DUST REGIONAL REANALYSIS UPDATE

EXTENSION TO 2017

BDRC-2023-002

Eleni Karnezi, Emanuele Emili, Jerónimo Escribano, Dene Bowdalo, Alba Vilanova, 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

21 December 2023

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 presents a temporal extension of the decadal high-resolution dust regional reanalysis for Northern Africa, the Middle East and Europe for the period 2007-2017. The original reanalysis (2007-2016) was produced in the framework of the ERA4CS DustClim project and is documented in 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 timeseries for each year. We also computed a regional based validation against time series of AERONET coarse AOD measurements, using the latest version of our model evaluation tool (PROVIDENTIA). This report sets the structure and the methodology for next yearly reports, which will progressively extend the reanalysis dataset into the most recent years.

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 first yearly extension (2017). Since it is the first report of this type, we reevaluate here the full reanalysis period in terms of dust optical depth and surface dust concentration, and establish a new protocol for the future reports.

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 2017. 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 2017 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 2017 reanalysis and previous years 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 could 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) .

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 (3:00, 6:00, ... 0:00 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 10 dust content and meteorological variables (see Table 1) 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 2017, is currently available at https://earth.bsc.es/thredds_dustclim/homepage .

Table 3.1. List of reanalysis variables. For each variable, the following ensemble statistics are calculated and archived: ensemble mean, standard deviation, max and median. Analysis and First Guess (first-guess is an analysis-initialized forecast) availability depends on the variable. Note all the variables provide instantaneous values except Dry and Wet Dust Depositions that consider accumulated values over the previous 3 hours.

Variable	Abbreviation	Unit	First-Guess	Analysis
Dust Optical Depth at 550 nm	od550du	-	x	x
Coarse Dust Optical Depth at 550 nm	od550ducoarse	-	x	x
Surface Dust Extinction Coefficient at 550 nm	sec550du	m^{-1}	x	x
Surface Dust Concentration per size bin	sconcdubin[1-8]	$kg\ m^{-3}$	x	x
Dust Load per size bin	loaddubin[1-8]	$kg\ m^{-2}$	x	x
Dry Dust Deposition	drydu	$kg\ m^{-2}\ s^{-1}$	x	
Wet Dust Deposition	wetdu	$kg\ m^{-2}\ s^{-1}$	x	
Global Horizontal Irradiance	ghi	$W\ m^{-2}$	x	
Direct Normalized Irradiance	dni	$W\ m^{-2}$	x	
Altitude above sea level	z	m	x	
Dust concentration per size bin (3D)	concdubin[1-8]	$kg\ m^{-3}$	x	x
Dust Extinction Coefficient at 550 nm (3D)	ec550du	m^{-1}	x	x

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 in Figure 3.1 and dust surface concentration in Figure 3.2 for the period of 2007-2017 together with the anomalies of each year. The annual climatologies for both variables (Figure 3.1 and 3.2, last plot) show the main dust sources in Northwestern Africa, El Djouf desert and Bodélé Depression and Middle East deserts and they are very similar to the previous report of the decadal climatology 2007-2016. From the anomalies of annual DOD (Figure 3.1) we notice years when the sources of North Africa contribute to higher DOD levels compared to the climatology, in particular 2017, years when the contribution from the North African sources can be higher while the ones from Middle East are lower as in years 2007, 2010 and 2015, or the opposite behavior as in years 2009 and 2012. In general, the interannual variability can be very significant (>50% of the climatological DOD). Similar conclusions can be drawn for the dust surface concentrations (Figure 3.2). However, the stronger sensitivity of surface concentration to local emissions enhances smaller scale patterns within the anomaly maps.

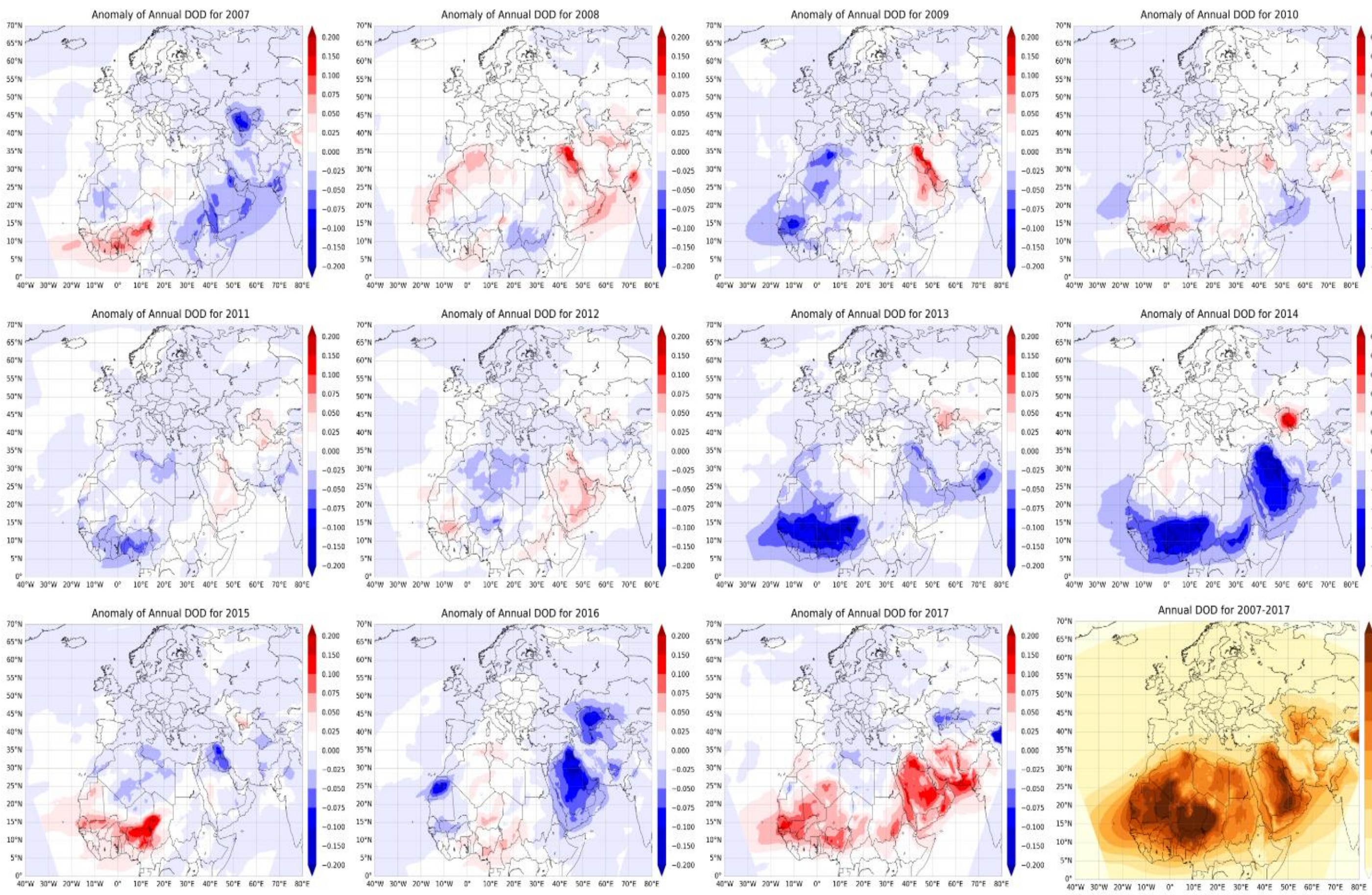

Figure 3.1 Yearly anomalies of Dust Optical Depth (DOD) at 550 nm together with the annual climatology (last plot) averaged over the 11-year period, 2007-2017.

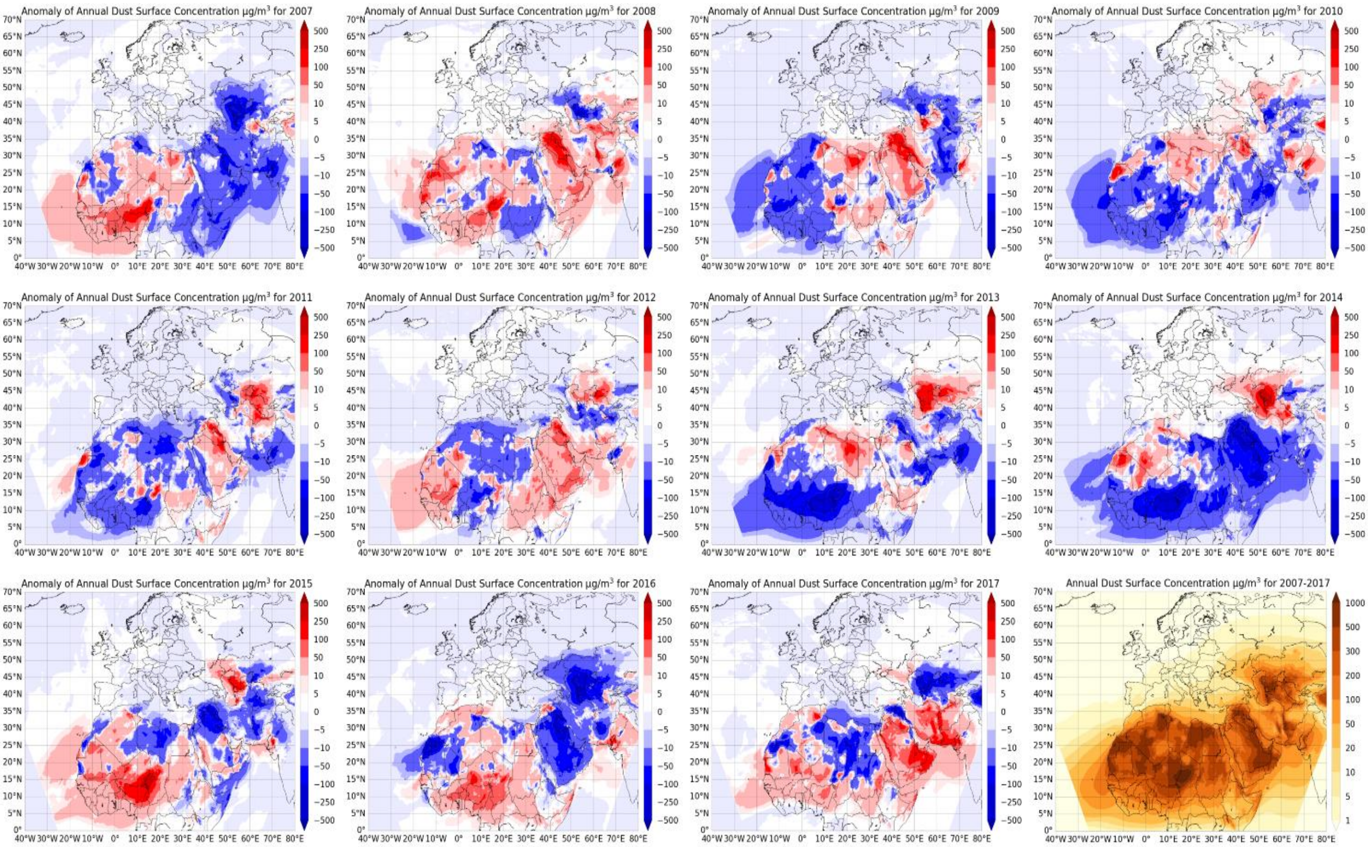

Figure 3.2 Yearly anomalies for dust surface concentration together with the annual climatology averaged over the 11-year period, 2007-2017.

Monthly timeseries of the DOD and the dust surface concentration for each year are reported in Figure 3.3. The dust cycles of the two variables are not identical to each other since the peak of the seasonal cycle occurs in different months of the year; however, they both present lower monthly means during autumn. Maxima in dust optical depth are found in spring and in summer, while seasonal dust surface concentration is the highest during winter and spring. There is a distinct seasonal cycle which is repeated throughout the years for both variables as well. For DOD a season of increased dust activity starts on average in February and ends in September, and then it is followed by a period characterized by low DOD values. The fact that the duration of the high DOD season can vary from year to year constitutes an indicator of the interannual variability. Strongest interannual variability occurs between spring and summer and is relatively low afterwards (2008 and 2017 being an exception). Dust surface concentration follows a seasonal cycle characterized by maximum dust concentration values during winter (December to March) which gradually declines reaching minimum values between August and October. The maximum winter surface concentrations are mainly driven by the main deserts in North Africa. It is during wintertime when low-level transport is produced in the Sahel due to the Harmattan winds. The maximum surface concentrations in summer are enhanced by the main deserts in Middle East, due to the Shamal and Levar winds.

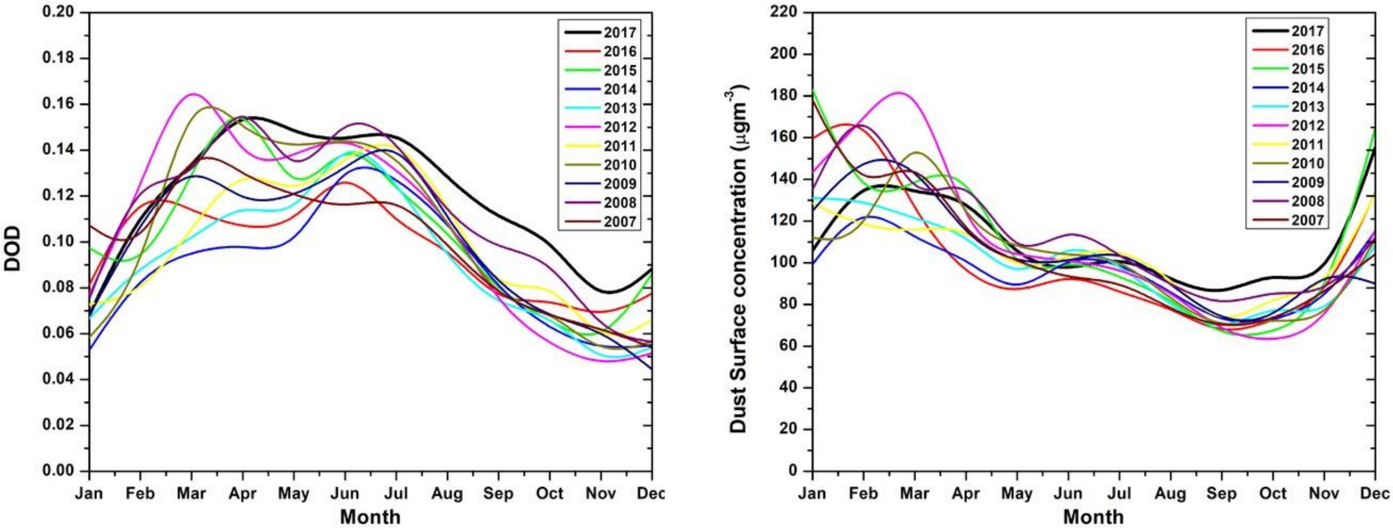

Figure 3.3 Timeseries for monthly DOD (left column) and dust surface concentration (right column) for each year of reanalysis from 2007-2017. The different colors represent each year. The annual DOD for each year (from 2007 until 2017 respectively) was (0.10, 0.11, 0.10, 0.10, 0.10, 0.11, 0.09, 0.09, 0.10, 0.10, 0.12) and the annual surface concentration was (106, 113, 105, 103, 104, 110, 100, 96, 111, 104, 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 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 4.1).

Table 4.1 Validation metrics used in this study and their definition.

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

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 2007-2017 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.

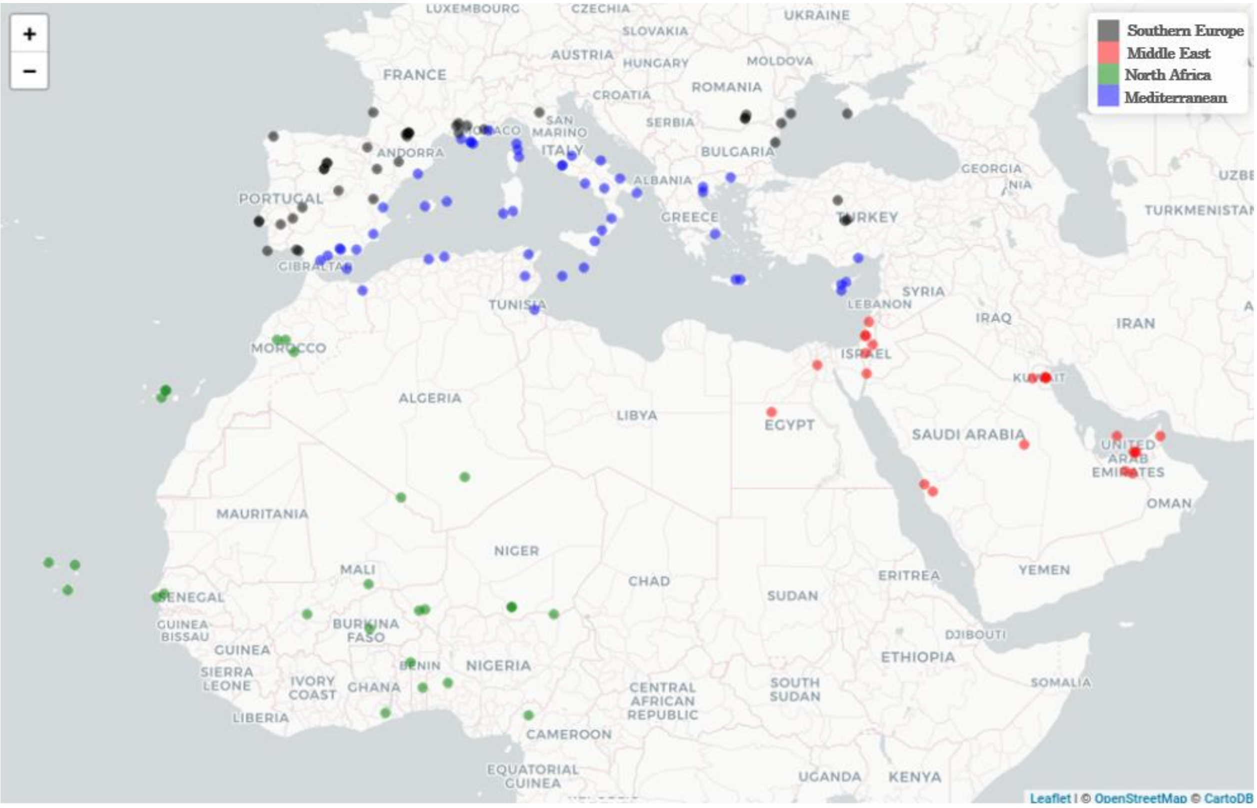

Figure 4.1 The AERONET stations used in this study per region they cover. With blue are represented the Mediterranean station, with green the North African stations, with red the Middle East stations and with blue the remaining Southern Europe stations.

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 colocated 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

Using Providentia, we constructed timeseries of colocated modeled and observed values for the whole period from 2007 until 2017 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.

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). The DODcoarse analysis mean is discussed in this evaluation. Using the median of the analysis ensemble instead of the average does not change significantly the results (not shown). From the timeseries of the DODcoarse/AODcoarse (Figure 4.2) either for the whole domain or each sub-region we see that every year the peaks are around the spring-summer months, in agreement with Figure 4.3 earlier. The strongest interannual variability is, as expected, found in regions where dust sources are located (North Africa and Middle East). There is a systematic underprediction of the monthly AODcoarse and this underprediction is similar in amplitude for Mediterranean, North Africa and Southern Europe but absent in the Middle East. Specifically, looking at the statistics of Table 4.2, the average MB for all NAMEE for a total of almost 372k measurements (in 3-hourly intervals) is -0.03, while for North Africa is the highest (-0.05), suggesting that the intensity of African dust sources is underpredicted. This behavior was already identified by Di Tomaso et al. (2022), applying also multiple dust identification strategies to AERONET data. Different reasons could explain such a systematic bias: contribution of other aerosols to the AERONET AODcoarse (especially in Southern Europe and the Mediterranean region), limitations in the calibration of the dust emission schemes used to compute the ensemble members, systematic biases between the assimilated observations (MODIS) and AERONET or a combination of them.

The correlation for all NAMEE is equal to 0.8, with higher values for the region of North Africa (equal to 0.81) where the main dust sources are located, 0.73 for Mediterranean, 0.71 for Middle East and 0.69 for Southern Europe. These values are almost the same as the ones reported in Di Tomaso et al. (2022), where the period though was 2007-2016. Also similar are the values for RMSE where for the whole NAMEE is equal to 0.09 (same for NAMEE in Di Tomaso et al. 2022 and the period 2007-2016). Higher are the RMSE with values between 0.13-0.15 for the regions of Middle East and North Africa while lower for Mediterranean and Southern Europe (0.05 and 0.07 respectively). The MFB for all stations is equal to -90.5% (or almost -0.91% as in Di Tomaso et al. 2022 using one less year for the analysis) with higher values once again for Mediterranean and Southern Europe and less for North Africa and Middle East.

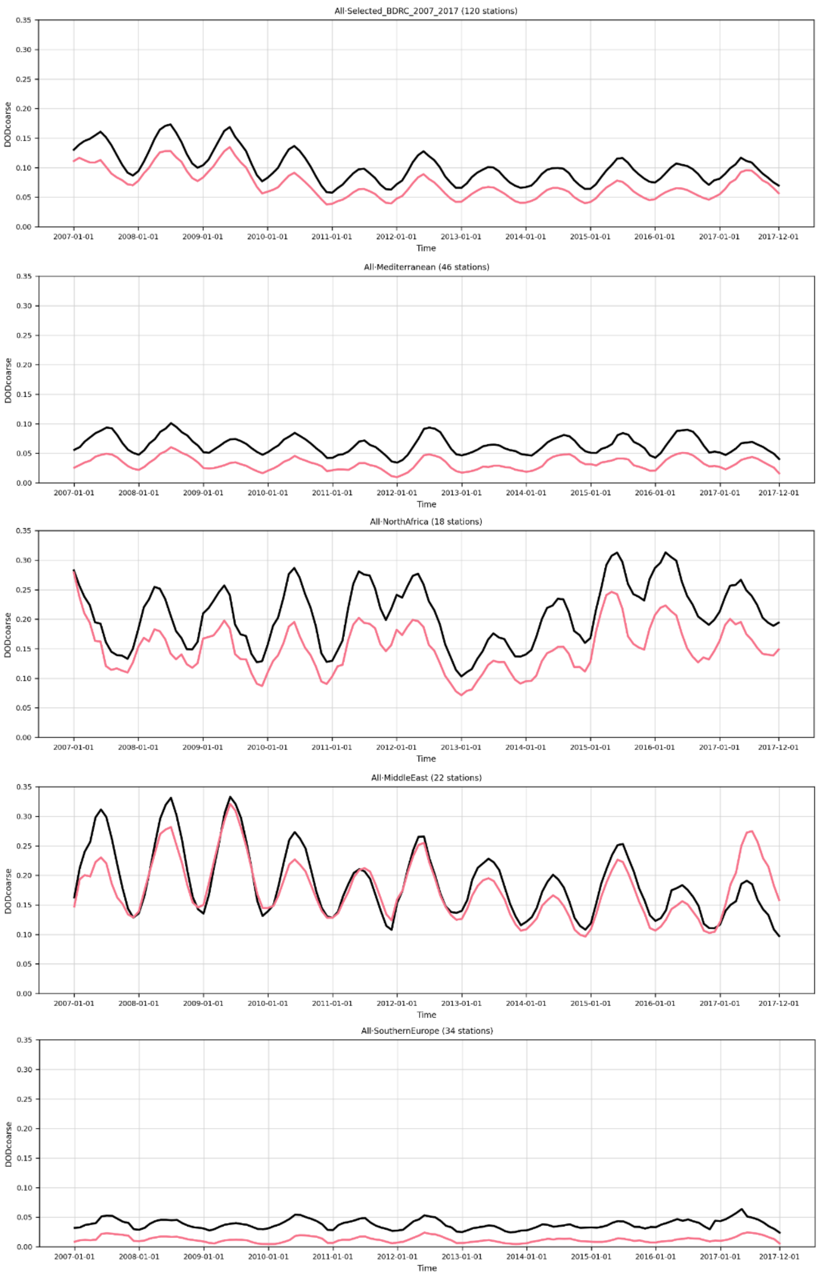

Figure 4.2 Timeseries in monthly intervals (calculated from 3hourly measurements) for the whole period of 2007-2017 of O'Neill AODcoarse AERONET measurements (black line) and DODcoarse from the reanalysis dataset (pink line). The first row is for the whole NAMEE stations, the second for the Mediterranean stations, the third for North Africa stations, the fourth for Middle East stations and the fifth for the Southern Europe stations.

Similar were the conclusions looking at the MFE, which is 110.2% for the NAMEE while for Mediterrean and Southern Europe is between 123-147% and for Middle East and North Africa between 56-75%. In general, the lowest fractional errors are found in dust sources regions and the highest away from sources, pointing either to some deficiencies in the modelling of atmospheric transport or to some potential limitations in the dust-filtering of AERONET AOD. Nevertheless, robust 3-hourly and monthly (not shown) correlations suggest that the reanalysis is quite capable of reproducing the seasonal and interannual variability of dust in all regions.

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 (2007–2017) for the whole NAMEE and for the Mediterranean, North Africa, Middle East, and Southern Europe regions.

	NDATA	r	RMSE	MB	MFB(%)	MFE(%)
NAMEE	372916	0.80	0.09	-0.03	-90.5	110.2
Mediterranean	140315	0.73	0.07	-0.03	-113.9	123.0
North Africa	48878	0.81	0.15	-0.05	-50.3	75.7
Middle East	76485	0.71	0.13	-0.01	-2.3	56.7
Southern Europe	107238	0.69	0.05	-0.03	-141.2	147.4

5. Conclusions

In this report we evaluated one additional year (2017) of the MONARCH dust reanalysis and recomputed climatological fields for Dust Optical Depth (DOD) and dust surface concentrations for the full available period (2007-2017). The objective was twofold: i) set up a new protocol to evaluate the dust reanalysis each time a new yearly dataset is produced, ii) ensure consistency with previously published time series (2007-2016).

The 2007-2017 reanalysis dataset was validated against AERONET AODcoarse measurements using for the first time the Providentia tool. Results are in line with those reported in previous publications (Di Tomaso et al., 2022). The same methodology will now be used for the follow-up dust reanalysis reports.

6. References

Anderson, T. L., Wu, Y., Chu, D. A., Schmid, B., Redemann, J., and Dubovik, O.: Testing the MODIS satellite retrieval of aerosol fine-mode fraction, J. Geophys. Res. Atmos., 110, D18204, https://doi.org/10.1029/2005JD005978, 2005.

Berrisford, P., Dee, D., Poli, P., Brugge, R., Fielding, K., Fuentes, M., ... & Simmons, A.: The ERA-Interim archive Version 2.0, Shinfield Park. Reading, 1, 23, 2011.

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.

Eck, T. F., Holben, B. N., Reid, J. S., Dubovik, O., Smirnov, A., O'Neill, N. T., Slutsker, I., and Kinne, S.: Wavelength dependence of optical depth of biomass burning, urban and desert dust aerosols, J. Geophys. Res., 104(D24), 31333–31350, 1999.

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., ... & Zhao, B.: The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). Journal of climate, 30(14), 5419-5454.Ginoux, P., Chin, M., Tegen, I., Prospero, J. M., Holben, B., Dubovik, O., & Lin, S. J. (2001). Sources and distributions of dust aerosols simulated with the GOCART model. Journal of Geophysical Research: Atmospheres, 106(D17), 20255-20273, 2017.

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., Garbuzov, D., and Hsu, N.C.: Identification of anthropogenic and natural dust sources using Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue level 2 data, J. Geophys. Res. Atmos., 115, doi:10.1029/2009jd012398, 2010.

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.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz‐Sabater, J., ... & Thépaut, J. N.: The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999-2049, 2020.

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.

M. Mytilinaios, L. Mona, S. Trippetta, F. Barnaba, S. Basart, E. Di Tomaso, J. Escribano , C. Pérez García-Pando, O. Jorba, B. Marticorena, P. Formenti, C. Di Biagio, J. Cuesta: Report on reanalysis evaluation results and associated uncertainties. ERA4CS DustClim Technical Report, 2021.

Mona, L., S. Trippetta, S. Basart, E. Di Tomaso, J. Escribano: Dust-filtered observations for data assimilation, ERA4CS DustClim Technical Report, 2018.

Mona, M., S. Ciamprone, M. Mytilinaios, S. Basart, E. Di Tomaso, C. Pérez García-Pando, O. Jorba: Report on the dust climatology results, ERA4CS DustClim Technical Report, 2021.

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., 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.

Pu, B. & Ginoux, P.: The impact of the Pacific Decadal Oscillation on springtime dust activity in Syria. Atmos Chem Phys 16, 13431–13448, doi:10.5194/acp-16-13431-2016, 2016.

Takemura, T., Uno, I., Nakajima, T., Higurashi, A., & Sano, I.: Modeling study of long – range transport of Asian dust and anthropogenic aerosols from East Asia. Geophysical Research Letters, 29(24), 11-1, 2002.