The role of atmospheric composition in the predictability at the S2S scale

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(ECMWF)

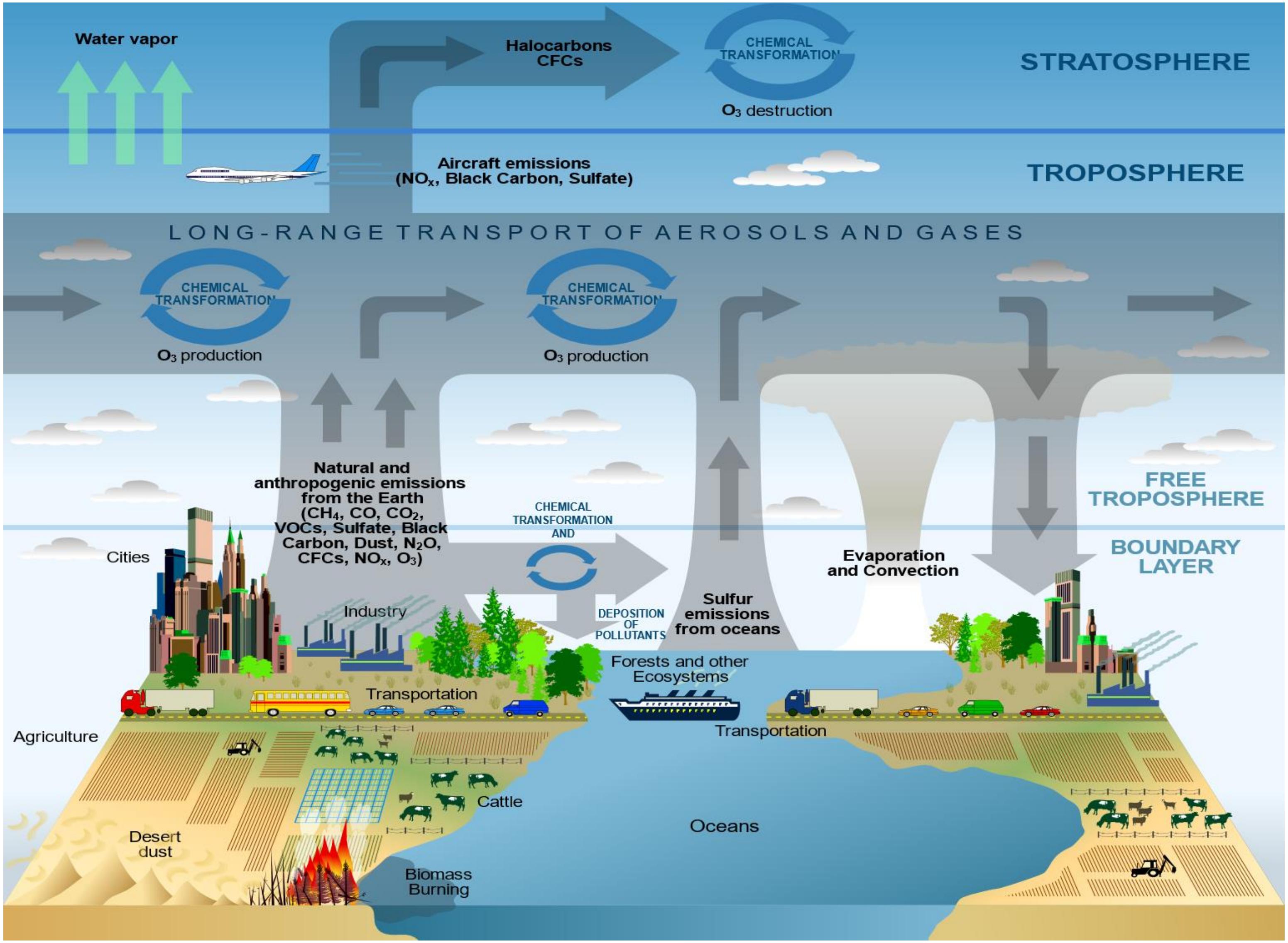
with many thanks to: external contributors, the Atmospheric Composition Team, the Copernicus Atmosphere Monitoring Service team and several other colleagues at ECMWF

ECMWF, Annual Seminar 2-5 September 2019

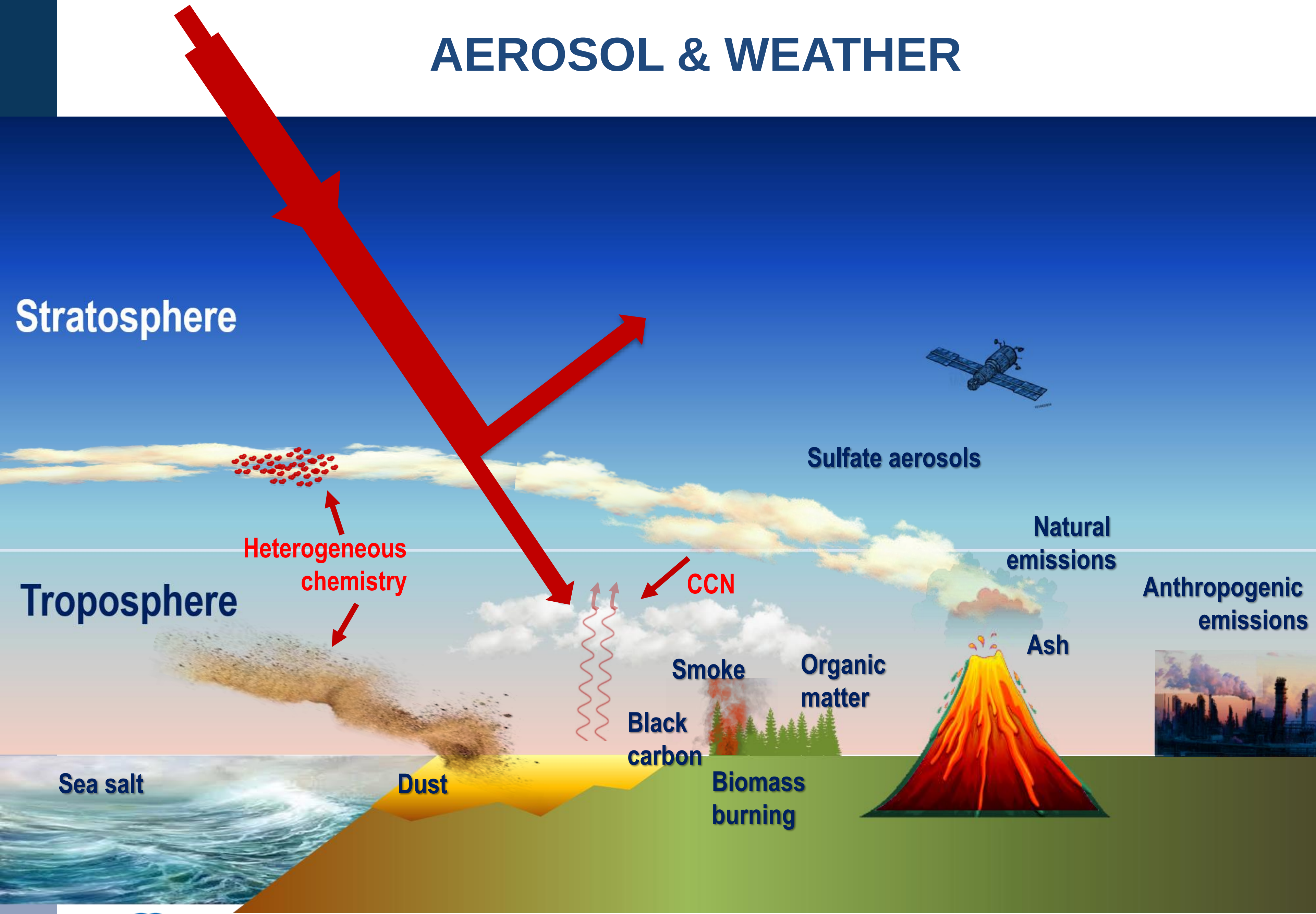
OUTLINE

- General background
- How atmospheric constituents impact NWP
- Examples from the ECMWF’s experience with focus on the S2S scales
- A survey
- A call to participate in a WMO-sponsored project
- Summary
- Open questions

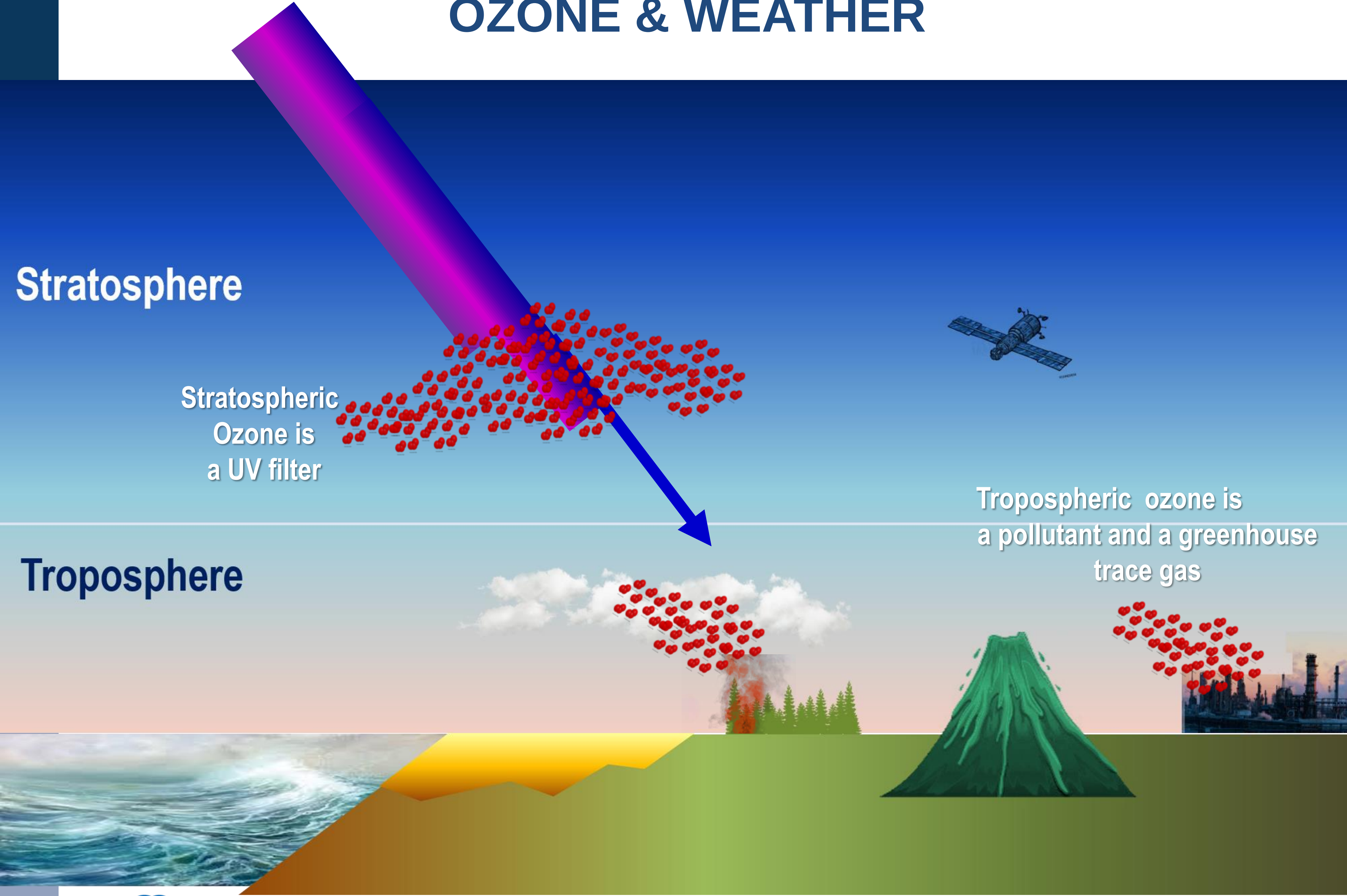
A COMPLEX SYSTEM!



AEROSOL & WEATHER



OZONE & WEATHER



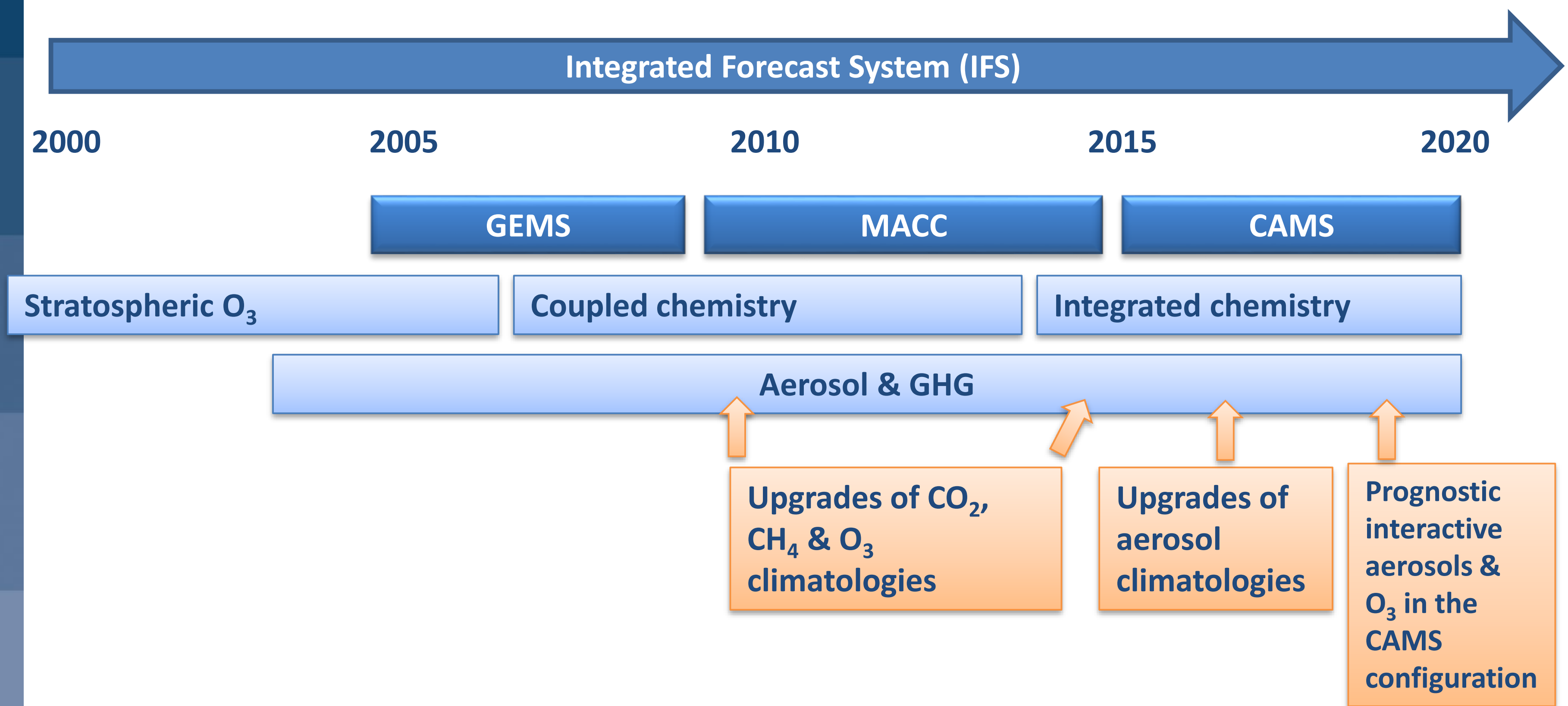
Atmospheric constituents affect NWP in several ways and across various scales

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

THE ECMWF EXPERIENCE: GENERAL BACKGROUND

Development of atmospheric composition in the Integrated Forecast System

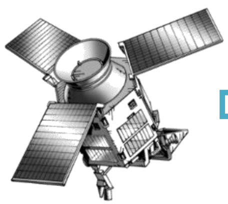


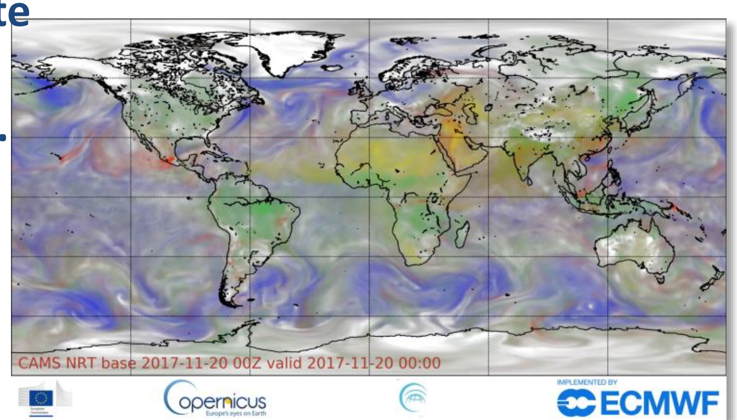
GEMS = Global and regional Earth-system (atmosphere) Monitoring using Satellite and in-situ data
MACC = Monitoring Atmospheric Composition and Climate
CAMS = Copernicus Atmosphere Monitoring System

Copernicus Atmosphere Monitoring Service

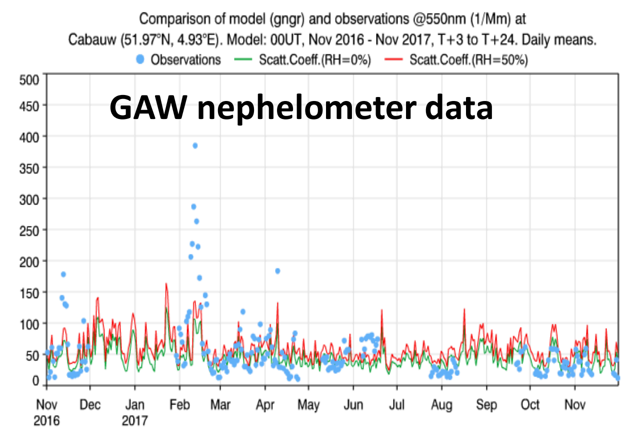
https://atmosphere.copernicus.eu/

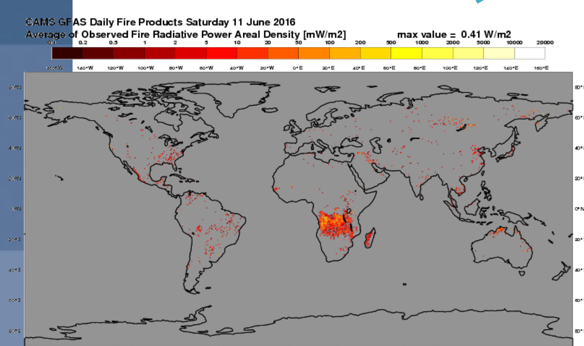
Transforming satellite observations into user-driven services.





Using ground-based observations to verify the model prediction





Fire emissions

Anthropogenic emissions

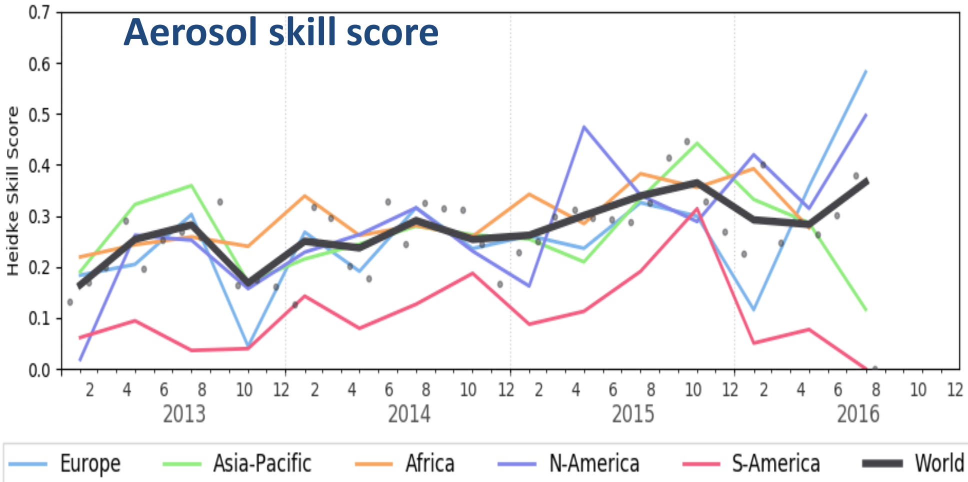
The CAMS/ECMWF model is based on:

- ECMWF 4D-var and meteorology
- Integrated chemistry and aerosol representation
- Integrated natural biosphere model

Richard Engelen, Vincent-Henri Peuch, ECMWF

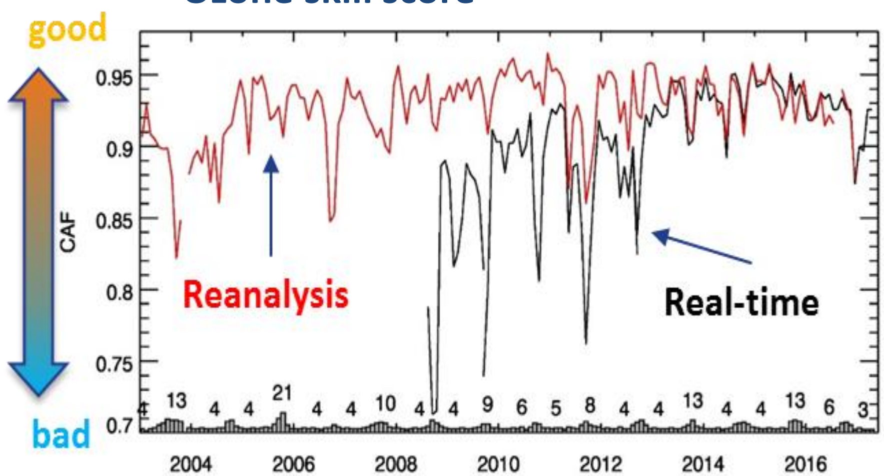
ECMWF EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

Quality of atmospheric composition forecasts



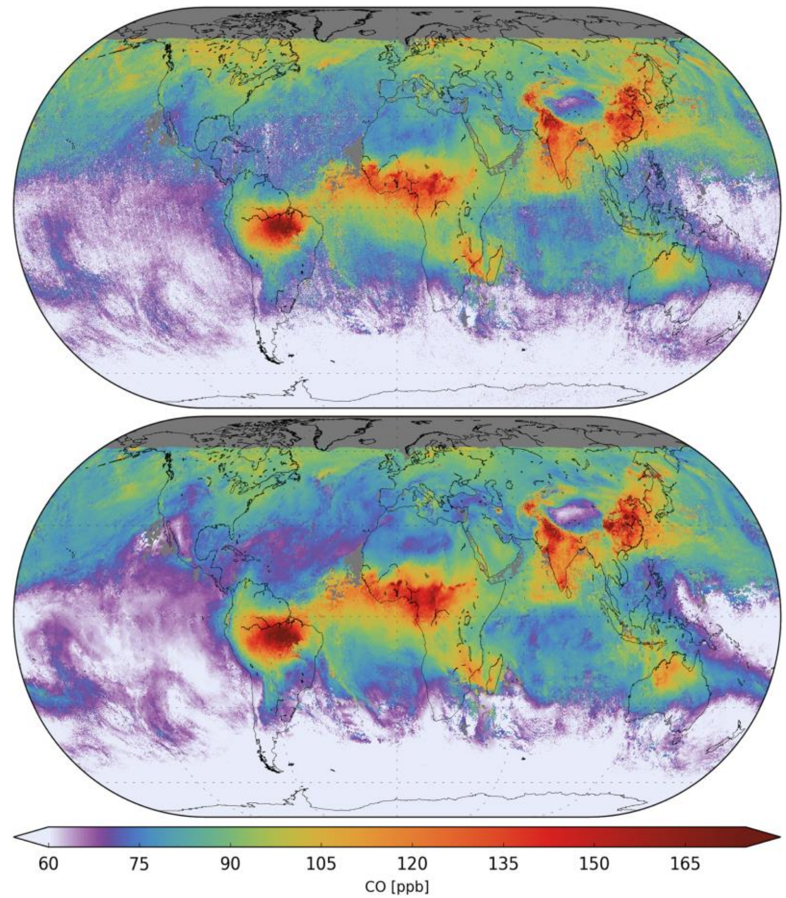
Michael Schulz, MetNo

Ozone skill score



Antje Inness, ECMWF

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



Borsdorff et al., JRL, 2018

THE ECMWF EXPERIENCE: AEROSOL AND OZONE IMPACTS AT THE S2S SCALES

Aerosol impacts at the S2S scales

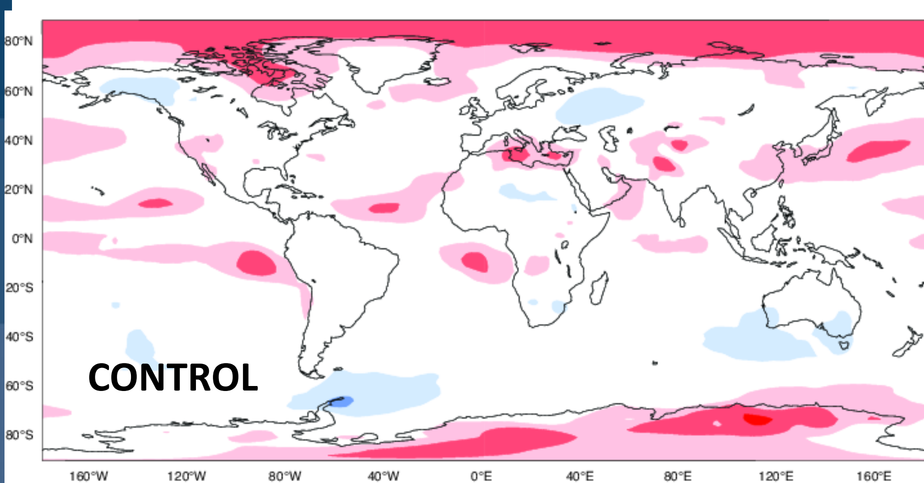
- Interactive aerosol simulations use fully prognostic aerosols in the radiation scheme – **only aerosol direct effects are included**
- Free-running aerosols with observed emissions for biomass burning
- Ensemble size is 11 members, T255 (about 60km) resolution, 91 levels
- 5 different start dates around May 1, 55 cases in total
- 6 months simulations

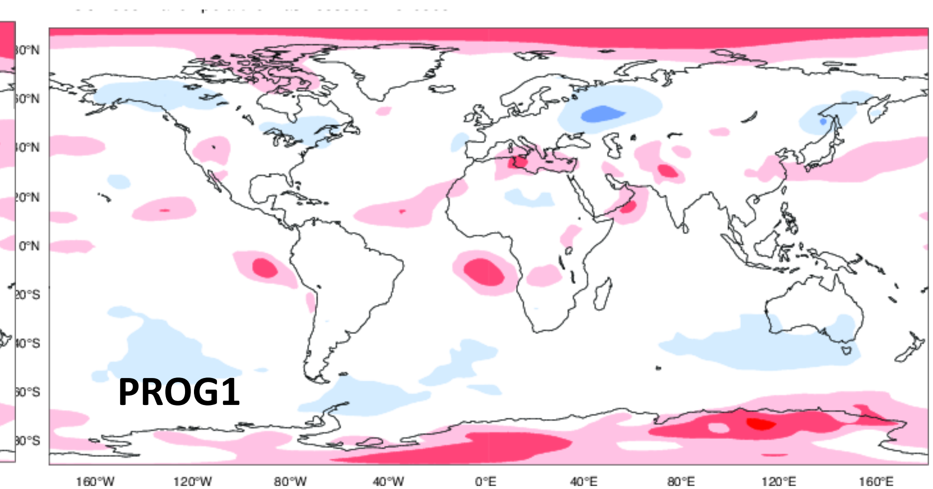
Period 2003-2015

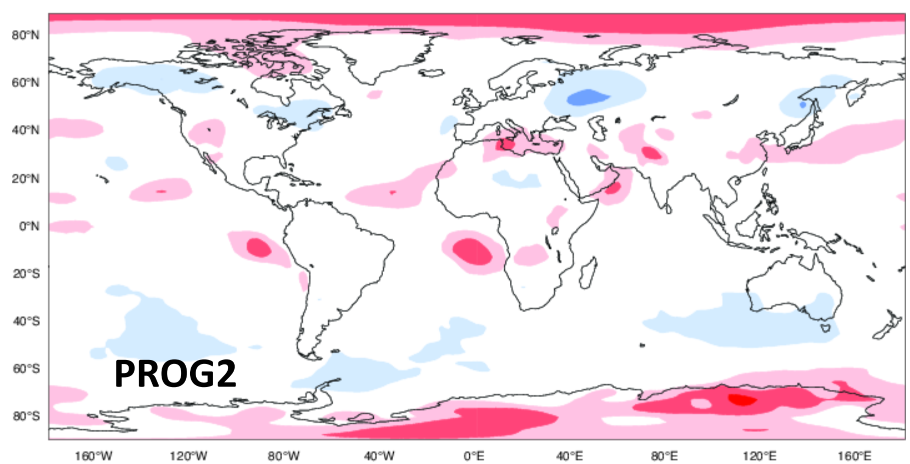
- Results summarized in **Benedetti and Vitart, MWR, 2018**

CONTROL1	Tegen et al (1997) climatology in the radiation
CONTROL2	Bozzo et al (2017) climatology in the radiation
PROG1	Interactive aerosols initialized from the CAMS Interim Reanalysis (Flemming et al 2017)
PROG2	Interactive aerosols initialized from a free-running aerosol simulation

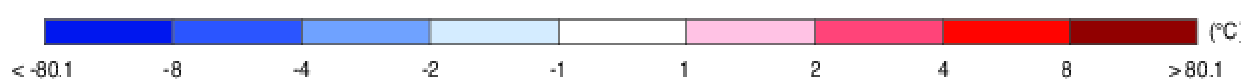
Aerosol impacts on the monthly forecasts: temperature bias week 4



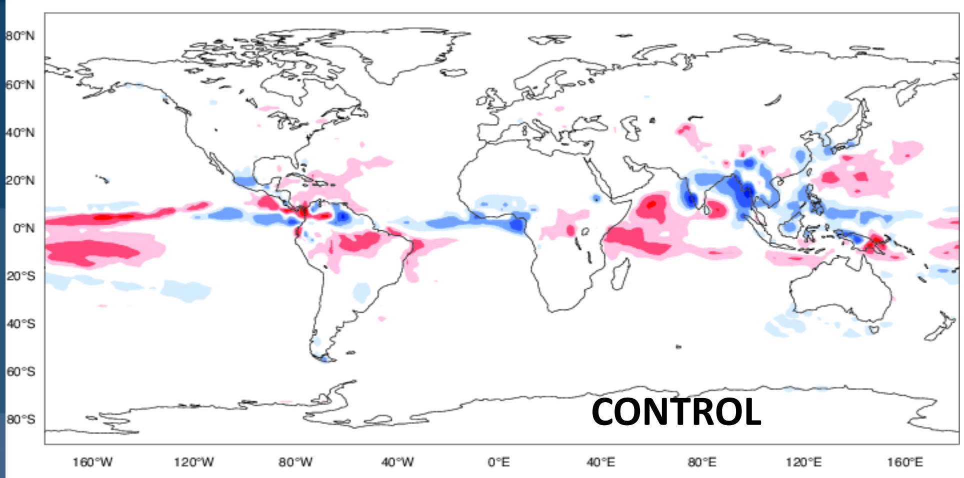


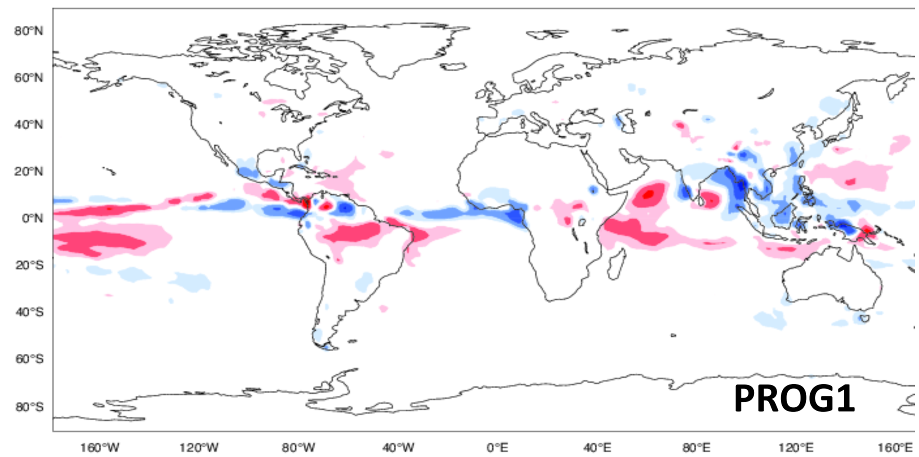


- Areas impacted: **Mediterranean basin, the Asian dust belt in the Northern Pacific Ocean and the North Atlantic dust belt**.
- In some areas the temperature bias is reduced between -**0.5 and 2.0 degrees**

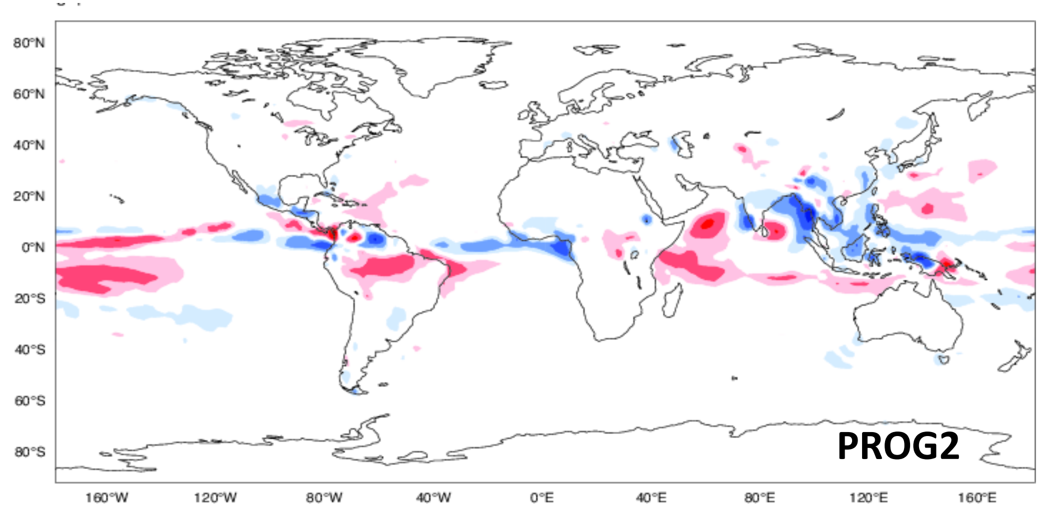


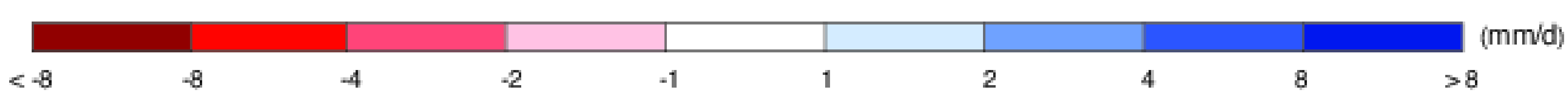
Aerosol impacts on the monthly forecasts: precipitation bias week 4



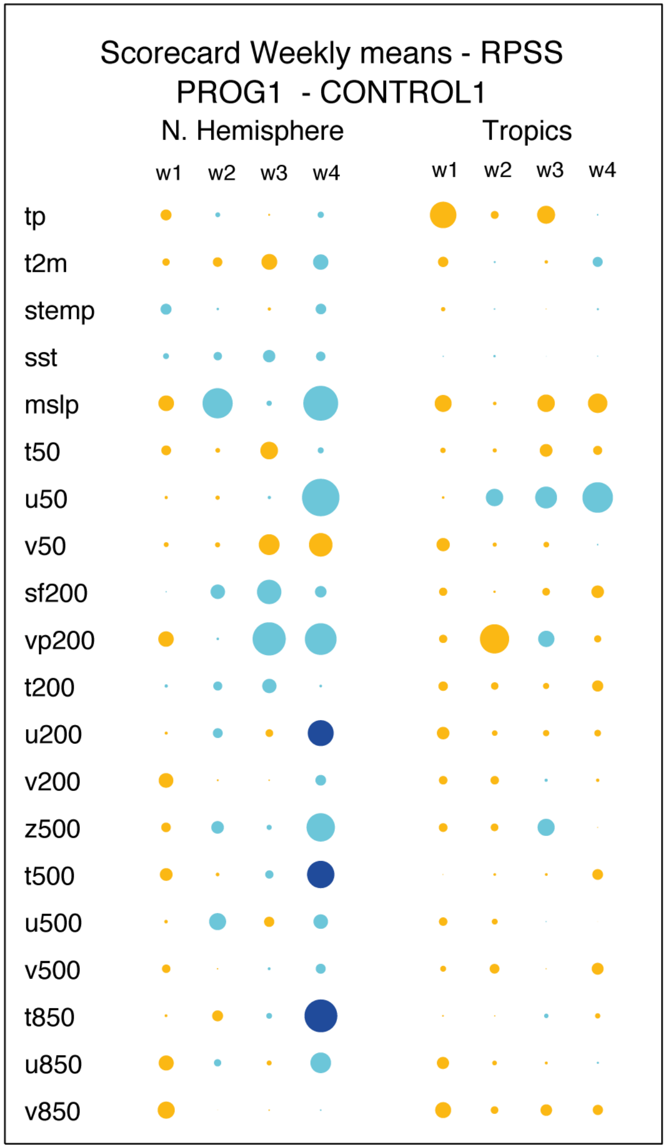


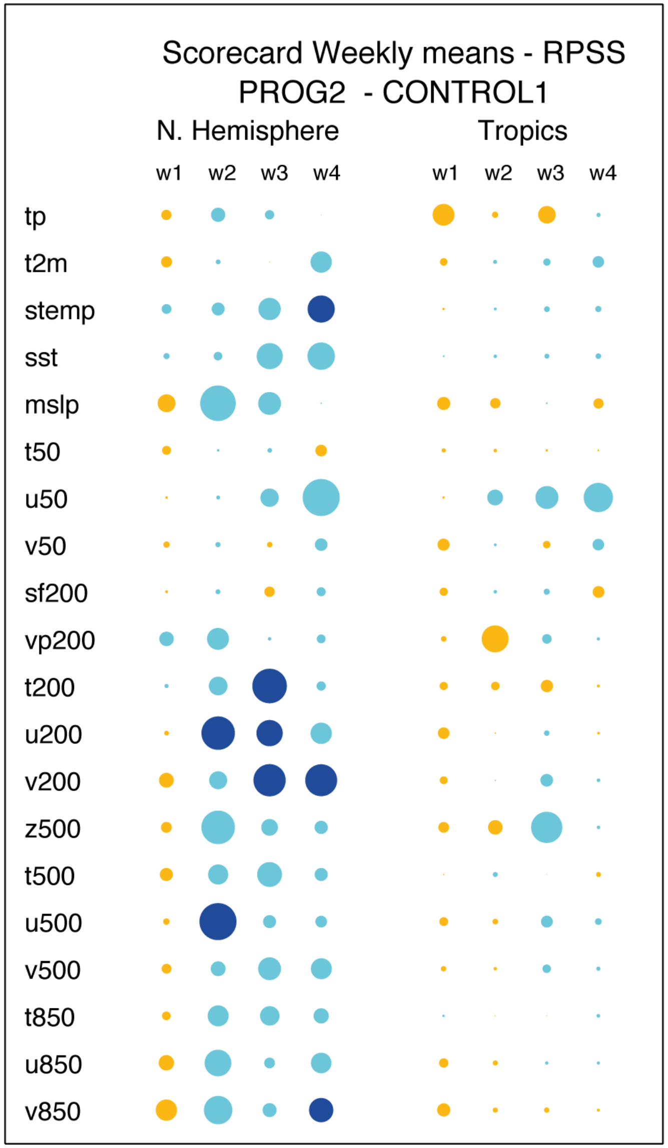
- Precipitation biases are also reduced over several **tropical regions**
- Precipitation bias reduction in East Asia amounts **to 0.5-1 mm/day.**





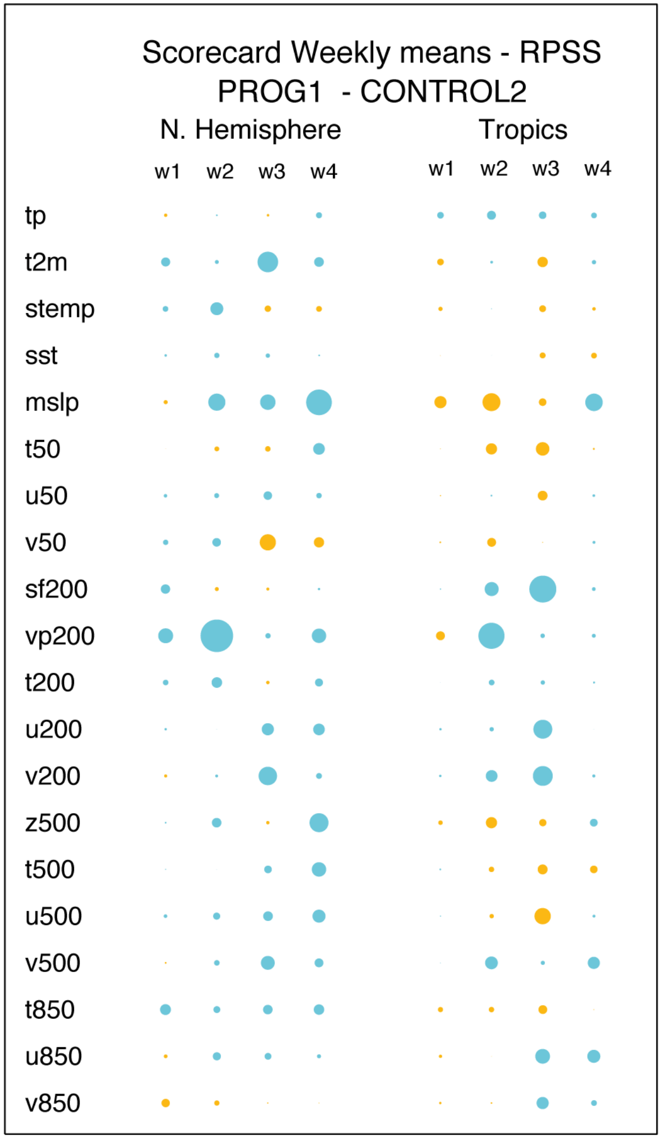
Aerosol impacts on the monthly forecasts: Rank probability skill scores

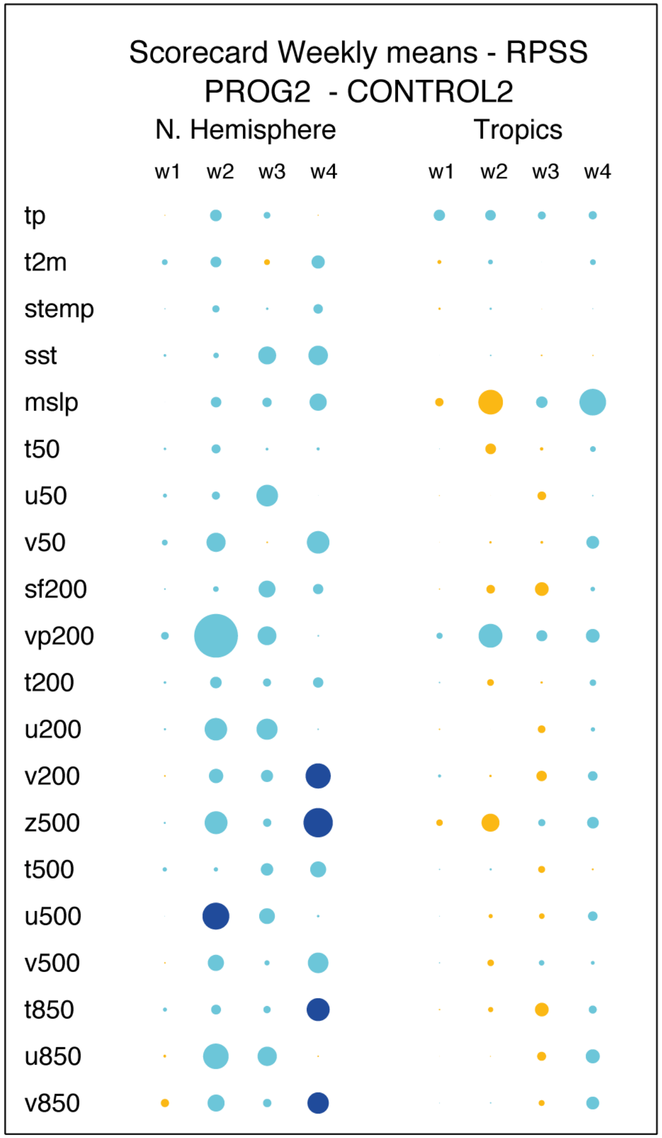




Pos. sign. Pos. not sign. Neg. sign. Neg. not sign.

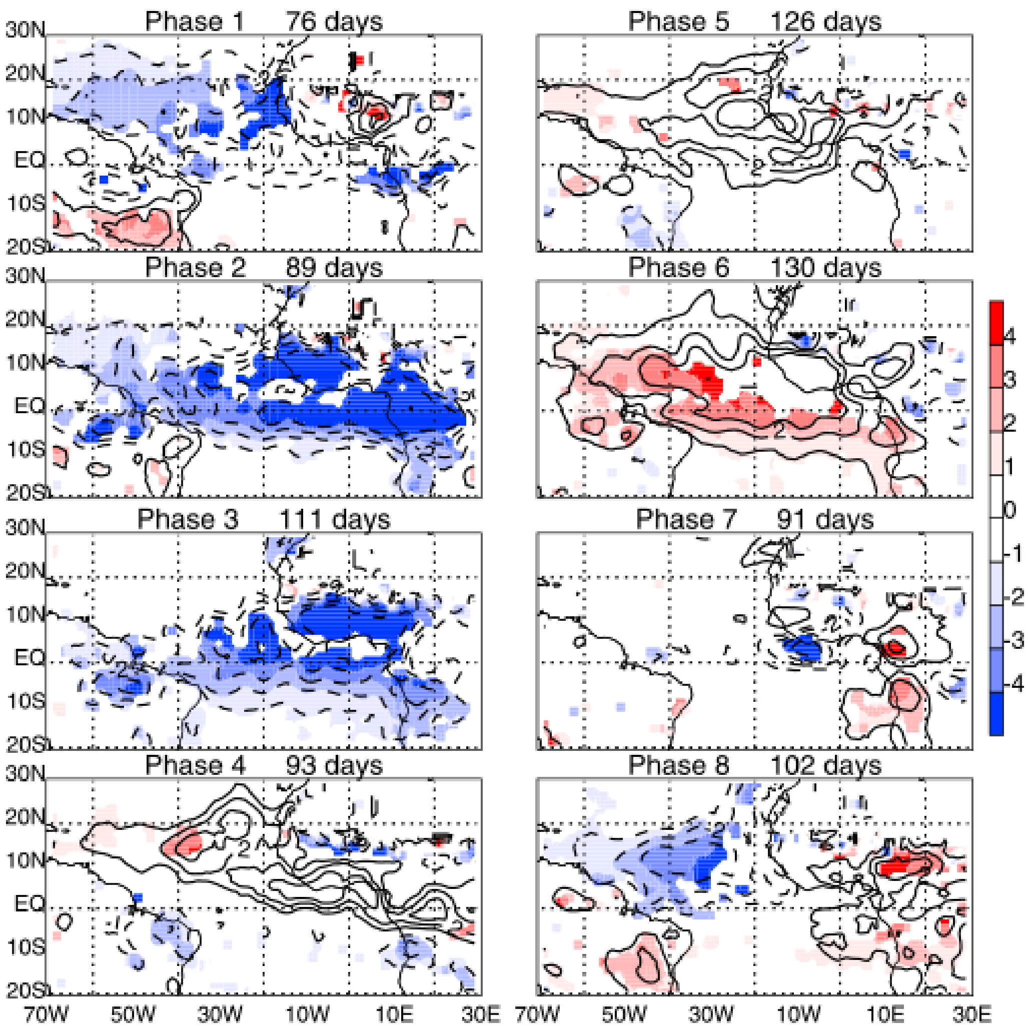
Aerosol impacts on the monthly forecasts: Rank probability skill scores



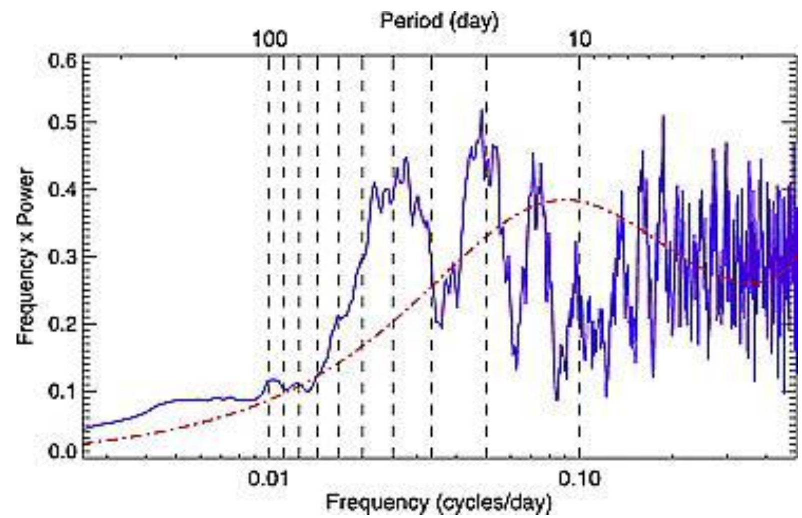


Pos. sign. Pos. not sign. Neg. sign. Neg. not sign.

Subseasonal aerosol variability



Time series spectrum of MODIS AOD anomalies over the Atlantic

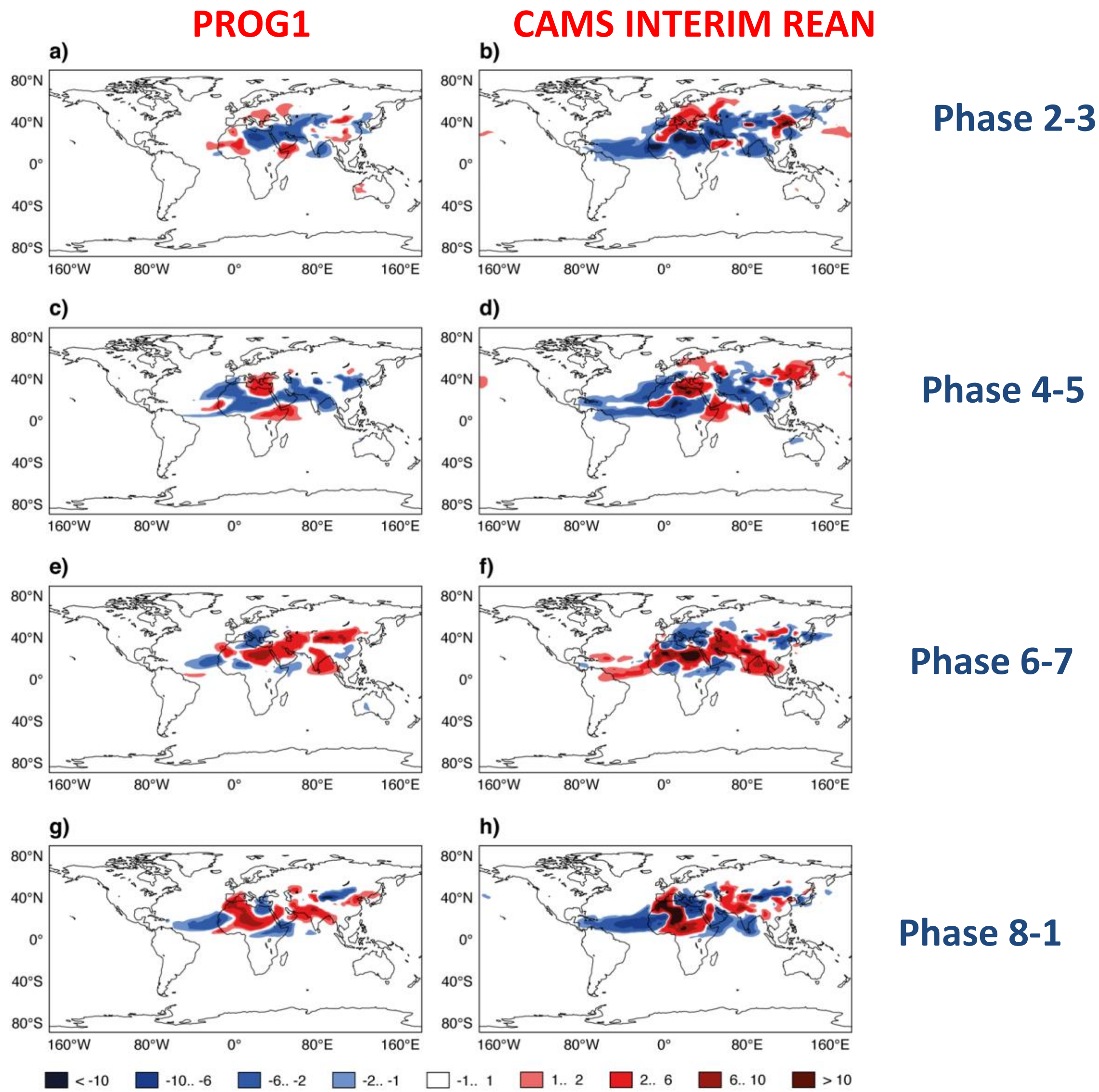


Tian et al, 2011

Intra-seasonal variance of AOD = ¼ total AOD variance

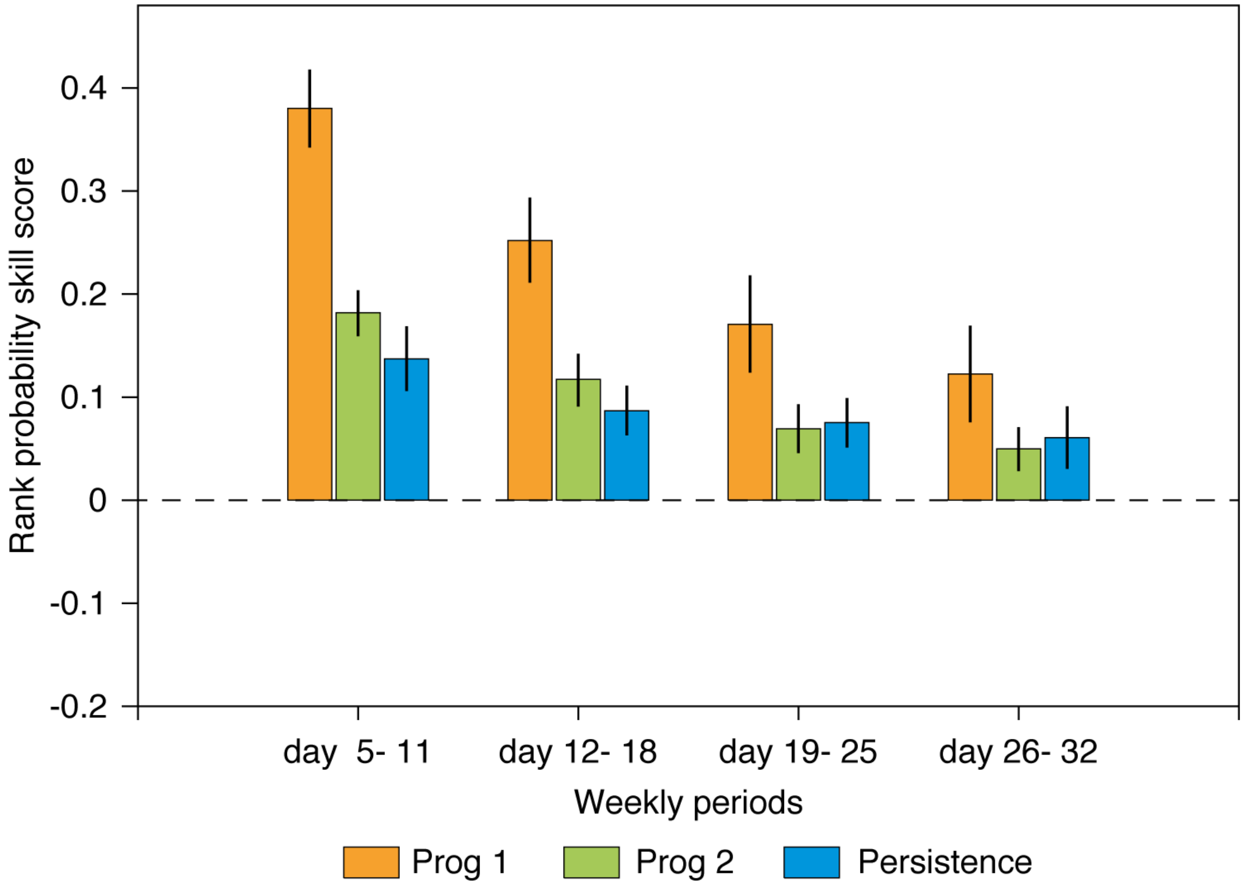
Aerosol modulation by the MJO: dust Aerosol Optical Depth anomalies

- **Composites of dust aerosol optical depth anomalies,** relative to the model climatology, have been **produced in the different phases of the MJO**
- Close similarity of patterns in the PROG1 experiment and in the CAMS Interim Reanalysis
- **Opposite phases of the MJO** (for instance phase 2-3 and phase 6-7) **have opposite impacts on the aerosol variability** suggesting that the **MJO modulation is a robust signal.**



ECMWF EURC

Predicting dust aerosols a month ahead

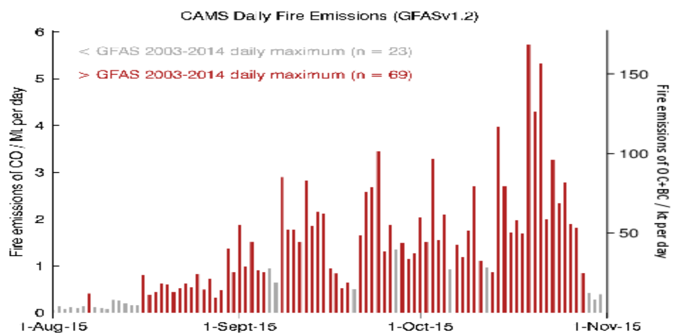


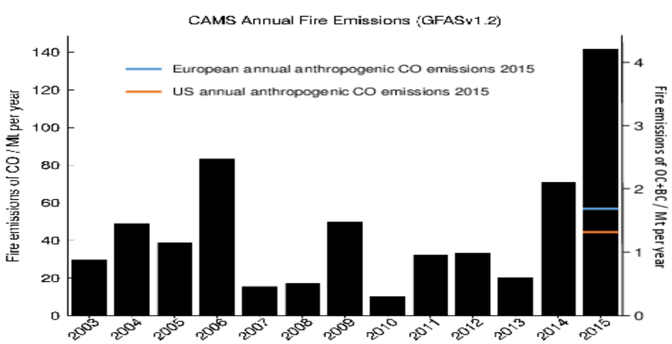
- RPSS for dust AOD from the experiments with interactive prognostic aerosols is higher than persistence as compared with the CAMS Interim Reanalysis

Extreme events: the Indonesian Fires of 2015

- **2015 was a record-breaking year for Indonesia.**
- During the burning season of August-October, wildfires spread widely across the region creating a humanitarian crisis due to the high levels of air pollution induced by the smoke.
- **Around 600 million tonnes of greenhouse gases were emitted,** an amount described as 'roughly equivalent to Germany's entire annual output'.

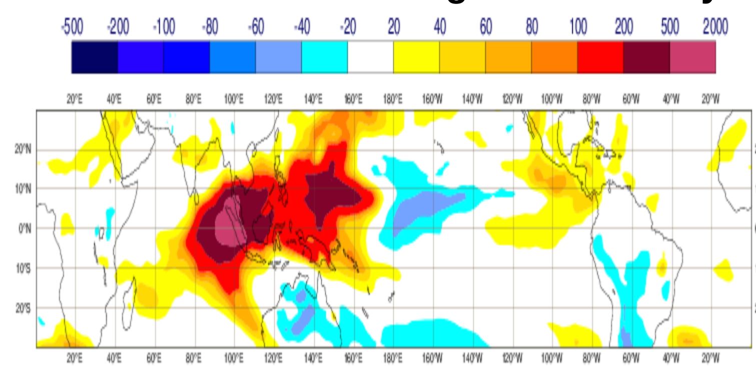
CAMS daily Fire emissions





A NASA satellite image showing the extent of the haze on 24 September 2015.

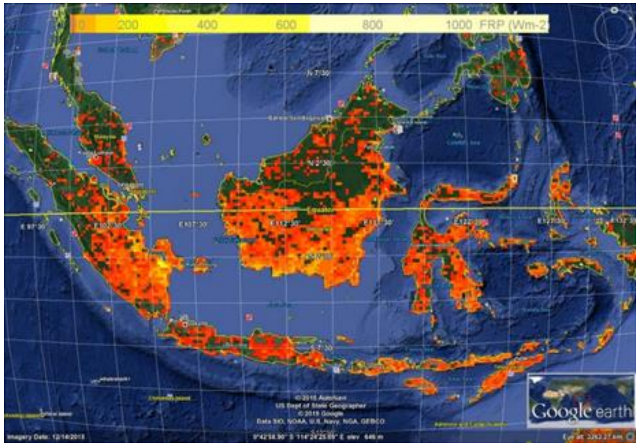
Biomass burning AOD anomaly



Benedetti *et al*, in State of Climate 2016, BAMS.

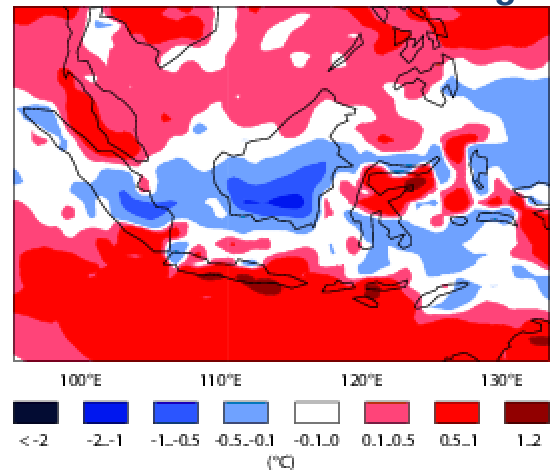
Extreme events: Indonesian Fires of 2015

Fire radiative power Aug-Oct 2015



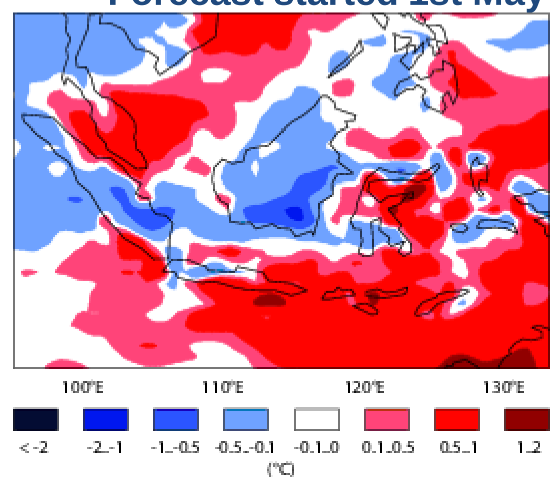
- The EPS system re-forecasts with interactive aerosols predicted the temperature anomalies corresponding to the fire-affected area **up to 6 months ahead**
- **Prescribed observed fire emissions** derived from Fire Radiative Power were used
- Inherent high predictability of these events connected to **El-Nino** (and agricultural practices in the area)
- Need for a **predictive fire dynamical model**

2m Temp anomaly Oct 2015 - Forecast started 1st Aug



Cooling due to smoke aerosols predicted
3 months ahead

2m Temp anomaly Oct 2015 - Forecast started 1st May

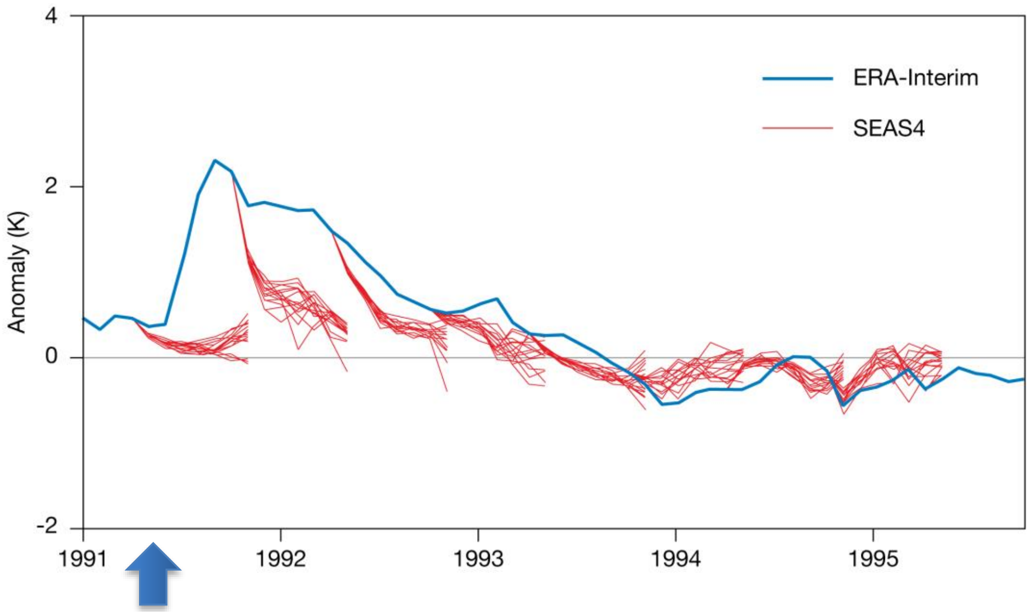


Cooling due to smoke aerosols predicted
6 months ahead

Benedetti, Vitart and Di Giuseppe, in preparation

Stratospheric sulphate aerosols for seasonal prediction

Temperature anomalies (30hPa, Month 7)

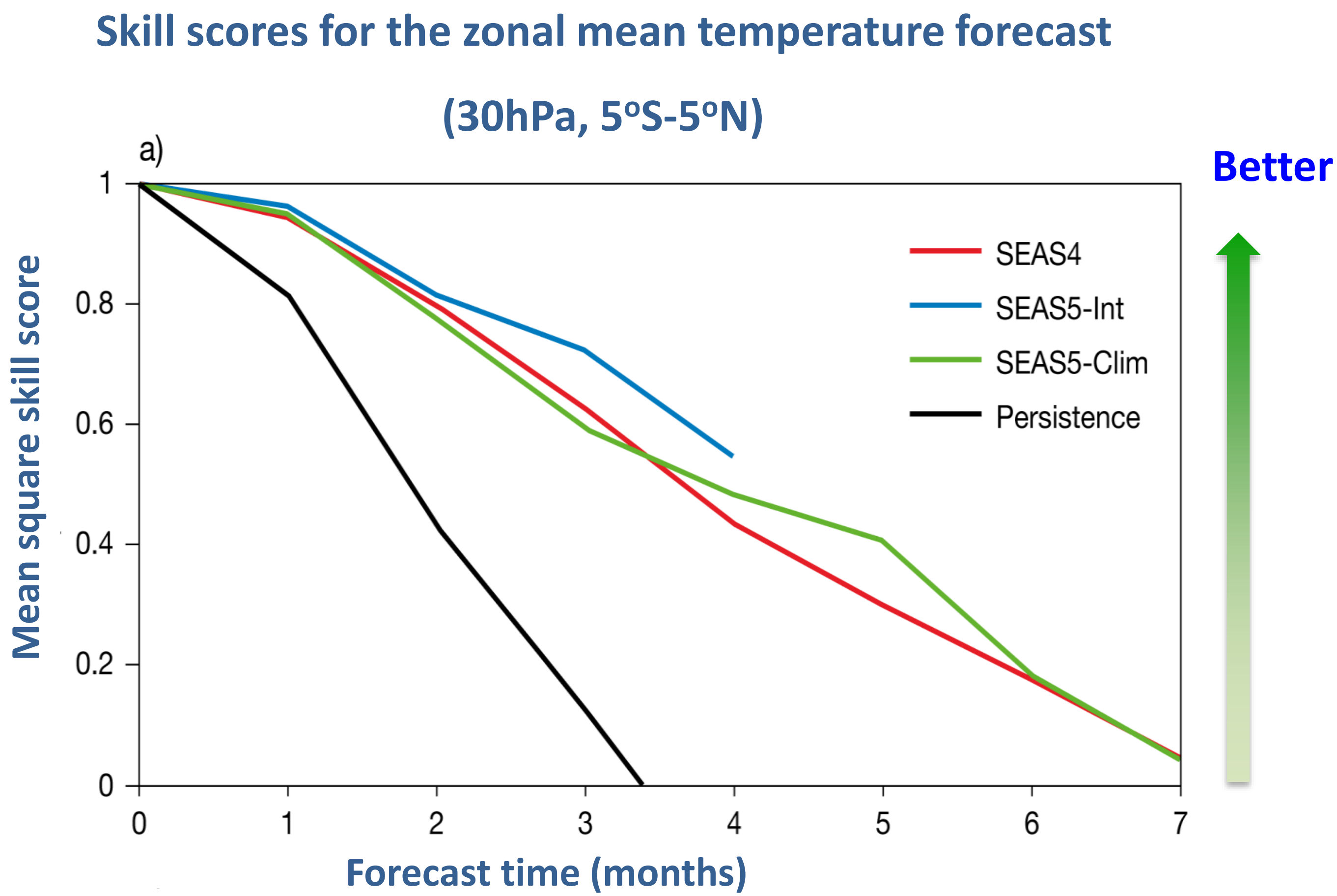


Eruption of Mount Pinatubo

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

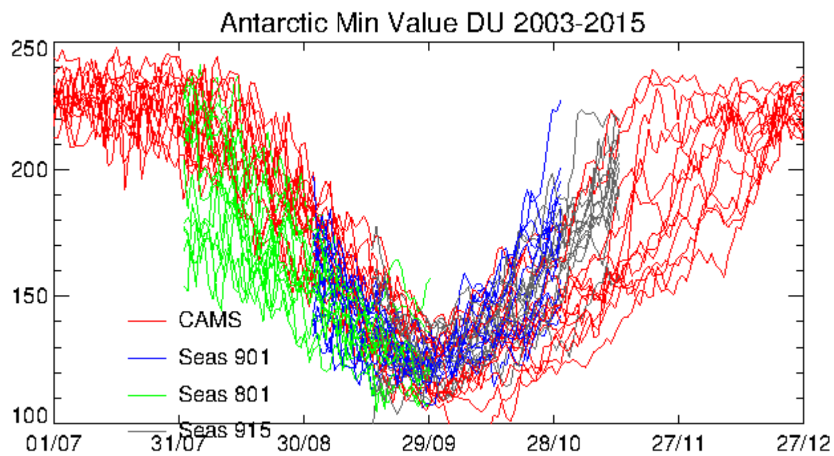
Tim Stockdale, ECMWF

Potential of interactive ozone at the <u>seasonal range</u>



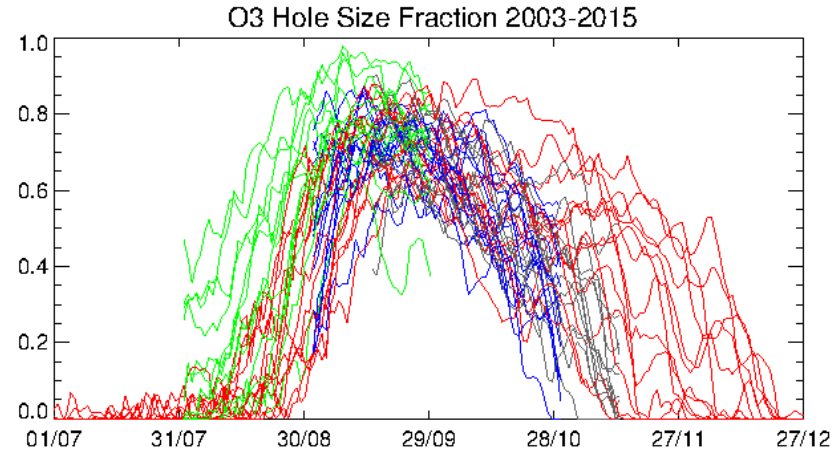
Tim Stockdale, ECMWF

Ozone hole prediction a month ahead



IFS initialized on 09/01

IFS initialized on 08/01



- Prognostic ozone (not radiatively interactive) is included in the IFS and available from the operational monthly run
- The prediction of the ozone Antarctic ozone Antarctic concentrations and ozone hole size fraction show skill of the monthly forecast in predicting the ozone hole a month ahead
- The **CAMS O3 reanalysis** is used for comparison.

J. Flemming, F. Vitart, A. Benedetti, ECMWF

EXPERIENCE FROM OTHER CENTRES: A SURVEY

Survey questions

1. What type of treatment for atmospheric composition variables (aerosols, ozone, CO_2, etc) is currently used in your system?

2. Have you performed studies or experiments to assess the impact of atmospheric composition variables on the S2S prediction? If yes, what experiments?

3. Are you planning to introduce changes to the description of atmospheric composition variables in your S2S system to improve performance? If yes, which variables will you be focusing on?

	Current treatment	Experiments performed	Future treatment
BoM (Harry Hendon)	• Monthly mean, zonal mean climatological values for aerosols and ozone. • CO2 is prescribed as observed monthly using historical values up to ~2006 and then follows RCP8.5	Prescribed observed ozone, large impact on stratospheric vortex	Include prognostic ozone (developments at ECMWF and UKMO)
CMA (Tongwen Wu)	• Fully coupled aerosols interactive with cloud, radiation and precipitation in BCC-CSM2-HR2 (from Octber 2019) • O3 and CO2 from CMIP6-recommended scenario data.	Not started yet	Prognostic O3and CO2 (2020-2021) forced with anthropogenic emissions, and feedback on the atmosphere radiation
ECCC (Hai Lin)	• Season-dependent O3 climatology • CO_2 concentrations with a linear trend for hindcasts and fixed value of 380ppm in realtime	N/A	Observed monthly mean values will be used in the hindcast

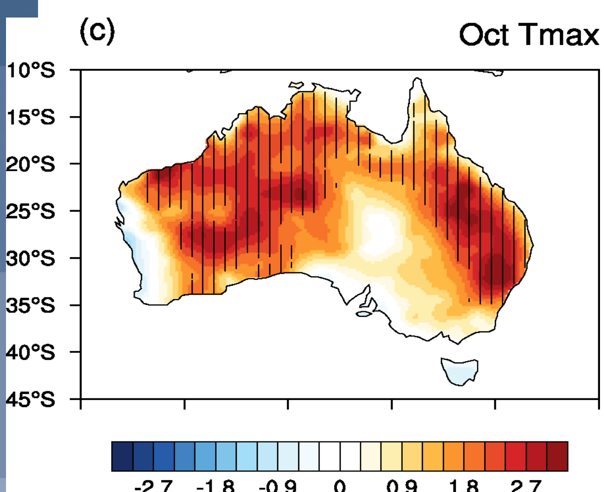
	Current treatment	Experiments performed	Future treatment
ECMWF (Frédéric Vitart)	• Aerosol climatology from Bozzo et al (2017) based on CAMS reanalysis • Prognostic O3, but CAMS O3 climatology in radiation code	• Benedetti and Vitart (2018) experiments show positive results from interactive aerosols • Ozone impact neutral/negative	Interactive O3 based on new statistical model by Tim Stockdale Plans in ECMWF Atmospheric Composition Roadmap (Dragani et al, 2018 TM 833).
HMCR (Mikhail Tolstykh)	• Monthly mean climatology for O3 and aerosols (fron GSFC 5x4deg fields) • CO2 constant depending on year	Not yet	• New aerosol climatology from Copernicus • Simplified ozone cycle.
JMA (Yuhei Takaya)	• 3-D O3 and aerosol climatologies both in hindcasts and real-time forecasts. • GHG concentrations are prescribed in hindcasts, but specified with a constant climatology in real-time forecasts.	MRI participated in WGNE-AER Phase 1 (aerosol impacts on the medium-range NWP). No S2S experiments yet.	Not decided

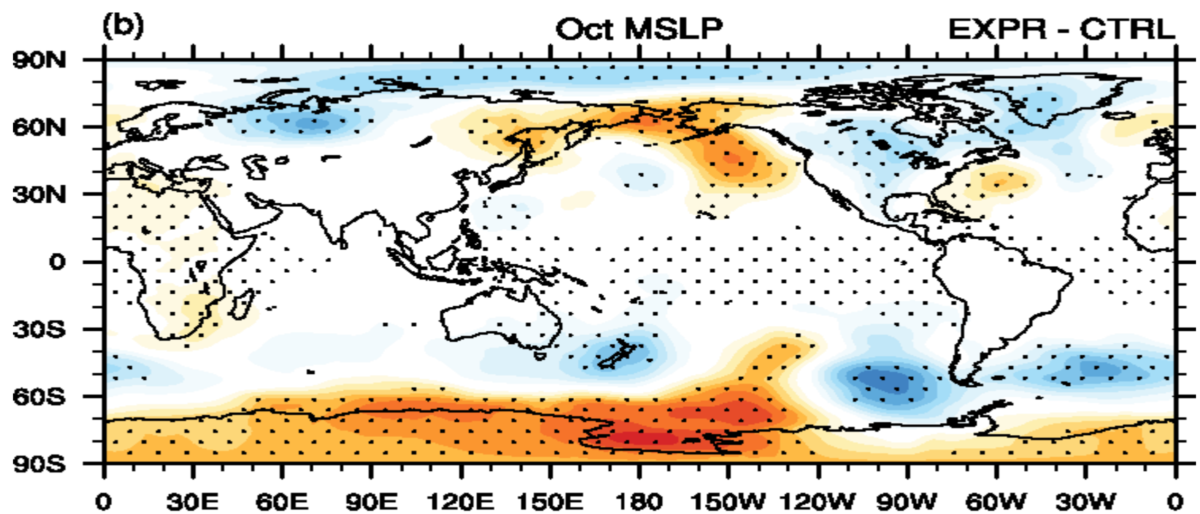
	Current treatment	Experiments performed	Future treatment
KMA	• Same as BoM and UKMO		
MeteoFrance (Lauriane Batte)	• Prognostic O3 initialized from a monthly climatology from the University of Reading. • Monthly aerosol concentrations corresponding to 1990 from Szopa et al. (2012). • GHG forcings (CO2 and CH4) from a historical run up to 2010 and a A1B scenario from 2010 onwards.	• Impact of initializing aerosols over the hindcast period with a reconstruction with CNRM-CM using prognostic aerosols (Michou et al. 2015) focusing on the seasonal time scales • Found local and limited influence on skill.	
UKMO (Craig MacLachlan)	Same as BoM and KMA	Not yet, but hope to investigate the use of prognostic aerosols (with BoM and KMA)	CMIP6 forcings to be used in 2020 when physics is upgraded

Impact of ozone in BoM model

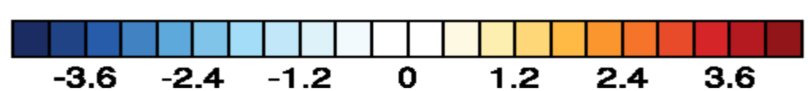
- Observed ozone was used to initialize ACCESS-S1 forecasts around 1 Aug 2002. There was a dramatic polar vortex warming event and a huge increase in stratospheric polar ozone in the southern hemisphere spring.

- Using observed ozone strengthened the coupling to the surface (low Southern Annular Mode response) by further weakening the vortex, thus amplifying the associated high temperature extremes over subtropical Australia.





Credits: Harry Hendon, BoM



Evaluating aerosols impacts on Numerical Medium-Range and Subseasonal Prediction –the WGNE-S2S-GAW Aerosol project

Ariane Frassoni (CPTEC, Brazil) and **François Engelbrecth** (WITS, S. Africa) for WGNE

Frederic Vitart and **Angela Benedetti** (ECMWF) for S2S

Paul Makar (ECCC, Canada) and **George Grell** (NOAA, USA) for GAW SAG APP

WGNE = Working Group on Numerical Experimentation
S2S = Subseasonal-to-Seasonal project
GAW = Global Atmosphere Watch
SAG APP = Scientific Advisory Group on Applications

The Second Phase of the WGNE-S2S-GAW Aerosol Project

Medium-range experiments

- Higher resolution regional/global configurations in order to address the importance of interactive aerosols on medium-range predictability
- Longer periods to test different situations (not case-based)

S2S experiments

- Subseasonal re-forecasts experiments based on ensemble approach in a global scale in order to address the importance of interactive aerosols on subseasonal predictability

Goals of the Project

This project aims to improve our understanding about the following questions:

How important are aerosols for predicting the physical system (at short-range, medium range and S2S time scales) as distinct from predicting the aerosols themselves?

What are the current capabilities of NWP models to simulate aerosol impacts on medium-range and subseasonal prediction?

How important is forecast skill for air quality forecasting?

Are the S2S air quality forecasts useful for impacts purposes?

Protocol for the S2S experiments

Set-up: re-forecasts will cover 2003-2018, focus will be on monthly runs with start dates of 1 May-Jun-July (Saharan dust) and 1 Aug-Sep-Oct (biomass burning aerosols), 5 ensemble members (minimum)

Variables to be analysed: T2m, surface winds, precipitation, AOD, upper-air variables, etc.

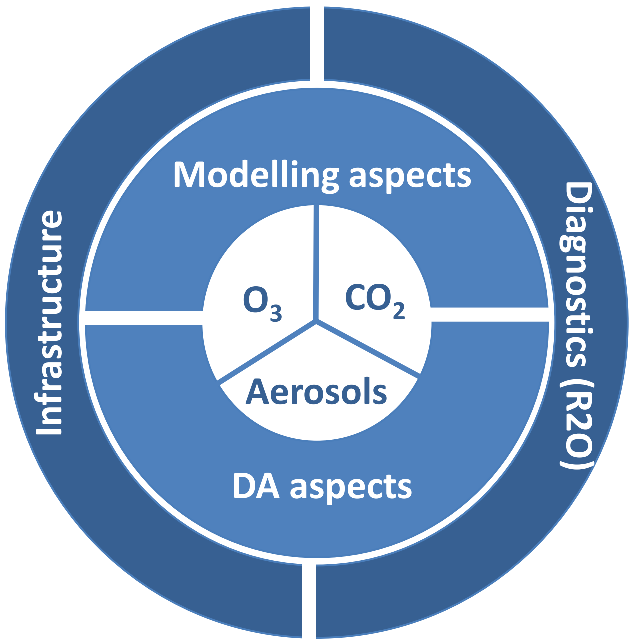
Storage: data will be collected and stored at CPTEC, format: netcdf

Verification: classical statistical scores Root mean Square Error (RMSE), Bias (Forecast-Observation: F-O), Contingency table scores, Scorecards (rank/probabilistic scores)

Next steps

- The protocol has just been finalized and is being distributed to the WGNE, S2S, GAW SAG APP mailing lists
- The timeline for the completion of the S2S experiments is 2 years
- Wide participation is hoped for, particularly from operational centres

ECMWF: A roadmap for the future



- Recommendations on **AC priority developments useful for NWP forecasting (up to seasonal** time scales) to be assessed in the 2019-2022 period, and possibly implemented by 2022 **(Dragani et al, ECMWF Tech Memo 833, 2018)**.
- The aim is to **understand** through thorough and coordinated testing **what** level of **complexity and/or coupling** these **AC species** need to have **in order to impact** the **NWP** forecasts.
- Focus on **O3, aerosols and CO2**

Summary

- **Atmospheric composition is an integral part on the Earth system**
- **Different approaches at the various centres involved in S2S prediction**
- **An accurate numerical weather prediction** (NWP) model with physical and chemical processes and realistic emissions **offers the perfect framework to model atmospheric composition (AC)**
- In return, some elements of the atmospheric composition **can improve the weather forecasts** at various temporal scales, including the S2S, via different interaction mechanisms
- The **degree of complexity** of AC needed in NWP **depends on the specific application**
- Potential for **S2S prediction of atmospheric composition fields** could open new avenues

Open questions for AC in S2S (and hints of answers)

- Complexity versus benefits – it's difficult to find one size that fits all in Atmospheric Composition modelling
- More scientific investigation is needed – limited experimentation has been performed
- Climatologies are extremely useful but not for extreme cases
- Cost of additional model complexity – single precision is still an unexplored avenue
- Code rewriting/optimising could also buy some complexity – creative solutions are the key