Forecasting atmospheric composition at ECMWF:

Achievements and challenges of the global CAMS system.

COPERNICUS ATMOSPHERE MONITORING SERVICE

Johannes Flemming (ECMWF)

Antje Inness, Mark Parrington, Angela Benedettie, Vincent-Henri Peuch, Richard Engelen, Vincent Huijnen (KNMI), Samuel Remy (HyGEOS), Zak Kipling, CAMS development section, CAMS 43,43,44 81 and 84

WHAT IS COPERNICUS?

- Copernicus is **a flagship Space programme** of the **European Union**
  - to monitor **the Earth,** its environment and ecosystems
  - to ensure its citizens are prepared and protected for **security risks** and **natural or man-made environmental risks and disasters**
- Copernicus as **user-driven** Programme
- It has **full, free and open to all** data policy
- Initiated in 1998, Copernicus became **operational in 2014**. Budget for 2014-2020 was **4.3 B€**. Foreseen budget for 2021-2027 is **5.8 B€**.

THE COPERNICUS SENTINELS

Copernicus

		Key Features
 SENTINEL-1: 4-40m resolution, 3 day revisit at equator	*S1A and 1B in orbit*	Polar-orbiting, all-weather, day-and-night radar imaging
 SENTINEL-2: 10-60m resolution, 5 days revisit time	*S2A and 2B in orbit*	Polar-orbiting, multispectral optical, high-resolution imaging
 SENTINEL-3: 300-1200m resolution, <2 days revisit	*S3A and S3B in orbit*	Optical and altimeter mission monitoring sea and land parameters
 SENTINEL-4: 8km resolution, 60 min revisit time	*1st Launch 2022*	Payload for atmosphere chemistry monitoring on MTG-S
 SENTINEL-5p: 7-68km resolution, 1 day revisit	*S5P in orbit*	Mission to reduce data gaps between ENVISAT, and Sentinel 5
 SENTINEL-5: 7.5-50km resolution, 1 day revisit	*1st Launch 2023*	Payload for atmosphere chemistry monitoring on MetOp 2ndGen
 SENTINEL-6: 10 day revisit time	*1st Launch 2020*	Radar altimeter to measure sea-surface height globally

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6 COPERNICUS THEMATIC SERVICES

Monitoring the State of the Earth System Environment ...

ECMWF

... Six cross-cutting Thematic Services

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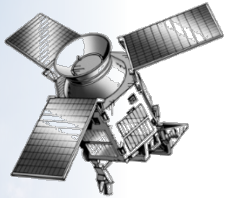
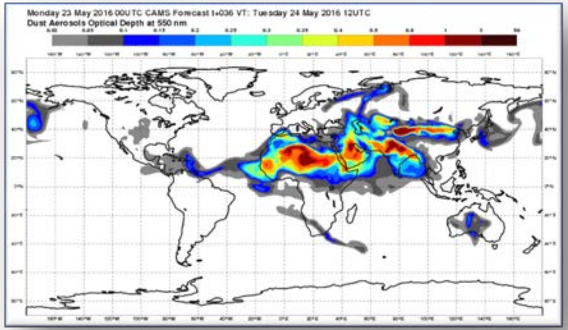
Atmosphere Monitoring

CAMS SYSEM OVERVIEW

Space Agencies

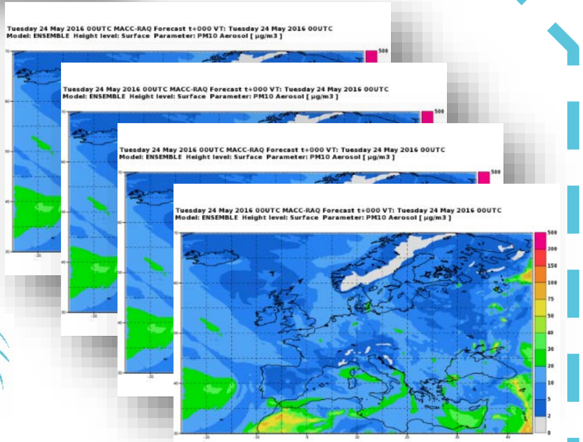




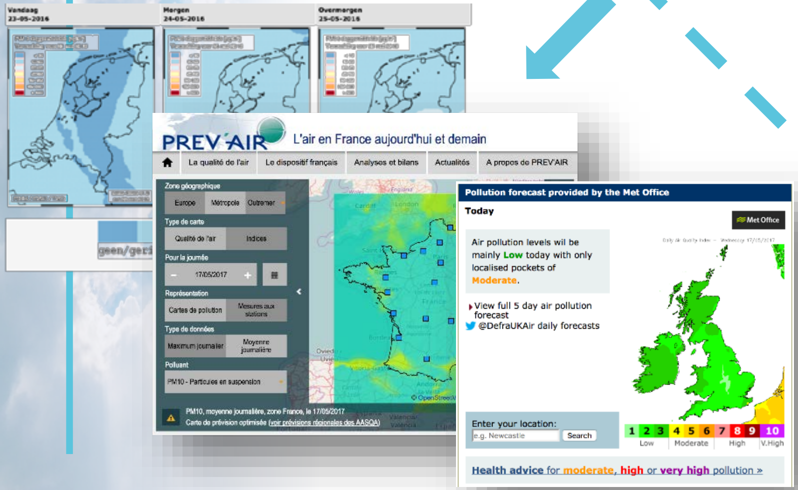
ECMWF/IFS

In-situ observations

7+2 regional CTMs



National scale



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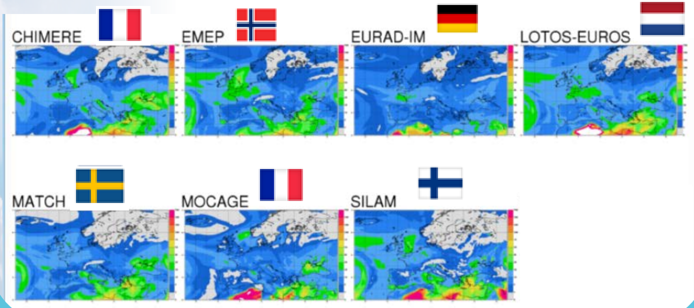
CAMS EUROPEAN AIR QUALITY PORTFOLIO

Atmosphere Monitoring

Based on a multi-model approach (same boundary conditions, same emissions, same meteo, assimilation of 1000+ surface observations for key species)

Individual operational AQ models



DEHM (AARHUS University)

GEM-AQ (IEP)

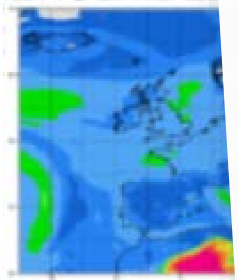
MINNI (ENEA)

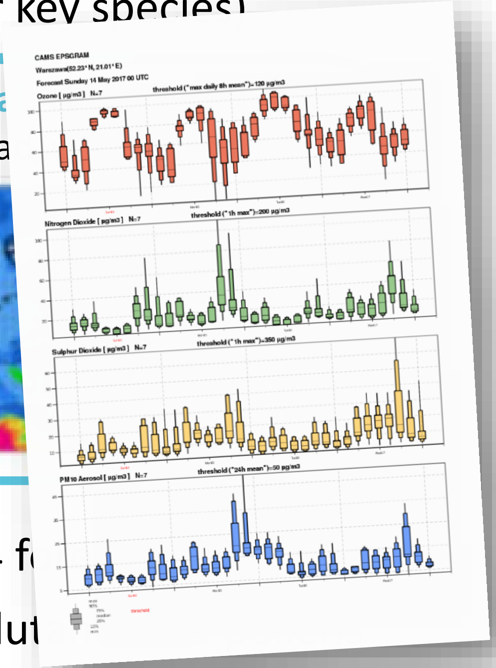
MONARCH (BSC)

http://regional.atmosphere.copernicus.eu

Operationa

(incl. sprea



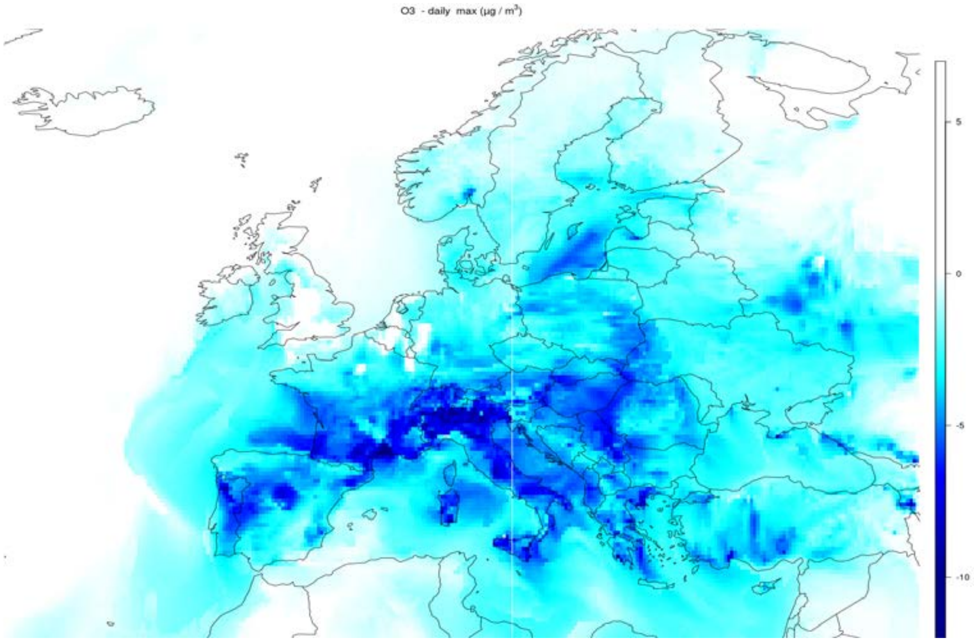


- Once daily D+4 f
- Regulatory pollut
- Annual reanalyses
- ~ 10km resolution

PRODUCTS IN SUPPORT OF POLICY USERS

Assess the effect of emission reductions on daily forecasts

CAMS_ACT : O3, PM10 (PM2.5 coming)

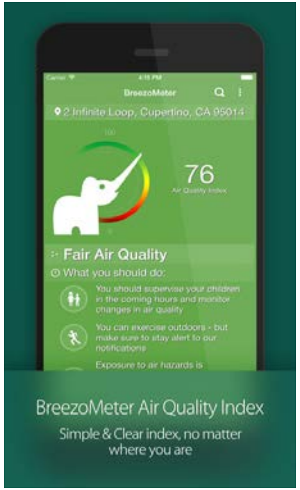


http://policy.atmosphere.copernicus.eu/CAMS_ACT.html

CAMS products are widely used

Atmosphere Mo

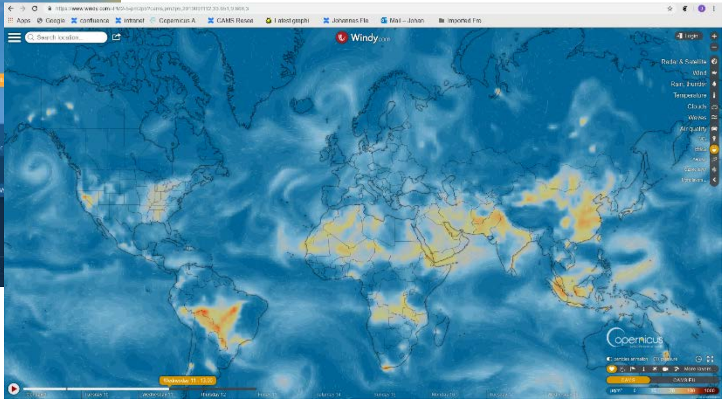
Plumelabs

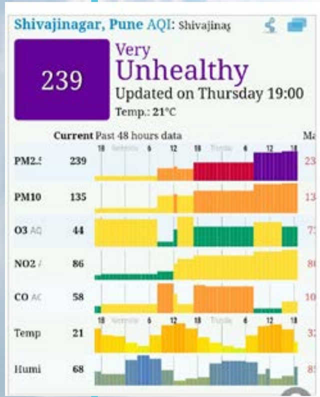


Breezometer

Euronews

www.windy.com





aqcin

Apple iOS 12 Weather app

The Weather Channel

TWC web and app

https://www.windy.com/-PM2-5-pm2p5?cams,pm2p5,2019091111,20.468,-18.124,3

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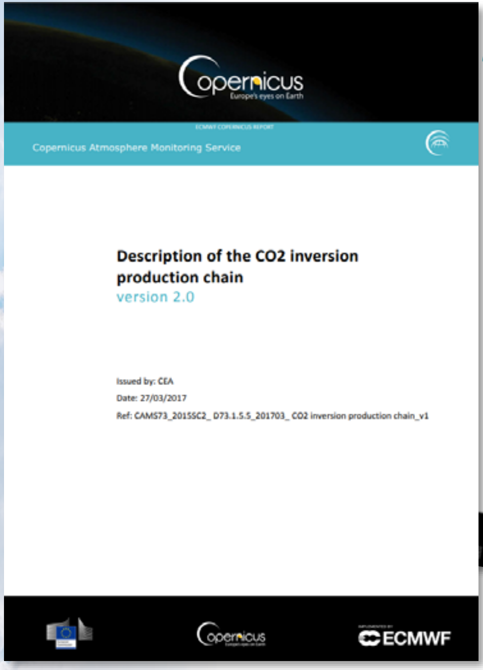
DOCUMENTATION & QUALITY CONTROL

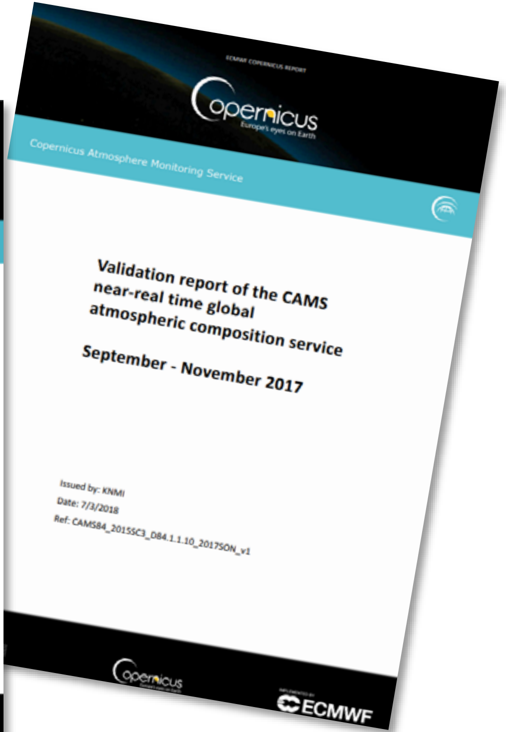
Atmosphere Monitoring


Copernicus
Europe's eyes on Earth
ECMWF COPERNICUS REPORT
Copernicus Atmosphere Monitoring Service

Description of the CO2 inversion production chain
version 2.0

Issued by: CEA
Date: 27/03/2017
Ref: CAMS73_2015SC2_ D73.1.5.5_201703_ CO2 inversion production chain_v1

Copernicus ECMWF

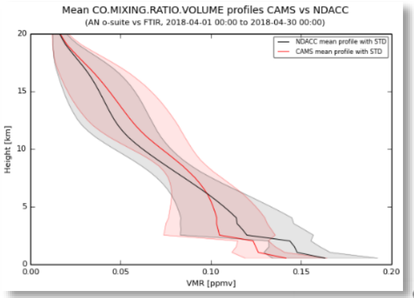

ECMWF COPERNICUS REPORT
Copernicus
Europe's eyes on Earth
Copernicus Atmosphere Monitoring Service

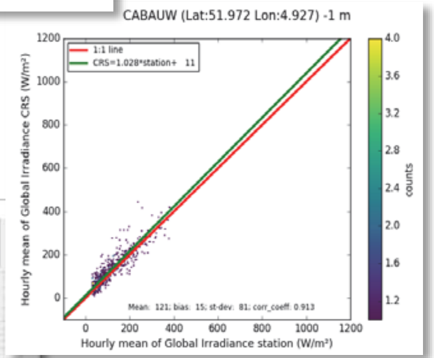
Validation report of the CAMS near-real time global atmospheric composition service

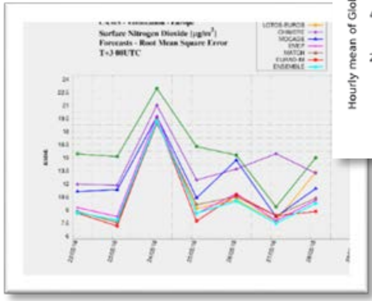
September - November 2017

Issued by: KNMI
Date: 7/3/2018
Ref: CAMS84_2015SC3_D84.1.1.10_2017SON_v1

Copernicus ECMWF







See talk by Henk Eskes

CAMS provides detailed information about how its products are produced and what the quality is

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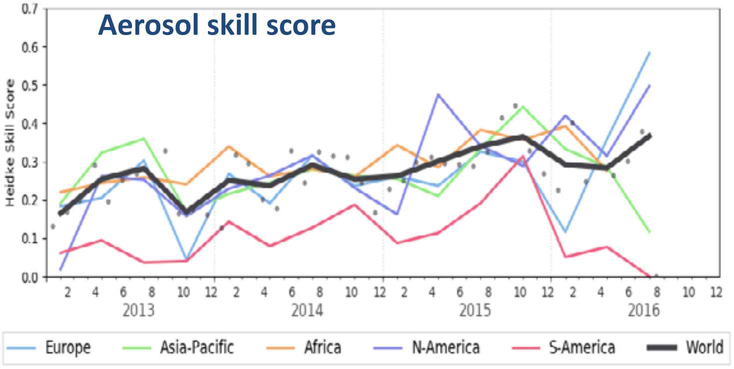
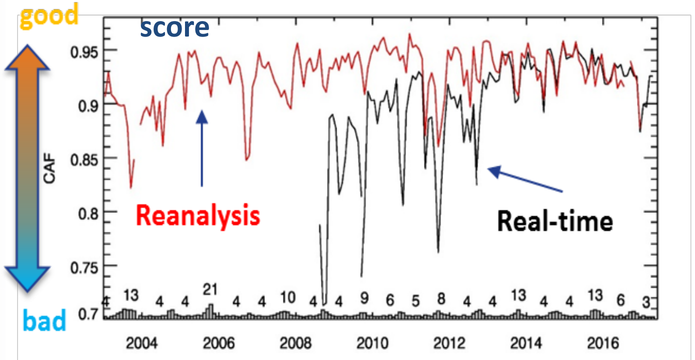
IMPROVMENTS of GLOBAL CAMS Forecast

Atmosphere Monitoring

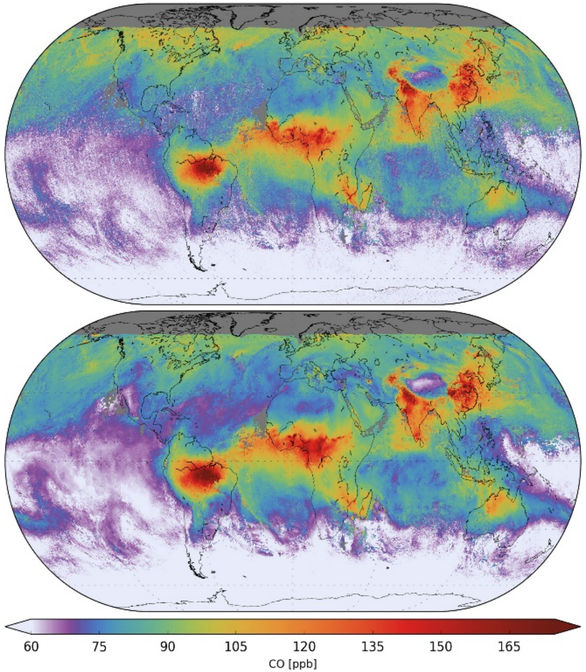


Michael Schulz, MetNo



Antje Inness, ECMWF

Carbon monoxide
Sentinel-5p observations (top) vs CAMS model (bottom)



Borsdorff et al., JRL, 2018

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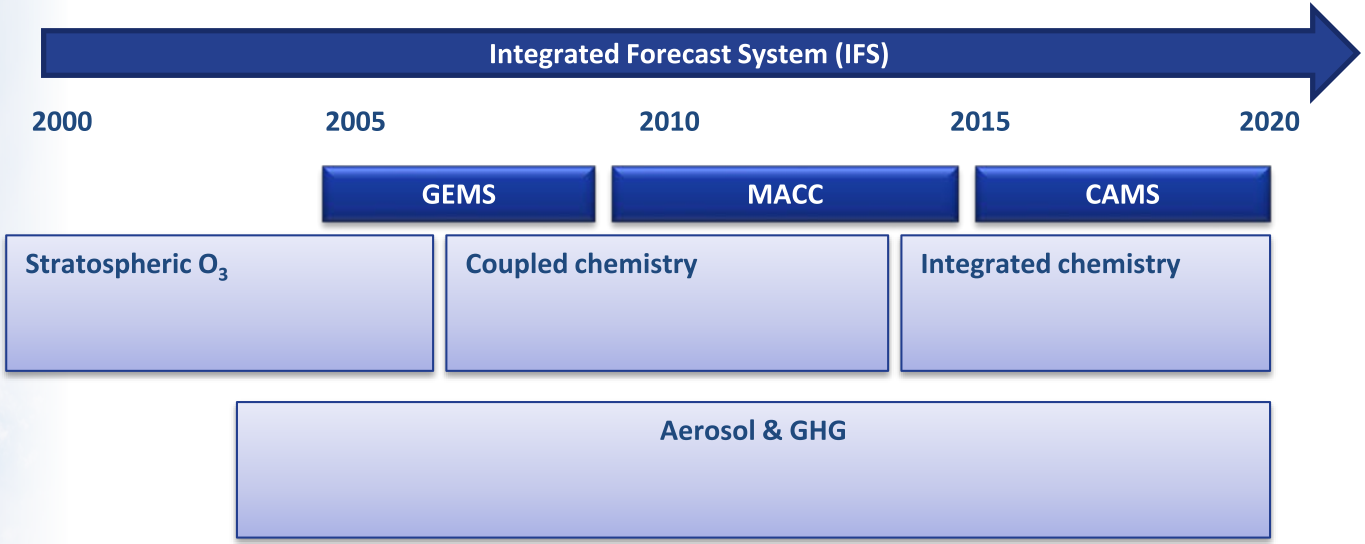
Development of atmospheric composition in the Integrated Forecast System

Atmosphere Monitoring



GEMS = Global and regional Earth-system (atmosphere) Monitoring using Satellite and in-situ data
MACC = Monitoring Atmospheric Composition and Climate
CAMS = Copernicus Atmosphere Monitoring System

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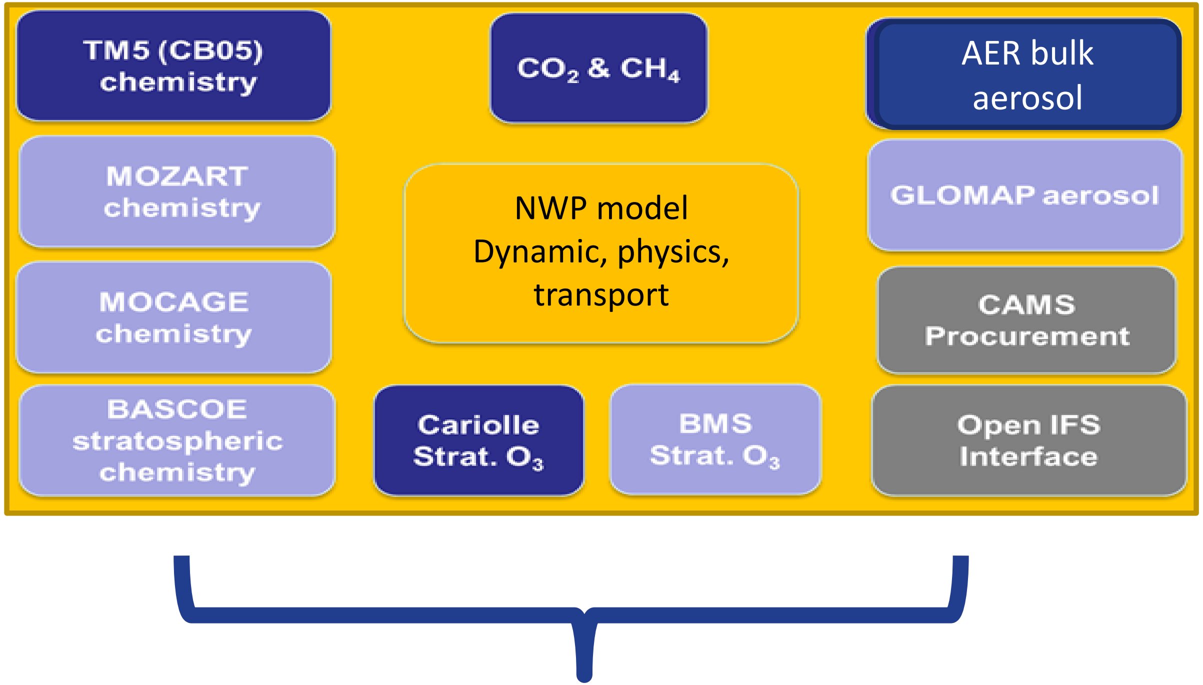
Atmosphere Monitoring

Atmospheric Composition in the IFS



ECMWF's Integrated Forecasting System (IFS)

Atmosphere Monitoring

The operational aerosol and chemistry schemes in the IFS (CAMS)

Aerosol (14 species):

AER Bulk scheme

SS_{small}	SS_{mid}	SS_{large}
DU_{small}	DU_{mid}	DU_{large}
OM_{hphob}	OM_{hphil}	
BC_{hphob}	BC_{hphil}	
SO_2	SO_4	
NO_3 fine	NO_3 coarse	NH_4

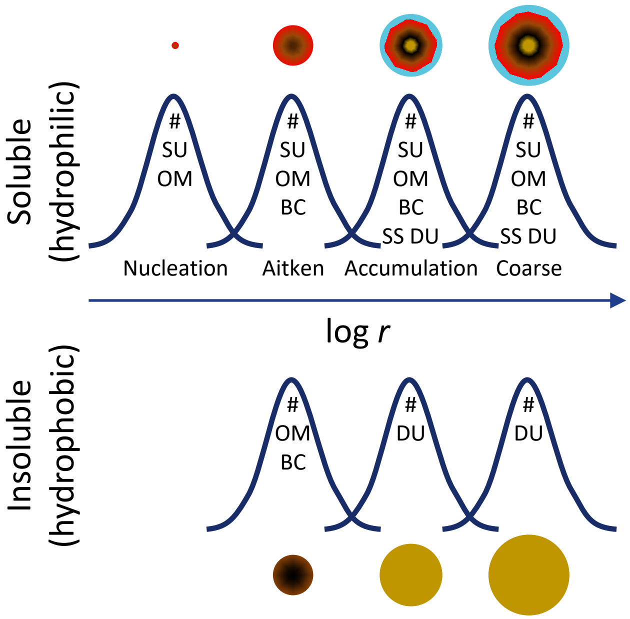
Chemistry (56 species):

CB05 & Cariolle stratospheric ozone scheme

O_3	NO_x	H_2O_2	CH_4	CO	HNO_3
CH_3OOH	CH_2O	PAR	C_2H_4	OLE	ALD_2
PAN	ROOH	ONIT	C_5H_8	SO_2	DMS
NH_3	SO_4	NH_4	MSA	CH_3COCHO	$O_{3\ (strat)}$
Rn	Pb	NO	HO_2	CH_3O_2	OH
NO_2	NO_3	N_2O_5	HO_2NO_2	C_2O_3	ROR
RXPAR	XO_2	XO_2N	NH_2	CH_3OH	HCOOH
MCOOH	C_2H_6	C_2H_5OH	C_3H_8	C_3H_6	$C_{10}H_{16}$
ISPD	NO_3	CH_3COCH_3	ACO_2	$IC_3H_7O_2$	$HYPROPO_2$
NO_xA	PSC				

In development: IFS–GLOMAP

- GLOMAP-mode (Mann et al., 2010) introduced as alternative aerosol scheme in 46r1
  - Two-moment modal scheme combining M7-like size modes with microphysical parameterisations from GLOMAP-bin (Spracklen et al., 2005).
  - Coupled with whole atmosphere chemistry as "IFS-CB05-BASCOE-GLOMAP".
  - AER(bulk) and GLOMAP use the same emissions



Atmosphere Monitoring

Mulitple chemistry schemes in the IFS

	IFS(CB05BASCOE) CBA	IFS(MOCAGE) MOC	IFS(MOZART) MOZ
Tropospheric chemistry	Carbon Bond	RACM	CAM4-Chem
Stratospheric chemistry	BASCOE	REPROBUS	MOZART3
Number of species/reactions	99 / 219	115 / 326	115 / 266
Complexity of organic chemistry	Explicit degradation pathways up to C3	Detailed lumping approach	Explicit degradation pathways up to C10
Aerosol interaction in troposphere	HO_2 and N_2O_5 heterogeneous reactions, aerosol impact on photolysis	HO_2 and N_2O_5 heterogeneous reactions (new!)	N_2O_5 heterogeneous reaction (revised!)
Photolysis parameterization	Modified Band (trop) LUT (strat)	LUT (revised!)	LUT (trop); Explicit transmission function (strat)
Solver	3rd order Rosenbrock (2x)	3rd order Rosenbrock (new!)	Explicit forward and implicit backward Euler
Emissions / Deposition	MACCity *or* CAMS_GLOB (new!) / Online deposition (new!)		

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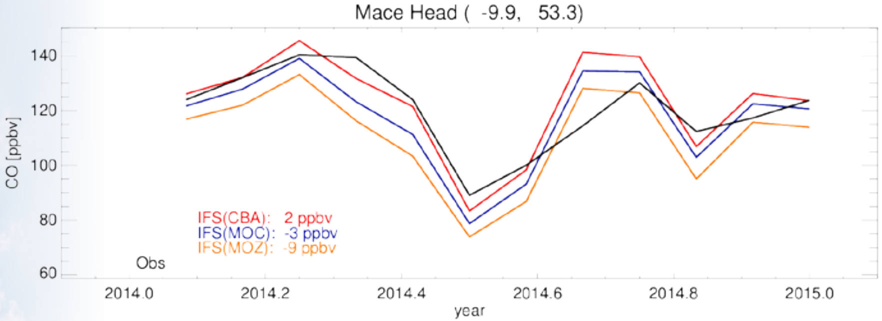
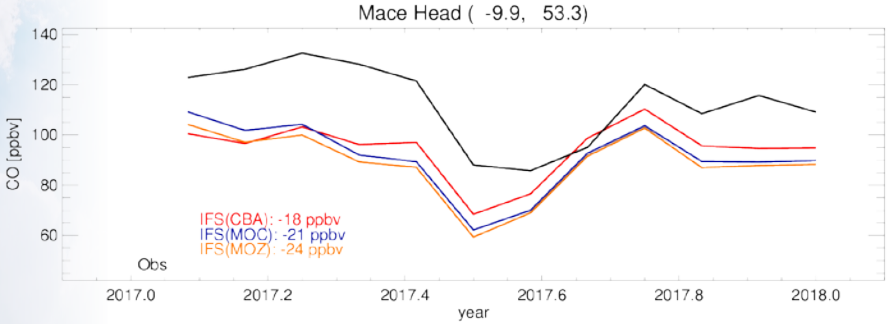
CO simulation with CAMS chemistry schemes



2014 MACCITY emission



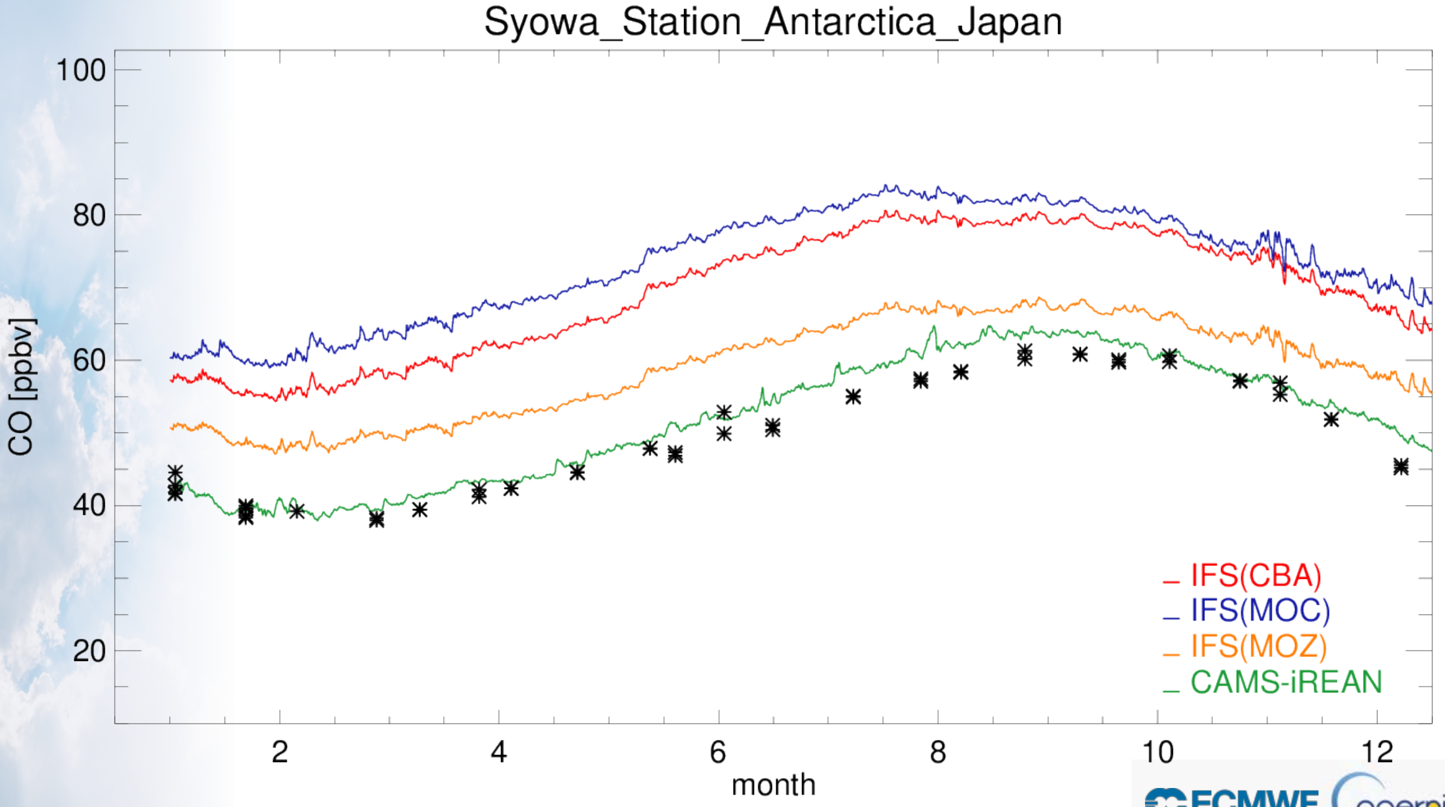
2017 CAMS GLOB ver2.1 emissions

All schemes have identical emissions and transport

10 ppb variation because of chemistry formulation

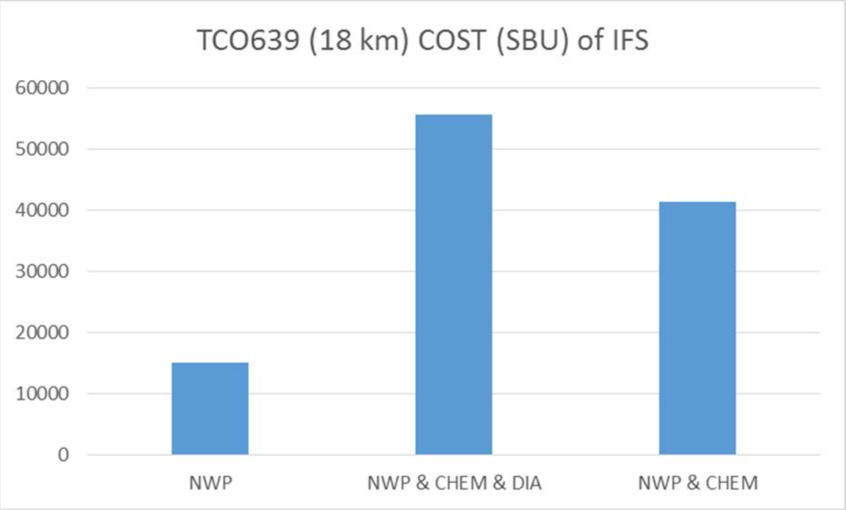
Huijnen et al. 2019

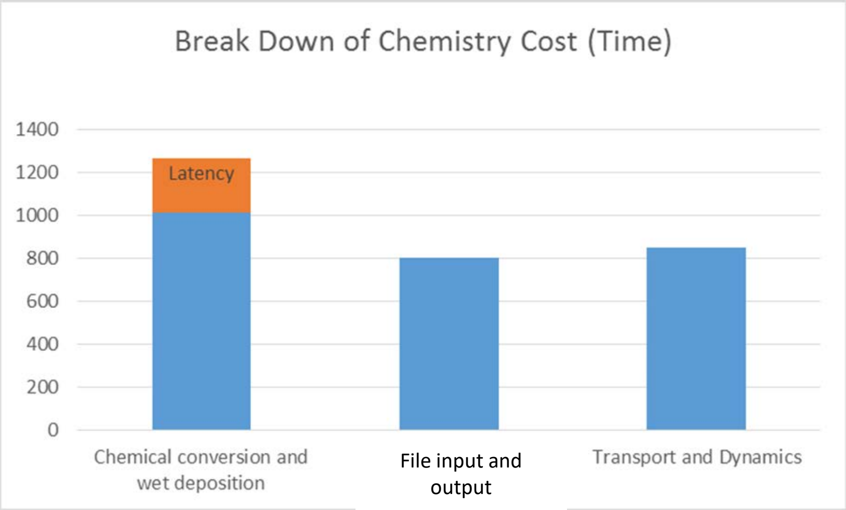
CO simulation with CAMS chemistry schemes



MACCITY

Computational cost of including Atmospheric Composition in IFS

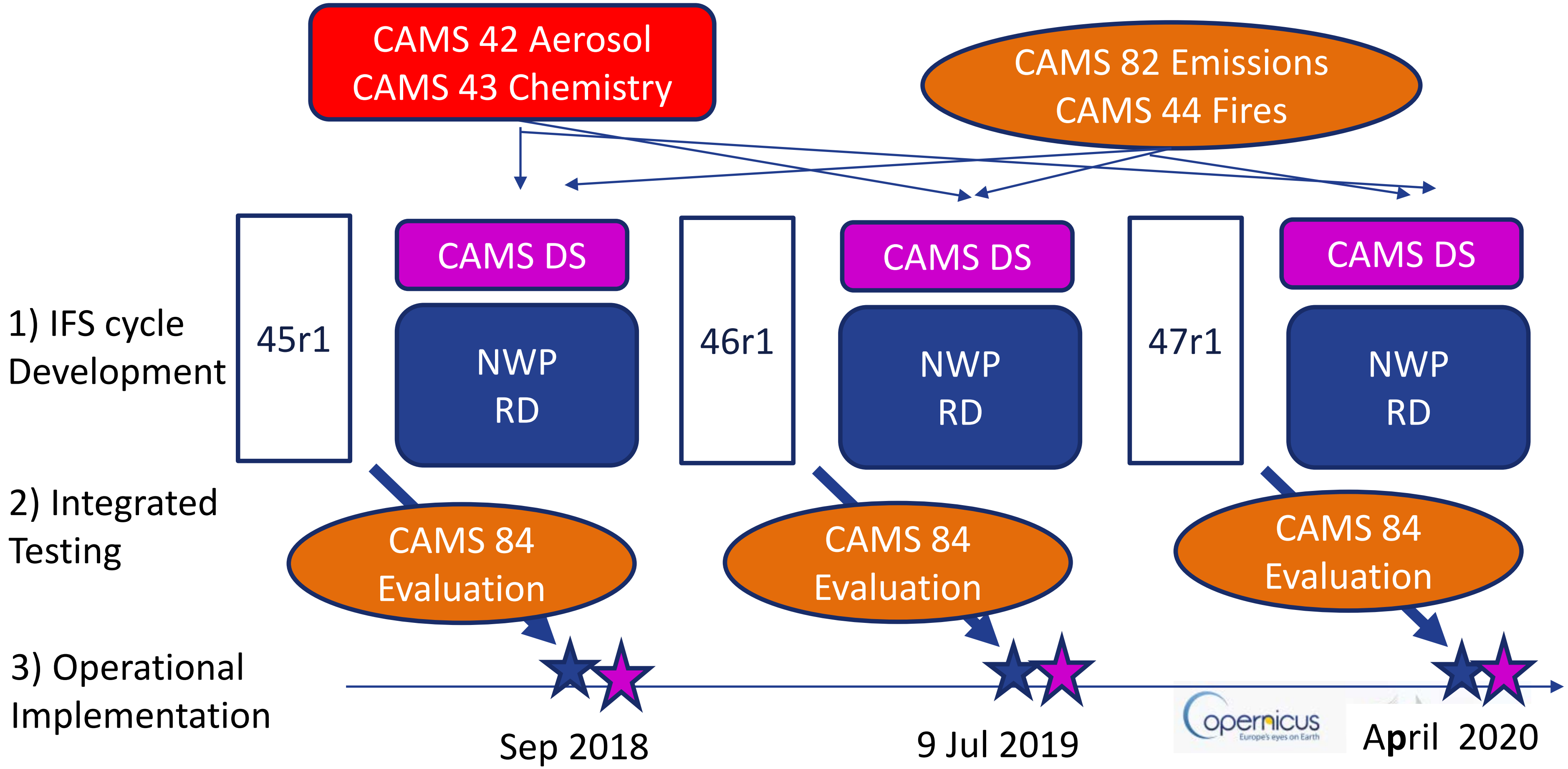




Cost of atmospheric composition in NWP (CB05 + AER)

- Model simulation only : x 4 more expensive
- Data assimilation suite: x 2 more expensive

NWP and CAMS IFS development cycle



Configuration of CAMS o-suite (46r1)

Atmosphere Monitoring

- Implemented 9 July 2019
- 00 and 12 UTC 5 day forecast
- 40 km x 40 km globally, 137 vertical levels (20 m lowest level depth) (upgrade)
- 00 and 12 UTC 5 day forecast
- Transport
  - Semi Lagrangigian Advection scheme, global mass fixers
  - Convective mass flux scheme
  - K-Theory / EDMF diffusion scheme including injection of emissions
- Emissions
  - CAMS GLOB 2.1 global emissions (anthropogenic, biogenic & natural)
  - GFAS fire emissions (based on MODIS FRP)
  - Injection height and parameterised diurnal cycle for Fire emissions
  - Customised SOA-emission (based on CO)
  - Online dust on and sea salt emissions
  - Lightning NO emission based on Meijer 2001 (Precipitation)
- Chemistry and aerosol
  - CB05 chemistry scheme
  - Cariolle ozone scheme
  - Bulk Aerosol + Nitrates and Ammonia
  - Coupling between CB05 / AER sulphur and nitrogen cycle

Updates w.r.t 45r1

References: Remy et al. GMDD (2019), Flemming et al. GMD, (2015), Inness et al ACP (2015), Benedetti et al. JGR (2009)

Latest cycle: https://atmosphere.copernicus.eu/cycle-46r1

Configuration of CAMS o-suite (46r1) cnt.

Atmosphere Monitoring

- Deposition
  - Wet deposition
  - Online Dry deposition for chemistry and aerosols
- NWP observation assimilation
- 4DVAR assimilation of AC
  - Adjoint and TL representation of transport only
  - Static Background error statistics (NMC, NWP ozone)
- Assimilated AC retrievals
  - AOD: MODIS, PMAP
  - CO: MOPITT, IASI
  - NO2: OMI
  - Volcanic SO2 (GOME-2)
  - Ozone: OMI, GOME-2, MLS, SBUV-2, S5P

- Planned updates for 47r1 o-suite (April 2020)
  - HLO update of Cariolle ozone scheme (based on CAMS RA)
  - Dust emission potential update
  - New sea salt emission scheme
  - CAMS GLOB 3.1 emissions
  - Parameterisation of VOC emissions diurnal cycle
  - Injection height for anthropogenic SO2 emissions
  - S5P CO and NO2 retrieval assimilation

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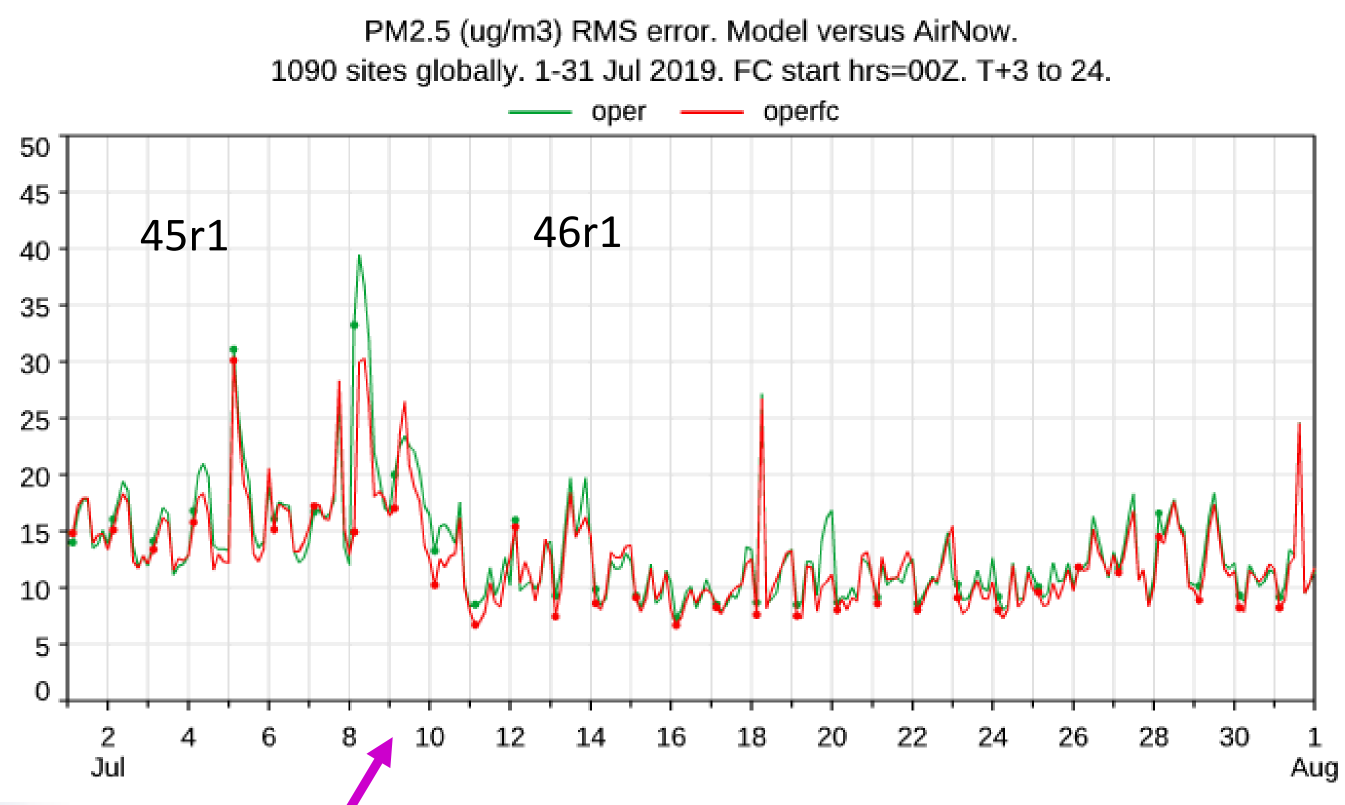
Atmosphere Monitoring



PM 2.5

Air NOW

US

July 2019

46r1 o-suite implementation 7th of July 2019

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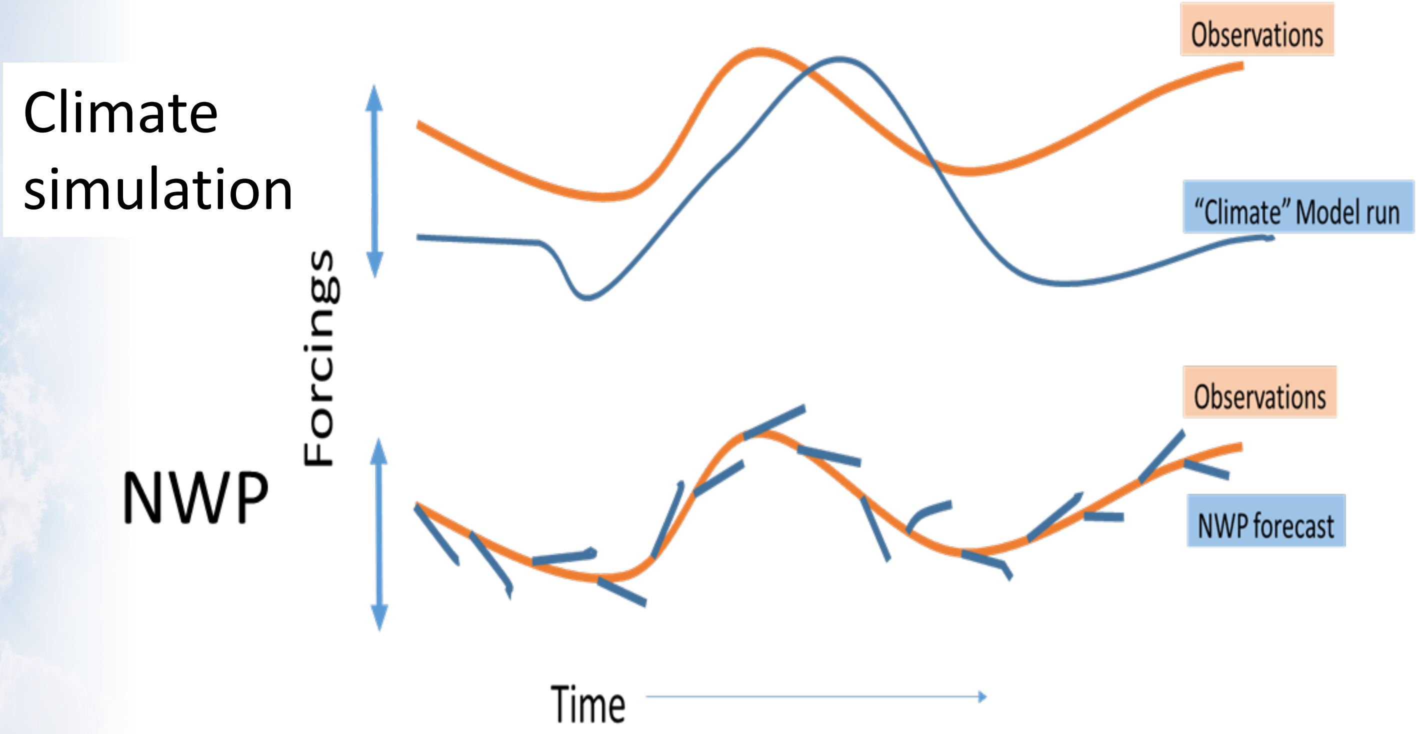
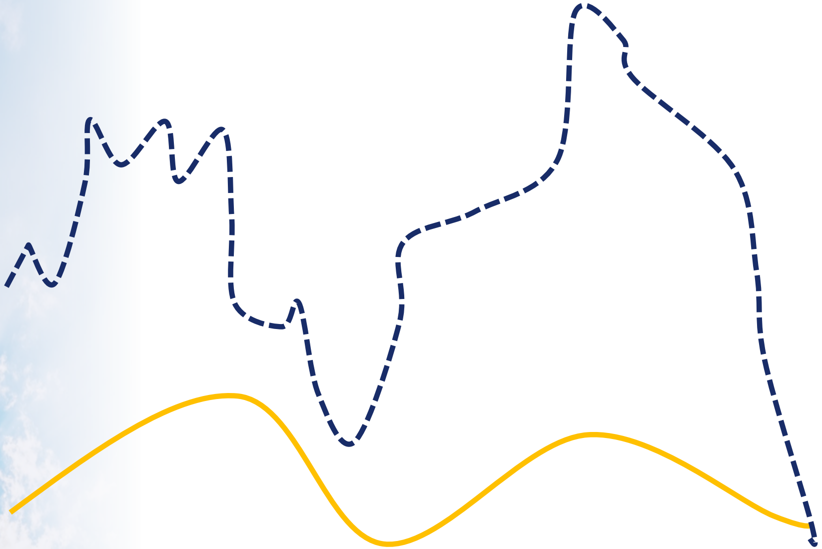
Atmosphere Monitoring



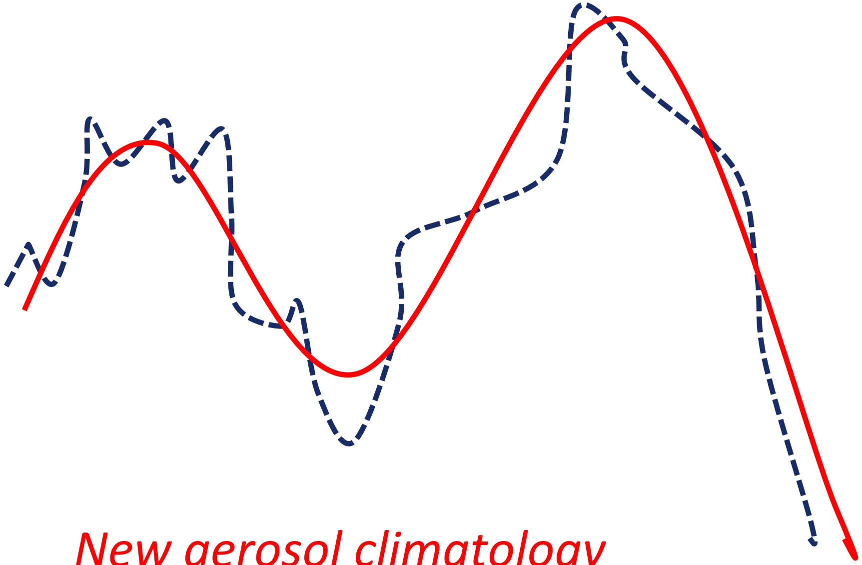
Atmosphere Monitoring



Old aerosol climatology

Prognostic aerosol biased against climatology

= combined mean and variability update



New aerosol climatology

Prognostic aerosol consistent with new climatology

= stepwise mean and variability update

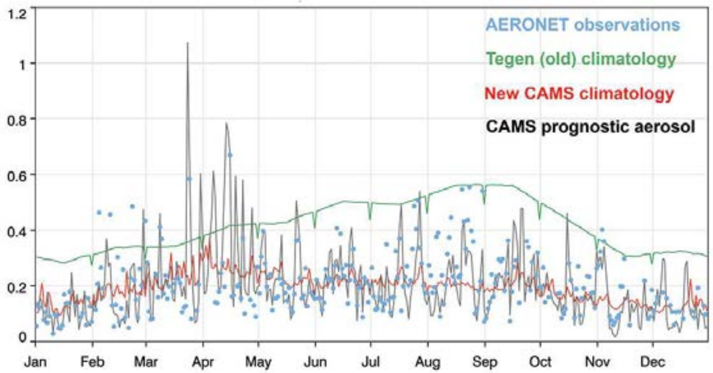
NWP – Weather feedbacks for NWP

- AC development for IFS not mainly driven by AC-NWP feedbacks
- Climatologies account for radiative (direct) effect of aerosol and reactive gases in operational
- Upgrade of operational IFS AC climatologies based on CAMS products
- Prognostics aerosol (scattering and absorption) and ozone in radiation scheme in CAMS o-suite (operational)
- Monthly forecasting including aerosol direct effect (still test)
  - Skill introduced by fire emissions not yet possible to forecast
- Seasonal forecasting using prognostic ozone (still test)
  - Progress after updating stratospheric ozone scheme
- AC NWP roadmap document (Dragani et al. 2019 ECMWF TM)
- NWP verification is a challenge
  - all times and areas i.e high and low AC cases considered
  - uses own analysis

Update of the IFS Aerosol climatology

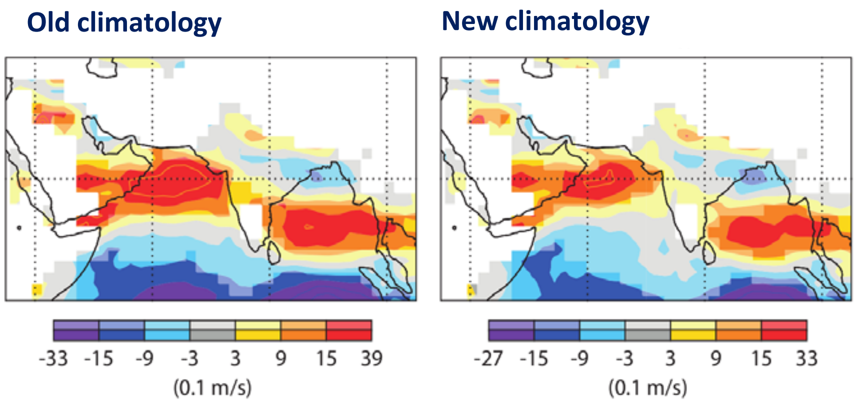
Atmosphere Monitoring

- **Bozzo et al. (2019, GMDD)** constructed an aerosol climatology from the CAMS interim reanalysis of aerosols (Flemming et al. 2017).
- It has been used operationally since 2016.



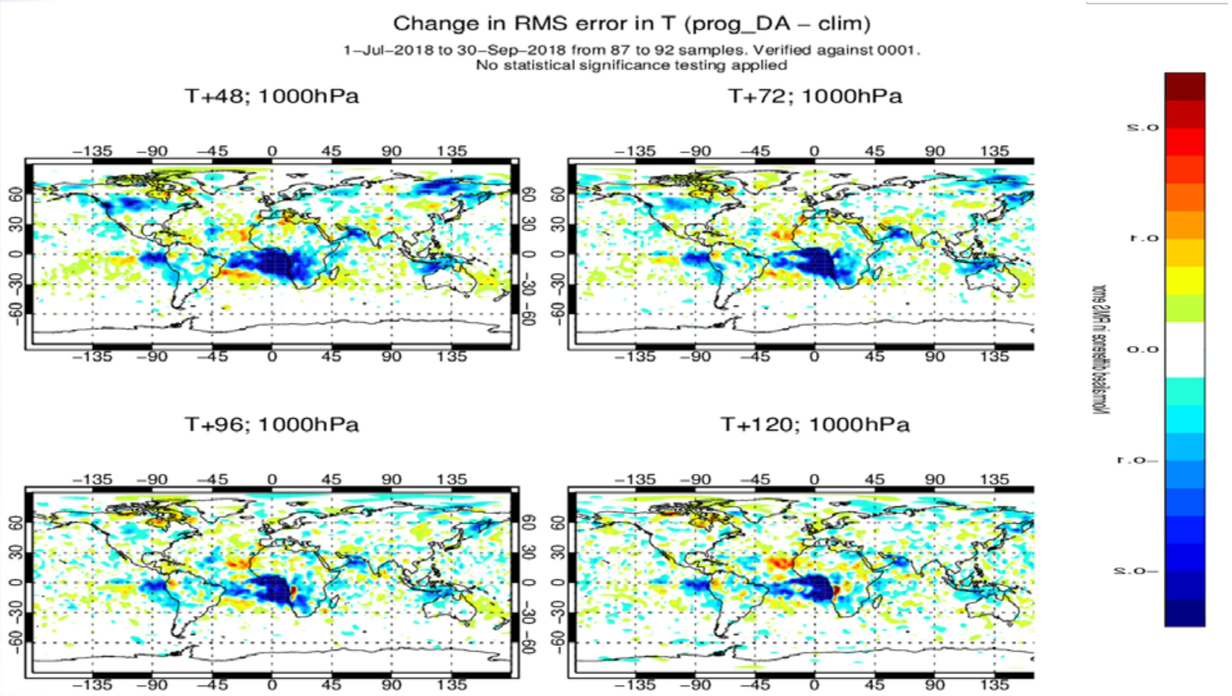
A. Bozzo and J. Flemming, ECMWF

Day-5 zonal wind bias at 925 hPa (JJA)



- Better agreement with Aeronet data.
- Reduced bias in the day-5 zonal wind forecasts at 925hPa.
- Higher consistency in IFS between the climatology and the prognostic aerosols.

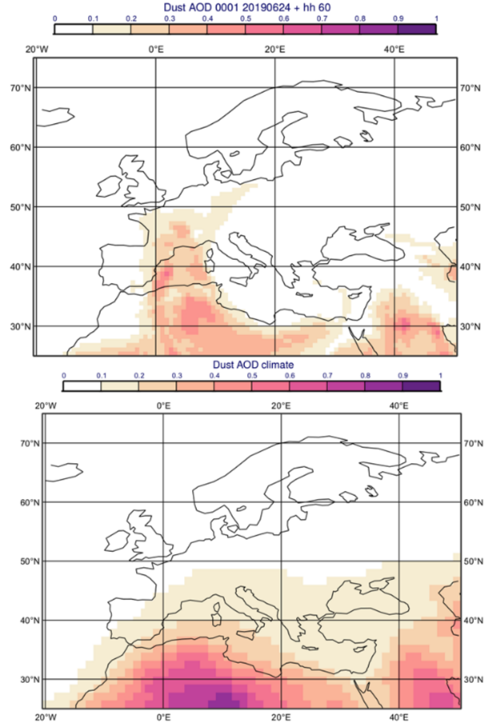
Improvements of NWP verification

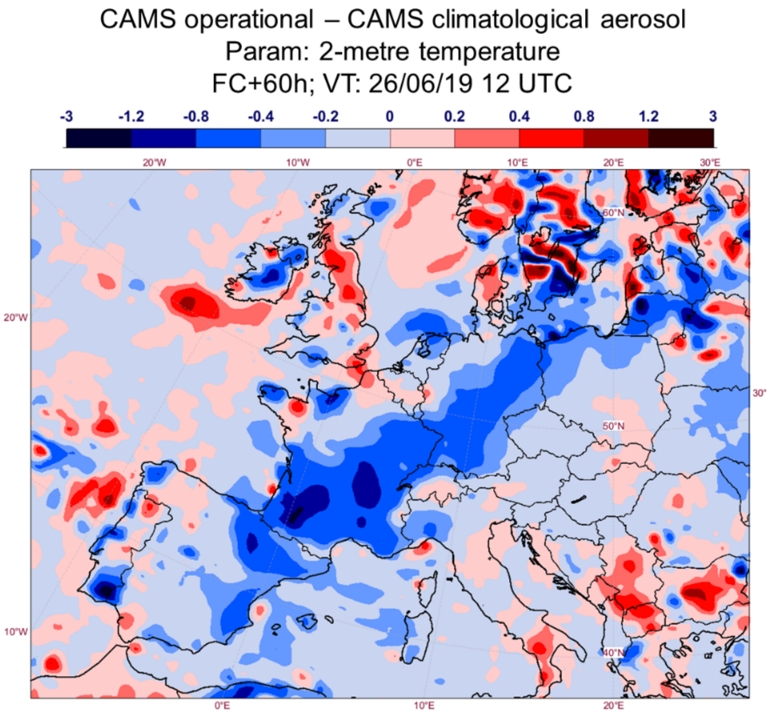


Difference in RMSE of temperature at 1000 hPa against analysis between prognostic and climatological aerosol and ozone. Blue areas indicate an improvement with prognostic aerosols and ozone.

Atmosphere Monitoring

Dust Transport Event during Heat Wave in Europe (26.6.2019)

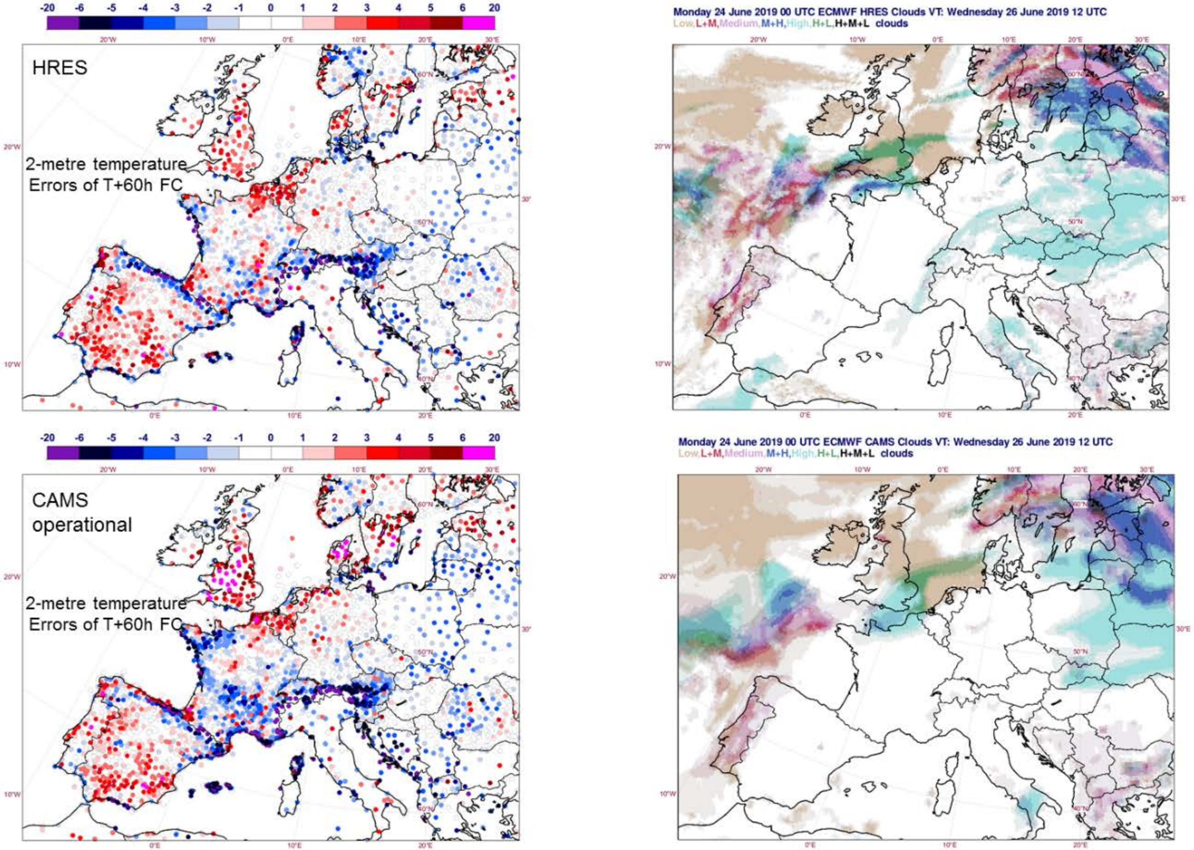




Up to 1 K cooling Of 2m Temperature because of Dust Transport

60 h Forecast

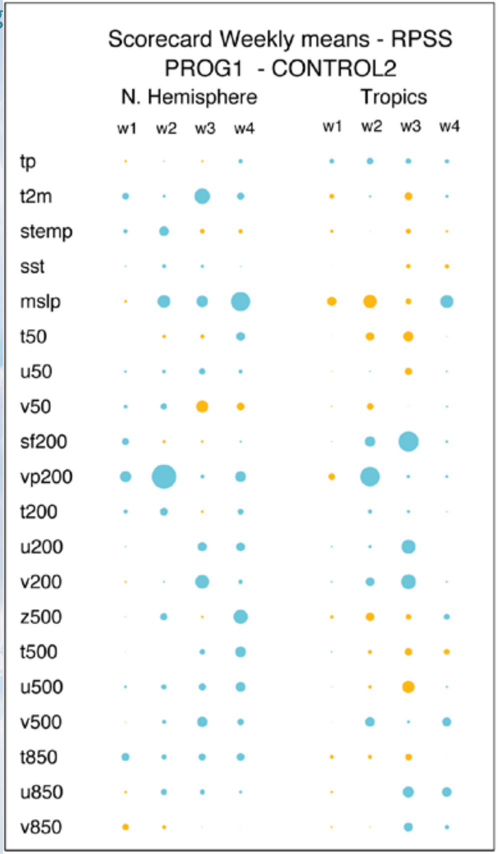
Dust Transport Event during heat wave (26.6.2019)

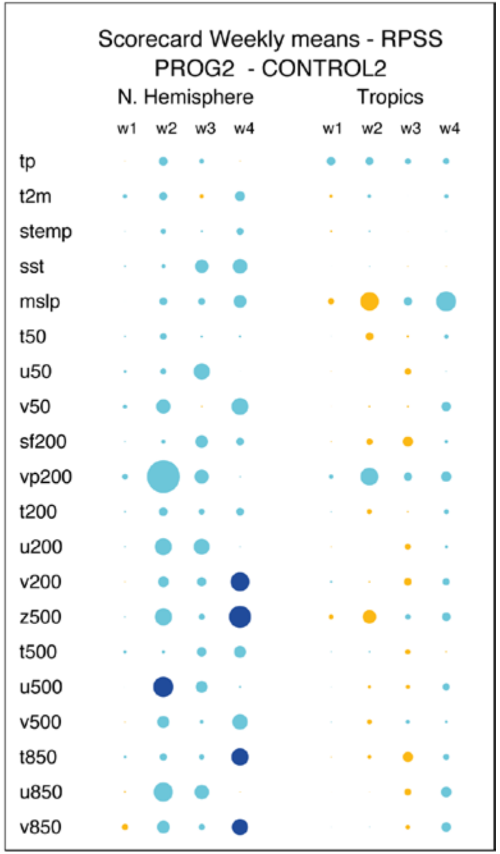


No improvement by prognostic aerosol compared to climatological aerosol over Central Europe

Atmosphere Monitoring

Aerosol impacts on the monthly forecasts: Rank probability skill scores





Interactive aerosol simulations use fully prognostic aerosols in the radiation scheme – **only aerosol direct effects are included**

Observed fire emission applied (GFAS)

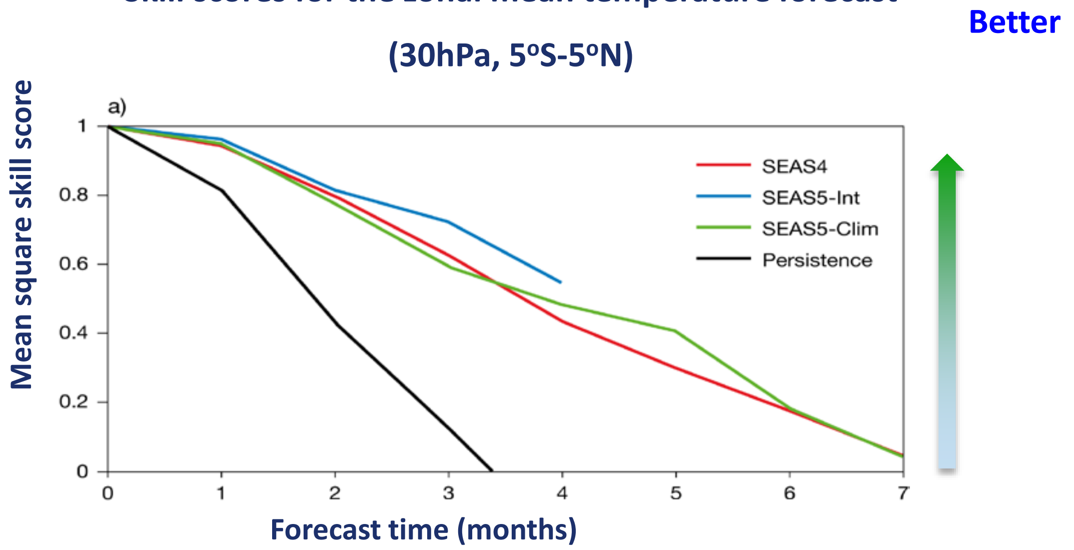
Benedetti and Vitart, MWR, 2018

Atmosphere Monitoring

Potential of interactive ozone at seasonal range

Skill scores for the zonal mean temperature forecast

(30hPa, 5°S-5°N)

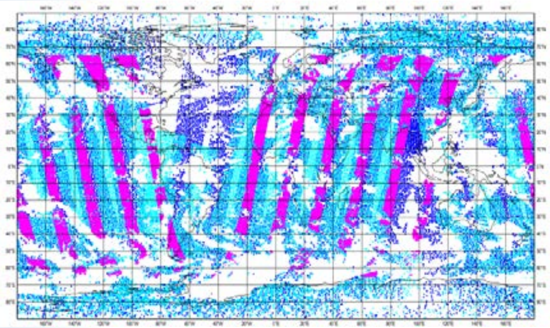


Tim Stockdale, ECMWF

Atmosphere Monitoring

Reactive gases data availability in CAMS NRT system

CO

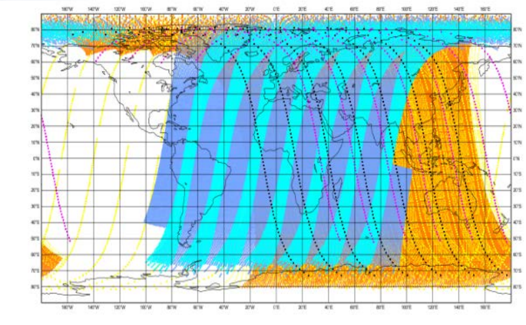


IASI Metop-A

IASI Metop-B

MOPITT TERRA

O3



GOME-2 Metop-A

GOME-2 Metop-B

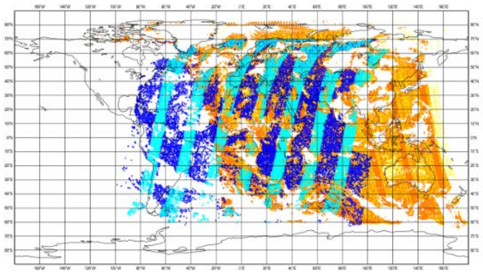
OMI, MLS AURA

SBUV/2 NOAA-19

TROPOMI S5P

OMPS SNPP

Tropospheric NO2



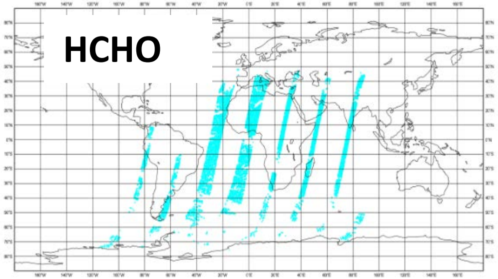
OMI AURA

TROPOMI S5P

GOME-2 Metop-A

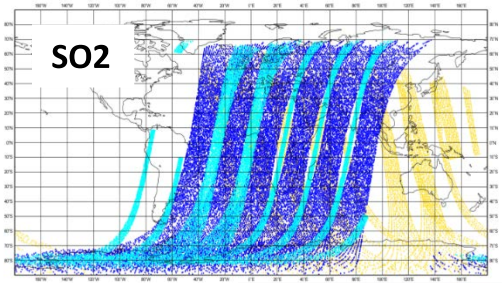
GOME-2 Metop-B

HCHO



GOME-2 Metop-A

SO2



OMI AURA

GOME-2 Metop-A

GOME-2 Metop-B

assimilated

monitored

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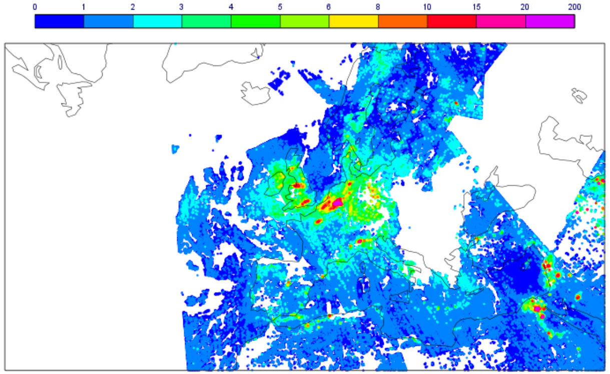
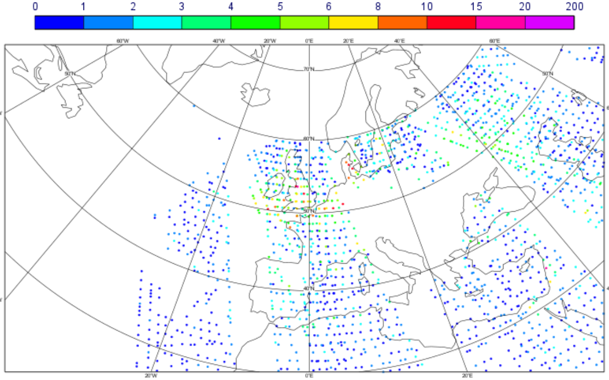
Atmosphere Monitoring

New data: NO2 Tropomi (S5P) data coverage

TROPOMI (ESA, full resolution)



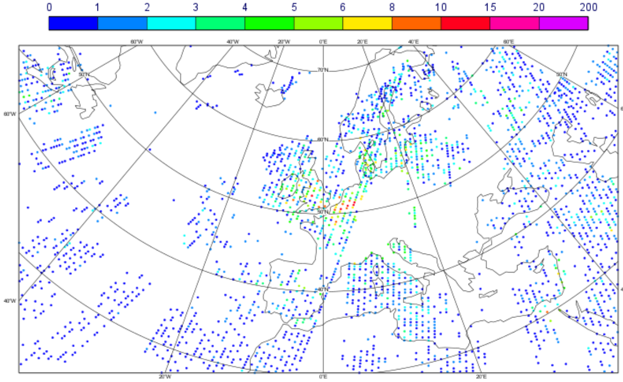
OMI (DOMINO-V2)



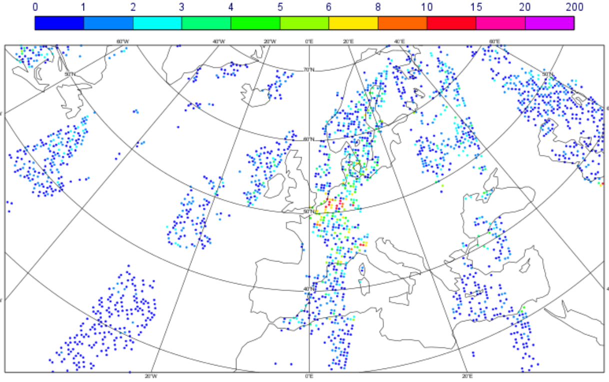
27 June 2018

- GOME-2 and OMI thinned to 0.5° x 0.5° and cloud cleared
- TROPOMI cloud cleared

GOME-2B (GDP v4.8)



GOME-2A (GDP v4.8)

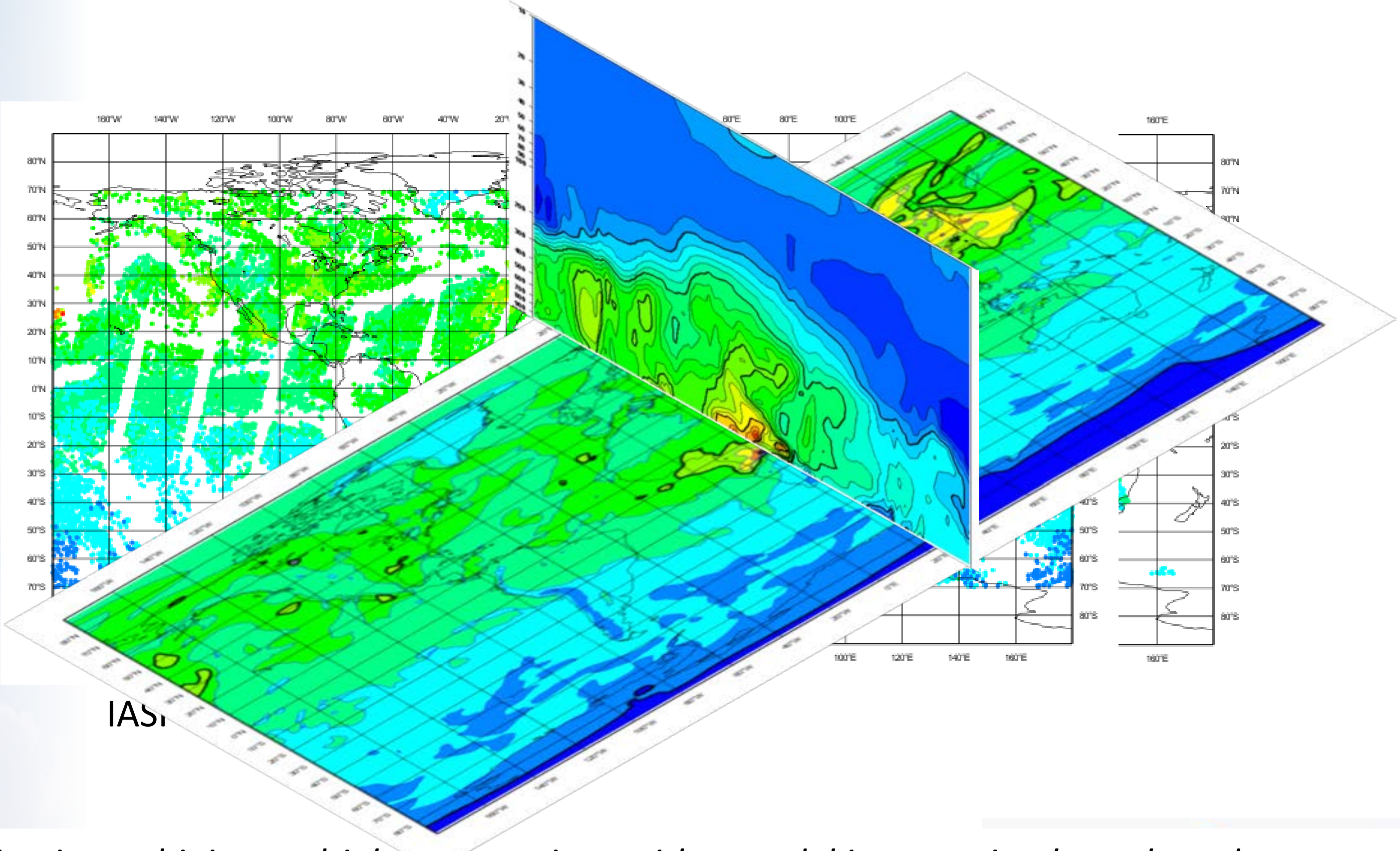


NO2 retrieval

European Commission

Assimilation of CO observations in a global model

Atmosphere Monitoring



Data assimilation is combining multiple observations with a model in an optimal way based on error statistics

CAMS (MACC) Re-analysis products

Atmosphere Monitoring

- GEMS RA (2003-2008) with the coupled system IFS-MOZART, 110 km resolution
- MACC RA (2003-2012) with the coupled system IFS-MOZART, 80km, Inness et al. (2013)
- CAMS interim RA (2003-2018) with IFS(CB05 & AER), 110 km, Flemming et al. (2017)
- CAMS RA (2003-present day) with IFS (CB05 & AER), 80km, Inness et al. (2019)
- A control run without assimilation of atmospheric composition (but the same meteorological forcing) has been carried to study the impact of the assimilation.
- The CAMS RA data are freely available from the CAMS data server

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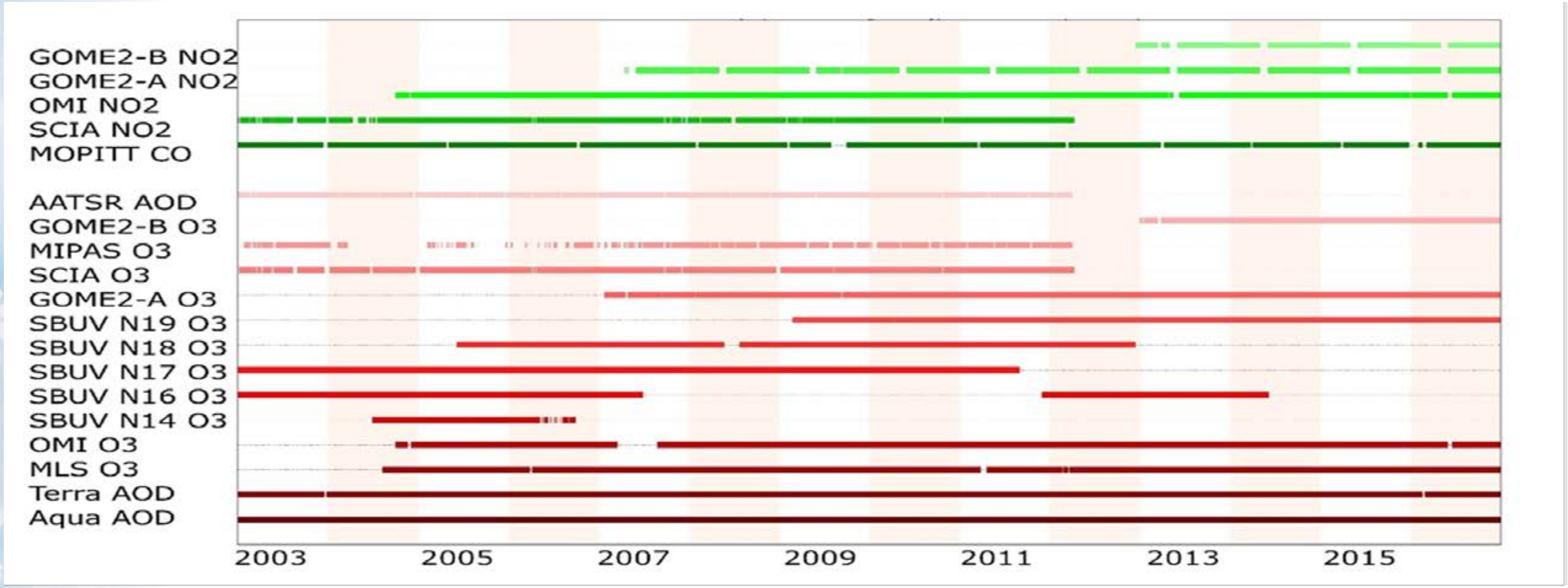
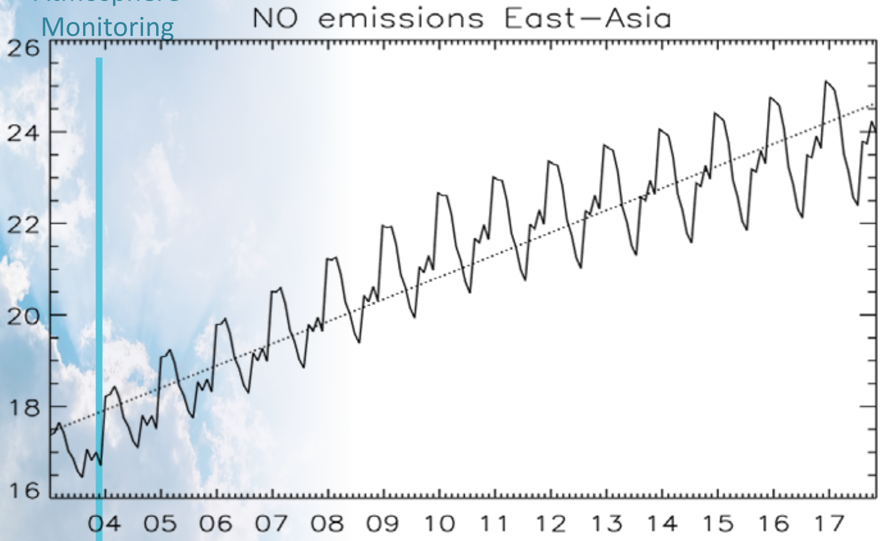
Atmosphere Monitoring



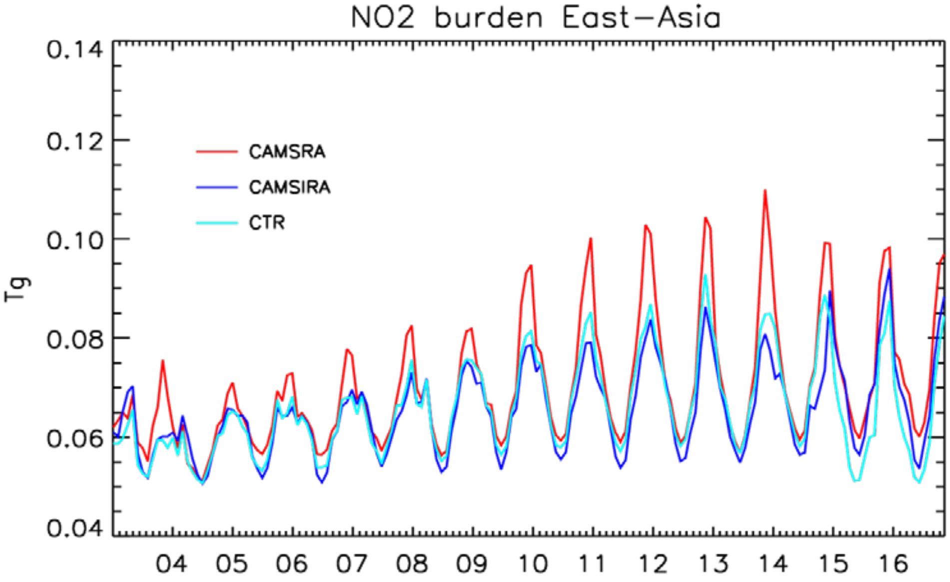
Retrievals assimilated in the CAMS RA between 2003 and 2016. In red are shown retrievals for which no averaging kernels were used, in green those where averaging kernels were use.

Impact of NO2 assimilation (GOME-2, OMI, SCIA)

Atmosphere Monitoring

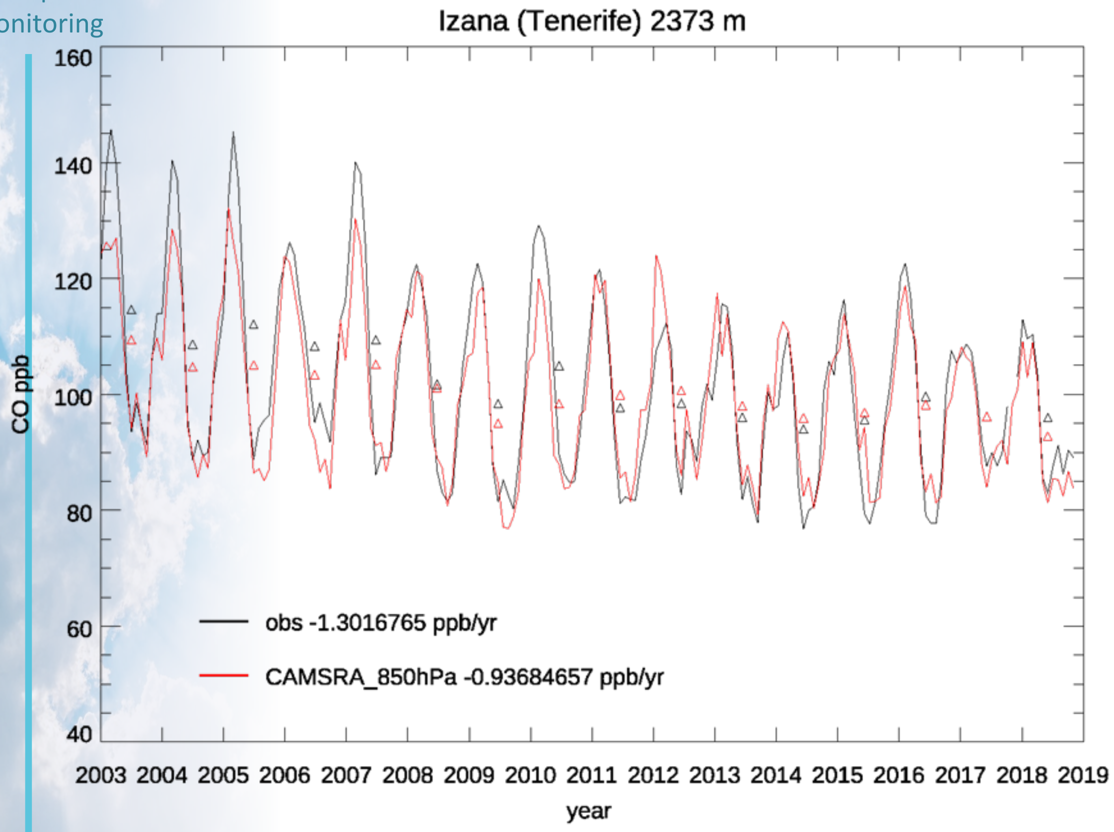


Time series of anthropogenic (Maccity) NO emissions over East-Asia



NO_2 total column over East Asia from the CAMS-RA (red), the control run (cyan, no composition DA) the CAMS interim RA (blue). Only the CAMS RA (NO_2 assimilation) shows a decrease of mean NO_2 after 2013.

Atmosphere
Monitoring



Monthly mean observed CO at Izana observatory on the Tenerife Island (2337 m a.s.l.) and the corresponding value from CAMS reanalysis. The legend shows the linear trend and its uncertainty over the period since 2003.

BAMS SoC 2018
Carbon Monoxide
Flemming and Inness 2019 in rev.

Atmosphere
Monitoring

CAMS interim reanalysis
Trends and significance (2003-2016)

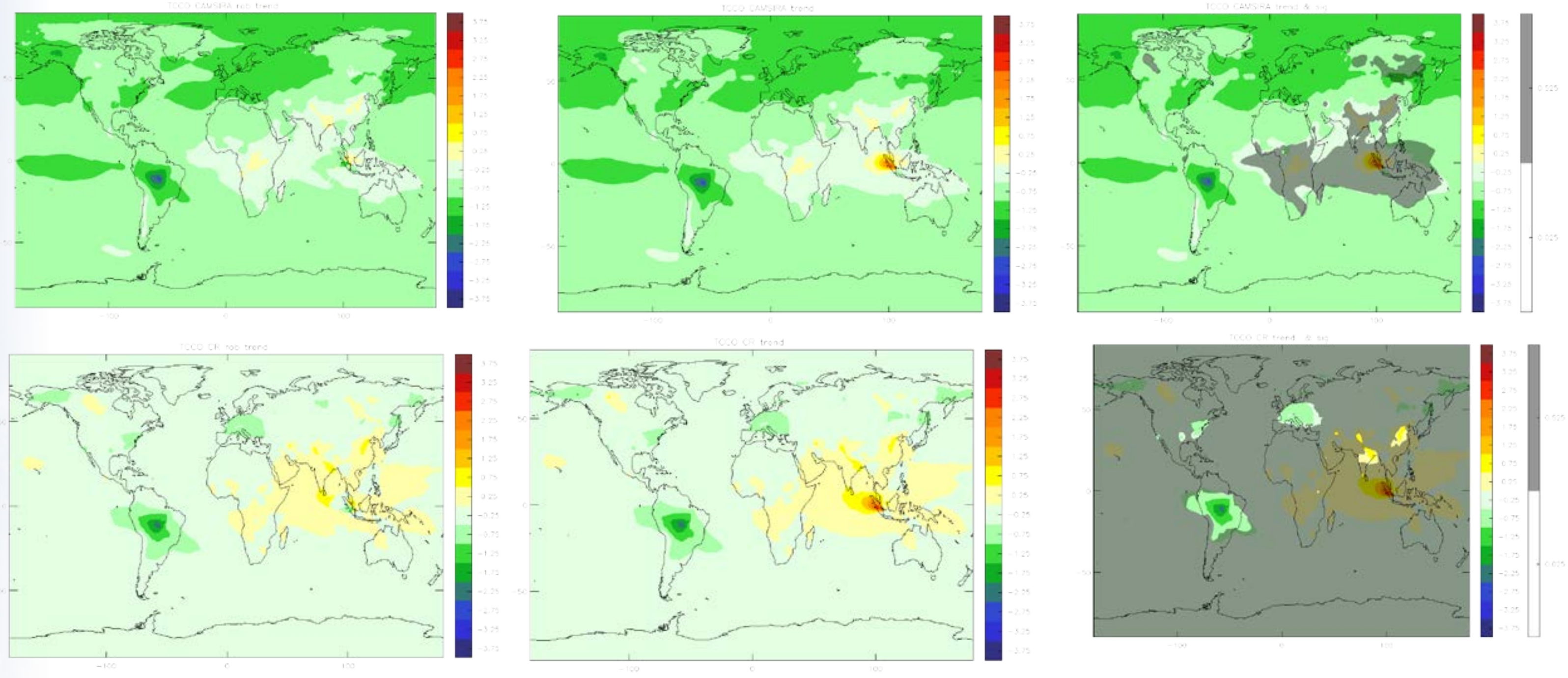
Robust linear trend %

Classic linear trend %

Classic linear trend & significance 95%

CAMSiRA (MOPITT + GFAS + MACCITY)

Control Run NO DA (MACCITY +GFAS)

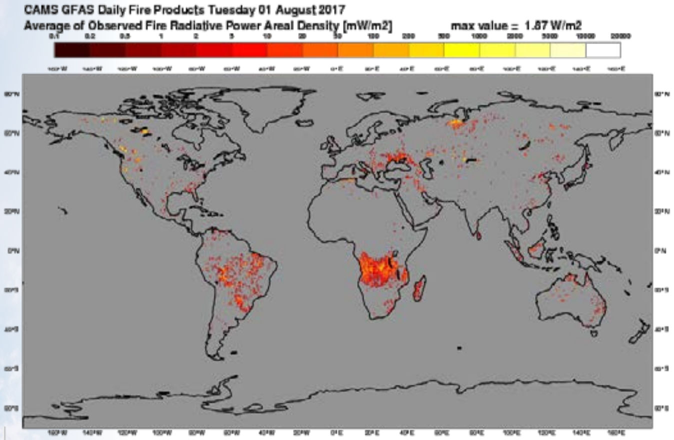


- Trends in the CR (emissions) are less pronounced than in CAMSiRA (emissions & MOPITT).
- Global CO trends are about -1%/year in 2003-2016 period
- Negative trends mainly over Europe and South-America

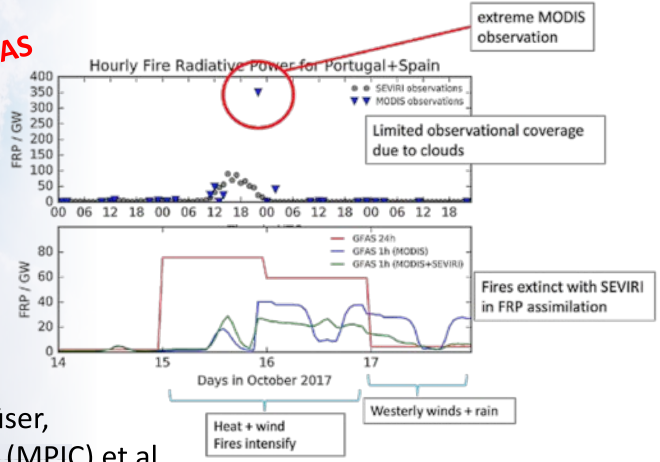
European Commission

ESTIMATING GLOBAL WILDFIRE EMISSIONS IN CAMS

Atmosphere Monitoring



Upcoming hourly GFAS

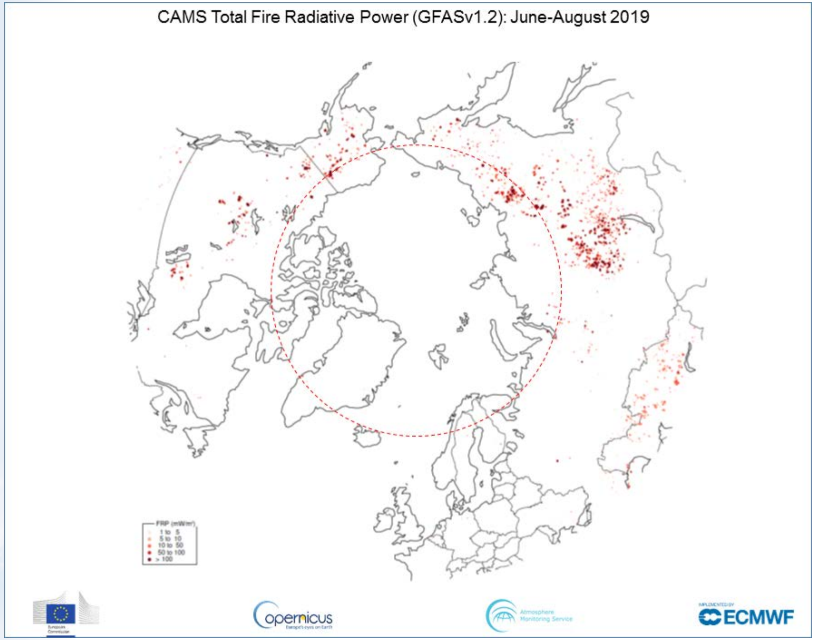


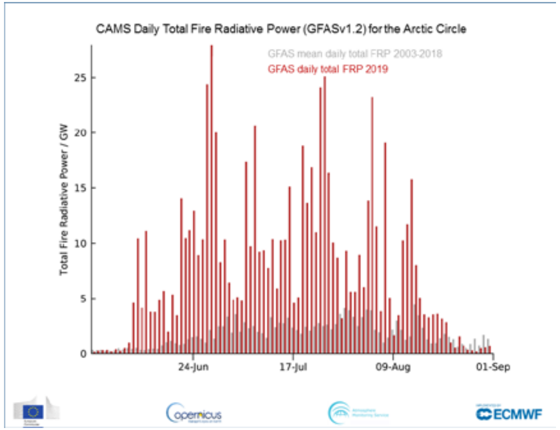
c/o I. Hüser,
J. Kaiser (MPIC) et al.

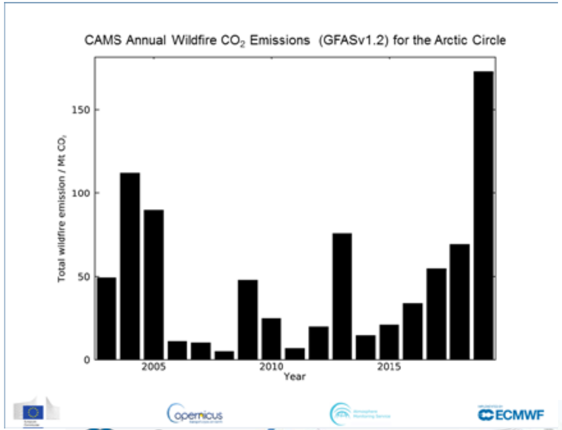
- Global Fire Assimilation System (**GFAS**); see http://apps.ecmwf.int/datasets/data/cams-gfas/
- Uses satellite observations of Fire Radiative Power (FRP)
  - Currently Aqua and Terra MODIS FRP observations
  - FRP from VIIRS, Sentinel-3 and geostationary satellites will be included in 2018
- Daily global coverage at ~10km resolution
  - 1-day behind NRT (diurnal cycle/hourly output coming operational in 2018)
- Emissions of aerosols and gases are estimated using factors dependent on vegetation type.
- Injection heights calculated with Plume Rise Model and IS4FIRES.

Monitoring Arctic wildfires during summer 2019

Atmosphere Monitoring

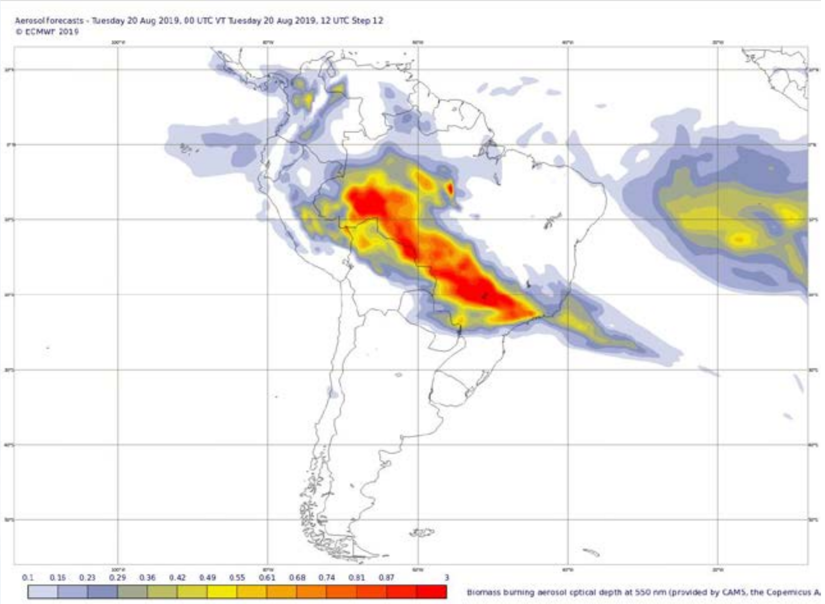


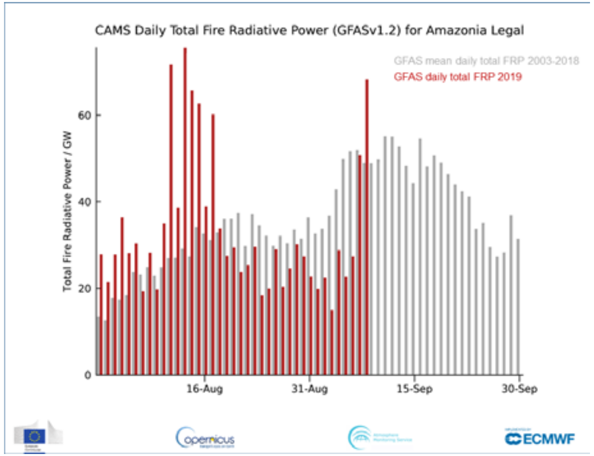


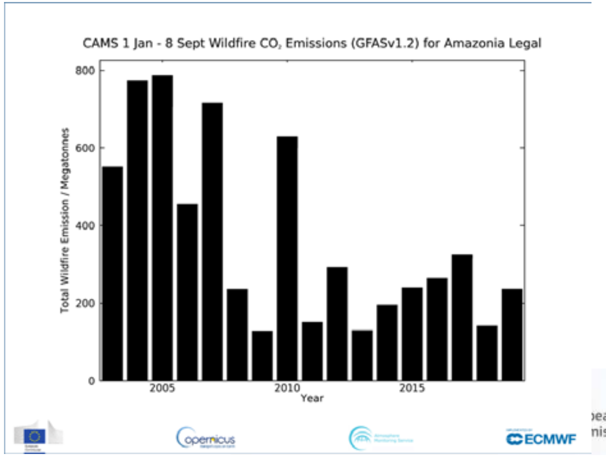


- Daily total wildfire emissions were well above the 2003-2018 average throughout the summer north of the Arctic Circle
- Many wildfires concentrated in the Sakha Republic, Russia with other fire activity in Alaska, Yukon Territory and Greenland
- Total estimated equivalent CO2 of ~170 megatonnes

Monitoring Amazon fires in August 2019







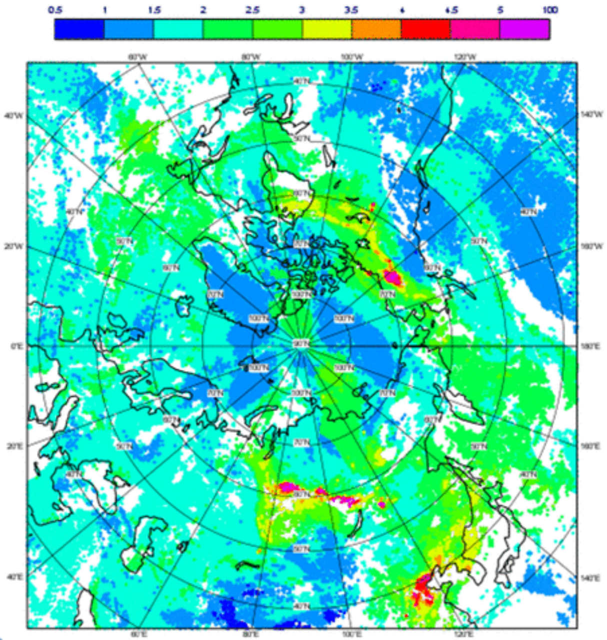
- Above average daily fire activity during first 2 weeks of August across the main states of the Brazilian Amazon (also in Bolivia and Paraguay) with smoke predicted by CAMS across much of southern Brazil
- Below average (2003-2018) daily activity through second half of August shows annual total (to 8 September) is not particularly high compared to previous years in GFAS dataset.

Atmo
Mon

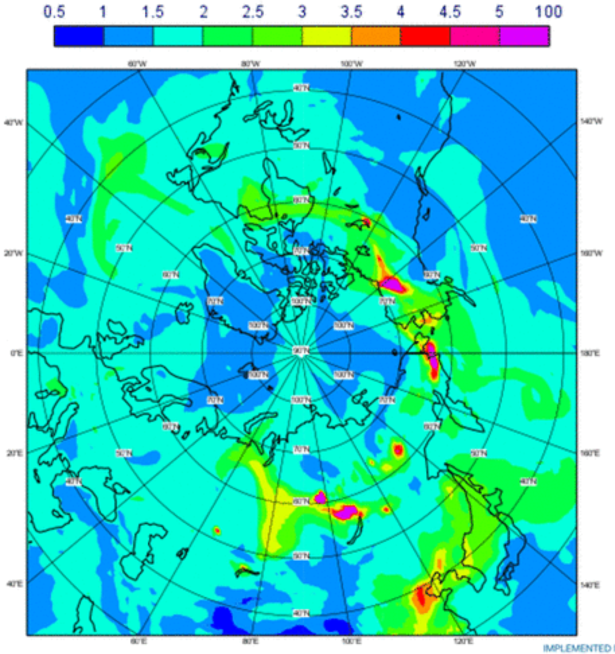
Total column CO on 18 July 2019

sentinel-5p

TROPOMI



CAMS analysis (12z)



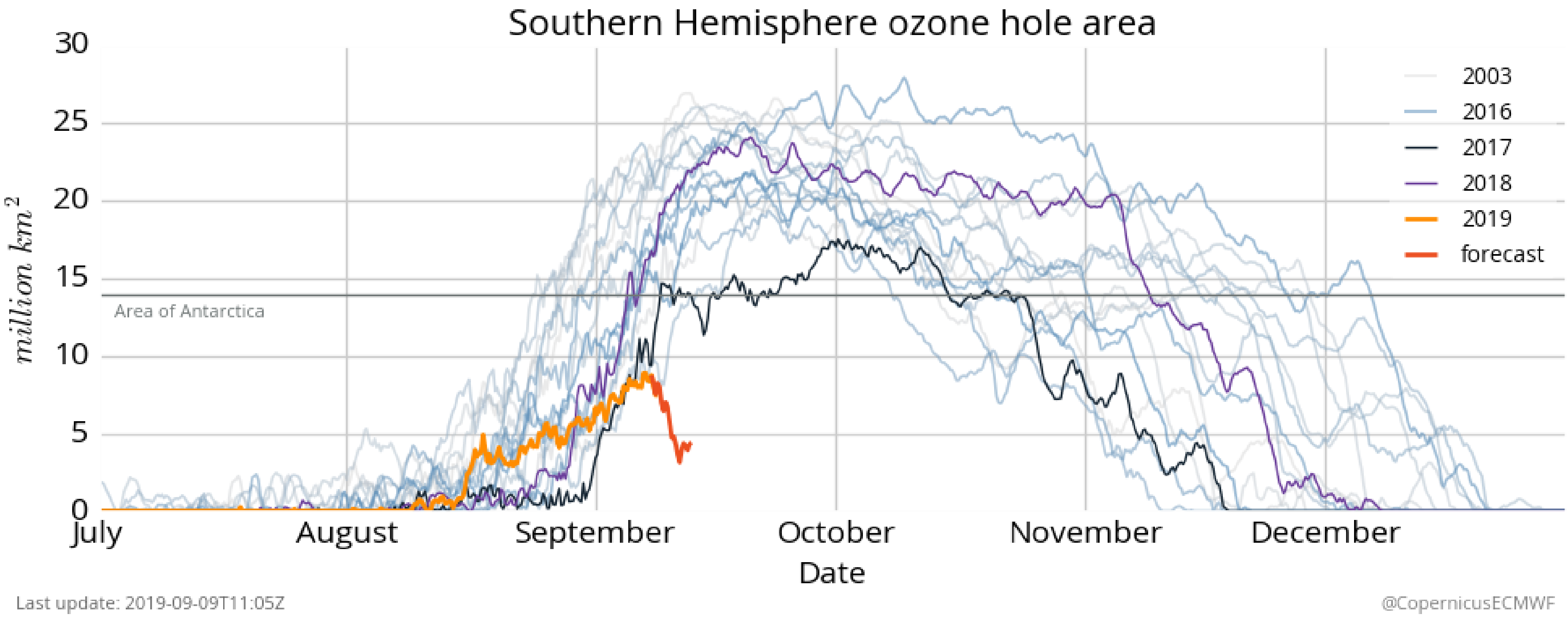
TROPOMI

Units: 10^{18} molec/cm^2

IMPLEMENTED BY ECMWF

European Commission

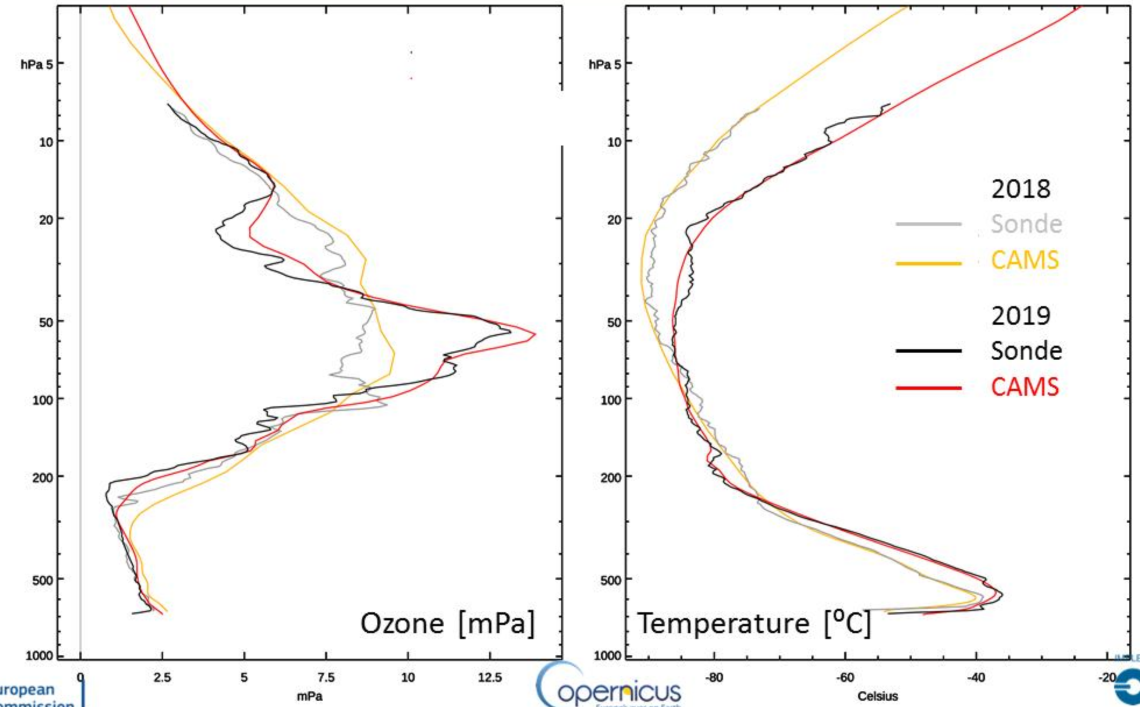
ECMWF opernicus Europe's eyes on Earth European Commission



2019: a smaller ozone hole so far because of an anticipated SSW

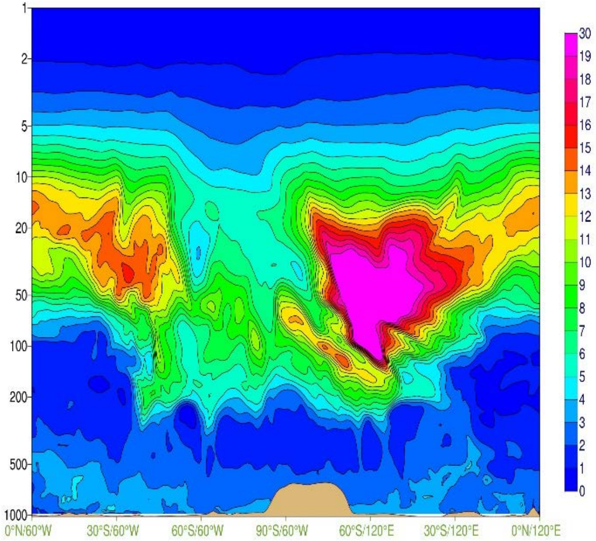
Atmosphere Monitoring

Ozone and temperature profiles at South Pole from CAMS and ozone sondes on 1 September2019 & 2018

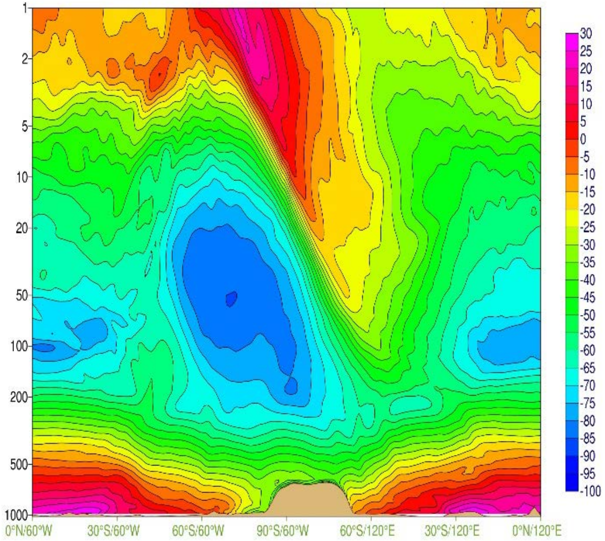


Ozone, temperature and zonal wind cross sections over the South Pole from CAMS on 20190908

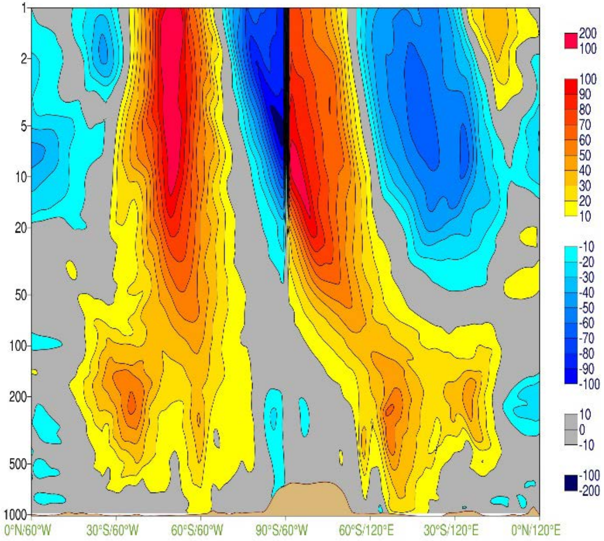
Ozone [mPa]



Temperature [^oC]



Zonal wind [m/s]



Cross sections from equator south along 60^oW, via the South Pole and back north to the equator along 120^oE

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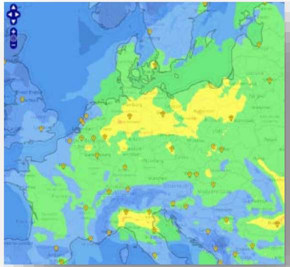
ECMWF

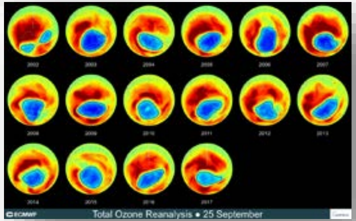
DATA IS FULLY OPEN AND FREE-OF-CHARGE

Atmosphere Monitoring

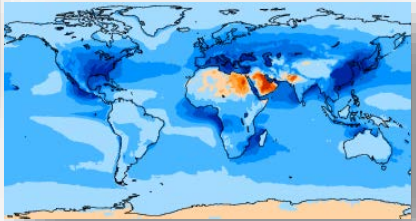


European Air Quality and products in support of policy users

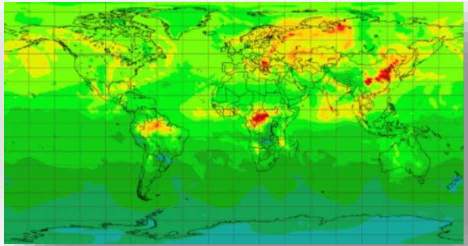
Ozone layer



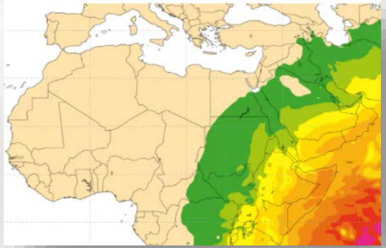
Climate forcings



Bottom-up emissions and surface fluxes of greenhouse gases



Global analyses, forecasts and reanalyses (2003-...)



Solar radiation and UV index

Summary

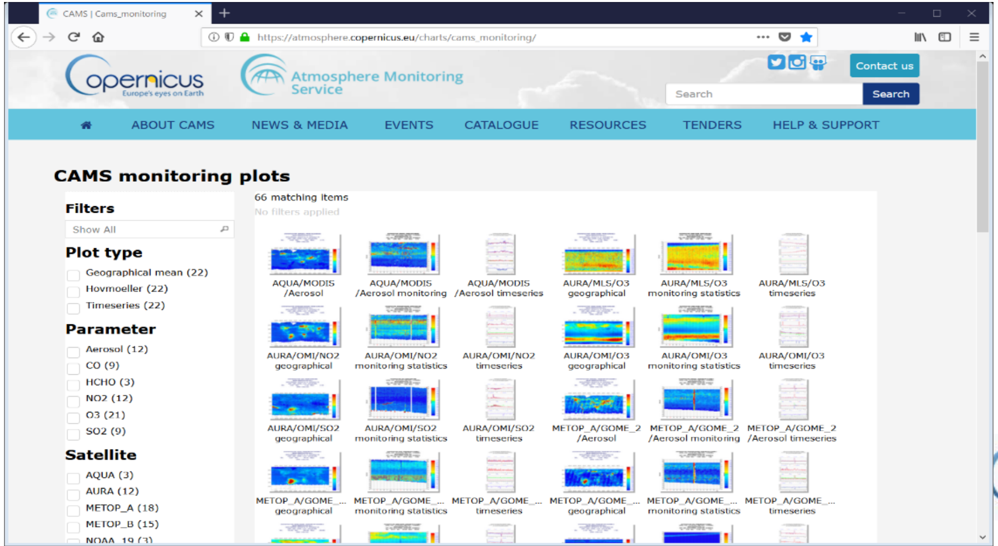
Atmosphere Monitoring

- CAMS delivers a wide range of NRT and retrospective global and European-scale products on atmospheric composition (AC) :
  - forecast, reanalysis, fires, emissions and radiative forcing products
  - CAMS is user driven and all data are free and open at atmosphere.copernicus.eu
- ECWMF pursues a step-wise approach by improving AC climatologies and testing prognostic AC for implementing AC-NWP weather feedbacks for medium to seasonal range forecasts
- CAMS assimilates AC retrievals (AOD, O3, CO, NO2 vSO2) to improve forecast IC and for reanalysis
  - Constraining aerosol speciation and surface values remains a challenge
  - High resolution S5P data are new great opportunity for NO2 and SO2
- The 2019 SH ozone and vortex will be an interesting case !

Atmosphere Monitoring

Summary

- TROPOMI/Sentinel-5P are monitored by CAMS
- O3 data have been operationally assimilated since Dec 2018
- Assimilation tests with NO2, CO and SO2 are under way
- Monitoring plots on: atmosphere.copernicus.eu/charts/cams_monitoring/



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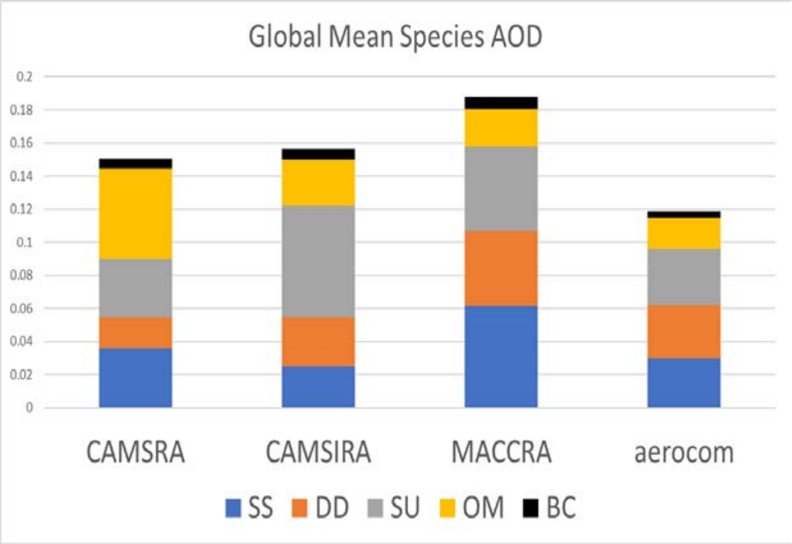
Aerosol Speciation in Data assimilation

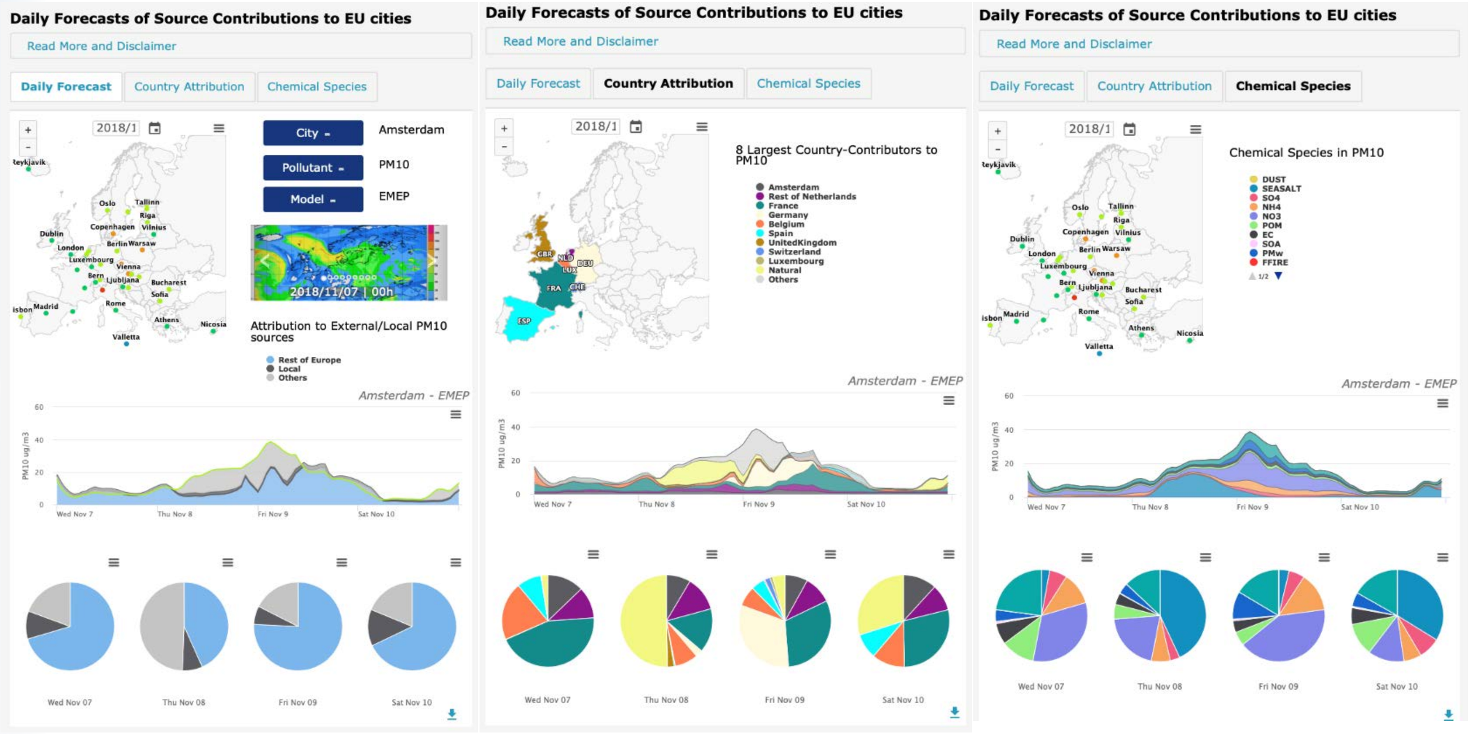


Global aerosol speciation (AOD) of CAMS, CAMS-interim and the MACC-RA and the median of the AEROCOM model (Kinne et al. 2006)

PRODUCTS IN SUPPORT OF POLICY USERS

Atmosphere Monitoring

Experimental: local vs imported, geographical origin, chemical speciation



http://policy.atmosphere.copernicus.eu/DailySourceAllocation.html

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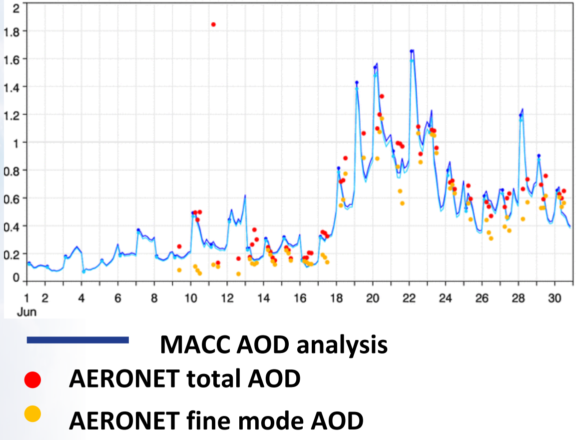
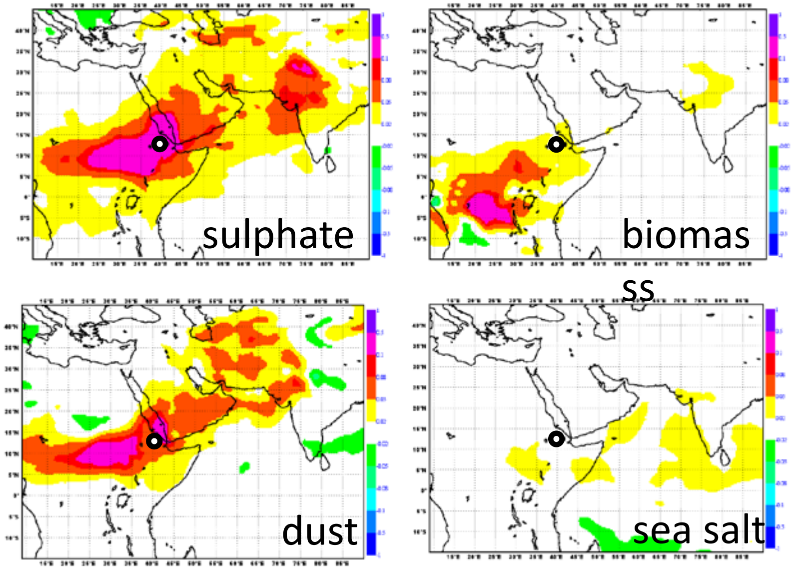
Example for wrong aerosol attribution

Atmosphere Monitoring

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

ICIPE-Mbita - AERONET





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

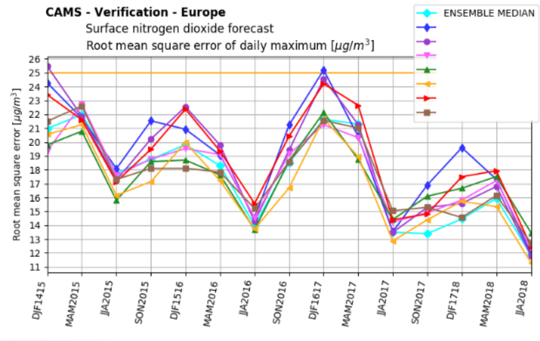
ECMWF Copernicus Europe's eyes on Earth European Commission

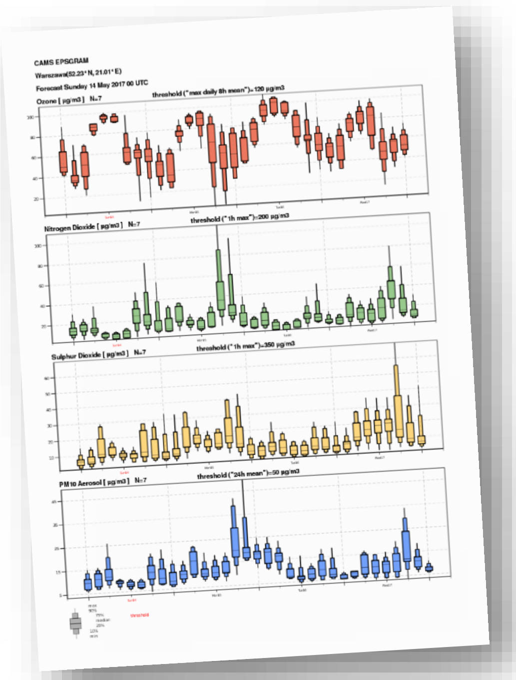
Credits: A. Benedetti

Atmosphere
Monitoring

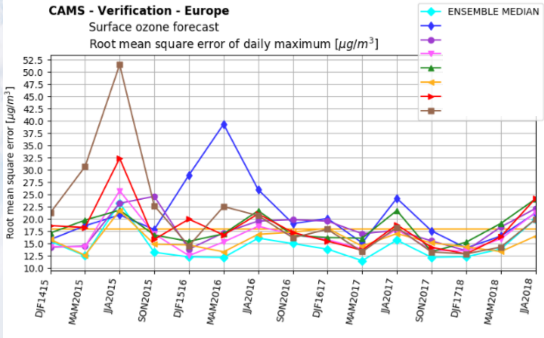
Ensemble products for Europe

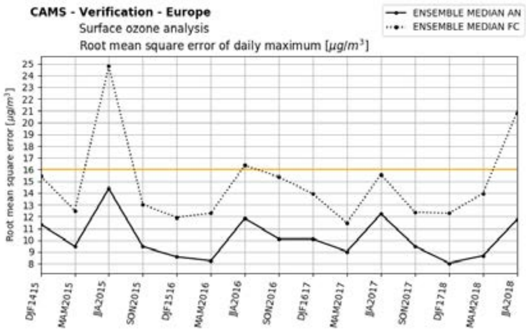
NO_2





Ozone





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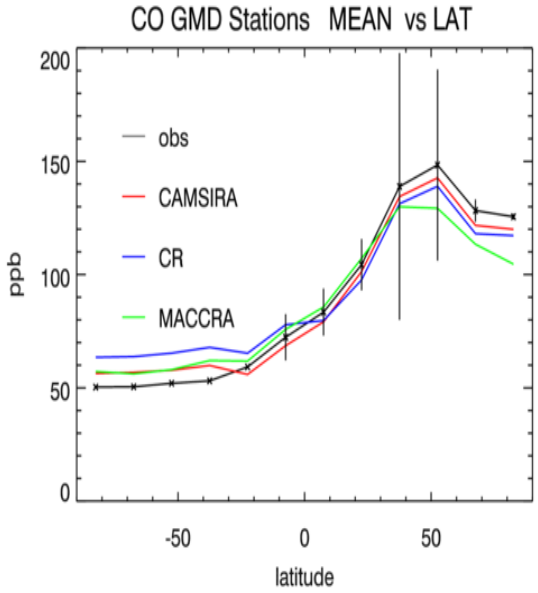
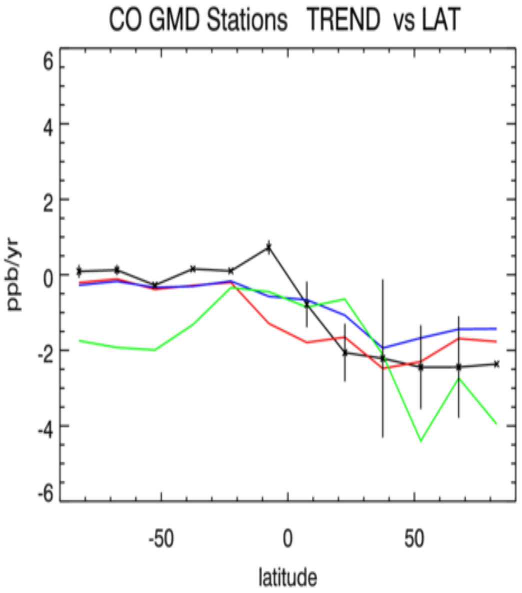
C O surface mean and trend

Atmosphere Monitoring



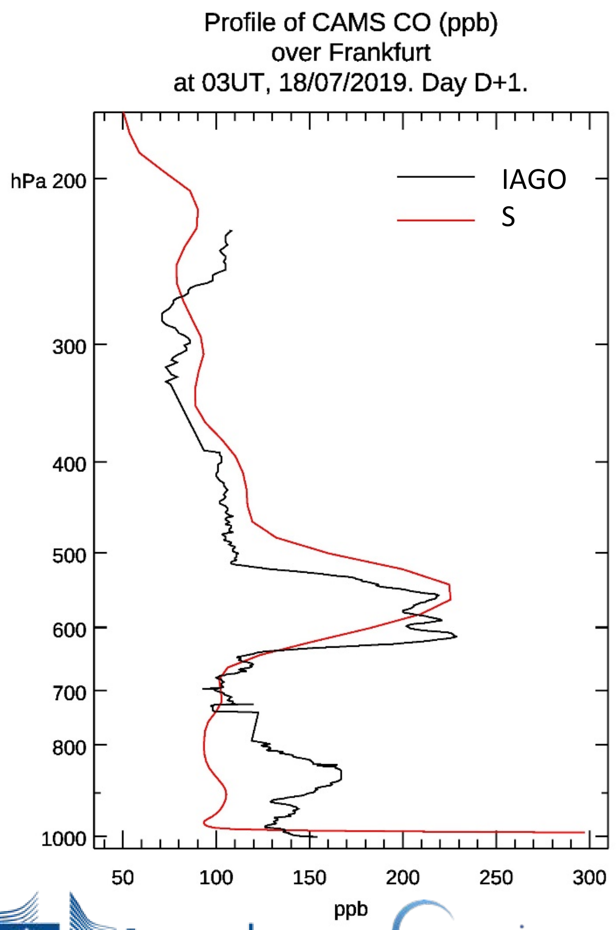
Mean

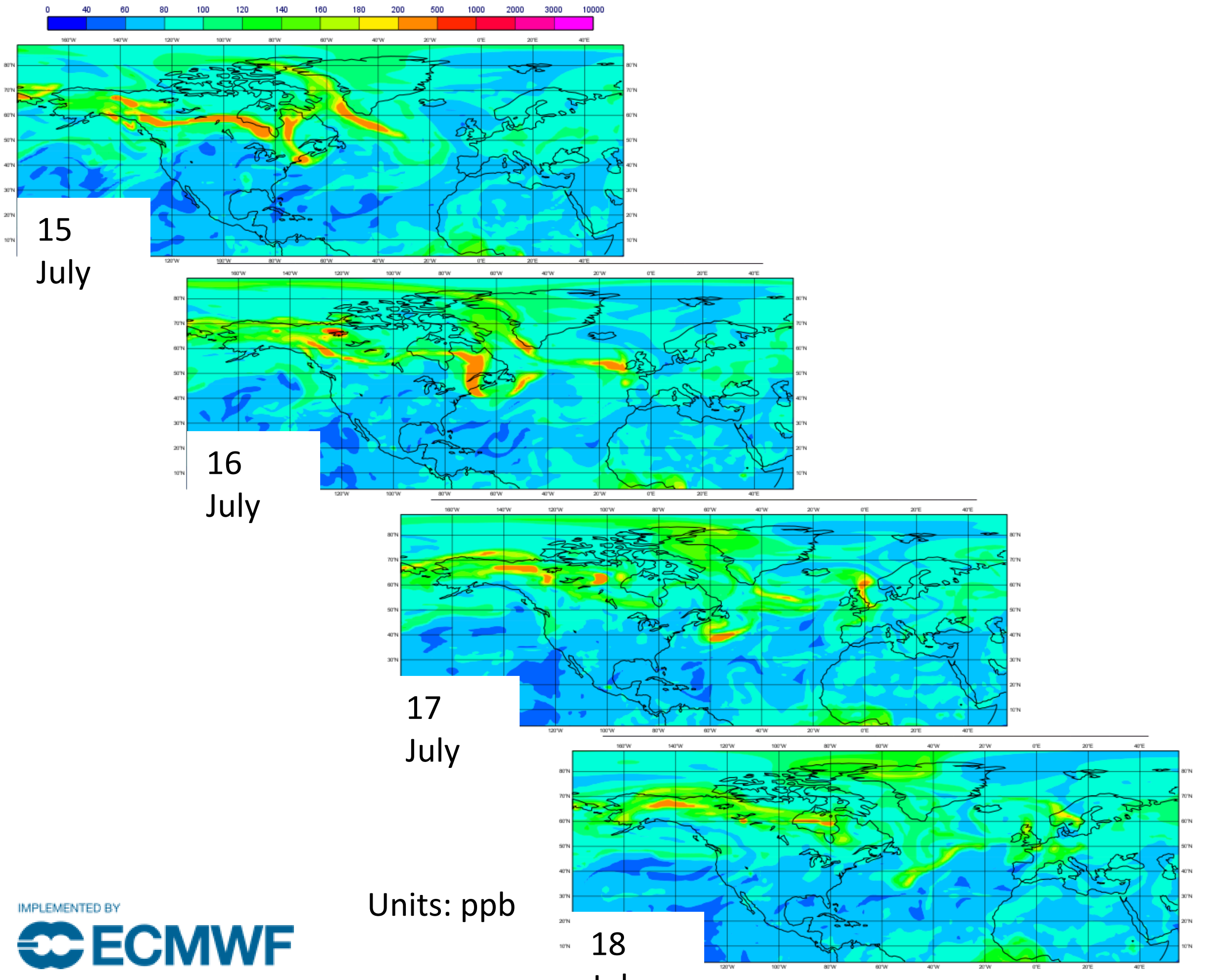


Trend (2003-2015)

Flemming et. al, 2017

CO transport form North American fires in July 2019





Units: ppb

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