Reply to Reviewer 1

Interactive comment on "Development of adynamic dust-source map for NMME-DREAM v1.0model based on MODIS NDVI over the ArabianPeninsula" by Stavros Solomos et al.

Parajuli (Referee)
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The paper proposes a dynamic dust source map based on NDVI values and use it in adust model. The "dynamics" of dust sources is an important aspect of dust emission,which is currently not represented in many dust models. In this regard, this paper attemptsto address an important concern of the dust modeling community. The paper is written concisely with great focus, which I greatly appreciate. However, some importantrelevant descriptions required are missing in the manuscript. In addition, it is not clearif the results dictate enough to justify the use of dynamic dust source map. My specificcomments are given below.

[REPLY] We thank the reviewer for the constructive comments. The general purpose of our work is to describe the development of this alternative method to our usual static representation of dust sources in DREAM. It is true that this first application is encouraging but cannot justify the replacement of current model configurations over different source regions. More tests for other areas and periods will be required with the new model setup before we conclude to an optimal dust source description which in the end might be a combination of both static and dynamic maps.

Line 52-59. It is mentioned that dust sources are represented by global datasets but it is not described 'how' exactly they are represented. Please describe how it is done, at least in DREAM. Please explain how exactly dust emission is affected when we usethe new dust source map in the DREAM model. Please show and explain the detail of the particular equation that is affected. I believe the main change is the fraction of agrid point covered by desert surface, as in equation 3 of Nicovic et al., (2001).

[REPLY] We have updated the model description section to include more information: "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. The global mapping of dust sources in Ginoux et al.,(2001) is determined from the comparison between the elevation of surface grid points at 1°×1° resolution with the surrounding hydrological basins and with the 1°×1° AVHRR (Advanced Very High Resolution Radiometer) vegetation map (DeFries and Townshend, 1994)."In the new version the ratio of arid and semi-arid vegetation points to the total vegetation points inside a model grid-box is used to calculate the corresponding dust productivity of each particular cell.

60-73: You describe other works that used dynamic dust source map but it is not clear how your 'proposed' work is similar/different to these previous works. Please make itclearer.

[REPLY]Our work is similar to Kim et al., 2013, Vukovic et al., 2014 and Solomos et al., 2017 in terms of the general objectives and methodology. We have added a revised section: "The main differences in our approach compared to the previous studies referenced above, is that we use a very high resolution NDVI product (500×500 m) in a regional modeling domain (e.g. Kim et al., 2013 used an 8×8 Km NDVI dataset extrapolated to 1°x1° global modeling domain) and our study is not limited to specific test cases (like for example Vukovic et al., 2014 and Solomos et al., 2017), but covers an extended time period, as presented below.”

78-79, in the 1) control run, do you use Ginoux et al. 2001 source map or Olson dataset? Please clarify the link between these two datasets.

[REPLY] Thank you for pointing this out. We use Ginoux et al., 2001. We have revised this sentence as: “Control run, where the dust source definition is based on the Ginoux et al., (2001) dataset”

91-99. this description is not so relevant to this study. It is not necessary to talk about partial differential equations or turbulent parameters here. This study is more about the dust source characterization so there should be more background or descriptionfrom ‘dust-source’ point of view. A few sentences about the overall model descriptionis sufficient. Rather, a brief description and comparison of different dust emissionmodels currently in use, e.g., GOCART (WRF), DEAD (CESM), MACC etc., would be helpful for the readers. Also the literature on dust source map should be extended to cover the most recent developments in this topic. Some relevant starting referencesare given below:

Parajuli, S. P and C. Zender (2017), Connecting geomorphology to dust emission through high-resolution mapping of global land cover and sediment supply, Aeol. Res., 27, pp. 47-65, doi:10.1016/j.aeolia.2017.06.002.

Ginoux, P., J.M. Prospero, T. E. Gill, N. C. Hsu, and M. Zhao (2012), Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS deep blue aerosol products, Rev. Geophys., 50(3), doi:10.1029/2012RG000388.

[REPLY] We have increased the information on the surface dust source map considerations. The revised section is now:

“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. The global mapping of dust sources in Ginoux et al.,(2001) is determined from the comparison between the elevation of surface grid points at 1°×1° resolution with the surrounding hydrological basins and with the 1°×1° AVHRR (Advanced Very High Resolution Radiometer) vegetation map (DeFries and Townshend, 1994). Recent studies indicated the contribution of both natural and anthropogenic dust sources to the overall dust emissions detected in MODIS Deep Blue product (Ginoux et al., 2012) and also the relevance of local geomorphological conditions and sediment supply (Parajuli and Zender, 2017) on the global dust emissions. All these advances in dust emissions are based on static map considerations.”

Line 103: Make it clear that August 2016 is test run but simulations are conducted forthe whole year.

[REPLY] This sentence is revised as follows: “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. One-year runs for the entire 2016 have been conducted to evaluate the performance of the static and dynamic database emission maps".

107-108: is it updated monthly or every 16 days? In many models, it is generally updated monthly. Please clarify. Also please describe the 'numerical procedure' that you mention in more detail explaining how the NDVI data is used to define the dustsources.

[REPLY] Yes we used the 500×500 m 16-day averaged NDVI from MODIS. We assume that regions with NDVI values from 0 to 0.1 correspond to bare soil and therefore can be efficient sources. The NDVI 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 ratio: number_of_dust_points / total points. The scaling of satellite data over model grid points allows the use of the same algorithm for different model configurations.

112/113: Is this ratio a modification from Nicovic et al., 2001, equation 3? Please clarify.

[REPLY] Yes, it is formally of the same kind but the input parameters are different. Instead of desert, semidesert, arid and semiarid vegetation points we use NVDI<0.1 points.

120: how are those mountainous areas removed? Western Saudi region has many dust sources with intermountain deposits; make sure that you do not overlook these sources. See below for those dust sources.

Anisimov et al. (2017), Quantifying local scale dust emission from the Arabian Red Sea coastal plain, Atmospheric Chemistry and Physics, 2017;17(2):993-1015 DOI 10.5194/acp-17-993-2017.

[REPLY] The following paragraph has been added in the revised version: "In order to exclude such unrealistic emissions from non-soil bare areas or snow-covered areas we have applied a limit of zero dust production above 2500 m over the entire domain. This simple approach has been selected in order to keep our straightforward NDVI mapping independent of vegetation and soil information. The threshold value of 2500 m does not suppress the emissions from lowlands and hillsides (e.g. the coastal areas of Hejaz Mountains in Red Sea that have been identified as hot dust spots by Anisimov et al., 2017)."

Line 146: How is effective strength of dust source defined? It is not described clearly.

[REPLY] "The high-resolution mask 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 A_{grid_box} in Eq.1"

155-165: This paragraph belongs to the 'methods' section, not the results section. Soit should appear early in the manuscript.

[REPLY] Done. We moved this paragraph to Section 1.1 (Model Description).

Line 156/157. Please describe how exactly the static Ginoux et al., 2001 dust sourcemap was used in the model previously? Is the dust emission equation 'tuned' to achieve a target AOD as commonly used in many dust models? The comparison would bebetter if the control and NDVI run both were tuned to achieve some observed AODvalue. Was the model tuned in some way to get a desired AOD?

[REPLY] The control run (CTRL) is our standard configuration and it is tuned to reproduce as much as possible the AOD over both African and Asia sources. The NDVI run is performed with exactly the same configuration other than the definition of dust sources (Eq.1).

Figure 2b. Is this map showing the values from A_gridbox that you defined earlier? Please clarify what exactlyare the plotted values.
[REPLY] Yes. This in now clarified in the caption.

Figure 3 titles: May be DREAM-CTRL and DREAM-NDVI are better titles?
[REPLY] Yes indeed, thank you. We have changed these titles throughout the revised text.

Figure 4. Please describe Figure 4 in the text properly.
[REPLY] In the revised manuscript we have changed lines 199-200 to: "The modeled dust optical depth is compared with the regional AERONET ground-based photometric measurements of AOD (Figure 4)…."

Figure 5. Please describe Figure 5 in the text properly. Is it NDVI_run or NDVI_topo_run in the legend? I think you use topographic source function (Ginoux et al., 2001) in the control run so it is confusing.
[REPLY] In the revised manuscript we use DREAM_CTRL and DREAM_NDVI instead.

You may not need to set the color bar maximum value to 6.4, which is very high. A lower value of 1-2 would be sufficient.
[REPLY] This probably refers to Figure 3. This color bar is now revised in this plot. A maximum value of 3.2 is selected, as this is the maximum value from the simulations output.

About the evaluation metrics used in the paper: This paper is about the benefit of representing 'dynamics' of dust sources. So the time-correlations should increase if the new changes are beneficial. Improvement in bias does not confirm that it is because of the better representation of the 'dynamical' aspect of dust sources. The simulated values of AOD and their range also affect the bias, which are sensitive to the process of model tuning. That is why I mentioned about tuning previously. In addition, the RMSE is reduced only in one case and it is increased in other three cases? What doesthis tell?
[REPLY]An overall tuning factor is often applied homogeneously over modeling domains. This can only result in a linear emission increase which may benefit the model results in one area but deteriorate the statistics in other areas. This is not the case here since the only change in the model (Eq.1) is the replacement of dust sources (Ginoux et al., 2001) with the NDVI dust points. The RMSE is increased for the DREAM_NDVI run due to the increase in maximum modeled AODs. For the severe dust episodes (AOD>1) the RMSE is improved.

We should perhaps think of better control and model experiments so that the comparison of the two is fairer and the difference will show the expected outcome.

[REPLY] In our opinion, the method presented in our work clearly shows the potential of satellite retrievals as an alternative method for the mapping of dust sources. In general, we believe that dust emissions should be described in atmospheric models based only on physical considerations without the need for empirical tuning factors. In this direction a combination of up to date and detailed land cover mapping with synchronous remote sensing information (e.g. NDVI from various sensors) could lead to better results in future work.

Table 1. What are fractional gross errors and mean fractional bias? Why are they relevant here? I think it is not necessary to show these values.
[REPLY] These are common statistical metrics used for example by the WMO SDS-WAS system and are included here for consistency with the operational evaluation of dust models. More description has been added in the revised text.

Some minor typing errors:
Line 6. Normalized difference
Line 9. One year
Line 31.Precipitation process
Line 68. ..be even ..
Line 248/249: rewrite the first sentence, themain purpose

[REPLY] Done, thank you.

Reply to the reviewer 2 comments

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Overall recommendation: Accept subject to minor revision

Rationale: The dust source map is one of the key aspects of the parameterization of the dust processes into NWP models. One of the biggest problems in the definition of sources is that soil conditions for dust emission change over time, cyclically through- out the year and with much less predictable inter-annual variations. Therefore, the introduction of dynamic dust source maps, based on satellite remote sensing products, seems a necessary step forward. The authors describe the implementation of a map of this type and show that with it the model considerably improves its performance.

[REPLY] We would like to thank the reviewer for his comments and suggestions. The replies to the specific comments follow:

Comments for authors:

Introduction. You should mention here previous attempts to scale the dust emissions by satellite NDVI that you mention in Section 3 (Summary and Discussion). You should emphasize the difference of your approach (if there is any).

[REPLY] We have added extended relevant sections in the revised version:

Introduction: “The main differences in our approach compared to the previous studies referenced above, is that we use a very high resolution NDVI product (500×500 m) in a regional modeling domain (e.g. Kim et al., 2013 used an 8×8 Km NDVI dataset extrapolated to 1°x1° global modeling domain) and our study is not limited to specific test cases (like for example Vukovic et al., 2014 and Solomos et al., 2017), but covers an extended time period, as presented below.”

Methodology: “The global mapping of dust sources in Ginoux et al.,(2001) is determined from the comparison between the elevation of surface grid points at 1°×1° resolution with the surrounding hydrological basins and with the 1°×1° AVHRR (Advanced Very High Resolution Radiometer) vegetation map (DeFries and Townshend, 1994).”

Summary and Discussion: “These findings support the previous results by Kim et al., 2013 who also showed an increase in dust emissions and a more realistic comparison with satellite observations in Saudi Arabia by the introduction of an NDVI based dynamic source mapping for GOCART model.”

Page 1, line 7: The expression ‘The new modeling system’ seems excessive, when you only change the dust source map.

[REPLY] The sentence has been changed to read: “The updated modeling system.”

Page 1, line 7: “. . . is tested for the analysis of dust particles dispersion...”. I assume that the model simulates emission and deposition, not only dispersion. Moreover, the new map influences dust emission. So, why do you write you analyse dispersion?

[REPLY] The model simulated both emission and deposition and our development actually changes only the emission of dust. The sentence has been changed to read: “. . . is tested for dust emission capabilities...” in order for that to be clear.

page 1, line 13: “The modeled AOD bias is improved from -0.140 to 0.083”. It is not necessarily an improvement, since you compare dust AOD with total AOD. A positive bias is always bad news, whereas a bias of -0.14 may be acceptable. Going from -0.933 to -0.424 that does seem an improvement.

[REPLY] The reviewer raises an interesting issue. Seeing as absolute numbers a bias of 0.083 is better than -0.140, which is what we write in the text. However, as the reviewer states, an overestimation is not something we want when evaluating dust production and transport. However in more severe cases (AOD>1) the model performs better. We believe that this issue could be resolved by increasing the resolution of the model domain, thus giving a more detailed representation of the dust source areas, something that our methodology allows us to do, since the resolution of NDVI product is already at 500×500 m.

Page 1, line 27: Some spaces between words are missed: ‘studies. Dust’ in page 1, line 27; ‘(CCN) and’ or ‘precipitation processes’ in page 1 line 31 and so on. Please, check it.

[REPLY] Corrected. Also the whole manuscript is revised and other instances have been corrected. Also some double spaces have also been corrected.

Page 2 line 54: define ‘SSib’

[REPLY] SSib stands for simplified simple biosphere. This has been added to the text along with its reference: Xue et al. 1991

Page 2 line 69. I would not say that the Arabian Peninsula is a good example of heterogeneous region.

[REPLY] We wanted to emphasize the use of the Arabian Peninsula as our area of interest, as it is a more heterogeneous region than the Saharan Desert, which could be used as a test area for our methodology. Of course there are more heterogeneous areas that it could potentially be tested, but the Arabian Peninsula is the second biggest desert area of the world and since we wanted a mix of desert size and soil heterogeneity, we deemed it proper for our work. A small comment has been added to the text.

Section 1.1. Although there are references on it, I would include a short paragraph describing the main aspects of the dust model (emission, deposition schemes, whether or not there is radiative feedback, ...)

[REPLY] Section 1.1 has been updated and new references have been added to include additional information about the model processes following the reviewer's suggestion.

Page 3 line 93: I would suggest 'nonlinear partial differential equation' instead of 'partial differential nonlinear equation'

[REPLY] We agree. It has been changed in the manuscript accordingly.

Page 3 line 111: 'The NDVI dataset is at finer resolution than the model grid'. Which is the resolution?

[REPLY] The resolution of the NDVI dataset is 500×500 m. This has been added to the sentence.

Page 3 line 117: 'we have applied a limit to dust efficiency over high mountain'. I think it would be worth explaining it a little. A limit on a threshold altitude?

[REPLY] The following paragraph has been added in the revised version: "In order to exclude such unrealistic emissions from non-soil bare areas or snow-covered areas we have applied a limit of zero dust production above 2500 m over the entire domain. This simple approach has been selected in order to keep our straightforward NDVI mapping independent of vegetation and soil information. The threshold value of 2500 m does not suppress the emissions from lowlands and hillsides (e.g. the coastal areas of Hejaz Mountains in Red Sea that have been identified as hot dust spots by Anisimov et al., 2017)."

Page 3 line 124 & page 4 line 152: In other parts of the text, you mention that the NDVI product is a 16-day average. Here, you present it as a monthly product. Please, clarify.

[REPLY] Corrected. The product presented here is the 16 day average from 1st to 16th of August 2016. It has been change in the revised text.

Page 4 line 137. Please, check the ratio's denominator in the equation below.

[REPLY] Corrected. It now reads $X_{nir} + X_{red}$

Page 4 line 138. 'top of the atmosphere reflectance'. Shouldn't be surface reflectance (measured from the top of the atmosphere)?

[REPLY]. This is actually surface reflectance as would be measured at ground level (i.e. corrected for atmospheric effects). This is now stated more clearly in the revised text.

Page 4 line 144: 'The high resolution masks was used…'. I don't understand what these masks are. I suppose you use the equation of line 113. In any case, '. . . masks were used...'

[REPLY] Correct. We change this to high resolution dataset in order to be clear.

Page 5 line 175: 'Arabian Gulf'. I don't want to participate in a naming dispute, but in most international treaties, documents and maps, this body of water is known by the name of Persian Gulf.

[REPLY] We changed this phrase to: "over the Red Sea and Gulf regions"

Page 6 line 184: I suppose you should comment on the deficiencies of the monthly average of MODIS AOD. I mean that the daily datasets do not cover, far from it, the entire territory due to the presence of clouds, excessive zenithal angle, etc.

[Reply] This is correct. We have added a description and reference to better highlight the limitations of the 16-day NDVI product, especially focusing on the compositing difficulties: "The 16-day composite is calculated by ingesting two 8-day composite surface reflectance granules, while the procedure takes into account pixel quality, presence of clouds, and viewing geometry. This procedure can lead to spatial discontinuities, as it is possible that data from different days are used for adjacent pixels, each representing different measurement conditions. If a pixels has with no useful measurements during the 16-day period, historic data are used as fill values (Didan et al., 2015)."

Page 6 line 195: 'miss-classification of Iran and Pakistan grid points'. The overestimation along the Iran-Pakistan coastline is very striking. Can you guess a possible cause of this miss-classification here?

[REPLY] Indeed the overestimation is an issue at that area because of the complexity of the terrain in that area, where barren land changes abruptly to desert and vice versa. As stated in the text this is probably "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."

Page 6 line 200: 'measurements of AOD?. Please, replace measurements with retrievals.

[REPLY] Corrected according to reviewer's comment

Section 2.2: In the first paragraph you compare monthly averages of MODIS AOD with monthly averages of simulations. You should explain what you compare in the second paragraph: montly averages, timeseries with individual retrievals, daily averages,

[REPLY] In the second paragraph of section 2.2 we compare monthly AOD values. A sentence has been added for clarity: "The first step is to examine how our methodology compares against the monthly average AOD in our study area. Therefore the monthly average AOD values produced from our two simulations (NDVI_run and CTRL_run) are compared."

Page 7 line 218. Please, re-phrase the sentence starting with 'The bias reverse is evident ...'

[REPLY] Rephrased. The sentence now reads: "Both cases show an improvement in the bias values over the control simulations. When we consider AOD>1 the NDVI_run still underestimates the observed values, but with a lower RMSE (0.586 versus 0.983 of the CTRL_run)."

Page 7 line 236.the sentence starting with 'These may include bog, marsh, ...' should be revised. Probably you refer to dried or dessicated bog, marshes,

[REPLY] Revised according to the reviewer's comment.

Different formats are used for citations. Please, check it.

[REPLY] The citations have all been reformatted according to the guidelines of the Journal

Reply to Reviewer 3

Interactive comment on "Development of adynamic dust-source map for NMME-DREAM v1.0 model based on MODIS NDVI over the ArabianPeninsula" by Stavros Solomos et al.

Anonymous Referee #3
Received and published: 23 December 2018
Review for "Development of a dynamic dust-source map for NMME-DREAM v1.0 model based on MODIS 1 NDVI over the Arabian Peninsula" by Stavros et al.

The authors developed a dynamic dust source map based on MODIS Normalized DigitalVegetation Index (NDVI) for the dust emission scheme in the NMME-DREAM v1.0 model over the Arabian Peninsula. Two groups of simulations are conducted for 2016,one with the dynamic source map (NDVI_run) and the other with the default static source map (CTRL_run). It was found that when using the dynamic dust source thesimulated AOD biases are reduced for dust episodes (i.e., when AOD>1) in comparisonwith the simulation using default setting. This paper explored the influence of the seasonal variation of vegetation coverage on dust emission scheme, which is a veryinteresting and important topic, and tested their methods over one major dust sourceregions, Arabian Peninsula. However, the overall presentation needs some improvement, some details need further clarification, and I also have some concerns about the methodology. My comments are listed below.
[REPLY] We thank the reviewer for the careful revision and useful comments. Indeed the seasonal variation of dust source efficiency is an important topic. In our study we focus to present an alternative method for dust source classification in the well-established DREAM dust model that will allow the system to incorporate the updated satellite NDVI for describing dust emissions. Specific replies to the reviewer's comments follow below.

Major comments:
1. In the introduction part when reviewing previous studies of dust source map, I think it is important to briefly introduce Ginoux et al. (2001), who determined dust source mainly based on topographic depressions. As mentioned in the later part of the paper,this is also the default setting used in the NMME-DREAM model. It is also informativeto explain what's new in the method used here compared with previous studies thatalso used NDVI to develop dust source map in the introduction section. And similarly, in the result section, it is better to discuss current results within the context of previouswork that also compared static dust source map with NDVI based source map in thisregion.
[REPLY] We have extended the corresponding sections in the revised manuscript by adding the following sentences in the introduction, methodology, summary and discussion sections:
Introduction: "The main differences in our approach compared to the previous studies referenced above, is that we use a very high resolution NDVI product (500×500 m) in a regional modeling domain (e.g. Kim et al., 2013 used an 8×8 Km NDVI dataset extrapolated to 1°x1° global modeling domain) and our study is not limited to specific test cases (like for example Vukovic et al., 2014 and Solomos et al., 2017), but covers an extended time period, as presented below."

Methodology: “The global mapping of dust sources in Ginoux et al.,(2001) is determined from the comparison between the elevation of surface grid points at 1°×1° resolution with the surrounding hydrological basins and with the 1°×1° AVHRR (Advanced Very High Resolution Radiometer)vegetation map (DeFries and Townshend, 1994).”

Summary and Discussion: “These findings support the previous results by Kim et al., 2013 who also showed an increase in dust emissions and a more realistic comparison with satellite observations in Saudi Arabia by the introduction of an NDVI based dynamic source mapping for GOCART model.”

2. Some details regarding the methodology need further clarification, for instance:
a) I think it will be informative to provide the equation of dust emission scheme in the NMME-DREAM model in section 1.1, so readers can see the role of the dust sourcefunction.

[REPLY]The following section has been added in the revised text: “The surface concentration is calculated using equation (11) from Nickovic et al., (2001):

$C_{sfc} = c_1 \cdot \delta \cdot u_*^2 \left[1 - \left(\frac{u_{*t}}{u_*} \right)^2 \right]$ where $c_1 = 2.4 \cdot 10^{-4} \frac{Kgr}{m^5 \sec^2}$ a tuning constant determined from model experiments, u_* and u_{*t} the friction velocity and the threshold friction velocity for dust production respectively and $\delta = a \cdot \gamma_k \cdot \beta_k$, where γ_k the ratio between the mass available for uplift and the total mass β_k the fractions of clay, silt and sand for each soil class, and a the desert mask (between 0 and 1) calculated from the Ginoux et al., (2001) dataset.”

b) How do you define “# of dust points” in your equation of “Agrid_box”?
[REPLY] The number of dust points are those that have NDVI values smaller than 0.1. A sentence has been added in the text to clarify that: “Where $\#\_of\_dust\_po\text{int}s$ is the number of points with NDVI values smaller than 0.1.”

c) How do you define dust efficiency in line 120 and “fractional gross error” and “meanfractional bias” in Table 2?
[REPLY] By "dust efficiency" we refer to how potent is a certain area in producing dust particles by mechanical processes (wind speed).

Fractional gross error calculated for n pairs of model values (m_i) and observations (o_i) is defined as

$$FGE = 2\ \overline{\left| \frac{m_i - o_i}{m_i + o_i} \right|}$$

where the bar denotes the mean value (Boylan and Russell, 2006). Similarly, mean fractional bias is defined as

$$MFB = 2\frac{\overline{m_i} - \overline{o_i}}{\overline{m_i} + \overline{o_i}}$$

following(Chang and Hanna, 2004).

We have added a new section that properly defines the quantities used for model evaluation.

Chang, J. C. and Hanna, S. R.: Air quality model performance evaluation, MeteorolAtmosPhys, 87(1–3), 167–196, doi:10.1007/s00703-003-0070-7, 2004.

Boylan, J. W. and Russell, A. G.: PM and light extinction model performance metrics, goals, and criteria for three-dimensional air quality models, Atmos. Environ., 40(26), 4946–4959, doi:10.1016/j.atmosenv.2005.09.087, 2006.

d) Section 1.2 has a lot of redundant lines, e.g., lines 131-133 are the same as lines140-142, while lines 128, 135 and 143 repeated the same information.
[REPLY] Thank you for this notice. The redundant lines have been removed at the revised version.

e) According to lines 183-184, it is not clear if the simulated AOD is purely dust AOD,or it also includes the optical depth contributed by other aerosol particles?
[REPLY] The simulated AOD is purely dust AOD. The MODIS AOD may include other aerosol types.

f) Line 162 seems indicating that the model settings are different for the CTRL_run and NDVI_run? Is this true?
[REPLY] No, the only difference between the two configurations is the definition of dust sources. This line is now removed for clarity.

g) It is also important to briefly introduce the datasets used for model validation insection 1, e.g., the MODIS AOD, AERONET AOD. What are the spatial and temporal resolutions?
[REPLY] We have added a new section (1.3 in the revised manuscript) describing the validation datasets.

3. Two major differences between Fig. 2a and b are the discrepancies of dust sourcestrength over western Saudi Arabia and over Iran and western Pakistan. I think the authorsshould discuss these differences in the end of section 1.1 and also correspondinglyin the result section. It seems to me that the NDVI source map overestimatesthe dust source strength over western Saudi Arabia and consequently led to too muchAOD in this region in Fig. 3b.
[REPLY] The following lines have been added in the revised text:
"The two dust source patterns present remarkable difference especially over the western Saudi Arabia and over Iran and Pakistan where the NDVI classification results in stronger emissions."
"The DREAM-NDVI AOD is also higher than MODIS AOD over western Saudi Arabia indicating a possible overprediction of dust sources at this area."

4. Section 2.1 discusses dust transport by atmospheric circulation in August 2006.First of all, it is not clear to me whether information presented here is based on modelsimulation or reanalysis or observational data. Please clarify. On the other hand, thoseweekly variations of surface winds and dust transport may not necessarily be revealedin the monthly AOD map in Fig. 3. I'd suggest either adding figures of weekly variationsof wind and AOD in this section or adding monthly surface wind vectors in Fig. 3 todiscuss how winds affect AOD pattern.

[REPLY] We have introduced a new plot (Figure 3 in the revised version) that shows the average modeled wind speed and vectors for August 2006 in order to facilitate the corresponding discussion.

5. As you mentioned in lines 233-236, NDVI mask do not have much seasonalvariations in permanent deserts, but may be important in those semi-arid regions, asalso pointed by Kim et al. (2013). I wonder if you can also plot 12-month NDVI mapin this region for 2016 to demonstrate the influences of NDVI seasonal cycle and thenyou can discuss the seasonal variations of AOD in Fig. 5 along with NDVI seasonalcycle.

[REPLY] The main purpose of our study is to provide a dynamic modeling tool for dust source definition in NMME-DREAM v1.0 model and demonstrate its capability as an alternative method. Therefore we intend to constrain our work to the description of our proposed methodology. A more in depth analysis of the seasonal dust source variability of at the area would require a longer study period and will be the scope of a forthcoming study.

6. The overall magnitude of AOD in the control run is quite low but does seem to haverelatively higher values over the eastern Arabian Peninsula, which is consistent with thepattern of MODIS AOD. I wonder if you tried to tune the model in the CTRL simulation to increase the overall magnitude of dust emission and then compare the pattern andseasonal cycle of AOD with the NDVI_run.

[REPLY] The default configuration is similar to the operational model setup used for example in SDS-WAS (https://sds-was.aemet.es/) and BEYONDhttp://beyond-eocenter.eu/dusthub/, which is tuned towards stations at Africa, Asia and Europe. It is also important to notice that our proposed method is not a simple homogeneous tuning factor but an overall different treatment of dust source definitions.

7. Kim et al. (2013) combined both the topographic depression-based dust source andNDVI seasonal masking for dust source map. I wonder if you can combine the dynamicsource developed here with the default Ginoux et al. (2001) static source, and see ifthe model performance is further improved. I think those high AOD over western SaudiArabia probably will be largely reduced.

[REPLY] We agree with the reviewer that finally a combined static and dynamic approach might be a solution for operational setups. However, we selected to perform two totally independent runs in order to clearly demonstrate the use of dynamic NDVI sources as an alternative method to the static approach for DREAM model without incorporating a vegetation map. We believe that in this way the advances and deficiencies of our development are more evident.

8. Here only modeled AOD in the two simulations are compared. I wonder if you also see any improvement in other aspects of dust life cycle such as surface dust concentration, vertical distribution, and deposition.
[REPLY] We focused on AOD for the verification since AOD observations are more regular, available and reliable than observations of profiles, surface concentrations and deposition.

Minor points:
1. Line 28, add "e.g.," before "Torge et al., 2011"
[REPLY] Done.

2. Line 31, add space between "precipitation" and "processes". Please fix all similaroccurrences.
[REPLY] Done.

3. Line 45, I don't think there is any "feedbacks" on "human health", please considerreorganizing the sentence.
[REPLY] Indeed, thank you. We have replaced "feedbacks" with "effects".

4. Line 63, please add brackets for "2013", and fix all similar occurrences.
[REPLY]Done, thank you.

5. Line 79, I think the original dust source function developed by Ginoux et al. (2001) did not use "Olson World Ecosystems dataset". Can you explain a bit more here?
[REPLY] The reviewer is correct. We have corrected this sentence in the revised text.

6. Line 109, you may want to add a line or two to explain why NDVI of 0.1 is selected instead of 0.15 as used by Kim et al. (2013).
[REPLY] Indeed it is not easy to define a "best estimate" threshold for all satellite NDVI sensors worldwide. A choice of 0.15 may be more representative on a global base as used by Kim et al. (2013) for AVHRR. Here we adopted the 0.1 threshold based also on previous studies at the area (Solomos et al., 2017) since due to the bareness of the specific modeling domain a higher value could overestimate the dust sources. This discussion is now added in the revised version.

7. Lines 200-201, not clear. Did you use Ångström exponent to mask AOD? In thatcase, the masked AOD may contain large particles such as dust and sea salt.
[REPLY] Yes this does not exclude sea salt but the contribution of marine particles to the total AOD is limited.

8. Fig. 3, it is better to mask out AOD outside the model domain in Fig. 3c for an easy comparison among the three plots.

[REPLY]Done.

9. Please clarify in Table 1 caption that this is for annual mean. And for correlation, do you use monthly data? Can you also mark whether the correlation coefficients are statistically significant?

[REPLY]Done. For correlation we use the daily AERONET data.

10. Table 2, are monthly or daily data used for correlation? Please add significance test as well.

[REPLY] We use individual AERONET measurements. The model retrievals are interpolated in time to match the AERONET measurement time. This is now stated more clearly in the revised text. To highlight the significance of correlation, in Table 2 we indicate with bold font all coefficients with p value < 0.01.

11. Fig. 5, are the time series calculated from single AERONET site (which one?) oraveraged over four stations on the Arabian Peninsula?

[REPLY]Fig.5 is averaged from the four Arabian stations. This is now more clearly stated in the text.

References:

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

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 sourcefunction, emission, and distribution, J. Geophys. Res. Atmos., 118, 871–886, doi:10.1029/2012JD017907, 2013.

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~~ Difference Vegetation Index (NDVI). Areas with NDVI<0.1 are classified as active dust sources. The ~~new~~ updated modeling system is tested for ~~the analysis of dust particles dispersion~~dust emission capabilities over SW Asia using a mesoscale model grid increment of 0.1°×0.1° km for a period of ~~1~~ one 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.

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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 (e.g. 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 precipitation process~~es~~ (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 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 severe ~~ity of the feedbacks~~ effects 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 (simplified simple biosphere, Xue et al. 1991) 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 be even more relevant at meso and local scales for determining landuse changes and potential dust sources, especially in heterogeneous regions such as the Arabian Peninsula (which has more diverse soil types than e.g. the Sahara Desert) 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 the Ginoux et al., (2001) dataset ~~Olson World Ecosystems dataset~~ and 2) Dynamic source run, where the NDVI values are used to identify the dust sources. The main differences in our approach compared to the previous studies referenced above, is that we use a very high resolution NDVI product (500×500 m) in a regional modeling domain (e.g. Kim et al., 2013 used an 8×8 Km NDVI dataset extrapolated to 1°x1° global modeling domain) and our study is not limited to specific test cases (like for example Vukovic et al., 2014 and Solomos et al., 2017), but covers an extended time period, as presented below. 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 developments and remote sensing data; Section 2 includes the results of the experimental runs and section 3 is a summary and discussion of 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 nonlinear partial differential equation ~~partial differential nonlinear equation~~ for dust mass continuity (Nickovic et al., 2001; Perez et al., 2006; Pejanovic et al., 2011, Nickovic et al., 2016). In DREAM the concentration approach is used for dust uplift, where surface concentration is used as a lower boundary condition and used for the calculation of surface fluxes, which in turn depends of the friction velocity (Nickovic et al., 2001). This surface concentration is calculated using equation (11) from Nickovic et al., (2001):

$$C_{sfc} = c_1 \cdot \delta \cdot u_*^2 \left[1 - \left(\frac{u_{*t}}{u_*} \right)^2 \right]$$

where $c_1 = 2.4 \cdot 10^{-4} \dfrac{Kgr}{m^5 \sec^2}$ a constant determined from model experiments, u_* and u_{*t} the friction velocity and the threshold friction velocity for dust production respectively and $\delta = a \cdot \gamma_k \cdot \beta_k$, where γ_k the ratio between the mass available for uplift and the total mass β_k the fractions of clay, silt and sand for each soil class, and a the desert mask (between 0 and 1) calculated from the Ginoux et al., (2001) dataset. Soil moisture and particle size dictate the threshold friction velocity which initializes dust production. 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. The model handles dust in eight size bins, with effective radii of 0.15, 0.25, 0.45, 0.78, 1.3, 2.2, 3.8, and 7.1 mm. Dust is treated as a passive tracer and doesn`t interact with radiation or clouds. Dust is eventually settled through rainfall and/or dry

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deposition processes parameterized according to the scheme of Georgi (1986) which includes deposition by surface turbulent and Brownian diffusion, gravitational settling and impact on surface elements.

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. One-year runs for the entire 2016 have been conducted to evaluate the performance of the static and dynamic database emission maps .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. The global mapping of dust sources in Ginoux et al.,(2001) is determined from the comparison between the elevation of surface grid points at 1°×1° resolution with the surrounding hydrological basins and with the 1°×1° AVHRR (Advanced Very High Resolution Radiometer) vegetation map (DeFries and Townshend, 1994). Recent studies indicated the contribution of both natural and anthropogenic dust sources to the overall dust emissions detected in MODIS Deep Blue product (Ginoux et al., 2012) and also the relevance of local geomorphological conditions and sediment supply (Parajuli and Zender, 2017) on the global dust emissions. All these advances in dust emissions are based on static map considerations.

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). In general it is not easy to define a global threshold value for all satellite NDVI sensors and all vegetation types worldwide. For example Kim et al. (2013) used a threshold of 0.15 to define global dust sources based on AVHRR retrievals (Tucker et al., 2005; Brown et al., 2006). Here we adopt the 0.1 NDVI threshold due to the bareness of the specific modeling domain since a higher value could overestimate the regional dust sources. The NDVI dataset is at finer resolution than the model grid (500×500 m) and in order to find the potential for dust production in each model grid box, we calculate the following ratio:

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

Where $\#\_of\_dust\_points$ is the number of points with NDVI values smaller than 0.1.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. 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.~~ In order to exclude such unrealistic emissions from non-soil bare areas or snow-covered areas we have applied a limit of zero dust production above 2500 m over the

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entire domain. This simple approach has been selected in order to keep our straightforward NDVI mapping independent of vegetation and soil information. The threshold value of 2500 m does not suppress the emissions from lowlands and hillsides (e.g. the coastal areas of Hejaz Mountains in Red Sea that have been identified as hot dust spots by Anisimov et al., 2017).

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 1-16 of August 2016. The two dust source patterns present remarkable difference especially over the western Saudi Arabia and over Iran and Pakistan where the NDVI classification results in stronger emissions. 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 DREAM-CTRL run from now on, and (2) using the dynamic NDVI database as described above, called DREAM-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.

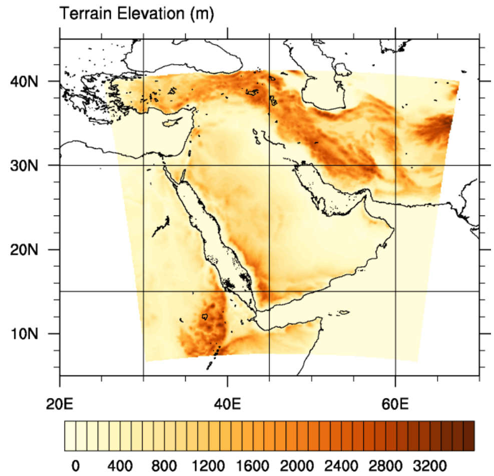

Figure 1: DREAM model domain and topography in meters

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.,

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

where X represents surface reflectance as would be measured at ground level (i.e. corrected for atmospheric gas and aerosol effects).~~ (measured from the top of the atmosphere)the top of the atmosphere reflectance~~ in each channel. The 16-day composite is calculated by ingesting two 8-day composite surface reflectance granules, taking into account pixel quality, presence of clouds, and viewing geometry. This procedure can lead to spatial discontinuities, as it is possible that data from different days are used for adjacent pixels, each representing different measurement conditions. If a pixel had no useful measurements during the 16-day period, historic data are used as fill values (Didan et al., 2015). 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~~ dataset 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.

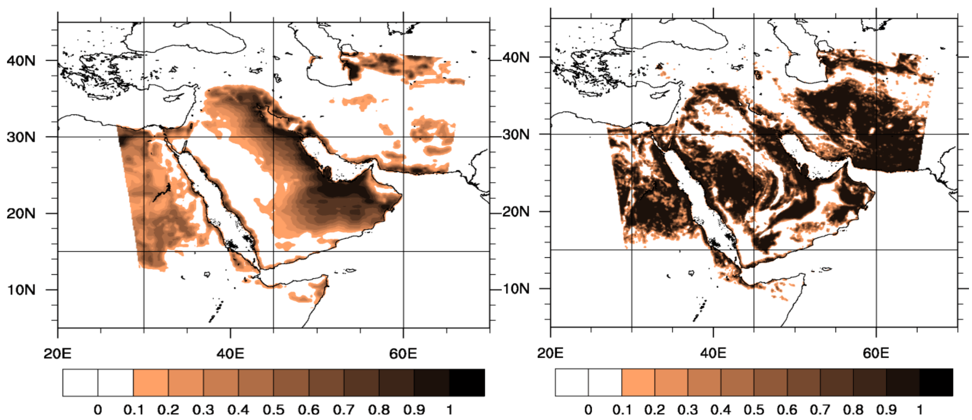

Figure 2: Dust source strength as defined by (a) the Ginoux et al., 2001 dataset and (b) the 1-16th of August 2016 mean NDVI

1.3 Evaluation datasets and metrics

Model evaluation is carried out two datasets. First, the MODIS monthly aerosol optical depth (AOD) is use to study the spatial distribution of dust in the model domain. For this we use the level 3 gridded atmosphere monthly product at 1x1 resolution, MOD08_ME (Platnick et al. 2017). Secondly, we evaluate model performance using AERONET AOD retrievals at 8 photometeric stations. AERONET is a network of sun/sky photometers that derive aerosol optical and microphysical properties at a large number of stations around the world (Holben et al., 1998). For this evaluation, we use Version 3 AOD retrievals that, in comparison with previous versions, improves automatic cloud screening (Giles et al, 2018). Level 2 datasets were used for all stations apart from Kuweit University, where only Level 1.5 data were available. Both model and AERONET AOD were calculated at 532nm; this was chosen to facilitate future intercomparing against lidar systems that frequently measure at this wavelength (e.g. Pappalardo et al., 2014). AERONET measurements were converted to this wavelength using the 440-870 angstrom exponent and taking into account AOD measurements at 440nm, 675nm, and 870nm; in the cases where the 440nm AOD was not available, the 500nm (Mezaira) or 443nm (KAUST campus) measurement was used instead.

We evaluation model performance using five metrics: mean bias, root mean square error, correlation coefficient, mean fractional bias, and fractional gross error. Concretely, assuming we have n pairs of model values (m_i) and observations (o_i), the mean bias (MB) is defined as:

$$MB = \overline{m_\iota - o_\iota}$$

where the bar denotes the mean value. Root mean square error (RMSE) is defined as

$$RMSE = \sqrt{\overline{(m_\iota - o_\iota)^2}}$$

The correlation coefficient (r) is defined as

$$r = \frac{\sum_{i=1}^{n}(m_i - \overline{m})(o_i - \bar{o})}{\sqrt{\sum_{i=1}^{n}(m_i - \overline{m})^2}\sqrt{\sum_{i=1}^{n}(o_i - \bar{o})^2}}$$

The fractional gross error (FGE) is defined as

$$FGE = 2\,\overline{\left|\frac{m_\iota - o_\iota}{m_\iota + o_\iota}\right|}$$

following Boylan and Russell, 2006. Similarly, mean fractional bias (MFB) is defined as

$$MFB = 2\,\frac{\overline{m_\iota} - \overline{o_\iota}}{\overline{m_\iota} + \overline{o_\iota}}$$

following Chang and Hanna, 2004.

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_runDREAM-CTRL run from now on, and (2) using the dynamic NDVI database as described above, called NDVI_runDREAM-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 (Figure 3) 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 Gulf during these dates.

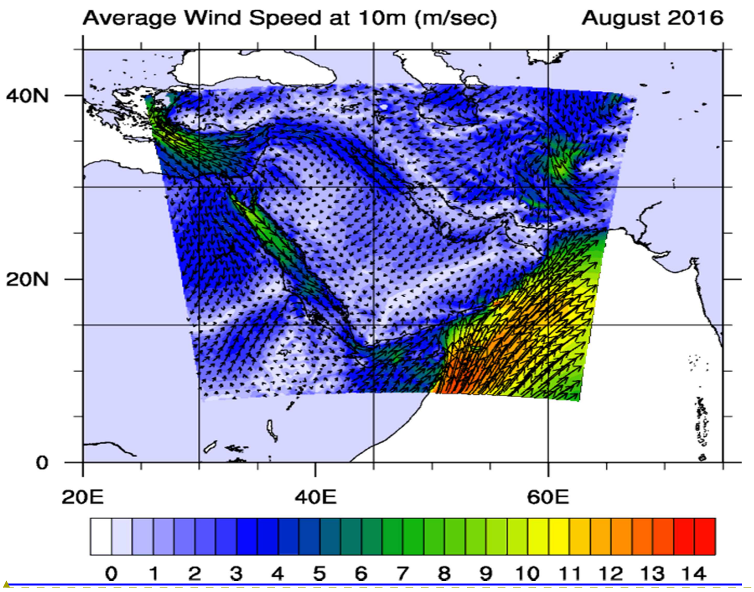

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Figure 3. Average wind speed (color scale) and vectors from NMME-DREAMv1.0 for August 2016.

2.2 Comparison with MODIS and AERONET

The monthly average AOD for August 2016 is shown in Figure ~~3~~ 4 for the two experimental runs (Figure ~~3~~4a,b). The ~~NDVI_run~~DREAM-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~~~~Persian~~ Gulf regions (Figure ~~3b~~4b). This dust pattern is closer to the MODIS observed AOD over the same period that is shown in Figure ~~3c~~4c. 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.

The first step is to examine how our methodology compares against the monthly average AOD in our study area. Therefore the monthly average AOD values produced from our two simulations (NDVI_runDREAM-NDVI run and CTRL_runDREAM-CTRL run) are compared. More specifically the NDVI_runDREAM-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_runDREAM-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_runDREAM-NDVI run again outperforms the CTRL_runDREAM-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. The DREAM-NDVI AOD is also higher than MODIS AOD over western Saudi Arabia indicating a possible overprediction of dust sources at this area.

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 individual AERONET measurements. The model retrievals are interpolated in time to match the AERONET measurement time the regional AERONET ground-based photometric measurements retrievals 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 5 and also in Table 2 these stations are clearly benefited from the experimental run.

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In general the two runs present a significant statistical difference and more remarkably a reverse of bias (MODEL-AERONET) from negative in the CTRL_runDREAM-CTRL run to positive in the NDVI_runDREAM-NDVI run. The NDVI_runDREAM-NDVI run produces increased AODs that are neither linearly proportional to the CTRL_runDREAM-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 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). Both cases show an improvement in the bias values over the control simulations. When we consider AOD>1 the ~~NDVI run~~DREAM-NDVI run still underestimates the observed values, but with a lower RMSE (0.586 versus 0.983 of the ~~CTRL run~~DREAM-CTRL run).~~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~~ 6 where the NDVI run is indeed more realistic for the Arabian stations 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 the annual runs and AERONET

	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 dried bog, marshes 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~~DREAM-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 corresponding MODIS satellite retrievals. These findings support the previous results by Kim et al., 2013 who also showed an increase in dust emissions and a more realistic comparison with satellite observations in Saudi Arabia by the introduction of an NDVI based dynamic source mapping for GOCART model. 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. Bold values indicate correlation coefficient with p <0.01.

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

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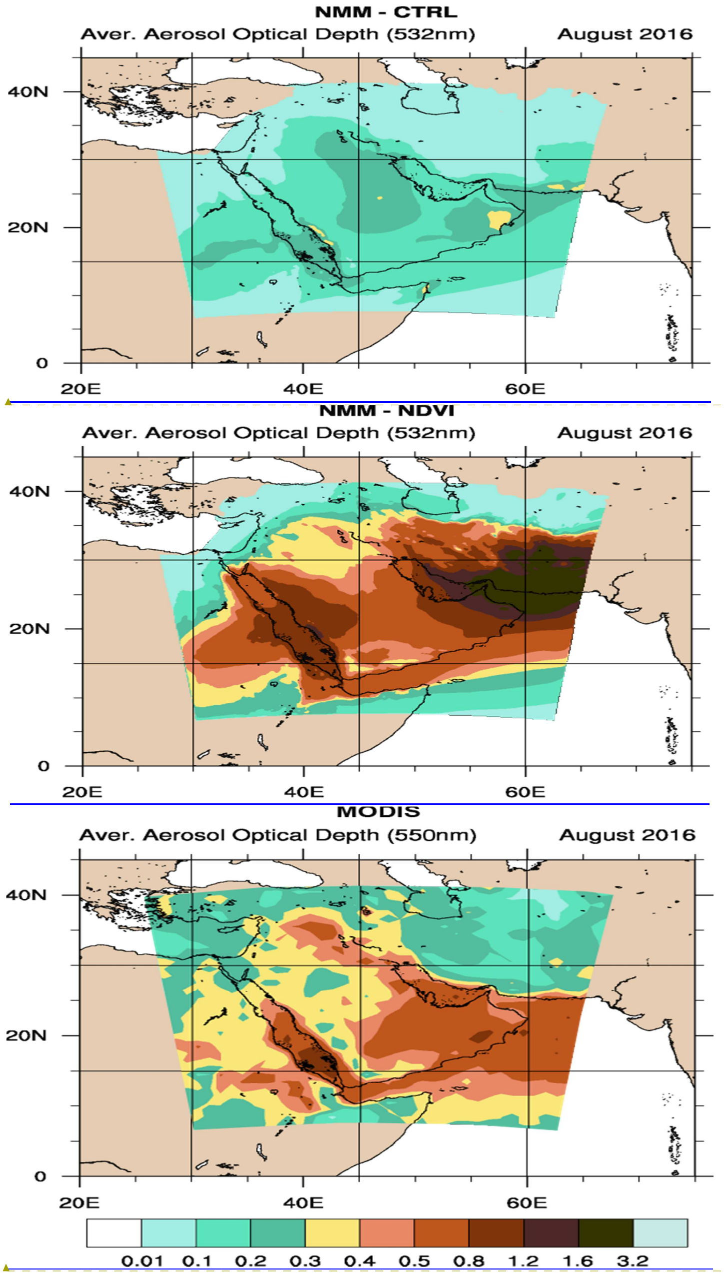

Figure ~~3~~4. Monthly average simulated AOD during August 2016 from ~~CTRL_run~~DREAM-CTRL run (a), ~~NDVI_run~~DREAM-NDVI run (b) and (c) MODIS. The dashed trapezoid in (c) denotes the location of the modeling domain.

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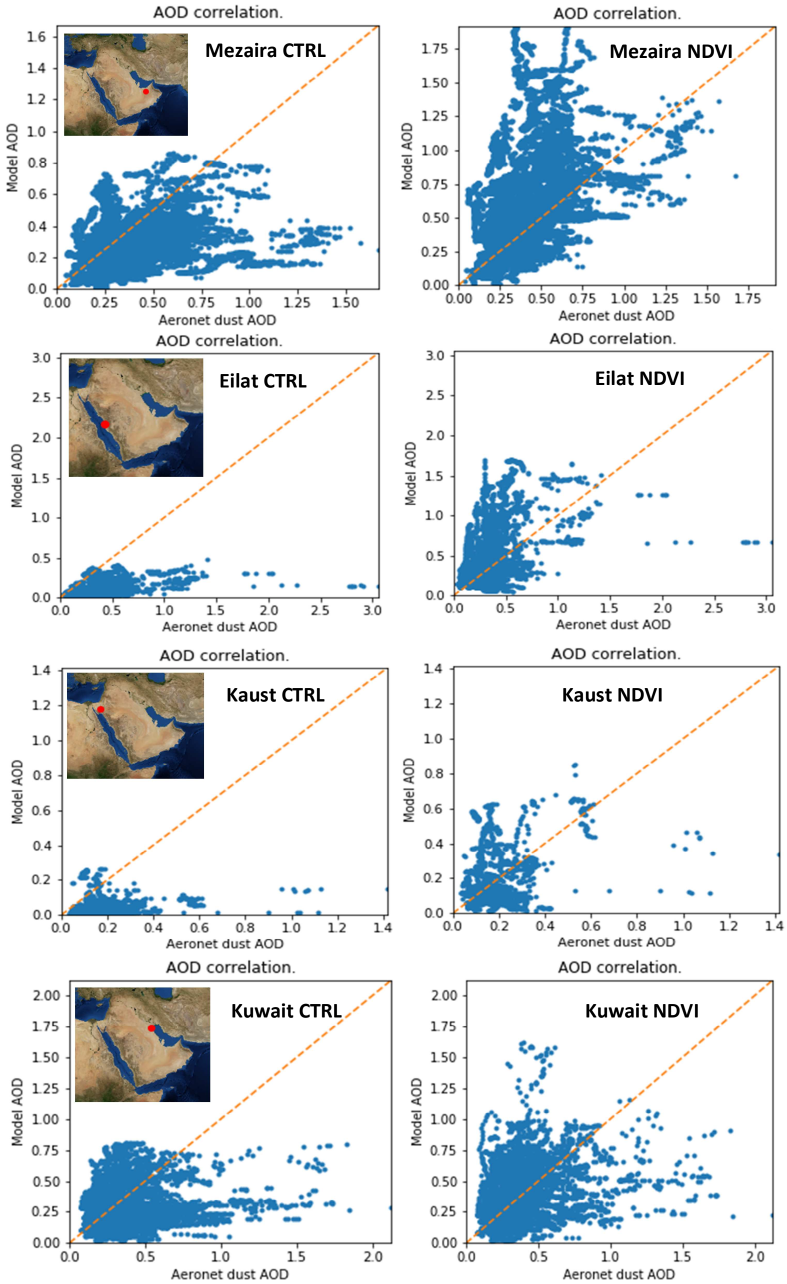

Figure 45. Correlation plots of modeled and AERONET dust AOD at the stations of Mezaira, Eilat, Kaust and Kuwait for 2016.

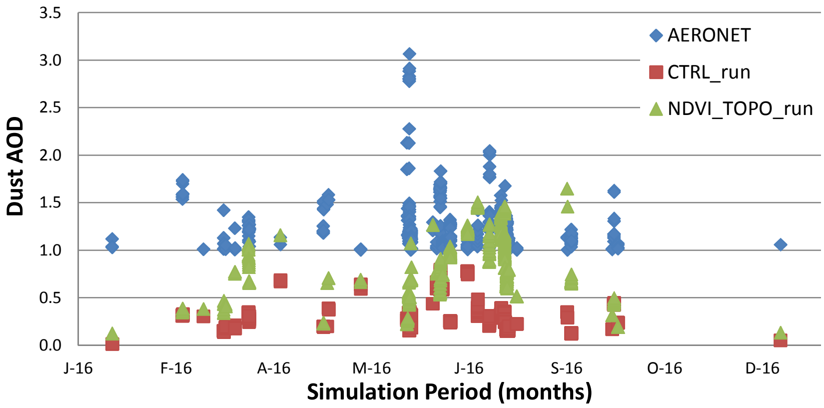

Figure ~~5~~6. Timeseries of measured and modeled dust AOD for the cases of AERONET AOD>1

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;

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