UPGRADES IN THE MONARCH OPERATIONAL FORECAST

BDRC-2024-001

Eleni Karnezi, Emanuele Emili, Oriol Jorba, Francesco Benincasa, Miriam Olid, Francesca Macchia, Gilbert Montané, Alejandro García López, Carlos Pérez García-Pando*

Barcelona Supercomputing Center, BSC

(*) Catalan Institution for Research and Advanced Studies, ICREA

Ernest Werner, Gerardo García-Castrillo

Spanish State Meteorological Agency, AEMET

19 August 2024

TECHNICAL REPORT

Series: Barcelona Dust Regional Center (BDRC) Technical Report

A full list of BDRC Publications can be found on our website under:

http://dust.aemet.es/about-us/technical-reports

Barcelona Dust Forecasting Center (BDRC)

Plaça d'Eusebi Güell, 1-3 | 08034 Barcelona (Spain)

Summary

This document summarizes the updates that have been introduced during 2024 in the MONARCH model used for the Barcelona Dust Regional Center (BDRC) operational forecasts. These include the output of dust concentration on selected vertical layers, a bug-fix in the mechanism of dry deposition and a correction in the wet scavenging. For assessing the skills of the updated model (v2.7.2) in comparison with the previous operational version (v2.1.0), model results for 2021 are evaluated in terms of dust optical depth against AERONET Sun photometers over North Africa, Mediterranean and Middle East (NAMEE) and particulate matter (PM) concentrations over the Iberian Peninsula. The upgraded model version provides in general slightly better forecasts than the former version. The upgraded MONARCH v2.7.2 is used as the new operational version, since July 2024, in the WMO Barcelona Dust Regional Center.

Contents

1. MONARCH model

1.1 Model overview

The Multiscale Online Nonhydrostatic AtmospheRe CHemistry model (MONARCH), developed at the Barcelona Supercomputing Center (BSC), is an online meteorology-chemistry model that provides short- and mid-term chemical weather forecasts on both regional and global scales (Pérez et al., 2011; Haustein et al. 2012; Jorba et al. 2012; Spada et al. 2013; Spada et al. 2015; Badia and Jorba 2015; Badia et al. 2017; Di Tomaso et al. 2017; Xian et al., 2019; Klose et al., 2021). MONARCH is based on the online coupling of the meteorological Nonhydrostatic Multiscale Model on the B-grid (NMMB; Janjic and Gall, 2012) developed at the National Centers for Environmental Prediction (NCEP), with a full chemistry module, including gas phase and all aerosol species, developed at the BSC. Therefore, the model is designed to account for the feedback among gases, aerosol particles and meteorology. The aerosol module is enhanced with a data assimilation (DA) system to optimally combine forecasts with observations and improve predictions (Di Tomaso et al. 2017; Di Tomaso et al. 2022; Escribano et al., 2022).

The desert dust module, previously known as NMMB/BSC-Dust (Pérez et al., 2011) that is embedded into the NMMB meteorological core, solves the mass balance equation for dust taking into account the following processes: i) dust generation and uplift by the wind, ii) horizontal and vertical advection, iii) horizontal diffusion and vertical transport by turbulence and convection, iv) dry deposition and gravitational settling, v) wet removal, including in-cloud and below-cloud scavenging. The MONARCH model is the reference model of the WMO Barcelona Dust Regional Center, while the model also contributes to the WMO SDS-WAS regional dust multi-model ensemble, the Copernicus Regional air quality multi-model ensemble, and the ICAP global operational aerosol multi-model ensemble.

The resolution of the model is set to 0.10º x 0.10º covering North Africa, Middle East and Europe (NAMEE, domain) and 40 layers vertically (top of the domain at 50hPa). The Global Forecast System (GFS) at 0.5° x 0.5° and produced at 12UTC by the National Centers for Environmental Prediction (NCEP), is used as initial meteorological conditions and boundary conditions at intervals of 6 h. The simulated dust distributions consist of daily runs of 84-hour forecast length, and the initial state of the dust concentration is defined by the 24-h forecast of the previous-day model run. Only in a 'cold start' of the model, concentration is set to zero.

In the previous upgrade (v2.1.0, June 2023) we included a dynamic coupling of dust with radiation, and improvements in the shortwave optical properties of dust by considering size-resolved mineralogical composition and asphericity. (https://dust.aemet.es/resources/upgrading-the-monarch-operational-forecast-v2-1-0).

1.2 Model upgrades (MONARCH v2.7.2)

The v2.7.2 version does not introduce significant changes in the model or in the model configuration with respect to the previous version (v2.1.0), but mostly contains bug-fixes. The main novelty of this version is the output of vertical layers of dust concentration that are now displayed on daily basis in the BDRC website. The version numbering of MONARCH has been also revised since last year, this being the reason for the significantly different subversion number.

The impaction collection efficiency factor within the aerosols dry deposition was corrected by factor of 1/G, where G is the gravitational constant, which was missing in the original parametrization described by Zhang et al. (2001). This leads to lower impaction collection efficiency and higher dust concentrations, all other aspects being unchanged. Dust wet scavenging, specifically below stratiform clouds, was strongly suppressing dust concentrations over sea surfaces and in the lowermost layers. The addition of a threshold controlling the amount of wet scavenging in presence of very light precipitations was added to mitigate this effect.

A summary of the main changes in the MONARCH model since the beginning of operational production are summarized in Table 1.1.

Table 1.1 The changes introduced in the operational version of the MONARCH model of the BDRC.

MONARCH Version	Date of deployment	Description of changes
v0.0.0	14th February 2012	• Pérez et al. (2011) version
v1.0.0	16th December 2020	• Introduction of different dust source functions • Introduction of different dust emission sources and emission schemes • Introduction of developments described in Perez et al. (2011), Spada (2015), Badia et al. (2017) and Di Tomaso (2017).
v2.1.0	15th June 2023	• Aerosol-radiation interaction allowed with dynamic coupling of dust-radiation • Introduction of spheroid particles • SNES postprocessor in the workflow
v2.7.2	25th July 2024	• Output of vertical layers of dust concentration • Correction in dry deposition • Change in threshold affecting wet scavenging below stratiform clouds

2. Evaluation strategy

The assessment of the model results for the different experiments considered in this sensitivity analysis are done comparing the model results against dust optical depth (DOD) observations and particulate matter (PM) concentrations. All model simulations are conducted for the reference year 2021. Within this framework, the comparison between model versions is limited to the first 24 hours of the forecasts. Standard statistics such as correlation coefficient (r), mean bias error (MB), mean fractional bias in % (MFB), mean fractional error in % (MFE) and root mean square error (RMSE) are used to measure the skill of the model at specific locations or for groups of sites. The definition of these statistics is reported in the next Table (Table 2.1).

Table 2.1 Validation metrics used in this study and their definition.

Metric	Definition
Mean bias (MB)	$\mathrm{MB} = \frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)$
Root mean square error (RMSE)	$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)^2}$
Pearson correlation coefficient (r)	$r = \frac{\sum_{i=1}^{N}(M_i-\overline{M})\cdot(O_i-\overline{O})}{\sqrt{\sum_{i=1}^{N}(M_i-\overline{M})^2}\cdot\sqrt{\sum_{i=1}^{N}(O_i-\overline{O})^2}}$
Mean fractional bias (MFB)	$\mathrm{MFB} = \frac{1}{N}\sum_{i=1}^{N}\frac{2\cdot(M_i-O_i)}{M_i+O_i}$
Mean fractional error (MFE)	$\mathrm{MFE} = \frac{1}{N}\sum_{i=1}^{N}\frac{2\cdot\lvert M_i-O_i\rvert}{M_i+O_i}$

2.1.1 Dust optical depth (DOD) observations: the global AERONET network

Dust-filtered AOD observations from AERONET (Aerosol, Robotic NETwork; Holben, 2001: http://aeronet.gsfc.nasa.gov/) are used for the assessment of the model results. The dust-filtering considered here is based on the Spectral Deconvolution Algorithm (SDA, also known as O'Neill; O'Neill et al., 2003) AERONET products that provide AODcoarse and AODfine fractions.

AODcoarse observations are fundamentally associated with maritime/oceanic aerosols and desert dust. Since sea-salt is related to low AOD (< 0.03; Dubovik et al., 2002) and mainly affects coastal stations, high AODcoarse values are mostly related to mineral dust (i.e. DODcoarse). For the present evaluation exercise, we use the SDA Version 3 cloud-screened (Level 1.5) observations. These observations are used for operational evaluation purposes in the WMO Barcelona Dust Regional Center.

For the comparison, modeled DODcoarse fields are bilinearly interpolated over the AERONET stations. Because AERONET data are acquired at 15-min intervals, all AERONET measurements within ±90 min of the 3-hourly instantaneous model outputs have been extracted and averaged to perform a model comparison. All AERONET stations that are available for the year 2021 and are included in the North Africa, Mediterranean and Middle East (NAMEE) domain are used in the evaluation. In Figure 2.1, we show the AERONET stations used as well as the correspondent subregions. For the statistical computations sub-regions will be treated both separately and all together.

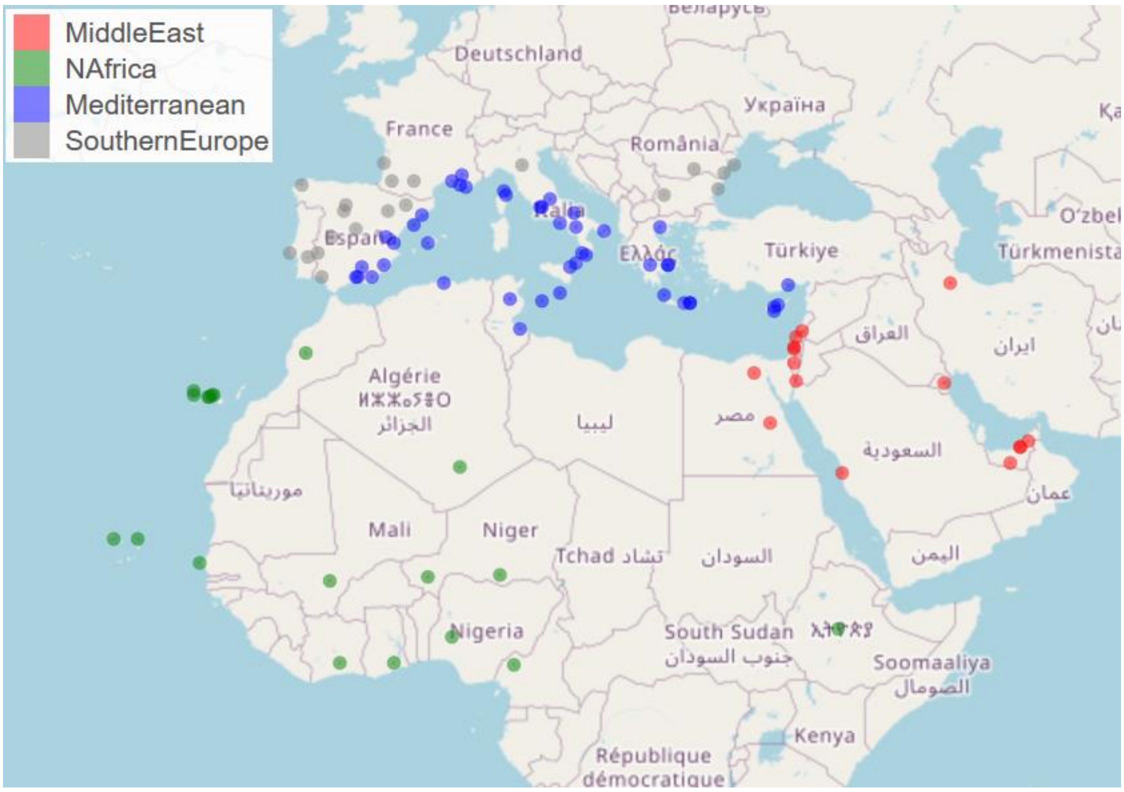

Figure 2.1 The AERONET stations used in this study per region they cover. With blue are represented the Mediterranean station, with green the North African stations, with red the Middle East stations and with grey the remaining Southern Europe stations.

2.1.2 Providentia tool

An important new feature of this report compared to previous one (https://dust.aemet.es/resources/upgrading-the-monarch-operational-forecast-v2-1-0) is that a new model evaluation tool developed at the Barcelona Supercomputing Center has been employed: Providentia. Providentia is designed to allow on-the-fly and offline analysis of numerical simulations, with respect to processed observational data. The Providentia workflow consists of i) interpolation of model fields at the location and time of observations ii) computation of statistics and plots. Once step i) is performed, Providentia allows multiple types of filters to be applied to the collocated observational and modeled time series. Then, temporal and spatial averaging can be applied to the filtered time series. Standard evaluation metrics (like those in Table 2.1) can be further computed using different aggregation strategies. For this study we used the so-called *flattened* computations, which consist in using all data points over the time record, across all selected stations. Hence, the reported statistics represent the skills of the reanalysis in predicting local and 3-hourly measurements for the ensemble of selected sites. This evaluation method was also introduced as a new protocol for validation purposes in the latest reanalysis report (https://dust.aemet.es/resources/dust-regional-reanalysis-update-extension-to-2017).

2.2 PM10 and PM2.5 comparison in Spain

For Spain, we include the comparison of MONARCH with the PM_{10} and $PM_{2.5}$ dust-filtered observations provided by the CSIC-IDAEA and available through the Spanish government website: (https://www.miteco.es/es/calidad-y-evaluacion-ambiental/temas/atmosfera-y-calidad-del-aire/calidad-del-aire/evaluacion-datos/fuentes-naturales/default.aspx). In this case 3-hourly outputs of our model are averaged on daily basis for the comparisons with the CSIC-IDAEA dataset. The validation metrics as in Table 2.1 are used in these comparisons as well as a contingency table to evaluate percentages of hit rates or of false alarms.

3. Results

3.1 Annual comparison

The annual comparison for the derived DOD and DODcoarse from the previous operational model (v2.1.0) and the model upgrade (v2.7.2) are shown in Fig. 3.1, as well as for the dust PM_{10} and $PM_{2.5}$ concentrations for the full NAMEE domain. The main dust sources in Africa are emphasized in both simulations (El Djouf desert and Bodélé Depression). The correction of the dry deposition systematically enhances dust optical depth and surface concentration in the vicinity of source regions. The increased concentrations within the main dust outflow regions are instead a result of the combination of the dry deposition and wet scavenging corrections (separate contributions not shown).

3.2 Coarse DOD comparison over NAMEE and subregions

The old operational (v.2.1.0) and upgraded (v.2.1.7) MONARCH setups have been compared using AODcoarse O'Neill (Version 3 Level 1.5) for the year 2021 (see Figure 3.2). For the evaluation we used the Providentia tool. The validation statistics were evaluated for all 94 AERONET stations for the two setups (Table 3.1), similarly as in the previous report. We added here also the statistics for the four subregions of North Africa, Mediterranean, Middle East and Southern Europe stations separately (Fig. 2.1). In Figure 3.2 we see the timeseries of the DODcoarse for the whole NAMEE region and for the four subregions, averaged over all stations of each region. For the statistics of the NAMEE region the correlation is the same (0.74) for both models' setups but we observe a decrease in the mean bias from -0.02 to 0.01 with the model upgrade, an increase in RMSE from 0.11 to 0.13 but a decrease in both MFE and MFB. In each subregion the MFE and MFB are always reduced, and the correlations increase slightly. In North Africa the MB increases to 0.05 but the correlation increases and the MFB decreases. Lower fractional errors indicate a better capability of the model to predict both low and high values of DODcoarse. From the timeseries we see in all subregions a slight increase of the DODcoarse compared to the previous operational setup, in agreement with the annual maps described earlier.

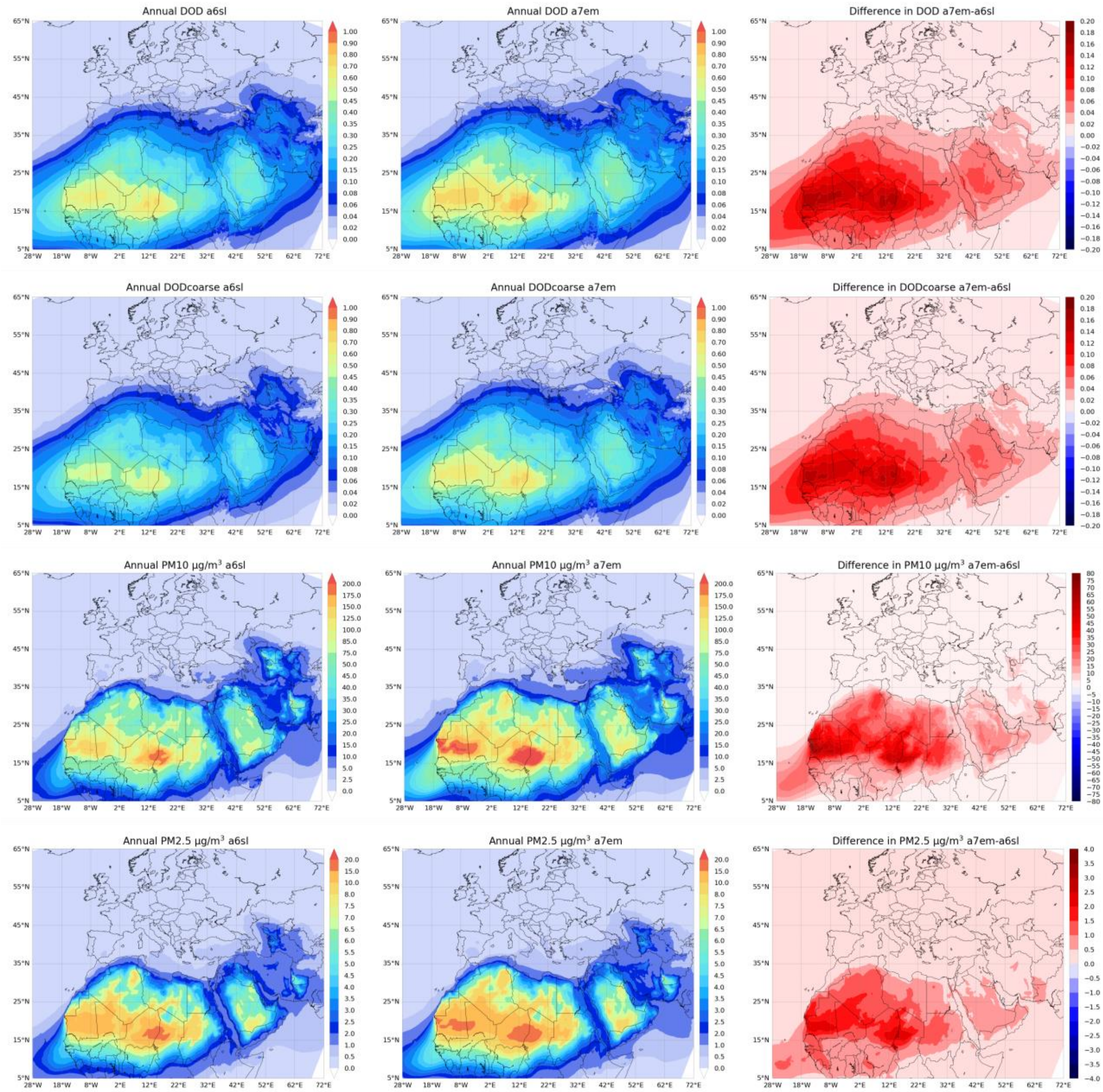

Figure 3.1 Annual DOD, DODcoarse, PM_{10} and $PM_{2.5}$ for the NAMEE domain for 2021. First is shown the MONARCH v2.1.0 (left columns), the MONARCH v2.7.2 (central column) and last the difference (MONARCH v2.7.2 - MONARCH v2.1.0, right column). The annual calculation is based on the averaging of 3-hourly inputs of the simulations.

Table 3.1. Evaluation statistics computed for the study period for AODcoarse measurements of all AERONET stations in the NAMEE region and for the Mediterranean, North Africa, Middle East, and Southern Europe subregions. We report the Mean Bias (Mean), the Root Mean Square Error (RMSE), the Correlation coefficient (r), the Mean Fractional Bias (MFB) and the Mean Fractional Error (MFE).

		Mean	RMSE	r	MFB	MFE
Selected_BDRC_2021	Operational	-0.02	0.11	0.74	-89.37	112.67
	Upgrade	0.01	0.13	0.74	-70.66	106.95
Mediterranean	Operational	-0.03	0.08	0.80	-110.14	122.28
	Upgrade	-0.01	0.09	0.81	-91.84	114.13
NorthAfrica	Operational	-0.00	0.20	0.61	-26.62	89.60
	Upgrade	0.05	0.22	0.63	-5.47	91.06
MiddleEast	Operational	-0.02	0.11	0.70	-36.67	62.79
	Upgrade	0.01	0.12	0.71	-13.29	58.66
SouthernEurope	Operational	-0.02	0.05	0.81	-142.71	149.53
	Upgrade	-0.02	0.06	0.82	-128.65	140.89

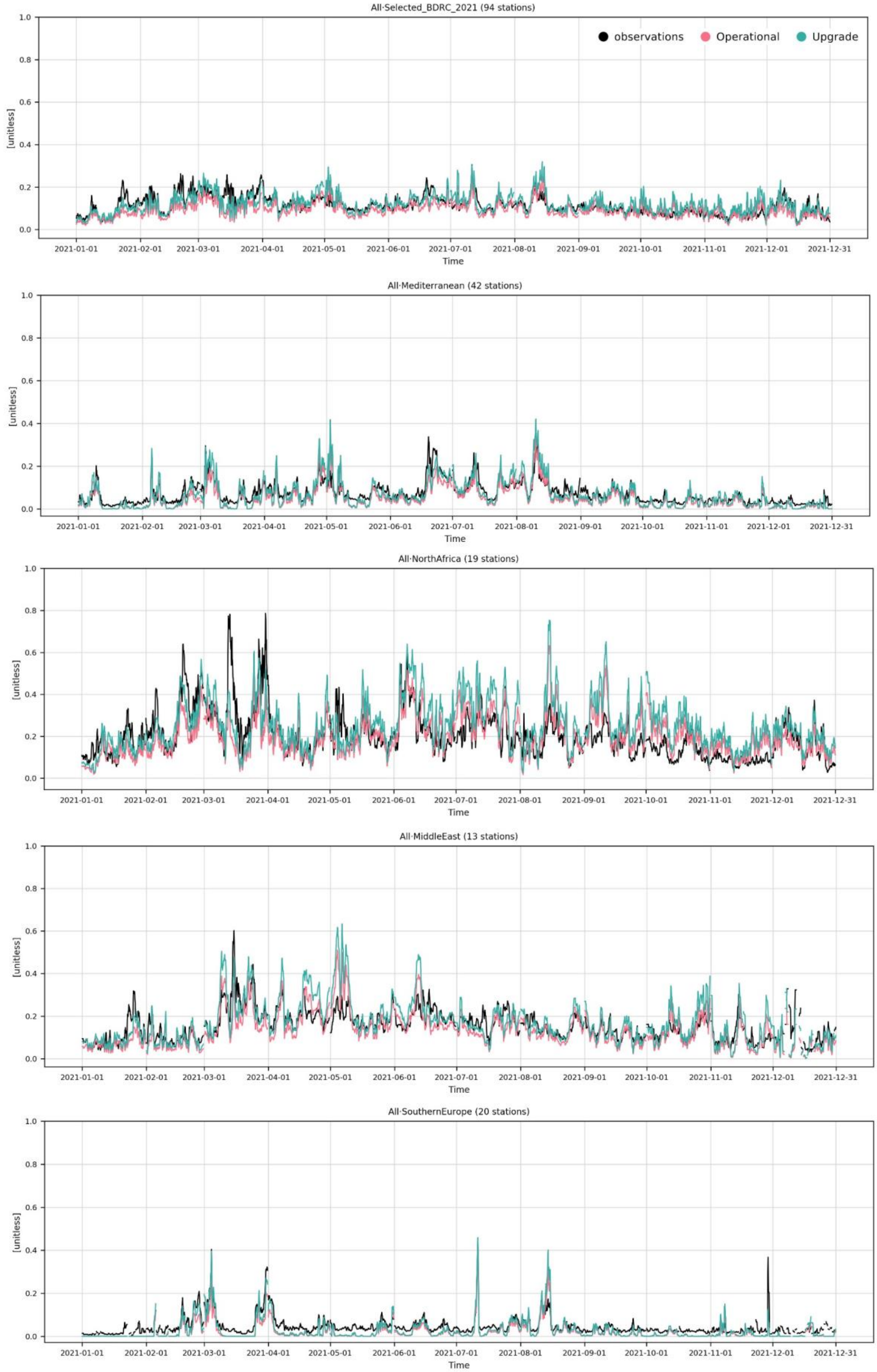

Figure 3.2 Timeseries of 3hourly values for 2021 of O'Neill AODcoarse AERONET measurements (black line), the old operational MONARCH v2.1.0 (pink line), and the upgraded MONARCH v2.7.2 (green line). The first row is for the whole NAMEE stations, the second for the Mediterranean stations, the third for North Africa stations, the fourth for Middle East stations and the fifth for the Southern Europe stations.

3.3 PM_{10} and $PM_{2.5}$ comparison in Spain

The old operational and upgraded MONARCH setups have been compared with PM_{10} and $PM_{2.5}$ dust-filtered observations in Spain provided by the CSIC-IDAEA. Both MONARCH runs can reproduce the observed daily PM_{10} dust variability, as in the three stations (see Figure 3.3) for 2021. In the new upgrade some peaks are increased and the statistics improve for PM_{10} concentrations. The correlations for PM_{10} increase and the mean biases decrease. There is only some slight increase in the RMSE in the station of Viznar, Granada for the PM_{10} concentrations but in general the statistics with the upgrade are improved.

The same conclusions appear in terms of annual statistics (Table 3.2) considering all 22 stations. The correlations increase for both PM_{10} and $PM_{2.5}$ concentrations from 0.51 to 0.53 and from 0.18 to 0.19 respectively. The mean and fractional biases, RMSE and fractional errors are also all decreased with the new upgrade since the underpredictions we had noticed in the previous operational setup are now slightly reduced.

Table 3.2. Statistics computed for the old operational and new upgrade of MONARCH for the for PM_{10} and $PM_{2.5}$ measurements of all CSIC stations in Spain. We report the Mean Bias (Mean), the Root Mean Square Error (RMSE), the Correlation coefficient (r), the Mean Fractional Bias (MFB) and the Mean Fractional Error (MFE).

MONARCH version	PM10du					PM2.5du				
	MB (µg/m³)	RMSE (µg/m³)	r	MFB	MFE	MB (µg/m³)	RMSE (µg/m³)	r	MFB	MFE
Old operational (v2.1.0)	-10.38	23.38	0.51	-85.15	132.45	-5.06	7.99	0.18	-103.63	152.28
New upgrade (v2.7.2)	-7.29	22.15	0.53	-58.3	116.68	-4.8	7.82	0.19	-93	143.87

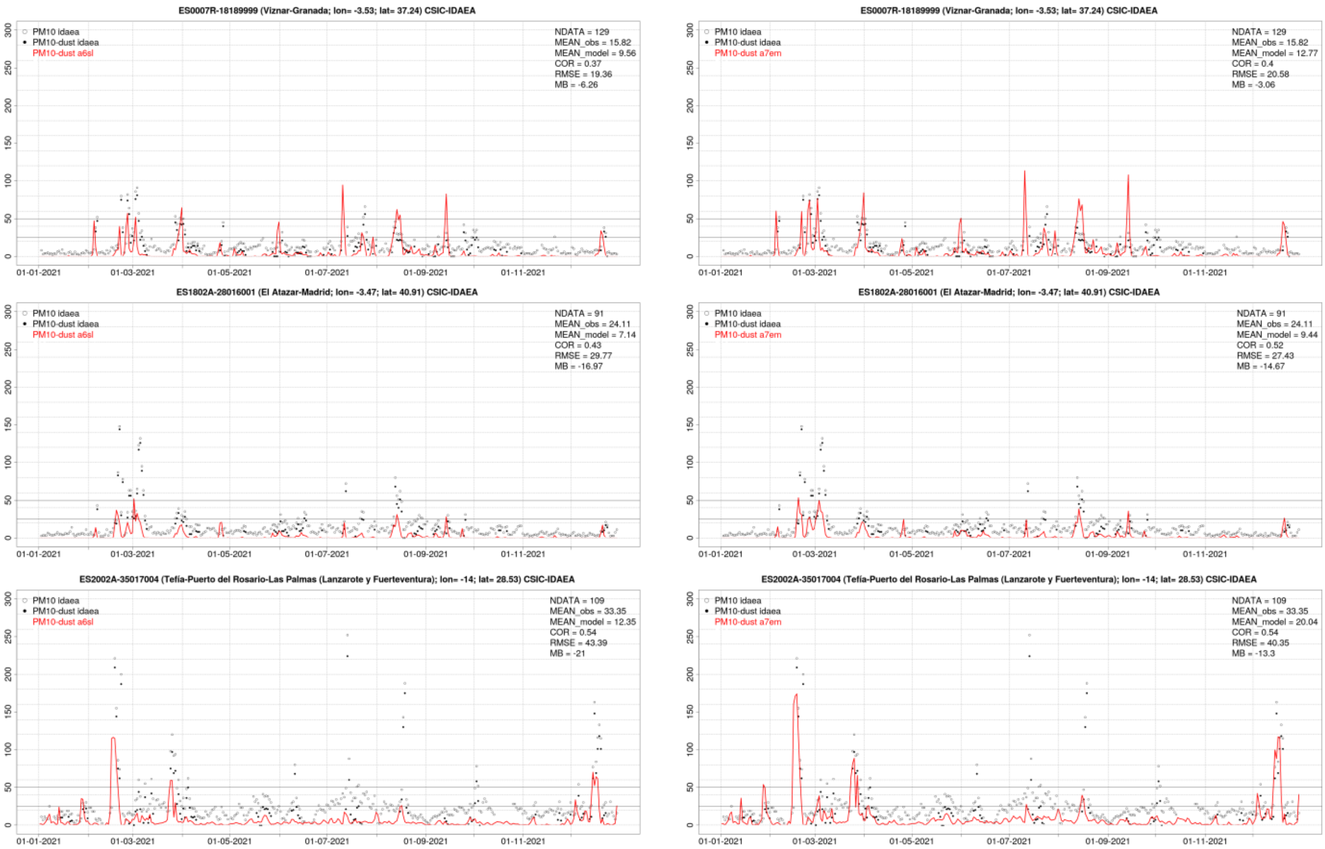

Figure 3.3 Daily PM_{10} time series. PM_{10} from CSIC-IDAEA (white circles, all aerosols), PM_{10}-dust from CSIC-IDAEA (black dots), PM_{10}-dust MONARCH (red line for 2021 over Viznar, Granada (first row), El Atazar, Madrid (second row) and Tefía of Puerto del Rosario, Las Palmas (third row). Left column: MONARCH v2.1.0. Right column: MONARCH v2.7.2. Skill scores per site and model are shown in the upper right corner (NDATA: available days, MEAN observations, MEAN model, correlation COR, RMSE, mean bias MB). Daily averages from the model are calculated using the 3-hourly dataset.

Finally, we constructed a contingency table to evaluate the two forecasts based on the percentages of times they exceed or not the daily threshold of PM_{10} equal to 50 μgm^{-3} (Table 3.2). As suggested also from Figure 3.3, for the station of Viznar, Granada the new upgrade shows an average increase of hit rates (from 13.4% to 19.6%). On the other hand, the new upgrade has a slight increase of false alarm rate from about 0.6% to 1.4%.

Overall, the comparison with CSIC-IDAEA observations shows that the upgraded version of the model presents improved skills scores in all the validation metrics and an increase for the hit rate, which remains, however, relatively low (less than 50%). The difficulties to match the absolute values of dust PMs concentration during the peaks suggests that some further scientific investigation is needed before considering such product for public dissemination.

Table 3.3. Hit rate and false alarm rate for dust PM_{10} measurements of all CSIC stations in Spain, based on a threshold daily dust PM_{10} exceedance of 50 $\mu g m^{-3}$.

	Hit rate	False alarm rate
MONARCH v2.1.0	13.4%	0.6%
MONARCH v2.7.2	19.6%	1.4%

4. Conclusions

MONARCH latest upgrade **(MONARCH v2.7.2)** included corrections in the mechanisms of dry deposition and wet scavenging. This upgrade predicts slightly higher dust concentrations with respect to the operational version, especially in the lowermost model layers and in the dust outflow regions over sea surfaces. The simulations showed improvement in most of the validation statistics. Thus, MONARCH **was upgraded on 25th of July** with the new changes discussed in this report.

5. References

Badia, A., & Jorba, O.: Gas-phase evaluation of the online NMMB/BSC-CTM model over Europe for 2010 in the framework of the AQMEII-Phase2 project. Atmospheric Environment, 115, 657-669, 2015.

Badia, A., Jorba, O., Voulgarakis, A., Dabdub, D., Pérez García-Pando, C., Hilboll, A., Gonçalves, M., and Janjic, Z.: Description and evaluation of the Multiscale Online Nonhydrostatic AtmospheRe CHemistry model (NMMB-MONARCH) version 1.0:gas-phase chemistry at global scale, Geosci. Model Dev., 10, 609–638, https://doi.org/10.5194/gmd-10-609-2017, 2017.

Di Biagio, C., Formenti, P., Balkanski, Y., Caponi, L., Cazaunau, M., Pangui, E., Journet, E., Nowak, S., Andreae, M. O., Kandler, K., Saeed, T., Piketh, S., Seibert, D., Williams, E., and Doussin, J.-F.: Complex refractive indices and single-scattering albedo of global dust aerosols in the shortwave spectrum and relationship to size and iron content, Atmos. Chem. Phys., 19, 15503–15531, https://doi.org/10.5194/acp-19-15503-2019, 2019.

Di Tomaso, E., Schutgens, N. A. J., Jorba, O., and Pérez García-Pando, C.,: Assimilation of MODIS Dark Target and Deep Blue observations in the dust aerosol component of NMMB/BSC-CTM version 1.0. Geosci. Model Dev., 10, 1107-1129, https://doi.org/10.5194/gmd-10-1107-2017, 2017.

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 Pinto, G., Mytilinaios, M., Obiso, V., Olid, M., Schutgens, N., Votsis, A., Werner, E., and Pérez García-Pando, C.: The MONARCH high-resolution reanalysis of desert dust aerosol over Northern Africa, the Middle East and Europe (2007–2016), Earth Syst. Sci. Data, 14, 2785–2816, https://doi.org/10.5194/essd-14-2785-2022, 2022.

Dubovik, O., Holben, B., Eck, T. F., Smirnov, A., Kaufman, Y. J., King, M. D., ... & Slutsker, I.: Variability of absorption and optical properties of key aerosol types observed in worldwide locations. Journal of the atmospheric sciences, 59(3), 590-608, 2002.

Escribano, J., Di Tomaso, E., Jorba, O., Klose, M., Gonçalves Ageitos, M., Macchia, F., Amiridis, V., Baars, H., Marinou, E., Proestakis, E., Urbanneck, C., Althausen, D., Bühl, J., Mamouri, R.-E., and Pérez García-Pando, C.: Assimilating spaceborne lidar dust extinction can improve dust forecasts, Atmos. Chem. Phys., 22, 535–560, https://doi.org/10.5194/acp-22-535-2022, 2022.

Ginoux, P., Chin, M., Tegen, I., Prospero, J. M., Holben, B., Dubovik, O., & Lin, S. J.: Sources and distributions of dust aerosols simulated with the GOCART model. Journal of Geophysical Research: Atmospheres, 106(D17), 20255-20273, 2001.

Ginoux, P., Prospero, J.M., Gill, T.E., Hsu, N.C., and Zhao, M.: Global-Scale Attribution of Anthropogenic and Natural Dust Sources and Their Emission Rates Based on Modis Deep Blue Aerosol Products, Rev. Geophys., 50, https://doi.org/10.1029/2012RG000388, 2012.

Haustein, K., Pérez, C., Baldasano, J. M., Jorba, O., Basart, S., Miller, R. L., Janjic, Z., Black, T., Nickovic, S., Todd, M. C., Washington, R., Müller, D., Tesche, M., Weinzierl, B., Esselborn, M., and Schladitz, A.: Atmospheric dust modeling from meso to global scales with the online NMMB/BSC-Dust model – Part 2: Experimental campaigns in Northern Africa, Atmos. Chem. Phys., 12, 2933–2958, https://doi.org/10.5194/acp-12-2933-2012, 2012.

Hess, M., Koepke, P., and Schult, I.: Optical properties of aerosols and clouds: The software package OPAC, B. Am. Meteorol. Soc., 79, 831–844, https://doi.org/10.1175/1520-0477(1998)079<0831:OPOAAC>2.0.CO;2, 1998

Holben, B. N., Eck, T. F., Slutsker, I., Tanré, D., Buis, J. P., Setzer, A., Vermote, E., Reagan, J. A., Kaufman, Y. J., Nakajima, T., Lavenu, F., Jankowiak, I., and Smirnov, A.: AERONET – A federated instrument network and data archive for aerosol characterization, Remote Sens.Environ., 66, 1–16, https://doi.org/10.1016/S0034-4257(98)00031-5, 1998.

Huang, Y., Adebiyi, A. A., Formenti, P., & Kok, J. F.: Linking the different diameter types of aspherical desert dust indicates that models underestimate coarse dust emission. Geophysical Research Letters, 48, e2020GL092054, https://doi.org/10.1029/2020GL092054, 2021.

Iacono, M. J., Delamere, J. S., Mlawer, E. J., and Shephard, M. W.: Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models, J. Geophys. Res.-Atmos., 113, D13103, https://doi.org/10.1029/2008JD009944, 2008.

Janjic, Z., & Gall, L.: Scientific documentation of the NCEP nonhydrostatic multiscale model on the B grid (NMMB). Part 1 Dynamics, 2012.

Jorba, O., Dabdub, D., Blaszczak-Boxe, C., Pérez, C., Janjic, Z., Baldasano, J. M., Spada, M., Badia, A., and Gonçalves, M.: Potential significance of photoexcited NO2 on global air quality with the NMMB/BSC chemical transport model, Journal of Geophysical Research: Atmospheres, 117, https://doi.org/10.1029/2012JD017730, 2012.

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. F., Miller, R. L., and Pérez García-Pando, C.: Mineral dust cycle in the Multiscale Online Nonhydrostatic Atmosphere Chemistry model (MONARCH) version 2.0, Geoscientific Model Development, 14, 6403–6444, https://doi.org/10.5194/gmd-14-6403-2021, 2021.

Kok, J. F., Mahowald, N. M., Fratini, G., Gillies, J. A., Ishizuka, M., Leys, J. F., Mikami, M., Park, M.-S., Park, S.-U., Van Pelt, R. S., and Zobeck, T. M.: An improved dust emission model – Part 1: Model description and comparison against measurements, Atmos. Chem. Phys., 14, 13023-13041, https://doi.org/10.5194/acp-14-13023-2014, 2014.

O'Neill, N. T., Eck, T. F., Smirnov, A., Holben, B. N., & Thulasiraman, S.: Spectral discrimination of coarse and fine mode optical depth. Journal of Geophysical Research: Atmospheres, 108(D17), 2003.

Pérez, C., Nickovic, S., Pejanovic, G., Baldasano, J. M., & Özsoy, E.: Interactive dust-radiation modeling: A step to improve weather forecasts. Journal of Geophysical Research: Atmospheres, 111(D16), 2006.

Pérez, C., Haustein, K., Janjic, Z., Jorba, O., Huneeus, N., Baldasano, J. M., Black, T., Basart, S., Nickovic, S., Miller, R. L., Perlwitz, J. P., Schulz, M., and Thomson, M.: Atmospheric dust modeling from meso to global scales with the online NMMB/BSC-Dust model – Part 1: Model description, annual simulations and evaluation, Atmos. Chem. Phys., 11, 13001–13027, https://doi.org/10.5194/acp-11-13001-2011, 2011.

Spada, M., Jorba, O., Pérez García-Pando, C., Janjic, Z., & Baldasano, J. M.: Modeling and evaluation of the global sea-salt aerosol distribution: sensitivity to size-resolved and sea-surface temperature dependent emission schemes. Atmospheric Chemistry and Physics, 13(23), 11735-11755m, 2013.

Spada, M.: Development and evaluation of an atmospheric aerosol module implemented within the NMMB/BSC-CTM, 2015.

Xian, P., Reid, J. S., Hyer, E. J., Sampson, C. R., Rubin, J. I., Ades, M., Asencio, N., Basart, S., Benedetti, A., Bhattacharjee, P. S., Brooks, M. E., Colarco, P. R., da Silva, A. M., Eck, T. F., Guth, J., Jorba, O., Kouznetsov, R., Kipling, Z., Sofiev, M., Pérez García-Pando, C., Pradhan, Y., Tanaka, T., Wang, J., Westphal, D. L., Yumimoto, K., and Zhang, J.: Current state of the global operational aerosol multi-model ensemble: An update from

the International Cooperative for Aerosol Prediction (ICAP), Q. J. Roy. Meteor. Soc., 145, 176–209, https://doi.org/10.1002/qj.3497, 2019.
Zhang, L., Gong, S., Padro, J., and Barrie, L.: A size-segragrated particle dry deposition scheme for an atmospheric aerosol module, Atmos. Environ., 35, 549–560, https://doi.org/10.1016/S1352-2310(00)00326-5, 2001.