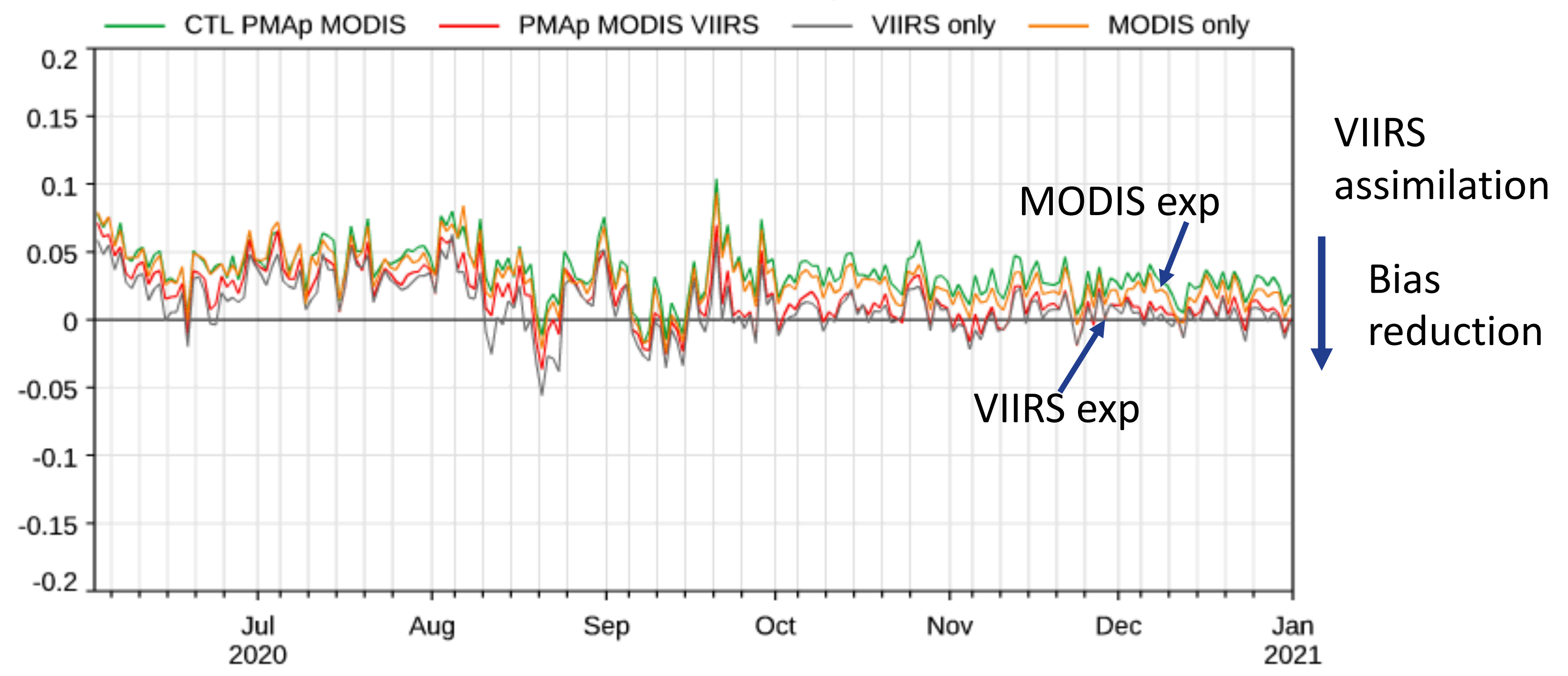


AOD decreases over ocean background and dust

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

Temporal average June-August 2020

Global bias



EXP$_{CTL}$: MODIS, PMAp

EXP$_{PMV}$: MODIS, PMAp, VIIRS

EXP$_{V}$: VIIRS only (anchor SNPP)

EXP$_{M}$: MODIS only (anchor AQUA)

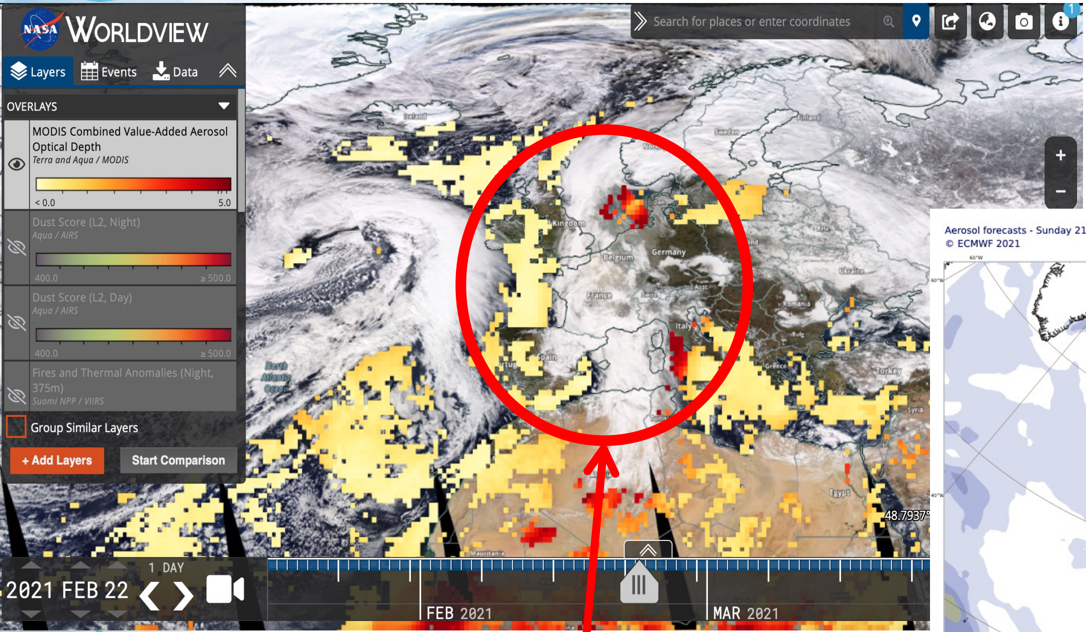
Atmosphere Monitoring

O U T L I N E S

1. Introduc
2. What is
3. Ff
4. Ff
5. Assimilation of dust AOD (From M. Ades)
6. Conclusi

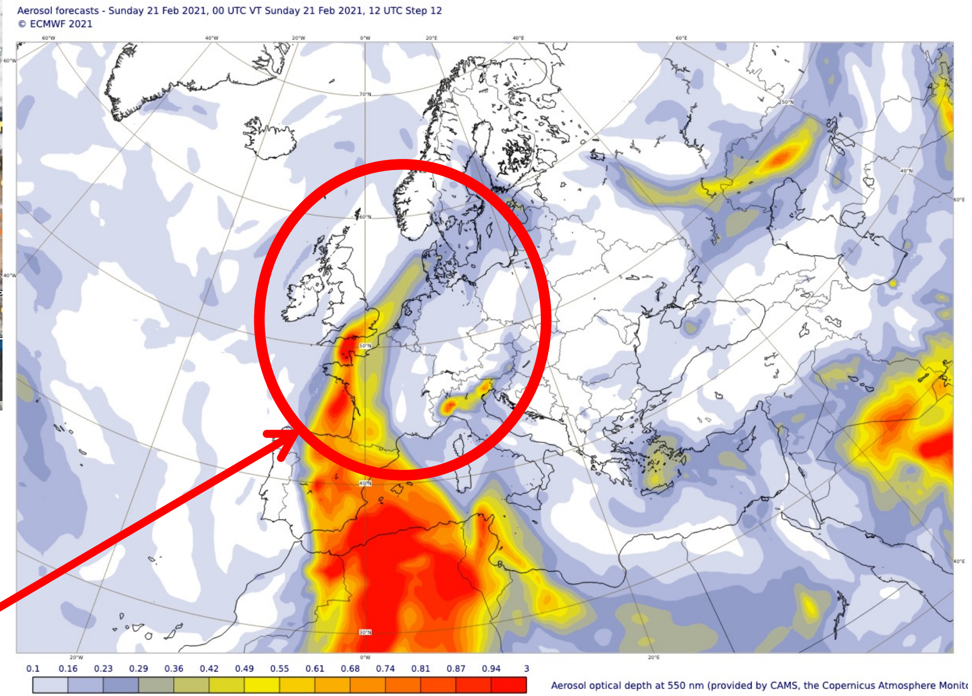
European Commission | Copernicus Europe's eyes on Earth | ECMWF

Dust AOD assimilation



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

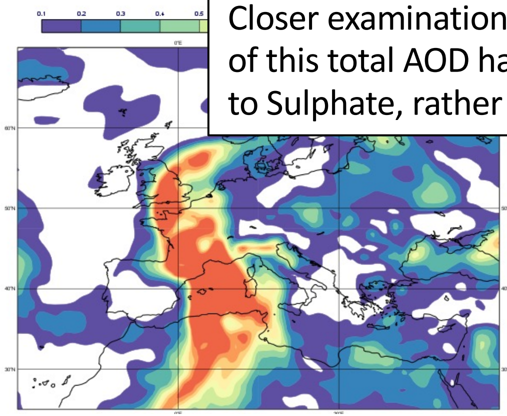
CAMS Total AOD at 550nm 12hr forecast valid at 20210222 12hr



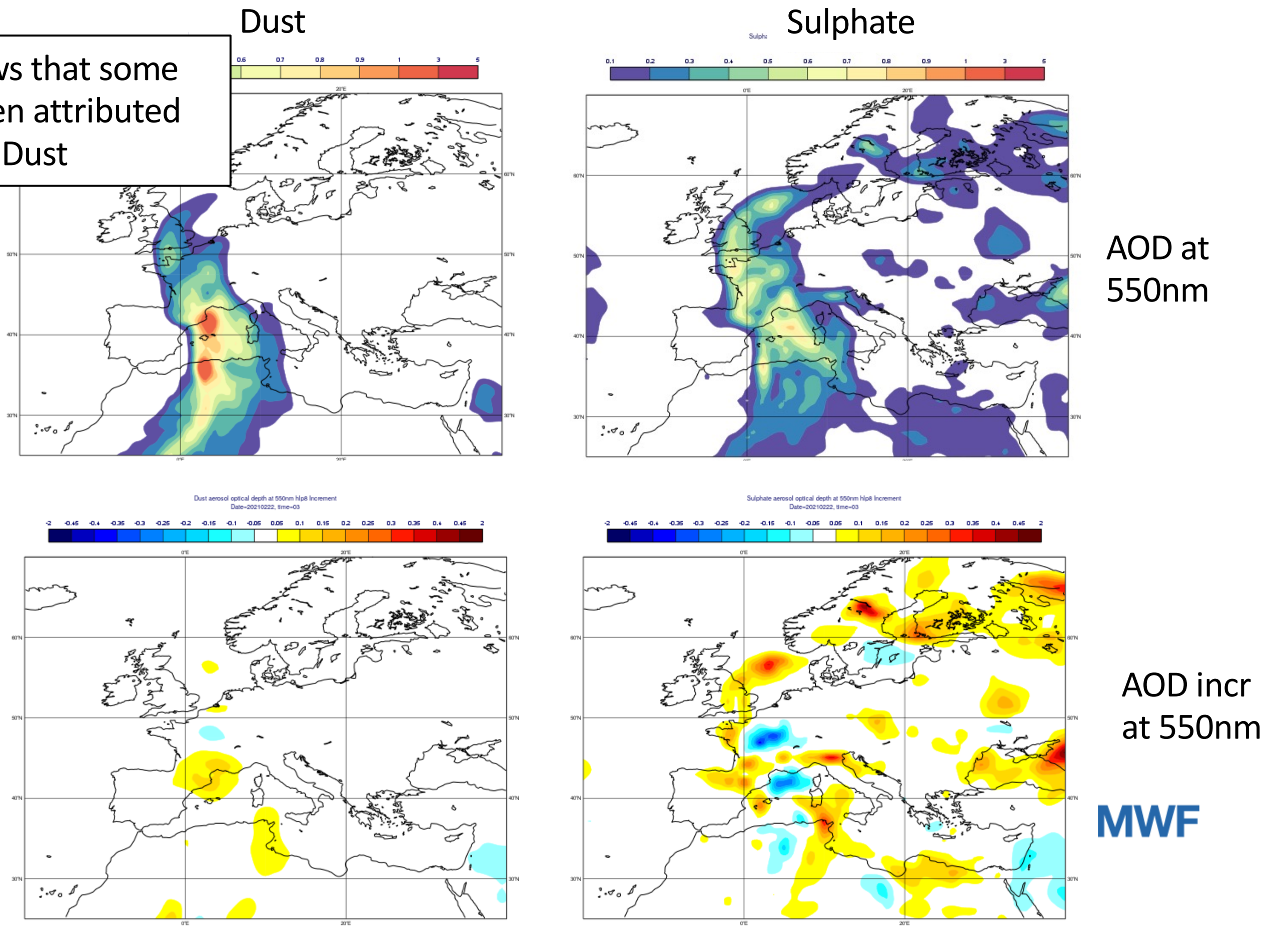
The CAMS forecast does a good job of forecasting the AOD plume from Africa over Northern Europe

Dust AOD assimilation

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



Total AOD at 550nm: 20210222 03hr



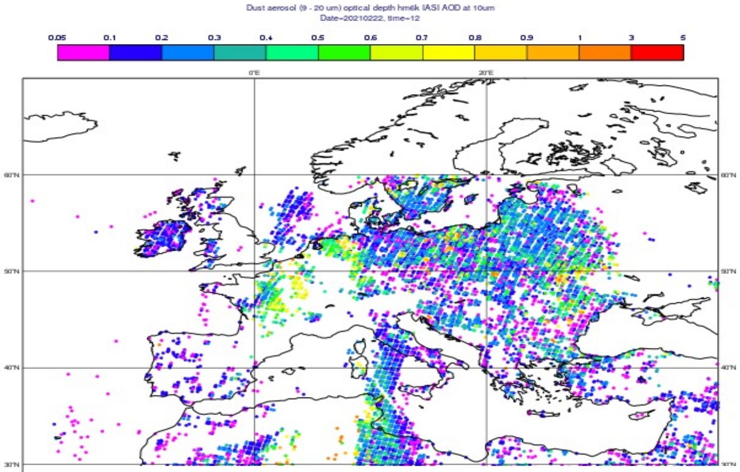
AOD increments are attributed to the different species according to their proportion in the nonlinear forecast. If there is no dust in the forecast in a specific location then the increment will be given to whatever species is there – in this case Sulphate

MWF

Dust AOD assimilation

Atmosphere Monitoring

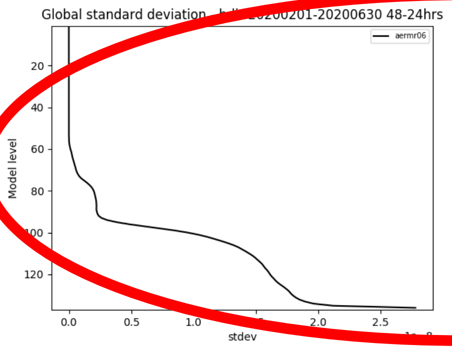
One solution would be to use additional observations, where available, of the separate species. These species could then be independently increased/decreased without relying on the distribution of total AOD increments.

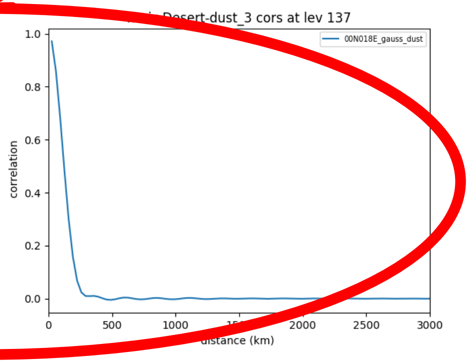


LMD IASI 10um obs 20210222 12hr
Valid for coarse dust bin

This requires introducing additional variables into the control vector with associated new fields in the backgound error statistics.

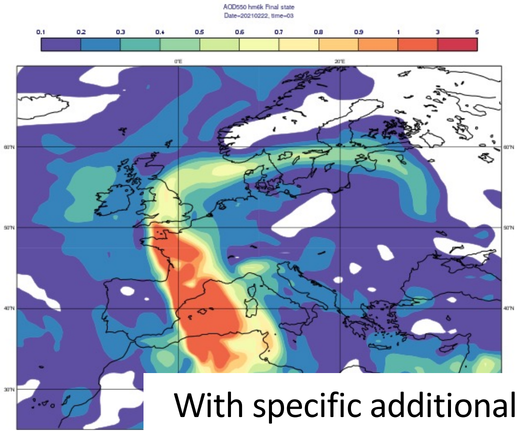
CAMS control variables	→	CAMS control variables
GO3		GO3
CO		CO
NO2		NO2
SO2/SO2VOLC		SO2/SO2VOLC
HCHO		HCHO
Total aerosol		Total aerosol
		Coarse dust bin 3

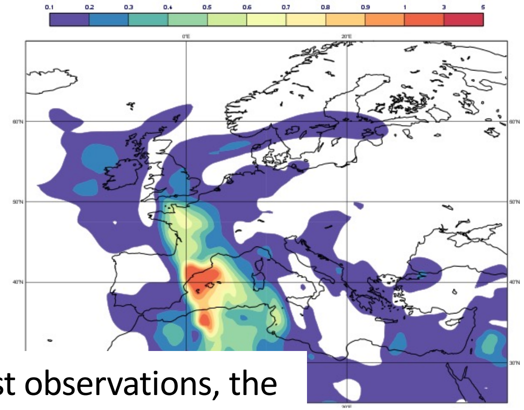


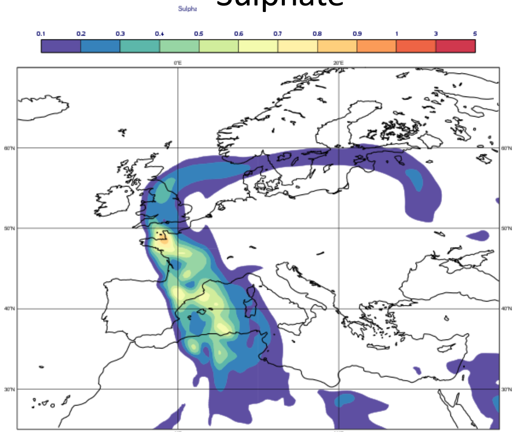


Dust AOD assimilation

Dust | Sulphate

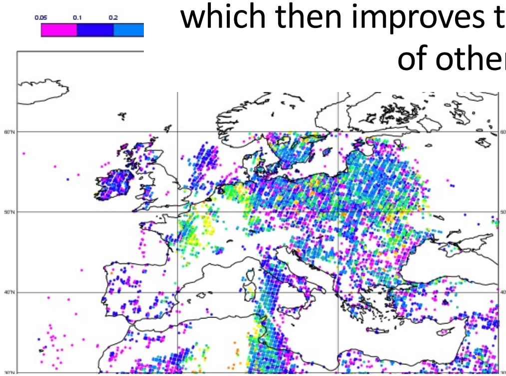


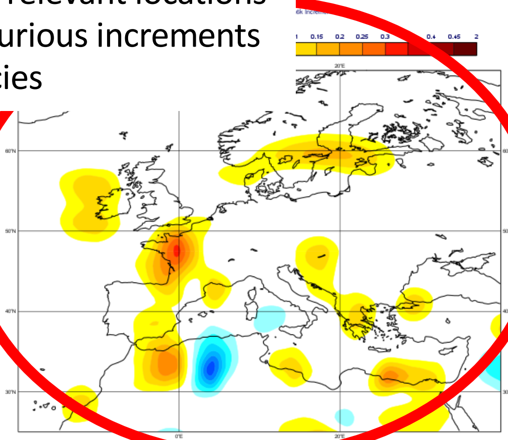


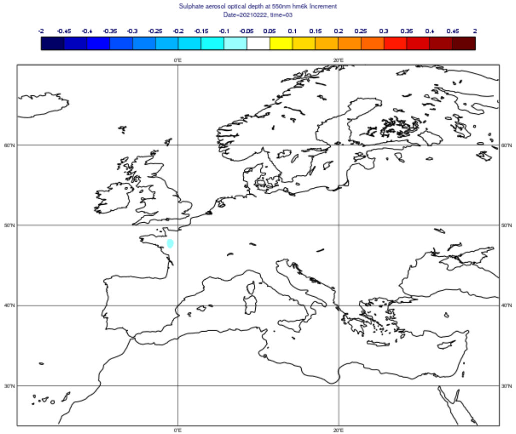


AOD at 550nm

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







AOD incr at 550nm

LMD IASI 10um obs 20210222

Atmosphere Monitoring

OUTLINES

1. Introduc
2. What is
3. Ff
4. Ff
5. Assimila
6. Conclusions

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

Atmosphere Monitoring

Conclusions

✓ **Aerosol model developments**

- Wet and dry deposition processes
- Second organic aerosols
- Dust size distribution and optical properties

✓ **Satellite AOD monitoring**

- Ocean
  - VIIRS < MODIS over ocean background and dust outbreak in the Atlantic
  - S3/SLSTR much lower due to too stringent cloud filtering
  - Differences between platforms due to radiometric biases in level-1 (e.g. SNPP)
- Land
  - VIIRS>MODIS over biomass burning regions and dust source regions

Atmosphere Monitoring

Conclusions

✓ Impact of assimilating VIIRS compared to MODIS

- Lower increment over ocean and mid-Atlantic dust outbreak
- Higher increment over biomass burning regions
- Positive impact on AOD forecast: reduction of bias, particularly for Europe and desert sites

✓ Assimilation of dust observations

- Improved aerosol speciation
- Technical demonstrator
- Uncertainties in IASI observations (limited sensitivity at the surface)

European Commission | Copernicus Europe's eyes on Earth ECMWF

Atmosphere Monitoring

- ADDITIONAL SLIDES

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

CAMS Global analyses and forecasts

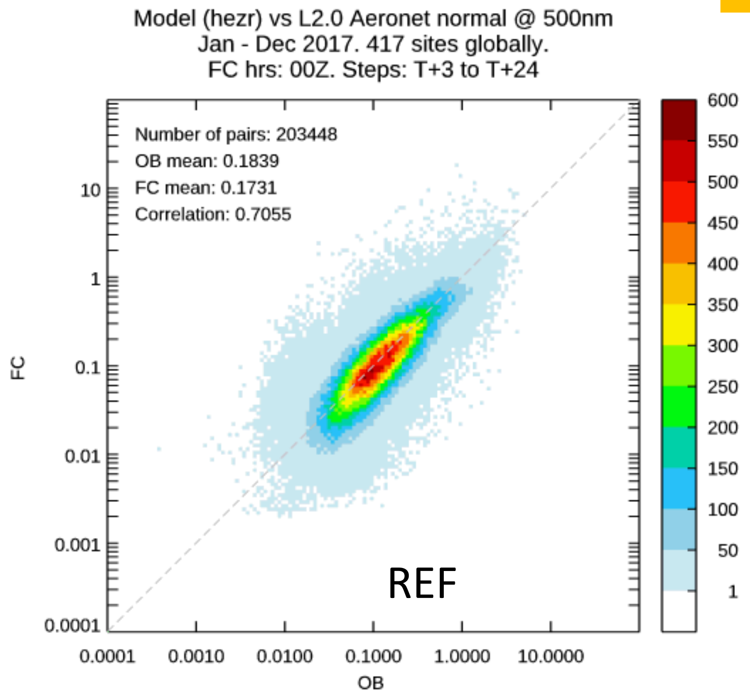
- The atmospheric composition forecasting system used in CAMS is the Integrated Forecasting System (IFS) of the ECMWF with aerosol (IFS-AER), trace gases and long-lived greenhouse gases extensions.
- IFS-AER is a simple bulk/bin aerosol scheme (Remy et al., 2022 and 2019; Morcrette et al., 2009).
  - 7 species: sea-salt, dust, organic matter (OM), black carbon (BC), sulfate, nitrate and ammonium
  - Three bins for dust and sea-salt,
  - For OM, BC, hydrophilic and hydrophobic components,
  - Two species for nitrate: produced by gas/particle partitioning (fine mode) or by heterogeneous reactions on dust and sea-salt particles (coarse mode)
- Gas-phase chemistry based on CB05 as used in the TM5 CTM; stratospheric chemistry from the BASCOE model (Huijnen et al., 2010; Flemming et al., 2015; Huijnen et al., 2016).
- All the results presented are from simulations without data assimilation.

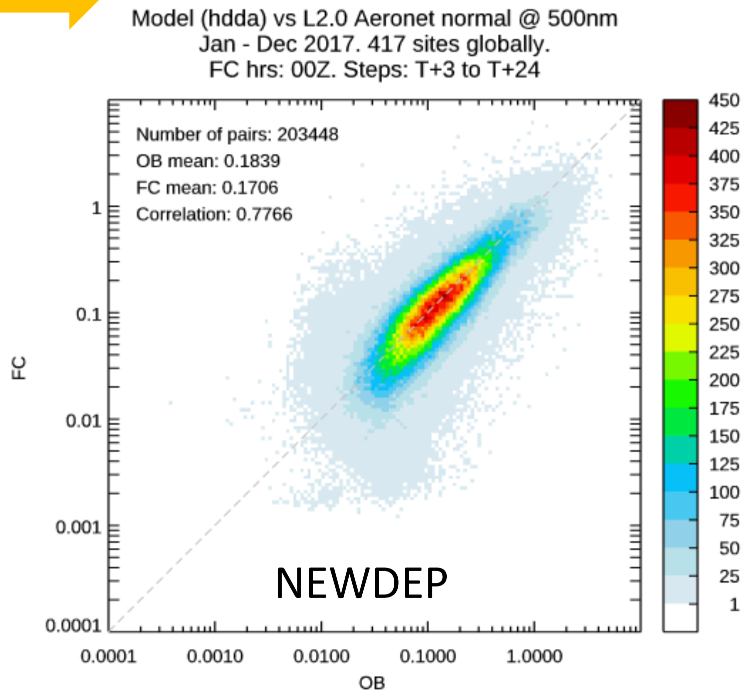
Atmosphere Monitoring

New dry and wet deposition schemes

Evaluation of the impact on simulated AOD globally (forecast only), against AERONET L2.0

Significant improvement in correlation





ECMWF

SATELLITE AOD USED IN CAMS

Atmosphere Monitoring

Products used in operational assimilation

- **MODIS**
  - AQUA, TERRA
  - C6
  - DB+DT product
  - 10 km
  - Land and ocean
  - Thinning
  - Spatially constant obs error

- **PMAp**
  - METOP-A,B,C
  - From GOME-2+IASI+AVHRR
  - V2.1
  - 40*10 km
  - Assimilated over ocean only
  - Thinning
  - Pixel-level observation error +inflation

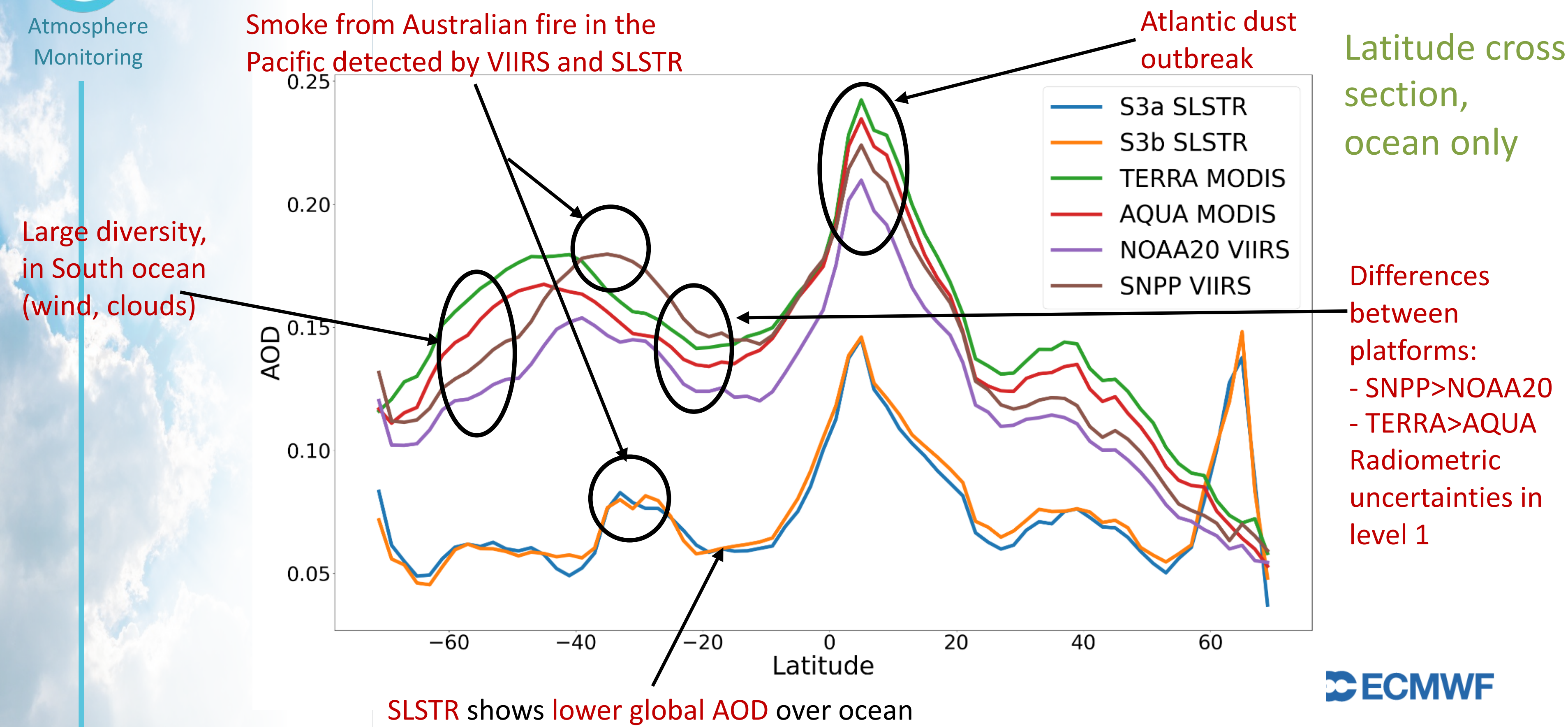
Monitored/tested new product

- **NOAA-EPS VIIRS**
  - NOAA-20 and S-NPP
  - V2r1
  - 0.750m
  - Land and ocean
  - Superobbing
  - Pixel-level observation error

Multi-satellite AOD product intercomparison

Atmosphere Monitoring

Latitude cross section, ocean only



ECMWF

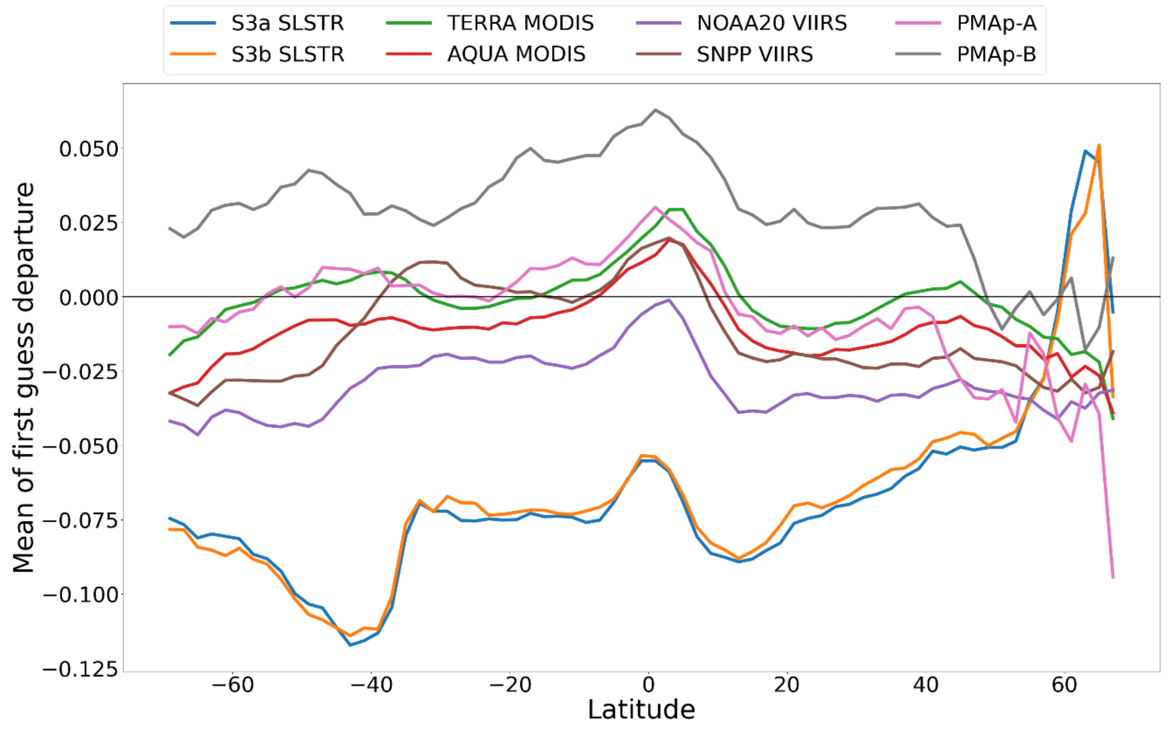
Ocean (Dec 2019-Feb 2020)

Garrigues et al., ACP, 2022

Multi-satellite AOD product intercomparison

Atmosphere Monitoring

Mean first guess departure (observation-model)



Latitude cross section, ocean only

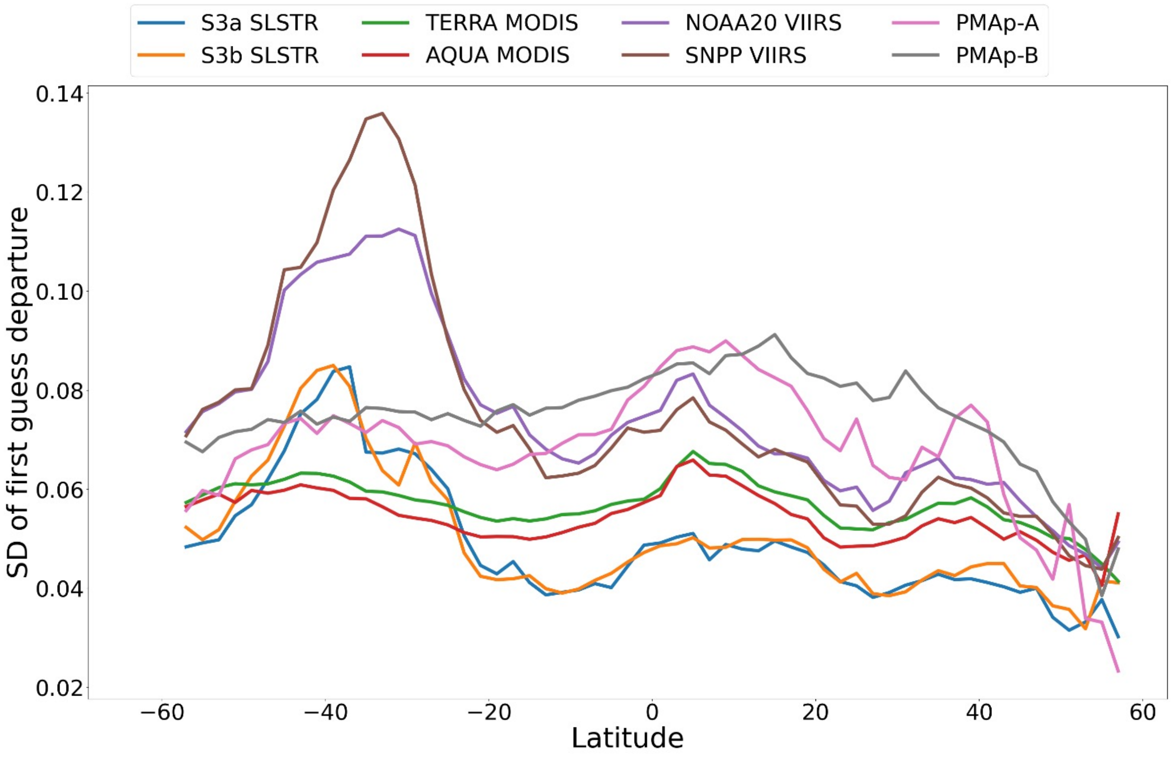
Ocean (Dec 2019-Feb 2020)

Garrigues et al., ACP, 2022

Atmosphere Monitoring

Multi-satellite AOD product intercomparison

SD of first guess departure (observation-model)



Latitude cross section, ocean only

ECMWF

Ocean (Dec 2019-Feb 2020)

Garrigues et al., ACP, 2022

Experiment design

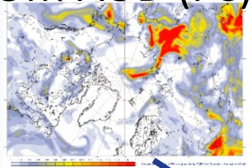
Experiments	Model	MODIS	VIIRS	PMAp
PMAp, MODIS - 47r3	47r3	Anchor: TERRA and AQUA	No	Bias Corrected
PMAp, MODIS, VIIRS-47r3	47r3	Bias Corrected	Bias Correction : SNPP, Anchor: NOAA20	Bias Corrected
VIIRS only-47r3	47r3	NO	Bias Correction : SNPP, Anchor: NOAA20	No
MODIS Only-47r3	47r3	Bias Corrected : TERRA, Anchor: AQUA	No	No
PMAp, MODIS-48r1	48r1	Anchor: TERRA and AQUA	No	Bias Corrected
PMAp, MODIS, VIIRS – 48r1	48r1	BC	Bias Correction : SNPP, Anchor: NOAA20	Bias Corrected

Summer 2020 atmospheric composition events

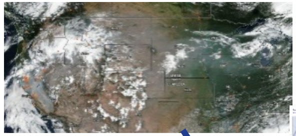
Atmosphere Monitoring

SIBERIA FIRE

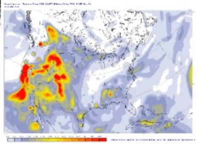
OM AOD (FC)



CALIFORNIA FIRES

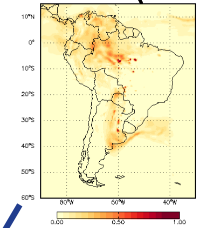


OM AOD (FC)

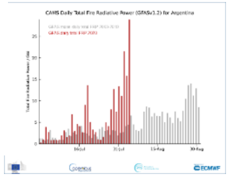


SOUTH AMERICA FIRES

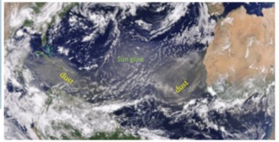
OM (AN)

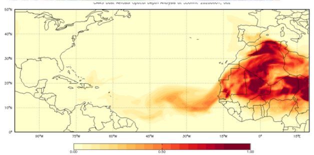


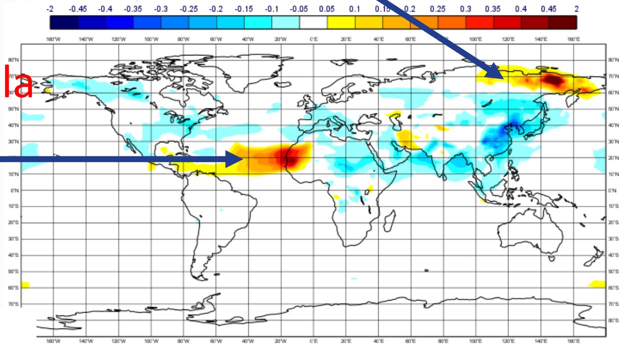
FRP



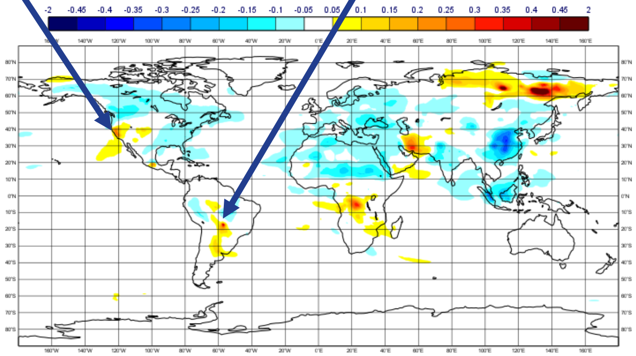
DUST (godzilla event)







CAMS June AOD anomalies



CAMS August AOD anomalies

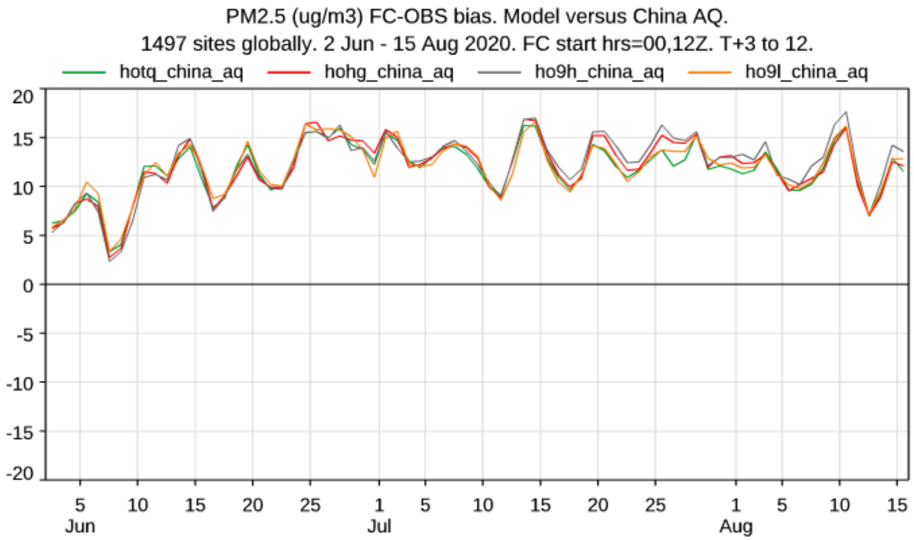
European Commission | Copernicus Europe's eyes on Earth | ECMWF

Credit: Mark Parrington (CAMS weather room, June-Sept 2020)

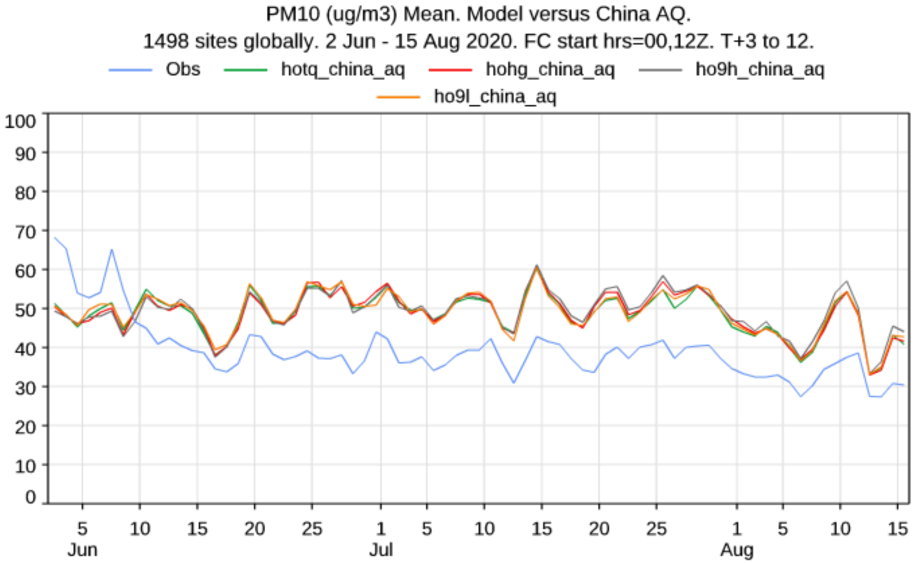
PM EVALUATION AGAINST AIRCHINA

Atmosphere Monitoring

PM2.5



PM10



No significant differences between experiments

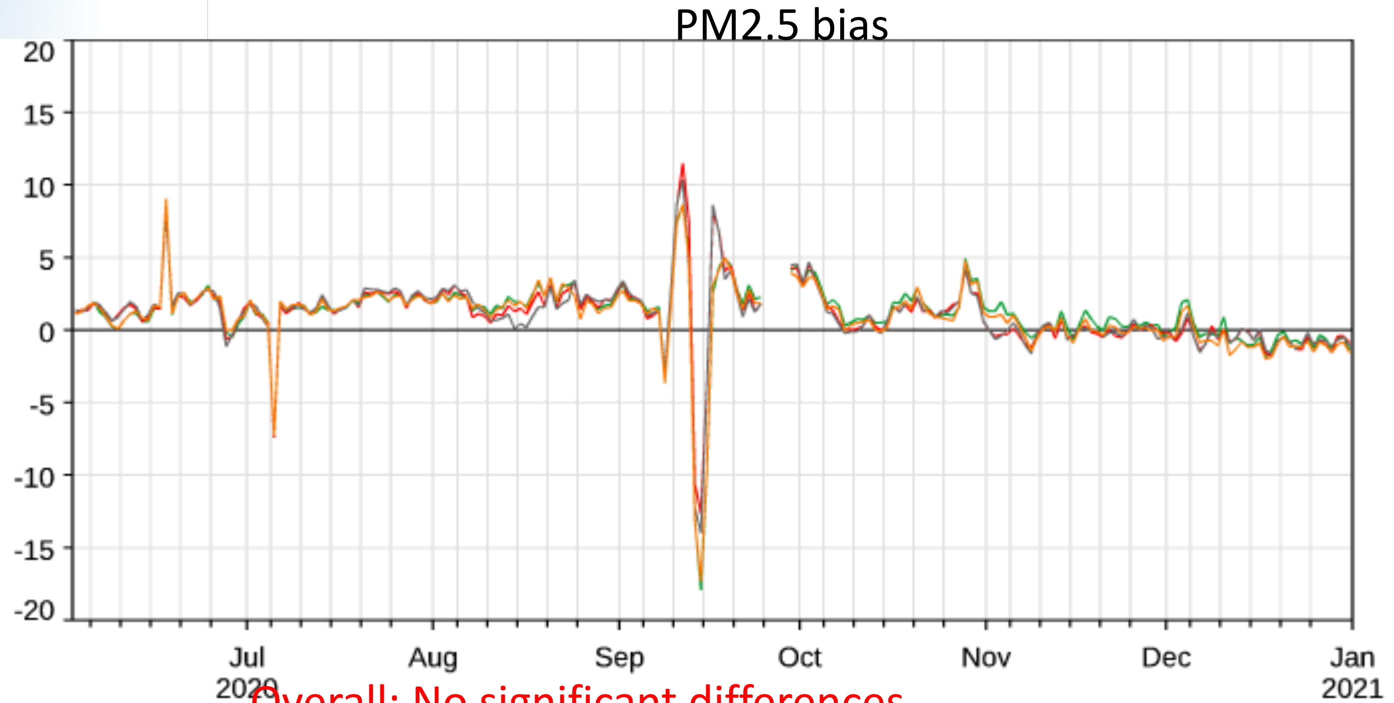
No significant impact of VIIRS assimilation

- EXP_{CTL} : MODIS, PMAp
- EXP_{PMV} : MODIS, PMAp, VIIRS
- EXP_{V} : VIIRS only (anchor SNPP)
- EXP_{M} : MODIS only (anchor AQUA)

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

Atmosphere Monitoring

PM2.5 EVALUATION AGAINST AIRNOW(US)



Overall: No significant differences

Mid-August: reduction of bias for the California fire season

- EXP_{CTL} : MODIS, PMAp
- EXP_{PMV} : MODIS, PMAp, VIIRS
- EXP_{V} : VIIRS only (anchor SNPP)
- EXP_{M} : MODIS only (anchor AQUA)

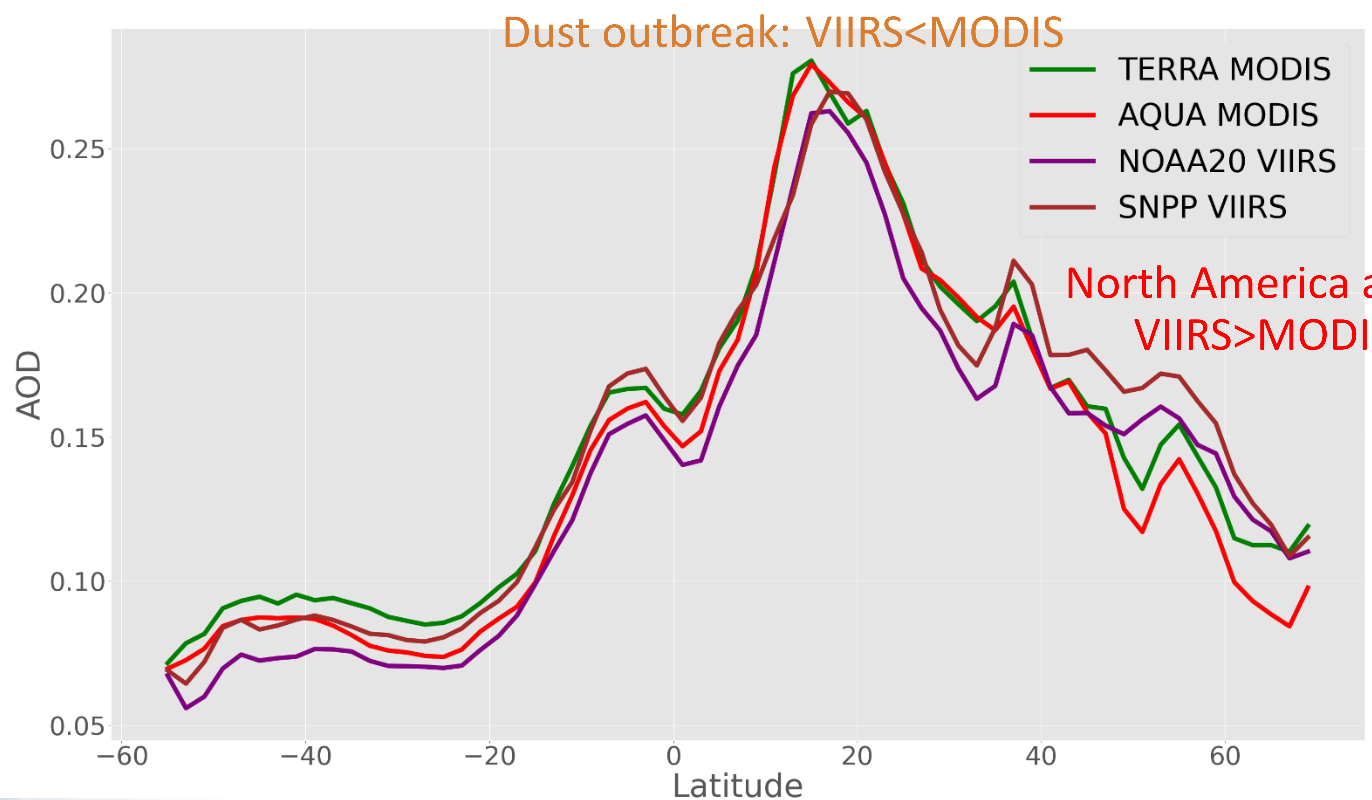
European Commission | Copernicus Europe's eyes on Earth | ECMWF

Comparison of VIIRS and MODIS AOD

Atmosphere Monitoring

Satellite AOD latitude transect (ocean and land)

Temporal average
June-August 2020



ECMWF

Impact of assimilation window

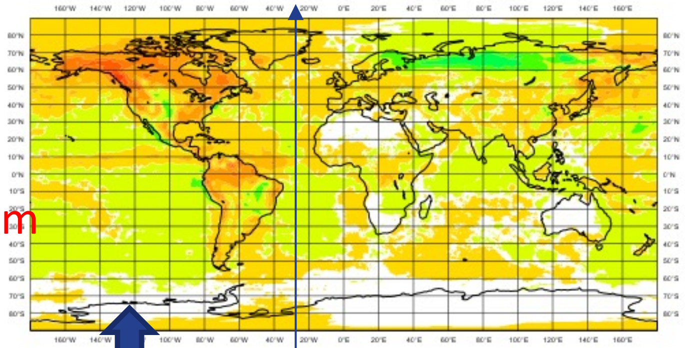
Atmosphere Monitoring

00z

3pm to 3am

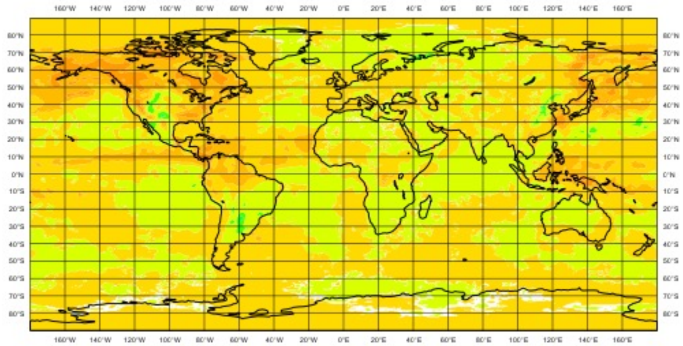
00z VIIRS only (anchor noaa20)

Mean: 4.65e-03 SDD: 2.13e-02

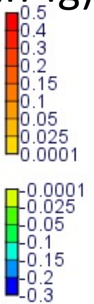


00z MODIS only (anchor AQUA)

Mean: 5.76e-03 SDD: 1.45e-02



Increments (an-fg)



Impact of VIIRS

Impact of VIIRS

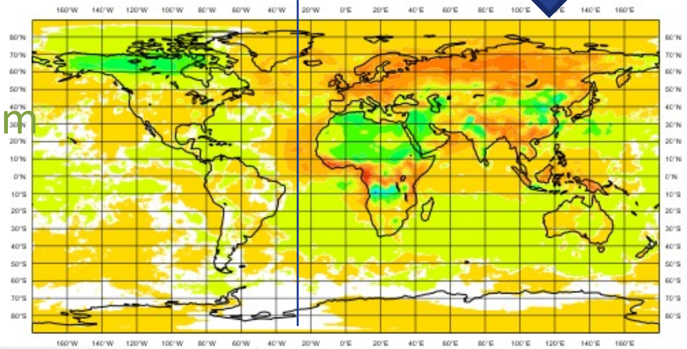
MODIS less impacted by assimilation window

12z

3am to 3pm

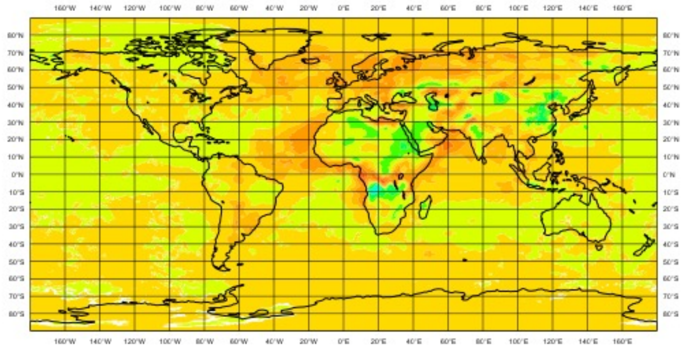
12z VIIRS only (anchor noaa20)

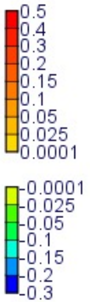
Mean: 5.11e-03 SDD: 2.50e-02



12z MODIS only (anchor AQUA)

Mean: 5.92e-03 SDD: 1.79e-02

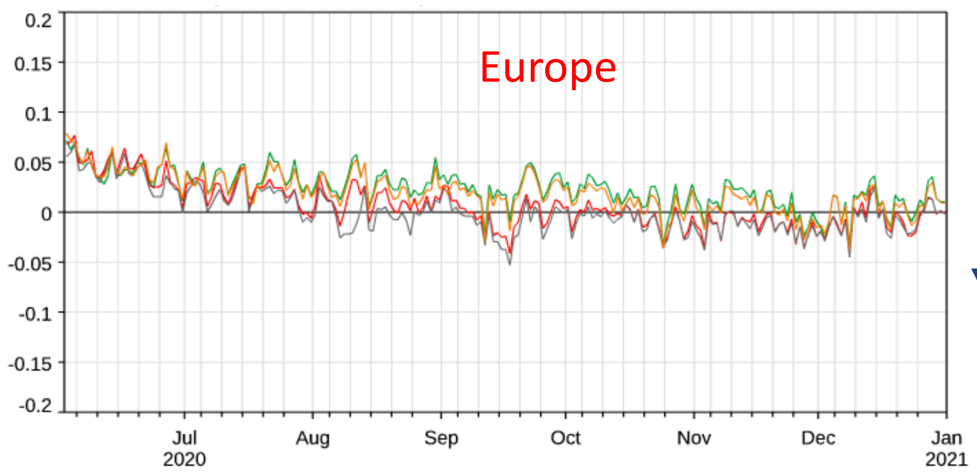




Regional EVALUATION AGAINST AERONET

Atmosphere Monitoring

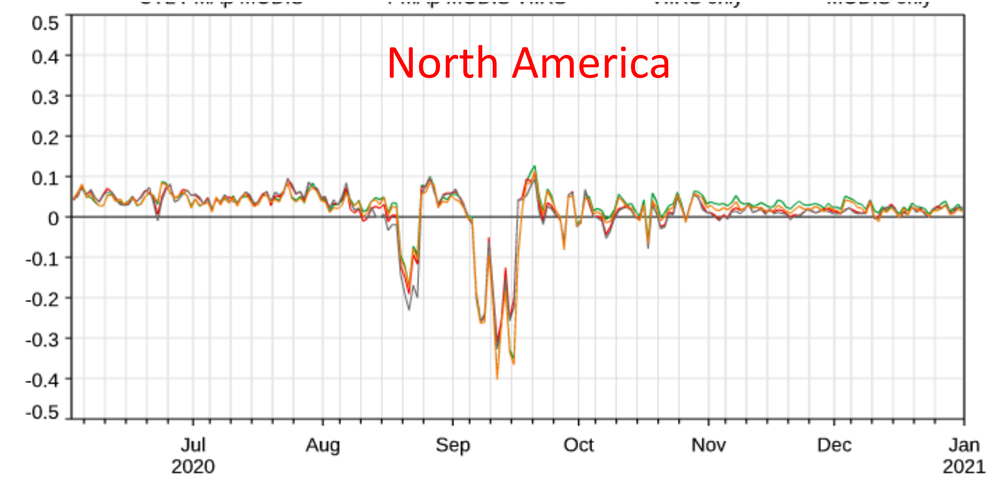
bias



VIIRS assimilation

Bias reduction

bias



VIIRS assimilation: No significant impact

- EXP_{CTL} : MODIS, PMAp
- EXP_{PMV} : MODIS, PMAp, VIIRS
- EXP_{V} : VIIRS only (anchor SNPP)
- EXP_{M} : MODIS only (anchor AQUA)

ECMWF

Regional EVALUATION AGAINST AERONET

Atmosphere Monitoring

Desert sites

Oceanic sites

VIIRS assimilation

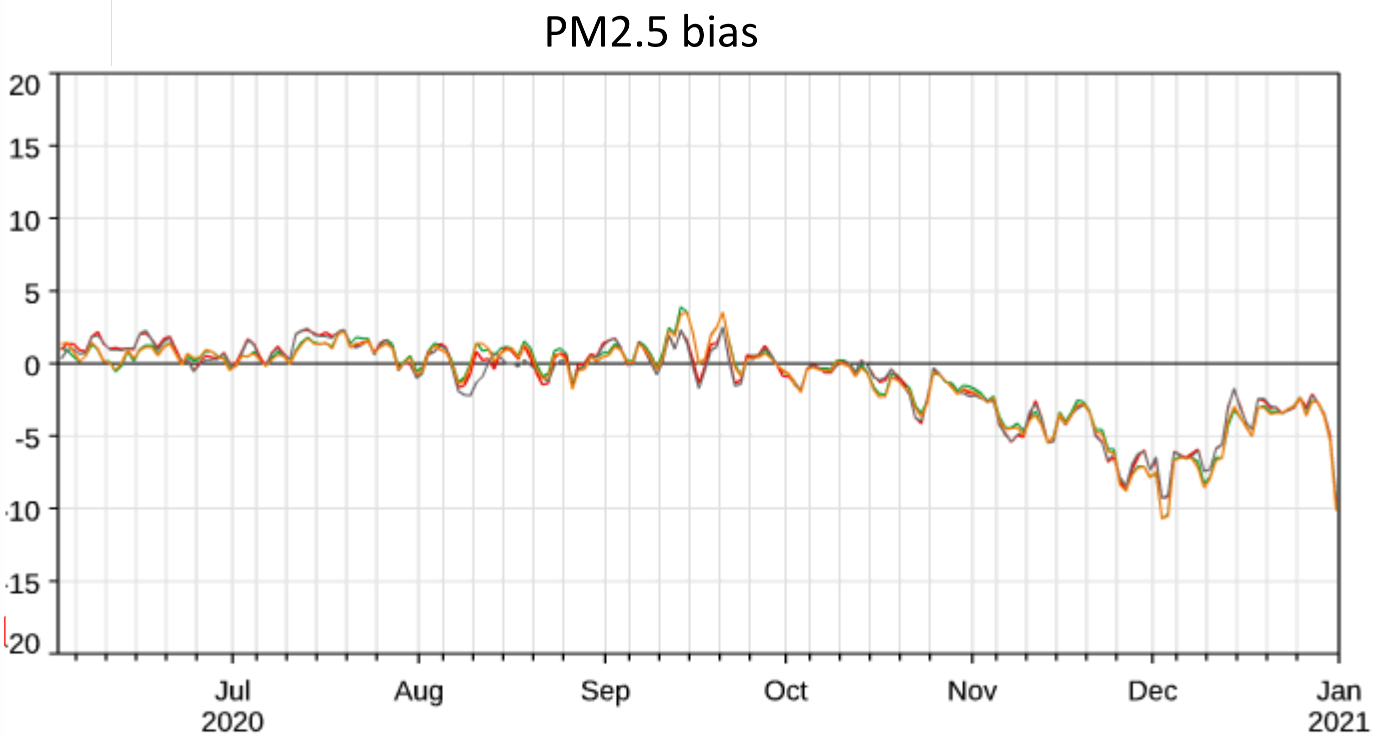
Bias reduction

Slight bias reduction

- EXP$_{CTL}$: MODIS, PMAp
- EXP$_{PMV}$: MODIS, PMAp, VIIRS
- EXP$_{V}$: VIIRS only (anchor SNP
- EXP$_{M}$: MODIS only (anchor A

ΛWF

PM EVALUATION AGAINST AIRBASE(Europe)



- EXP_{CTL} : MODIS, PMAp
- EXP_{PMV} : MODIS, PMAp, VIIRS
- EXP_{V} : VIIRS only (anchor SNPP)
- EXP_{M} : MODIS only (anchor AQUA)