DUST REGIONAL REANALYSIS UPDATE

EXTENSION TO 2018

BDRC-2024-002

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13 December 2024

TECHNICAL REPORT

Series: Barcelona Dust Regional Center (BDRC) Technical Report

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Summary

This document presents a temporal extension of the decadal high-resolution dust regional reanalysis for Northern Africa, the Middle East and Europe for the period 2007-2018. The original reanalysis (2007-2016) was produced in the framework of the ERA4CS DustClim project and is documented by Di Tomaso et al. [2022]. We recomputed climatological values of dust optical depth and surface dust concentrations for the full period; we report here yearly anomalies and monthly time-series for each year. We also computed a regional validation against time series of AERONET coarse AOD measurements, using the latest version of our model evaluation tool (PROVIDENTIA). We use the same structure and methodology that was introduced in the first reanalysis report issued in 2023 [BDRC-2023-002] and discuss here only novel findings. We finally elaborate on the occurrence of a positive bias of dust optical depth over Middle East during the reanalysis extended period (2017-2018).

Contents

1.Background

Over the past decade, there has been growing recognition of the significant role that sand and dust storms (SDS) have on weather, climate and atmospheric chemistry, as well as their adverse impacts on life, health, environment, property, and economy. All this has generated a high societal and research interest to better understand atmospheric dust processes, predict dust events and prevent or mitigate their unwanted impacts. Understanding, managing and mitigating SDS risks requires the availability of relevant dust information on past trends and current conditions as well as the provision of skillful forecasts and projections. To achieve these objectives, one of the major challenges is the lack of historical and routine dust observations - mainly in the countries most affected by SDS - which represent a key element for the reconstruction of comprehensive dust information. To cover this gap and overcome the sparse coverage, low temporal resolution and partial information provided by local-scale in situ or remote sensing measurements, high resolution reanalysis with the assimilation of dust-related satellite products over source regions and the thoroughly evaluation of their products represent a powerful tool able to describe with accuracy the dust variability and trends. This also provides extensive information for the socio-economic evaluation of major events, and their short (direct) and long-term (induced) impacts on society.

The first 2007-2016 MONARCH dust regional reanalysis was produced in the context of the "Dust Storms Assessment for the development of user-oriented Climate services in Northern Africa, the Middle East and Europe" (DustClim) project in which the Barcelona Supercomputing Center (BSC) and the Spanish State Meteorological Agency (AEMET) took part. The DustClim project was a 3-years project conducted in the framework of the European ERA4CS Joint Call for Transnational Collaborative Research Projects. DustClim sought to produce and deliver an advanced dust regional model reanalysis for Northern Africa, Middle East and Europe covering the satellite era of quantitative aerosol information, and to develop dust-related services tailored to specific socio-economic sectors.

The regional dust reanalysis has been produced using the mineral dust module of the MONARCH chemical weather system (Di Tomaso et al., 2017; Pérez et al., 2011; Klose et al., 2021) and by assimilating satellite observations of aerosol optical depth (AOD) with specific observational constraints for dust (Di Tomaso et al., 2022). The evaluation of the reanalysis performance was carried out using independent datasets grouping observations of variables that are included in the model simulations and are relevant for its scoring (M. Mytilinaios et al., 2021).

During the ongoing contract between AEMET and the BSC, it has been agreed to extend the original reanalysis in time to cover more recent years. This document covers the second yearly extension (2018). Following the previous report where a new protocol was established for the evaluation, the reevaluate here the full reanalysis period in terms of dust optical depth and surface dust concentration.

The report is structured as follows: section 2 recalls the main information about the model configuration, assimilated observations and data assimilation methodology, section 3 reports annual and monthly climatologies of dust optical depth and surface concentrations, section 4 presents the validation of the reanalysis dust optical depth against the AERONET network of ground-based sun-photometers.

2. Reanalysis setup

This section describes the model and data assimilation configuration along with the satellite observations of dust-filtered aerosol optical depth used for the production of the dust reanalysis between 2007 and 2018. Full details of the sensitivity analysis performed to define the reanalysis configuration for 2007-2016 can be found in Di Tomaso et al. (2020) and Di Tomaso et al. (2022). The computation of the extra year of 2018 has been achieved using the same configuration used for the previous years, to ensure continuity in the full dataset and avoid artificial trends due to different modeling or observational choices.

The reanalysis was produced using the Local Ensemble Transform Kalman Filter (LETKF) data assimilation in the Multiscale Online Non-hydrostatic AtmospheRe CHemistry model (MONARCH) developed at the Barcelona Supercomputing Center. The use of ensemble model simulations allows for the estimation of flow-dependent background uncertainty which is otherwise difficult to estimate due to the highly varying nature of dust concentrations. The assimilated data are coarse-mode dust optical depth (DOD) retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue level 2 product. More information on this can be found also in Di Tomaso et al. (2022). Here, we briefly recall the main aspects of the methodology used in the data assimilation.

2.1 Assimilated observations

After an overview of the potential dust-related satellite products that could be used for data assimilation summarized in Mona et al. (2018), we opted for an innovative dust optical depth (DOD) dataset derived from the MODIS Deep Blue aerosol products (Collection 6), which covers all cloud-free and snow-free surfaces. Deep Blue (DB) aerosol retrievals are available over areas not easily covered by other observational data sets, e.g., very bright reflective surfaces such as deserts, and are therefore particularly relevant for dust applications. More specifically, we have assimilated the coarse-mode DOD retrieved from MODIS DB Level 2 aerosol products as described in Ginoux et al. (2010, 2012) and Pu and Ginoux (2016). The generation of the dust retrievals includes the different steps of formatting, dust filtering and retrieval. First, aerosol products such as AOD, single scattering albedo, and the Ångström exponent are interpolated to a regular grid of 0.1° latitude×0.1° longitude using the algorithm described by Ginoux et al. (2010). The DOD is then derived from AOD following the methods of Ginoux et al. (2012) with adaptations to MODIS Collection 6 aerosol products. To separate dust from other aerosols, two variables are used: the Ångström exponent, which has been shown to be highly sensitive to particle size (Eck et al., 1999), and the single scattering albedo which is less than one for dust due to its absorption of solar radiation (Takemura et al., 2002). Subsequently, an empirical continuous function relating the Ångström exponent to fine-mode AOD (Anderson et al., 2005; their Eq. 5) is applied to retrieve the dust fine-mode fraction of optical depth. The derived dust coarse-mode fraction is used in this work and is indicated hereafter as coarse DOD (DODcoarse). Since the retrievals are based on visible reflectances, their availability is limited to daytime only. We have considered for assimilation only DODcoarse retrievals based on measurements from MODIS on-board the Aqua platform. In our 3-hourly discretization of the assimilation window, the assimilated observations are associated with the time slot centered at 12 UTC. We have used 0.07+0.075·DODcoarse to characterize the observation uncertainty of the assimilated observations and assumed a diagonal observation error covariance matrix, i.e. uncorrelated error between the different retrievals. Observation coordinates were pre-processed to be mapped on the rotated longitude–latitude regional grid of MONARCH.

The only major difference between the extension years 2017 and 2018 and the previous decadal (2007-2016) reanalysis period, is related to the version of the MODIS DB retrievals being used, which were updated from Collection 6.0 to Collection 6.1. Systematic differences in DOD between the two Collections and over the region of interest could not be evaluated because we do not dispose of both datasets on a common period. Typically, systematic differences in total AOD have been found in elevated regions and could impact some of the regions covered by the reanalysis (https://atmosphere-imager.gsfc.nasa.gov/sites/default/files/ModAtmo/modis_deep_blue_c61_changes2.pdf).Wei et al. (2018) compared Collection 6.0 and 6.1 aerosols products globally during the period 2013-2017 and found a systematic increase in Deep Blue AOD of about 0.1 over Middle East. Unless other retrieved properties (e.g. Ångström exponent) changed as well, this could introduce a systematic increase of dust in our reanalysis starting from 2017. .

2.2 Model and data assimilation configuration

The MONARCH model has been run on the domain of the WMO Barcelona Dust Forecast Center bounded by latitude 25° West and 60° East and longitude 0° South and 65° North, at 0.10° x 0.10° horizontal resolution, with 40 vertical layers, with top pressure of the domain at 5000 Pa, a temporal integration step of 20 seconds. Interaction of aerosols with radiation and its coupling with meteorology was turned on. Simulation output is provided every 3 hours (03:00, 06:00, ..., 00:00 UTC) which is also the time resolution of the reanalysis product.

The data assimilation scheme coupled with MONARCH is the Local Ensemble Transform Kalman filter (LETKF; Di Tomaso et al., 2017) with an ensemble size of 12 members. The implementation of the ensemble forecast for MONARCH has been enhanced for the present regional dust reanalysis with the perturbation of meteorological initial and boundary conditions and the use of different parameterization schemes for dust emission modeling, additionally to the already implemented perturbations of model emission parameters. The meteorological initial and boundary conditions are issued from reanalysis datasets. Six ensemble members used ERA-Interim (Berrisford et al. 2011); among them, two members used the dust emission scheme from Perez et al. (2011), two members used the dust emission scheme from Ginoux et al., (2001) and two members used the dust emission scheme from Kok et al. (2014). The other six members used MERRA2 (Gelaro, et al., 2017) with ERA5 soil (Hersbach et al., 2020), plus the same three dust emission scheme mentioned before. A spin-up period has been run for the soil variables that need a longer period to adjust. A one year spin-up with a two-member experiment, each of them using either MERRA2 or ERA5 meteorology, was run in 2006.

3. Climatology

The dust reanalysis data set consists of 12 dust related variables (Table 1 in BDRC-2023-002) which include upper air (dust mass concentrations and extinction coefficient), surface (dust deposition and solar irradiance fields, among them) and total column variables (e.g., dust optical depth and load). Some dust variables, such as concentrations and total load, are expressed for a binned size distribution that ranges from 0.2 to 20 µm in particle diameter. Both analysis and first-guess fields are available for the variables that are diagnosed from the control vector. The first-guess are model forward simulations initialized with an analysis. When available, the analysis field is the recommended output for that variable. A set of ensemble statistics are calculated and archived for each output variable, namely the ensemble mean, standard deviation, maximum and median. The spread among the ensemble members, represented by the standard deviation with respect to the ensemble mean, can be interpreted as a measure for the uncertainty in the mean estimates. While model fields have been produced on 40 vertical levels, the data are stored on 15 standard pressure levels between 1000 and 100hPa (i.e., 1000, 975, 900, 850, 750, 700, 600, 500, 400, 350, 300, 250, 175, 150, 100hPa). In that way the storage space is reduced while easing the use of vertical information. The full dataset, including the latest processed year 2018, is currently available at https://earth.bsc.es/thredds_dustclim/homepage .

A climatology of the reanalysis dust optical depth (DOD), vertical extinction profiles and dust surface concentrations for the period 2007-2016 can be found in Mona et al. (2021). Here we present the climatology for the annual DOD and dust surface concentration in Figure 3.1 for the period of 2007-2018 together with the anomalies of each year for the annual DOD in Figure 3.2 and for the dust surface concentration in Figure 3.3. The 2018 DOD map shows a significant positive anomaly in Southern Middle East countries (> 0.1) and a negative one in correspondence of the Bodele depression (Chad). Values are close to climatological ones elsewhere. The positive DOD anomaly in Middle East appear as a distinctive feature of 2017 and 2018, whereas anomalies of such amplitude in the Bodele depression can be found in previous years. Anomaly of surface concentrations display similar behavior as DOD but with increased regional variability.

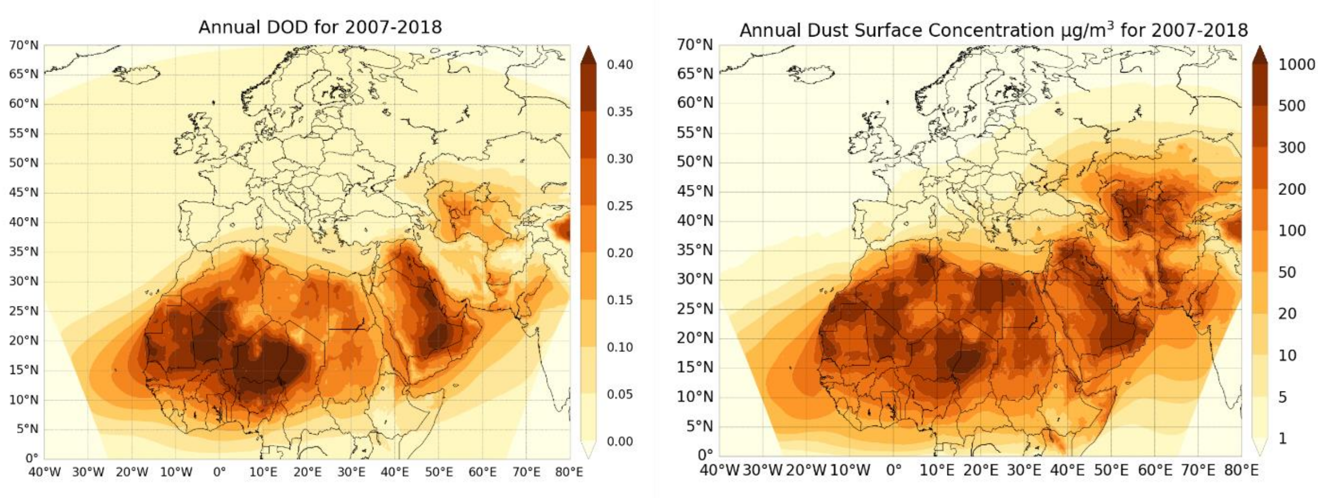

Figure 3.1 Annual climatologies of Dust Optical Depth (DOD) (left column) and dust surface concentration (right column) averaged over the 12-year period, 2007-2018

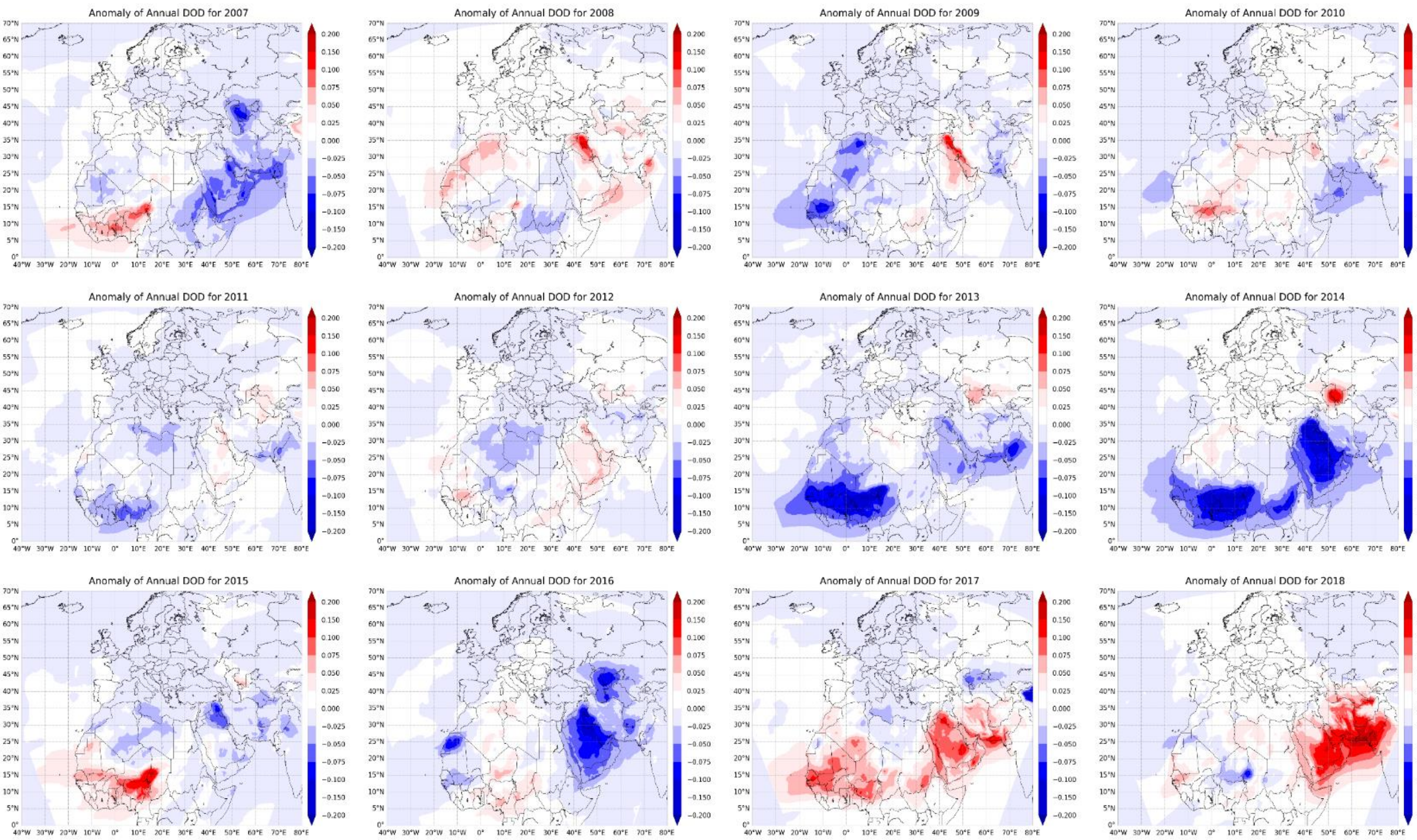

Figure 3.2 Yearly anomalies of Dust Optical Depth (DOD) at 550 nm for the 12-year period, 2007-2018.

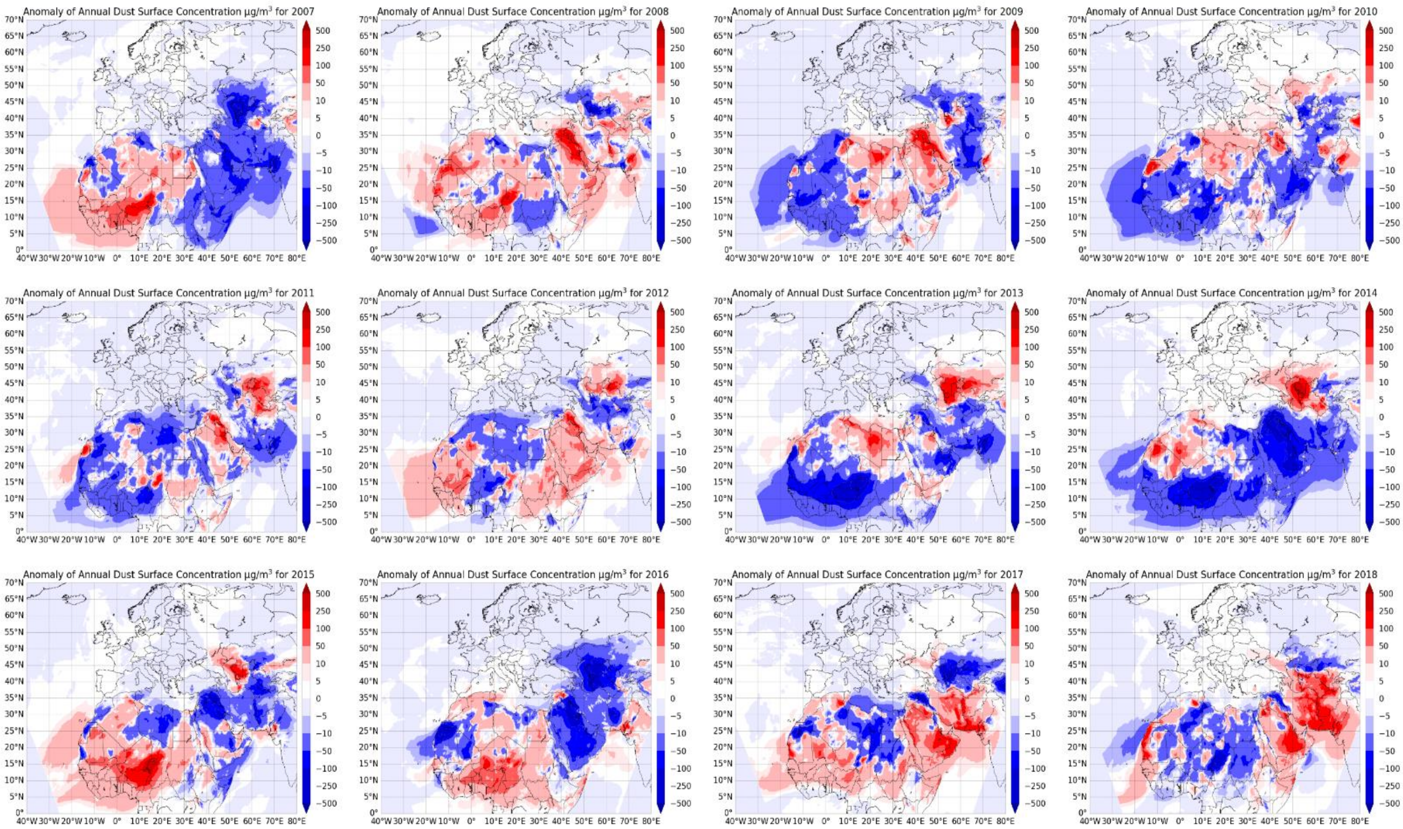

Figure 3.3 Yearly anomalies for dust surface concentration for the 12-year period, 2007-2018.

Monthly time-series of the average DOD and dust surface concentration for each year are reported in Figure 3.4. 2018 stands with 2017 among the years with the highest overall DOD, and has the highest average DOD during summer. Peak DOD months are April and June-July whereas peak of surface concentrations occurs in January. Average surface concentrations during the rest of the year 2018 sit within typical climatological variability.

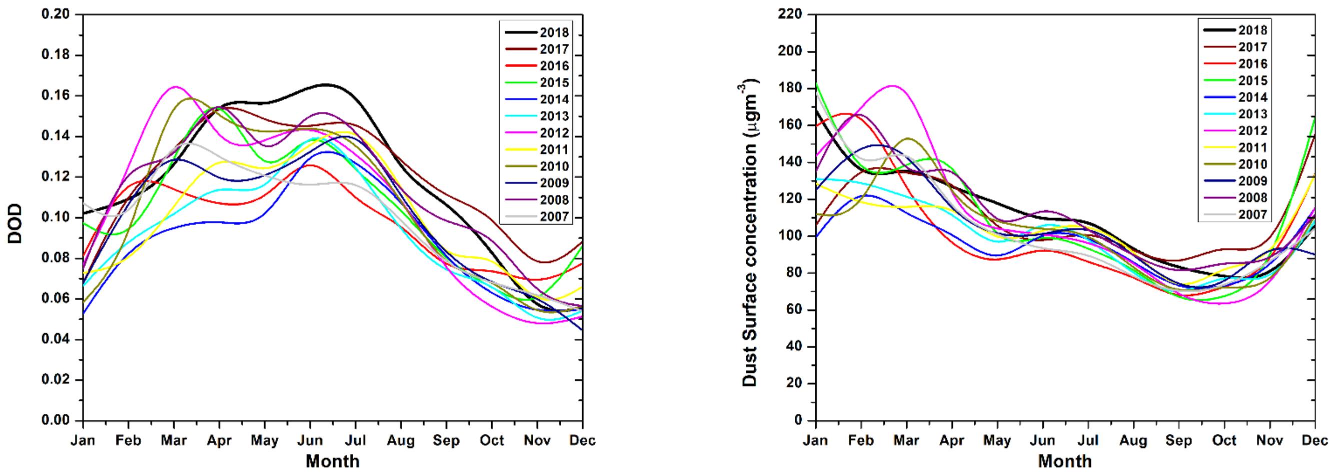

Figure 3.4 Time-series for monthly DOD (left column) and dust surface concentration (right column) for each year of reanalysis from 2007-2018. The different colors represent each year. The annual DOD for each year (from 2007 until 2018 respectively) was (0.1, 0.11, 0.1, 0.1, 0.1, 0.11, 0.09, 0.09, 0.1, 0.1, 0.12, 0.12) and the annual surface concentration was (106, 113, 105, 103, 104, 110, 100, 96, 111, 104, 111, 111 µg m^{-3}).

4. Validation

The assessment of the reanalysis skills is done comparing the analysis fields against dust optical depth (DOD) observations. Standard statistics such as correlation coefficient (r), mean bias error (MB), mean fractional bias (MFB), mean fractional error (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 4.1).

Table 4.1 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)	$\mathrm{MFE} = \frac{1}{N}\sum_{i=1}^{N}\frac{2 \cdot \lvert M_i - O_i \rvert}{M_i + O_i}$

4.1 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 and quality assured (Level 2.0) observations. For the comparison, modeled DODcoarse fields are bilinearly interpolated over the AERONET stations. Because AERONET data are acquired at 15-

min intervals on average, all AERONET measurements within ±90 min of the model outputs have been averaged and used for the model comparison on a 3-hourly basis.

All AERONET stations that are available for the period 2007-2018 and are included in the North Africa, Mediterranean and Middle East (NAMEE) domain, as described in Di Tomaso et al. (2022) are used in the evaluation. In Figure 4.1 we show the AERONET stations used as well as the correspondent region.

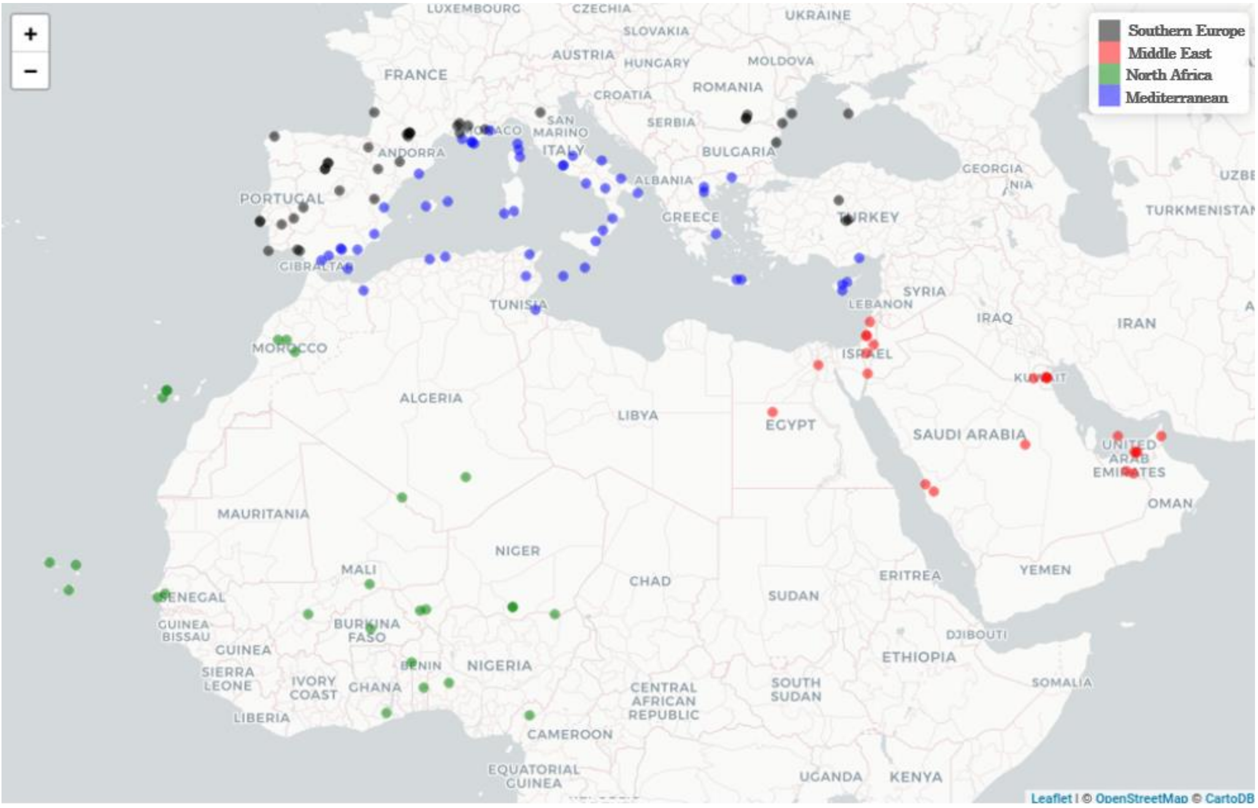

Figure 4.1 The AERONET stations used in this study per region they cover. With blue are represented the Mediterranean station, with green the North African stations, with red the Middle East stations and with blue the remaining Southern Europe stations.

4.2 Providentia tool

To validate the reanalysis, we will use the Providentia tool, developed at the Barcelona Supercomputing Center. 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 Tab. 4.1) 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.

4.3 Evaluation over NAMEE and sub-regions

We constructed time-series of collocated modeled and observed values for the whole period from 2007 until 2018 for the NAMEE area for a total of 120 AERONET stations and for the subregions of the Mediterranean (46 stations), North Africa (18 stations), Middle East (22 stations) and Southern Europe (34 stations). All AERONET O'Neill measurements have been extracted and used for the model comparison on a 3-hourly basis and are shown in Figure 4.2 after monthly averaging. Time-series of measured AODcoarse do not show particularly high values in 2018 versus previous years in any of the sub-regions. Indeed AODcoarse is below the climatological average in Middle East during both 2017 and 2018, which contradicts somehow our initial conclusions based on reanalysis anomalies (Sec. 3). The 2018 modeled DODcoarse confirms that the overestimation observed first in 2017 was not aleatory but appears to be systematic within the extended reanalysis period. In all other sub-regions the extended reanalysis (2017-2018) is instead consistent with the 2007-2016 period in terms of differences between modeled and observed values.

The number of samples (3-hourly measurements) and the verification statistics including the correlation (r), mean bias (MB), root mean square error (RMSE), MFB and MFE in % for AODcoarse O'Neill are summarized (Table 4.2). Including one additional year (2018) does not alter the verification statistics with respect to those reported previously for 2007-2017 [BDRC-2023-002]. The updated table confirms the capabilities of the reanalysis to track well seasonal, inter-annual and geographical variability of mineral dust within the NAMEE region.

To further explore possible reasons introducing the observed DOD increase in Middle East we computed additional reanalysis diagnostics. In Fig. 4.3 we report monthly collocated time series of the reanalysis DODcoarse, the corresponding model first guess (model's ensemble average before the assimilation step), the assimilated satellite observations and the AERONET AODcoarse observations. A comparison between timeseries in 2015-2016 and 2017-2018 allows to assess the impact of changing MODIS-AQUA Collection from 6.0 to 6.1 in January 2017. Indeed, the figure shows that the forecast model tends to systematically overestimate DODcoarse along all years (green line). MODIS-AQUA observations show a good agreement with AERONET in 2015-2016 (Collection 6.0) but a positive overestimation of about 0.1 in 2017-2018 (Collection 6.1). The reanalysis is strongly corrected towards the assimilated observations and ends up decreasing the first guess DODcoarse but only marginally in 2017-2018. To summarize, there is a clear systematic difference in MODIS-AQUA DODcoarse between Collection 6.0 and 6.1 and this introduces a systematic difference in the dust reanalysis starting from 2017. Evaluation statistics versus AERONET is reported in Table 4.3 and show that MB and MFB are respectively 0.09 and 40% in 2017-2018 (Collection 6.1) against 0.01 and 10% in 2015-2016 (Collection 6.0). Even if different time periods are compared here, a systematic difference of about 0.1 between the two Collections is in line with results of Wei et al. [2019]. Despite the increased bias, the reanalysis skills during 2017-2018 are comparable in terms of correlation with previous years and better than both first guess and MODIS-AQUA observations for all statistical indicators.

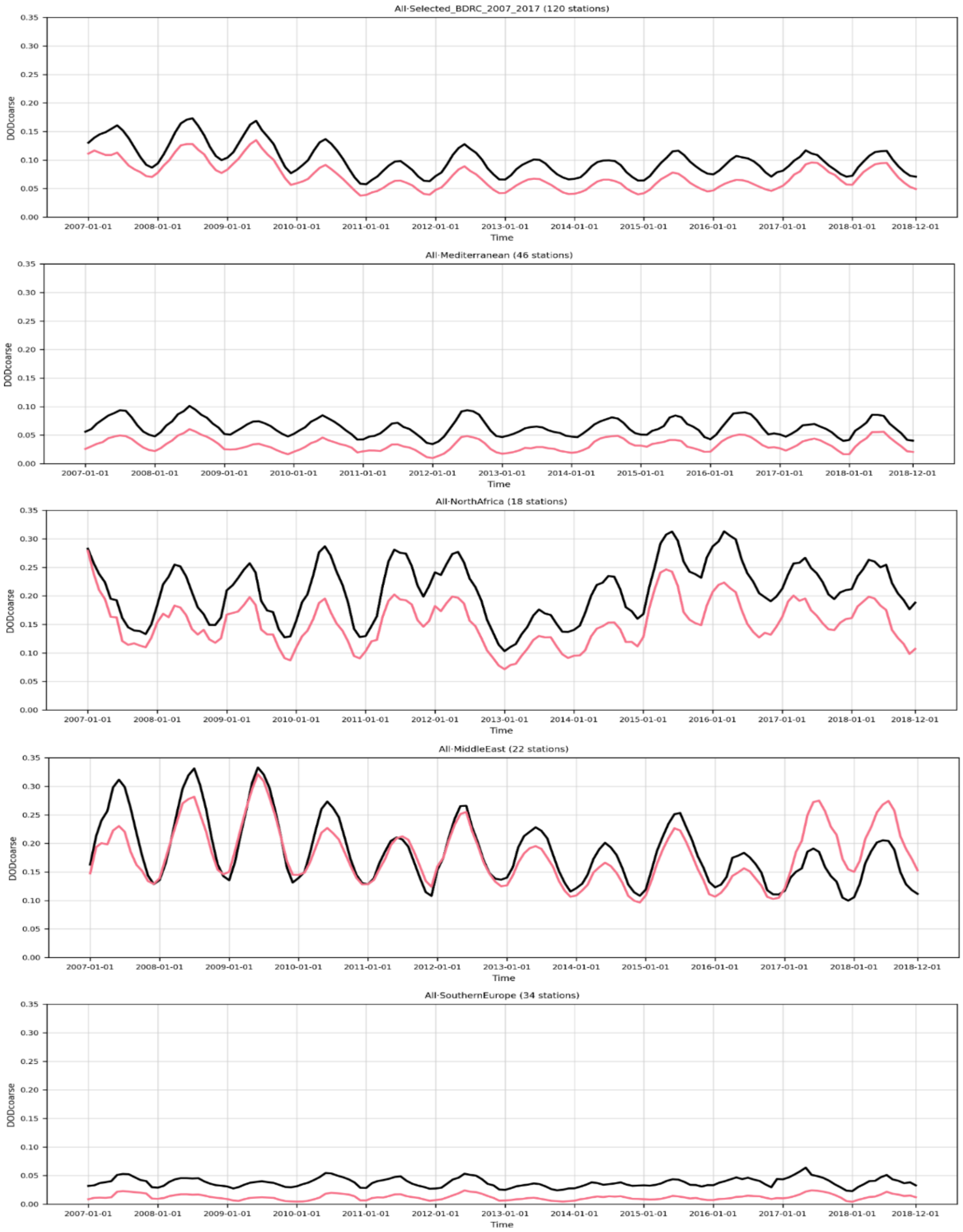

Figure 4.2 Time-series in monthly intervals (calculated from 3hourly measurements) for the whole period of 2007-2018 of O'Neill AODcoarse AERONET measurements (black line) and DODcoarse from the reanalysis dataset (pink line). The first row is for the whole NAMEE stations, the second for the Mediterranean stations, the third for North Africa stations, the fourth for Middle East stations and the fifth for the Southern Europe stations.

Table 4.2. Number of samples (NDATA) and verification statistics (r, RMSE, MB, MFB and MFE) for the reanalysis DODcoarse versus AERONET O'Neill AODcoarse for the entire period (2007–2018) for the whole NAMEE and for the Mediterranean, North Africa, Middle East, and Southern Europe regions.

	NDATA	r	RMSE	MB	MFB x 100	MFE x 100
NAMEE	416544	0.80	0.10	-0.03	-89.7	109.9
Mediterranean	156165	0.74	0.07	-0.03	-112.2	121.7
North Africa	54236	0.81	0.15	-0.06	-51.1	75.5
Middle East	84231	0.71	0.14	0.0	0.1	57.7
Southern Europe	121912	0.69	0.05	-0.03	-139.9	146.2

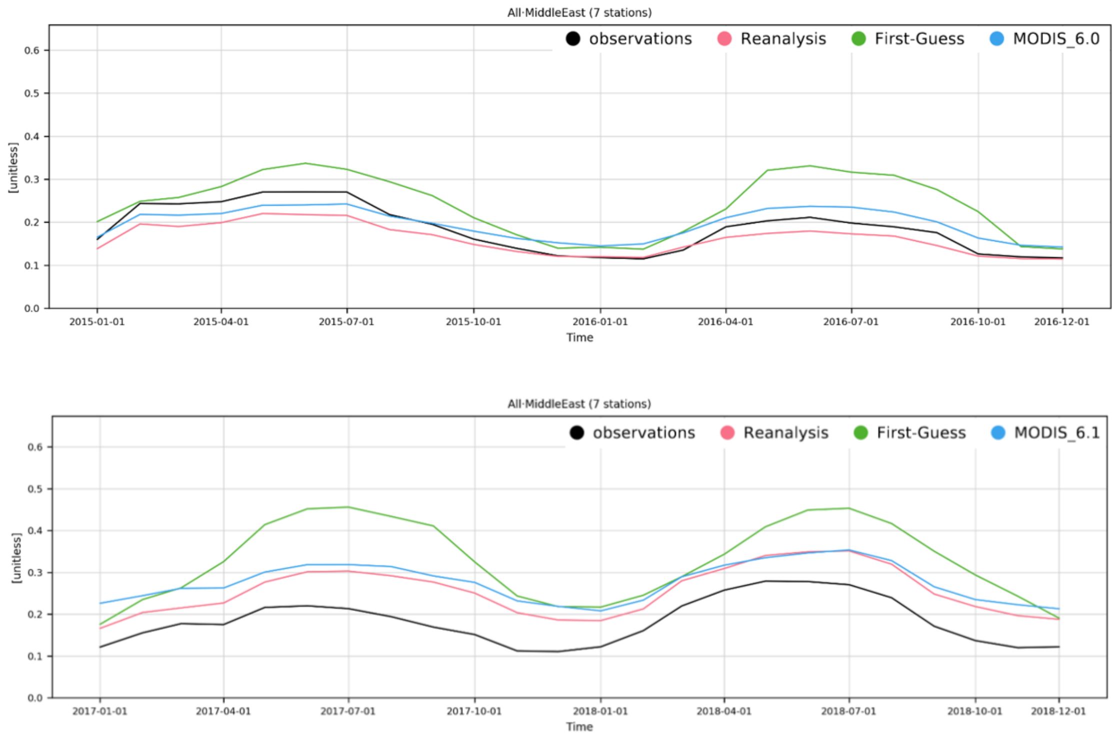

Figure 4.3 Time-series in monthly intervals (calculated from 3hourly measurements) for the whole period of 2015-2016 (top column) and 2017-2018 (bottom column) of O'Neill AODcoarse AERONET measurements (black line), DODcoarse from the reanalysis dataset (pink line), DODcoarse from the first-guess dataset (green line) and DODcoarse from MODIS satellite intervals. The time-series is an average of all the stations in the Middle East region.

Table 4.3. Verification statistics (r, RMSE, MB, MFB and MFE) for the reanalysis DODcoarse versus AERONET O'Neill AODcoarse for the years 2015 and 2016 (first rows) and years 2017 and 2018 (last rows) for the Middle East region. The results are based on monthly intervals.

Middle East	r	RMSE	MB	MFB x 100	MFE x 100
2015 and 2016					
FG	0.49	0.25	0.05	10.9	48.5
Reanalysis	0.90	0.09	-0.03	-10.8	38.2
MODIS 6.0	0.85	0.09	0.01	10	45.5
2017 and 2018					
FG	0.65	0.28	0.14	45.1	62.2
Reanalysis	0.86	0.13	0.07	32.8	56.3
MODIS 6.1	0.81	0.15	0.09	40.7	63.8

5. Conclusions and perspectives

In this report we evaluated one additional year (2018) of the MONARCH dust reanalysis and recomputed climatological fields for Dust Optical Depth (DOD) and dust surface concentrations for the full available period (2007-2018). Significant and positive anomalies of about 0.1-0.15 in DOD have been observed in 2018 in the Middle East region and negative ones within the Bodele depression. Overall, 2018 appears among the years with the highest average DOD and dust surface concentrations since the beginning of the reanalysis time series in 2007.

The 2007-2018 reanalysis dataset has been evaluated against AERONET AODcoarse measurements. Results are in line with those reported in previous publications (Di Tomaso et al., 2022) in terms of reanalysis skills across the different NAMEE sub-regions. However, a closer look at time series in the Middle East region showed that the upgrade of assimilated observations from MODIS Deep Blue Collection 6.0 to Collection 6.1 introduced a systematic bias of about 0.1 in coarse DOD starting from 2017. This bias agrees with a systematic increase of about 0.1 of the Deep Blue AOD over Middle East discussed in previous studies. Since the production of Collection 6.0 retrievals stopped during 2017, there is no simple solution to ensure a perfect continuity to the dust reanalysis other than recomputing it from the beginning using only Collection 6.1 data. Hence, the production of the following reanalysis years (2019 and beyond) will be based on Collection 6.1 and additional care will be put into identifying and documenting other possible systematic effects due to this change. Finally, ERA-Interim production stopped during 2019, which will force the switch to ERA-5 for the computation of the next year of dust reanalysis (2019). A prior evaluation of the impacts of the different meteorological inputs will be done on an overlap period before proceeding with the reanalysis extension.

6. References

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