MONARCH Regional Reanalysis of Desert Dust Aerosols: An Initial Assessment

Enza Di Tomaso, Jerónimo Escribano, Sara Basart, Paul Ginoux, Francesca Macchia, Francesca Barnaba, Francesco Benincasa, Pierre-Antoine Bretonnière, Arnau Buñuel, Miguel Castrillo, Emilio Cuevas, Paola Formenti, María Gonçalves-Ageitos, Oriol Jorba, Martina Klose, Lucia Mona, Gilbert Montané, Michail Mytilinaios, Vincenzo Obiso, Miriam Olid, Nick Schutgens, Athanasios Votsis, Ernest Werner, and Carlos Pérez García-Pando

Abstract Aerosol reanalyses are a well-established tool for monitoring aerosol trends, for validation and calibration of weather chemical models, as well as for the enhancement of strategies for environmental monitoring and hazard mitigation. By providing a consistent and complete data set over a sufficiently long period, they address the shortcomings of aerosol observational records in terms of temporal and spatial coverage and aerosol speciation. These shortcomings are particularly severe for dust aerosols. A 10-year dust aerosol regional reanalysis has been recently produced on the Barcelona Supercomputing Center HPC facilities at the high spatial resolution of 0.1°. Here we present a brief description and an initial assessment of this data set. An innovative dust optical depth data set, derived from the MODIS Deep Blue products, has been ingested in the dust module of the MONARCH model by means of a LETKF with a four-dimensional extension. MONARCH ensemble

E. Di Tomaso (✉) · J. Escribano · S. Basart · F. Macchia · F. Benincasa · P.-A. Bretonnière · A. Buñuel · M. Castrillo · M. Gonçalves-Ageitos · O. Jorba · M. Klose · G. Montané · V. Obiso · M. Olid · C. Pérez García-Pando
Barcelona Supercomputing Center (BSC), Barcelona, Spain
e-mail: enza.ditomaso@bsc.es

P. Ginoux
Geophysical Fluid Dynamics Laboratory (GFDL), Princeton, NJ, USA

F. Barnaba
Consiglio Nazionale delle Ricerche-Istituto di Scienze dell'Atmosfera e del Clima (CNR-ISAC), Bologna, Italy

E. Cuevas
Izaña Atmospheric Research Center, AEMET, Santa Cruz de Tenerife, Spain

P. Formenti
LISA, UMR CNRS 7583, Université Paris-Est-Créteil, Université de Paris, Institut Pierre-Simon Laplace (IPSL), Créteil, France

M. Gonçalves-Ageitos
Universitat Politècnica de Catalunya - BarcelonaTech (UPC), Department of Project and Construction Engineering, Terrassa, Spain

C. Mensink and O. Jorba (eds.), *Air Pollution Modeling and its Application XXVIII*, Springer Proceedings in Complexity, https://doi.org/10.1007/978-3-031-12786-1_33

has been generated by applying combined meteorology and emission perturbations. This has been achieved using for each ensemble member different meteorological fields as initial and boundary conditions, and different emission schemes, in addition to stochastic perturbations of emission parameters, which we show is beneficial for dust data assimilation. We prove the consistency of the assimilation procedure by analyzing the departures of the assimilated observations from the model simulations for a two-month period. Furthermore, we show a comparison with AERONET coarse optical depth retrievals during a period of 2012, which indicates that the reanalysis data set is highly accurate. While further analysis and validation of the whole data set are ongoing, here we provide a first evidence for the reanalysis to be a useful record of dust concentration and deposition extending the existing observational-based information intended for mineral dust monitoring.

Keywords Dust · Aerosol regional reanalysis · Aerosol data assimilation · Modis deep blue · Aerosol speciation

1 Introduction

Desert dust plays a key role in the Earth's system: it influences the atmospheric radiation balance by scattering and absorbing solar and terrestrial radiation (Miller et al., 2014), it affects cloud formation and chemistry (Cziczo et al., 2013), it acts as a fertilizer when deposited over the ocean and land (Jickels et al., 2005; Yu et al., 2015). This has implications both in the short-term (in particular upon air quality and visibility, but also upon weather), and in the long-term by producing a radiative

M. Klose
Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research (IMK-TRO), Department Troposphere Research, Karlsruhe, Germany

L. Mona · M. Mytilinaios
Consiglio Nazionale delle Ricerche-Istituto di Metodologie per l'Analisi Ambientale (CNR-IMAA), Rome, Italy

N. Schutgens
Department of Earth Science,Vrije Universiteit Amsterdam, 1081 HVAmsterdam, Netherlands

A. Votsis
Department of Governance and Technology for Sustainability (BMS-CSTM),University of Twente, Enschede, Netherlands

Finnish Meteorological Institute (FMI), Weather and Climate Change Impact Research, Helsinki, Finland

E. Werner
State Meteorological Agency (AEMET), Madrid, Spain

C. Pérez García-Pando
Catalan Institution for Research and Advanced Studies, (ICREA), Barcelona, Spain

forcing on the climate system. Atmospheric dust concentrations vary considerably in space and time. Different types of measurements monitor its cycle and are done either in-situ or remotely by satellite, air-borne and ground-based sensors. Dust observations are best exploited by being combined with model simulations either to provide optimal initial conditions (analyses) to model forecast or to monitor current and past states of the atmosphere through the production of reanalyses.

We present here an initial assessment of a regional reanalysis of desert dust aerosol which has been produced by the Barcelona Supercomputing Center. The reanalysis spans a 10-year period, from 2007 to 2016, has a horizontal resolution of 0.1° latitude $\times$ 0.1° longitude, and a 3-hourly temporal resolution. It provides a regional reconstruction of past dust conditions for Northern Africa, the Middle East and Europe, obtained by combining satellite remote sensing observations of dust with a dynamical model.

2 Methodology

The dust reanalysis is based on three pillars: (i) the Multiscale Online Non-hydrostatic AtmospheRe CHemistry model (MONARCH; Klose et al., 2021; Pérez García-Pando et al., 2011); (ii) the Local Ensemble Transform Kalman Filter (LETKF) data assimilation scheme (Di Tomaso et al., 2017; Hunt et al., 2007; Schutgens et al., 2010); (iii) coarse-mode dust optical depth (DOD) at 550 nm retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue Level 2 products (Collection 6; Ginoux et al., 2012; Pu & Ginoux, 2016). MONARCH ensemble has been generated for data assimilation purposes with the use of different meteorological initial and boundary conditions (MERRA-2 with ERA5 soil and the ECMWF ERA-Interim reanalysis) and emission schemes, additionally to perturbations of model emission parameters. Previous studies showed that combined meteorology and aerosol source ensembles are necessary to produce sufficient spread in outflow regions. Similarly, our test experiments showed the benefit of using different meteorology and emission schemes for dust data assimilation (see Fig. 1).

3 Results

We describe here an initial validation of the reanalysis coarse DOD at 550 nm for a period of 2012 in terms of data assimilation inner diagnostics (statistics of departures from assimilated observations) and in terms of a comparison against independent observations that have not been assimilated. A more detail analysis can be found in (Di Tomaso et al., 2021) and (Mytilinaios et al. 2022, in prep.). Figure 2 shows an example for July 9 2012 of assimilated retrievals of coarse DOD, model ensemble mean first-guess and analysis DOD at 550 nm, while Fig. 3 reports the BIAS, RMSE, CORR, FRGE of the DOD at 550 nm of a free-run experiment (with no data assimilation),

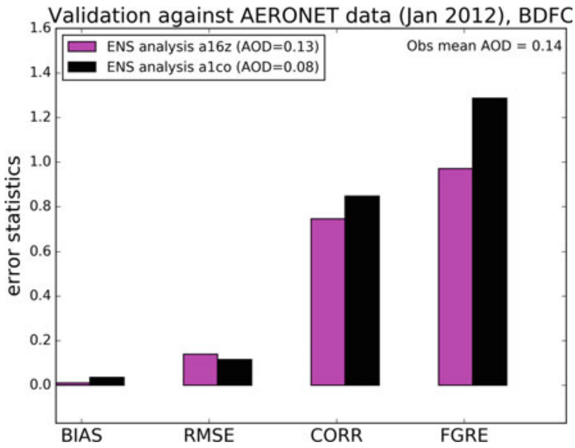

Fig. 1 Mean bias (BIAS), root mean square error (RMSE), Pearson correlation coefficient (CORR), and fractional gross error (FRGE) calculated against AERONET retrievals for the DOD at 550 nm of an assimilation experiment with emission parameter perturbation (magenta) and with the use of different emission schemes and meteorology initial and boundary conditions, additionally to the perturbation of emission parameters (black)

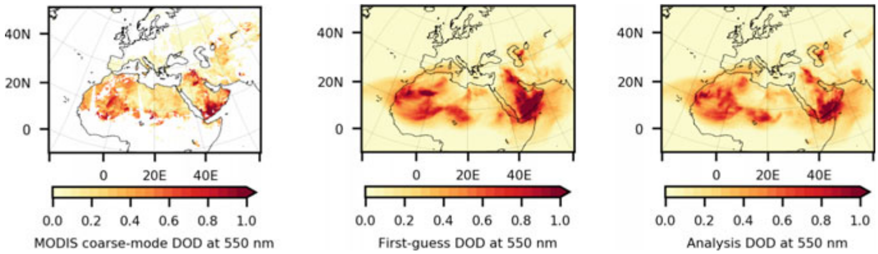

Fig. 2 Assimilated retrievals of coarse DOD at 550 nm from the Aqua MODIS Deep Blue Collection 6 Level 2 product (left), DOD at 550 for the ensemble mean first-guess (centre) and ensemble mean analysis (right) for July 9 2012

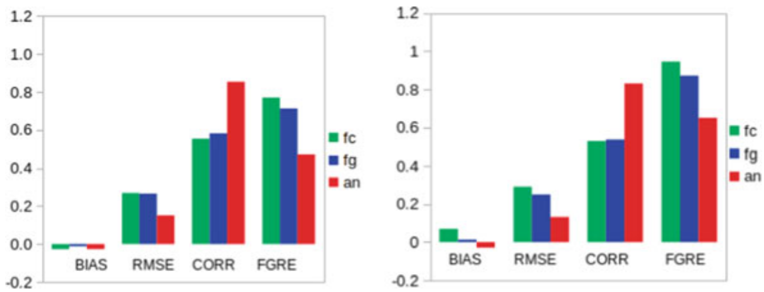

Fig. 3 Bias, RMSE, CORR, FRGE calculated against MODIS assimilated retrievals for the coarse DOD at 550 nm of a free-run experiment (fc; green), the first-guess (fg; blue) and the analysis (an; red) for a summer month (August; left) and a winter month (February; right) of 2012. Model fields are ensemble mean

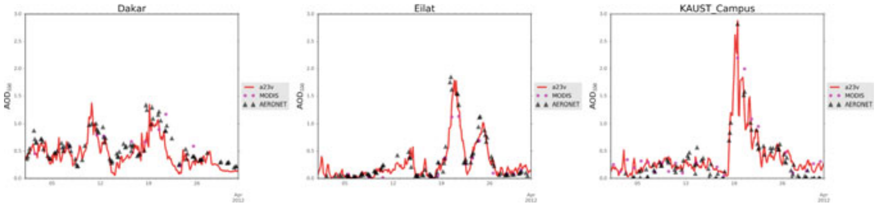

Fig. 4 Time series of coarse DOD values for a period of 2012 at three AERONET stations for the mean analysis (red), for AERONET SDA AOD (black triangles) and for MODIS coarse DOD retrievals

of the first-guess and of the analysis versus MODIS coarse DOD at 550 nm for a summer month and a winter month of 2012. As expected, the analysis is closer to the assimilated observations than the first-guess and outperforms a simulation without data assimilation. Timeseries of model coarse DOD at 550 nm for the mean analysis at three AERONET stations are in Fig. 4 together with coarse AOD retrievals at 550 nm (level 2.0, version 2.0) from the spectral de-convolution algorithm (SDA; O'Neill et al., 2003), and assimilated MODIS data, when available. We use the AERONET value closest to the model time step and within a ±30 min interval. These timeseries show that the analysis characterizes well most dust events at sites close and far from emission areas.

Acknowledgements We acknowledge the DustClim project which is part of ERA4CS, an ERA-NET initiated by JPI Climate, and funded by FORMAS (SE), DLR (DE), BMWFW (AT), IFD (DK), MINECO (ES), ANR (FR) with co-funding by the European Union's Horizon 2020 research and innovation programme (Grant n. 690462). BSC co-authors also acknowledge support from the European Research Council under the European Union's Horizon 2020 research and innovation programme (grant n. 773051; FRAGMENT), the AXA Research Fund, the Spanish Ministry of Science, Innovation and Universities (grant n. RYC-2015-18690 and CGL2017-88911-R), the European Union's Horizon 2020 research and innovation programme (grant n. 792103; SOLWARIS). This work has been partially funded by the contribution agreement between AEMET and BSC to carry out development and improvement activities of the products and services supplied by the WMO Sand and Dust Storm Regional Centres. Jerónimo Escribano and Martina Klose have received funding from the European Union's Horizon 2020 research and innovation programme, respectively, under the Marie Skłodowska-Curie grant agreements H2020-MSCA-COFUND-2016-754433 and H2020-MSCA-IF-2017-789630. Martina Klose further acknowledges support through the Helmholtz Association's Initiative and Networking Fund (grant agreement n. VH-NG-1533). We acknowledge PRACE (eDUST, eFRAGMENT1, and eFRAGMENT2) and RES (AECT-2019-3-0001, AECT-2020-1-0007, AECT-2020-3-0013) for awarding access to MareNostrum at the BSC and for providing technical support. The authors thank all the Principal Investigators and their staff for establishing and maintaining the NASA and PHOTONS AERONET sites, and the MODIS mission scientists and associated NASA personnel for the production of the data used in this study.

Questions and Answers

Questioner: Andy Delcloo.
Question: ERA-Interim is still used, can you please elaborate why and when will you switch to ERA-5?
Answer: Indeed we have used in this work the ERA-Interim reanalysis as meteorological initial and boundary conditions of our simulations. We have not used ERA5 (with the exception of ERA5 soil) since, when testing its use, we faced technical issues to simulate some specific dates. Extending the current reanalysis with ERA5 (in particular from the end day of production of ERA-Interim on 31 August 2019) would not be correct for the production of a consistent data set and could introduce spurious trends associated to the change of meteorological initial and boundary conditions. However, we can switch to the use of ERA5 in a new version of our reanalysis. This will allow us to extend our data set to present dates.
Questioner: Andy Delcloo.
Question: Ensemble approach, can you please explain about the introduction of spread in the ensemble, using Kalman filtering.
Answer: We adopted the LETKF scheme for the estimation of our dust reanalysis. Therefore, model uncertainty is estimated from the realizations of the dust fields in MONARCH ensemble simulations. The use of ensemble simulations allows for the estimation of a flow-dependent background uncertainty which would be otherwise difficult to estimate for a dust model due to the highly varying nature of dust concentrations. More specifically, MONARCH ensemble has been generated with the use of different meteorological initial and boundary conditions (MERRA-2 with ERA5 soil and ERA-Interim reanalysis) and different emission schemes, additionally to perturbations of model emission parameters. The latter choice was made on the basis that uncertainties in dust emission is one of the major contributor to model error. Previous studies showed that combined meteorology and aerosol source ensembles are necessary to produce sufficient spread in outflow regions. Similarly, the test experiments presented in this work showed the benefit of using different meteorology and emission schemes for dust data assimilation.

References

Cziczo, D. J., Froyd K. D., Hoose C., Jensen, E. J., Diao, M., Zondlo, M. A., Smith, J. B., Twohy, C. H., & Murphy D. M. (2013). Clarifying the dominant sources and mechanisms of cirrus cloud formation. *Science, 340*(6138). https://doi.org/10.1126/science.1234145

Di Tomaso, E., Escribano, J., Basart, S., Ginoux, P., Macchia, F., Barnaba, F., Benincasa, F., Bretonnière, P.-A., Buñuel, A., Castrillo, M., Cuevas, E., Formenti, P., Gonçalves, M., Jorba, O., Klose, M., Mona, L., Montané, G., Mytilinaios, M., Obiso, V., Olid, M., Schutgens, N., Votsis, A., Werner, E., & Pérez García-Pando, C. (2021). The MONARCH high-resolution reanalysis of desert dust aerosol over Northern Africa, the Middle East and Europe (2007–2016). *Earth System Science Data*. [preprint]. https://doi.org/10.5194/essd-2021-358

Di Tomaso, E., Schutgens, N. A. J., Jorba, O., & Pérez García-Pando, C. (2017). Assimilation of MODIS dark target and deep blue observations in the dust aerosol component of NMMB-MONARCH version 1.0. *Geoscience Model Development, 10*, 1107–1129. https://doi.org/10.5194/gmd-10-1107-2017

Ginoux, P., Prospero, J. M., Gill, T. E., Hsu, N. C., & Zhao, M. (2012). Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on Modis Deep Blue aerosol products. *Reviews of Geophysics, 50*. https://doi.org/10.1029/2012rg000388

Hunt, B. R., Kostelich, E. J., & Szunyogh, I. (2007). Efficient data assimilation for spatiotemporal chaos: A local ensemble transform Kalman filter. *Physica D, 230*.

Jickels, T. D., An, Z. S., Andersen, K. K., Baker, A. R., Bergametti, G., Brooks, N., Cao, J. J., Boyd, P. W., Duce, R. A., Hunter, K. A., Kawahata, H., Kubilay, N., LaRoche, J., Liss, P. S., Mahowald, N., Prospero, J. M., Ridgwell, A. J., Tegen, I., & Torres, R. (2005). Global iron connections between desert dust. *Ocean Biogeochemistry, and Climate, Science, 308*, 67–71. https://doi.org/10.1126/science.1105959

Klose, M., Jorba O., Gonçalves Ageitos, M., Escribano, J., Dawson, M. L., Obiso, V., Di Tomaso, E., Basart, S., Montané Pinto, G., Macchia, F., Ginoux, P., Guerschman, J., Prigent, C., Huang, Y., Kok, J., Miller, R. L., & Pérez García-Pando, C. (2021). Mineral dust cycle in the Multiscale Online NonhydrostaticAtmospheRe CHemistry model (MONARCH) version 2.0. Geoscientific Model Development [preprint].

Miller, R. L., Knippertz, P., García-Pando, C. P., Perlwitz, J. P., & Tegen, I. (2014). Impact of dust radiative forcing upon climate. In *Mineral dust* (pp. 327–357). Springer.

Mytilinaios, M., Ciamprone, S., Trippetta, S., Basart, S., Di Tomaso, E., Jorba, O., Pérez García-Pando, C., Formenti, P., Cuesta, J., Gkikas, A., Kahn, R., & Mona, L. (2022). *Evaluation of the MONARCH reanalysis dust and coarse dust optical depth over Northern Africa, Middle East and Europe, using MODIS*. MISR: IASI and AERONET observations, in preparation.

O'Neill, N. T., Eck, T. F., Smirnov, A., Holben, B. N., & Thulasiraman, S. (2003). Spectral discrimination of coarse and fine model optical depth. *Journal of Geophysical Research: Atmospheres, 108*. https://doi.org/10.1029/2002JD002975

Pérez, C., Haustein, K., Janjic, Z., Jorba, O., Huneeus, N., Baldasano, J. M.,T. Black, T., Basart, S., Nickovic, S., Miller, R. L., Perlwitz, J. P., Schulz, M., & Thomsonet, M. (2011). Atmospheric dust modeling from meso to global scales with the online NMMB/BSC-Dust model - Part 1. *Atmospheric Chemistry and Physics, 11*.

Pu, B., & Ginoux, P. (2016). The impact of the Pacific Decadal Oscillation on springtime dust activity in Syria. *Atmospheric Chemistry and Physics, 16*(21), 13431–13448.

Schutgens N. A. J., Miyoshi, T., Takemura, T., & Nakajima T. (2010) Applying an ensemble Kalman filter to the assimilation of AERONET observations in a global aerosol transport model. *Atmospheric Chemistry and Physics, 10*.

Yu, H., Chin, M., Yuan, T., Bian, H., Remer, L. A., Prospero, J. M., Omar, A., Winker, D., Yang, Y., Zhang, Y., Zhang, Z., & Zhao, C. (2015). The fertilizing role of African dust in the Amazon rainforest: A first multiyear assessment based on data from Cloud-Aerosol Lidar and Infrared Path finder Satellite Observations. *Geophysical Research Letters, 42*.