The Second Phase of the WGNE Aerosol Project: Evaluating aerosol impacts on Numerical Weather and Subseasonal Prediction

Ariane Frassoni*, Angela Benedetti[o], Frederic Vitart[o], Francois Engelbrecht[+]

*Center for Weather Forecasting and Climate Studies, Brazilian National Institute for Space Research, Cachoeira Paulista, SP, Brazil; [o]European Centre for Medium-range Weather Forecasts, Reading, UK; [+]Global Change Institute University of the Witwatersrand, South Africa

1. Introduction

The role of aerosols due to their interaction with radiation (direct effect) and changes in cloud lifecycle and precipitation (indirect effect) impacts the climate circulation and has been explored in several studies, serving as one of the main uncertainties on Earth's energy budget and radiative forcing for climate change estimation (Boucher et al. 2013). However, despite the importance of aerosols on the climate variability, their impact on Numerical Weather (NWP) and Climate Prediction (CP) have been addressed recently, first with the incorporation of climatologies of aerosols to improve the skill of global models (e.g. Tompkins et al. (2005)) and then with the inclusion of real-time treatment (or interactive aerosols with respect of dynamics, radiation and microphysics) in operational forecasting systems in regional (e.g. Freitas et al. (2005)) and global models (e.g. Reale et al. (2011)), there is still uncertainty regarding the magnitude of the impact as well as the degree of model sophistication that is needed to capture fully the effects of aerosols. It is known that interactive aerosols increase the computational cost of a numerical prediction system the more complex the aerosol scheme. The representation of aerosols and atmospheric feedback on numerical models vary extensively around the world mainly due computational capabilities in meteorological centres, and it is not clear which level of complexity is required to better represent aerosol-cloud-radiation interactions, as well as provide skillful information to early warning from weather to climate timescales as well as air quality forecasts. Benedetti and Vitart (2018) performed sub-seasonal experiments using the European Centre for Medium-Range Weather Forecasts (ECMWF) coupled model including the direct effect of dust and carbnaceous aerosols in an interactive approach and found significant skill in predicting the weekly variability of aerosols and also significant improvements in the tropical and extratropical circulation skill scores. In addition, the authors suggest a modulation of dust aerosols by the Madden Julian Oscillation (MJO) which is an important source of predictability in the Tropics at the subseasonal to seasonal (S2S) timescales.

Weather and climate sciences are advancing for an integrated and "seamless" Earth-System approach to provide numerical forecasts from short to climate timescales for the wellbeing of society. The responses of weather and climate forecasts to the atmospheric composition changes are key factors (Baklanov et al. 2017) that should be addressed by meteorological centres. The adoption of a fully integrated weather/climate/chemistry forecast system is necessary to better represent the atmospheric feedbacks and provide skillful forecasts in a seamless approach, both for weather and climate as well as air quality management. Therefore it is important understand what the current capabilities of meteorological operational centres worldwide in representing aerosols are and their impacts on different timescales. The development of a joint collaboration from weather and climate communities is necessary to understand the impact of aerosols.

The Working Group on Numerical Experimentation (WGNE; http://wgne.meteoinfo.ru/), jointly established by the World Climate Research Programme (WCRP), Joint Scientific Committee (JSC) and the World Meteorological Organization (WMO) Commission for Atmospheric Sciences (CAS) has been promoting numerical experimentation linking international research with the goal to explore atmospheric variability and predictability, as well as ways to refine numerical techniques and physical process formulations. Examples are the Drag (Sandu et al. 2017) and the Grey Zone (Tomassini et al. 2017) Projects. In the same way, WGNE conducted a project to evaluate the impact of aerosols on NWP (Freitas 2015). The main goal of the project was to understand how important aerosols are for atmospheric predictability at short timescales. Three case studies were chosen considering selected strong or persistent events of aerosols and included a dust storm over Egypt on 18 April 2012, urban pollution in China on 12-16 January 2013 and smoke event associated with biomass burning in South America on 5-15 September 2012. To diagnose their impacts on NWP, eight operational meteorological centres worldwide provided their NWP systems and performed a set of experiments considering runs with no aerosols and with prognostic aerosols. Only one centre provided data from a numerical system considering climatological aerosols instead a prognostic configuration. Centres also provided observational data for model evaluation. Four of them provided inputs from their global operational models and four from limited–area models. The global configuration was provided by ECMWF, the Japan Meteorological Agency (JMA), the National Aeronautic and Space Administration (NASA) and the National Centres for Environmental Prediction (NCEP) in the USA, while the limited–area configuration was provided by the Barcelona Supercomputer Center (BSCC) in Spain, the Center for Weather Forecasting and Climate Studies of the Brazilian National Institute for Space Research (CPTEC/INPE), the Earth System Research Laboratory of the National Oceanic and Atmospheric Administration (ESRL/NOAA) in the United States of America (USA) and the Meteorological Service of France/Meteorological Service of Algeria (Météo-France). Different model characteristics (domain, grid-spacing, aerosol species, emissions, aerosol and cloud physics, and assimilation techniques) were considered, taking into account the complexity of the operational systems

* *Corresponding author address:* Ariane Frassoni, Center for Weather Forecasting and Climate Studies, Rodovia Presidente Dutra Km 40, Cachoeira Paulista, SP, Brazil
E-mail: ariane.frassoni@inpe.br

available in the participating centres. The results of the case studies showed strong differences across the forecasts, which was expected due to the range of different model configurations. The impact of aerosols was observed in most meteorological variables analyzed. The main results of including aerosols in the forecast systems were observed in a local scale and impacted the radiative shortwave flux at surface and 2-meter air temperature, in association with the aerosol direct effect. The mean difference between the experiments considering prognostic aerosols and no–aerossols indicated a strong negative decrease in radiative shortwave flux at surface and 2–meter air temperature when considering prognostic aerosols, indicating the cooling effect associated with high concentration of aerosols. Rémy et al. (2015) described the results from the same dust episode of 18 April 2012 considered in the WGNE experiment in addition to another dust storm, which took place on 12 and 13 April 2012 in the central Sahara region and pointed out the impact of dust over the radiative fluxes at the surface as well as the feedback on the dust load though modifications in the planetary boundary layer. Freitas (2015) also pointed out that when climatological aerosol fields are used within the forecast systems instead of interactive aerosols, the transient and strong pollution events are not realistically represented in the forecasts. Despite the important results found with the First Phase of the WGNE Aerosol Project (hearafter WGNE-AerI), a lack on the statistical significance of results was identified due to the nature of the study which was based on case studies.

Considering that the effects of aerosol on NWP should be better understood by a more statistically robust study that considers a larger number of cases or a longer period of model evaluation, and that their effects should be more considerable in extended-range forecasts as shown by Benedetti and Vitart (2018), WGNE jointly with the WWRP/S2S Steering Group and the WMO Global Atmosphere Watch (GAW) Scientific Advisory Group (SAG) on Modelling Applications (SAG–APP) is proposing the extension of the aerosol project, lauching the WGNE-S2S-GAW Aerosol Project (hearafter WGNE-S2S-GAW-Aer) in 2019 to address the role of aerosols on NWP both at the short to medium-range and subseasonal timescales. This article provides information on how the WGNE-S2S-GAW-Aer will be designed and conducted. The Section 2 describes the main details of the WGNE-S2S-GAW-Aer and finally the Section 3 presents the main considerations regarding the WGNE–S2S–SAG–APP initiative.

2. The second phase of the WGNE Aerosol Project

Currently few operational meteorological centres are able to run a fully integrated weather/chemistry NWP system with interactive aerosols and even less are able to run fully coupled modelling systems for longer timescales, like S2S. All the operational S2S models contributing to the S2S WWRP–WCRP joint research project database use climatological aerosols (WWRP/WCRP 2018), which may represent a limitation in S2S forecasts (for more information about S2S project visit `http://s2sprediction.net`). Such models do not represent the direct and indirect effects of aerosols, impacting the skill of the atmospheric circulation and do not represent persistent and intense events specially considering biomass burning and synoptic dust events. The S2S WWRP–WCRP joint research project (WWRP/WCRP 2018) recognizes the importance of aerosols on subseasonal to seasonal timescales that was not explored in WGNE-AerI and understands that the incorporation of interactive aerosols on S2S models can be an opportunity to improve the skill of models as well as contribute strongly to support policy makers and end-users providing skillful air quality forecasts. As the aerosols often have serious impacts on air quality and human health, there may be socioeconomic benefits in the use of S2S air quality forecasts specially for regions highly impacted by forest fires and urban pollution (WWRP/WCRP 2018).

To further explore the importance of interactive aerosols in short to medium-range and subseasonal predictability, it is necessary to coordinate a systematic and statistically robust study and associated database to support the analysis. This project proposes the development of the WGNE-S2S-GAW-Aer that should consider a longer period of evaluation. The project considers two main components: one is built on WGNE-AerI by running higher resolution regional models in order to address the importance of interactive aerosols on weather predictability; the second component considers subseasonal re-forecasts experiments based on ensemble approach in a global scale in order to address the importance of interactive aerosols on subseasonal predictability and will be conducted jointly with the WWRP/S2S Steering Group. Considering the expertise of the Joint Working Group on Forecast Verification Research (JWGFVR), the WGNE-S2S-GAW-Aer will benefit from the expertise of model verification experts regarding the best metrics to be used to assess both NWP and ensemble forecasts, taking advices on what metrics will fit better to evaluate meteorological and air quality variables.

Constraining the investigation to specific (prescribed) model configurations would be expensive in terms of human and computational resources. We thus propose to build WGNE-S2S-GAW-Aer on the experimental design of the WGNE-AerI, by largely relying on the existing configurations of the models used at meteorological centres and research institutes, to set-up a range of experiments that explore the effects of interactive aerosols on predictive skill. The goal of the project is the understanding of the effects of aerosols on NWP and S2S under current model capabilities available in participating institutions. Therefore, in the scope of the WGNE-S2S-GAW-Aer, a systematic study should consider the diversity and complexity of participating modelling groups. We understand the scientific importance of standardised experiments considering the same initial and boundary conditions, physical and dynamical consistencies as much as possible and pre-defined emission database. However, it would be expensive and not feasible specially for operational centres to adopt such practices due to human and computational resources. In the same way, it is not realistic to provide a feedback for such centres based on such kind of experiments and suggest the adoption of practices other than those currently adopted by centres. This is why our proposal is based on the current model, computational and human resources available in each participating institution. The proposed protocol is under definition and counts the collaboration of many expert scientists on modeling, observational and forecast verification research under the WMO WCRP, WWRP and GAW programs.

a. Experiment setup

We propose two different sets of experiments, focusing on the short timescale and the subseasonal timescale. The general model configuration to be adopted by modelling groups (grid-spacing, vertical resolution, data assimilation, cloud and aerosol complexity, spin-up for atmospheric composition, emission sources) should be compatible with the configuration of the operational system currently used for short-range and S2S prediction, if applicable. The list of variables to be used as model output is extense and includes meteorological and air quality variables as well as optical properties of aerosols. The experiments will consist of a set of runs that should include the aerosol direct effect and another with no-aerosol loading or climatological aerosols for regional experiments and climatological loading in addition to direct effect for S2S experiments. The inclusion of indirect effects will be optional for both domains.

1) Limited-area domain (focus on short timescale)

Modelling groups can contribute with limited-area models in one or more experiments for regional domains. Pre-defined domains consider South America and South Africa. A domain over Asia is under definition. The experiments configuration should consider:

- Forecast length: 72h (3-days forecasts) from 00:00 UTC;
- Time resolution: 3 hours;

The domains are chosen considering the impact of different kind of aerosols (biomass burning, desert dust, pollution in megacities). More details will be provided under the protocol to be delivered to the participating modelling groups.

2) Global domain (focus on subseasonal timescale)

The experiments configuration should consider:

- Aerosol events to be analyzed:
  1. Focus on dust over Egypt;
  2. Focus on biomass burning smoke.
- Period of analysis: 2003-2018
  1. Dust: March-April-May;
  2. Biomass burning smoke: August-September-October.
- Forecast length: 768 h (32-days) from 00:00 UTC once a month;
- Time resolution: 6 hours;
- Minimum number of ensemble members: 5.

b. Verification framework

The availability of NWP and subseasonal predictions that will be produced within the WGNE-S2S-GAW-Aer experiments requires investigating the quality of the forecasts produced by the participating modelling groups. As a common practise in NWP forecast verification, the forecast quality assessment of meteorological variables will be provided considering classical deterministic statistical scores like Root Mean Square Error (RMSE), bias [Forecast–Observation (F–O)], Contingency table scores [like Equitable Threat Score (ETS), Probability Of Detection (POD), False Alarm Ratio (FAR)], and the use of scorecards, that provide a quick visual overview over the performance of specific experiment scores compared to other experiment, presented in a simplified summary of verify error plots of domains specified by the user, scores, parameters etc (ECMWF Access: 2019).

The verification strategy proposed for subseasonal predictions includes the assessment of deterministic predictions considering a reduced number of ensemble members as a minimum of 5. Following recent subseasonal prediction quality assessments [e.g. Coelho et al. (2018); Benedetti and Vitart (2018); de Andrade et al. (2019)] the metrics that will be considered include: bias of the ensemble mean; correlation between ensemble mean anomalies and corresponding observations; mean squared error skill score (MSSS); standard deviation ratio (ratio of the predicted ensemble mean anomaly standard deviation and the observed anomaly standard deviation); and the use of the scorecards. However, the verification approach will also consider that it is important to determine the difference of the probabilistic skill between experiments produced by different models, and learn if the difference between them is statistically significant, which is a slightly different issue for verification. Leutbecher (2018), using the fair Continuous Ranked Probability Score (CRPS) proposed by Ferro (2014) pointed out that small ensemble size (for example 5 members) is sufficient to detect differences between experiments for research and development purposes. Therefore, the fair CRPS will also be computed.

3. Concluding remarks

The impact of aerosols on weather and climate is largely heterogeneous and can impact meteorological variables. The lack of understanding on how aerosols can impact significantly the quality of the forecast skill at the regional and global scales will be addressed by the WGNE-S2S-GAW Aerosol Project in a systematic study. Understanding how accurate air quality forecasts provided by modelling groups are and how models differ from one another mainly based in their complexities will provide important information that has the potential to address future investments. The undestanding of how skillful meteorological and air quality forecasts from weather to subseasonal timescales are can contribute to the development of early warning systems with important societal benefits. The joint collaboration between the different WMO programs maximize opportunities to integrate research and development on seamless coupled chemistry-meteorology/climate modelling.

Acknowledgments. The WMO Joint Working Group on Forecast Verification Research (JWGFVR) is acknowledged for providing recommendations on verification metrics for assessing the quality of the predictions that will be produced. We also thank WGNE members for their useful suggestions that improved the quality of the manuscript. We also thank Elena Astakhova for providing recommendations on how to advertise the WGNE-S2S-GAW Aerosol Project in the 2019 WGNE Blue Book.

References

Baklanov, A., and Coauthors, 2017: Key issues for seamless integrated chemistry–meteorology modeling. *Bulletin of the American Meteorological Society*, **98 (11)**, 2285–2292, doi:10.1175/BAMS-D-15-00166.1.

Benedetti, A., and F. Vitart, 2018: Can the direct effect of aerosols improve subseasonal predictability? *Monthly Weather Review*, **146 (10)**, 3481–3498, doi:10.1175/MWR-D-17-0282.1, URL https://doi.org/10.1175/MWR-D-17-0282.1, https://doi.org/10.1175/MWR-D-17-0282.1.

Boucher, O., and Coauthors, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Clouds and Aerosolstomk, 571–657. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Coelho, C. A., M. A. Firpo, and F. M. de Andrade, 2018: A verification framework for south american sub-seasonal precipitation predictions. *Meteorologische Zeitschrift*, **27 (6)**, 503–520, doi:10.1127/metz/2018/0898, URL http://dx.doi.org/10.1127/metz/2018/0898.

de Andrade, F. M., C. A. S. Coelho, and I. F. A. Cavalcanti, 2019: Global precipitation hindcast quality assessment of the subseasonal to seasonal (s2s) prediction project models. *Climate Dynamics*, **52 (9)**, 5451–5475, doi:10.1007/s00382-018-4457-z, URL https://doi.org/10.1007/s00382-018-4457-z.

ECMWF, Access: 2019: Https://www.ecmwf.int/en/forecasts/documentation-and-support/evolution-ifs/scorecards/scorecard-ifs-cycle-40r1, On-line.

Ferro, C. A. T., 2014: Fair scores for ensemble forecasts. *Quarterly Journal of the Royal Meteorological Society*, **140 (683)**, 1917–1923, doi:10.1002/qj.2270, URL https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.2270, https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/qj.2270.

Freitas, S. R., 2015: Evaluating aerosols impacts on numerical weather prediction: A wgne/wmo initiative. URL http://www.researchgate.net/publication/273258328_Evaluating_aerosols_impacts_on_Numerical_Weather_Prediction_A_WGNEWMO_Initiative, last access: Apr 2019.

Freitas, S. R., and Coauthors, 2005: Monitoring the transport of biomass burning emissions in south america. *Environmental Fluid Mechanics*, **5**, 135–167, doi:10.1007/s10652-005-0243-7.

Leutbecher, M., 2018: Ensemble size: How suboptimal is less than infinity? *Quarterly Journal of the Royal Meteorological Society*, **0 (0)**, 1–22, doi:10.1002/qj.3387, URL https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.3387, https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/qj.3387.

Reale, O., K. M. Lau, and A. da Silva, 2011: Impact of interactive aerosol on the african easterly jet in the nasa geos-5 global forecasting system. *Weather and Forecasting*, **26 (4)**, 504–519, doi:10.1175/WAF-D-10-05025.1, URL https://doi.org/10.1175/WAF-D-10-05025.1, https://doi.org/10.1175/WAF-D-10-05025.1.

Rémy, S., and Coauthors, 2015: Feedbacks of dust and boundary layer meteorology during a dust storm in the eastern mediterranean. *Atmospheric Chemistry and Physics*, **15 (22)**, 12 909–12 933, doi:10.5194/acp-15-12909-2015, URL https://www.atmos-chem-phys.net/15/12909/2015/.

Sandu, I., A. Zadra, and N. Wedi, 2017: Impact of orographic drag on forecast skill. *ECMWF newsletter*, 18–24, doi:10.21957/icghjblyn7, URL https://www.ecmwf.int/node/18163.

Tomassini, L., P. R. Field, R. Honnert, S. Malardel, R. McTaggart-Cowan, K. Saitou, A. T. Noda, and A. Seifert, 2017: The "grey zone" cold air outbreak global model intercomparison: A cross evaluation using large-eddy simulations. *Journal of Advances in Modeling Earth Systems*, **9 (1)**, 39–64, doi:10.1002/2016MS000822, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016MS000822, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2016MS000822.

Tompkins, A. M., C. Cardinali, J.-J. Morcrette, and M. Rodwell, 2005: Influence of aerosol climatology on forecasts of the african easterly jet. *Geophysical Research Letters*, **32 (10)**.

WWRP/WCRP, 2018: Wwrp/wcrp sub-seasonal to seasonal prediction project (s2s) phase ii proposal. URL https://www.wcrp-climate.org/images/Newsletter/2018/Cover_Phase_II.png, last access: Apr 2019.