Sub-seasonal prediction of aerosols fields and impact on meteorology using the ECMWF's coupled Ensemble Prediction System

Angela Benedetti and Frédéric Vitart (Corresponding author: Angela.Benedetti@ecmwf.int)

Motivation In recent years the role of aerosols in numerical weather prediction has received more attention at operational centres. Thanks to the development of operational aerosol forecasting systems such as the one run by the Copernicus Atmosphere Monitoring Service, ECMWF has been in a unique position to test the impact of aerosols in its complex modelling environment known as the Integrated Forecast System (IFS). Recent efforts have been aimed at investigating the aerosol impacts in the coupled Ensemble Prediction System (EPS) at the sub-seasonal time scales. Results are exciting and indicate that the integration of full prognostic aerosols could be beneficial for the model skill in the extended range. A positive side effect of this line of research is the monthly prediction of aerosols *per se* which could provide new useful products to the user community. Moreover, the potential to predict large aerosol events associated to wild-fires which have strong seasonality and are influenced by El-Nino could be the next frontier in the field, provided that a dynamical fire emission model is developed.

Experiment set-up

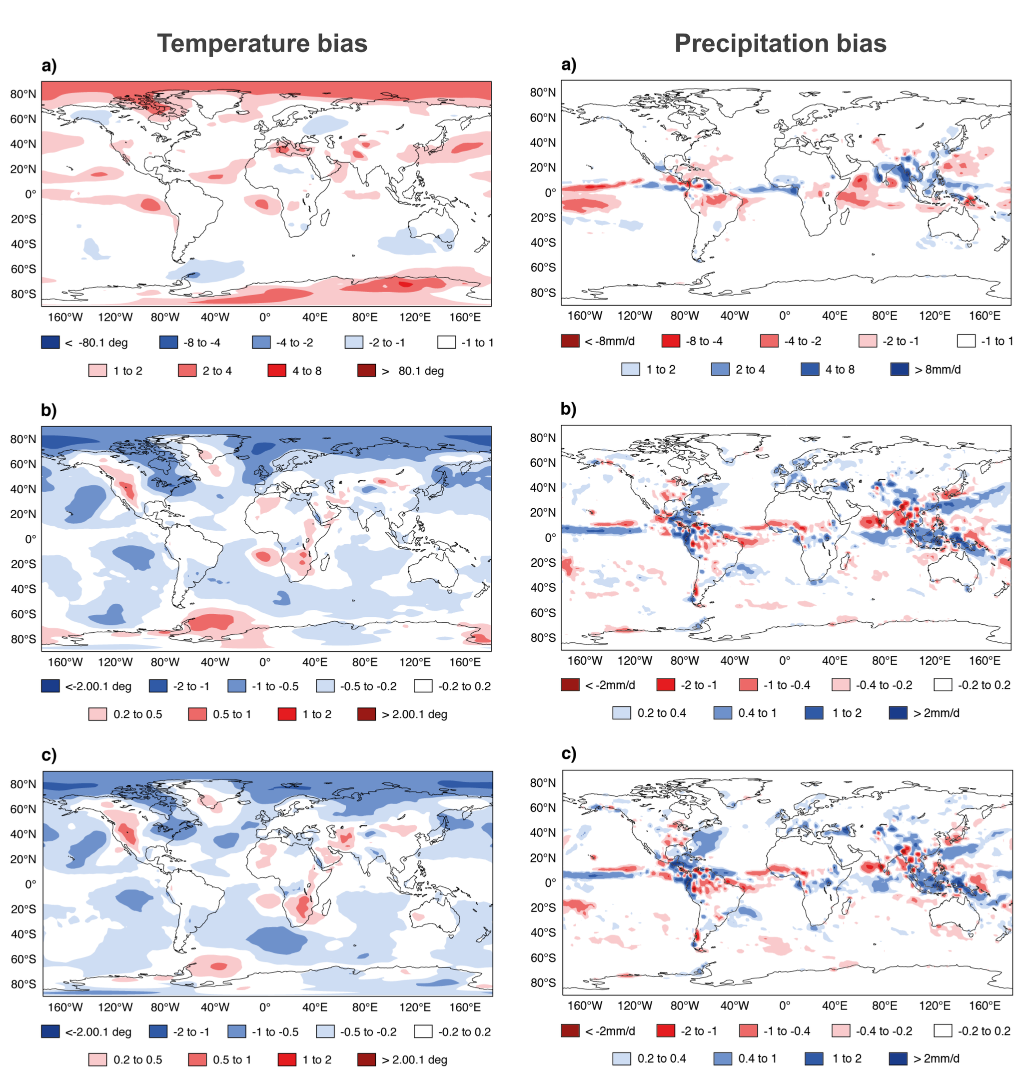
- Two control runs for the period 2003-2015 were used: one with the Tengen et al 1997 climatology (CONTROL1) and one with the Bozzo et al 2017 climatology (CONTROL2)
- Interactive aerosol simulations cover the same period and use fully prognostic aerosols in the radiation scheme – only aerosol direct effect are included
- Two initializations used for the experiments: one using the CAMS Interim Reanalysis (PROG1) and another using an average aerosol state from a free-running model simulation (PROG2)
- 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, 5 days apart (55 cases in total)
- The experiments were run for 6 months

Aerosol impacts on monthly forecasts

Bias plots for temperature and precipitation averaged for the weekly period starting from day 26 to day 32 (week 4) are shown here with respect to CONTROL1. For a start date of May 1, this corresponds to the end of May/beginning of June. The bias is estimated by computing the difference between the model weekly climatology as a function of lead time and the weekly mean climatology from ERA Interim computed over the same years (2003-2015).

The bias in temperature at 850hPas is shown in the figure on the left four weeks into the simulation. The change in bias for experiments PROG1 and PROG2 with respect to CONTROL1 is also shown in the same figure. Areas particularly affected are the Mediterranean basin, Central Africa, the Asian dust belt in the Northern Pacific Ocean and to a lesser extent, the North Atlantic dust belt. The Arctic also appears quite noticeably with a reduction in bias, although few grid points are actually included in that region. In some areas the temperature bias is reduced between -0.5 up to 2.0 degrees: this is particularly noticeable in the North Pacific. The bias in the Mediterranean Sea is also reduced.

Precipitation biases are also reduced over several Tropical regions, the Tibetan plateau and the North Pacific as shown in the figure on the right. Particularly interesting is the bias reduction in East Asia which amounts to 0.5-1 mm/day.

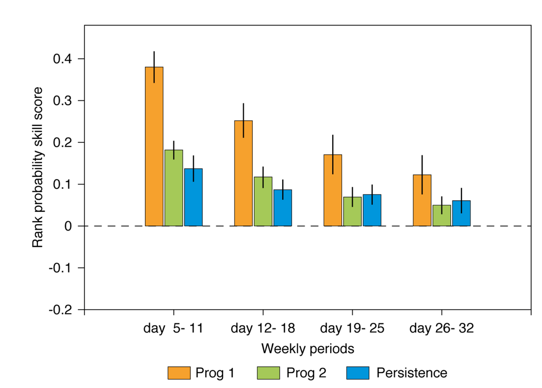


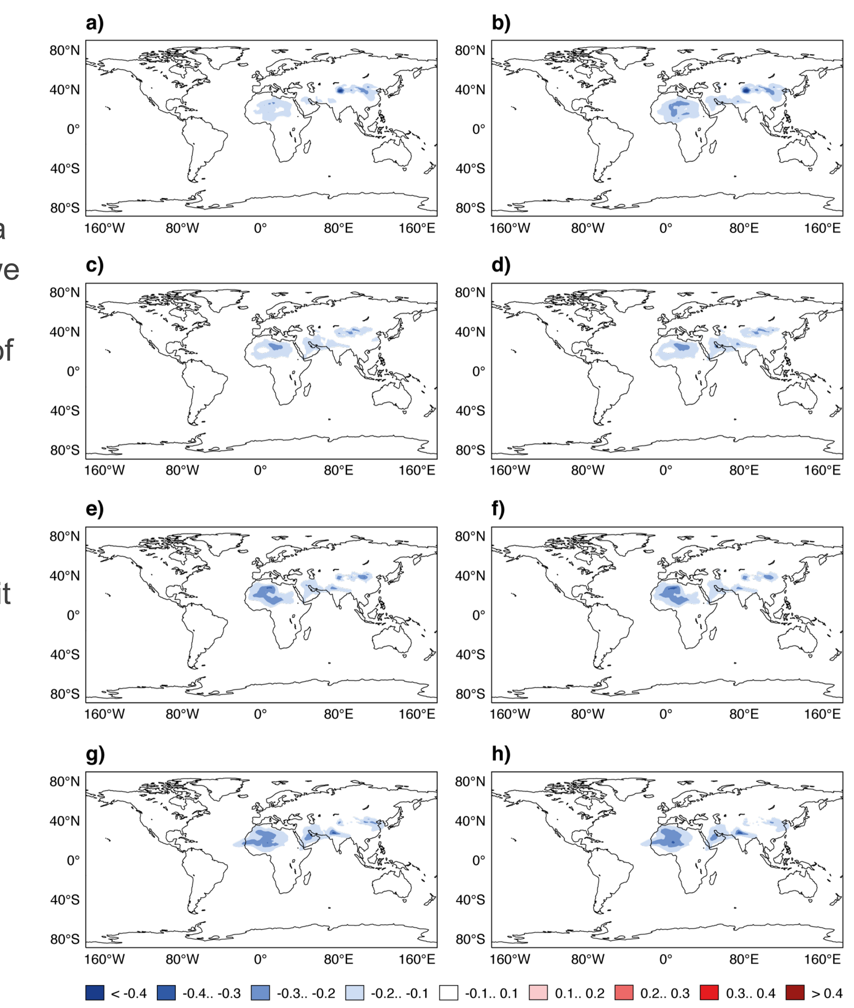
Improvements to sub-seasonal skill scores

- Scorecard measures the performance of interactive aerosol experiment with respect to a control run for several parameters.
- Blue circles indicate positive impact (dark blue for significant impact)
- Overall the experiments with prognostic aerosols perform well against the CONTROL experiments, particularly PROG1

Skill in the monthly prediction of aerosols

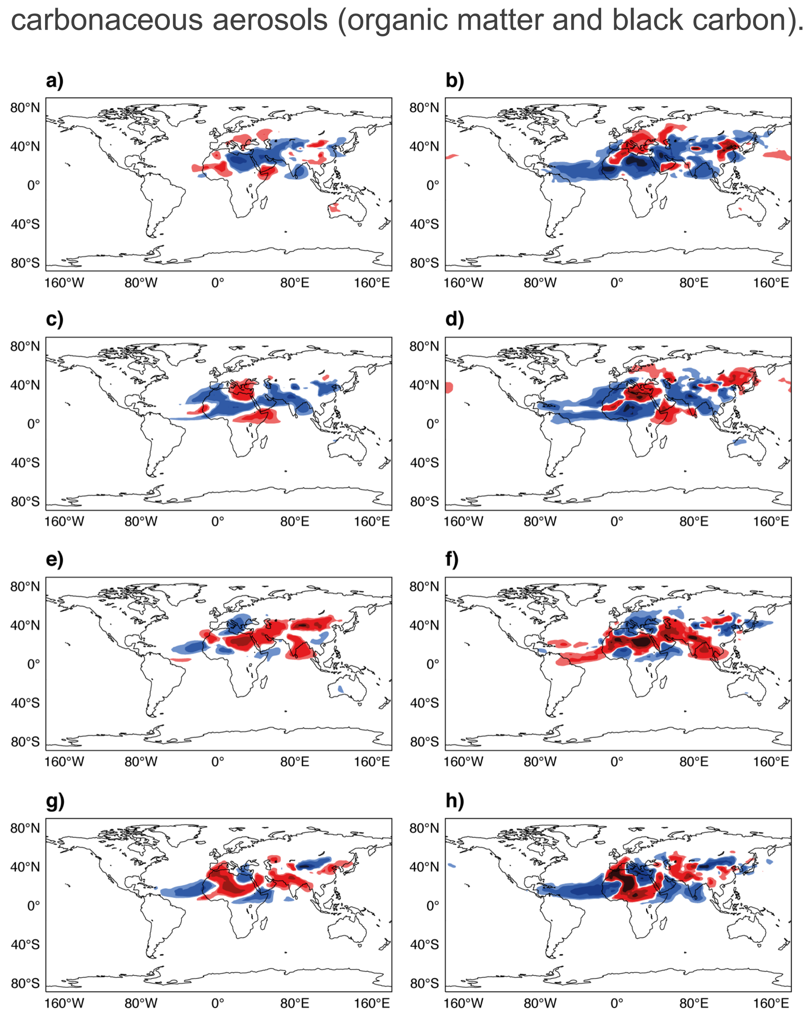
As a welcome side effect, having prognostic aerosols in the monthly system also means to have a monthly prediction of the aerosols themselves. The figure on the left shows the dust bias distribution at week 1 (5-11 days), 2 (12-18 days), 3 (19-25 days) and 4 (26-32 days) from the PROG1 (left) and PROG2 (right)integrations with respect to the CAMS Interim Reanalysis (CAMSira) which we use here as a reference dataset. For an extensive evaluation of CAMSira we refer to Flemming *et al* (2017). The dust distribution is not overly different and the bias is low, indicating a high degree of skill in the dust aerosol prediction in the monthly run. The figure below shows the Rank Probability Skill Score (RPSS) for the PROG1 and PROG2 integrations for the Tropics. Persistence is also shown for comparison. Both forecast experiments have higher RPSS than persistence for dust aerosols. PROG1 scores the highest, related to the fact that it has been initialized with CAMSira.



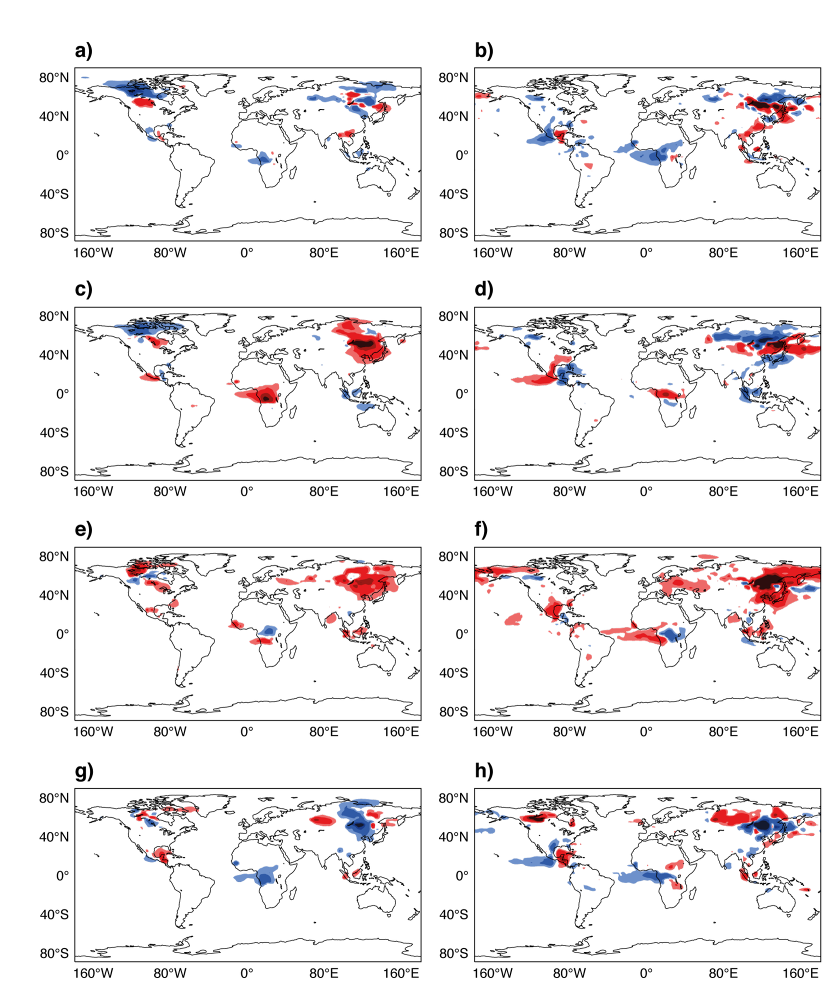


Aerosol modulation by the MJO

In order to assess the impact of the MJO on aerosols in the model simulations as well in CAMSira, composites of dust and carbonaceous optical thickness anomalies, relative to the model climatology, have been produced when the active phase of the MJO is located over the Indian Ocean (Phases 2 and 3, see Wheeler and Hendon (2004) for the definition of MJO phases), Maritime Continent (Phases 4 and 5), western North Pacific (Phases 6 and 7) and western Hemisphere (Phase 8 and 1). The left panels of the figures below show the anomaly of the dust field from PROG1 induced by the MJO with respect to the climatological distribution. For comparison, the right panels show the patterns of modulation obtained from CAMSira for the same MJO phases. The similarity of patterns and the fact that opposite phases of the MJO (for instance phase 2+3 and phase 6+7) have opposite impacts on the aerosol variability suggest that the MJO modulation is a robust signal, visible both in CAMSira and in the PROG1 forecast, although the amplitude of the impact is smaller in the models simulations that in the reanalysis. The figure on the right illustrates the same concept but for carbonaceous aerosols (organic matter and black carbon).



Anomaly of dust aerosol optical depth in the different phases of the MJO for the PROG1 experiment (left) and the CAMS Interim Reanalysis (right). From top to bottom: phase 2-3 (a,b), phase 4-5 (c,d), phase 6-7 (e,f), phase 8-1 (g,h).



Same as figure on the left, but for carbonaceous aerosols.

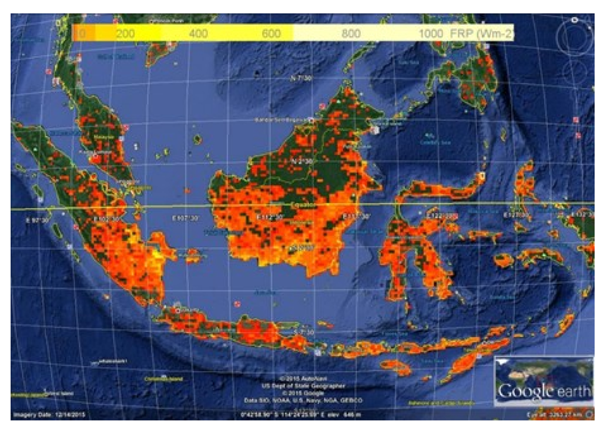
Side topic: Indonesian fires of 2015

2015 was a record-breaking year for Indonesia. During August-October, wildfires spread widely across the region creating a humanitarian crisis due to the high levels of air pollution induced by the smoke.

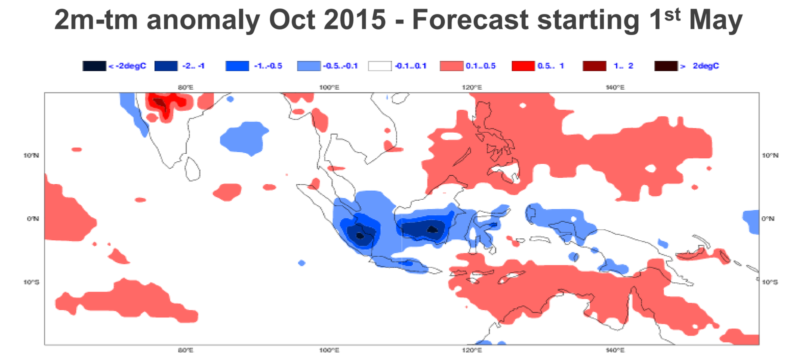
The EPS system re-forecasts with interactive aerosols was able to simulate the temperature anomalies corresponding to the fire-affected areas thanks to the prescription of the observed fire emissions.

This type of events have inherent high predictability connected to El-Nino. If a dynamical fire emission model is developed, it would be possible to predict them in advance at the seasonal scale.

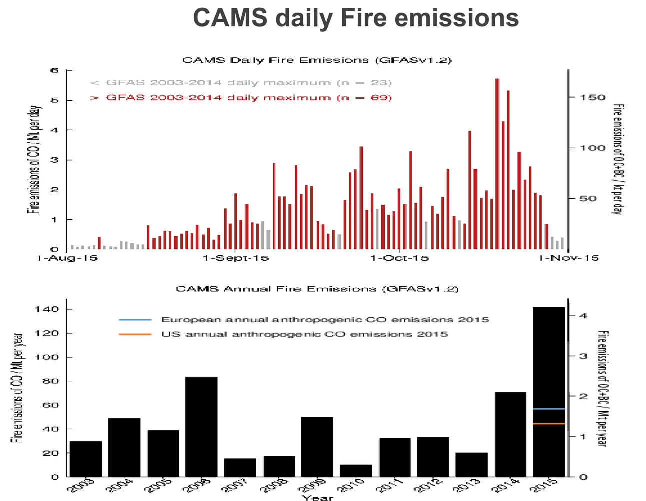
Fire radiative power Aug-Oct 2015



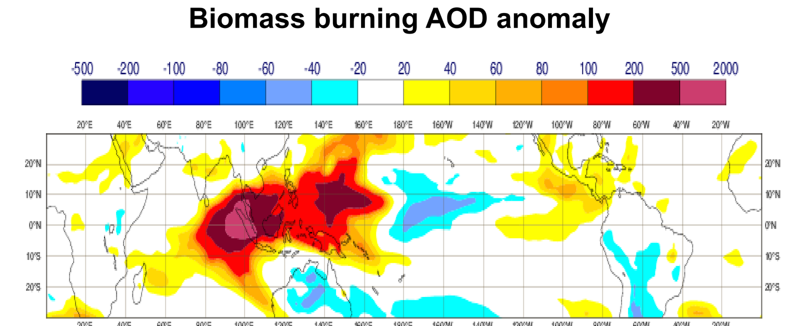
2m-tm anomaly Oct 2015 - Forecast starting 1st May



CAMS daily Fire emissions



Biomass burning AOD anomaly



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

Perspectives

- Using prognostic aerosols interactively in the radiation results in increased model skill at the sub-seasonal range for various meteorological parameter, the extent of the improvement being dependent on the aerosol model initialization.
- The simulation with climatological initialization performs better than the one with initialization provided by the CAMS Interim Reanalysis.
- MJO modulation of aerosol fields seems the most likely mechanism through which this aerosol impact is delivered as it explains most of the aerosol variance at the monthly scale.
- Prediction of aerosol fields at the monthly scales is possible and show a good degree of skill.
- Extreme events like the Indonesian fires of 2015 could only be captured with prognostic aerosols (and fire emissions) – these events are connected to El Niño and have a high degree of predictability at the seasonal scale.

References

Benedetti *et al*, 2016 in Blunden, J. and D.S. Arndt, 2016: State of the Climate in 2015. Bull. Amer. Meteor. Soc., 97, Si–S275, https://doi.org/10.1175/2016BAMSStateoftheClimate.1

Benedetti A. and F. Vitart, 2018: Can the direct effect of aerosols improve sub-seasonal predictability? Under revision for Monthly Weather Review.

Bozzo *et al*, 2017 Implementation of a CAMS-based aerosol climatology in the IFS, Technical Memorandum 801, available from ECMWF.

Flemming *et al*, 2017: The CAMS interim Reanalysis of Carbon Monoxide, Ozone and Aerosol for 2003–2015. Atmospheric Chemistry and Physics, European Geosciences Union, 2017, 17 (3), pp.1945 - 1983.

Tegen, I., P. Hollrig, M. Chin, I. Fung, D. Jacob, and J. Penner, 1997: Contribution of different aerosol species to the global aerosol extinction optical thickness: Estimates from model results, J. Geophys. Res., 102(D20), 23895–23915, doi:10.1029/97JD01864.

Wheeler, M.C. and H.H. Hendon, 2004: An All-Season Real-Time Multivariate MJO Index: Development of an Index for Monitoring and Prediction. Mon. Wea. Rev., 132, 1917–1932.