Exploring synergies in composition and NWP data assimilation

Antje Inness (ECMWF)

Workshop on data assimilation (Bonn): 9 April 2025

With thanks to: Johannes Flemming, Noureddine Semane, Ziga Zaplotnik, Sebastien Massart, Marco Matricardi, ….

Atmosphere Monitoring

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Outline

1. CAMS overview
2. Stratospheric humidity analysis *(Noureddine Semane)*
3. Impact of using interactive aerosols *(Johannes Flemming)*
4. Wind information from tracers *(Ziga Zaplotnik, Sebastien Massart, Noureddine Semane)*
5. Using CAMS CO2 in RTTOV *(Marco Matricardi)*
6. Summary

COPERNICUS ATMOSPHERE MONITORING SERVICE (CAMS)

Atmosphere Monitoring

Within the 6 Copernicus Services, CAMS mandate is to deliver consistent and quality-controlled information related to **the chemical composition of the atmosphere**, its drivers (**air pollutants and GHG**) and its impact on air quality and health, solar energy, climate forcing, in Europe and everywhere in the world.

Air quality

Policy tools

Solar energy

Ozone layer and UV radiation

Emissions and surface Fluxes

Climate forcing

CAMS integrated framework

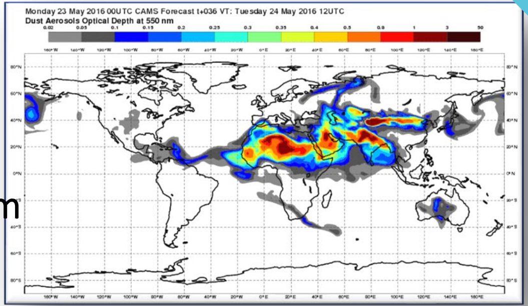
Atmosphere Monitoring

Global CAMS Emissions

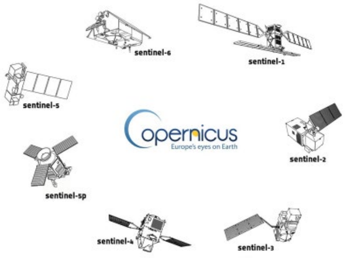
GFAS wildfire emissions

European CAMS Emissions

ECMWF IFS global, 40x40 km

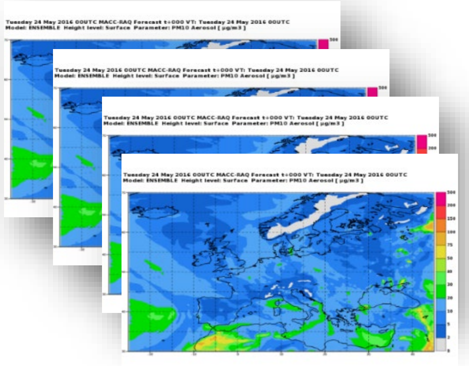


Data assimilation

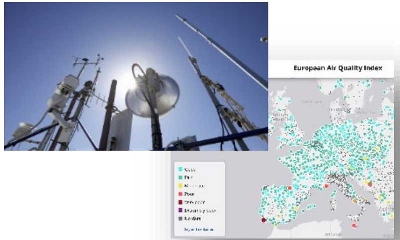


Satellite Observations (AOD, O_3, CO, NO_2, SO_2,CH_4,CO_2

Boundary Conditions



11 regional CTMs over Europe, 10x10 km



Surface AQ observations

Data assimilation

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Examples of CAMS services

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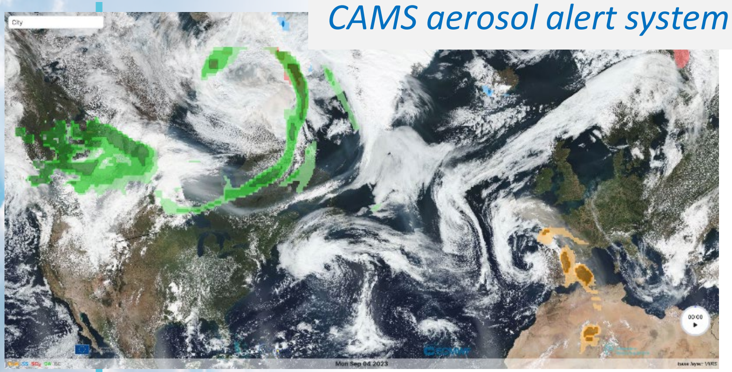
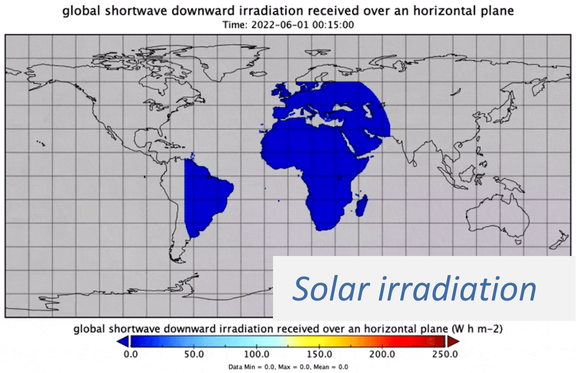
https://aerosol-alerts.atmosphere.copernicus.eu

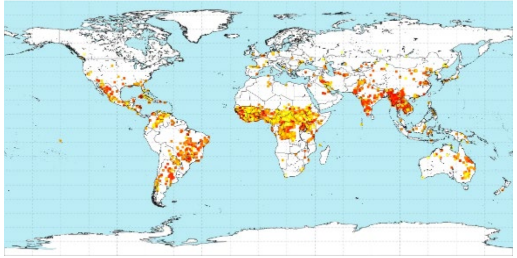
CAMS aerosol alert system



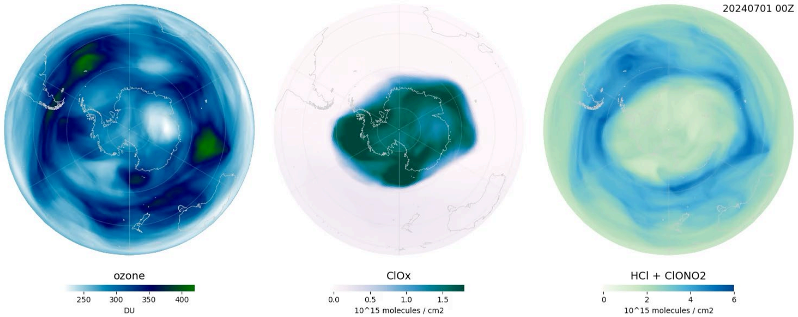


Solar irradiation

Wildfires

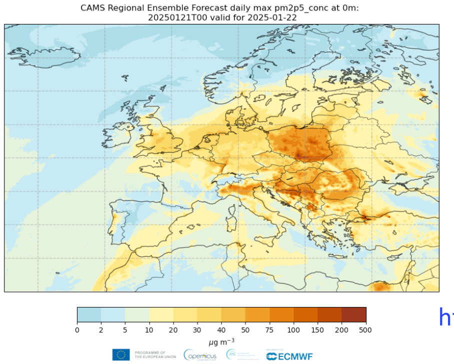


Ozone hole

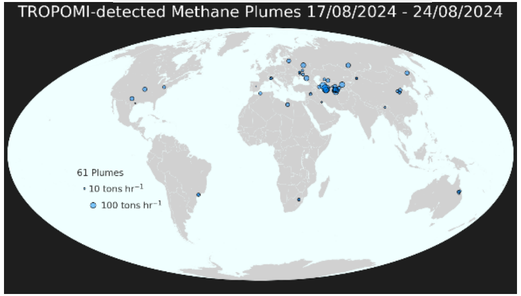


https://atmosphere.copernicus.eu/monitoring-ozone-layer

European air quality



Methane Hot-spots



Data provided by SRON

https://apps.atmosphere.copernicus.eu/methane-explorer

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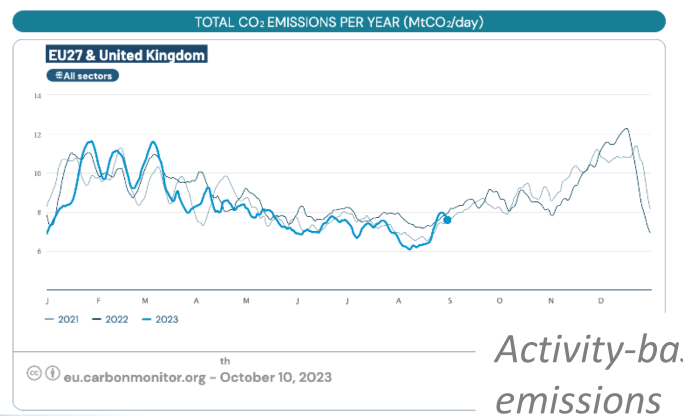
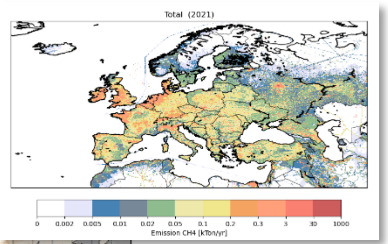
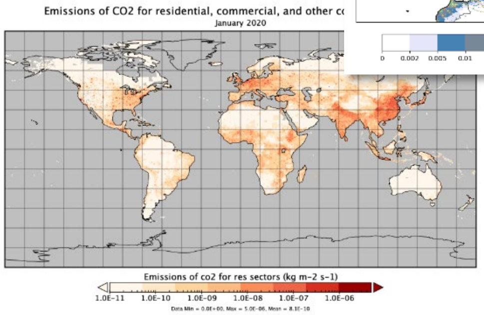
CAMS current offer on GHG information products



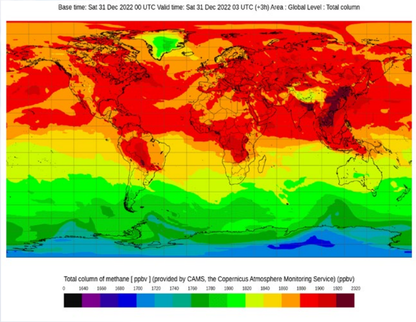
Activity-based emissions

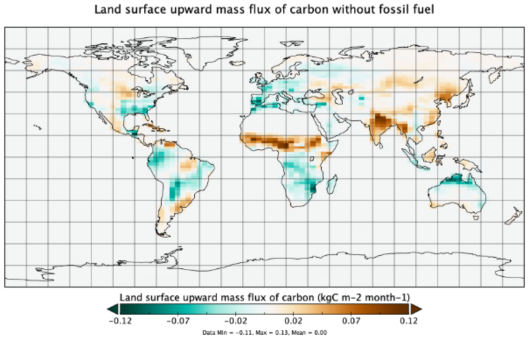
Inventory-based emissions





Daily global forecasts of atmospheric CO_2 and CH_4 concentrations at high resolution





Annually updated flux inversions (monthly) for CO_2, CH_4, and N_2O

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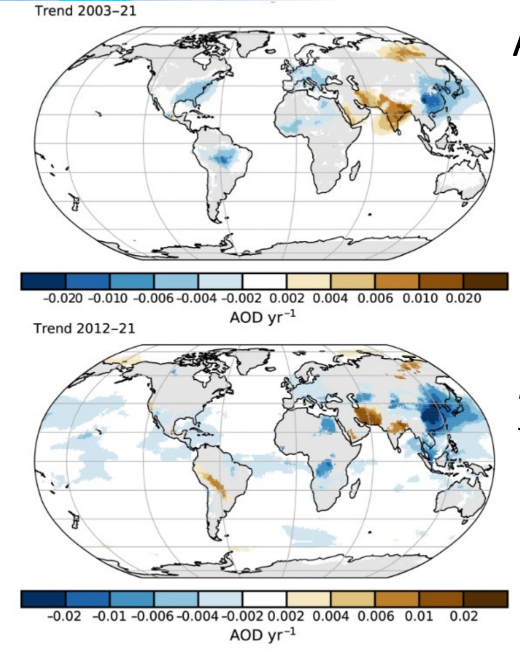
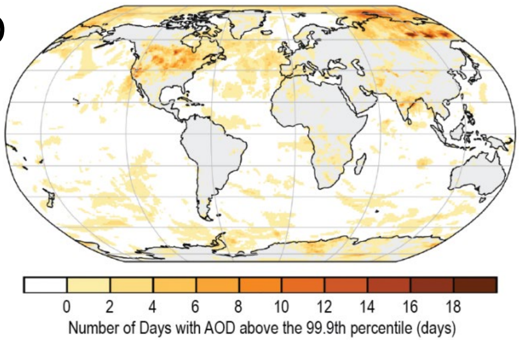
CAMS reanalysis of atmospheric composition (EAC4)



CAMS reanalysis linear trends of total AOD for 2003-2021 and 2012-2021

AOD



Remy et al. (2022), STOC 2021

CAMS reanalysis data have been used for almost a decade to contribute to BAMS State of the Climate reports

Extreme AOD days in 2021 correspond to extreme boreal fire events, including transport to the Arctic

Comparison of xCO with TCCON at Parkfalls

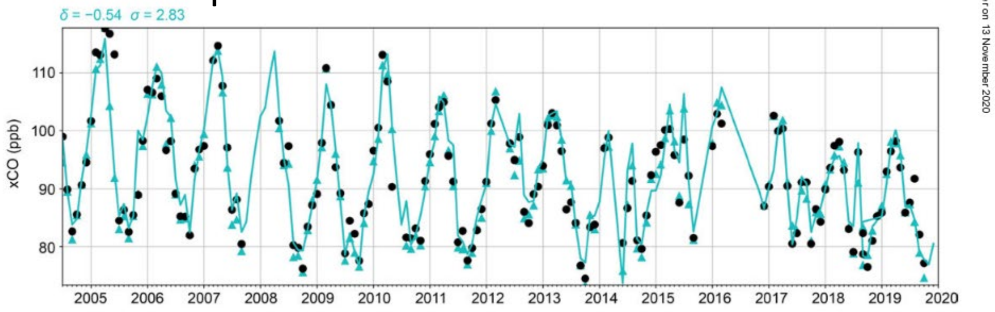


Fig. 2.62. Column-averaged CO (xCO, in ppb) at the Park Falls TCCON station. Monthly mean observations are shown by the black dots, and corresponding monthly mean xCO columns calculated using the TCCON-averaging kernels are shown by the blue triangles. The continuous blue line is the monthly xCO from the CAMS reanalysis.

Flemming et al. (2020), STOC 2019

TCCON data from: https://tccondata.org/

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TCCON total carbon column observing network

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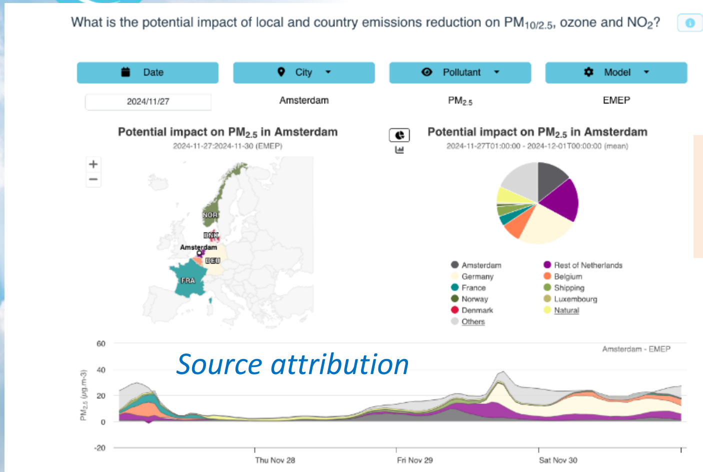
Interactive policy tools

https://policy.atmosphere.Copernicus.eu

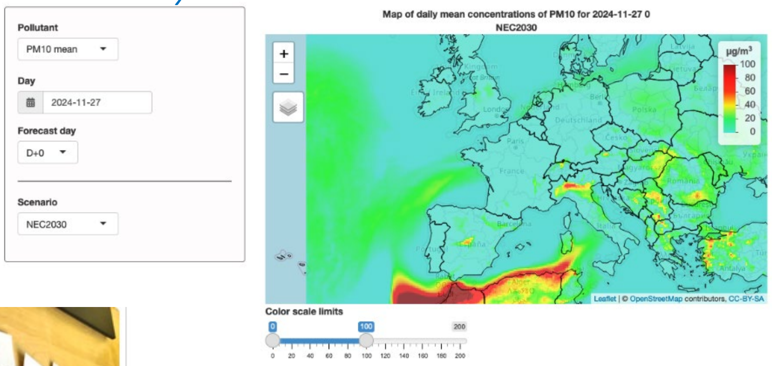


Source attribution

CAMS regional service

How would different policy scenarios of emission reductions affect current air quality?

Policy scenarios

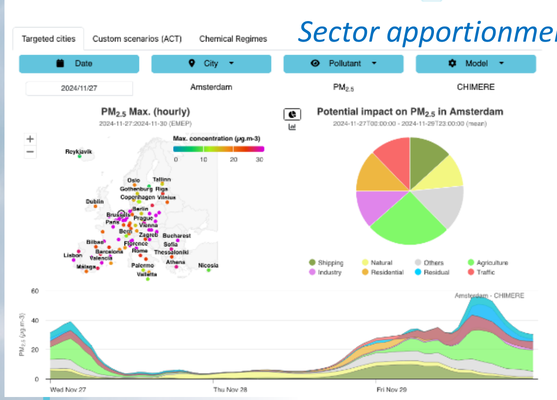


Air Quality Reports

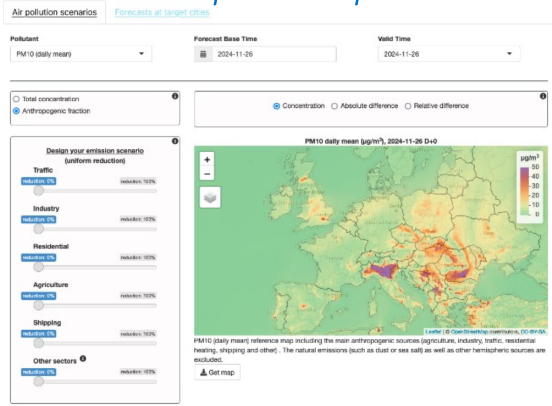
Find reports on **major air pollution episodes** in Europe (fine particles, ozone, forest fires, ...), as well as **annual assessment** reports.

What is the potential impact of different measures affecting sector emissions?

Sector apportionment



CAMS ACT: Atmospheric composition toolbox



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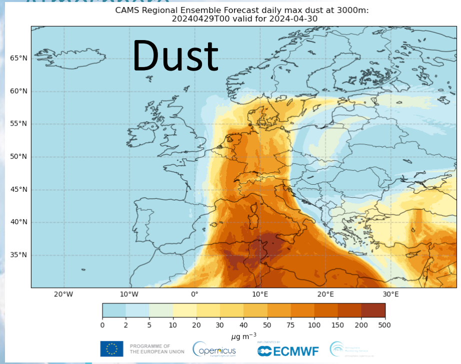
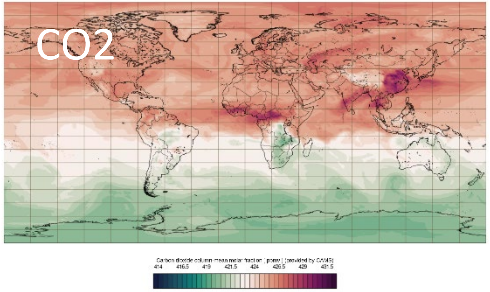
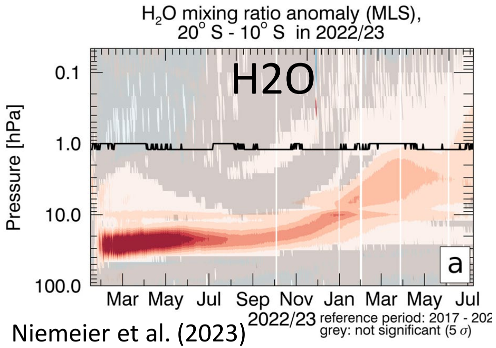
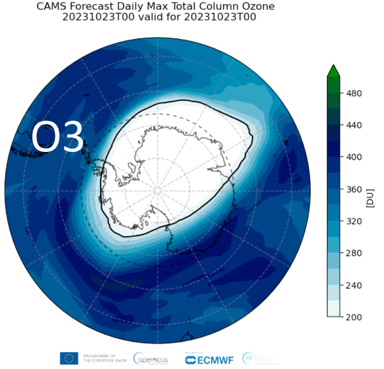
Potential impact of atmospheric composition on NWP



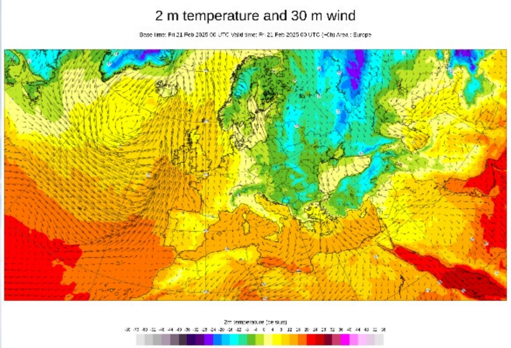


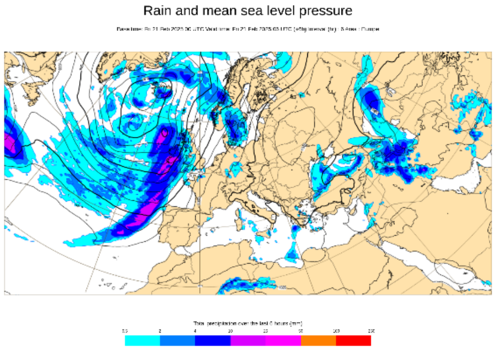


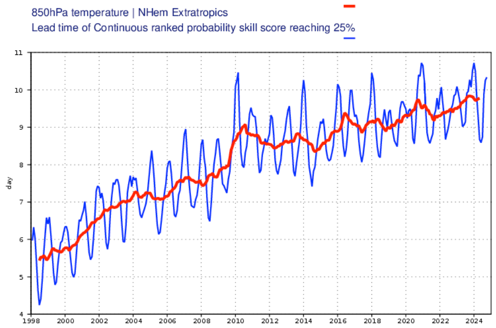
Niemeier et al. (2023)
https://doi.org/10.1029/2023GL106482



?????







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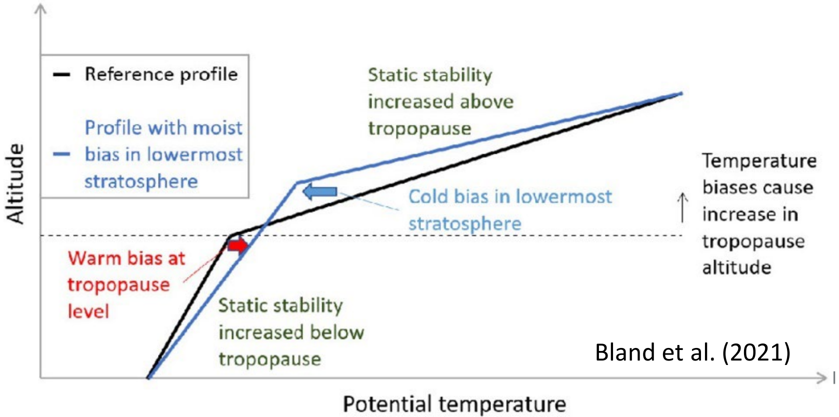
2. Stratospheric humidity analysis

Credit: N. Semane

- ECMWF’s stratospheric humidity field currently not updated by 4D-Var (CY49R1)
    - Analysis increments forced to be zero above the model tropopause.
- Humidity above tropopause is changed only to remove supersaturation caused by a temperature increment.
- This was introduced in 2003 to avoid spurious humidity increments in the stratosphere that degraded forecast scores
- Humidity levels in lowermost stratosphere are overestimated in IFS (Bland et al., 2021)

  ⇒ Excessive longwave radiative cooling

  ⇒ Increasing cold bias in temperature forecasts, with a cooling rate of –0.2 K per day



Bland et al. (2021)

Atmosphere Monitoring

Experiment setup: stratospheric humidity analysis

Credit: N. Semane

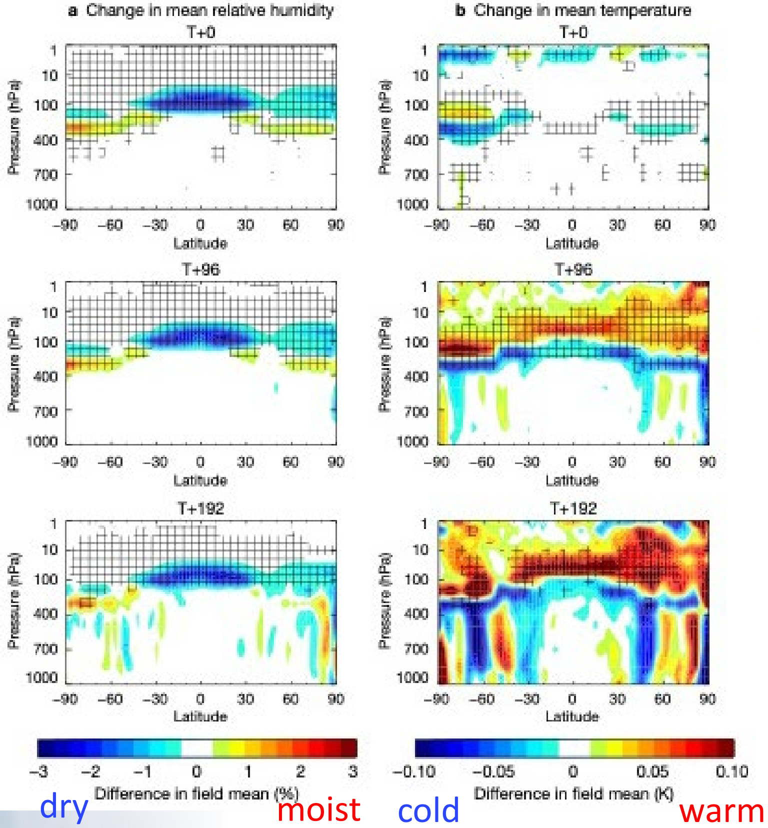
Exp	Description
CTL	CY49R1 humidity analysis • Radiosonde humidity profiles • GNSS-RO bending angles • Radiances from satellite microwave and infrared sounders • No stratospheric humidity increments
QIN	CTL + analysis of stratospheric humidity
MLS	QIN + • Radiosonde RS41 humidity obs up to 60 hPa • Assimilate EOS-Aura Microwave Limb Sounder (MLS) H2O retrievals

Change in relative humidity and temp (MLS – CTL)

Atmosphere Monitoring

Rel humidity

Temperature



- Enabling stratospheric humidity analysis and assimilating MLS & extended sonde humidity observations leads to

⇒ a drying of the lower stratosphere and moistening below tropopause

⇒ a warming of the lower stratosphere and cooling of upper troposphere

- Mitigates known IFS biases
- Sharpens the tropopause (weak & diffuse tropopause is also a known issue in ECMWF forecasts/analyses - Krüger et al. (2023)

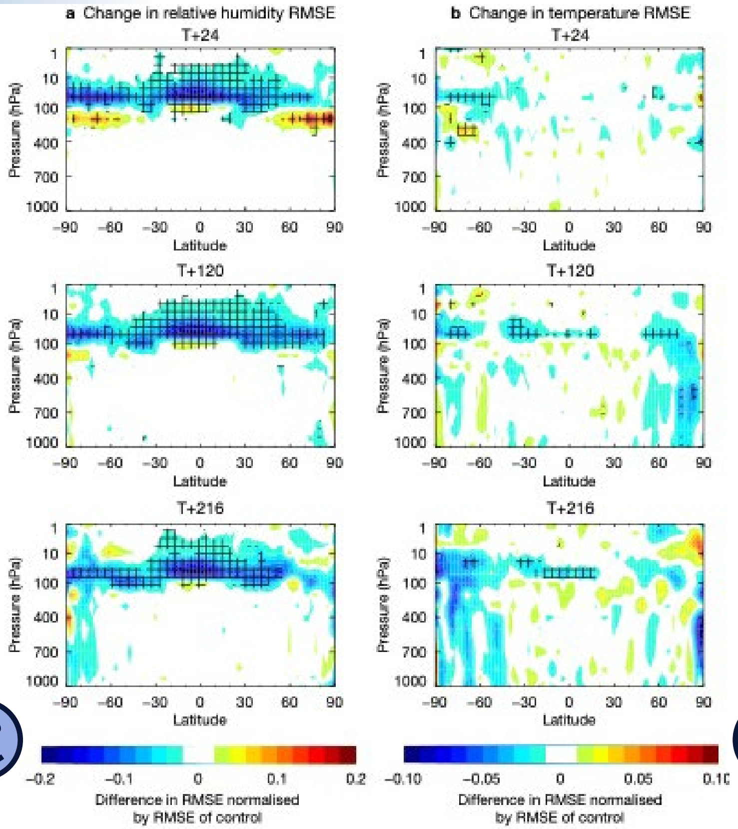
Credit: N. Semane (ECMWF newsletter 183)

Impact on forecast scores (MLS – CTL)

Atmosphere Monitoring

Rel humidity

Temperature



- Improved forecasts across all lead times.
- Enhancements most pronounced in UTLS
- Indications that improvements propagate into troposphere with increasing lead time.

- **Stratospheric humidity analysis will be activated in CY50R1**

Credit: N. Semane (ECMWF newsletter 183)

Atmosphere Monitoring

3. Use of interactive aerosols

- ECMWF’s NWP system currently uses a monthly aerosol climatology (Bozzo et al., 2020; GMD)
- CAMS uses prognostic aerosols interactively in the radiation scheme
- What is the benefit of using prognostic aerosol in the IFS radiation scheme compared to using the aerosol climatology?

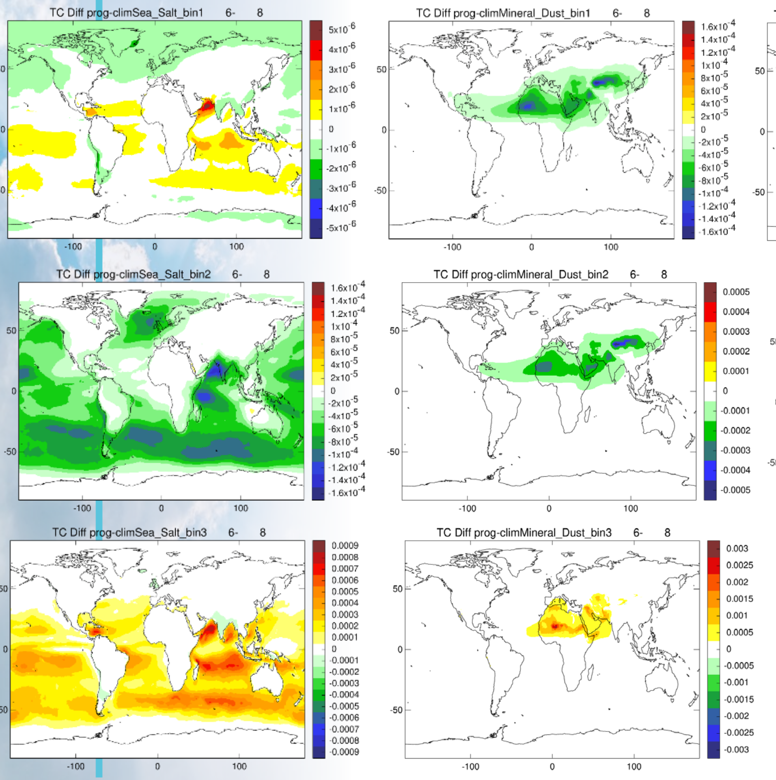
Pete Laing/BC Wildfire Service

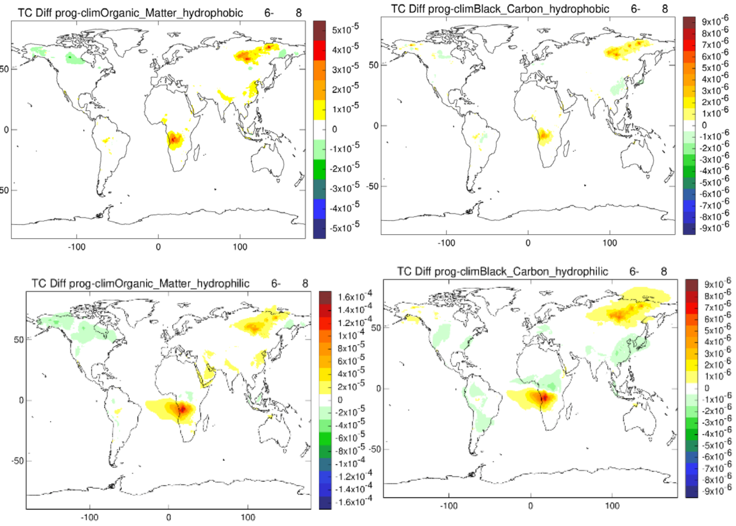
Pavliha/iStockphoto

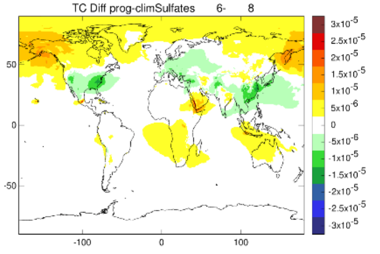
Mean Difference between climatological and prognostic aerosols (Total column mass) JJA 2019

Credit: J. Flemming

Sea Salt | Dust | OM | BC | SO4





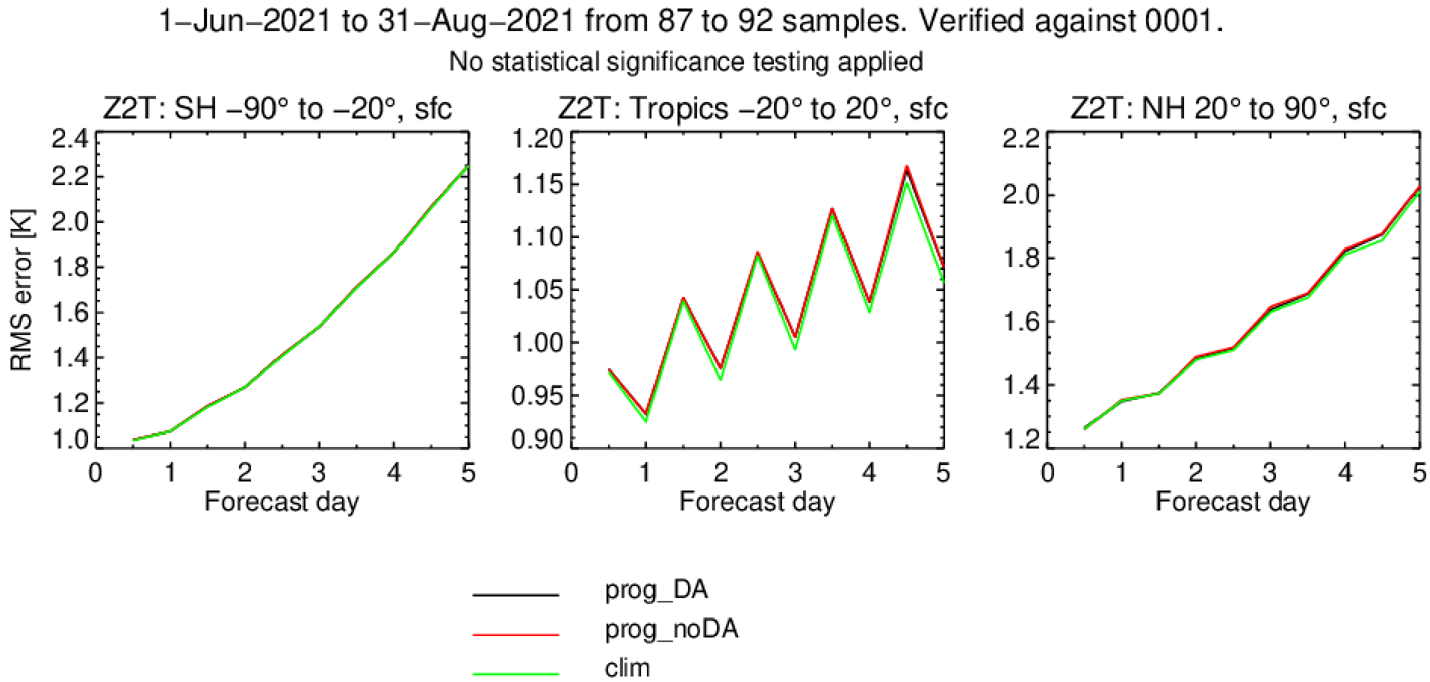


Note:
Nitrates, NH4 and SOA NOT in climatology

- Considerable mean differences for dust and sea salt
- Biomass burning signals in OM and BC
- Increased prognostic SO4 probably because of Raikoke eruption

Impact on forecast scores

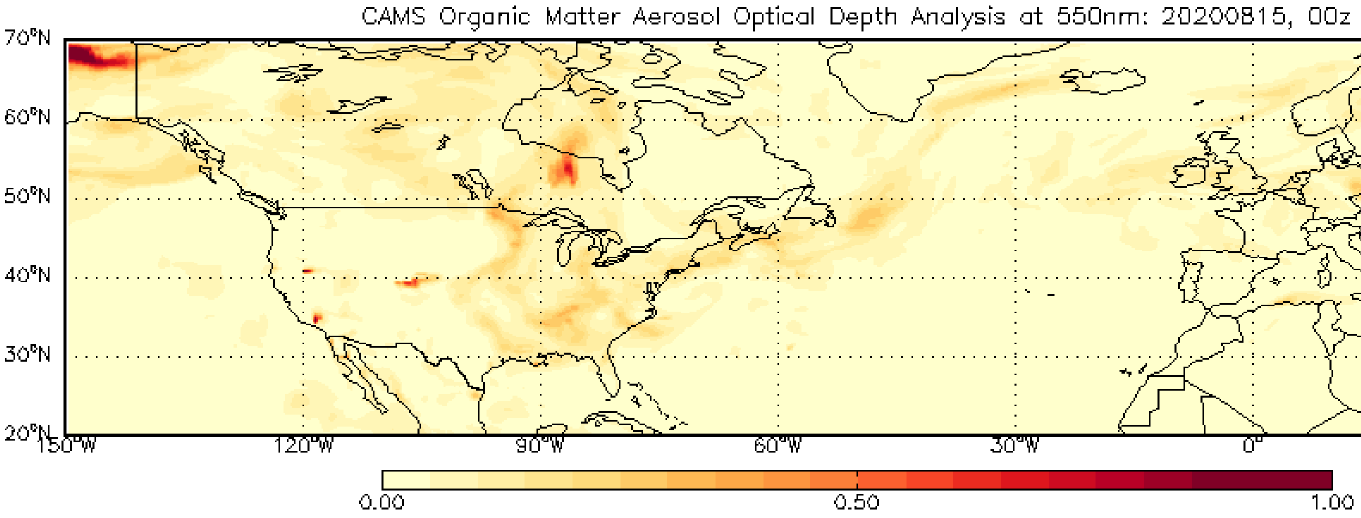
Credit: J. Flemming



Using prognostic aerosol makes no noticeable difference for “average” NWP scores, e.g. RMS 2mT with lead time

California and Western US fires 2020

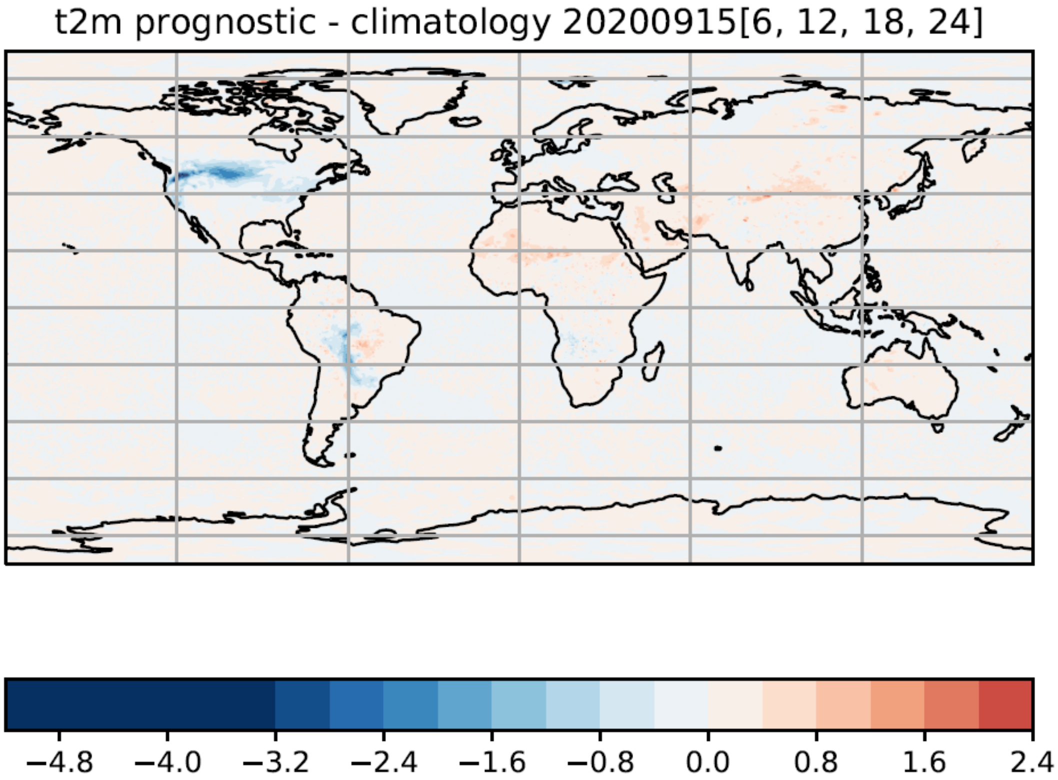
Smoke transport from wildfires



Mark Parrington
CAMS Weather Room

2mT difference: prognostic aerosols

Credit: J. Flemming



CAMS o-suite (prog Aerosol) minus CAMS-CLIM (clim aerosol)

Up to 5 K reduction in daily mean 2mT

CAMS o-suite uses prognostic aerosol and ozone in radiation scheme

CAMS-CLIM control forecast (00) using aerosol and ozone climatology tun in NRT

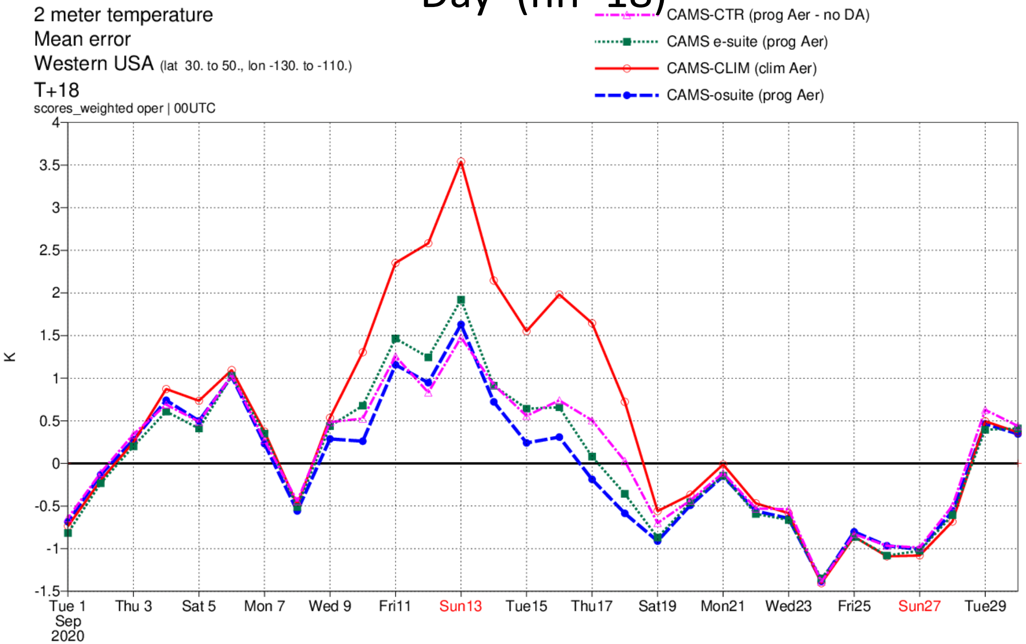
Atmosphere Monitor

2 m T Mean error Western USA

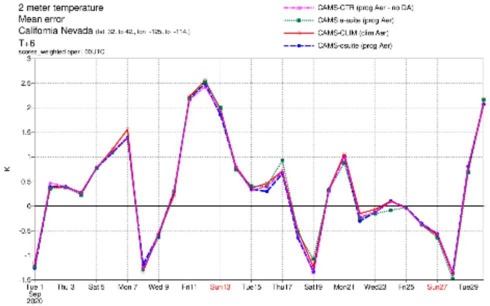
Credit: J. Flemming

clim Aero
prog Aero DA (47r1)
prog Aero DA (46r1)
prog_Aero noDA (46r1)

Day (hh=18)

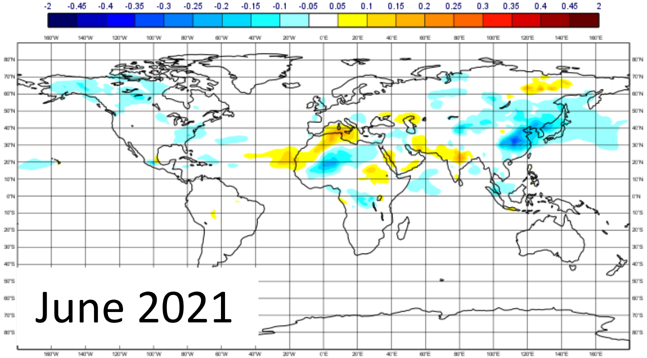


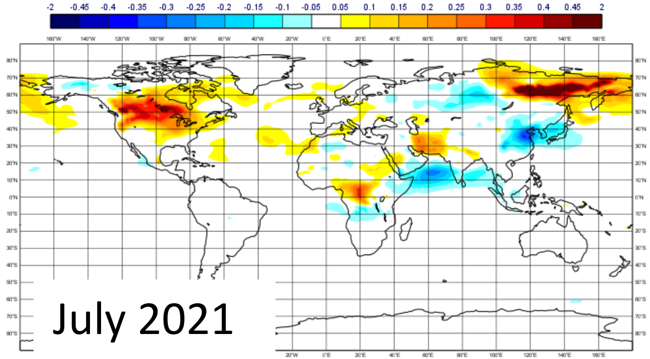
Night (hh=6)



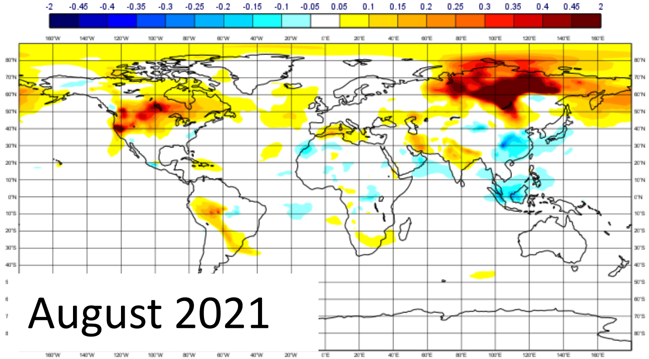
Increased positive bias with aerosol climatology in CAMS-CLIM CTR

AOD anomalies and boreal wildfires 2021



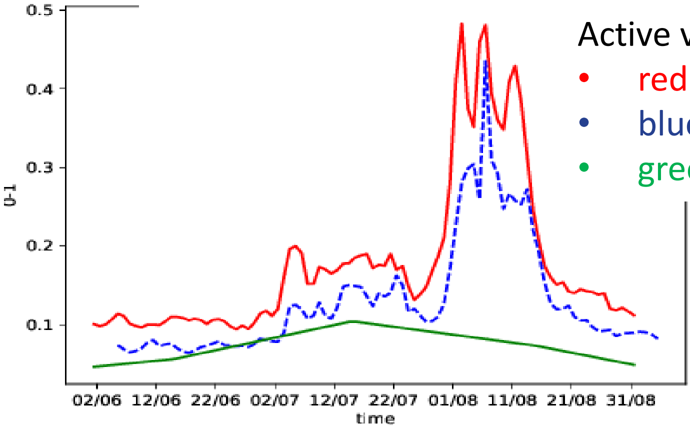


AOD anomalies due to Siberian and N-American wildfires in JJA 2021



Anomalies calculated against 2003-2020 monthly means from CAMS reanalysis

AOD mean Arctic JJA 2021

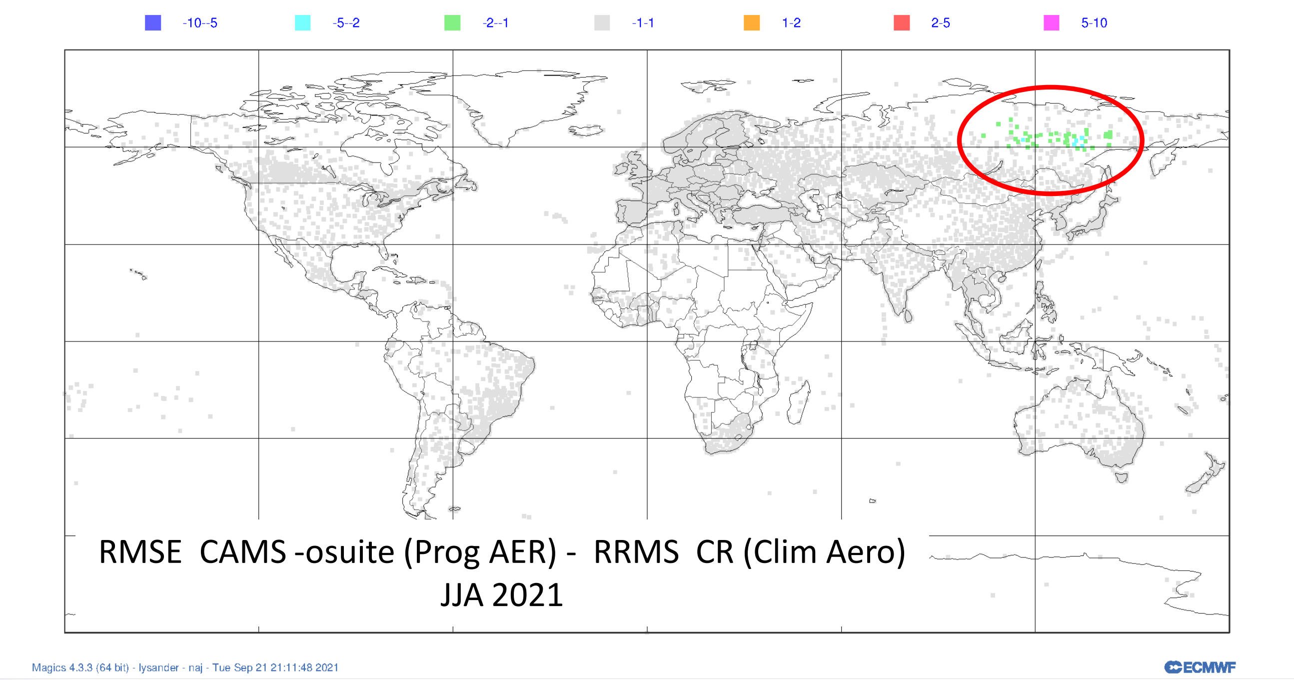


Active vegetation fires in Siberia

- red: AOD analysis,
- blue: 108 h forecast
- green: climatology

Impact on Artic wildfires on 2m temperature forecasts (JJA 2021)

Credit: J. Flemming



Using prognostic aerosols leads to decrease in 2mT RMSE against synop observations

Credit: Johannes Flemming

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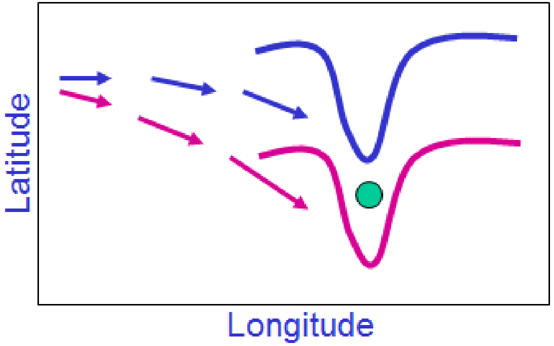
Summary interactive aerosols

- Compared to using the CAMS/ECMWF aerosol climatology:
  - Cooling of several K in the case of large AOD anomalies
  - Clear indication of improved 2mT forecast against synop observations in case of large fire events (US, Canada, Siberia)
  - No overall improvement in standard NWP scores

- Prognostic aerosol in IFS for NWP purposes is ongoing research topic at ECMWF
- Potential to improve medium-range and monthly seasonal forecast recognised

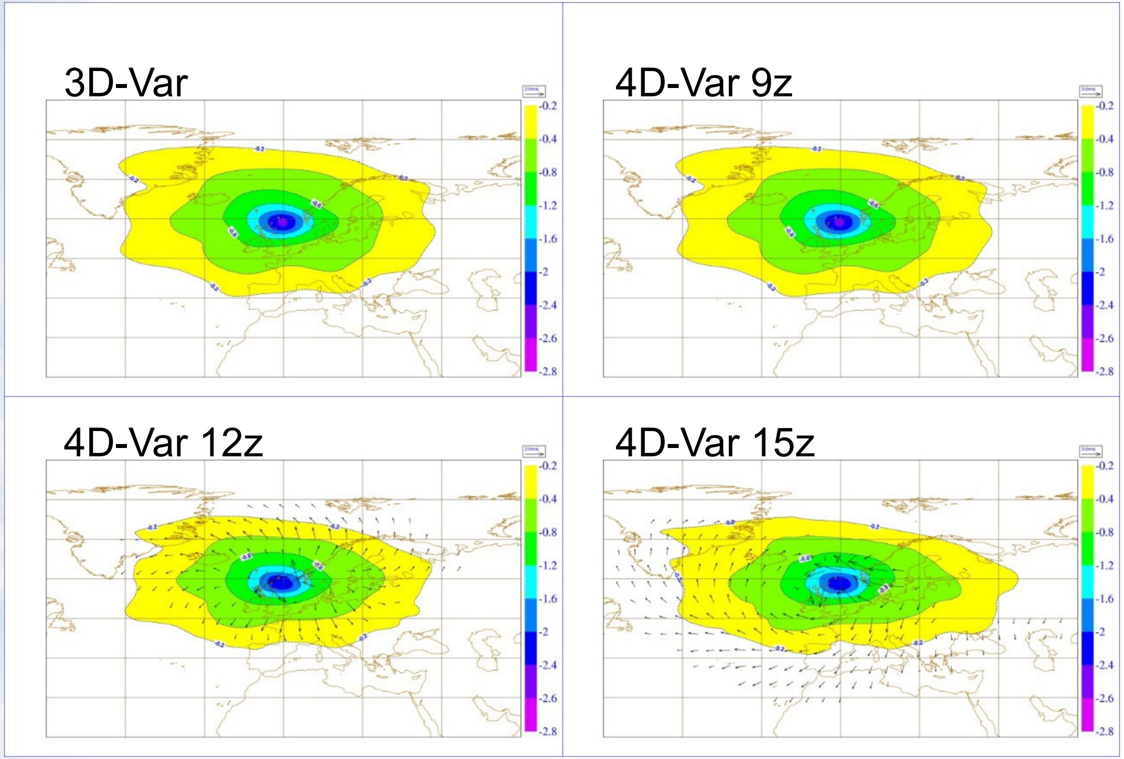
4. Wind information from tracers

- Prospect to extract wind information from long lived tracers in stratosphere and upper troposphere, e.g. O3, H2O, N2O
- Similar to cloud track winds but data coverage worse
- Potential was demonstrated a long time ago in early studies for H2O (Thepaut 1992) and O3 (Daley 1995; Riishojgaard 1996; Holm 1999; Peuch et al. 2000).
- Could compliment existing wind observations and help in areas where there is a lack of adequate global wind profile data
- Potential to extract wind info indirectly through TL and AD of tracer advection



Atmosphere Monitoring

Single observation experiment: O3 and wind increments



Level 20,
≈ 30 hPa

Impact in 6h 4D-Var [window from 9z-15z] from single obs at 9z, 12z or 15z

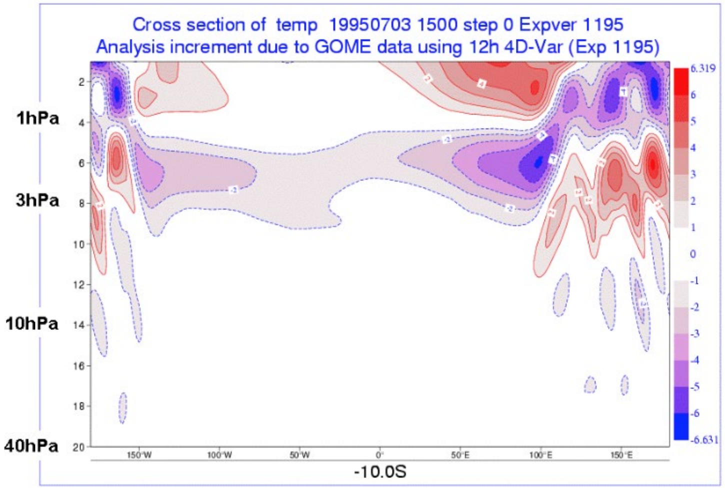
Flow-dependent wind tracing

Credit: Z. Zaplotnik, S. Massart, N. Semane

Year 2007, Slide courtesy of Dick Dee

4D-Var ozone assimilation

The impact of the ozone data on the temperature analysis at 10S



Ozone assimilation

Can 4D-Var infer stratospheric winds from ozone data?

- The answer is: **Not yet.**
- Assimilation of ozone profile data causes large and unrealistic T/U/V increments near the stratopause to accommodate the observed discrepancies between background and data

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Flow-dependent wind tracing

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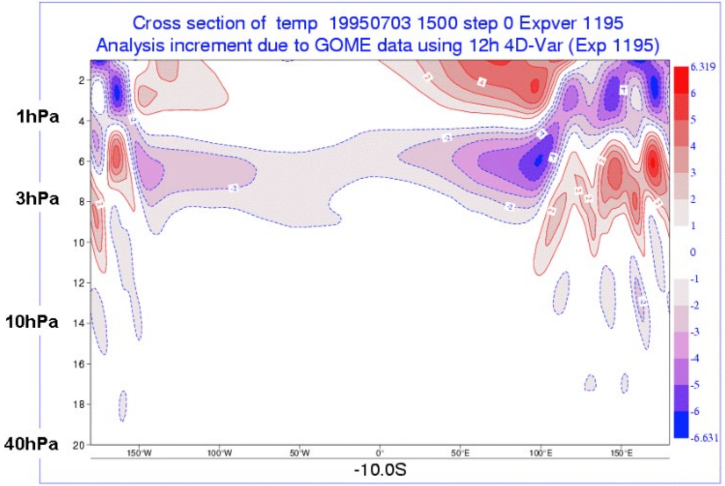

Ozone assimilation

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- The answer is: Not yet.
- Assimilation of ozone profile data causes large and unrealistic T/U/V increments near the stratopause to accommodate the observed discrepancies between background and data

Year 2024

- Wind-tracer coupling in 4D-Var via the TLM integration:

$$\frac{\partial \delta \mathbf{v}}{\partial t} = -(\delta \mathbf{v} \cdot \nabla)\mathbf{v} - (\mathbf{v} \cdot \nabla)\delta \mathbf{v}$$

$$\frac{\partial \delta c}{\partial t} = \boxed{-\gamma(x,y,t)} \, (\nabla \cdot (\delta \mathbf{v}\, c)) - \nabla \cdot (\mathbf{v}\delta c)$$

… and the backwards ADM integration:

$$-\frac{\partial \delta \mathbf{v}^*}{\partial t} = (\mathbf{v} \cdot \nabla)\delta \mathbf{v}^* - (\nabla \otimes \mathbf{v})\delta \mathbf{v}^* \boxed{+\gamma(x,y,t)} \, (-\delta c^* \nabla c + c \nabla \delta c^*)$$

$$-\frac{\partial \delta c^*}{\partial t} = -\nabla \cdot (\delta c^* \mathbf{v}) + \frac{\partial J}{\partial c}.$$

Parameter γ controls the "level" of tracer-wind coupling in the assimilation.

γ=1: on
γ=0: off

Zaplotnik, Ž., Žagar, N. & Semane, N.(2023) Flow-dependent wind extraction in strong-constraint 4D-Var. QJRMS, 149(755, 2107–2124

Flow-dependent wind tracing

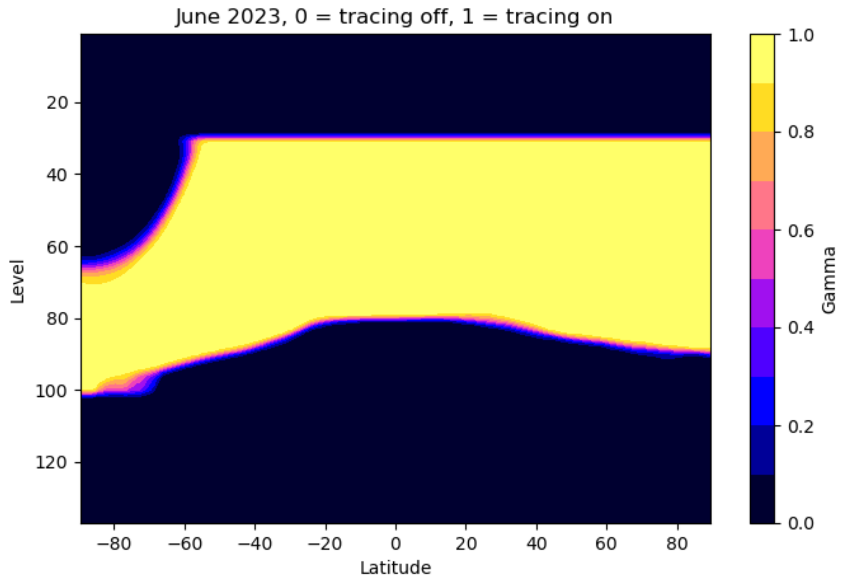
Credit: Z. Zaplotnik, S. Massart, N. Semane

Tracing turned off:

- In the mid- and lower-troposphere
- In the 4D-Var sponge layer (above 10 hPa)
- In the areas with T<195 K, where less predictable heterogeneous chemistry is an important contributor to $\partial r(O_3)/\partial t$ in the nonlinear model

- Different γ for each month based on ERA5 climatology
- Fully flow-dependent γ based on latest background implemented and being tested

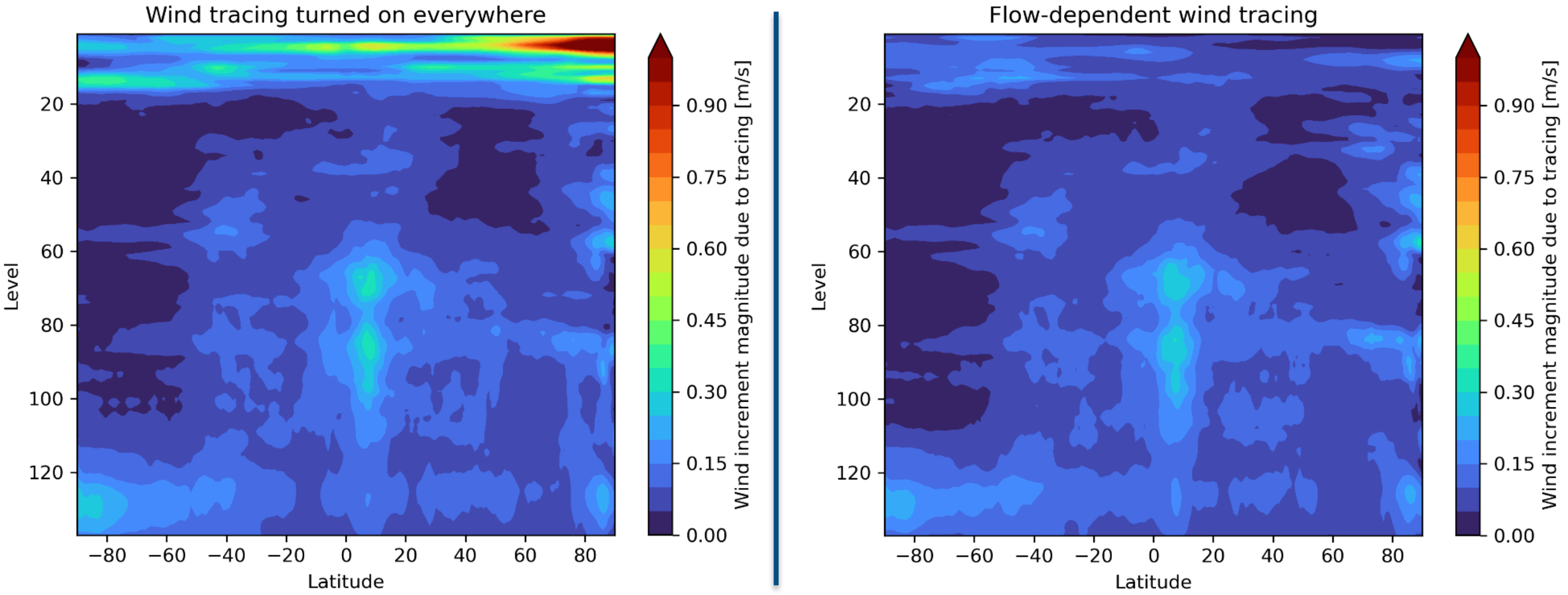
$$\gamma(x, y, \eta, t)$$



Zaplotnik, Ž., Žagar, N. & Semane, N.(2023) Flow-dependent wind extraction in strong-constraint 4D-Var. Quarterly Journal of the Royal Meteorological Society, 149(755, 2107–2124

Wind analysis increments due to tracing

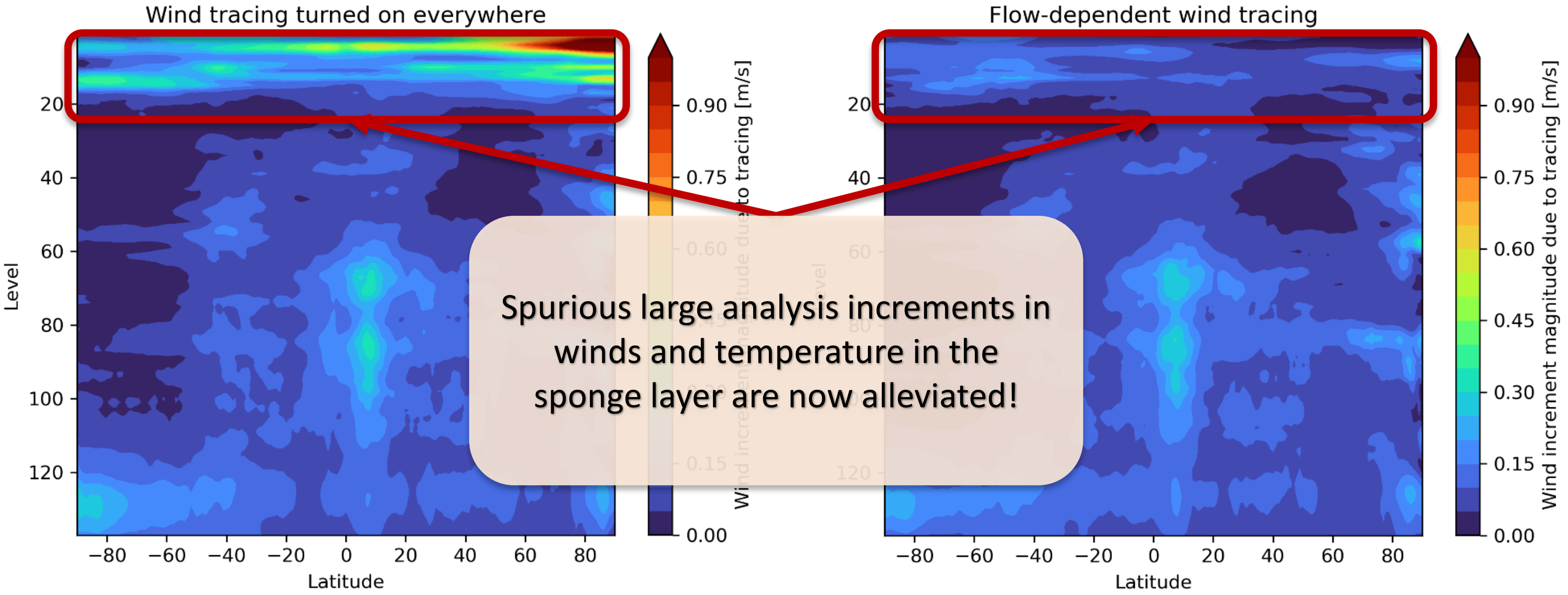
Credit: Z. Zaplotnik, S. Massart, N. Semane



- Positive impact on O-B statistics for ozone-sensitive channels (IASI, CRIS, AIRS), neutral-to-positive impact on other O-B statistics
- Ozone-wind tracing is undergoing testing for CY50R1

Wind analysis increments due to tracing

Credit: Z. Zaplotnik, S. Massart, N. Semane



- Positive impact on O-B statistics for ozone-sensitive channels (IASI, CRIS, AIRS), neutral-to-positive impact on other O-B statistics

Validation against ozone sondes

Credit: Z. Zaplotnik, S. Massart, N. Semane

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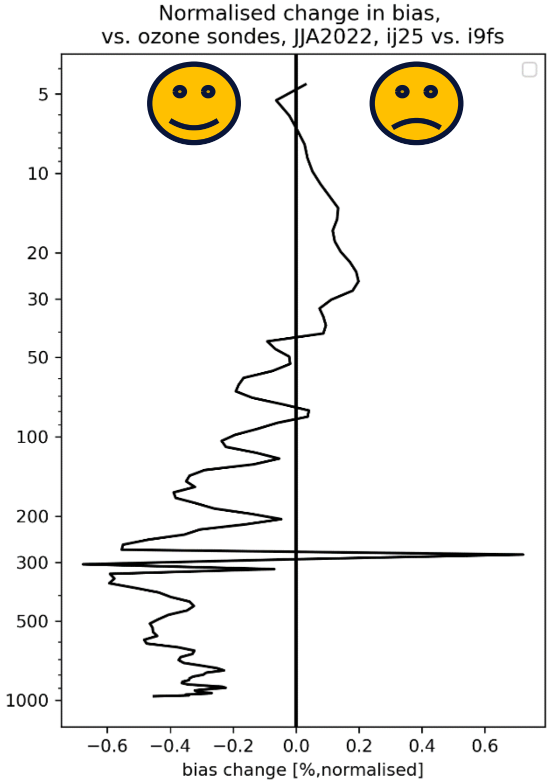
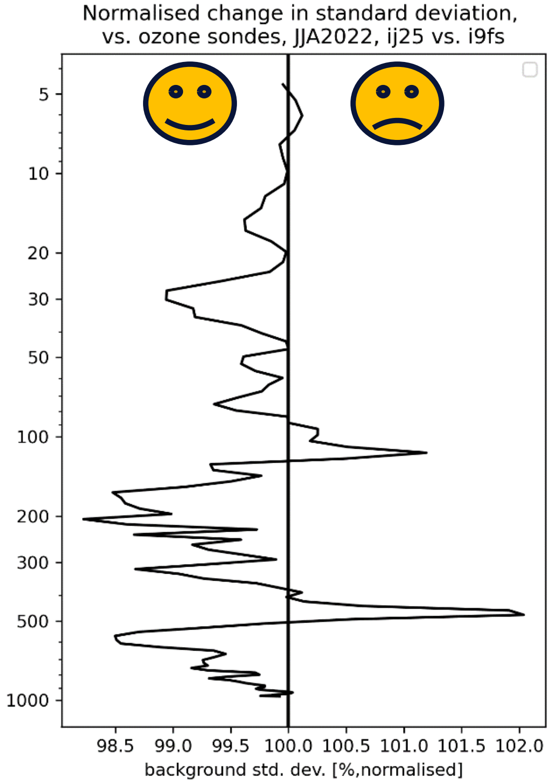
Change in bias



Change in stdv



- Improved fit to ozone sondes with flow-dependent wind tracing
- **Ozone-wind tracing will be activated in CY50R1**

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5. Using CAMS CO2 in RTTOV

Credit: M. Matricardi

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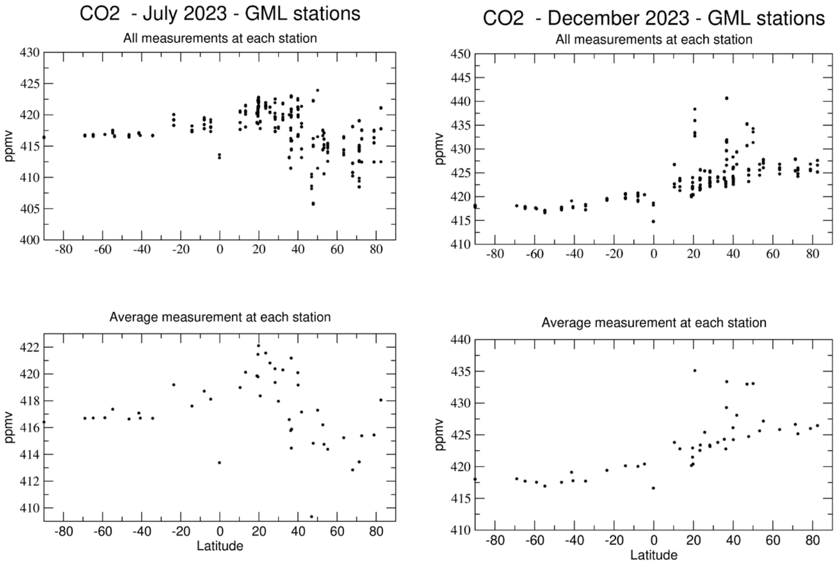
- RTTOV calculations are carried out with a fixed CO2 profile (no change with latitude or month) with values ~ 401 ppmv in troposphere
- Testing of using varying CO_2 profiles in the RTTOV calculations, obtained from a bi-dimensional monthly mean climatology derived from one year of CAMS reanalysis (EGG4)

=> CO_2 mixing ratios used in the RTTOV calculation vary with altitude, latitude and month

All obs

Average



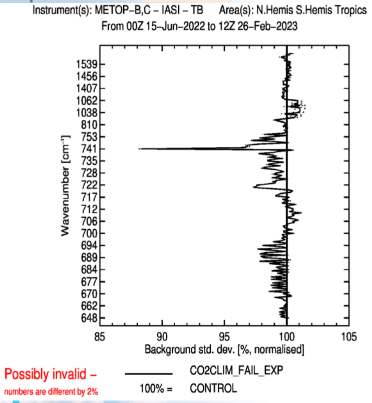
Surface CO2 obs from Global Monitoring Laboratory network

Impact on fit to observations

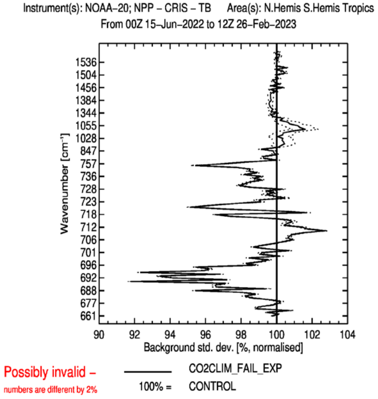
Credit: M. Matricardi

In this spectral region the main absorber is N_2O, not CO_2

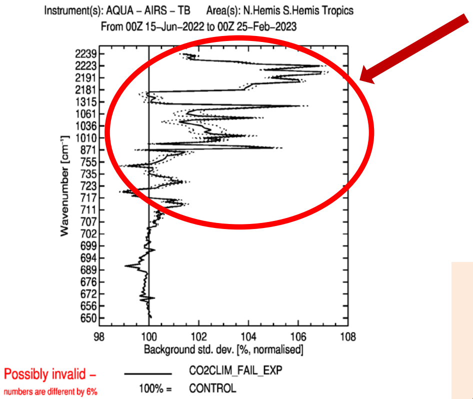
IASI



CrIS

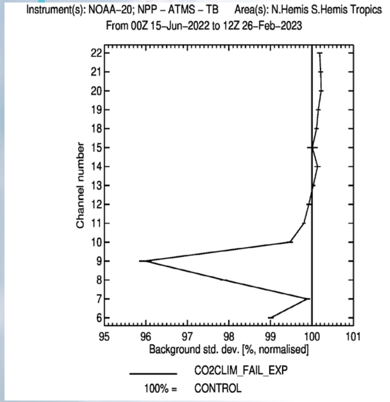


AIRS

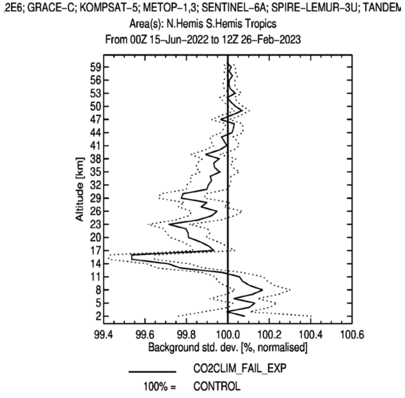


Better fit to the hyperspectral data affected by the CO_2 changes and better fit to independent observations

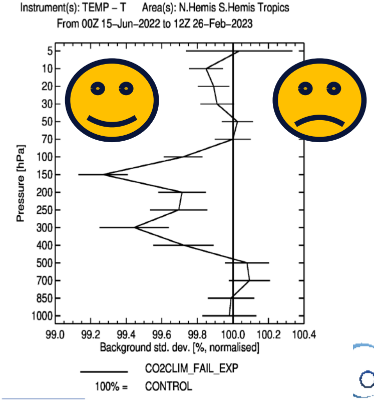
ATMS



RO



Radiosonde - T



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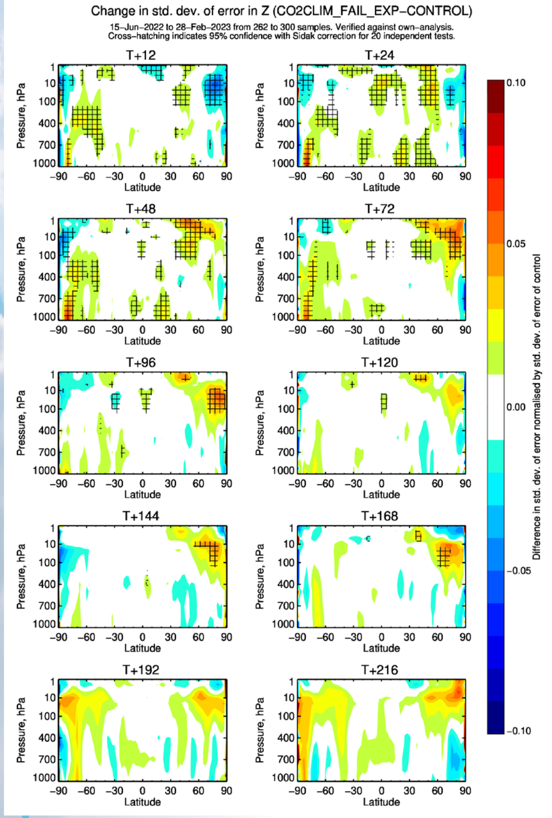
Impact of variable CO_2 on forecast scores

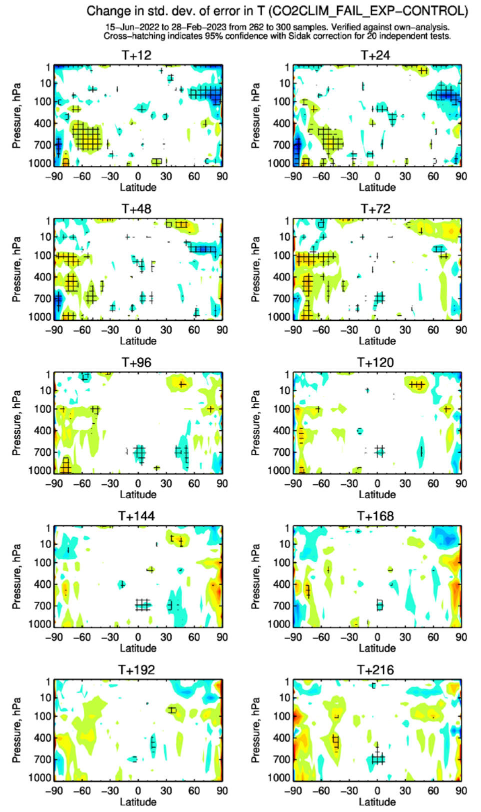
Credit: M. Matricardi

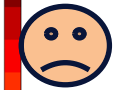
Atmosphere Monitoring

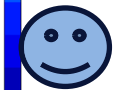
Z



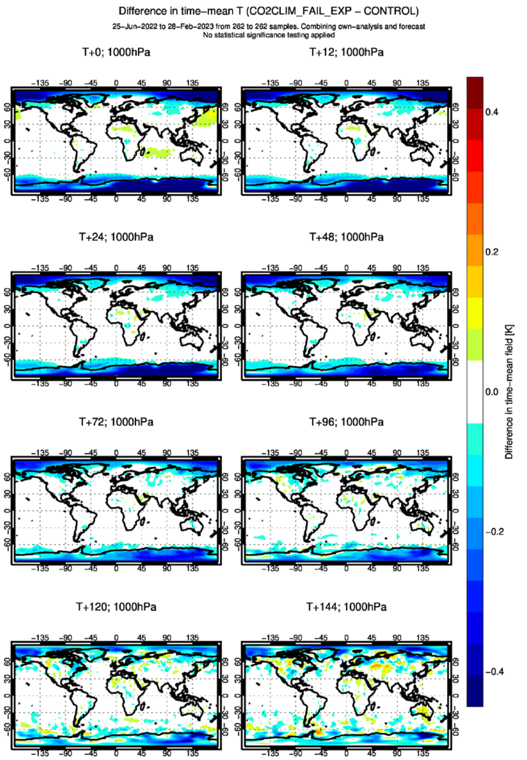
T







Difference in mean T



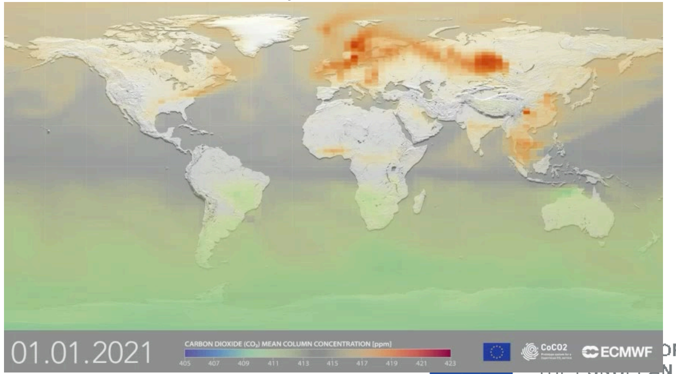
Initial results using CO2 climatology in RTTOV

- The system based on the CO_2 climatology produces an analysis that, overall, is better than the analysis produced by the operational system

  => Better fit to the hyperspectral data affected by the CO_2 changes and fit to independent observations

- Medium range forecast scores launched from the improved analysis do not improve the operational scores.
- The system based on the climatological CO_2 seems to cool the atmosphere at the poles.
- More work to come, e.g. exploring use of NRT CO2 data from CAMS instead of climatology

Atmospheric CO2



Credit:
M. Matricardi
A. Agusti-Panareda

CoCO2 Prototype system for a Copernicus CO_2 service
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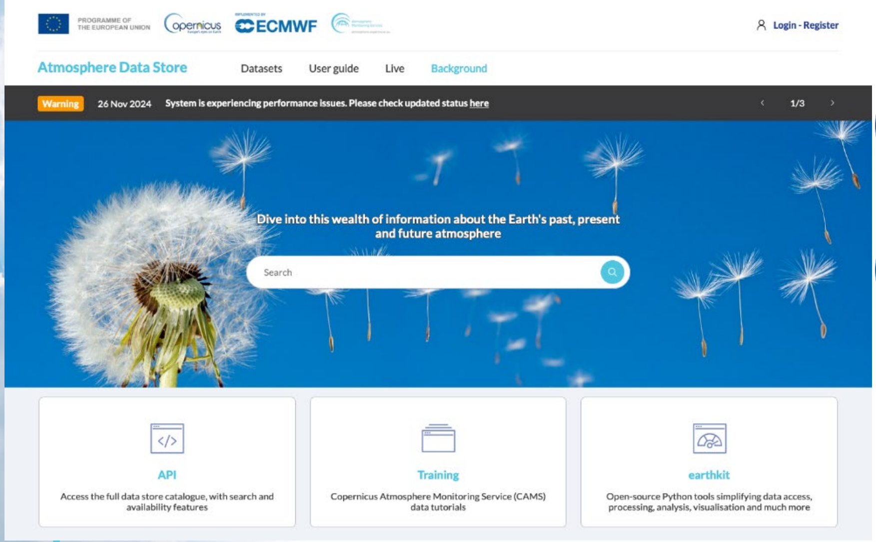
6. Summary

- CAMS provides a wide range of atmospheric composition products
  - Useful in their own right and freely available
- Exciting potential to improve NWP forecasts with atmospheric composition information. E.g.
  - Stratospheric humidity analysis (active in CY50R1)
  - Ozone wind tracing (active in CY50R1)
  - Using aerosols interactively in the radiation scheme
  - Using variable CO2 in RTTOV

The Atmosphere Data Store (ADS)

Atmosphere Monitoring

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



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www.copernicus.eu
atmosphere.copernicus.eu

Documentation of atmospheric composition in IFS:
https://www.ecmwf.int/en/elibrary/81374-ifs-documentation-cy48r1-part-viii-atmospheric-composition

Validation reports from:
https://atmosphere.copernicus.eu/quality-assurance

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Atmosphere Monitoring

Thank you !

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