UPGRADE OF THE MONARCH OPERATIONAL FORECAST

BDRC-2025-003

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Summary

This document summarizes the updates that have been introduced during 2025 in the MONARCH model used for the Barcelona Dust Regional Center (BDRC) operational forecasts. A major change implemented this year was the introduction of satellite data assimilation, with the aim to improve the initial condition of the forecasts in near-real time. Additional changes include the revision of dust emissions calibration and a bugfix on surface concentration outputs. For assessing the skills of the updated model (v2.11.0) in comparison with the previous operational version (v2.7.2), model results for the period from July 2024 until June 2025 are evaluated in terms of dust optical depth against AERONET Sun photometers over North Africa, Mediterranean and Middle East (NAMEE). The upgraded model version provides better forecasts than the former version. The upgraded MONARCH v2.11.0 has been used as the new operational version, since July 2025, 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 0.5º x 0.5º 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.

1.2 Model upgrades (MONARCH v2.11.0)

1.2.1 Satellite data assimilation

Operational data assimilation has been implemented based on the experience gained with the MONARCH MODIS dust reanalysis exercise (Di Tomaso et al. 2022) and SUOMI-NPP dust assimilation study (Escribano et al. 2022). Since the MODIS mission is approaching its end, we implemented the assimilation of aerosol optical depth from the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument onboard the polar-orbiting satellite NOAA-20. VIIRS AOD retrievals are already assimilated in several operational centers (e.g. ECMWF, Météo France), proving to be a successful replacement for the afternoon over-pass of MODIS. We used VIIRS

NASA Level 2 Deep Blue retrievals (v2, Lee et al. 2024), made publicly available in near-real time (NRT) by the University of Wisconsin Atmosphere SIPS (https://sips.ssec.wisc.edu).

We assimilate VIIRS Total Aerosol Optical Depth at 550nm (Aerosol_Optical_Thickness_550_Land_Ocean_Best_Estimate) over the entire NAMEE domain (land and ocean) but only use observations flagged as dust contaminated by the retrieval algorithm (Hsu et al. 2019). This choice reduces the number of observations being used but avoids to a certain extent the correction of simulated dust with unrelated aerosols (e.g. smoke or anthropogenic pollution). Observation errors are assigned to a value of 0.05 ± 0.2 AOD as in Escribano et al. (2022). The observations preprocessor selects retrievals with Quality Assurance (QA) flag equal or greater than 3 and 2 respectively over ocean and land. Finally original satellite Level 2 retrievals (6 km resolution at nadir) are regridded and averaged into the MONARCH NAMEE grid (10 km resolution) at 3-hourly steps to match model outputs.

A Local Ensemble Transform Kalman Filter (LETKF) algorithm is used to compute 3D corrections to the modeled dust concentrations as described in Di Tomaso et al. (2017, 2022) and Escribano et al. (2022). The main step consists in executing an ensemble of model forecasts to represent the uncertainty of the dust prediction. For operational deployment we chose an ensemble of 12 members, with perturbations applied to: i) global emissions calibration factor (DCAL) ii) size dependent emissions calibration factors (DCALBIN1-8) iii) spatially varying emissions calibration factors (PERTMAP). Model equivalents of satellite optical depths at 550 nm are computed according to MONARCH dust optical properties (OPAC tri-axial spheroids). Since the size of the ensemble is relatively small, localization is needed to avoid spurious assimilation corrections far away from satellite observations. The localization radius is set to 150 km horizontally and 1 grid point vertically. The setup of the data assimilation configuration has been done considering past studies but also operational constraints. Different setups have been tested during short periods before launching the definitive e-suite in summer 2024.

1.2.2 New workflow

There are two new distinct workflows that operate in synergy to produce the upgraded forecasts: i) the assimilation workflow propagates and correct the ensemble of 24 hours long forecasts on day D using satellite observations found until 18h UTC ii) the forecast workflow computes a deterministic forecast for the days D+1, D+2 and D+3 based on the ensemble mean at 24 UTC of day D. The scheduling and execution times have been optimized to issue the final 3 days forecast before 24h UTC of the current day. In case of missing satellite observations or failure of the data assimilation task the final forecast is automatically initialized with the previously available one.

1.2.3 Other changes

The MONARCH model itself has not been changed this time but the global emissions calibration factor (DCAL) has been revised down with respect to the former value. This was done because the dry deposition fix introduced with v2.7.2 was found to produce higher dust concentrations but emissions recalibration was not performed during the last upgrade (Kernezi et al. 2024).

Additionally, a bug affecting only dust concentrations outputs has been found that reduced them by a factor of 2. The recalibration of emissions (30% lower than before) and the bug-fix of concentrations outputs will produce lower dust optical depths but higher dust concentrations with respect to v2.7.2.

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
v2.11.0	22nd July 2025	• Initialization with Data Assimilation of NOAA-20 VIIRS observations • Revision of dust emissions calibration factor • Bug-fix in the postprocessor for the expression of dust concentrations

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. The v2.11.0 forecasts (e-suite) have been executed daily from July 2024 until June 2025 and are here compared to the v2.7.2 operational forecast (o-suite). 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 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.

For 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. In this comparison we used the so-called *flattened* computations, which consist in using all data points over the time record, across all selected stations. All AERONET stations that are available for the period between July 2024 until June 2025 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.

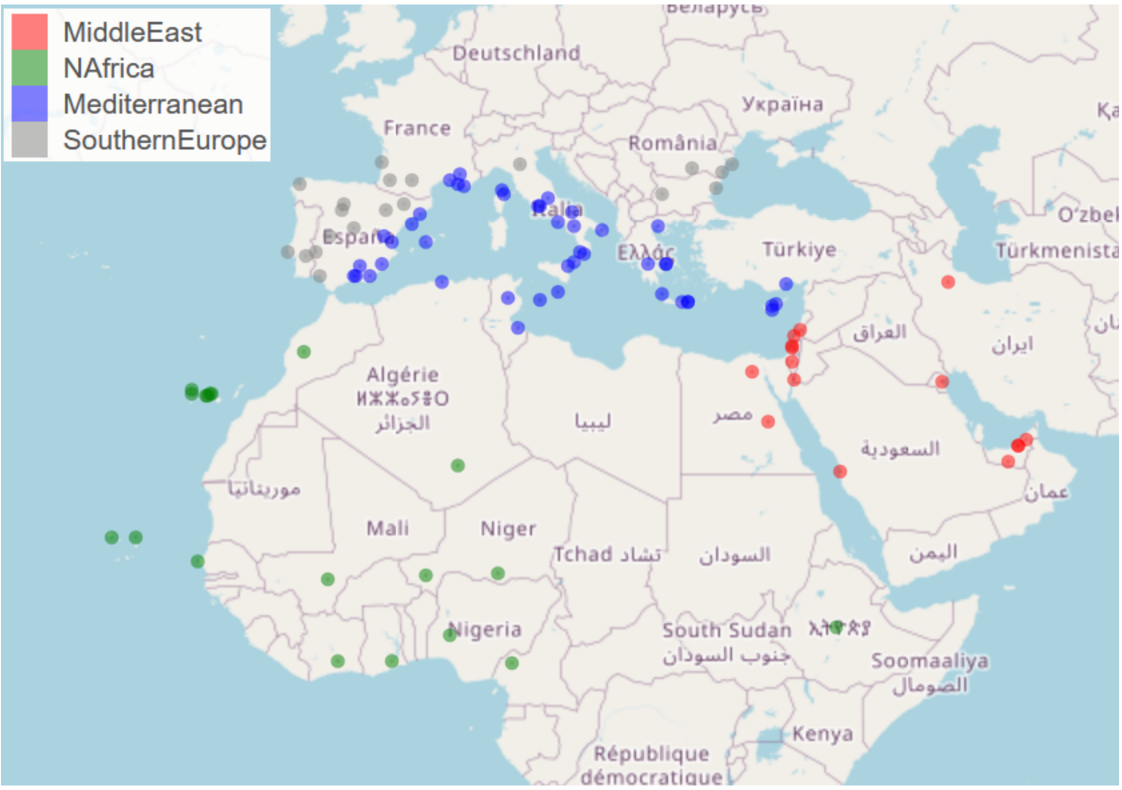

Figure 2.1 The AERONET stations used in this study per region they cover. With blue are represented the Mediterranean station, with green the North African stations, with red the Middle East stations and with grey the remaining Southern Europe stations.

3. Results

3.1 Comparison of yearly averages

Annual maps of the DOD, DODcoarse, surface dust PM_{10} and $PM_{2.5}$ concentrations from the operational model (v2.7.2) and the model upgrade (v2.11.0) are shown in Fig. 3.1. Changes in DOD are affected by both the impact of satellite assimilation and revised emissions calibration: the maps show decreased values around Bodélé depression and El Djouf desert areas and increased values elsewhere. Since model emissions have been globally decreased in v2.11.0, the increased DOD in Sub-Saharan regions and Middle East can be attributed to the impact of VIIRS assimilation. Surface dust concentrations (PM10 and PM2.5) show an overall systematic increase due to the combination of decreased emissions, satellite assimilation and the factor 2 increase (postprocessor bugfix), the latter change dominating over the first two.

3.2 Coarse DOD comparison over NAMEE and subregions

The operational (v.2.7.2) and upgraded (v.2.11.0) MONARCH first day forecasts have been compared using AERONET SDA AODcoarse (Version 3 Level 1.5) from July 2024 until June 2025. (see Figure 3.2). For the evaluation we used the Providentia tool described in past model upgrade reports. The validation statistics were computed for all 79 AERONET stations (Table 3.1) and separately the four subregions of North Africa, Mediterranean, Middle East and Southern Europe stations (Fig. 2.1). In Figure 3.2 we show the timeseries of the DODcoarse for the whole NAMEE region and for the four subregions, averaged over all stations of each region. A better agreement is observed between the observations and the upgraded forecast across the different regions.

For the NAMEE region, the correlation coefficient improved from 0.75 to 0.79, while the mean bias remained unchanged. The RMSE decreased from 0.10 to 0.09, accompanied by systematic reductions in both MFE and MFB. At the subregional scale, MFE and MFB consistently decreased, and correlation values increased in all cases except for Southern Europe, where the correlation remained invariant between the two configurations.

In North Africa, the correlation increased from 0.68 to 0.75, the mean bias decreased from 0.05 to 0.03, and the RMSE declined from 0.18 to 0.15, indicating an overall improvement in model performance. In the Middle East—where the upgraded configuration exhibited enhanced DOD in the annual assessment—the correlation increased from 0.68 to 0.72. The mean bias increased slightly to 0.03, whereas the MFB showed a substantial reduction, from –24.5 to nearly zero, indicating a marked improvement in error symmetry.

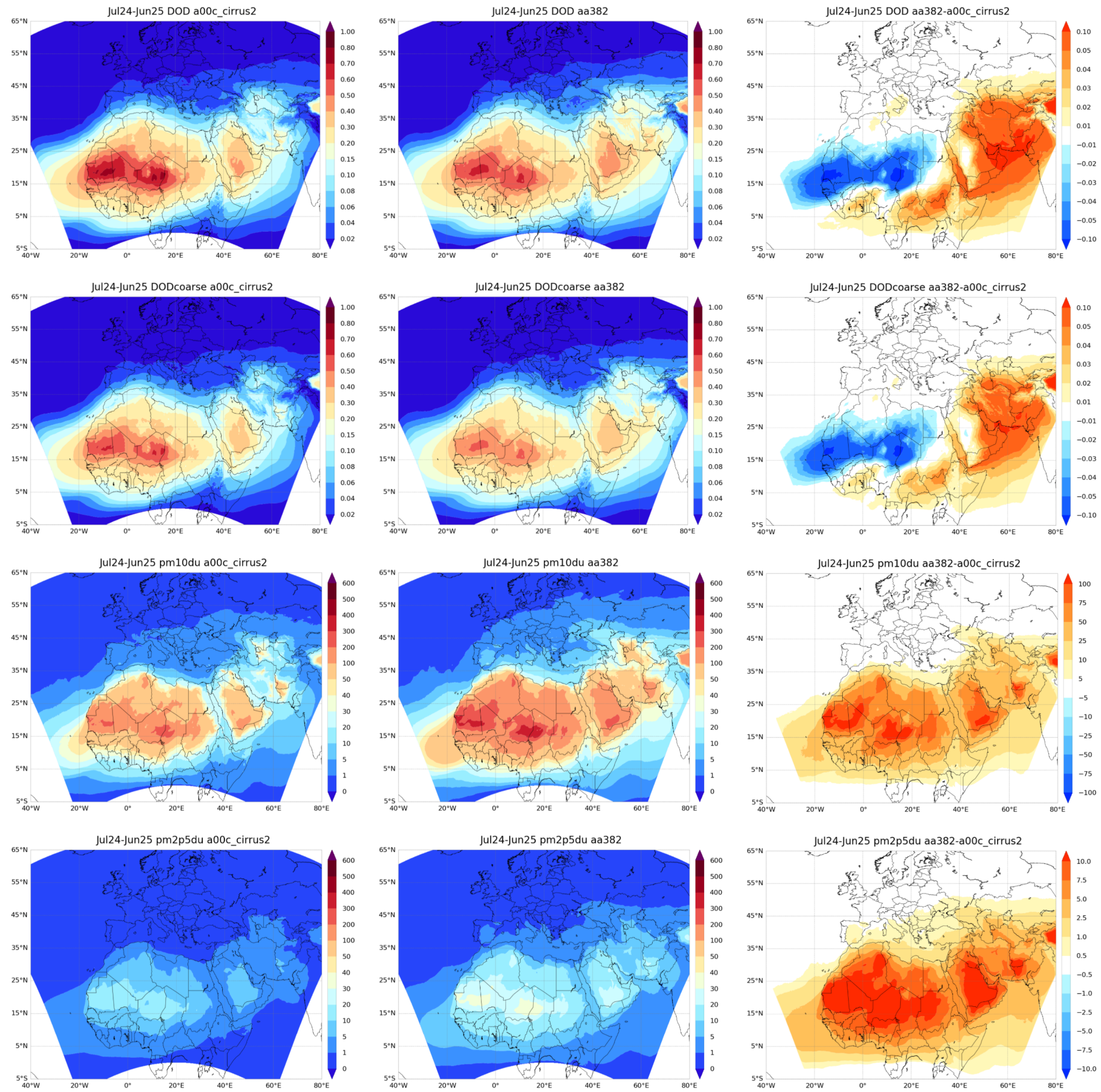

Figure 3.1 Annual DOD, DODcoarse, PM_{10} and $PM_{2.5}$ for the NAMEE domain for the period July 2024 to June 2025. First is shown the MONARCH v2.7.2 (left columns), the MONARCH v2.11.0 (central column) and last the difference (MONARCH v2.11.0 - MONARCH v2.7.2, right column). The annual calculation is based on the averaging of 3-hourly outputs for the first day of forecasts.

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	Oper	-8.00e-04	0.10	0.75	-72.49	107.52
	OperDA	0.00	0.09	0.79	-63.51	101.29
Mediterranean	Oper	-0.02	0.06	0.71	-95.86	114.61
	OperDA	-0.02	0.06	0.75	-85.33	106.50
NorthAfrica	Oper	0.05	0.18	0.68	-4.38	82.21
	OperDA	0.03	0.15	0.75	-4.30	76.59
MiddleEast	Oper	-3.03e-04	0.10	0.68	-24.50	70.25
	OperDA	0.03	0.10	0.72	0.89	67.13
SouthernEurope	Oper	-0.01	0.05	0.68	-123.20	141.57
	OperDA	-0.02	0.04	0.68	-119.33	136.14

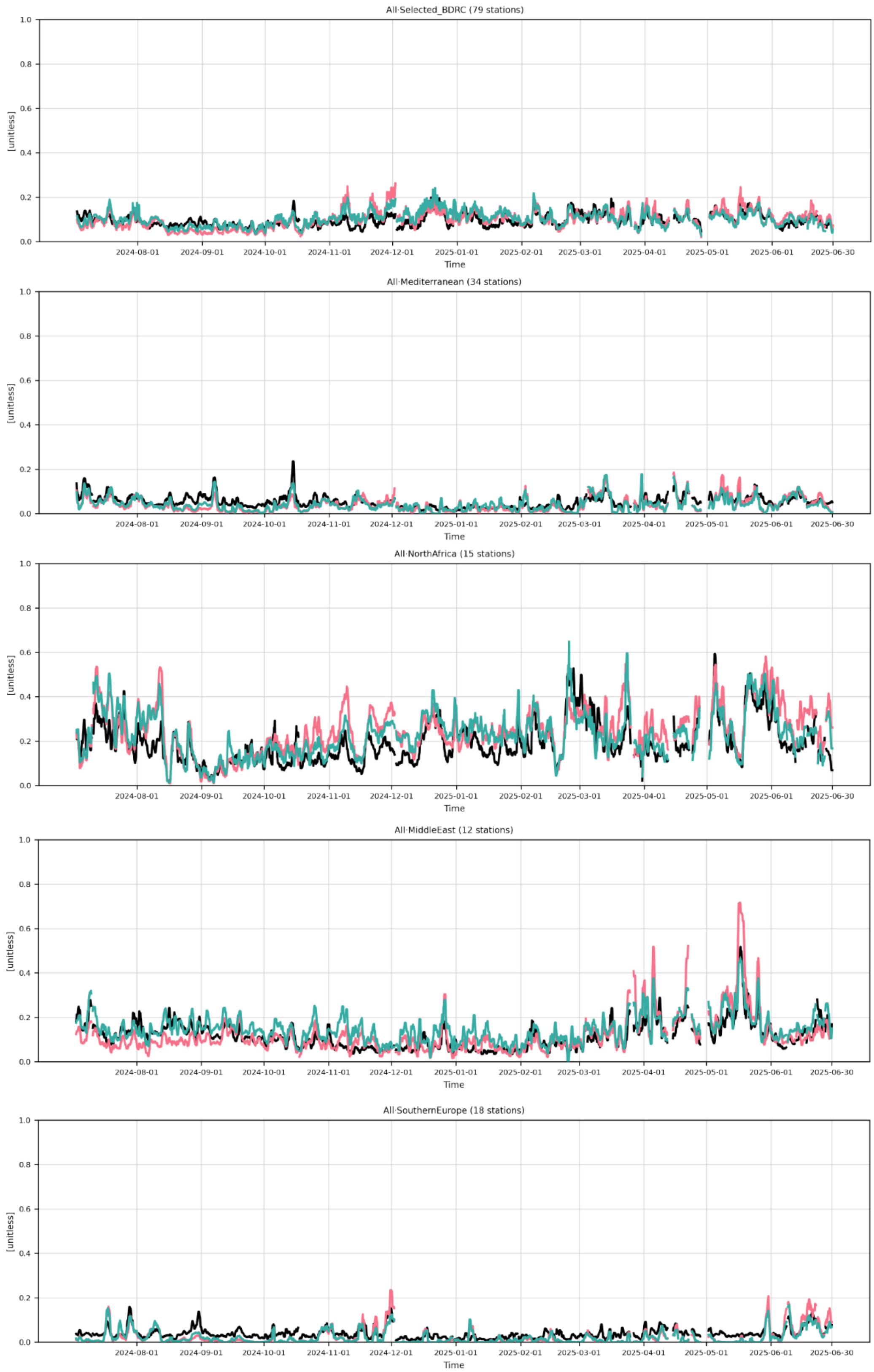

Figure 3.2 Timeseries of 3hourly values for July 2024 until June 2025 of O'Neill AODcoarse AERONET measurements (black line), the old operational MONARCH v2.7.2 (pink line), and the upgraded MONARCH v2.11.0 (green line). The first row is for the whole NAMEE stations, the second for the Mediterranean stations, the third for North Africa stations, the fourth for Middle East stations and the fifth for the Southern Europe stations.

4. Conclusions

MONARCH latest upgrade **(MONARCH v2.11.0)** introduced the near-real time assimilation of VIIRS satellite observations from NOAA-20 polar orbiting satellite. Additional changes concerned the recalibration of dust emissions and a bugfix of dust concentration outputs. A new workflow has been deployed as an e-suite and evaluated during a period of about 1 year (July 2024 – July 2025): skills in dust optical depth predictions have been significantly improved across the different regions of the domain both in terms of errors (RMSE, MFE, MFB) and correlations. Surface concentrations are broadly increased and more in line with expected values but have not been fully evaluated in this report. Thus, MONARCH **was upgraded on 22nd of July** with the version 2.11.0.

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