Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-251
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 November 2018

Geoscientific Model Development
Discussions

Development of a dynamic dust-source map for NMME-DREAM v1.0 model based on MODIS NDVI over the Arabian Peninsula

Solomos Stavros[1,2], Abdelgadir Abuelgasim[2], Christos Spyrou[3], Ioannis Binietoglou[4], Slobodan Nickovic[5]

Abstract We developed a time dependent dust source map for NMME-DREAM v1.0 model based on the satellite MODIS Normalized Digital Vegetation Index (NDVI). Areas with NDVI<0.1 are classified as active dust sources. The new modeling system is tested for the analysis of dust particles dispersion over SW Asia using a mesoscale model grid increment of 0.1°×0.1° km for a period of 1 year (2016). Our results indicate significant deviations in simulated Aerosol Optical Depths compared to the static dust-source approach and general increase in dustloads over the selected domain. Comparison with MODIS Aerosol Optical Depth (AOD) indicates a more realistic spatial distribution of dust in the dynamic source simulations compared to the static dust sources approach. The modeled AOD bias is improved from -0.140 to 0.083 for the case of dust events (i.e. for AOD >0.25) and from -0.933 to -0.424 for dust episodes with AOD>1. This new development can be easily applied to other time periods, models and different areas worldwide for a local fine tuning of the parameterization and assessment of its performance.

[1] Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing (IAASARS), National Observatory of Athens, Athens, Greece, stavros@noa.gr

[2] Department of Geography and Urban Planning, National Space Science and Technology Center, United Arab Emirates University

[3] Department of Geography, Harokopio University of Athens (HUA), El. Venizelou Str. 70, 17671 Athens, Greece.

[4] National Institute of R & D for Optoelectronics, Magurele, Ilfov, Romania

[5] Republic Hydrometeorological Service of Serbia , Belgrade, Serbia

Keywords: dust, Arabian Peninsula, DREAM, NDVI, model, satellite

Introduction

The importance of natural particles, namely desert dust, in the weather and climate has been underlined in a great number of studies.Dust is a climatic regulator, as it modifies extensively the radiative balance of the atmospheric column (Torge et al., 2011; Spyrou et al., 2013; Mahowald et al., 2014). At the same time dust aerosols modify the atmospheric water content (Spyrou 2018), the way clouds are formed by acting as cloud condensation nuclei (CCN)and ice nuclei (IN) and the precipitationprocesses (Kumar et al., 2011; Solomos et al., 2011; Nickovic et al., 2016). In addition, there is a clear connection between dust particles and human health disorders, as the size of the produced aerosols is small enough to cause respiratory and cardiovascular diseases, as well as pathogenic conditions due to the microorganisms that they can potentially carry (Mitsakou et al., 2008; Esmaeil et al., 2014).

The Arabian Peninsula is one of the most important sources of mineral dust worldwide and contributes together with the Saharan and Gobi Deserts in the formation of a North Hemisphere “dust belt” as described by Prospero et al. (2002). Severe dust storms over the Peninsula are quite common, especially during long periods without rain, in the spring and

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-251
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 November 2018

summer (Almazrouia et al., 2012). Particles injected into the atmosphere from arid soils, under favorable weather conditions (high wind speeds and dry soil), can affect large areasaround the sources but also remote locations like the Eastern Mediterranean (Mamouri et al., 2016; Solomos et al., 2017) and the Indian Ocean (Chakraborty et al. 2006).

Due to the multitude and severity of the feedbacks of dust particles not only on the weather and the ecosystem but to human health as well, the proper description of the production, transport and eventual deposition of the dust cycle, in numerical weather prediction models (NWPs) is essential. In order to be able to accurately describe the dust life-cycle in the atmosphere, we need a clear understanding of the areas which can potentially act as "dust sources". The definition of such areas dictates the emission strength and therefore the amount of particles inserted into the atmosphere. A proper representation of dust sources is therefore an essential first step, in studying the impacts of mineral particles in the climate and human societies. Usually the definition of the areas that can act as dust sources is made using global datasets. For example Nickovic et al. (2001) used a subjective correspondence between the Olson World Ecosystems (Olson et al., 1983) and the thirteen SSib vegetation types to identify arid and semi-arid areas. Similarly, Spyrou et al., (2010) used a 30sec global land use/cover database, classified according to the 24 category U.S. Geological Survey (USGS) land use/cover system (Anderson et al., 1976), to define active areas in SKIRON dust model. Solomos et al., 2011 used the LEAF soil and vegetation sub-model of the Regional Atmospheric Modeling System (RAMS) (Walko et al., 2000) to identify the active dust sources in RAMS-ICLAMS model.

However, the above mentioned methodologies have some significant drawbacks.The datasets are usually not up-to-date, therefore recent land-use modifications are not included and not represented. In addition, such "static" databases mean that possible seasonal variations are not taken into account. Towards the direction of overcoming the above limitations and improving global dust forecasts, Kim et al., 2013 developed a dynamical dust source map for the GOCART dust model by characterizing NDVI values < 0.15 as active dust spots. Similarly Vukovic et al., 2014 combined MODIS landcover types with pixels having NDVI < 0.1 to identify the seasonal dust sources that enforced the severe Phoenix haboob of July 2011 in the US. Such information can beeven more relevant at meso and local scales for determining landuse changes and potential dust sources, especially in heterogeneous regions such as the Arabian Peninsula and the greater SW Asia. In this context, Solomos et al., 2017, used the Landsat-8 NDVI data (assuming also NDVI<0.1 as active sources) to identify recent changes in landuse due to the war in Iraq and Syria resulting in a significantly more realistic simulation of dust properties in the Middle East.

In the current study we present the implementation of a dynamical dust source map in the well-established and widely used DREAM v1.0 dust model (Nickovic et al., 2001; Perez et al., 2006). The new development is first tested here for the greater SW Asia but can be extended for use in mesoscale dust modeling applications worldwide. Two experimental simulations are performed for one month period (August 2016) over the greater SW Asia: 1) Control run, where the dust source definition is based on Olson World Ecosystems dataset and 2) Dynamic source run, where the NDVI values are used to identify the dust sources. The model results from both runs are compared to available satellite observations and station measurements inside the modeling domain. In section 1 we describe the methodological steps regarding the model

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-251
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 November 2018

developments and remote sensing data; Section 2 includes the results of the experimental runs and section 3 is a summary and discussionof the study findings.

1. Methodology

1.1. Model description

The modeling system used in this study is NMME-DREAM v1.0. The meteorological core is the NCEP/NMME atmospheric model (Janjic et al., 2001). The Dust Regional Atmospheric Model (DREAM v1.0) is a numerical model created with the main purpose to simulate and predict the atmospheric life-cycle of mineral dust using an Euler-type partial differential nonlinear equation for dust mass continuity (Nickovic et al., 2001; Perez et al., 2006; Pejanovic et al., 2011, Nickovic et al., 2016). Once particles have been lifted from the ground they are driven by the atmospheric model variables and processes. Therefore turbulent parameters are used in the beginning of the process, when dust is lifted from the ground, and transported by model winds in the later phases when dust travels away from the sources. Dust is eventually settled through rainfall and/or dry deposition processes.

In order to test the use of NDVI for source characterization, the model is setup with a horizontal resolution of 0.1°x0.1°, covering the Arabian Peninsula parts of SW Asia and parts of NE Africa (Figure 1). On the vertical we use 28 levels stretching from the surface to the top of the atmosphere. August 2016 has been selected as a test period for the model development due to the significant dust activity and variability in wind properties during this month. The original classification of dust sources in DREAM is based on Ginoux et al., 2001 that takes into account the preferential sources related to topographic depressions and paleolake sediments. In our work, a numerical procedure has been developed to insert the NDVI satellite information into the model and to update such info each time the NDVI changes, during the simulation period. We assume that regions with NDVI values from 0 to 0.1 correspond to bare soil and therefore can be efficient sources (“dust points”; DeFries and Townshend, 1994; Solomos et al., 2017). TheNDVI dataset is at finer resolution than the model grid and in order to find the potential for dust production in each model grid box, we calculate the following ratio:

$$A_{grid\_box} = \frac{\#\_of\_dust\_points}{Total\_\#\_of\_points}$$

This approach allows for a dynamic description of dust source areas over the model domain to replace the previously used static database. Moreover, the scaling of satellite data over model grid points allows the use of the same algorithm for different model configurations. Additionally, we have applied a limit to dust efficiency over high mountains. Several mountains in the area (e.g. the Sarawat Mountains along the Red Sea coast and the Zagros Mountains in Iraq) could be misclassified as dust sources due to low NDVI values. These areas need to be excluded from the new dust-source map and the modeled dust efficiency is modified accordingly.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-251
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 November 2018

Geoscientific Model Development Discussions Open Access

In Figure 2a we show the static sources in the original model version with a factor of 0 to 1 depending on the source area strength. Accordingly in Figure 2b we show the new dynamic sources for August 2016.

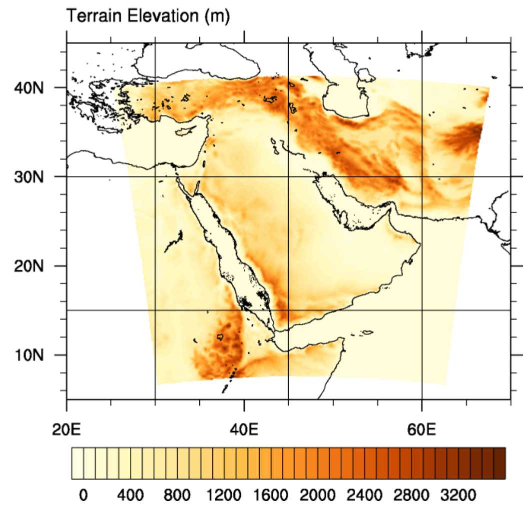

Figure 1: DREAM model domain and topography in meters

1.2 NDVI description

For the purposes of our study we used the 500m 16-day averaged NDVI from MODIS (Didan, 2015) for the period of interest. The NDVI is a normalized transform of the near infrared to red reflectance ratio, designed to provide a standard for vegetation and takes values between -1 and +1. Since it is expressed as a ratio, the NDVI has the advantage of minimizing certain types of band-correlated noise (positively-correlated) and influences attributed to variations in irradiance, clouds, atmospheric attenuation and other parameters (Solano et al., 2010).

To create an accurate time-dependent dust source map, we have utilized the Normalized Difference Vegetation Index (NDVI) derived from the MODIS/Terra instrument. NDVI is calculated as the normalized difference of reflectance in the red and near-infrared channels (Rouse et al., 1974; Huete et al. 2002) i.e.,

$$NDVI = \frac{X_{nir} - X_{red}}{X_{nir} + X_{nir}}$$

where X represents the top of the atmosphere reflectance in each channel. For terrestrial targets, NDVI will take values near 0.8 for vegetated areas and near 0 for barren soil (Huete et al., 1999). Since it is expressed as a ratio, the NDVI has the advantage of minimizing certain types of noise and influences attributed to variations in irradiance, clouds, cloud-shadows, atmospheric attenuation, and other parameters (Solano et al., 2010). Specifically, we have used the 500m 16-day averaged NDVI from MODIS/Terra instrument (Didan, 2015) to calculate high-resolution barren soil. The high-resolution masks was used to calculate the percentage of barren land in each 0.1°x0.1° model grid cells and this percentage was used to define the effective strength of dust sources in each cell.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-251
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 November 2018

Geoscientific Model Development
Discussions
Open Access

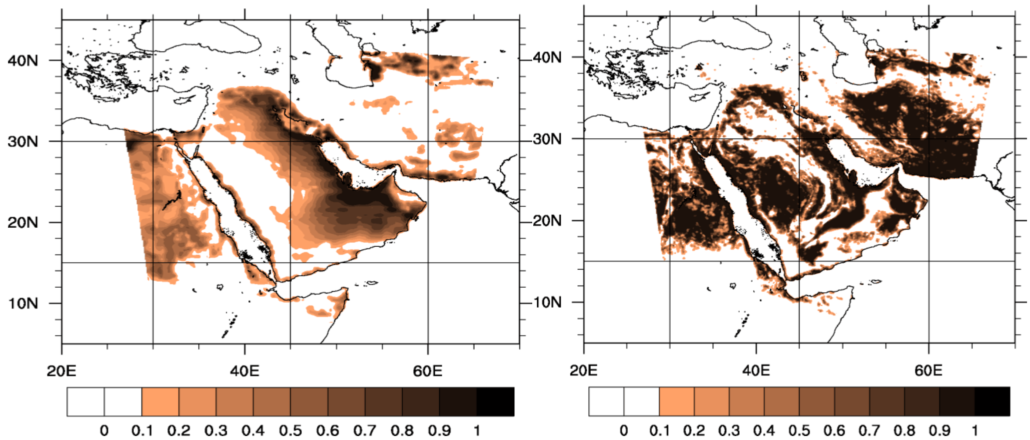

Figure 2: Dust source strength as defined by (a) the Ginoux et al., 2001 dataset and (b) the August 2016 NDVI

2. Results

In order to test the performance of the new methodology we run the model in two different configurations: (1) Using the static Ginoux et al., 2001 dust source database, called CTRL_run from now on, and (2) using the dynamic NDVI database as described above, called NDVI_run from now on. Both setups are initialized using the NCEP GFS analysis files (0.5°×0.5° at 00, 06, 12 and 18 UTC), which were used for boundary conditions as well. The two model configurations are identical other than the dust source database. The test simulation period is 1-31 August 2016 and the results from both simulations are compared to MODIS and AERONET AOD until we conclude to an optimal model setup. A five days spin up model run, prior to the experimental period, is used for establishing the dust background over the domain. After finalizing the experimental model configuration we perform a complete one-year run (2016) and evaluate the results against AERONET stations.

2.1 Dust transport during August 2016

The selected 1-month period is characterized by a significant variability in wind speeds and directions which allows the evaluation of the new model version under different conditions. During 1-10 August, east winds prevail over the region and increased dust concentrations are found mostly along the central, east and south coastal areas of the Arabian Peninsula. An anticyclonic circulation is established during 10-15 over the Arabia Desert and increased dust concentrations are mostly found over the central desert areas. On 16-26 August the circulation is mainly from north directions and thick dust plumes are advected southwards towards the Arabian Sea. The north winds veer to east on 26-31 August and increased dustloads are found over the Arabian Gulf during these dates.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-251
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 November 2018

2.2 Comparison with MODIS and AERONET

The monthly average AOD for August 2016 is shown in Figure 3 for the two experimental runs (Figure 3a,b). The NDVI_run results in a significantly modified spatial distribution of dust presenting increased dustloads over the entire domain and most profoundly over the Red Sea and Arabian Gulf (Figure 3b). This dust pattern is closer to the MODIS observed AOD over the same period that is shown in Figure 3c. The MODIS AOD in this area is mostly related to dust, however it must be taken into account that other aerosols not parameterized in the model (e.g. sea salt, sulphates, nitrates) may also contribute to the observed MODIS AOD.

More specifically the NDVI_run reproduces the MODIS observed AOD pattern that is in general characterized by values 0.3-0.4 at the NW parts of the Arabian Peninsula and by values 0.4-0.8 at the SE parts. Significant improvement is also evident over the Red Sea and NE Africa. The NDVI_run captures the maximum observed AOD values reaching up to 1.6 over the Red Sea and also the southwesterly extension of an AOD tongue of 0.3-0.8 towards Soudan. At the east parts of the modeling domain the NDVI_run again outperforms the CTRL_run since it reproduces the spatial distribution of AOD 0.4-0.8 over the Arabian Sea and the maximum of 0.8-1.2 at the SE edge of Arabian Peninsula. Inside the Gulf, the NDVI run correctly represents the 0.4-0.8 AOD but the dust concentration is over-predicted at the Strait of Hormuz and along the Iran - Pakistan coastline. This is mostly due to the prevailing NE winds during the last days of the August 2016 modeling period and due to a possible miss-classification of Iran and Pakistan grid points as effective dust sources thus favoring unrealistic southeasterly transport towards the Gulf of Oman.

As a second step we run the same model configurations (CTRL and NDVI) for the entire 2016. The modeled dust optical depth is compared with the regional AERONET ground-based photometric measurements of AOD considering only dust relevant measurements with Angström Coefficient <0.6 (Holben et al., 1998) and the results are shown in Table 1. For completeness we first consider all AERONET stations inside the modeling domain for the evaluation. However the stations that are at the margins of our domain (Cairo_EMA_2, SEDE_BOKER, AgiaMarina_Xyliatou and El_Farafra) are also affected by other dust source areas (e.g. Sahara Desert) and their statistics are not representative for Arabian and Middle East sources. Instead, the comparison with Arabian Peninsula stations (Eilat, Kuwait_University, KAUST_Campus and Mezaira) provides more insight on the effects of the new source characterization. As seen in Figure 4 and also in Table2 these stations are clearly benefited from the experimental run.

In general the two runs present a significant statistical difference and more remarkably a reverse of bias (MODEL-AERONET) from negative in the CTRL_run to positive in the NDVI_run. The NDVI_run produces increased AODs that are neither linearly proportional to the CTRL_run AODs nor uniformly distributed over the domain. When considering only Arabian stations, the statistical metrics in Table 1 and especially the fractional gross error and bias are improved but the RMSE is increased due to the increase in maximum modeled AODs. In order to investigate

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-251
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 November 2018

Geoscientific Model Development Discussions

the sensitivity of our results towards the severity of dust events we further assume two additional air quality states in Table 1: (i) dust events (AOD>0.25) and (ii) severe dust episodes (AOD>1). The bias reverse is evident in both cases however when considering AOD>1 even the NDVI run under-predicts the dustloads however with a lower RMSE (0.586 versus 0.983). This is clearly evident in Figure 5 where the NDVI run is indeed more realistic but still does not reproduce the extreme AOD during severe episodes. For most of the cases such high AODs should be attributed to duststorms from convective downdrafts (haboobs). These processes are not resolved at mesoscale model resolutions (Solomos et al., 2012, 2017; Vukovic et al., 2014) and thus cannot be represented here.

Table 1. Statistical metrics from the comparison between model runs and AERONET photometers

	Mean bias (Model-Observation)		RMSE		Correlation		Fractional gross error		Mean fractional bias	
	CTRL	NDVI	CTRL	NDVI	CTRL	NDVI	CTRL	NDVI	CTRL	NDVI
AOD > 0 (All Stations)	-0.163	0.015	0.258	0.312	0.408	0.464	0.887	0.803	-0.639	0.043
AOD > 0 (Arabia Stations)	-0.142	0.122	0.252	0.332	0.340	0.426	0.644	0.515	-0.455	-0.187
AOD > 0.25 (Arabia Stations)	-0.140	0.083	0.283	0.350	0.238	0.328	0.640	0.462	-0.527	-0.142
AOD > 1 (Arabia Stations)	-0.933	-0.424	0.983	0.586	0.032	0.009	1.230	0.481	-1.211	-0.413

The AERONET stations used in this study are: Eilat (29N,34E), Cairo_EMA_2 (30N,31E), Kuwait_University (29N,47E), KAUST_Campus (22N,39E), SEDE_BOKER (30N,34E), AgiaMarina_Xyliatou (35N,33E), Mezaira (23N,53E) and El_Farafra (27N,27E)

3. Summary and Discussion

Previous attempts to scale the dust emissions by satellite NDVI in the global model GOCART (Kim et al., 2013), the mesoscale model NMME-DREAM v1.0 (Vukovic et al., 2014) and in the high resolution model RAMS-ICLAMS (Solomos et al., 2017) showed the potential of this approach for replacing the static dust source maps in the models by a dynamic dataset. In this study we present the development of a dynamic dust source map for implementation in NMME-DREAM v1.0 over the Arabian Peninsula and the greater areas of Middle East, SW Asia and NE Africa. Although the major dust sources worldwide are located in permanent deserts where the NDVI is almost always <0.1 (e.g. Bodele Depression, Gobi Desert, Arabian Desert), the dynamical scaling of dust emissions presented here can be important for providing up-to-date evidence of active dust sources over non-permanent deserts. These may include bog, marsh and semi-desert areas as well as irrigated and non-irrigated farms where landuse changes occur throughout the year. Analysis of the modeling results for one year test period (2016) over SW Asia indicated the improved performance of the new parameterization. The NDVI_run showed a significant increase in dustloads over the greater Arabian Peninsula area and a more realistic representation of the spatial distribution of AOD compared to the

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-251
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 November 2018

Geoscientific Model Development Discussions
Open Access

corresponding MODIS satellite retrievals. Comparison with AERONET measurements also showed significant improvement especially at higher AODs that are also relevant to the model efficiency for air quality purposes (i.e. the model bias is reduced from -0.140 to 0.083 at AOD>0.25 and from -0.933 to -0.424 at AOD>1). However, the model statistics are not improved for all AERONET measuring stations and for all air quality states (Table2), mainly due to a possible misclassification of dust sources in the highlands of Iran and Pakistan.

The main purpose of our work was the development and first testing of this new modeling version. A major advance of our study is the ability to implement the real-time properties of dust sources in air quality simulations (as represented by the satellite NDVI) and thus capture local or seasonal effects. In general, one year is not sufficient for extracting robust statistical results and further analysis is required to examine the performance of the proposed methodology over longer time periods and also over different areas worldwide. For example the simple approach of employing a uniform value of NDVI<0.1 for determining the active dust sources may not be adequate to represent fine-scale land properties and further adjustments may be required depending on local-scale characteristics. This new approach for the dynamic characterization of active dust sources based on NDVI can be easily implemented in other atmospheric dust models at different configurations and spatial coverage for improving their performance.

Table 2. Statistical metrics at AERONET stations

Station	Mean bias		RMSE		Correlation		Fractional gross error		Mean fractional bias	
	CTRL	NDVI	CTRL	NDVI	CTRL	NDVI	CTRL	NDVI	CTRL	NDVI
AgiaMarina_Xyliatou	-0.188	-0.185	0.226	0.224	-0.005	0.001	1.825	1.780	-1.828	-1.767
Cairo_EMA_2	-0.355	-0.344	0.406	0.399	-0.053	0.018	1.689	1.646	-1.687	-1.591
Eilat	-0.138	0.006	0.186	0.165	0.110	0.312	1.183	0.610	-1.166	0.034
El_Farafra	-0.186	-0.190	0.259	0.263	0.170	0.138	1.155	1.248	-1.218	-1.257
KAUST_Campus	-0.245	0.152	0.322	0.376	0.412	0.386	0.966	0.609	-1.001	0.342
Kuwait_University	-0.097	0.007	0.275	0.278	0.152	0.266	0.588	0.537	-0.290	0.018
Mezaira	-0.130	0.161	0.228	0.347	0.353	0.445	0.528	0.475	-0.382	0.332
SEDE_BOKER	-0.151	-0.125	0.198	0.201	0.030	0.034	1.202	1.209	-1.228	-0.921
Weizmann_Institute	-0.207	-0.180	0.264	0.255	-0.088	-0.100	1.494	1.323	-1.521	-1.197

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-251
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 November 2018

Geoscientific Model Development Discussions
Open Access

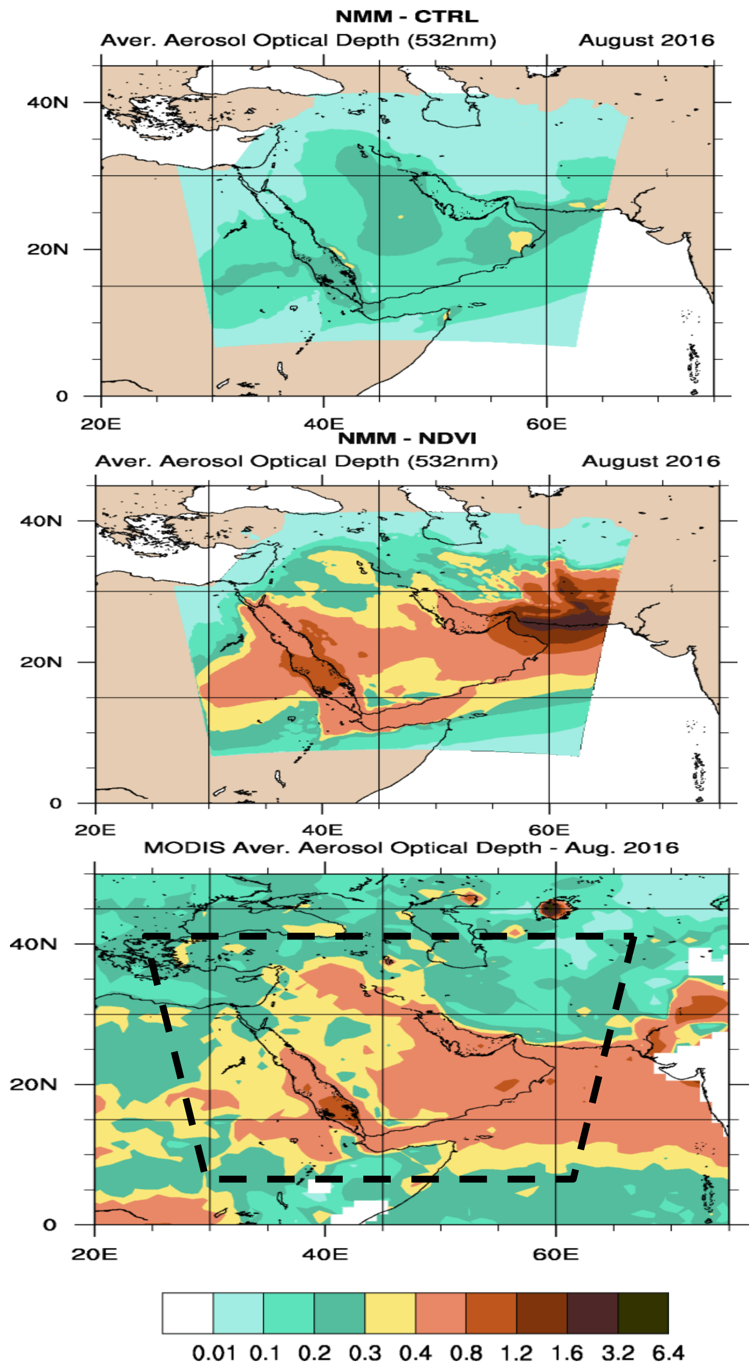

Figure 3. Monthly average simulated AOD during August 2016 from CTRL_run (a), NDVI_run (b) and (c) MODIS. The dashed trapezoid in (c) denotes the location of the modeling domain.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-251
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 November 2018

Geoscientific Model Development
Discussions
Open Access

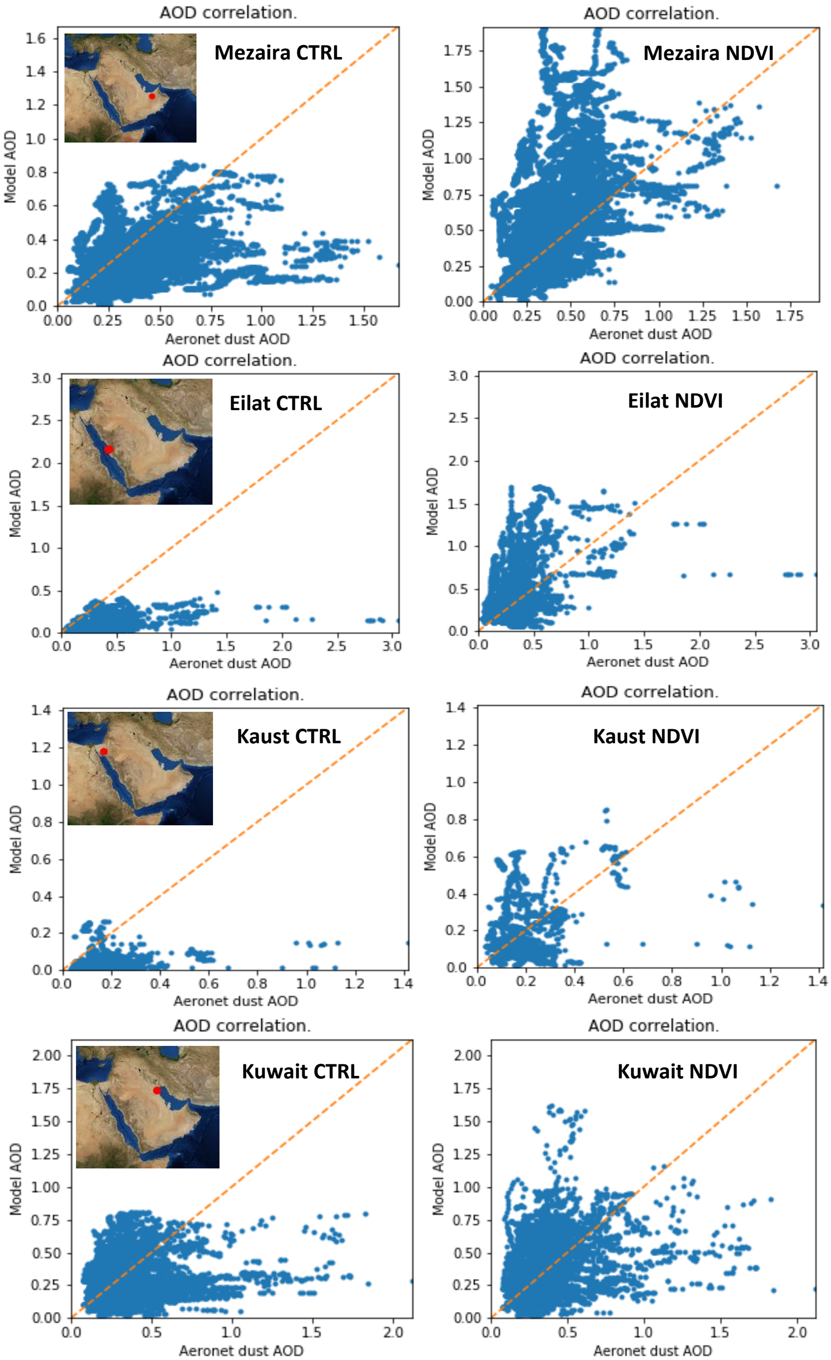

Figure 4. Correlation plots of modeled and AERONET dust AOD at the stations of Mezaira, Eilat, Kaust and Kuwait for 2016.

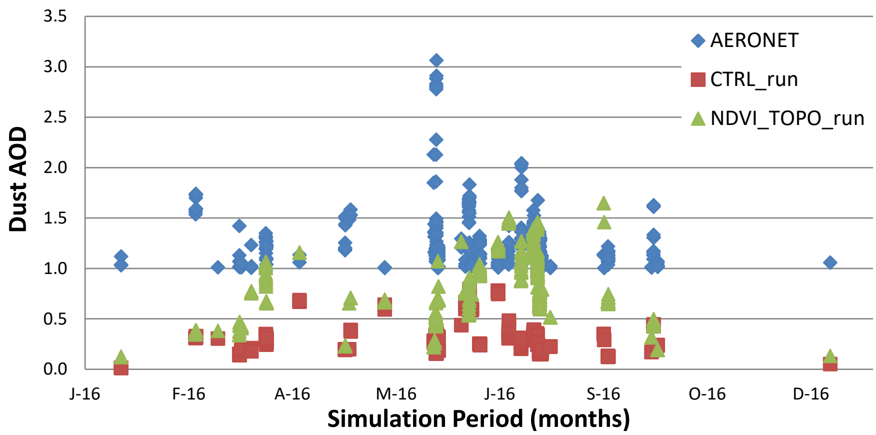

Figure 5. Timeseries of measured and modeled dust AOD for the cases of AERONET AOD>1

Code and Data availability

All code and data used in this study are available upon request

Author Contribution

SS: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft, Writing – review & editing;

AA: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing;

CS: Software, Data curation, Visualization, Writing – review & editing;

IB: Conceptualization, Formal analysis, Software, Writing – review & editing;

SN: Methodology, Supervision, Writing – review & editing;

Acknowledgements

This work was funded by a grant from the National Space Science and Technology Center of the United Arab Emirates University under grant number NSS Center 7 -2017.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-251
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 November 2018

References

Almazrouia, M., M. NazrulIslama, P.D. Jonesa, H. Athara and M. AshfaqurRahmana, Recent climate change in the Arabian Peninsula: Seasonal rainfall and temperature climatology of Saudi Arabia for 1979–2009. Atmospheric Research, 111, July 2012, p.p. 29–45., 2012

Anderson, J., E. Hardy, J. Roach, and R. Witmer, A land use and land cover classification system for use with remote sensing data, U.S. Geol. Prof. Pap. 964, U.S. Gov. Print.Off., Washington, D. C., 1976

ChakrabortyArindam, Ravi S. Nanjundiah and J. Srinivasan, Impact of African orography and the Indian summer monsoon on the low-level Somali jet, Int. J. Climatol. 29: 983–992 (2009), DOI: 10.1002/joc.1720, 2009

DeFries, R. S. and Townshend, J. R. G.: NDVI-derived land cover classifications at a global scale, Int. J. Remote Sens., 15, 3567–3586, doi:10.1080/01431169408954345, 1994.

Didan, K. , MOD13A1 MODIS/Terra Vegetation Indices 16-Day L3 Global 500m SIN Grid V006 [Data set].NASA EOSDIS LP DAAC.doi: 10.5067/MODIS/MOD13A1.006, 2015

Esmaeil N., M. Gharagozloo, A. Rezaei, G. Grunig, 2014. Dust events, pulmonary diseases and immune system, Am J ClinExpImmunol 2014 3(1):20-29, 2014.

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, 106(D17), 20,255–20,273. https://doi.org/10.1029/2000JD000053, 2001

Holben, B.N., Eck, T.F., Slutsker, I., Tanre, D., Buis, J.P., Setzer, A., Vermote, E., Reagan, J.A., Kaufman, Y., Nakajima, T., Lavenu, F., Jankowiak, I., Smirnov, A., AERONET a federated instrument network and data archive for aerosol characterization. Rem. Sens. Environ. 66, 1e16., 1998

Huete, A. R., Justice, C., and van Leeuwen, W., MODIS Vegetation index (MOD 13): Algorithm Theoretical Basis Document, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, 1999

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G., Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sensing of Environment,83, 195–213., 2002

Janjic, Z.I., GerrityJ.P.Jr., and *Nickovic*, *S.*, An Alternative Approach to Nonhydrostatic Modeling. Monthly Weather Review, 129: 1164-1178., 2001

Kim, D., M. Chin, H. Bian, Q. Tan, M. E. Brown, T. Zheng, R. You, T. Diehl, P. Ginoux, and T. Kucsera, The effect of the dynamic surface bareness on dust source function, emission, and distribution, J. Geophys. Res.Atmos., 118, 871–886, doi: 10.1029/2012JD017907., 2013

Kumar, P., Sokolik, I. N., and Nenes, A.: Measurements of cloud condensation nuclei activity and droplet activation kinetics of fresh unprocessed regional dust samples and minerals, Atmos. Chem. Phys., 11, 3527–3541, doi:10.5194/acp-11-3527-2011, 2011.

Mahowald, N, Albani, S., Kok, J. F., Engelstaeder, S., Scanza, R., Ward, D.S., Flanner, M.G., The size distribution of desert dust aerosols and its impact on the Earth system, Aeolian Research, 15, 2014, Pages 53-71, https://doi.org/10.1016/j.aeolia.2013.09.002., 2014

Mamouri, R.-E., Ansmann, A., Nisantzi, A., Solomos, S., Kallos, G., and Hadjimitsis, D. G.: Extreme dust storm over the eastern Mediterranean in September 2015: satellite, lidar, and

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-251
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 November 2018

Geoscientific Model Development Discussions

surface observations in the Cyprus region, Atmos. Chem. Phys., 16, 13711-13724, https://doi.org/10.5194/acp-16-13711-2016, 2016

Mitsakou, C., Kallos, G., Papantoniou, N., Spyrou, C., Solomos, S., Astitha, M., and Housiadas, C.: Saharan dust levels in Greece and received inhalation doses, Atmos. Chem. Phys., 8, 7181-7192, https://doi.org/10.5194/acp-8-7181-2008, 2008.

Nickovic, S., G. Kallos, A. Papadopoulos, and O. Kakaliagou, A model for prediction of desert dust cycle in the atmosphere, J. Geophys. Res., 106(D16), 18,113–18,129, 2001

Nickovic, S., Cvetkovic, B., Madonna, F., Rosoldi, M., Pejanovic, G., Petkovic, S., and Nikolic, J.: Cloud ice caused by atmospheric mineral dust – Part 1: Parameterization of ice nuclei concentration in the NMME-DREAM model, Atmos. Chem. Phys., 16, 11367-11378, https://doi.org/10.5194/acp-16-11367-2016, 2016.

Olson, J. S., J. A. Watts and L. J. Allison, Carbon in Live Vegetation of Major World Ecosystems, Report ORNL-5862, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA., 1983

Pejanovic, G., S. Nickovic, M. Vujadinovic, A. Vukovic, V. Djurdjevic, M. Dacic, Atmospheric deposition of minerals in dust over the open ocean and possible consequences on climate. WCRP OSC Climate Research in Service to Society, 24-28 October 2011, Denver, CO, USA, 2011

Pérez, C., S. Nickovic, J. M. Baldasano, M. Sicard, F. Rocadenbosch, and V. E. Cachorro, A long Saharan dust event over the western Mediterranean: Lidar, Sun photometer observations, and regional dust modeling, J. Geophys. Res., 111, D15214, doi:10.1029/2005JD006579., 2006

Prospero J. M., P. Ginoux, O. Torres, S. E. Nicholson, and T. E. Gill, Environmental characterization of global sou7rces of atmospheric soil dust identified with the nimbus 7 total ozone mapping spectrometer (TOMS) absorbing aerosol product, Rev. Geophys., 40(1), 1002, doi:10.1029/2000RG000095, 2002

Rouse Jr, R. H. Haas, J. A. Schell, and D. W. Deering. "Monitoring vegetation systems in the Great Plains with ERTS."In NASA. Goddard Space Flight Center 3d ERTS-1 Symp., Vol. 1, Sect. A p 309-317, 1974

Solano, R., K., Didan , A., Jacobson and A. Huete, MODIS Vegetation Index User's Guide, ver. 2.0, Vegetation Index and Phenology Lab, http://vip.arizona.edu, The University of Arizona., 2010

Solomos, S., Kallos, G., Kushta, J., Astitha, M., Tremback, C., Nenes, A., and Levin, Z.: An integrated modeling study on the effects of mineral dust and sea salt particles on clouds and precipitation, Atmos. Chem. Phys., 11, 873–892, doi:10.5194/acp-11-873-2011, 2011.

Solomos, S., Ansmann, A., Mamouri, R.-E., Binietoglou, I., Patlakas, P., Marinou, E., and Amiridis, V.: Remote sensing and modelling analysis of the extreme dust storm hitting the Middle East and eastern Mediterranean in September 2015, Atmos. Chem. Phys., 17, 4063-4079, https://doi.org/10.5194/acp-17-4063-2017, 2017

Spyrou, C., Direct radiative impacts of desert dust on atmospheric water content, Aerosol Science and Technology, DOI: 10.1080/02786826.2018.1449940., 2018

Spyrou, C., G. Kallos, C. Mitsakou, P. Athanasiadis, C. Kalogeri and M. J. Iacono, 2013: Modeling the radiative effects of desert dust on weather and regional climate. Atmos. Chem. Phys., 13, 5489–5504, doi:10.5194/acp-13-5489-2013, 2013

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-251
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 November 2018

Geoscientific Model Development Discussions
Open Access

Spyrou, C., C. Mitsakou, G. Kallos, P. Louka, and G. Vlastou, An improved limited area model for describing the dust cycle in the atmosphere, J. Geophys. Res., 115, D17211, doi:10.1029/2009JD013682., 2010

Torge, A., Macke, A. ,Heinold, B. And Wauer, J., Solarradiative transfer simulations in Saharan dust plumes: particle shapes and 3-D effect. Tellus B, 63: 770-780. doi:10.1111/j.1600-0889.2011.00560.x, 2011

Vukovic, A., Vujadinovic, M., Pejanovic, G., Andric, J., Kumjian, M. R., Djurdjevic, V., Dacic, M., Prasad, A. K., El-Askary, H. M., Paris, B. C., Petkovic, S., Nickovic, S., and Sprigg, W. A.: Numerical simulation of "an American haboob", Atmos. Chem. Phys., 14, 3211-3230, https://doi.org/10.5194/acp-14-3211-2014, 2014

Walko RL, Band LE, Baron J, Kittel TGF, Lammers R, Lee TJ, Ojima D, Pielke RA Sr, Taylor C, Tague C, Tremback CJ, Vidale PJ, Coupled atmosphere-biophysicshydrology models for environmental modeling. J Appl Meteor 39: 931–944, 2000