Atmospheric composition observations: overview, recent developments and gap analysis in the context of weather prediction

Angela Benedetti
(ECMWF)

With thanks to many people (see acknowledgements throughout the presentation)

Outline

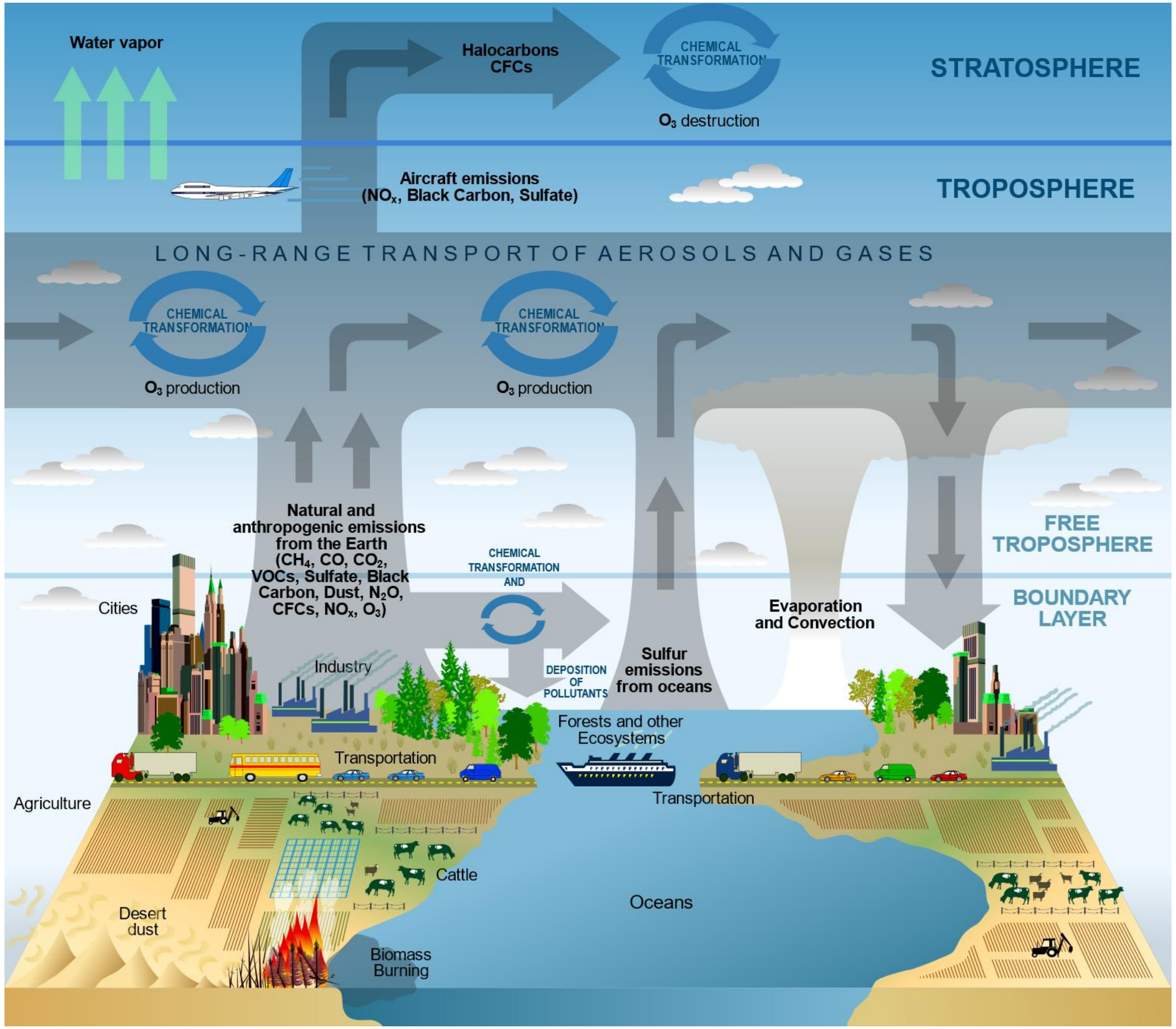
1. How is Atmospheric Composition relevant for NWP?

2. What is the role of observations and DA for AC in NWP?

3. What observations are needed to improve performance in analysis and forecasts and reap more benefits?

4. Future outlook

A complex inter-connected system



Weather is responsible for a significant part of the synoptic variability and therefore NWP models are well-suited for forecasting atmospheric composition, e.g., through our Copernicus services.

But atmospheric composition also affects the weather…

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Atmospheric constituents affect NWP in several ways and across various scales

AC species	Impact on NWP	Mechanism
O_3, Aerosols, GHG	Dynamics , thermodynamics	Radiative interaction
Aerosols	Precipitation and clouds	Cloud Condensation Nuclei and radiative effects
O_3, CO, Aerosols	Winds	4D-Var tracer mechanism
O_3, CO_2 [, N_2O], Aer	Radiance assimilation (Temp,WV)	Observation operator for radiative transfer
CH_4	Water Vapour	Oxidation
CO_2	Surface heat fluxes	Land/sea- atmosphere interface exchange

Analysis → Medium range → Sub-seasonal range → Seasonal range

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From 2018 Council lecture by Rossana Dragani and Richard Engelen (ECMWF)

Atmospheric composition in the Integrated Forecast System: a two-way interaction

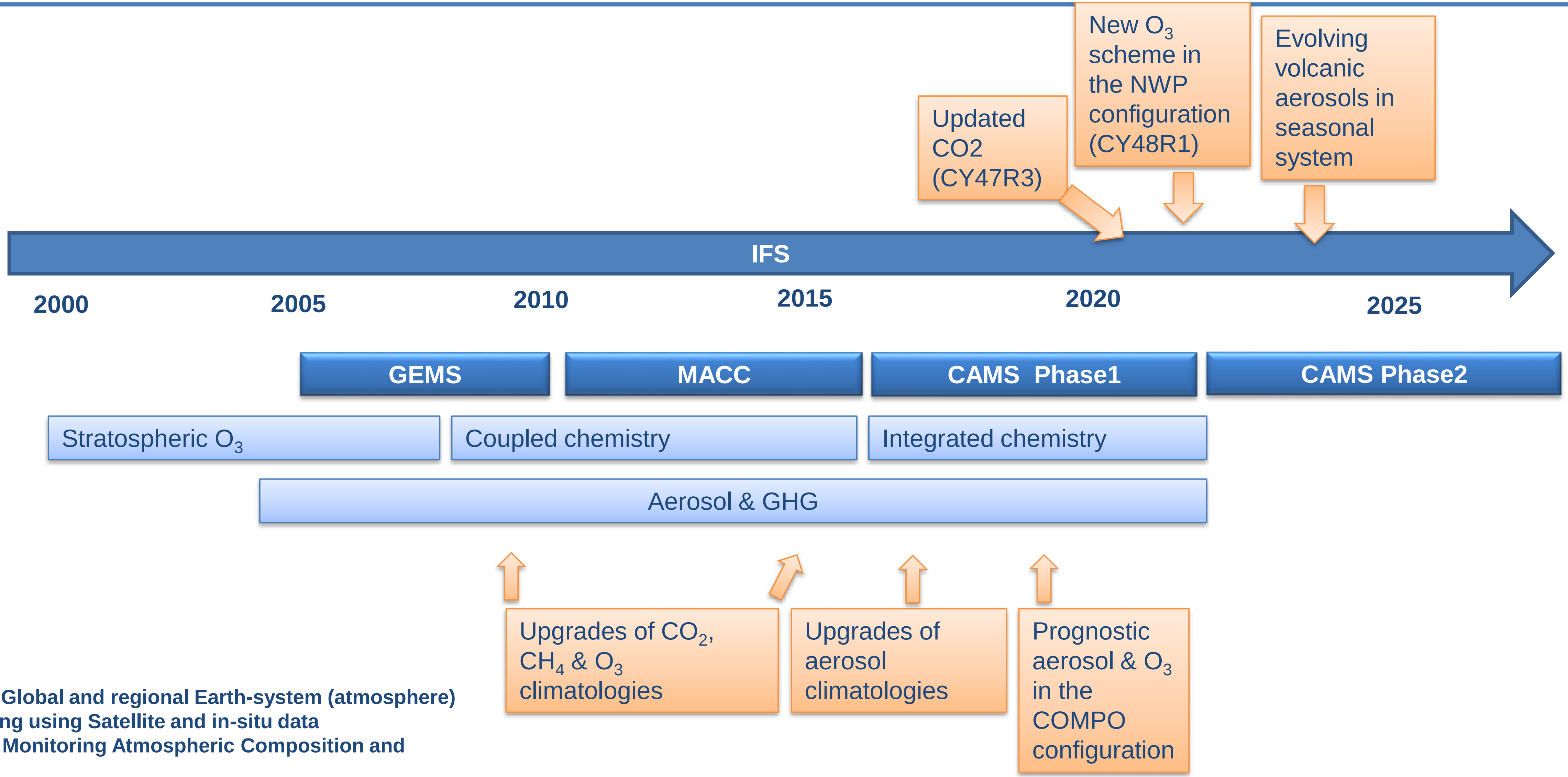
NWP configuration:
HIGH-RES (~9km), CAMS-derived climatologies for aerosols, ozone and CO2 in radiation
(Meteo Operations)

COMPO configuration:
Same dynamics and physics, lower resolution (~40km), O3 and aerosols fully interactive with radiation
(CAMS operations)

What can we learn from interactive aerosols and ozone in the COMPO configuration to inform the NWP configuration?

Adapted from 2018 Council lecture by Rossana Dragani and Richard Engelen (ECMWF)

Developments of AC in IFS



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

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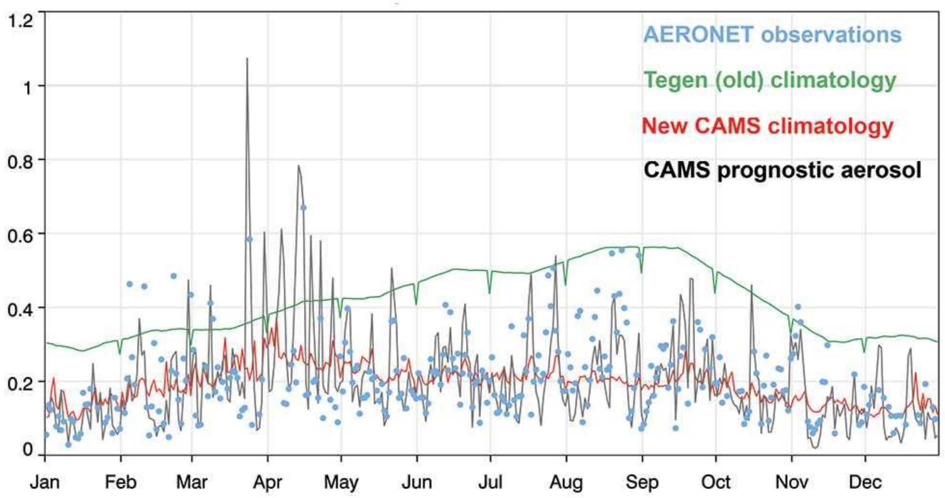
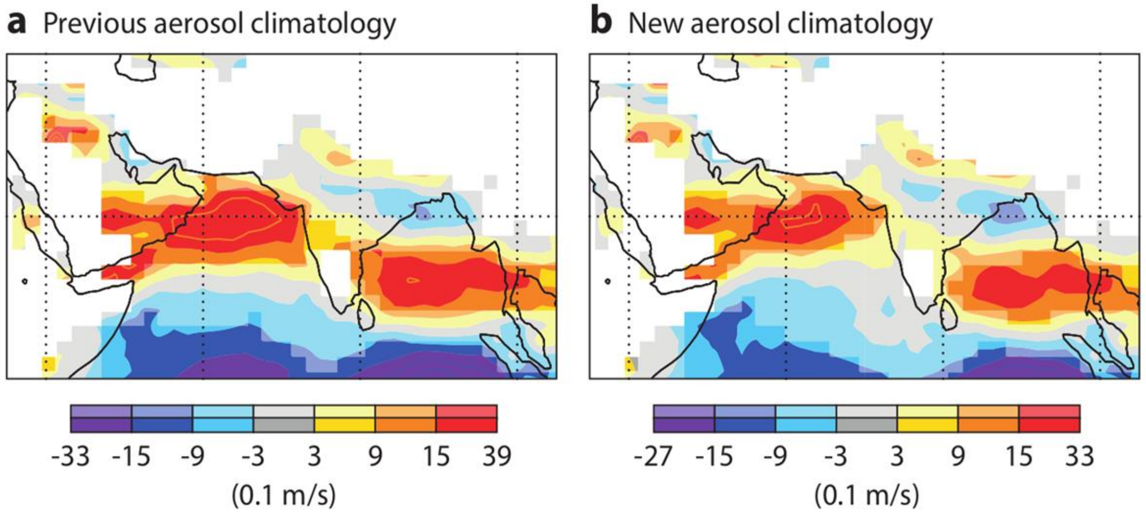
Adapted from 2018 Council lecture by Rossana Dragani and Richard Engelen (ECMWF)

Use of AC reanalyses to build climatologies

- Bozzo et al. (2020, GMD) constructed an aerosol climatology from the CAMS interim reanalysis of aerosols (Flemming et al. 2017).
- It has been used operationally since 2016.



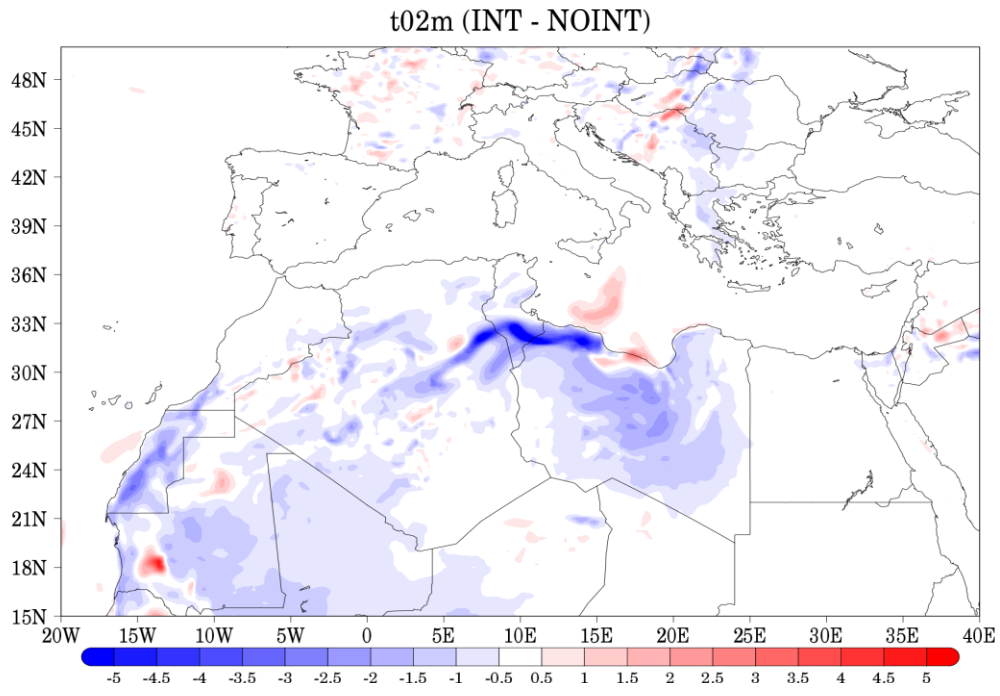
Day-5 zonal wind bias at 925 hPa (JJA)



- 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.

Courtesy of A. Bozzo and J. Flemming

Aerosols impacts in the medium-range

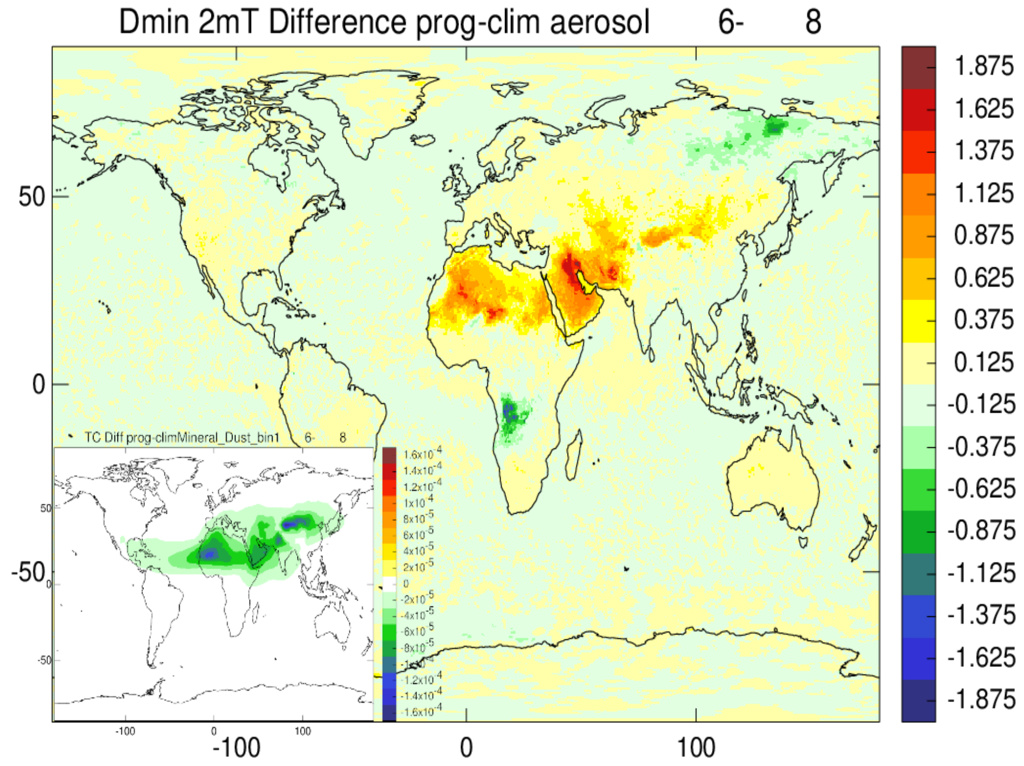


2-meter temperature WRF/ARW/IAASARS 36h-forecast differences - interactive (INT) versus non-interactive (NOINT) aerosol experiments.

Clear impact of the interactive aerosols, but different sign for the two systems in dust areas associated to differences between climatologies and prognostic aerosols

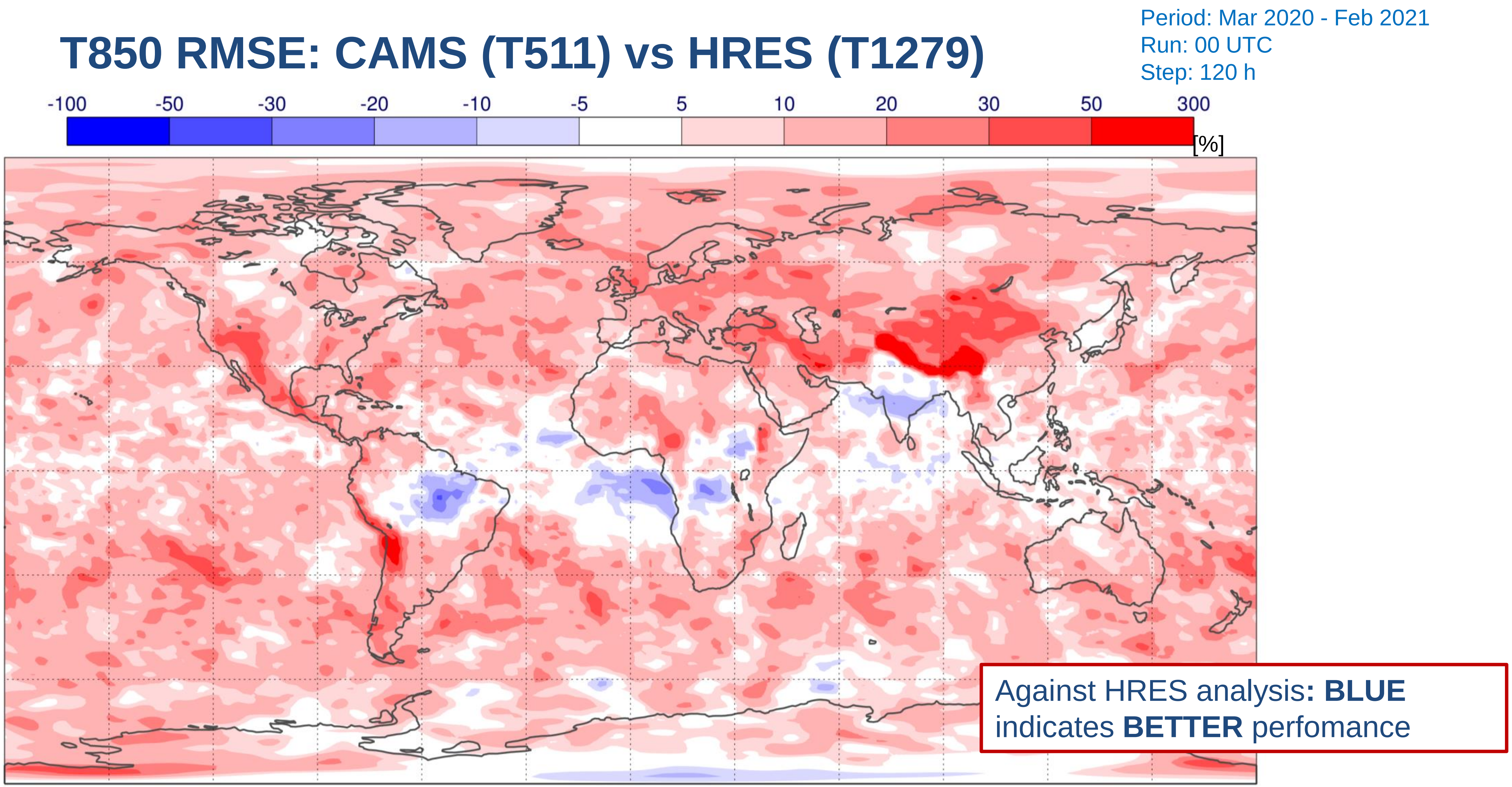
IFS 2-meter temperature forecasts mean differences for experiments with prognostic and climatological aerosols (06/2019-08/2019) and total column dust (bin1)

Credits: Johannes Flemming (ECMWF)



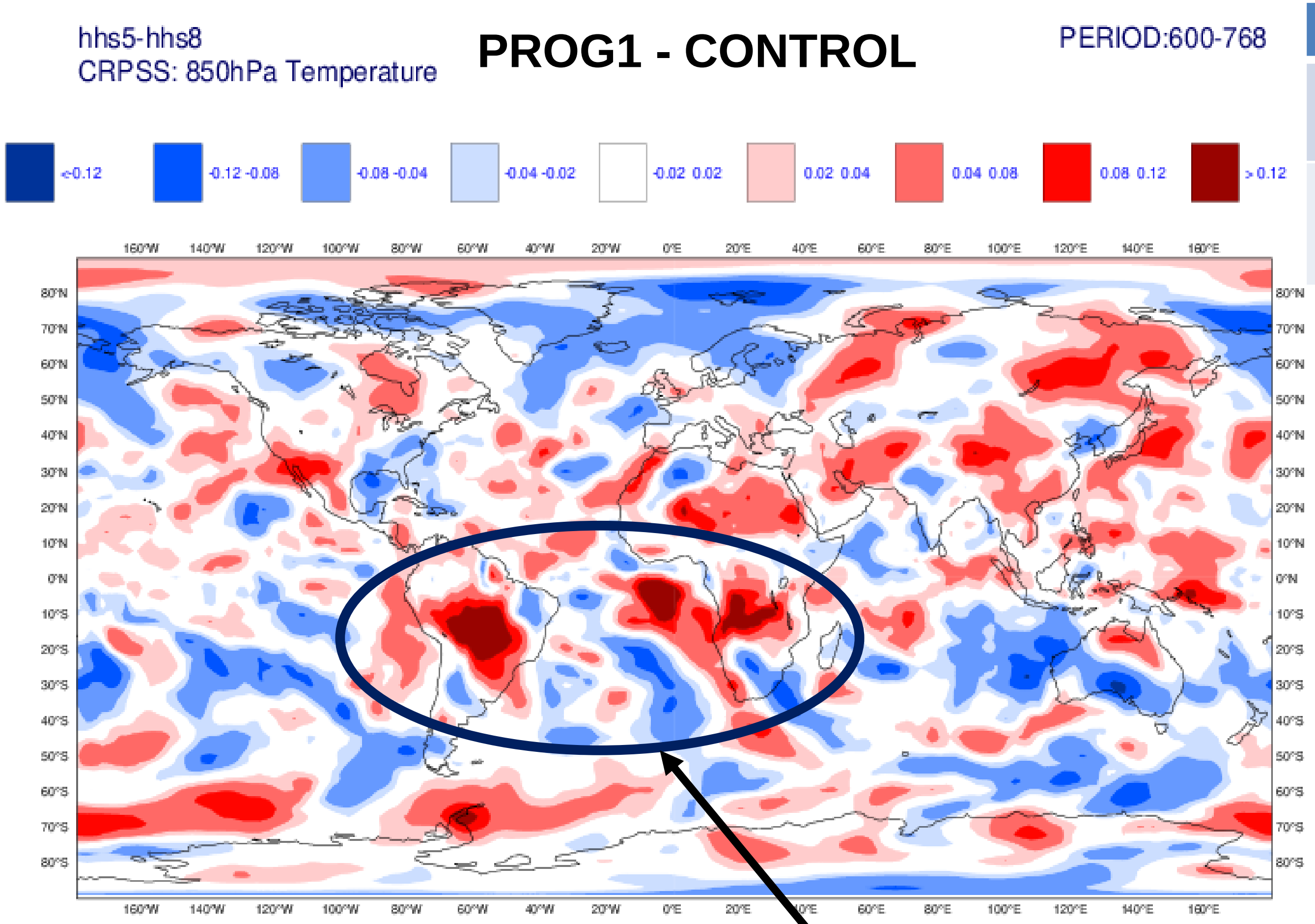
Courtesy of Ariane Frassoni (National Institute for Space Research) – WMO WGNE-S2S-GAW Aerosol Project

Aerosols impacts in the medium-range



Courtesy of Thomas Haiden (ECMWF)

Aerosol impacts at the S2S scale



CONTROL	Bozzo et al (2020, GMD) climatology in the radiation
PROG1	Interactive aerosols initialized from the CAMS Reanalysis (Inness et al 2019)

- Sept 1 start date, week 4
  RED is **positive signal** in CRPSS for 850hPa Temp (scores courtesy of Frédéric Vitart)
- Part of the WMO WGNE-GAW-S2S aerosol experiments
- New experiments planned under the CONFESS project (**https://confess-h2020.eu/**)

- For the Sept 1 start date focused on biomass burning (BB) aerosols, experiment shows high sensitivity to interactive aerosols
- Aerosol contribute to an increase in skill in the monthly prediction particularly in areas of high BB

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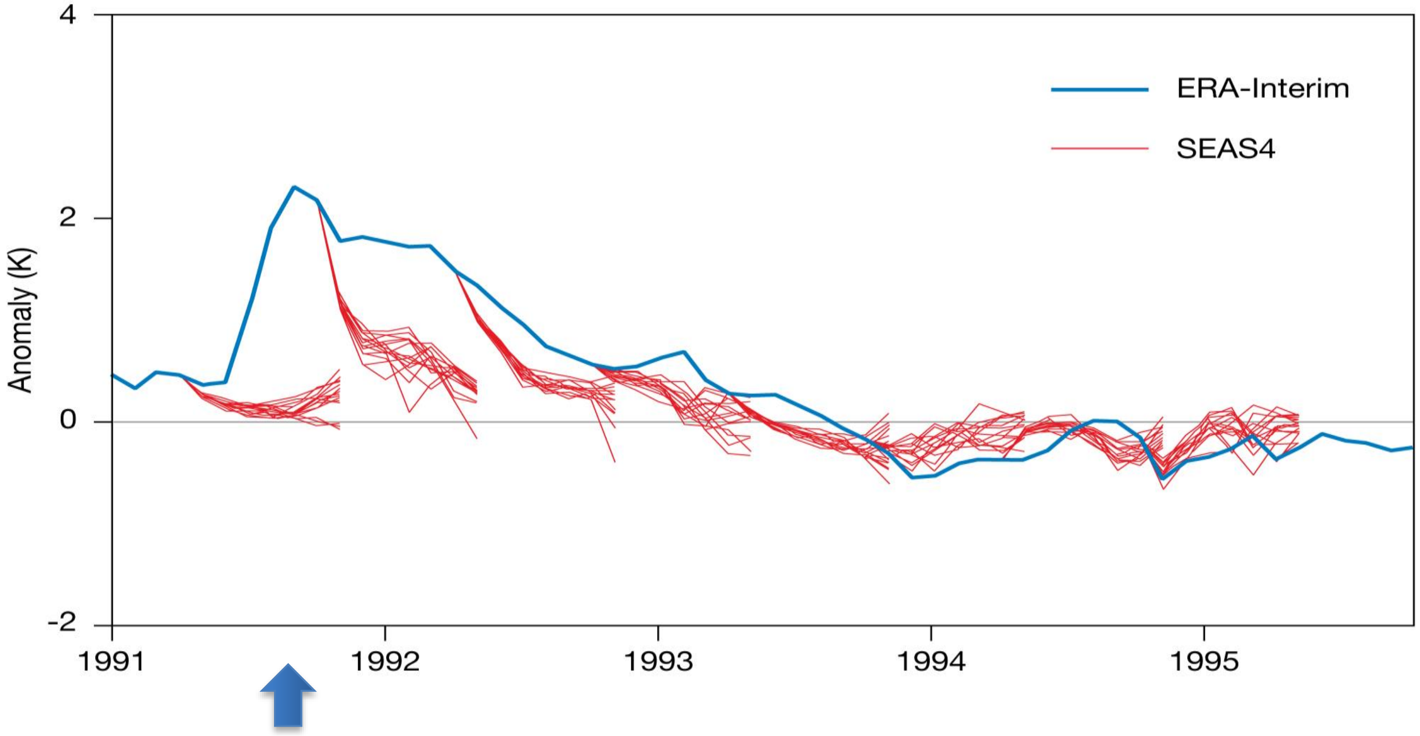
Stratospheric sulphate aerosols for seasonal prediction

Temperature anomalies (30hPa, Month 7)



Eruption of Mount Pinatubo

With an incorrect vertical distribution of stratospheric volcanic sulfates, the temperature response of the seasonal forecast system is wrong in the case of major volcanic eruptions

Now volcanic aerosols are being included in IFS within the EU-funded project CONFESS (**https://confess-h2020.eu/**)

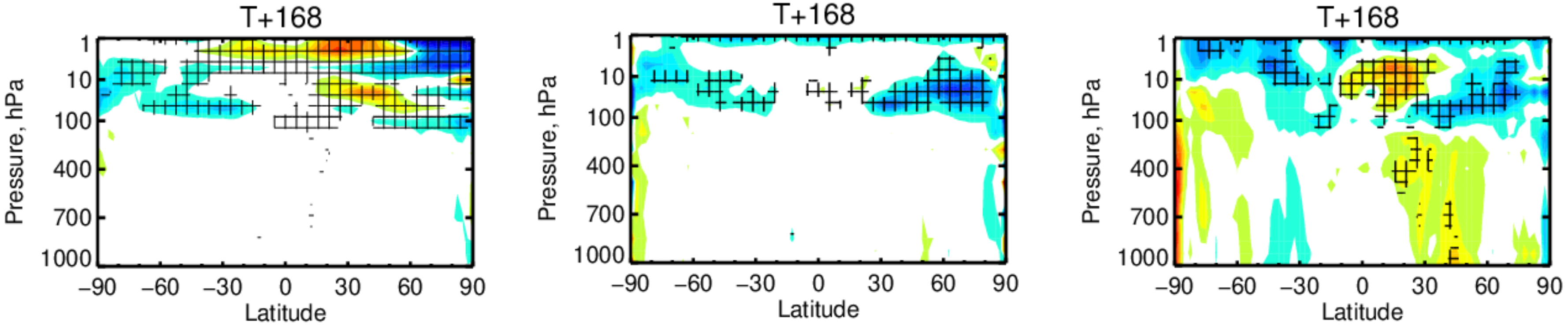
Credits: Tim Stockdale, ECMWF

New Hybrid Linear Ozone scheme

- The HLO scheme developed by **Tim Stockdale** and based on the **CAMS reanalysis** improves model performance with respect to the Cariolle (operational) scheme
- Currently operational in CAMS, where it is interactive with radiation in short-range forecasts
- 23 months of Tco399 analysis (control & experiment), 6 months of Tco1279 forecasts (control & two experiments) + numerous other experiments have been run (credits **Robin Hogan**) – experiments still under scrutiny!
- Operational implementation expected in CY48R1

Day 7 scores ← Blue is good | Red is bad →

T ΔRMSE, ±15% | **T Δstddev, ±10%** | **VW ΔRMSE, ±4%**



- **Scores insensitive to bias are improved** in the extra-tropics in the HIGH-RES
- Good performance in the analysis with respect to IR observations, ozonesondes and MLS ozone profiles

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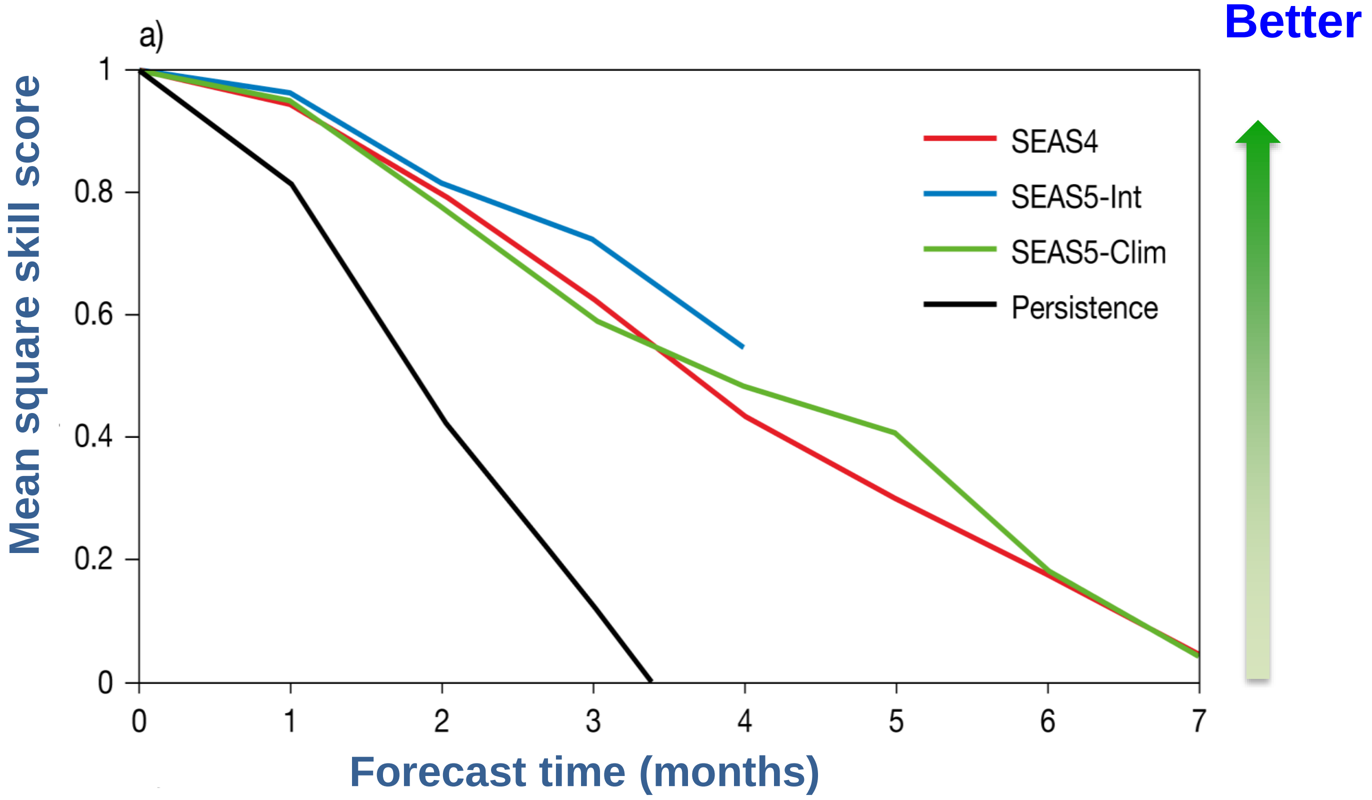
Potential of interactive ozone at the seasonal range

Skill scores for the zonal mean temperature forecast

(30hPa, 5ºS-5ºN)

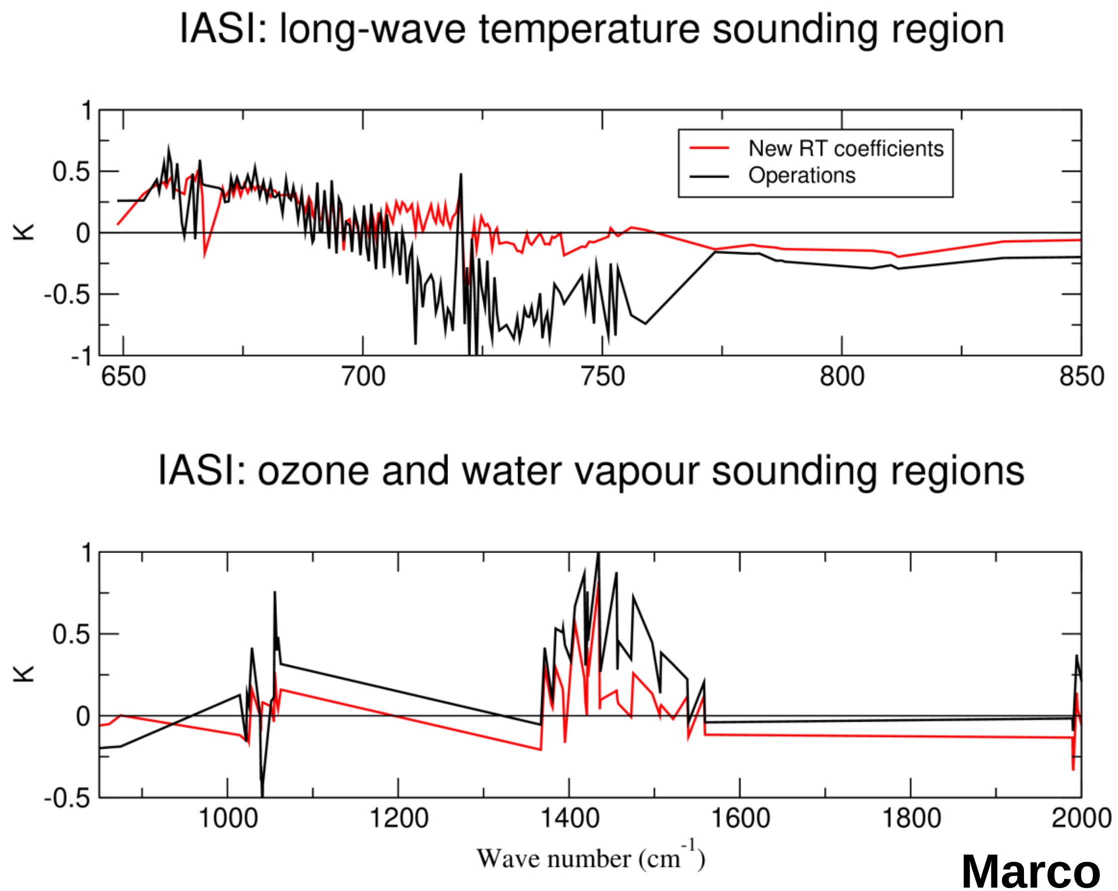


Tim Stockdale, ECMWF

Updates in CO2 profile and spectroscopy

- Bias reduction resulting from the use of the new RT coefficients. The region between 700 and 775 cm^{-1} in the top panel shows the effect of improved CO_2 spectroscopy and CO_2 profile.

- Circa 75% of the bias reduction is due to the improved CO_2 profile, the rest to improved spectroscopy



Marco Matricardi, ECMWF

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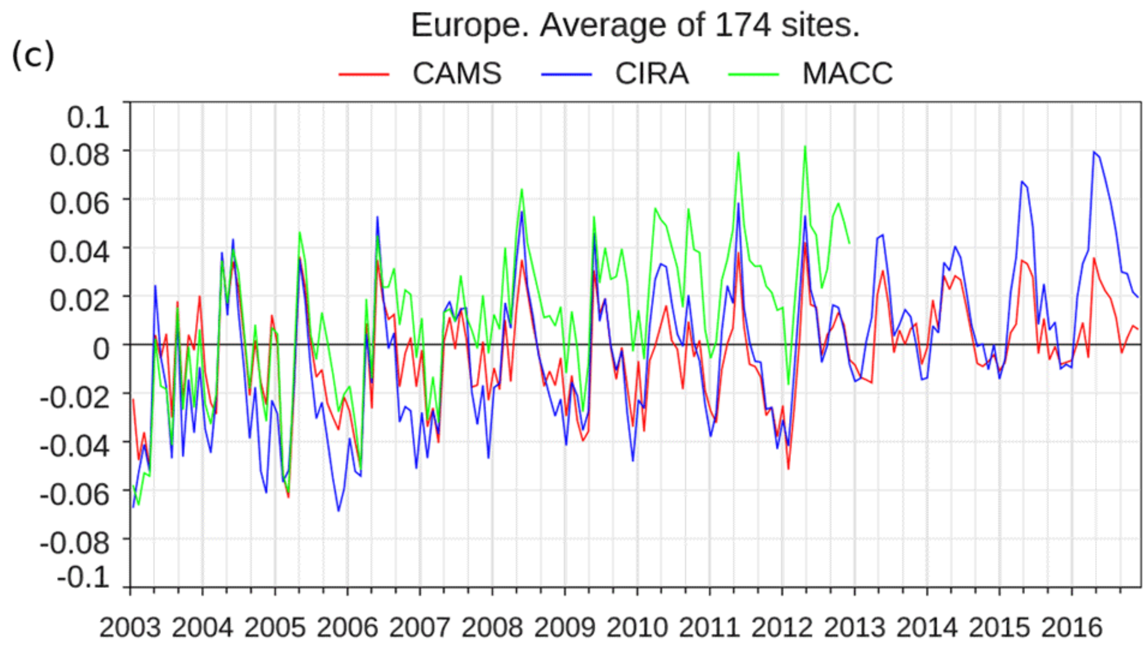
2. What is the role of observations? Is DA effective?

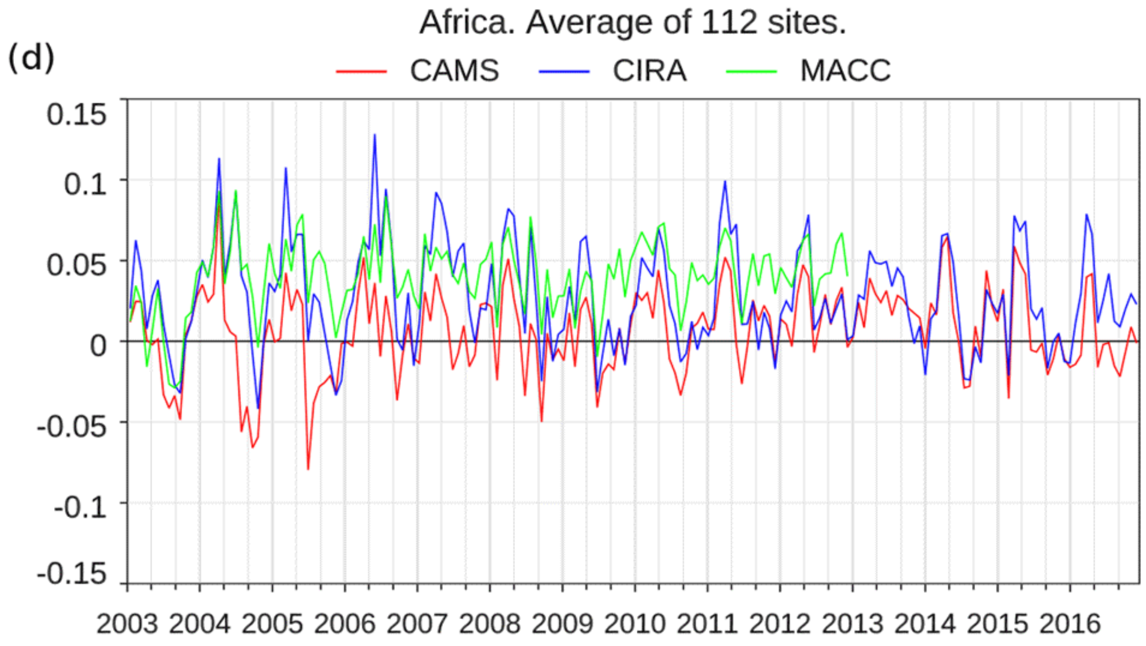
Examples from the aerosol world

CAMS reanalysis



- Clear improvements in AOD with respect to previous versions against independent AERONET observations (https://aeronet.gsfc.nasa.gov/)

- Good reanalysis are very important to build robust climatologies and support model development (i.e. HLO scheme is based on the CAMS reanalysis)



Innes et al, 2019
https://doi.org/10.5194/acp-19-3515-2019

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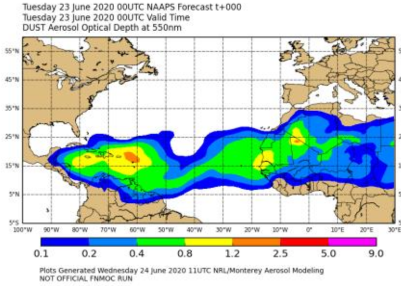
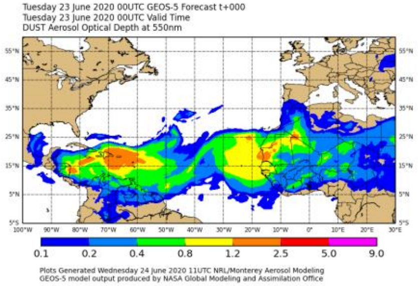
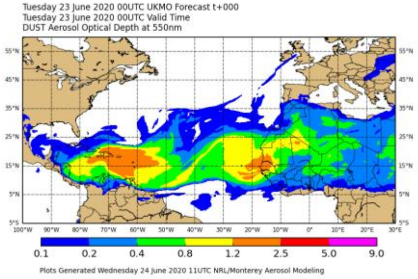
Model intercomparisons: International Cooperative for Aerosol Prediction

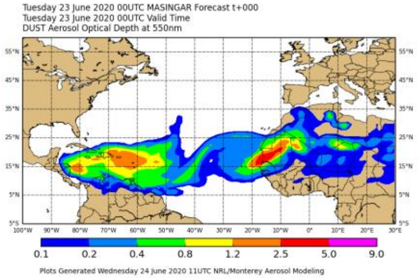
Dust AOD, June 23, 2020

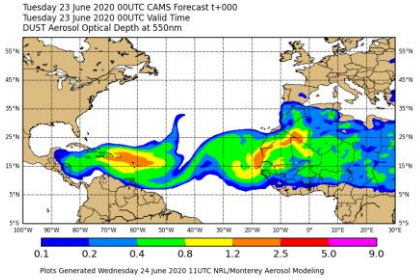
Models with aerosol data assimilation



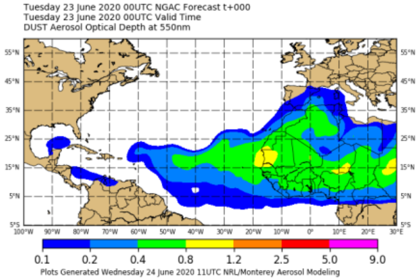


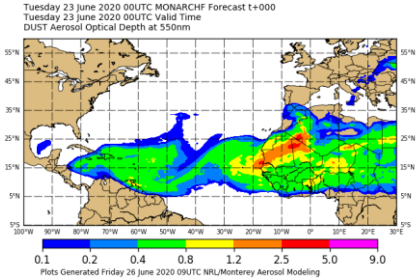


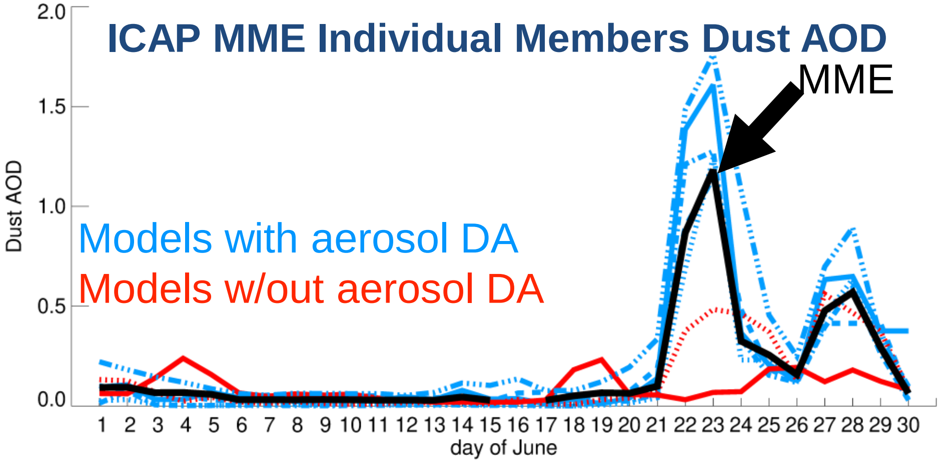


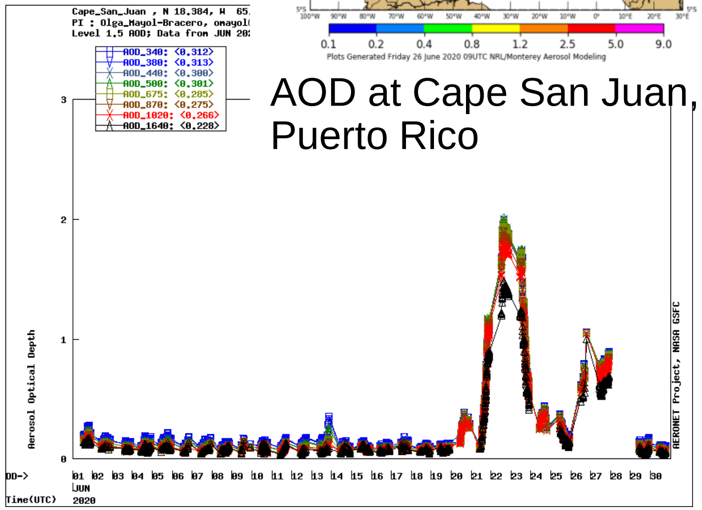


Models with no aerosol data assimilation









AOD at Cape San Juan, Puerto Rico

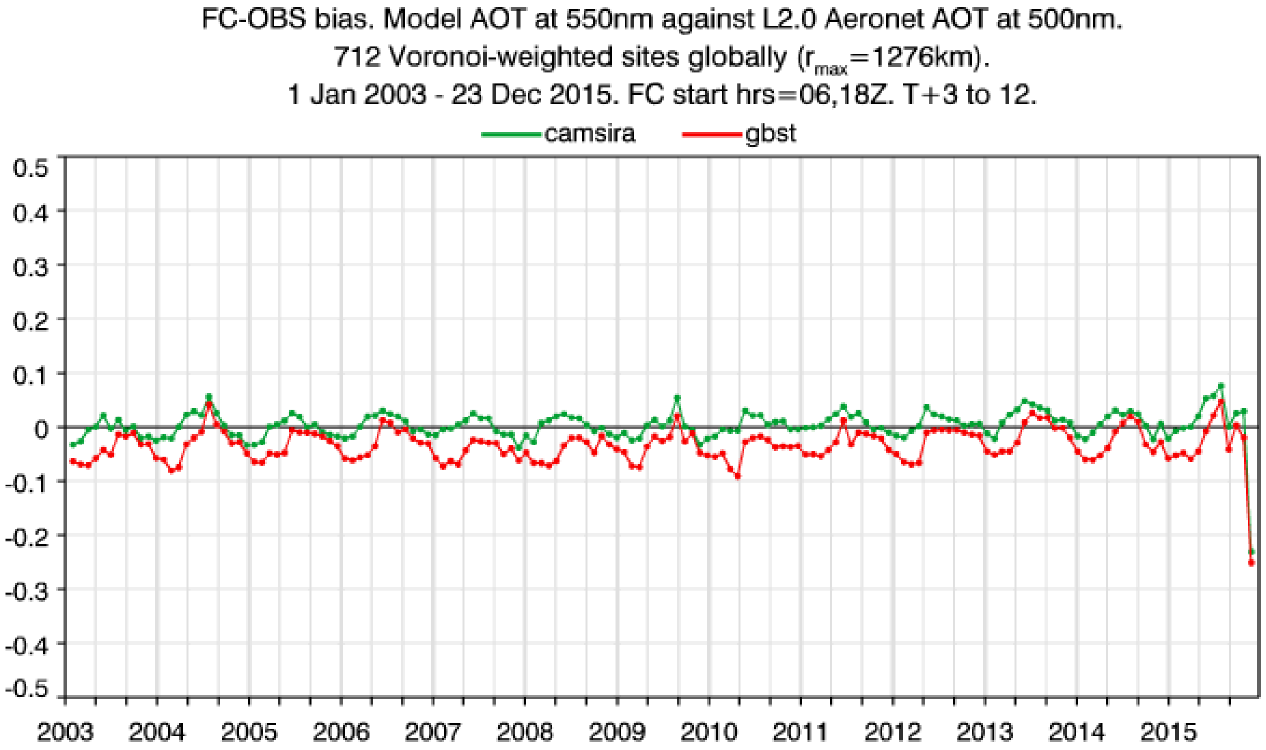
AERONET Level 1.5 AOD

Credits:
Pete Colarco (NASA)

ECMWF

Information saturation: what more can we extract from AOD?

- Assimilation of single-wavelength Aerosol Optical Depth (a column-integrated quantity) has been ongoing for 13 years, reaching now (possibly) a saturation point.



CAMS Interim Reanalysis

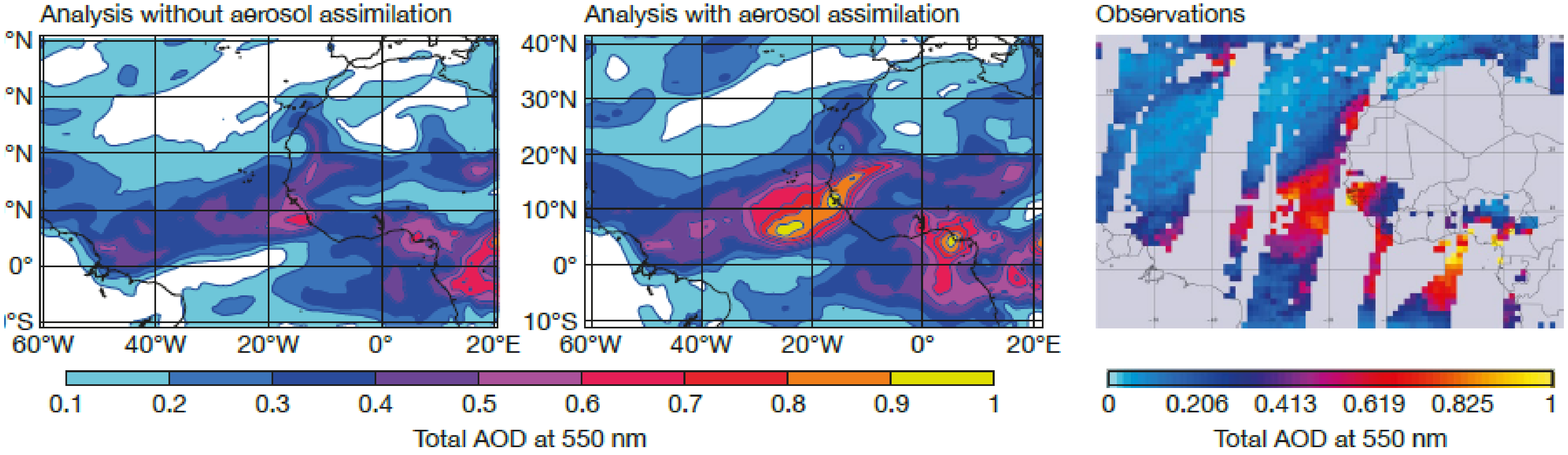
CAMS free-running model

ECMWF

3. What other observations can be exploited?

Assimilation of MODIS reflectances

The Aerosol Radiance Assimilation Study (ARAS) project, a collaboration between RAL space and ECMWF, ran from April 2018 to March 2020 with the goal of understanding the relative strengths of reflectance versus AOD assimilation.



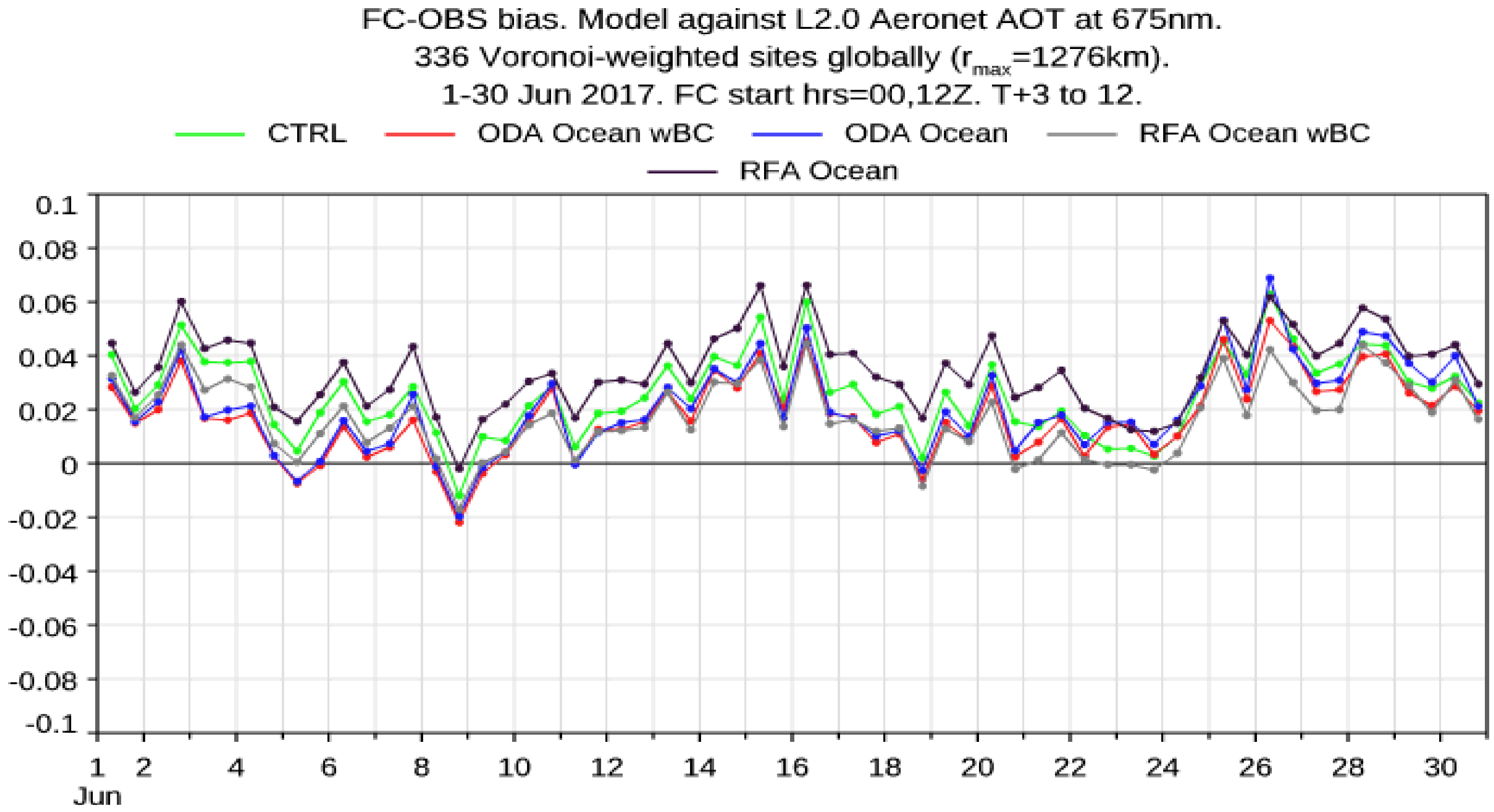
ECMWF Winter Newsletter 2020 and ECMWF Science Blog

https://www.ecmwf.int/en/about/media-centre/news/2020/progress-towards-using-visible-light-satellite-data-weather

ESA funding AO/1-8768 is gratefully acknowledged
Project officer: Ben Veilhelmann (ESA)
Team: Angela Benedetti, Samuel Quesada Ruiz, Julie Letertre-Danczak, Marco Matricardi (ECMWF), Gareth Thomas (RAL)

ARAS conclusions

- Comparable performance of AOD and reflectance (RFA) assimilation over **ocean** as verified against AERONET data
- Crucial role of the **bias correction** for reflectances
- Better performance of RFA for Angstrom exponent
- More work is needed over land: the weak link is the **surface reflectance**

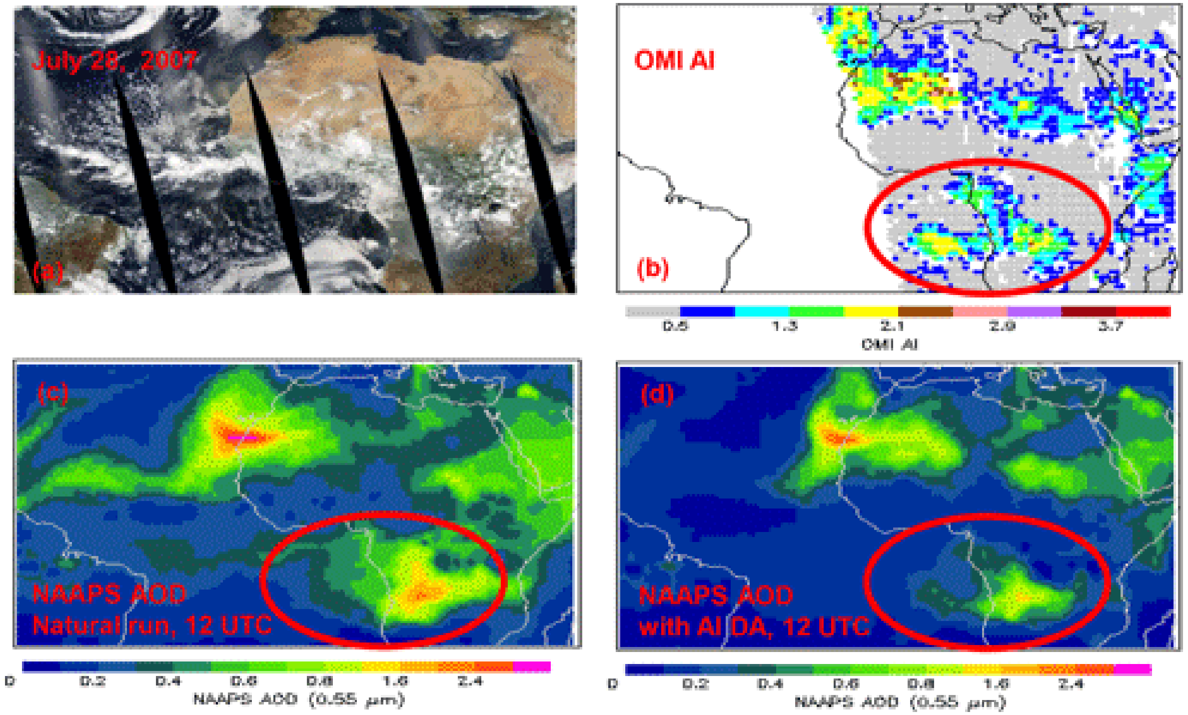


Assimilation of UV Aerosol Index

Aerosol Index assimilation of OMI AI over bright surfaces and cloudy regions for aerosol analyses and forecasts with potential to improve vertical profiles too – very powerful for **reanalysis** as there is a long time series of this type of observations available

Challenges:

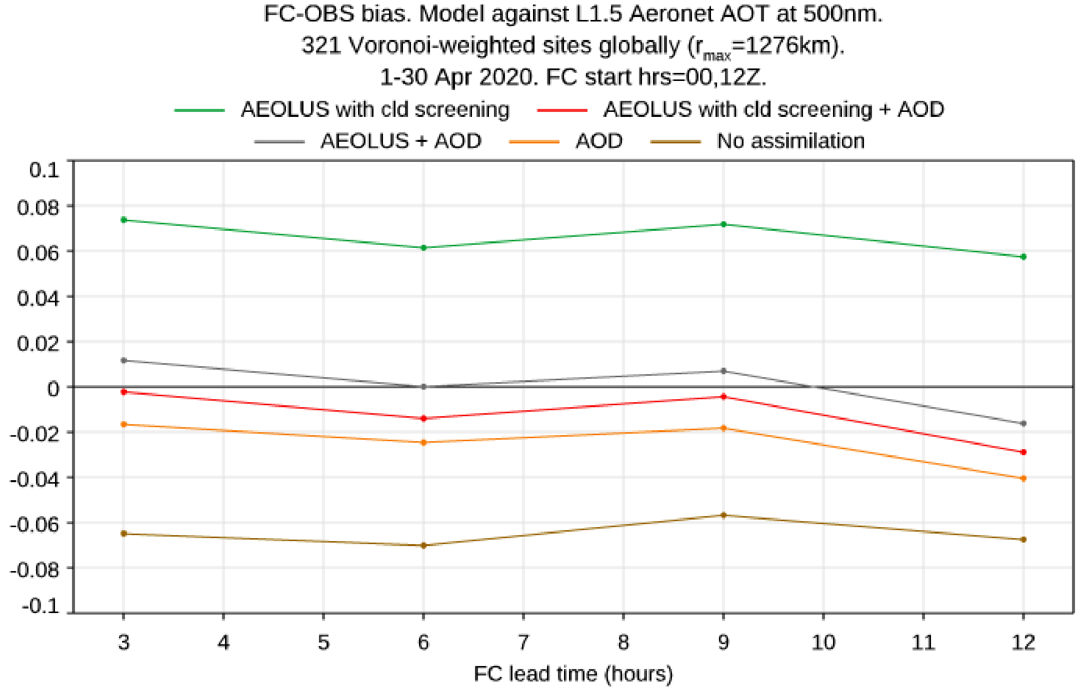
- Computational cost of full radiative transfer calculations in the UV -> **Need for fast RT**
- High Sensitivity to Single Scattering Albedo (absorbing aerosols)
- AOD assimilation still difficult to “beat”

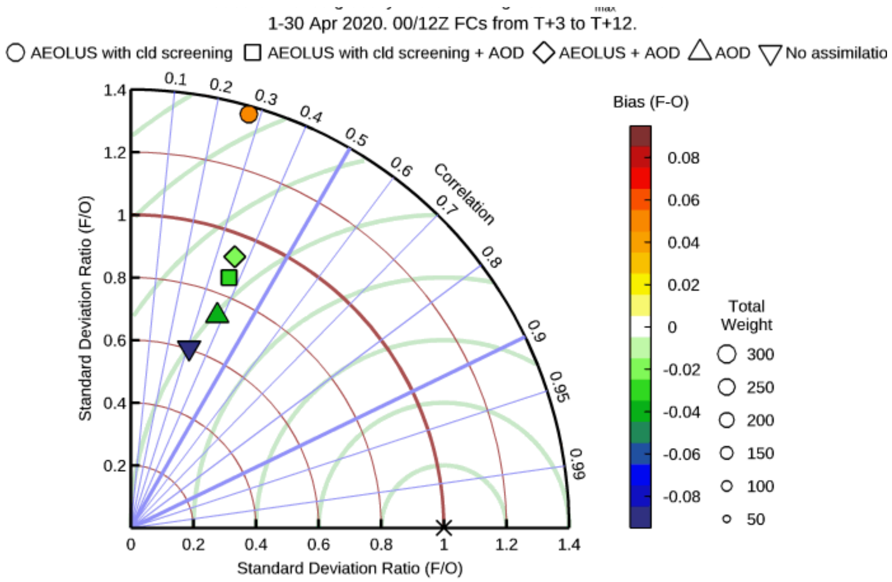


Zhang et al, 2021:
Geosci. Model Dev., 14, 27–42, 2021
https://doi.org/10.5194/gmd-14-27-2021

Potential of Aeolus particle lidar backscatter assimilation

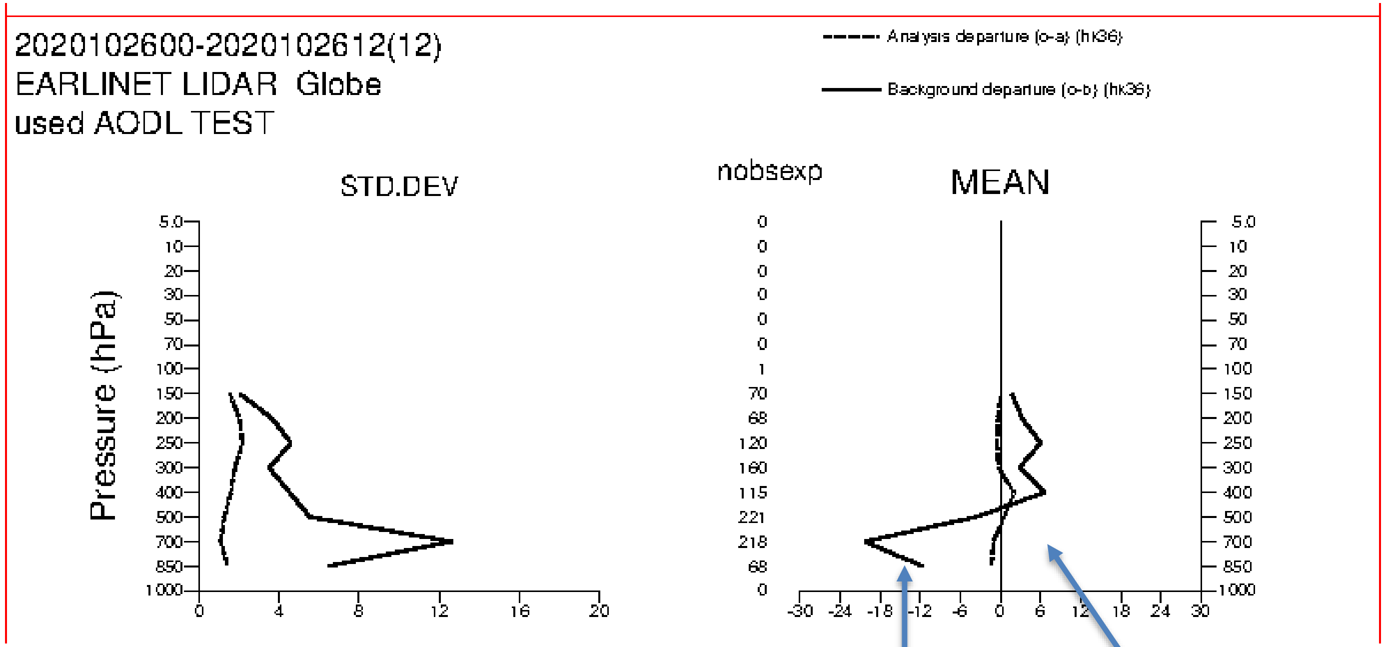
- ESA-funded projects **A3S** (concluded) and **A3D** (just started) for the exploitation of the L2A product
- First attempt to exploit particle backscatter data at 355nm from Aeolus platform in a global model
- Best results for preliminary tests during April 2020 are given by the joint assimilation of AOD and **AEOLUS**.The assimilation of AEOLUS-only shows a positive bias and low correlations
- Valuable lessons learned in preparation of assimilation of ESA's **EarthCARE** aerosol profile data





A3S Team: Angela Benedetti, Julie Letertre-Danczak, Drasko Vasiljevic, Samuel Quesada Ruiz (ECMWF)
Dimitri Trapon, Thomas Flament, Alain Dabas (MeteoFrance)

Assimilation of aerosol backscatter from ground-based sensors



Units: 10-7 sr-1 m-1

Model too close to the surface

Right position of the aerosol layer coming from the observations

- The assimilation of **EARLINET** aerosol backscatter is demonstrating a positive impact on the analysis by reattributing the right position to the aerosol layer

- Possible synergy between satellite and ground-based instruments both for joint assimilation and calibration

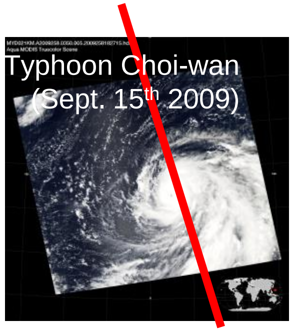
Credits: Julie Letertre-Danczak (ECMWF)

4. Future Outlook

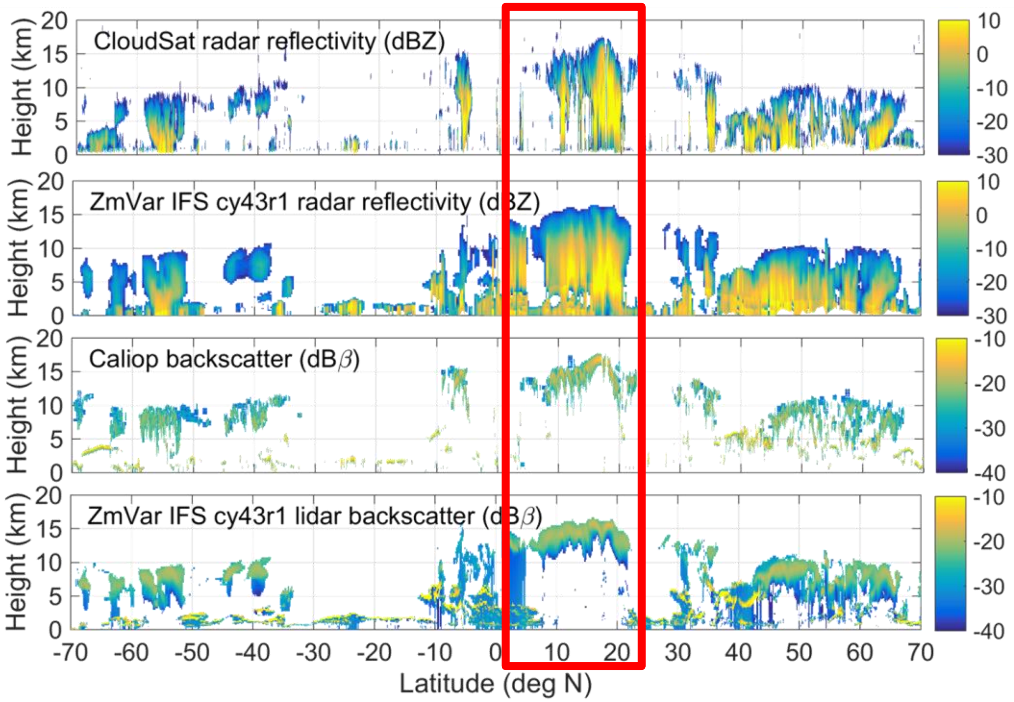
Observation needs/gaps

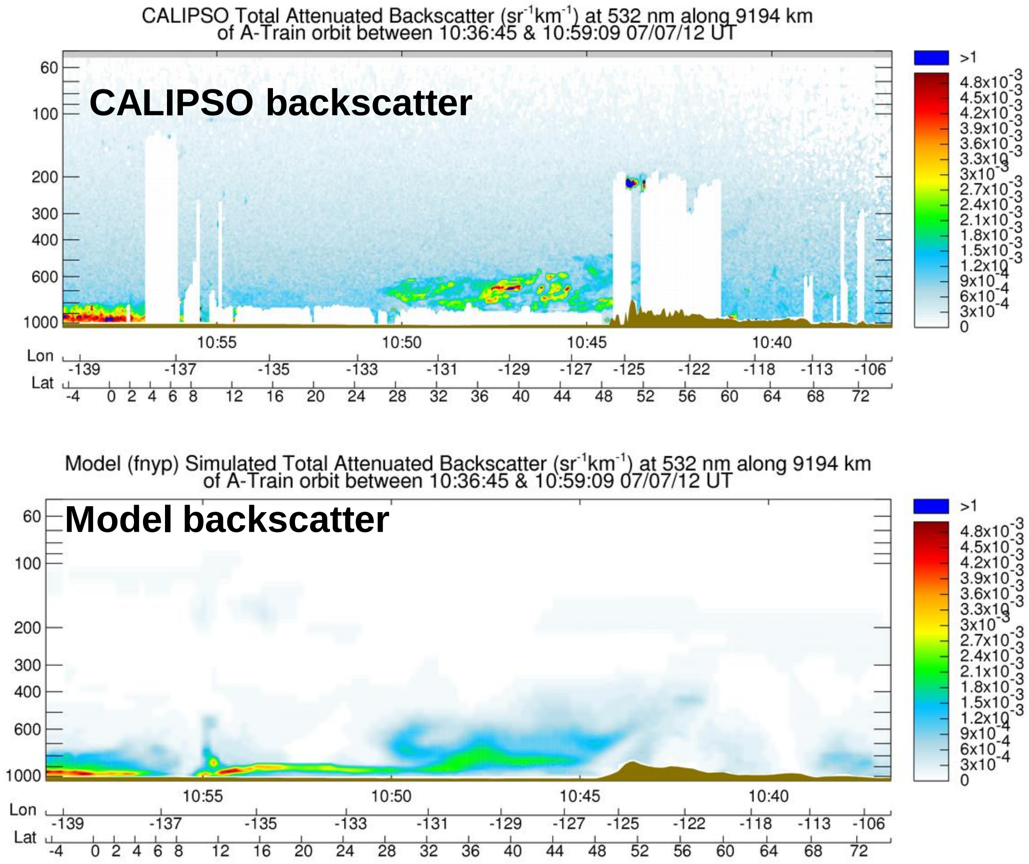
- **Enhanced vertical resolution for ozone** to complement IR and UV observations that also have a day/ night capability (e.g. limb sounders like the Microwave Limb Sounder, MLS, which is near end of life) and more widespread **in-situ data** (ozonesondes) **in real time** to help calibrate the satellite sensors
- Observations of **speciated aerosols** to constrain better the aerosol fields – in the case of assimilation of total optical depth, for example, the distribution of the increments in the analysis is based on the model either through the background error covariance matrices when all species are in the control vector or via a redistribution of the increments in total aerosol mixing ratio as it is done in IFS
- **Depolarization** from lidars would help with a speciation of non-spherical aerosol particles such as dust, and would support research in parameterizations of Ice Nuclei (IN) for use in NWP
- **Absorption optical depth and vertical profiles to constrain absorbing aerosols** which are an uncertain component of the total aerosol load, but which has an important impact on temperature
- **Combined observations of cloud and aerosols** in order to understand the interactions between those components and support both joint cloud/aerosol assimilation and inform model parameterizations (planned in ESA EarthCARE, https://earth.esa.int/eogateway/missions/earthcare and NASA ACCP, https://vac.gsfc.nasa.gov/accp/ to mention a few)

Joint cloud and aerosol assimilation



- ECMWF's radar and lidar observation operators now show great agreement with CloudSat and CALIPSO measurements
- 4D-Var assimilation experiments show forecast improvements!
- Cloud and aerosol lidar operators do not currently "talk" to each other but they imply the same model physics and transport – combining them would be a big leap forward

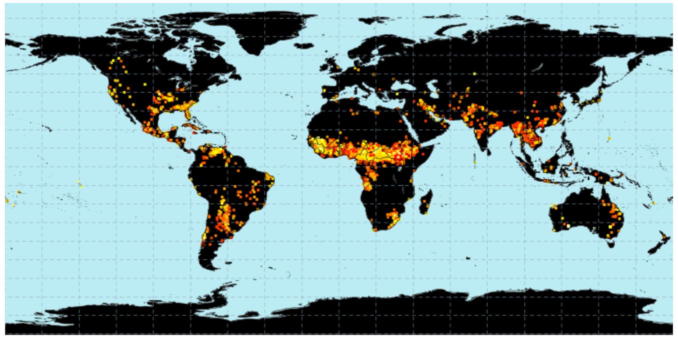




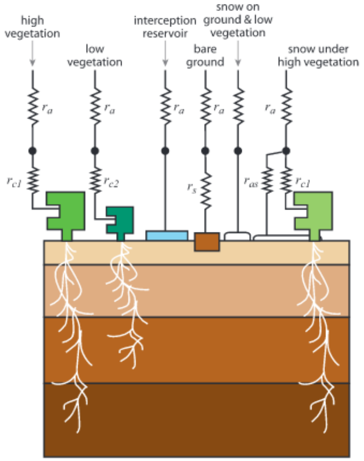
Janisková and Fielding, 2020, QJRMS; https://doi.org/10.1002/qj.3879

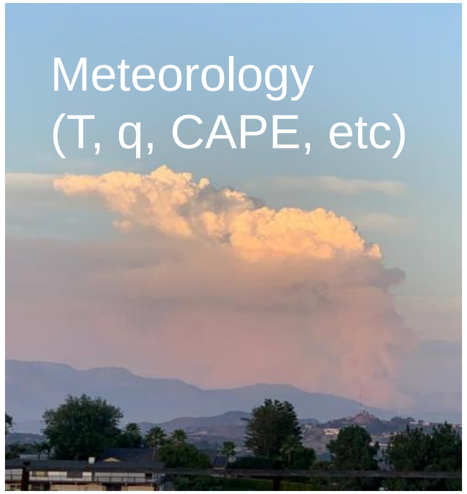
Improved / coupled processes in models to better exploit observations

Example: Fire emissions from the Global Fire Assimilation System (GFAS, Kaiser et al 2012) are estimated from Fire Radiative Power



Vegetation classes in GFAS are defined separately from those in H-TESSEL, the ECMWF's land scheme (Balsamo et al, 2009)



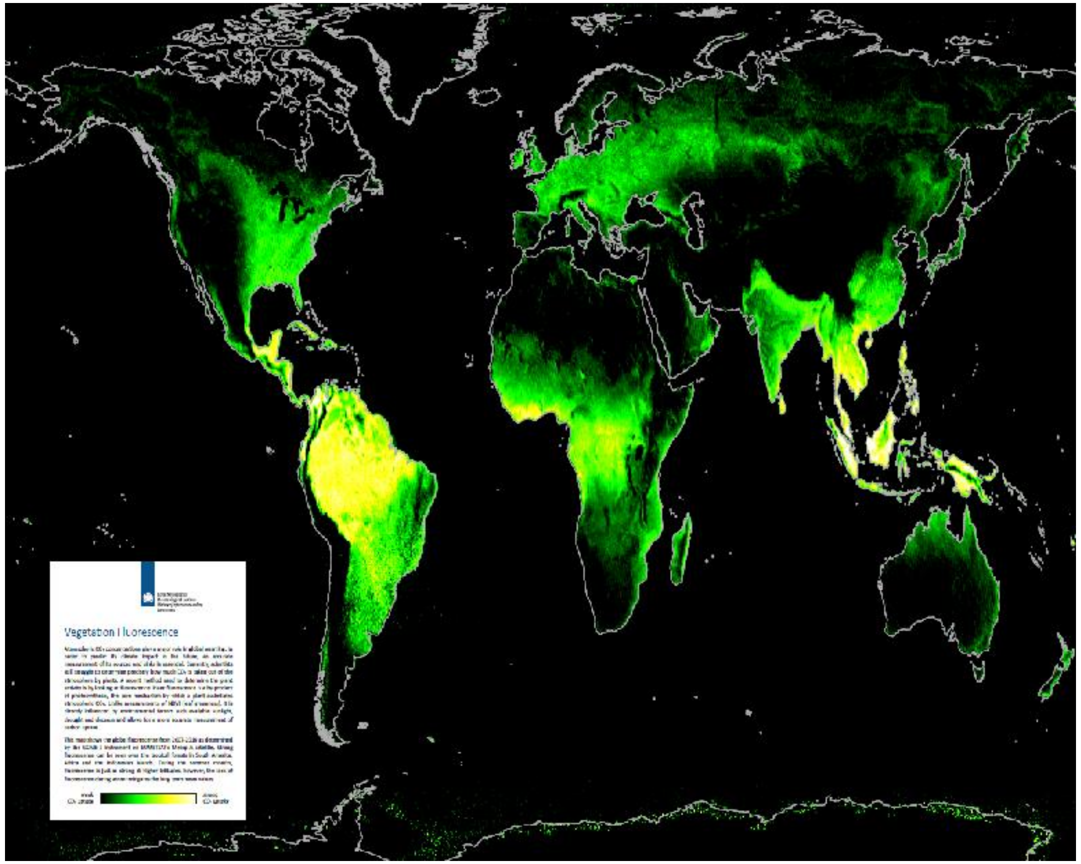


If the fire assimilation system were coupled with the land assimilation system, there would be a link with the underlying meteorological and composition model (IFS)

Ideas from Francesca Di Giuseppe (ECMWF/CEMS) and Angela Benedetti

Exploiting different observations

- Example: Solar Induced Fluorescence to estimate photosynthesis and CO2 fluxes/vegetation parameters
- A photosynthesis model based on the ORCHIDEE is being developed to be included in IFS



Courtesy of Anna Augusti Panareda (ECMWF)

Take home messages

- Atmospheric composition is important for NWP
- Climatologies are being replaced with **prognostic interactive schemes** (i.e. ozone and aerosols) at lower resolutions, but are still heavily used in NWP high-res configurations
- There is the need for well-constrained reanalysis to develop **robust climatologies** and develop **model parameterizations**
- Assimilation of column-integrated observations is still **beneficial** but it does not solve all problems
- **Old and new aerosol observations** (visible and UV radiances, lidar backscatter and extinction) are being explored to improve the analysis - some degree of success has been obtained with **radiances and lidar observations** but more development is needed (**fast UV and VIS RT codes, surface reflectance over land, etc**)
- Lots of **synergies** possible with ground-based observations for assimilation
- **Ground-based observations** needed in real time for **calibration of satellite sensors** and **verification**
- **Physical processes need to be integrated** in the assimilation for a full exploitation of the observations and the model
- Excitement in the AC community over the upcoming new missions/observations of the future (Copernicus Sentinels, EarthCARE, ACCP, Aeolus follow-on, etc)

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