Anonymous Refereef #1:

Major comments:

1. *Section 2.1: The authors concentrate on a narrow (100km) coastal plain with complex circulation (e.g. sea breezes) but use a model resolution that is too coarse (10km). They use the same resolution also when testing varying emission resolutions. Even if this is due to computational constraints, surely short tests of specific dust events can be conducted at higher resolution to properly test dust dispersion. Can the authors identify such events and complement the paper with higher resolution model runs?*

In this study, we focus on the effect of the spatial resolution of the surface characteristics on the dust generation. It is especially important over the coastal plain where the surface is heterogeneous. We fixed the meteorological forcing to isolate the impact from high-resolution datasets. The text is modified to make this point clearer.

Following the reviewer's advice, we have complemented the paper with a short-term high-resolution (4-km) WRF-Chem simulation of dust storm event in January 2009 and the results of the work by Kalenderski et al. (2013). The CLM4 results are shown to be in good agreement with WRF-Chem runs. Short-term WRF-Chem simulations suggest that amount of dust generated during the series of outbreaks is even 40–50% larger than in CLM4, confirming the conclusions of the study. The spatial pattern of dust generation is also consistent with that presented in the paper. The text is modified to reflect this comparison.

2. *The authors allude to a year-to-year strong variability (Sec.2.3, p.7 l.18), yet only simulate the short period of 3 consecutive years. Are the results meaningful and how are any resulting systematic uncertainties constrained?*

Actually, in this study, we are more concerned to evaluate the effect of spatial changes than temporal variability, which, as we mentioned in the paper, is not very strong and the coastal plane is a steady dust source every year. The phrase on (Sec.2.3, p.7 l.18) is related to flash floods that differ from year to year but have about decadal frequency. The individual flash floods are small-scale events that cannot make significant changes to vegetation and other surface characteristics. They cause short-term local reductions of dust emission due to their impact on soil moisture. In the long run, however, flash floods are responsible for bringing the alluvial material that is a source for dust generation, but this process is important on much longer timescales. Following the comment, we have expanded and improved the text.

3. *The authors do not address dust aging and its potential effects. They should comment if it's relevant before deposition. Does short atmospheric residence time make it not significant?*

We mention the importance of chemical and physical processes that occur during atmospheric transport (dust aging) when discussing dust deposition to the Red Sea. However, the study is aimed at quantifying dust emission processes and does not consider any transport processes. The detailed analysis of dust transport, lifetime and aging is beyond our current scope and requires a separate modeling framework. But, because of the close proximity of the coastal plain to the Red Sea, the transport is short, and atmospheric processing is not very important for dust generated from the coastal plain. Following the comment, we have made this statement clearer.

4. *Section 2.2 describes mostly the dust generation mechanisms that I understand is not the authors own work and is available in the literature. The whole section should be shortened, replacing the details of model parameterisations with references.*

Thank you for pointing it out. Following the suggestion, we have shortened Section 2.2 to make it more focused. However, we want to keep this section, as it is useful to introduce different parameters we use in the paper. A large part of section 2.2 is devoted to the description of the source function, which is one of the key points of the study.

5. *Section 2.4,5: Given the very coarse resolution and the relatively small size and high complexity of the region under study of the MERRAero grid, is it advisable to scale to the emission total? What is the overall point of this section? Sections 2.4 and 2.5 should be merged.*

We paid a special attention to model calibration, as we believe this is one of the key points of the study. The reanalysis products with atmospheric aerosol component have just recently become available. The spatial resolution of MERRAero reanalysis is enough to capture the dust generation hot spot area in the western Arabian Peninsula. Although it is too coarse to represent the spatial structure of dust emission, the integral multi-year estimate of total dust generation from approximately 150000 km^2 area is a reasonable reference point for model calibration. Following the reviewer's suggestion, we have merged Section 2.4 and Section 2.5.

6. *Section 3.1: Given the same forcing in all experiments, and differences of a few percent between emission resolutions, what is the point of sensitivity tests? Surely the sensitivity to meteorological conditions and climatic variability is more important and should be studied. The authors should comment and better motivate their study.*

The sensitivity tests are aimed at quantifying the impact of high-resolution satellite datasets on spatial patterns of dust generation. In order to perform these tests, the meteorological forcing should be fixed. Although the integral dust generation does not differ strongly, it does not mean that the impact of input datasets is negligible. Locally, dust emissions may change up to 100 % (Fig. 2). We do not analyze the dust emission long-term variability, as it is beyond the scope of the current paper and might be a topic of the further studies. However, we point out that the spatial pattern of dust hot spots is stable (Fig. 6 a-c, Fig. 7) and thus high-resolution inventories should add value regardless of meteorological forcing. Following the suggestion, we have expanded and clarified the corresponding section.

7. *Section 3.2: Surely statistical testing can't involve changing thresholds until significance is reached. Also are monthly values used when hourly are available? Given the strong diurnal variability, isn't the latter advisable?*

To test the temporal variability of modeled dust emission, we process the hourly values to produce monthly time series of dust frequency and intensity, as seasonal variability was the primary focus of the study. Applying the thresholds for model data cannot be avoided, as the station data also have a “threshold”: the visibility and weather code is only reported when it drops below 10000 m. Due to this fact, there is no actual diurnal statistics in visibility data, as reported visibility reductions usually only last for several hours, and diurnal cycle cannot be validated. Depending on station’s location, meteorological and environmental conditions, the same visibility reduction may be caused by the different level of dust loading; therefore, changing thresholds could not be avoided as well. We show that for the most of the stations, the results are statistically significant in the wide range of threshold values. The statistical metric of model spatial performance, however, does not use thresholds.

8. *Section 4: Again given varying vegetation and land type, isn’t 3 years to short a time span to produce an emission climatology?*

The focus of the study is on the spatial structure of dust emission with special attention on generation regime in the hot spots. The hot spot areas are the stable structures that are conditioned by land surface characteristics, whereas the amount of generated dust is mostly driven by wind velocity. We agree with the reviewer that wind circulation regime changes, associated with climate variability, lead to changes in dust emission. However, based on results from MERRAero reanalysis we show that interannual variability of dust generation from the coastal plain during 2003 – 2015 is relatively small (7.2 ± 0.5 Mt a^{-1}) and the seasonal cycle is stable (see fig. 7). The three-year simulation period was enough to capture the significant improvement of the dust emission spatial pattern with the use of high-resolution satellite data. We agree with the reviewer, however, that referring to climatological time scale should be replaced by “multi-year estimate”.

Minor comments:

1. Using the study-specific acronyms FineALL, HighALL, LowALL, etc. is confusing to the reader. Propose to just change with quoting model resolution and if necessary input data (ie. 1km, 10km, 50km, etc.)

Following the suggestion, we have changed the experiment acronyms.

2. *Please include the span of years modelled in the abstract.*

The modeling period have been added to the abstract.

3. *Abstract l. 26: appears to be -> is estimated to be [...] suggests -> shows*

Thanks, changed.

4. *P.9 2nd paragraph: First it’s stated that it is not rare to have no dust reports, thus the visibility measurement is used, then that the authors prefer sampling as most station visibility* *are complemented with weather codes. Aren't these statements contradictory? Please re-write the paragraph for more clarity.*

The referred statement means that there were no visibility reduction reports at all, not that visibility reductions came without weather code reports. We have re-formulated these statements.

5. *P.9 l.11 current month -> that particular month*

Changed.

6. *P.13 l.9 Please elaborate how Yu et al is questioned based on the results of the present study - not just by quoting another paper.*

Thanks for the comment. We have re-formulated the statement to address the questioned issue in more details. The idea proposed by Yu et al. (2013) that the primary aerosol in the coastal area is not dust was questioned in (Osipov et al., 2015), not in the current study. It was reported, based on CALIPSO lidar measurements during 2007–2013, that the ratio of the "not dust" to "dust" successful retrievals over the Arabian Peninsula is 2.04 %. A narrow coastal area of the Arabian Peninsula, that is itself a dust generation zone, is not likely to be have a primary aerosol of a non-dust origin.

7. *P. 19 l.8 Paragraph/line incomplete? Missing full stop?*

Full stop has been added.

Anonymous Referee #2:

***1. Abstract, main part, and conclusions**: The amount 7:5 Mt a^{-1} of total dust emission as presented in the abstract, the successively derived magnitude of dust emission from different locations, and the quantification of the amount of iron oxides and phosphorus are all predetermined by the calibration of the model. For the lack of measured dust emission rates, the calibration is done by assuming the same emitted dust amount in the land model as in the MERRAero reanalysis over the investigated time period, which is not based on measured values, but calculated using a dust module.*

This is correct, our total dust generation and other bulk estimates (e.g. mineralogical composition) are based on calibration with respect to the best, in the absence of observations, assimilation product. However, the main focus of this paper is on the spatial heterogeneity and seasonal variability of dust sources from the coastal plain, and their dependence on the surface data sets. These results are invariant with respect to total bulk emission. Our bulk emission estimates could be easily recalibrated when better estimates of total emission are available.

This approach rests on the assumption that the magnitude of the dust emission in MERRAero is a reliable estimate of the true dust emission from this region. To my knowledge, no evaluation has been published with respect to the dust emission from this region in MERRAero. The authors themselves acknowledge that the resolution of the reanalysis is too low to provide reliable estimates of the dust emission from this region, and they show with their own analysis that the magnitude of dust emission increases with refinement of the horizontal resolution.

See our answer above. In addition, we have to mention that the MERRAero resolution is too low to resolve the spatial heterogeneity of the emissions, but is less deficient for estimating the bulk emissions from the entire area

Thus, this suggest the conclusion that the magnitude of the presented total dust emission, the emission amount from individual locations, and the amount of iron oxides and phosphorus are highly uncertain. This uncertainty should be addressed. Perhaps, one could use the variability of the emission in MERRAero from the whole time period 2003-2015, which already has been used in the manuscript by the authors, to provide a first estimate of the lower and upper range of the emission related quantities presented in the paper, especially for the ones presented in the abstract, even though that still wouldn't address any possible bias in the MERRAero dust emission. The issue of the uncertainty and its sources for the estimates provided in the paper should also be thoroughly discussed in the conclusions. Also, when providing the absolute quantities in the abstract, it should be pointed out that the values are just first estimates that are still highly uncertain.

The uncertainty mentioned by the reviewer is unfortunately, a state of the art problem. However, the proposed approach allows easy recalibration when better estimates are available. We have updated the abstract and the text mentioning that the presented values are the first estimates, and indicated the uncertainty range based on MERRAero variability through the paper, as suggested. We have to mention that although MERRAero dust emission has not been validated yet, the recent paper (Ridley et al., 2016) reports better seasonality of dust AOD in

MERRAero compared to other datasets, and points to potentially better dust emission due to finer spatial resolution and representation of surface winds.

2. Page 4, lines 10–13: *The assumption that the mineral composition of dust aerosols and the mineral composition of the soils in Claquin et al. (1999) and Nickovic et al. (2012) were close does not (always) hold just because of changes during the life cycle of dust from emission to deposition, even more importantly, it does not hold because the measurements of the soil mineral fractions were done for soils that had been wet-sieved. Wet sieving is a technique that strongly disperses soil aggregates (Shao, 2001), which is not realistic for dust emission from the parent soils of the dust sources. This caveat to the assumption made by the authors should be added to the manuscript.*

Having said this, the authors are mainly interested in the amount of iron oxides and phosphorus. Nickovic et al. assume the same iron oxide fraction in the clay and silt size range, and phosphorus is provided only for the clay and the silt-size range together. Therefore, the fractions of these minerals are less affected by the wet-sieving problem, based on these assumptions. Also, in the present manuscript, only the integrated amount over all size bins defined in the dust module is presented. Thus, other sources of uncertainty probably affect the calculated iron oxide and phosphorus amount more than the wet-sieving problem. The wet-sieving issue still may be are more relevant source of error for the other minerals presented in Figure. 9, though.

We thank the reviewer for this detailed suggestion. We have updated the text with the remarks on the additional source of uncertainty linked with wet sieving technique.

3. Page 7, lines 4–7*: How the choice for the threshold value for the statistical source function was made should be explained in detail. It is not clear for the reader from simply stating, "The threshold value is chosen with respect to the temporal frequency of the SEVIRI instrument".*

Thanks for pointing this out. The threshold has to be applied to filter out background dust and is usually chosen empirically (Schepanski et al., 2012). We have tested the thresholds in the range of 0.8 – 1.15 and found the spatial patterns of the source functions to be very similar. The chosen threshold value of 1.12 is larger than the one used in (Ginoux et al., 2012) but comparable to other studies (Schepanski et al., 2012). The choice of relatively large threshold was motivated by several reasons. First, the background dust AOD in Arabian Peninsula is much higher than globally observed one. Second, SEVIRI was shown to overestimate AOD under moist conditions and low dust loadings that are the case for the Red Sea coastal plain (Banks et al., 2013). Overall, this larger threshold allows us to better represent intensive dust sources, in contrast, e.g. to (Ginoux et al., 2010; Ginoux et al., 2012) that aimed at capturing and classifying smaller sources. The text has been updated to account for these remarks.

4. Page 15, line 5*: Do not say "Dust emission climatology", since the analysis is done only for three simulates years. Name the section "Multi-year dust emission" or similar.*

Thanks for this important suggestion, the section has been renamed.

5. Page 14, line 23*: The unit of the total dust emission in the text should be the same as in Fig. 4a, i.e., g m a.*

Changed.

6. Page 17, line 29*: "All of the quantities have a pronounced diurnal cycle, …" should be phrased more precisely as "Total dust generation, frequency, and maximum emission rate have a pronounced diurnal cycle, …". The authors themselves discuss the exception for the intensity further below.*

Changed.

7. Page 18, line 20*: Add Scanza et al. (2015).*

The reference has been added.

8. Page 31, Table 1*: The used individual components of the WRF model configuration should be presented in a way that is friendly to the reader who is not an insider of the WRF model. That is, not just by using acronyms, but fully spelled out, with references added and information how these components can be accessed.*

Thanks for the suggestion. The corresponding information has been added.

Anonymous Referee #3:

General comments:

1. *The main result of the work is not actually quantifying the emissions as suggested by the title and in the manuscript but distributing them in space through the use of the CLM4 model. Authors should be more consistent throughout their paper between their claims and what is actually done.*

In this study we quantified the spatial distribution of dust emissions in the Red Sea coastal plain. The total emission estimate is obtained from the MERRAero reanalysis and we specifically emphasized this in the text. This figure is calculated by us and was previously not known. Therefore we believe it is legitimate to use the term quantification.

2. *The total emitted amount is scaled in order to fit the total MERRAero emissions but the scaling factor is never provided.*

The scaling coefficient is provided in Table 4. We have stressed the reference in the text to make it more noticeable.

3. *Models do tune their emissions to fit AOD but by doing so they implicitly take into considerations the full aerosol cycle (i.e emission, transport and deposition) and are therefor consistent. However, by simply scaling the emissions to a given model the potential usefulness of the estimate is lost since it is not an independent estimate.*

The reviewer is, probably, familiar with the fact that the closure of the dust mass budget requires "… to quantify precisely the amount of emitted dust, the atmospheric dust load, and the deposited mass (dry and wet). However, this budget is sufficiently constrained if, at least, two of these three terms are quantified … " (Bergametti and Forêt, 2014). Therefore, the models that tune their emissions to fit AOD (i.e. dust burden) also incorporate uncertainty and cannot provide an "independent" emission estimate. So we question the remark that this approach is more consistent if the study is aimed at assessing dust emission mass. The scaling based on AOD observations alone could still be biased due to other reasons, i.e. errors in deposition velocity or size distribution representation.

In our modeling framework, we calculate only dust emissions, scale them using the most recent and reliable reanalysis dataset (see the answer to the next remark) and verify their spatial and temporal variability using station visibility observation. To our best knowledge, this is the most consistent and straightforward approach possible at present.

4. *It is not clear if it will actually improve performance for other models. How model dependant is this estimate? Even more, how large is the model uncertainty in the emissions for this region? How much dust is emitted by other models in this region?*

We are not sure if we understand the question completely. In our study, we did not compare different models, but different land cover dataset. Our results show that, certainly, using finer land cover datasets will improve spatial variability of the dust emissions and will be beneficial for the models.

The uncertainties mentioned by the reviewer are a state of the art problem. To our best knowledge, only a few estimates of dust emission were made so far for the Arabian Peninsula, and most of them are done using coarse-resolution models. No specific work has been done for the Red Sea coastal plain, so our work is a pioneering attempt of this type.

The MERRAero meteorology-aerosol reanalysis is the most appropriate data source to tune the regional dust emissions. E.g., Ridley et al., (2016) reported better seasonality of dust AOD in MERRAero compared to other datasets and pointed to potentially better dust emission due to finer spatial resolution and representation of surface winds. However, we agree with the reviewer that the uncertainty estimation needs additional attention. Following the suggestion from the anonymous reviewer #2, we have complemented the manuscript with the uncertainty range estimation based on the interannual variability of dust emission in MERRAero reanalysis. Moreover, following the suggestion from the anonymous reviewer #1, we have performed the one-month WRF-Chem simulation of dust storm event in January 2009 to compare with the off-line emissions from this study. The CLM4 results appear to be in good agreement with WRF-Chem, producing similar spatial pattern of dust emission. The total estimate of dust generation in this short-term WRF-Chem simulation is 40 % larger than in CLM4, supporting the conclusion of the study that the local dust generation is significant. The text is modified to reflect this comparison.

5. *Furthermore, what is the size distribution of the emitted dust in the MERRAero model and how does it compare to the one estimated in this study? Although only the total emission is analysed the size distribution of the emitted dust is key to determine the impact of these emissions in terms of transport and deposition. The authors should provide a discussion addressing these issues.*

It is well known that dust size distribution is important for dust transport and deposition. However, in the current study, we only simulate dust generation and do not consider transport and deposition. Within this framework, analyzing the size distribution of emitted dust would not allow to reduce uncertainty or make any additional quantitative conclusions on its transport and deposition. To do it, one needs to simulate the full cycle of airborne dust, which is a subject of future research.

6. *The authors use visibility data as a mean to validate the estimated flux and draw conclusions on the source of the dust causing this reduced visibility. Visibility is a subjective local measurement reflecting the extinction of light in a given place, but it does not provide any information on the magnitude of the source causing the reduced visibility. Therefore it cannot be concluded on the magnitude of the emission based solely on these observations whether the source is local or not, other variables such as wind direction and magnitude need to be included for this analysis or a model needs to be applied.*

The authors use the Spearman correlation as a statistic to validate the emission intensity. Besides the fact mentioned above that visibility is not appropriate parameter to validate *emission intensity, the correlation reflect similarity in variability (spatial and/or temporal) but does not provide any information on the difference or "distance" between the observed variable and the estimated one. The authors should include additional analysis to actually validate the emission intensity.*

The reviewer, probably, refers to weather code reports when talking about the subjective character of the measurements. The visibility measurements that complement the weather code report are not subjective, as they are usually done by ASOS (Automated Surface Observing System) visibility sensor. We agree with the reviewer on his concerns regarding the limitations of visibility and weather code data. Indeed, the detailed discussions about the limitation are already present in the manuscript. However, we cannot agree that visibility measurements are not appropriate for testing dust emission models. In the absence of direct observation of emission, visibility data are the most relevant data sources for these purposes. These observations provide valuable information and may serve as a reference for qualitative comparison with modeled dust emission fluxes and determine optimal model configuration (Engelstaedter et al., 2006; Tegen, 2003). They were used in a large number of dust-related studies. For example, the present weather code reports from meteorological records have been used for evaluation of dust event frequency and dust climatology (Goudie and Middleton, 2006; Shao and Dong, 2006; Wang et al., 2011; Notaro et al., 2013; Yu et al., 2013; Cowie et al., 2014; Hamidi et al., 2014), and derive soil erodibility fields (Shao, 2008). In (Camino et al., 2015; Rezazadeh et al., 2013; Shao et al., 2003) parameterization for assessing near-surface dust concentration from visibility measurement has been proposed. Mahowald et al. (2007) stated that visibility-derived observations should better capture the temporal variability of surface dust fluxes compared to AOD measurements. In our study, we use both weather code reports and visibility measurements to evaluate the frequency and intensity of simulated dust emission.

Specific comments:

1. *Page 1, line 26, (Abstract): Remove "The total dust emission from the coastal plain appears to be 7.5 Mt per year". This is not a result of the study but a constrain taken form a model and therefore should not be presented as result.*

Following the reviewer's comment, we have reformulated this phrase to make clear we obtained this figure from the reanalysis. This was first time calculated so it is a legitimate result of all reasonable means. There are tons of results in the literature obtained from the reanalysis data and nobody question their originality based only on that they are obtained from a reanalysis. The total dust emission estimate from the coastal plain is important for this study and, we believe, has to be clearly outlined in the abstract.

2. *Page 2, line 31: "Regional uncertainties are probably even higher", on what evidence is this statement based? Authors should provide a reference for this.*

It could be proofed straight mathematically, as the integral of the function over the entire globe is less variable than a function itself. Huneeus et al. (2011) reported that globally averaged model estimates of dust emission, deposition and optical properties vary by a factor of 10.

Apparently, these discrepancies are driven from even larger regional ones, as global models do not simulate regional processes. Following the suggestion, we improved the text to make it more clear.

***3.** Page 3, line 25: "Our principal objective was to obtain new. . .in order to evaluate its impact on the Red Sea". This objective should be reformulated and made consistent with the actual work done in this study. The emissions are first of all not estimated since they are scaled and for the same reason they can't be new. Furthermore, the impact of the dust deposition on the Red Sea is not evaluated. The work as presented does not have the tools to address this issue. I would therefore strongly recommend removing this last part or reformulating it in order to make it consistent with the work that is presented in the manuscript.*

We should say that the study has been motivated by that the coastal emissions are important for the Red Sea as a significant amount of this material could deposit to the Sea. We agree with the reviewer that as long as the impact on the Red Sea is not calculated directly, the statement should be removed and the objectives to be re-formulated.

***4.** Page 4, line 4: Replace "availably" with "availability".*

Thanks, replaced.

***5.** Page 4, line 10: ". . .are close of those of the parent soil." Later in the text it is said that they are the same, what is it? The same or close? Please be consistent.*

They are the same as in the parent soil. Changed.

***6.** Page 5, lines 3-7: How was the setup or configuration of the WRF model defined? Please specify.*

WRF setup generally follows default recommendations from the user guide and is identical to that used in (Jiang et al., 2011). Following the suggestion, we have included this information in the text.

***7.** Page 6, line 10: The variable "S" should be presented as source function at this point and not on line 14 as it is at present.*

Thanks, changed.

***8.** Page 7, line 2-3: Please provide a reference for the assumption that the intensity of the dust source is proportional to the frequency of occurrence of atmospheric dust. On what is this based?*

The "frequency method" was first proposed by Prospero et al. (2002), and later used in a number of other studies (Ginoux et al., 2010, Ginoux et al., 2012, Schepanski et al., 2012). Following the suggestion, the text was updated with the references.

***9.** Page 7, lines 6-7: It is still unclear how the threshold of 1.12 was chosen. Please elaborate.*

The choice of this threshold has been already explained in the reply to the comment #3 by anonymous referee #2.

***10.** Page 9, line 3: Why these two thresholds? Please explain why these two thresholds were used.*

Please refer to the question #7 by anonymous referee #1. Depending on weather station's location, meteorological and environmental conditions, the same visibility reduction may be caused by the different level of dust loading; therefore, changing thresholds could not be avoided. These two particular thresholds were chosen empirically and are aimed to demonstrate that results are not very sensitive to a threshold value.

***11.** Page 10, lines 5-8: Please provide a reference for what is said in these lines.*

Following the suggestion, the GOCART aerosol scheme description paper was repeatedly referenced in this place of the text.

***12.** Page 10, line 15: According to whom is it not captured?*

We have also analyzed the dust emissions in the MACC reanalysis. We have updated the text to make it clearer.

***13.** Page 12, lines 30-31: "Yu et al. (2013) offered several explanations for this". It is not clear to what does it refer. One would expect it refers to the previous statement, but then on the next sentence satellite data are mentioned. Please reformulate.*

Thanks for the suggestion. The statement is related to issues discussed in author's own paper. The phrase was reformulated.

***14.** Page 13, lines 5-9: I do not agree with what the authors claim in these lines. Whether the data used in this study nor the analysis conducted allow to conclude on whether the dust is emitted locally or transported from elsewhere. High correlations only indicate similar variability but are not an indication of distance between observations and model. One could have high correlations but also have dust coming from elsewhere. The explanation may appear reasonable, but it is not supported (nor refuted) by evidence presented in the manuscript. I suggest either removing completely these lines or reformulating it presenting evidence to support this claim.*

It is not clear enough from the reviewer's remark what particular point of our claims is questioned. Following that, we have expanded the corresponding section to make the discussion clearer. The idea that dust activities in our area of interest have small spatial scales was proposed by Yu et al. (2013). The authors reported low correlations (0.1 – 0.3) between the monthly AOD observations and station dust reports in the west of Arabian Peninsula, compared to much higher ones in the central and eastern Peninsula (usually more than 0.4). This means that, for some reason, dust events reported on stations could not be detected by satellite instruments. The authors also report that there is a large probability of observing low AOD values on dusty days. Several explanations for this contrast were proposed. Noting the shortcomings of remote sensing instruments that perform worse in the complex mountainous terrain of the western Arabian Peninsula, they claimed that this contrast might be caused by the small spatial-temporal scales of dust processes. In our manuscript, we claim our results to support these ideas and to be consistent with the proposed mechanisms. Higher correlation coefficients of station dust event time series and simulated emission fluxes compared to those reported by Yu et al. (2013) suggest that a large part of detected variability could be explained by local dust generation. Mahowald et al. (2007) also supported this conclusion suggesting that station observations should better capture the temporal variability of surface dust fluxes compared to AOD measurements.

***15.** Page 13, line 25: Is this model skill the correlation coefficient? Or does it refer to another statistic? Please clarify.*

Thanks for noting that, we meant the correlation coefficient here. Changed.

***16.** Page 14, line 7: "provide quite realistic results", please reformulate. How much is "quite"? Please explain better why only the FineALL case is only consider in the remaining analysis.*

The FineALL experiment was used in the remaining analysis as it has the highest resolution and the spatial correlation for it is the highest.

***17.** Page 15, line 30: Replace or eliminate "reasonably". How much is "reasonably"?*

We consider the correspondence of dust emission patterns between the two datasets as reasonable, with regard to the coarse resolution of MERRAero. Most of the hot spot areas that are present in MERRAero are also present in CLM4. CLM4 also features smaller hot spots that could not be resolved in MERRAero.

***18.** Page 15, line 31: Although SM1 and SM2 can be identified in MERRAero, the authors should acknowledge the differences between both representations (this work and MERRAero). For instance MERRAero locates a dust source further to the north than suggested by this study.*

Thanks for this suggestion. Following this and the previous comment, we have updated the text with a more detailed discussion about the location of emission hot spots in our run and MERRAero reanalysis.

***19.** Page 17, line 1: I do not fully agree on the statement made on the first sentence of the paragraph. Although hotspots present variability consistent with the seasonal cycle, not all features can be explained by the hot spots (hotspots show very little variability from March to August in contrast to emissions from the entire region which shows strong seasonality). The seasonal cycle of sources other than hotspots should also be included in the figure to clarify the real weight of hotspots in modulating the emissions in the area of interest.*

We thank the reviewer for this thoughtful suggestion. We agree that the corresponding statement is not fully correct. We have revised the paragraph and reformulated our claim.

20. *Page 17, lines 29-30: "All quantities. . .", this is actually not entirely true since figure 8b presents variability not consistent with the solar peak and this is actually described later on. Please make the analysis consistent.*

Thanks for this suggestion. We have made the statement more precise.

21. *Page 18, lines 15-18: Why is so little said about the diurnal cycle of the dust maximum emission? Or why is it included? Authors should spend at least the same effort in analysing it as on the other variables, otherwise I would suggest removing it. Actually, how does it contribute to the general goal of this study?*

We consider the maximum emission rate an important characteristic that provides the reader with a better understanding of the diurnal cycle of dust generation. Therefore, we prefer to retain the corresponding figure. Following the suggestion, we have expanded the manuscript with a more detailed discussion of the diurnal cycle of maximum dust emission rate.

22. *Page 19, line 1: I would suggest include "estimated" or "calculated" before "emitted mineral fraction".*

Thanks for the suggestion, changed.

23. *Page 19, lines 17-20: This entire paragraph should be removed from this section (it is not a conclusion of this work) and placed after the last paragraph of section 2.1.*

Following the suggestion, the paragraph has been shifted.

24. *Page 19, lines 24-26: "The results confirmed. . .." This conclusion cannot be made based on the evidence presented in this work. See comment made before.*

Following our comment above, we suppose this conclusion should be retained.

25. *Page 19, lines 27-28: This is true for the case when source function is used, while when the source function is not used this is not the case as stated in lines 25-28 of page 13. Please reformulate in order to make it consistent.*

Thanks for the important suggestion. The statement has been reformulated.

26. *Page 20, line 23: Shouldn't it be early afternoon when referring to 12:00-14:00 UTC?*

Thanks for spotting. Changed.

27. *Page 20, lines 28-31: First of all the 7.5 Mt/a are not estimated but imposed. This should be corrected. Then, the fact that emissions and deposition have comparable magnitude does not allow to conclude that it is an essential source of nutrients for the Red Sea, specially if one considers that the total amount was imposed from the beginning. Although one would expect that some of the emitted dust in the coastal plain should be deposited in the Red Sea, how much of it needs to be determined by another study. I would suggest removing this sentence.*

Thanks for the suggestion. These few statements have been changed to reflect the reviewer's concerns.

References:

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Quantifying local-scale dust emission from the Arabian Red Sea coastal plain

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Abstract. Dust plumes emitted from the narrow Arabian Red Sea coastal plain are often observed on satellite images and felt in local population centers. Despite its relatively small area, the coastal plain could be a significant dust source, however, its effect is not well quantified as it is not well approximated in global or even regional models. In addition, because of close proximity to the Red Sea, a significant amount of dust from the coastal areas could be deposited into the Red Sea and serve as a vital component of the nutrient balance of marine ecosystems.

In the current study, we apply the off-line Community Land Model version 4 (CLM4) to better quantify dust emission from the coastal plain during the period of 2009 – 2011. We verify the spatial and temporal variability of model results using independent weather station reports. We also compare the results with the MERRA Aerosol Reanalysis (MERRAero). We show that the best results are obtained with 1-km model spatial resolution and dust source function based on Meteosat Second Generation Spinning Enhanced Visible and InfraRed Imager (SEVIRI) measurements. We present the dust emission spatial pattern, estimates of seasonal and diurnal variability of dust event frequency and intensity, and discuss the emission regime in the major dust generation hot spot areas. We demonstrate the contrasting seasonal dust cycles in the northern and southern parts of the coastal plain and discuss the physical mechanisms responsible for dust generation.

This study provides the first estimates of the fine-scale spatial and temporal distribution of dust emissions from the Arabian Red Sea coastal plain constrained by the MERRAero reanalysis and short-term WRF-Chem simulations. The estimate of total dust emission from the coastal plain, tuned to fit emissions in MERRAero, is 7.5±0.5 Mt a^{-1}. Small inter-annual variability indicates that the study area is a stable dust source. The mineralogical composition analysis shows that the coastal plain generates around 76±5 Kt of iron oxides and 6±0.4 Kt of phosphorus annually. Over 65 % of dust is emitted from the northern part of the coastal plain.

1 Introduction

The mineral dust has a significant impact on climate at regional and global scales (Choobari et al., 2014; Miller et al., 2014; Shao et al., 2011a). Dust particles also play an important role in soil and forest biogeochemistry. Atmospheric deposition is a vital component of the nutrient balance of marine ecosystems (Jickells et al., 2005; Mahowald et al., 2005; Nickovic et al., 2012 and references therein; Schulz et al., 2012). Dust air-pollution also affects human health, increasing the risk of human morbidity and mortality (Morman and Plumlee, 2014).

The exploration of dust generation and transport, as well as climatology and seasonality of the dust cycle in the Arabian Peninsula, is gaining increased attention in recent years (Hamidi et al., 2013; Hamidi et al., 2014; Kalenderski and Stenchikov, 2016; Kalenderski et al., 2013; Notaro et al., 2013; Notaro et al., 2015; Prakash et al., 2015; Rezazadeh et al., 2013; Shalaby et al., 2015; Shi et al., 2016; Yu et al., 2013; Yu et al., 2015; Alobaidi et al., 2016). Along with a strong climate effect, dust outbreaks in this region affect the nutrient balance of the semi-enclosed Red and Arabian Seas. For example, it was shown that the passage of major dust storms over the Arabian Sea causes chlorophyll blooming (Singh et al., 2008). The Red Sea, bordered by the Sahara and Arabian deserts, and with little or no river discharge and infrequent flash floods from land, is highly oligotrophic, especially in the northern part, rendering nutrients coming from the Indian Ocean almost unobtainable (Acker et al., 2008; Chase et al., 2011; Weikert, 1987). Therefore, atmospheric dust and gaseous depositions are especially important as nutrient supplies for the Red Sea (Kalenderski et al., 2013; Prakash et al., 2015).

Although previous studies indicate that dust outbreaks are most frequent over the eastern sector of Saudi Arabia (Barkan et al., 2004; Goudie and Middleton, 2006; Prospero et al., 2002; Shalaby et al., 2015; Washington et al., 2003), satellite images and ground observations show that there is a zone of increased dust activity in the western part of the Arabian Peninsula (Ackerman and Cox, 1989; Furman, 2003; Ginoux et al., 2012; Shao, 2008; Shao et al., 2011a; Walker et al., 2009; Yu et al., 2013). Located next to the Red Sea, the narrow coastal plain could make a significant contribution to the overall amount of dust depositing to the sea, transporting iron, phosphorus, and nitrogen. However, despite the importance of this source area for the nutrient balance of the Red Sea, no specific studies have been focused on the semi-desert coastal region and no estimates of the amount of dust emitted from these areas have been made yet, partly due to the scarcity of observations and partly because the narrow coastal plain is a subgrid area in most global and even regional modeling studies.

The concentration of dust particles in the atmosphere depends on small-scale emission processes, which are spatially heterogeneous and involve complex nonlinear interactions controlled by meteorological conditions and properties of land surfaces. As the measurement of emission in field conditions is extremely difficult, numerical models are the principal tools for dust emission evaluation. At the same time, the results from the AeroCom intercomparison project for atmospheric models that comprise aerosol components (Huneeus et al., 2011) suggest large discrepancies in model estimates of global dust emission and deposition up to a factor of 10. As global models can not approximate fine-scale circulations well regional uncertainties in dust emissions are expected to be even higher. Due to the relatively small area and complex terrain structure of the western Arabian coastal plain, large-scale and even mesoscale models are not able to reproduce the dust emission processes here with the desired accuracy. Even for similar meteorological conditions, a number of studies reported substantial differences in dust fluxes predicted by different models, indicating the model deficiencies in accounting for fine-scale features such as soil texture and surface vegetation cover (Ginoux et al., 2012; Kang et al., 2011; Koven and Fung, 2008; Prospero et al., 2002; Shao, 2008; Textor et al., 2006; Todd et al., 2008; Zender et al., 2003b). Raupach and Lu (2004) identified key challenges in modeling wind erosion related to the representation of land surface processes, including the fidelity of parameterizations and the availability of high-resolution input data for dust generation calculations. Therefore, to obtain reliable estimates of dust emissions, especially in such highly heterogeneous regions as the Arabian Red Sea coastal plain, fine-resolution surface information is required.

Recently, satellite-derived high resolution datasets of surface properties have emerged and provided an opportunity for improving dust emission calculations (Bullard et al., 2011; Ginoux et al., 2012; Kang et al., 2011; Knippertz and Todd, 2012; Pérez et al., 2011; Shao et al., 2011a). For example, Kim et al. (2013) and Hamidi et al. (2014), using a dynamic vegetation dataset, enabled a simple dust emission scheme to account for the control of seasonally varying vegetation cover on dust emission, which is usually accounted for in more advanced schemes (Bullard et al., 2011; Mahowald et al., 2006; Zender et al., 2003a). Menut et al. (2013) reported that the State Soil Geographic Database (STATSGO-FAO), remapped from the Food and Agriculture Organization of the United Nations (FAO) two-layer 5-minute global soil texture dataset (Nickovic et al., 2012) provides realistic spatial patterns of dust emission for the Middle East and North Africa. Shi et al. (2016) discussed the impact of the satellite-derived vegetation dataset on patterns and intensity of dust emission in the Arabian Peninsula. Many studies have been devoted to accurately locating dust source regions using different criteria, accounting for sediment availability and erodibility due to geographic influences, and applying satellite datasets to define so-called source functions (Ginoux et al., 2012; Kim et al., 2013; Parajuli et al., 2014; Walker et al., 2009; Zender et al., 2003b).

In this study, we focus on dust emission from a relatively small local area: the narrow semi-desert western coast of the Arabian Peninsula. We employ the high-resolution Community Land Model version-4 (CLM4) with the Dust Entrainment and Deposition (DEAD) module to conduct simulations for the three-year span of 2009–2011. Our principle objective is to conduct multi-year emission simulations and study fine-scale dust generation areas, evaluate the temporal variability of dust emissions and assess the mineralogical composition of local dust, as a potential source of nutrients for the Red Sea. We utilize the fine-scale input datasets of soil characteristics derived from satellite-based instruments and examine the model's sensitivity to their horizontal resolution. Using high-frequency satellite measurements, we also calculate and apply the dust emission statistical source function and demonstrate the benefits of using high-resolution inventories.

We compare the results with independent weather code and visibility reports from meteorological stations. Although these data are indirectly related to local dust emissions and cannot be applied for accurate model validation, they may provide valuable information and serve as a reference for determining optimal model configuration (Engelstaedter et al., 2006; Tegen, 2003). We also compare (and calibrate) our dust emission estimates with MERRA Aerosol Reanalysis (MERRAero) (Buchard et al., 2016), a recent reanalysis product that includes an aerosol model component and has the highest spatial resolution compared with analogous products, and with short-term Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) simulations.

Marine productivity is largely limited by the availability of iron (Mahowald, 2009), which in turn depends on the solubility of iron-containing compounds in seawater. It has been shown that aerosol source mineralogy is a crucial factor for iron content and solubility as well as aging in the course of particle transport (Baker and Croot, 2010 and references therein). Together with iron, both phosphorus and nitrogen also frequently limit marine productivity (Okin et al., 2011). To evaluate the possible mineralogical composition of nutrients deposited in the Red Sea from local sources, we apply the global dataset of soil texture and mineral composition, GMINER30, developed by Nickovic et al. (2012). We assume that the mineral composition and size fractioning of the emitted dust are the same as those of the parent soil. This assumption does not always hold (Claquin et al., 1999; Perlwitz et al., 2015). Moreover, airborne dust changes its size distribution and mineralogical composition during its life cycle. Nevertheless, due to the short pathway from the coastal plain to the sea, the atmospheric processing of dust particles from this closely located source is less important compared to those subjected to long-range transport, and our assessment may serve as an initial estimate of the mineralogical composition of dust particles deposited to the Red Sea.

The rest of the article is organized as follows: In Sect. 2, we present the model description and characterize the study domain and observational datasets. In Sect. 3, we describe numerical experiments, examine model sensitivity to land surface datasets and compare results with station observations. A detailed analysis of dust generation and its spatial-temporal variability is conducted in Sect. 4. We summarize our results and draw conclusions in Sect. 5.

2 Data and methods

2.1 CLM4 model and meteorological forcing

We perform the numerical experiments using the off-line CLM4 (Lawrence et al., 2011; Oleson et al., 2010) implemented with the DEAD module (Zender et al., 2003a). CLM4 is the land surface model used with the global Community Earth System Model (CESM) (Hurrell et al., 2013), and some other regional models [i.e. Regional Climate Model (RegCM4) (Wang et al., 2016) and Weather Research and Forecasting (WRF) (Zhao et al., 2016)]. CLM4 calculates turbulent fluxes of momentum, heat, and water vapor from the surface into the atmosphere, interaction of solar and thermal radiation with soil and vegetation, and heat and moisture fluxes in soils. CLM4 also simulates vegetation processes. The off-line version of CLM4 can be run at a finer spatial resolution than driving meteorological fields to account for high heterogeneity of land surface. Additionally, some soil characteristics in CLM4 can be prescribed, instead of being calculated within the model. In this study, we turn off the transient land cover change calculations and the dynamic global vegetation model to conduct historical simulations using observed high-resolution satellite land cover and vegetation datasets instead.

CLM4 is forced by meteorological fields including the wind, surface pressure, precipitation, temperature, and incoming solar and thermal radiation. The driving meteorological fields for CLM4 are provided by the WRF model (Skamarock et al., 2008) run at a 10 km × 10 km resolution over the Arabian Peninsula (8.06° N–34.6° N, 30.3° E–60.9° E) for the period of 2009–2011. The domain completely covers the Arabian Red Sea coastal area (Fig. 1). The WRF configuration used in our simulations is detailed in Table 1. It generally follows default recommendations from the user guide and is identical to that used in (Jiang et al., 2011).

2.2 Dust generation

The DEAD module (Zender et al., 2003a) is designed to calculate dust emission at both local and global scales, generally following the microphysical and micrometeorological model of dust mobilization developed by Marticorena and Bergametti (1995). Soil moisture, vegetation properties, land use, and soil texture data needed to drive DEAD are provided by CLM4. DEAD falls into the category of intermediate complexity models that are more sophisticated than simple bulk mobilization schemes (Tegen and Fung, 1994) and not as complex and calculation-heavy as fully microphysical schemes (Marticorena and Bergametti, 1995; Shao, 2004; Shao et al., 2011b). Intermediate complexity models use microphysical parameterizations where possible, but make simplifying assumptions and use empirical coefficients to shortcut complex calculations (Zender et al., 2003a). The total vertical mass flux of dust F (kg m^{-2} s^{-1}), generated from the ground into the atmosphere is calculated using the following equation:

$$F = TSf_m Q_s \sum_{j=1}^{4} \alpha_j M_j, \quad (1)$$

where T is a spatially uniform tuning constant that controls the average emission rate (see Sect. 2.4).

The f_m parameter is a grid cell fraction of soils suitable for dust mobilization. It depends on the land fraction of bare soil (which is calculated dynamically depending on soil conditions), the plant function type (PFT), leaf area index (LAI), stem area index (SAI), and top soil layer water content, calculated within CLM4.

The α_j coefficients are sandblasting mass efficiencies for each of the four dust transport size bins j. They depend on the mass fraction of clay particles (CLY) in the soil, which is defined by SOILPOP30, a 30-second soil population dataset developed by Nickovic et al. (2012) from STATSGO-FAO. This soil dataset is widely used in dust-related studies (e.g., Menut et al., 2013).

M_j is a mass fraction of dust size bin j. The size bins approximate particles with diameters from 0.1 μm to 1 μm, from 1 μm to 2.5 μm, from 2.5 μm to 5.0 μm and from 5 μm to 10 μm. In the original model formulation, the emission flux is calculated separately for each size bin. Here, we consider total emitted dust mass and therefore, sum up fluxes from all the bins in equation (1).

Q_s is the total horizontally saltating mass flux (kg m^{-2} s^{-1}). It is proportional to the third power of wind friction velocity u_{*s} (m s^{-1}) when it exceeds threshold velocity u_{*t}:

$$Q_s = \begin{cases} \frac{c_s \rho_{atm} u_{*s}^3}{g}\left(1-\frac{u_{*t}}{u_{*s}}\right)\left(1+\frac{u_{*t}}{u_{*s}}\right)^2, \text{ for } u_{*s} > u_{*t}, \\ 0, \text{ for } u_{*s} \le u_{*t} \end{cases} \quad (2)$$

where c_s is the saltation constant equal to 2.61, ρ_{atm} is the atmospheric density (kg m^{-3}), and g is the acceleration of gravity (m s^{-2}). Saltation wind friction velocity u_{*s} is calculated from wind friction velocity u_* (m s^{-1}) accounting for the Owen effect of increasing u_* during saltation (Zender et al., 2003a). Threshold friction velocity u_{*t} is calculated within CLM4 as a function of surface roughness and soil moisture.

S is a spatially varying dimensionless dust emission source function. It has a sense of soil erodibility and accounts for the susceptibility of soil to wind erosion (Webb and Strong, 2011). In the default CLM4 configuration $S = 1$, assuming that the emission is calculated based on winds and available surface and soil properties only. However, it has been reported recently that the models based on purely physical properties of soils represent quite inaccurate spatial patterns of dust emission, especially on the regional scale (Huneeus et al., 2011; Knippertz and Todd, 2012). This is caused by the deficiencies of parameterizations and inaccurate input information. Thus, the source function S is introduced to improve the spatial distribution of dust emission simulations.

Different approaches have been discussed and a number of principles to calculate the source function recently introduced (Kim et al., 2013; Parajuli et al., 2014; Walker et al., 2009). Ginoux et al. (2001) proposed calculating the source function based on a topographic approach, assuming that the areas with topographic depressions are the most probable locations for sediments to accumulate. The geomorphic source function (Zender et al., 2003b) is based on the assumption that dust emission is likely to occur from areas of potential runoff collection. Similar to the topographic source function, it only depends on elevation. Another family of source functions is instead based on observations (mostly remote sensing), assuming that the most active dust source areas are those where airborne dust is more frequently observed. The statistical source function introduced by Ginoux et al. (2010) and Ginoux et al. (2012) uses Moderate Resolution Imaging Spectroradiometer (MODIS) estimates of aerosol optical depth and land cover data to identify the dust source areas.

In this study, we calculate source function using the dust aerosol optical depth (AOD_D) product developed by (Brindley and Russell, 2009) and (Banks and Brindley, 2013), based on high-frequency measurements from the Meteosat Second

Generation Spinning Enhanced Visible and InfraRed Imager (SEVIRI) instrument. The SEVIRI instrument is located on board the Meteosat-9 geostationary satellite and provides measurements every 15 minutes (Brindley and Russell, 2009; Banks and Brindley, 2013), much more frequently than MODIS. SEVIRI measurements were recently utilized to analyze dust sources in Northern Africa (Schepanski et al., 2012; Evan et al., 2015). To calculate the source function we adopt the frequency method, first proposed by Prospero et al. (2002), and later used in a number of other studies (Ginoux et al., 2010, Ginoux et al., 2012, Schepanski et al., 2012). It assumes that the intensity of a dust source is proportional to the frequency of occurrence of atmospheric dust:

$$S = N\ (AOD_D > AOD_t)\ /\ N\ (AOD), \tag{3}$$

where statistical source function S is defined in each location as a ratio of the number of events $N\ (AOD_D > AOD_t)$ when dust-caused AOD_D exceeds the threshold value AOD_t, to the total number of observations $N\ (AOD)$. The threshold is meant to filter out background dust and is usually chosen empirically (Schepanski et al., 2012). We have tested the thresholds in the range of 0.8 – 1.15 and found that the spatial patterns of the source functions are quite similar. The chosen threshold value of 1.12 is larger than the one used in the global study (Ginoux et al., 2012) but comparable to regional studies of Saharan dust sources (Schepanski et al., 2012). The choice of relatively large threshold was motivated by several reasons. First, the background dust AOD in Arabian Peninsula is much higher than globally observed one. Second, SEVIRI was shown to overestimate AOD under high humidity conditions and low dust loadings that are the case for the Red Sea coastal plain (Banks et al., 2013). Overall, this larger threshold allows us to better represent intensive dust sources, in contrast, e.g. to (Ginoux et al., 2010; Ginoux et al., 2012) that aimed at capturing and classifying smaller sources. Below we show that the source function based on high-frequency measurements significantly improves the simulation results.

2.3 Observations, metrics and an overview of the study area

The targeted study area is the eastern coast of the Red Sea in western Saudi Arabia. It is shown in Fig. 1a bounded by a solid red line. The coastal area has the historical name of Tihamah. It covers both plain and hill landscapes, from the Tihamat Al-Hejaz (northern part) and Tihamat ‘Asir (southern part) coastal plains to the Scarp Mountains of Midyan, Ash Shifa’ and Asir (Edgell, 2006). The land cover, precipitation, and surface wind speed are highly heterogeneous in this narrow (on average 100 km wide) area. In the eastern part of the coastal plain, closer to the mountain area, the land is covered by more or less continuous shrubs and steppe vegetation due to higher precipitation (see Fig. 1c–e). In the northern coastal plain vegetation cover is sparser (Fig. 1f) as the annual precipitation is only 50 mm. Southward, in most of the piedmonts, annual rainfall of 100–200 mm supports denser vegetation cover (Vincent, 2008). Infrequent extreme precipitation events that cause flash floods in western Saudi Arabia (de Vries et al., 2016 and references therein) lead to accumulation of sediments in the coastal low-land areas.

The Red Sea environment has been identified as a zone of complex wind circulation (Langodan et al., 2014). Due to the strong land-sea diurnal temperature contrasts, land and sea breezes persist through the entire year. The large-scale circulation systems interact with breezes and are reinforced by orographic structures, which create a complex pattern of mesoscale circulation. The most prominent mesoscale feature of the Red Sea is the Tokar Gap jet on the western coast (Davis et al., 2015 and references therein). Westward-blowing mesoscale jets also exist on the eastern coast (Gille and Llewellyn Smith, 2014; Jiang et al., 2009). These jets originate mostly in Winter due to the cold/dry air outbreaks from the central Arabian plateau and channel through a series of mountain gaps. They may last for several days and have a prominent diurnal cycle. The jets, along with the breezes, cause small-scale dust updrafts in the coastal area. The generated dust plumes are sometimes observed by satellites over the Red Sea. For example, a dust storm with narrow dust plumes caused by the jet winds captured by MODIS/TERRA at 7:45 UTC on 14 January 2009 is shown in Fig. 1b.

In order to cover the study area, we run the CLM4 model over the two rectangular domains shown in Fig. 1a. Also shown are the meteorological observation stations that are used in the current study. We use hourly data from the Integrated Surface Dataset (ISD) developed by the National Climatic Data Center (NCDC) (Smith et al., 2011). We selected 15 stations in Saudi Arabia and 1 station in Jordan inside the CLM4 domains with continuous observation records for 2009–2011. The stations provide meteorological observations including weather code and visibility reports. The automated visibility measurement and manned weather code observation are reported on an hourly basis, but the weather code is only present when visibility reduces to below 10000 m. Otherwise, just a constant visibility of 10000 m is reported (indicating fair weather). The weather codes that correspond to the presence of dust are 06 – dust in suspension, 07 – dust raised, 08 – dust whirl, 09, 30 to 35 – dust storm. Most of the weather stations (except that in Makkah) are located on the site of regional or international airports, thus the data archive was primarily assembled from SYNOP or METAR/SPECI weather reports (Smith et al., 2011).

Although the station visibility measurements are only indirectly related to the amount of locally emitted dust, they are one of the most relevant data sources for assessing dust emission fluxes in the absence of other observations. These data are frequently used in dust-related studies. For example, the present weather code reports from meteorological records have been used for evaluation of dust event frequency and dust climatology (Cowie et al., 2014; Goudie and Middleton, 2006; Hamidi et al., 2014; Notaro et al., 2013; Shao and Dong, 2006; Wang et al., 2011; Yu et al., 2013). In some other studies, these observations were used to derive soil erodibility fields (Shao, 2008). The parameterization formula for assessing near-surface dust concentration based on visibility measurement has also been proposed (Camino et al., 2015 and references therein; Rezazadeh et al., 2013; Shao et al., 2003). Mahowald et al. (2007) used the station visibility measurements to study dust sources and stated that visibility-derived observations should better capture the temporal variability of surface dust fluxes compared to AOD measurements. But still, these data cannot serve as a quantitative measure of model performance, being non-automated (in the case of weather code), and being highly influenced by remote dust transport, the presence of water vapor, and dust physical properties and composition (Shao, 2008). Another limitation of station observations is a weak sensitivity to low and moderate reductions in visibility that is only reported and complemented by the weather code when it drops below 10000 m. Camino et al. (2015) also note that clear skies are often reported under hazy atmospheric conditions when dust is present. Thus we do not expect out analysis to give an absolute assessment of model emissions, but to allow comparison of different model configurations.

We apply several metrics to compare the model statistics of dust events with station data, making use of both weather code reports and visibility measurements. First, we assess the temporal variability of dust event frequency and intensity, correlating the monthly-averaged time series. We follow the classical definition of dust event frequency F_d from hourly weather code reports (Shao and Dong, 2006):

$$F_d = N_d / N_{tot}, \quad (4)$$

where N_d is the number of reported dust events, and N_{tot} is the total number of reports (including those when visibility was not reduced below 10000 m and no weather code was reported). All of the weather codes indicating the presence of dust (i.e. 06 to 09, and 30 to 35) were considered corresponding to a dust event. Based on this definition, we construct the monthly-averaged time series, so that the frequency is calculated separately for each month. To obtain the model estimate of dust event frequency, we calculate it as a fraction of time when hourly-averaged emission is above the certain threshold. We apply two constant thresholds of 1 μg m^{-2} s^{-1} and 4 μg m^{-2} s^{-1}, approximately corresponding to 70^{th} and 85^{th} quantiles of hourly emission rates. Taking the fraction of the time with dust emission above the threshold during the month, we obtain the model monthly time series of dust event frequency.

To analyze the intensity of individual dust events, we sample the visibility measurements for each station taking only those time steps that correspond to dust events, and calculate the monthly-averaged visibility reduction, treating it like "dust event intensity". In the case of no visibility reductions reported during the month (which is not a rare case for some stations), the 10000 m visibility value is presumed. The corresponding model time series are obtained in a way similar to that of frequency, applying the same thresholds. Dust generation intensity is considered equal to zero if there are no events above the threshold during that particular month. An approach alternative to sampling was proposed in (Mahowald et al., 2007). The authors noted the scarceness of weather code reports and proposed to filter non-aerosol (fog-driven) visibility reductions based on dew-point temperature measurements. In our case, we prefer a sampling approach as most of the station visibility reduction measurements are complemented with weather codes.

Both of the metrics described above reflect the primarily temporal, not spatial, variability of the model results. We apply the metrics to different model configurations and, as their basic effect is aimed at improving the spatial patterns, no significant differences are found. Thus some other metrics are needed to assess the reliability of dust emission spatial distributions. The technique we propose for assessing spatial patterns of dust emission is to sample the hourly visibility time series by dust event reports, choosing the time steps when a dust event was reported, and to calculate the daily, and then 3-year mean visibility for each station. The mean emission rate is also calculated from model data sampled for the same time steps. Station data are sampled to correspond to hourly instantaneous model output: thus SPECI reports that usually take place between regular reports are not considered. We, therefore, obtain two samples of 3-year averaged station dust intensity and model emission rate (with the sample length equal to the number of stations) and calculate the correlation coefficient between them.

We calculate correlation coefficients between samples that reflect diverse highly non-linear physical phenomena. As we do not have the physical ground to assume the linear relation between these phenomena, we use Spearman's rank correlations instead of Pearson's correlations for all cases. The dust emissions and station visibility are negatively correlated, whereas the opposite is true of station dust frequency. For the sake of simplicity, here we report the emission – intensity correlations with reversed sign, keeping both coefficients positive.

2.4 MERRAero reanalysis and dust emission calibration

Very recently, a few aerosol reanalysis products have become available (Buchard et al., 2016; Inness et al., 2013). In this study, we utilize the dust emissions from MERRAero aerosol reanalysis developed by NASA (Buchard et al., 2016), which was calculated using meteorological fields from Modern-Era Retrospective Analysis for Research and Applications (MERRA I) (Rienecker et al., 2011). The reanalysis has a spatial resolution of 50 × 50 km and is available from 2003 onwards. MERRAero is built on the Goddard Earth Observing System version 5 (GEOS-5) atmospheric model, which comprises an aerosol module based on a version of the Goddard Chemistry, Aerosol, Radiation, and Transport (GOCART) model (Chin et al., 2002; Ginoux et al., 2001). GOCART simulates the interactive cycle of dust, sulfate, sea salt, black and organic carbon aerosols. MERRAero assimilates AOD observations from the MODIS sensor flying both on TERRA and AQUA satellites. The GOCART dust scheme in GEOS5 uses a topographic source function (Ginoux et al., 2001).

It is a common approach for atmospheric dust calculations to use calibration based on observations of total AOD (or assimilate AODs as in MERRAero reanalysis), as it is the basic observed quantity that characterizes an amount of aerosols in the atmosphere (Kalenderski et al., 2013; Prakash et al., 2015; Zhao et al., 2013; Zhao et al., 2010). However, in our off-line CLM4 simulations we do not calculate AOD and therefore cannot compare our results with the observed AOD directly (Shi et al., 2016). In the absence of quantitative measurements of dust generation the direct model validation is not possible (Laurent et al., 2008; Bergametti and Forêt, 2014). Therefore, we calibrate the model emissions integrated over the entire coastal area using the dust emissions from MERRAero reanalysis. We note that it is difficult to expect a global reanalysis with a relatively low spatial resolution to produce detailed spatially resolved estimates of dust emission over a narrow coastal zone. The coastal plain is only covered by one or two grid boxes (in width) by the MERRAero grid. On the other hand, the reanalysis captures the enhanced dust activity area on the western coast of the Arabian Peninsula and its integral (over the entire coastal area) multi-year estimates of dust emission from approximately 150000 km^2 area is a reasonable reference point for model calibration. Although MERRAero dust emission has not been validated directly, the recent paper (Ridley et al., 2016) reported better seasonality of dust AOD in MERRAero compared to other datasets and pointed to potentially better dust emission patterns due to finer spatial resolution and representation of surface winds. Thus, we rely on the MERRAero estimate of 2009–2011 annual dust emission from the coastal plain (7.5 Mt) and set the T constant in (1) to produce the same dust amount in CLM4. The scaling factor depends on whether the dust emission source function is used or not. The values of scaling factors applied in our experiments are given in Table 4. We also examined the Monitoring Atmospheric Composition and Climate (MACC) reanalysis product available from ECMWF (Cuevas et al., 2015; Bellouin et al., 2013), but its spatial resolution of 80 × 80 km is coarser than that of MERRAero and it does not capture the enhanced dust emission from the coastal plain.

2.5 WRF-Chem simulations

To test the off-line CLM4 dust emission simulations we also conduct simulations with the WRF-Chem model (Grell et al., 2005). WRF-Chem includes interactive calculations of transport and chemical/microphysical transformations of trace gases and aerosols, including mineral dust and calculates dust emissions interactively. However, the WRF-Chem model is computationally demanding and at present cannot be used for multi-year fine resolution simulations in a meaningfully large spatial domain. Therefore, we compare our off-line dust generation estimates with those from two short-term WRF-Chem simulations. First, we use the results from (Kalenderski et al., 2013), who performed a 10-km run for the period of 1–20 January 2009, which included several major dust outbreaks from the Arabian Peninsula across the Red Sea. Additionally, we have performed a finer scale 4-km simulation for 1–31 January 2009, but in a smaller spatial domain focused on the Red Sea coastal plain (Fig. 1). The experiment setup is generally identical to (Kalenderski et al., 2013). The main difference is that we use a more sophisticated 8-bin Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) (Zaveri et al., 2008) and photochemical Carbon Bond Mechanism (CBM-Z) (Zaveri and Peters, 1999). Another update is that instead of topographic source function (Ginoux et al., 2001) used in (Kalenderski et al., 2013), to be consistent with the current study, we use the SEVIRI source function described in section 2.2. Kalenderski et al. (2013) calibrated the dust emission calculations based on AOD observation from Solar Village AERONET station (see the previous section). As there are no AERONET stations in the smaller domain of our WRF-Chem simulation, we calibrate our model run using AODs from (Kalenderski et al., 2013) (Fig. S1).

3 Sensitivity analysis

The dust emission parameterizations calculate dust influx in the atmosphere using meteorological fields, land-surface physical properties, and, sometimes, empirical proxy information about land-surface erodibility, see Equation (1). Here we use the improved datasets of soil and vegetation physical properties and high-frequency source function as input for our dust generation calculations. To evaluate the effect of these improved input datasets on dust generation, we use the same meteorological fields fixed in all sensitivity simulations. Firstly, we assess the sensitivity of the parameterized dust emissions to varying spatial resolution of land surface characteristics. Secondly, we apply the dust emission source function and test the results using weather station data.

3.1 Sensitivity to the horizontal resolution of surface data

Shi et al. (2016) discussed CLM4 sensitivity to the type and resolution of vegetation datasets for the entire Arabian Peninsula. They quantified the impact of high-resolution surface characteristics derived from MODIS measurements compared to the default ones on dust emission in the Arabian Peninsula. They found that dust emission is most sensitive to surface vegetation, especially in sparsely vegetated areas, which is the case for the western coastal plain. Here, we extend the sensitivity study of Shi et al. (2016) to finer scales, examining the sensitivity to the horizontal resolution of plant function type (PFT), leaf area index (LAI), stem area index (SAI), and clay mass fraction (CLY) fields. The description of those datasets is given in Table 2.

First, we consider the sensitivity of dust emissions, when changing the spatial resolution of each of the input surface characteristics separately. We perform a control experiment with all of the surface data taken at 10 × 10 km resolution (10kmALL), and four additional simulations. In the 10kmLPFT, 10kmLLAI, and 10kmLCLY experiments, we degrade the spatial resolution of one of the datasets (PFT, LAI, or CLY, respectively) in comparison with 10kmALL to 50 × 50 km. In the 50kmALL experiment, the spatial resolution of all of the above characteristics is degraded to 50 × 50 km. Wind forcing and model grid resolution of (10 km × 10 km) are kept the same for all simulations. See the definition of all relevant experiments in Table 3. Spatially uniform tuning constant $T = 0.011$ is used in all experiments (Table 4) based on 10kmALL calibration. It is important to mention that T does not affect the spatial patterns of emission, which is the primary focus of our attention in these experiments.

The differences between annual mean dust generation in 10kmALL and other simulations is depicted in Fig. 2, a–c. Overall, using high-resolution vegetation results in an appreciable increase in total dust generation with comparable contribution from PFT and LAI datasets. The changes are not strictly additive, as the emission process is non-linear, and are spatially non-uniform. Total dust emission from the coastal plain in 50kmALL is around 10 % smaller than in 10kmALL. The partial differences are smaller: 6 % (10kmLLAI) and 3 % (10kmLPFT). The spatial structure of dust generation changes with the increased resolution of vegetation datasets is spatially non-uniform. The highest differences occur along the mountain areas with substantial vegetation cover (Fig. 1a). Locally, in the central and southern parts of the coastal plain, dust generation may increase more than 50 % (Fig. 1c). In some areas south of the coastal plain, high-resolution plant function type leads to decreasing of dust emissions. The difference between the 10kmALL and 10kmLCLY simulation is not shown, as the changes are very small (less than 1 g m^{-2} a^{-1}). The likely explanation for the low model sensitivity to soil texture dataset resolution is that its data sources may initially have been based on relatively coarse resolution observations, which have subsequently been reinterpolated to a finer grid.

To analyze the impact of fine-resolution surface data on dust generation, we perform an additional 1kmALL experiment with 1 × 1 km model grid and all the input datasets taken at the highest resolution possible (Table 2). The wind forcing is kept at 10-km resolution. The difference of annual dust emission between 1kmALL and 10kmALL simulations is shown in Fig. 2d. The results confirm the previous finding. Total dust emission further increases when switching to 1-km resolution, although the magnitude of these changes is smaller than the difference between 10kmALL and 50kmALL (Fig. 2c). Similarly, the changes are mostly associated with the vegetation and confined to the southern part of the coastal plain.

3.2 Model test with station data

In this section, we compare the model results with observations at meteorological stations, keeping in mind the limitations of this approach discussed in Sect. 2.3. To obtain the model values at station locations, we use bilinear interpolation from four surrounding grid points. If bilinear interpolation is not possible (for the coastal stations), the nearest neighbor grid point is used. First, we assess the model's ability to capture the temporal variability of dust generation in the region on monthly scales. The temporal variability of model dust emissions is mostly driven by the wind forcing. As the wind forcing is the same for all experiments, it is not surprising to find that correlation coefficients are similar in all model simulations. Therefore, we show the results for both dust event frequency (Fig. 3a) and intensity (Fig. 3b) based on 10kmALL simulation only.

For most of the stations, there are positive correlation coefficients of dust event frequency, ranging from 0.3 to 0.7 with the mean value of 0.47 ± 0.15 for 1 µg m^{-2} s^{-1} threshold and 0.52 ± 0.14 for 4 µg m^{-2} s^{-1} threshold. Most of the correlations are statistically significant at the 95 % level, suggesting reasonable model skill. For Jeddah, Bisha and Madinah, correlations become significant when a larger threshold is applied, and for Najran and Abha, only correlations with the smaller threshold are significant. The intensity correlations are not fully independent from frequency, as average visibility drop is related to the number of dust reports (in the case of severe dust storms, there are usually a number of concurrent reports that increase the frequency estimate). Despite that, we report visibility-based correlations of intensity, as these measurements are used for the spatial metrics. The results are slightly worse than for dust frequency with the mean correlation around 0.4 ± 0.2 for both thresholds, but correlations are still significant for 12 stations out of 16. Overall, the obtained correlations demonstrate a good model ability to simulate the monthly variations of dust activities.

Our correlations for most of the stations in western Saudi Arabia (Yenbo, Al Wajh, Jeddah, Makkah, Taif, Tabuk, Jizan) are higher than those between monthly satellite AOD and dust reports calculated by Yu et al. (2013). The authors reported lower correlations (0.1 – 0.3) between the monthly AOD observations and station dust reports in the west of Arabian Peninsula, compared to much higher ones in the central and eastern Peninsula (usually more than 0.4). The authors also reported a large probability of low AOD values on dusty days for stations in the western Peninsula. Several explanations were proposed for this effect. Mentioning the instrumental shortcomings of satellite sensors over complex terrain and their low temporal resolution, Yu et al. (2013) indicated that a lot of dust is transported to the western coastal area from remote sources at higher altitudes, and therefore not captured by surface stations. On the other hand, low AOD during the days when a dust event is reported might be due to the small spatial scale of dust plumes over complex terrain. Similar mechanisms explaining low correlations between local station visibility observations and nearby AOD measurements from AERONET were also proposed in Mahowald et al. (2007).

The results obtained in the current study are consistent with those proposed by Mahowald et al. (2007) and Yu et al. (2013), supporting the proposed mechanisms. Higher correlation coefficients between station dust events and simulated emission fluxes compared to those reported by Yu et al. (2013) suggest that a large part of detected variability could be explained by local dust generation. On the other hand, Yu et al. (2013) also suggested that over the Red Sea coastal plain dust is not a predominant aerosol. This statement was questioned recently by Osipov et al. (2015) who reported, based on the CALIPSO lidar measurements during 2007–2013, that the ratio of the "not dust" to "dust" successful retrievals over this area is 2.04 %.

To assess the spatial distribution of simulated dust emissions and choose the best model settings, we use the metrics described in Sect. 2.3. The model and station data are sampled to include the visibility reductions during dust reports only. The number of reported dust events per station during the 3 years considered in the study ranges from less than 100 at two stations (72 dust reports in Makkah and 64 dust reports Al Wajh) to up to 400. Given this, the two stations with the lowest numbers of observations are excluded from the final spatial analysis. The Al Wajh station is situated just several hundred meters away from the sea shore, and the low number of dust reports may be due to small-scale circulation features. Model and satellite dataset resolution may be not enough to represent the local circulation, surface characteristics and emission rate with the desired accuracy. As for the Makkah station, the low number of dust reports may be caused by instrumentation errors and insufficient quality control; the station is not collocated with the airport and the data are not used in aviation services.

The spatial correlations with station samples are calculated for three basic simulations (50kmALL, 10kmALL and 1kmALL) with and without the statistical source function (Fig. 3c). The results show that using the SEVIRI source function significantly improves the spatial structure of dust emission. Even our short-sample statistics allow high correlations to be obtained for all of the three basic simulations. Increasing the surface datasets' resolution, together with applying the source function, leads to increasing the correlation coefficient to 0.68, 0.77 and 0.85 depending on the basic simulation. The correlation coefficients for simulations without source functions are not statistically significant. The 50kmALL correlation is almost zero, whereas correlations in 10kmALL and 1kmALL experiments are almost equal. This result is expected, implying high-resolution datasets only add small-scale details that are difficult to capture with a coarse observational network.

Along with the SEVIRI source function, we use several others (see Sect. 2.2). However, topographic, geomorphic and MODIS-based source functions are all unable to significantly increase the model skill. For topographic and geomorphic source functions this can be explained by the fact that they were developed for large-scale models initially, thus, they are not expected to work well on regional scales. The MODIS source function, on the other hand, is based on measurements from a polar-orbiting satellite that has low temporal resolution (only two measurements per day), insufficient to capture the local dust phenomena caused primarily by circulations with a prominent diurnal cycle (Ginoux and Torres, 2003; Kocha et al., 2013; Yu et al., 2013) (see Sect. 4.3).

4 Dust emission multi-year estimate

The above analysis shows that 50kmALL, 10kmALL and 1kmALL model configurations with the source function based on high-frequency satellite measurements provide quite realistic results (spatial correlation with respect to observations of 0.68, 0.77 and 0.85). 1kmALL simulation with the SEVIRI source function has the highest resolution and correlation coefficient; therefore, we use it for further analysis of dust emission climatology and discuss the major dust source areas within the coastal plain, diurnal and seasonal cycles of emission from those areas, as well as their annual mean and variability.

4.1 Emissions from the main dust sources

We first address the spatial distribution of dust generating areas (hot spots), and then turn to the temporal variability. To examine the dust generation regime, we discuss the three-year averaged (2009–2011) spatial patterns of total generated dust amount (Fig. 4), dust emission frequency, intensity and maximum emission rate (Fig. 5). Dust emission hot spots are defined as areas where generated dust amount and emission frequency are two times higher, and dust event intensity is 1.5 times higher than domain-averaged values. The locations of hot spots are shown by shaded areas on a real color satellite image (Fig. 4c).

To analyze the mechanisms initiating dust generation, we examine the wind forcing and its variability (Fig. 6). We pay special attention to dust generation mechanisms in the hot spot areas. Although the period of three years is quite short to be considered as climatologically representative, it is shown below that dust generation in this area generally, has low interannual variability. In the current and subsequent sections, we use the same threshold for frequency and intensity (4 $\mu g\ m^{-2}\ s^{-1}$) as for calculation of correlation coefficients with observations.

The total dust emission is spatially variable, changing from zero to more than 100 $g\ m^{-2}\ a^{-1}$ in some areas (Fig. 4a). Figure 4a and Fig. 5a–b depict a similar pattern, suggesting that the areas with the largest and most frequent dust outbreaks coincide. The dust emission hot spots occupy around 8 % of the total coastal area (Fig. 4c). The zones where the maximum emission rate occurs (Fig. 5c) comply well with the hot spots. Most of the hotspots correspond to lowlands. The hotspots are located not directly near the coastal areas, but rather near the western hillsides of the Hejaz Mountains, in the dry riverbeds ("wadis") where alluvial deposits are available. The primary hot spot zone in the northern part of the study area (SM1, Fig. 5c) spans along the coast between the cities of Yenbo and Umluj. Emission intensity reaches its maximum value here (over 12 µg m^{-2} s^{-1}), and emission frequency is over 0.25. As seen from Fig. 6d, this hot spot is mostly driven by high winds. Dust event frequency is highly variable here, which is explained by the wind forcing variability (Fig. 6e). Dust generation and wind forcing peak in Spring. These hot spot conditions are prevalent in this part of the coastal plain.

The chain of dust hot spots in the southern part of the coastal plain stretches from Makkah to Abha. Three isolated hot spot zones can be identified. The first one lies to the south of Makkah and Taif (SM2, Fig. 5c). The second zone is in the proximity of Al Bahah (SM3). A third small but intensive zone is located on a coast near the city of Al Qunfudhah (SM4). The frequency of dust events is around 0.25 in these southern hot spot areas, and emission intensity reaches more than 10 µg m^{-2} s^{-1}.

The SM2 hot spot is driven by moderate winds with considerable intermonth variability, thus the frequency of dust activity changes during the year, having its peak in Summer months. In the rest of the southern hot spots (SM3 and SM4, Fig. 5c), wind activity is weak (Fig. 6d) and dust emission is mainly facilitated by the low erosion threshold and is increased due to source function correction. The intermonth variability of dust emission is relatively low here and is predominantly driven by dust frequency variations. There are two other smaller, isolated emission zones: a hot spot near the Gulf of Aqaba in the north (SM6, Fig. 5c) and an intensive hot spot area in the south near Jizan (SM5, Fig. 5c).

Dust emission in the large area between 21° N and 24° N is relatively uniform and reaches quite a considerable volume. Although there are no major hot spots, this area contributes significantly to the total dust generation, producing around 2 Mt of dust per year. The annual-mean dust frequency is around 0.15 here, and the average dust intensity is 7–9 µg m^{-2} s^{-1}, with both of them reaching maximum in Winter. Dust generation shows high intermonth variability, but in contrast to SM1, the variability is mostly caused by variations in dust emission intensity. Examining the wind circulation in this area, we find that the high variability of dust event intensity is caused by high monthly mean values in Winter and early Spring. Dust intensity averaged over this part of the coastal plain reaches 36 µg m^{-2} s^{-1} during a January 2009 dust storm and 28 µg m^{-2} s^{-1} during March 2011. High maximum values of dust intensity are also seen in Fig. 5c. On the other hand, the intermonth variability of dust frequency is relatively low here. Dust outbreaks are driven by short-lived wind gusts, likely to be explained by diurnally varying jet winds (Gille and Llewellyn Smith, 2014; Jiang et al., 2009). This is confirmed by analyzing the sub-month variability of winds (not shown). During January 2009 and March 2011, hourly wind speed variability was two times higher than average, although mean wind speed was only 20 % higher than the annual average. Due to the non-linear character of dust generation, these wind gusts may lead to high monthly values of dust generation intensity. Similar processes also occur in the north of the SM1 hot spot.

To further confirm this idea we analyze the WRF-Chem simulations discussed in section 2.5. The jets that originate in the coastal plain and bring dust over the Red Sea are both observed by satellites and simulated in the models (Fig. S1). The spatial patterns of dust generations in WRF-Chem and CLM4 simulations are consistent (Fig. S2). However, the magnitude of dust emission in the models varies. In the 20-days simulation by Kalenderski et al. (2013), 1.39 Mt of dust is generated compared to 0.66 Mt in CLM4. In the WRF-Chem–MOSAIC run performed in the current study 1.5 Mt of dust is produced during January 2009 compared to 0.92 Mt in CLM4. Thus, the daily average dust generation from the coastal plain in WRF-Chem is 40–50% larger than in CLM4 which is in the range of expected uncertainty between off-line and coupled dust simulations.

The annual mean spatial distribution of dust emission in MERRAero for the period of 2003–2015 is depicted in Fig. 4b. Due to its coarse resolution, MERRAero hardly resolves the local-scale emission areas. Nevertheless, the dust generation pattern reasonably complies with the results obtained with the high-resolution model and features the primary emission zones. Two major emission zones in Fig. 4b can be identified as SM1 and SM2, although SM1 is smaller than in our results and its peak generation is further to the north. The SM2 source area is the strongest, covering large neighboring territories. MERRAero generates some dust in the area of SM3 and SM4 hot spots, although the amount is less than in CLM4. The emission zone near Jizan (SM5) is also present in the reanalysis. Overall, the dust emission patterns from CLM4 and independent reanalysis are quite consistent. Below we show that CLM4 dust emission seasonal cycles are consistent with reanalysis as well.

4.2. Temporal variability of dust emissions

4.2.1 Seasonal cycle of dust emissions

The seasonal and interannual variability of dust storms in the Arabian Peninsula has been extensively discussed in recent studies (Alobaidi et al., 2016; Notaro et al., 2013; Notaro et al., 2015; Rezazadeh et al., 2013; Shalaby et al., 2015; Yu et al., 2013; Yu et al., 2015). Most of the studies report the period of maximum dust activity is from February until July–August, but the peak month varies depending on location and data source (Notaro et al., 2013; Shalaby et al., 2015; Yu et al., 2013). In the north of the Arabian Peninsula, late Winter – early Spring peak is more common, and in the south – southeast desert regions dust activity tends to reach its maximum in Summer. According to Notaro et al. (2013) and references therein, the late Winter – early Spring dust peak in the north-west is due to the cold fronts associated with cyclones from the Mediterranean, whereas the Summer peak in the south is due to diurnal heating, turbulent mixing, and strong Summer Shamal winds (Yu et al., 2015). In this study, we find the seasonality of dust emission from local sources to be quite consistent with previously reported results.

The seasonal cycles (averaged over three years) of total dust generation, monthly mean dust frequency, intensity and monthly maximum emission rate are shown in Fig. 7. The analysis is conducted over the entire coastal domain and separately for the northern and southern parts (separated at 21° N) of the coastal plain and hot spot areas. To compare our model results with reanalysis, the corresponding values from MERRAero averaged over 2003–2015 are also plotted together with standard deviation intervals.

The total emission flux (Fig. 7a) exhibits a pronounced seasonal cycle with a dual maximum in March and July and minimum in February and October. The peaks originate from a distinct character of seasonal cycles in the northern and southern parts of the coastal plain. The March peak is only evident in the northern area and is mostly caused by increased intensity during the dust storm episodes (Fig. 7c). High intensity is also seen in January in the north, partially caused by a dust storm in 2009. The peak Winter and Spring seasons for dust intensity in the north are also shown in Fig. 5b. Conversely, the July peak is due to both frequency (Fig. 5a, Fig. 7b) and intensity (Fig. 5b, Fig. 7c) reaching its maximums in the southern part of the coastal plain, although they are lower than that in the northern coastal plain. The seasonal cycle of maximum dust emission rate (Fig. 7d) generally follows that of intensity. Overall, we can conclude that the different climate and surface conditions in the north and south of 21˚N drive the spatial variations of the seasonal cycle of dust emission.

The seasonal cycle of dust emissions from the hot spots is consistent with the seasonal variability of the total dust generation from the coastal plain. Since the hot spots are in both the northern and southern parts of the coastal plain, the seasonal cycles of total emissions are smoother than for the northern and southern coastal plain separately. In the hot spots, magnitudes of dust frequency, intensity, and maximum emission rate are 2–2.5 times higher than that for the total coastal area and are above the mean plus standard deviation threshold in MERRAero. The overall amount of dust emitted from the hot spot areas is 1.9 Mt a^{-1} or 25 % of the total emissions, while hot spots occupy only 12800 km^2 or less than 10 % of the total area. This fact indicates that the soil mineralogical composition and wind variability have to first be studied in these hot spot areas (Prakash et al., 2016).

The seasonal cycles of dust emissions in MERRAero and CLM4 show similar behavior. As CLM4 dust emissions are scaled to match MERRAero, we only compare the seasonal variations, not averages. In general, seasonal cycles are in good agreement. Summer dust emissions are the largest in MERRAero, similar to CLM4 results in the southern part of the coastal plain. The Spring peak is not present in the reanalysis. One of the possible reasons is the coarse resolution of reanalysis that does not capture the local-scale wind patterns that cause the Spring peak. Similarly, Yu et al. (2013) reported that satellite AOD measurements in the western Arabian Peninsula do not feature the early Spring peak (as opposed to station dust records), attributing it to the local character of springtime dust generation.

With the exception of the March peak, the seasonal cycle of CLM4 dust generation lies within the MERRAero standard deviation interval. This is also true for dust event frequency and intensity, although the frequency is slightly smaller than in reanalysis and intensity is slightly larger. It may be caused by the fact that, in the case of MERRAero, these quantities were calculated with the same threshold, but based on three-hourly data; therefore, some dust outbreaks on the threshold borderline are missed. As expected, maximum dust emission rates in CLM4 are larger than in reanalysis, being substantially above the standard deviation interval, especially in March and July.

The total annual dust emission from the entire 147000 km^2 coastal area is 7.5 Mt as in MERRAero reanalysis. This dust influx in the atmosphere is substantial, and assuming that a significant portion of this dust could be transported to the Red Sea, might cause dust deposition to the Red Sea comparable to that of 6 Mt a^{-1} from the major dust storms (Prakash et al., 2015). About 4.9 Mt a^{-1}, or 65 % of the total emission is generated from the northern part of the coastal plain. Analyzing dust emission in MERRAero for the entire 2003 – 2015 period we find it varies only slightly 7.5 ± 0.5 Mt a^{-1}. Small inter-annual variability of emissions and a permanent distribution of the dust hot spots (Fig. 6 a-c, Fig. 7) suggest that the coastal plain is a stable dust source.

4.2.2 Diurnal cycle of dust emissions

The annual average diurnal cycles of total dust generation, frequency, intensity and maximum emission rate are computed from the 3-year simulations (Fig. 8 a–d). Total dust generation, frequency, and maximum emission rate have a pronounced diurnal cycle, consistent with wind speed intensifying during solar peak. Both total dust emission and frequency peak around early afternoon, at 12:00–14:00 UTC, with a slight shift between the northern and southern parts of the coastal plain due to the latitudinal extent. The frequency of dust events during the daily maximum is around 0.35 both in the north and in the south. Overall, around 80 % of airborne dust is generated between 07:00–16.00 UTC. The nighttime dust emission in the northern part is much stronger due to the larger number of cold fronts passing through the northern Red Sea (Notaro et al., 2013; Yu et al., 2015). In the south, the frequency of nighttime dust events is lower due to the different character of wind forcing with a more pronounced diurnal cycle (Notaro et al., 2013). The frequency of dust events in the hotspot areas during the peak hours reaches 0.8, but during the nighttime, it is less than 0.05.

Dust emission intensity has a different diurnal cycle. In the north, the daytime maximum of dust frequency corresponds to minimum intensity. The total distribution of dust events above the threshold during these hours is characterized by a large number of moderate-intensity events, thus, the average emission is relatively small. On the other hand, the small total number of dust events above the threshold in the nighttime leads to a larger contribution from strong events and increased average intensity. The diurnal range of emissions in the northern coastal plain is from 7 to 12 µg m^{-2} s^{-1}. In the southern part, the nighttime intensity is smaller due to the presence of areas with zero contribution to the average intensity, as there are no dust events exceeding the threshold intensity. This results in an almost uniform diurnal intensity cycle in the southern part of the coastal plain (5–7 µg m^{-2} s^{-1}). In the hot spot areas, average dust intensity has two diurnal peaks at 13.00 and 22.00, and reaches the minimum at 17.00 UTC.

The diurnal cycle of dust maximum emission rate is also different in the north and south. It peaks at 9:00 UTC in the northern areas with a diurnal range of 20–50 µg m^{-2} s^{-1}, and at 14:00 UTC in the south with a diurnal range of 15–35 µg m^{-2}

s^{-1}. Maximum emission rate averaged over the coastal plain follows the one in the north, but the peak value is smaller (40 μg m^{-2} s^{-1}). In the hot spot areas, the diurnal cycle of maximum emission rate is even more pronounced. Daily maximum emission peaks during 9:00–15:00 UTC and reaches 100 μg m^{-2} s^{-1}. It is still significant during the nighttime, reaching more than 50 μg m^{-2} s^{-1}. High nighttime values of dust emission intensity and maximum emission rate in the hot spot areas despite low event frequency indicate that the rare, severe nighttime dust generation is much more pronounced in the hot spots compared to other areas of the coastal plain.

4.3 Mineralogical composition

Dust elemental composition has a variety of physical and biogeochemical impacts. Perlwitz et al. (2015), Scanza et al. (2015), and Zhang et al. (2015) have applied sophisticated modeling tools to study the dust mineral composition on global scales. In our case, we concentrate on a fine-scale narrow coastal area, as generated dust has the potential to deposit directly to the sea. Thus, we aim at estimating the amount of minerals generated from the coastal plain and assume it is representative of the mineral composition of dust deposited to the Red Sea. To calculate the emitted mineral fluxes we use the global datasets of dust mineral composition, GMINER30, and soil texture, SOILPOP30, developed by Nickovic et al. (2012). SOILPOP30 provides the global coverage of fractions for three soil texture classes (clay, silt, and sand). GMINER30 provides the soil type and corresponding mineral composition. We assume that the relative proportions of minerals in the airborne dust are the same as those of the parent soils. The largest size bin of emitted dust (transport bin) in CLM4 is 5–10 μm, whereas the silt fraction in GMINER30 corresponds to 2–50 μm. This allows us to assume following Nickovic et al. (2013) that emitted dust is a mixture of clay and silt particles only (without coarser fractions). Thus, emitted mineral fractions are weighted with the clay and silt content in the soil. For minerals that are present in both clay and silt, the weighted values are summed.

Our assumption that the mineral composition of emitted dust is the same as that of parent soil is reasonable for clay soil fraction (Caquineau et al., 1998; Lafon et al., 2004), but it does not always hold in general case (Claquin et al., 1999; Perlwitz et al., 2015). During the airborne dust life cycle, both chemical (dust aging) and physical fractionation processes occur and change the dust mineral composition and size distribution. However, due to the short pathway from the coastal plain to the sea, dust composition changes due to gravitational settling and chemical transformations become less important for local dust particles compared to those subjected to long-range transport. Another issue is the instrumental bias of GMINER30 dataset that was produced using the wet sieving technique. This technique strongly disperses soil aggregates (Shao, 2001; Laurent et al., 2008; Perlwitz et al., 2015), adding uncertainty to the partitioning of minerals between clay and silt fractions. As long as of our primary interest are the iron oxides and phosphorus that limit the marine productivity, the instrumental bias is less important in our case.. Nickovic et al. (2012) assume the same fraction of phosphorus and nearly the same of iron oxides in clay and silt. Having said this, our assessment may serve as an initial rough estimate of the mineral composition of dust deposited in the sea from local sources.

The minerals' annual emissions are calculated using dust emission flux obtained with the 1kmALL simulation and the SEVIRI source function applied. Figure 9 shows annual amounts of minerals emitted from the coastal plain. Quartz is the most abundant mineral, comprising around 40 % of the total emission. 25 % of the total emission corresponds to feldspars, followed by illite, smectite, kaolinite, calcite, gypsum, hematite and goethite (the iron source), and phosphorus. The Arabian Red Sea coast provides 76±5 Kt of iron oxides and 6±0.4 Kt of phosphorus annually. Over 60 % of iron oxides and phosphorus are emitted from the northern part of the coastal plain, acting as a nutrition source for the oligotrophic northern part of the Red Sea. Although only a portion of dust emitted from the Arabian coast is deposited to the Red Sea, due to the close proximity of the dust generation area to the sea (especially in the northern coastal plain) and the structure of mesoscale circulation that includes jets and breezes, its role in total mineral deposition to the Red Sea could be significant.

5 Conclusions

This study focused on the dust emission from the Red Sea Arabian coastal plain. We applied the off-line CLM4 land surface model to perform high-resolution simulations of dust emission for 2009–2011 using up-to-date land surface datasets. The magnitude of integrated over the entire area dust emissions was tuned to fit the estimate from MERRAero reanalysis, while the spatial structure was calculated within CLM4, forced by 10 × 10 km resolution meteorology from WRF simulations. To test the simulated dust emission, we developed the corresponding metrics and performed a comparison with the weather station reports of horizontal visibility and present weather code. We obtained significant correlations for monthly time series of dust event frequency and intensity (station-mean correlation coefficients of 0.5 and 0.4), indicating reasonable model performance. The results confirmed that dust emission from local sources on the Arabian Red Sea coastal plain is significant and supported the hypothesis by Yu et al. (2013) that the dust activity in this area may be caused by local-scale dust outbreaks.

Within the proposed framework, we performed a sensitivity study and demonstrated that high-resolution input surface datasets might add fine-scale details to dust generation patterns. The spatial resolution of vegetation datasets was shown to alter total dust emissions by up to 10 %. We confirmed the findings by Shi et al. (2016), showing that the increased resolution of the vegetation dataset leads to significant dust flux in some zones where it was very weak when coarse input data fields were used. We estimated the comparable contribution to total dust emission from the increased resolution of the plant function type dataset on one hand and the leaf area index and stem area index on the other hand.

To improve the spatial structure of dust generation, we calculated and applied a statistical source function based on the high-frequency geostationary measurements from the SEVIRI instrument. We showed that this approach allows a better representation of dust sources. Depending on model resolution, the statistically significant model skill (spatial correlation coefficient based on comparison with 14 ground stations) varied from 0.68 to 0.85. Without the source function, the spatial model skill was not statistically significant.

Following the evaluation tests, we based our estimates on model simulation with 1 × 1 km spatial resolution and SEVIRI source function. The estimate of total dust emission from the coastal plain, tuned to fit emissions in the MERRAero reanalysis, is 7.5±0.5 Mt a^{-1} (approximately 50 g m^{-2} a^{-1}). Over 65 % of dust is generated in the northern part of the coastal plain. The seasonality of dust emission differs substantially in the northern and southern parts of the coastal plain. In the south, the annual maximum of dust emission occurs in July, whereas in the north March is the peak month of dust activity. This distinct character is due to the contrasting forcing mechanisms: in the north, emission is caused by strong, diurnally variable, cold season winds, whereas in the south it is largely controlled by a low erodibility threshold and soil moisture. These features result in dual maximum values within the seasonal cycle of total dust emission from the coastal area in March and July.

The spatial pattern of total annual dust emission is highly non-uniform, reaching more than 100 g m^{-2} a^{-1} in some hot spot areas. The chain of hot spots stretches alongside the coastal zone, with most of them located in the lowlands near the western hillsides of the Hejaz Mountains – riverbeds that are usually considered the source of alluvial material. The hot spots occupy around 8 % of the coastal area and generate over 25 % (1.9 Mt a^{-1}) of total dust. The emission pattern is in reasonable agreement with the coarse-resolution results from the MERRAero global reanalysis, despite the fact that the reanalysis dust model uses a different source function. We also showed that dust generation has a pronounced diurnal cycle. Around 80 % of dust is generated during the daytime, between 07:00–16.00 UTC, with dust emission rate and emission frequency peaks during early afternoon (12:00–14:00 UTC).

The total dust generation from the coastal plain of 7.5±0.5 Mt a^{-1} is comparable to the estimate of annual dust deposition to the Red Sea of 6 Mt a^{-1} due to major dust storms (Prakash et al., 2015). Small inter-annual variability indicates that the study area is a stable dust source. The comparison with the short-term WRF-Chem simulations suggests that this estimate could be even larger, as WRF-Chem produces 40–50 % more dust, supporting the finding that the coastal plain is a significant dust source. Our calculations of the dust mineralogy suggest that 76±5 Kt of iron oxides and 6±0.4 Kt of phosphorus are emitted from the coastal plain annually.

Author contributions

Anatolii Anisimov performed the data processing, developed the technique for comparison with observations, conducted the comparison with reanalysis, performed the WRF-Chem simulation, formulated the results and wrote the final paper.
Weichun Tao designed the experiments, ran the model simulations, calculated the source functions, performed the basic analysis and wrote the paper draft.
Georgiy Stenchikov formulated the problem, directed the research, and edited the paper.
Stoitchko Kalenderski ran the WRF model to obtain the meteorological forcing for the dust emission calculations.
P. Jish Prakash and Weichun Tao worked together on the dust mineral analysis.

Zong-Liang Yang, one of the developers of CLM4, helped in setting the CLM4 runs.

Mingjie Shi and Weichun Tao worked together on collecting the land surface data.

Acknowledgements

We thank Prof. V. Ramaswamy and Dr. Paul A. Ginoux of GFDL for valuable discussions. We also thank Prof. Johann Engelbrecht and Ms. Linda Everett for proofreading the article. The research reported in this publication was supported by the King Abdullah University of Science and Technology (KAUST). For computer time, this research used the resources of the Supercomputing Laboratory at KAUST in Thuwal, Saudi Arabia.

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Table 1. WRF model configuration.

Process	**WRF Option**
Microphysics	Lin (Lin et al., 1983)
Shortwave radiation	Goddard (Chou and Suarez, 1999)
Longwave radiation	RRTM (Mlawer et al., 1997)
Cumulus parameterization	Kain-Fritsch (Kain, 2004)
Surface layer	Monin-Obukhov (Janjić, 1994)
Land-surface model	Noah LSM (Tewari et al., 2004)
Boundary layer scheme	YSU (Hong et al., 2006)
Boundary and initial conditions	NCEP Final Analysis FNL
Sea Surface Temperature	NCEP RTG_SST_HR

Table 2. Land surface data used in model setup.

Input data	Parameters affected	Default data in CLM4	Data used	
		Resolution	Original data Resolution	Source
PFT	f_m	0.5° × 0.5°	500m × 500m	MODIS Land Cover Product MYD12
LAI			1km × 1km	MODIS MCD15
SAI			1km × 1km	Calculated from LAI
CLY	α_j, f_w		1km × 1km	STATSGO-FAO (10km × 10km)
ERD	S	Constant=1	See Table 4	

Table 3. Spatial resolution of input datasets used in simulations.

		Simulation					
		10kmALL	50kmALL	1kmALL	10kmLPFT	10kmLLAI	10kmLCLY
Input data	PFT	10 km	50 km	1 km	50 km	10 km	10 km
	LAI & SAI	10 km	50 km	1 km	10 km	50 km	10 km
	CLY	10 km	50 km	1 km	10 km	10 km	50 km
	Wind forcing	10 km					

Table 4. Tuning constants used in the simulations

Source function	Algorithm	T in (1)	Data source	Remarks
No source function	Eq. (1), $S = 1$	0.011	Calculated based on 10kmALL experiment	Used in 50kmALL, 10kmLPFT, 10kmLLAI, 10kmLCLY, 10kmALL and 1kmALL experiments.
SEVIRI statistical	Eq. (3)	1.28	SEVIRI AOD data (Brindley and Russell, 2009; Banks and Brindley, 2013)	Used in 1kmALL simulation with SEVIRI source function.

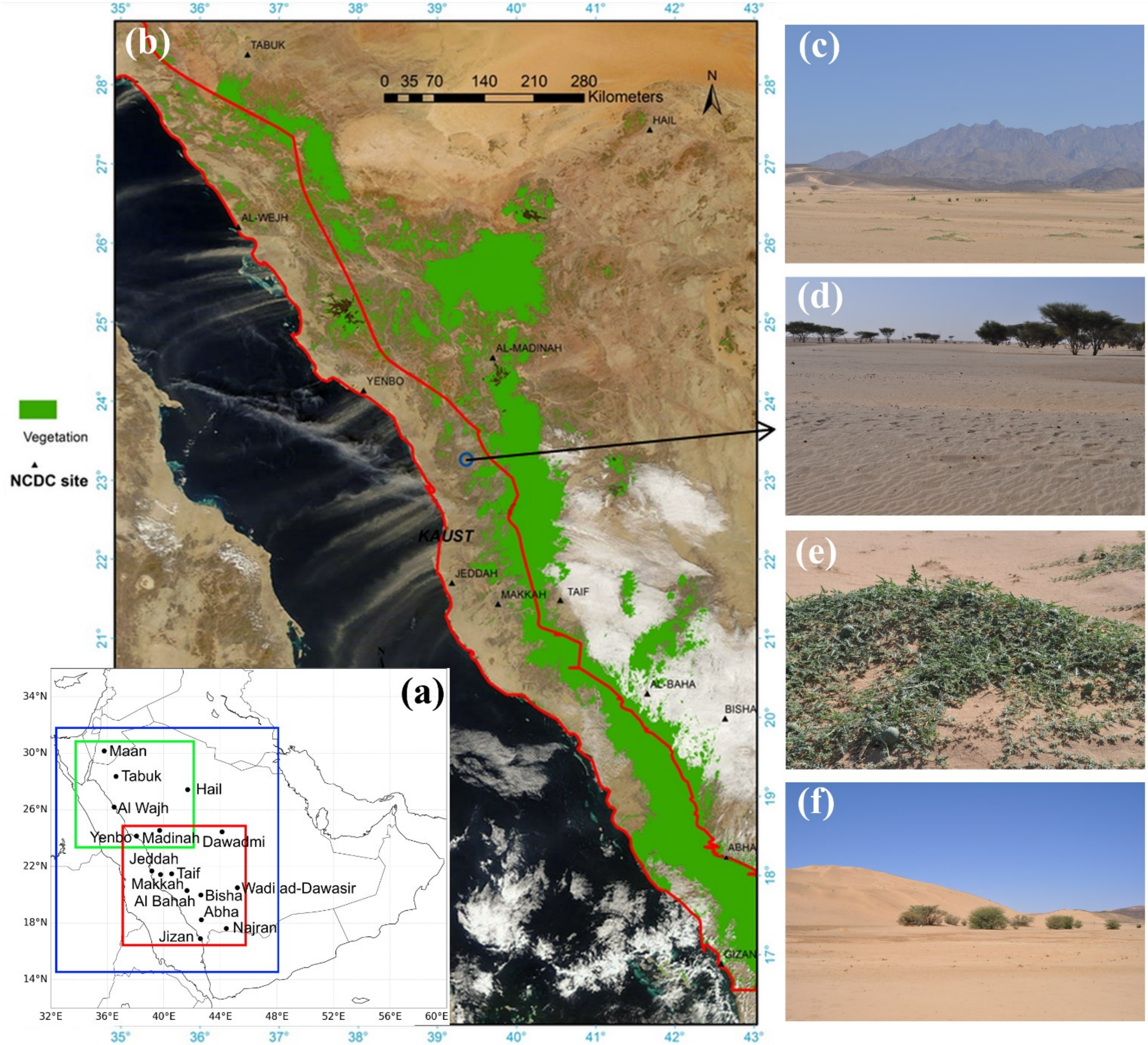

Figure 1. (a) The CLM4 model domains (green and red), WRF-Chem domain (blue), and 16 ground observation stations. (b) Dust plume above the Red Sea observed by MODIS/TERRA at 7:45 UTC on 14 January 2009. Overview of the landscapes: (c) piedmont; (d) trees over the sand; (e) wild watermelons over the sand; (f) sand dunes and scattered vegetation.

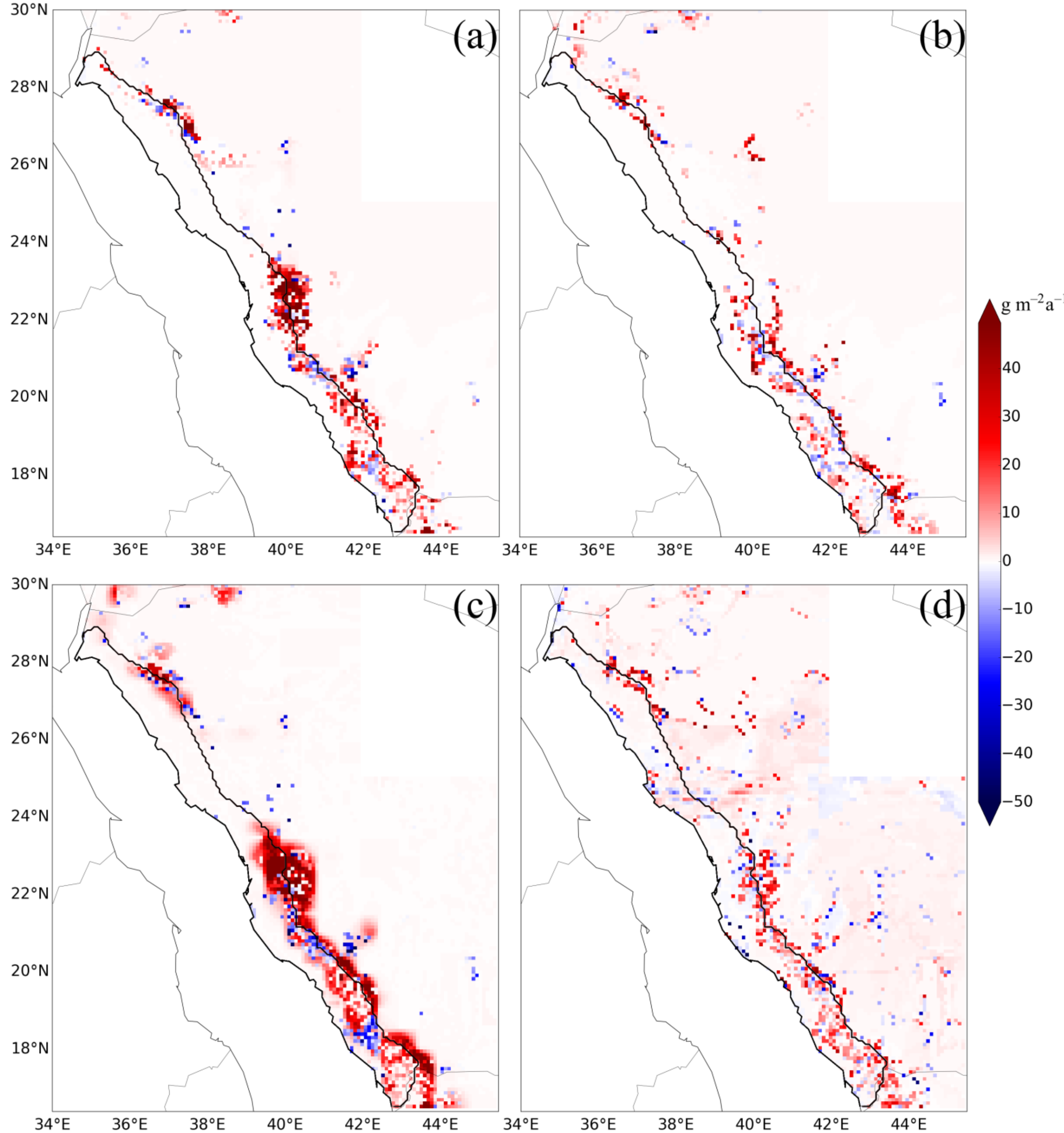

Figure 2. Differences between annual mean dust emission in model simulations (g m^{-2} a^{-1}): (a) 10kmALL – 10kmLLAI; (b) 10kmALL – 10kmLPFT; (c) 10kmALL – 50kmALL; (d) 1kmALL – 10kmALL.

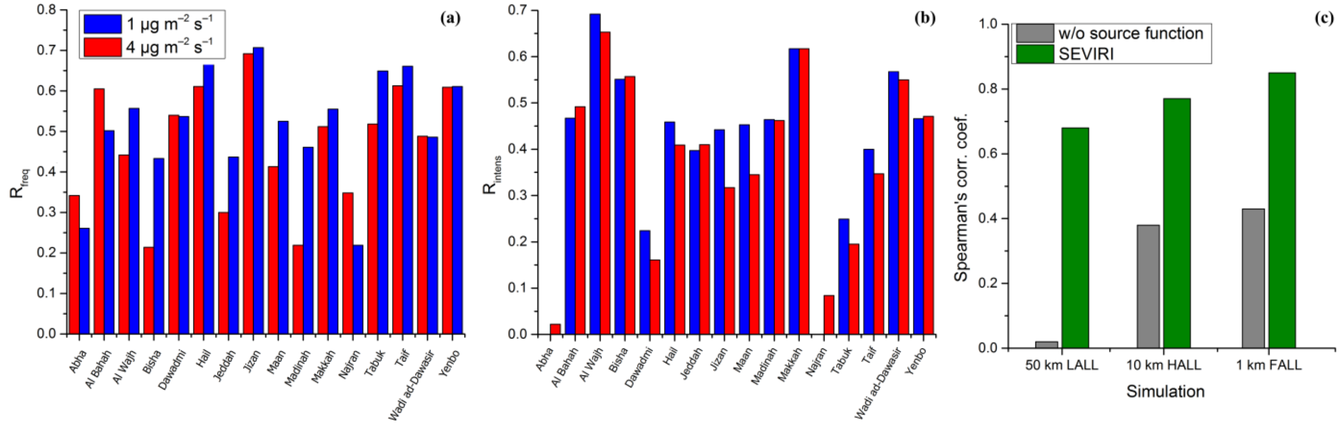

Figure 3. Spearman's correlation coefficients for monthly-mean series of (a) dust event frequency and (b) intensity between station data and results from 10kmALL experiment. (c) Spatial metrics of model performance (see text for definition) for three basic experiments with and without SEVIRI source function.

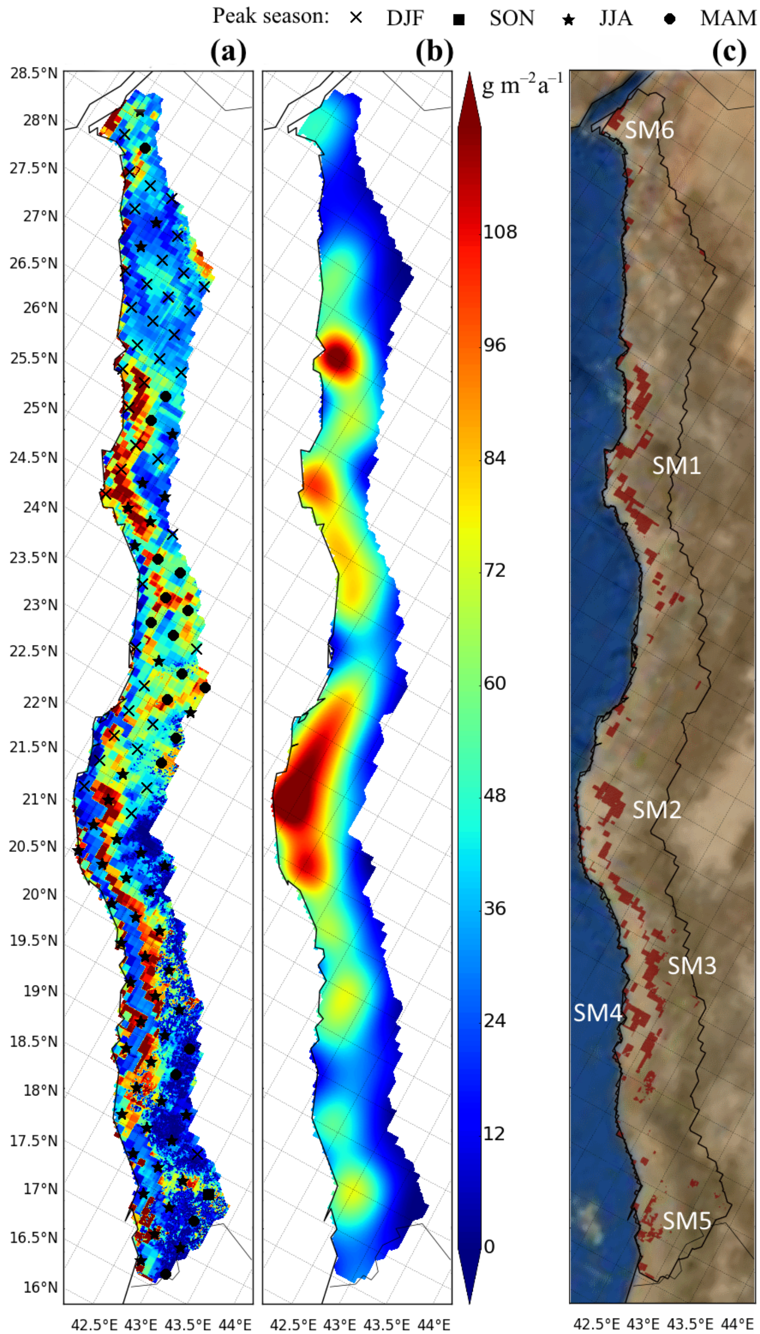

Figure 4. Annual dust emission (g m^{-2} a^{-1}) in (a) 1kmALL experiment with SEVIRI source function (2009–2011); (b) MERRAero reanalysis (2003–2015). (c) Main dust emission hot spot areas mapped on real color satellite image. Peak season is shown by marks (see figure legend).

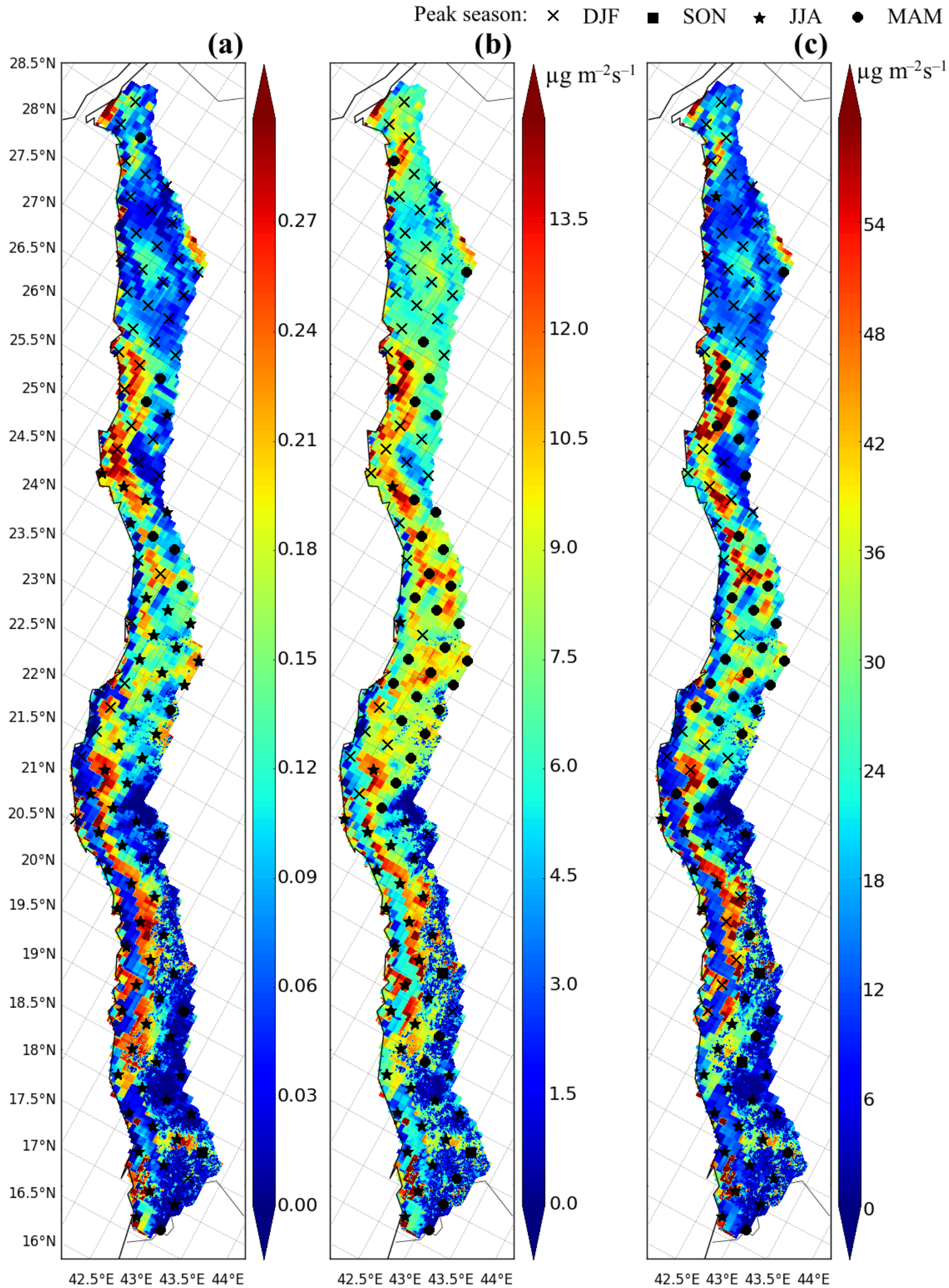

Figure 5. Average 2009–2011 (a) dust event frequency; (b) average emission intensity (μg m^{-2} s^{-1}); (c) yearly maximum emission rate (μg m^{-2} s^{-1}) in 1kmALL experiment with SEVIRI source function. Peak season is shown by marks (see figure legend).

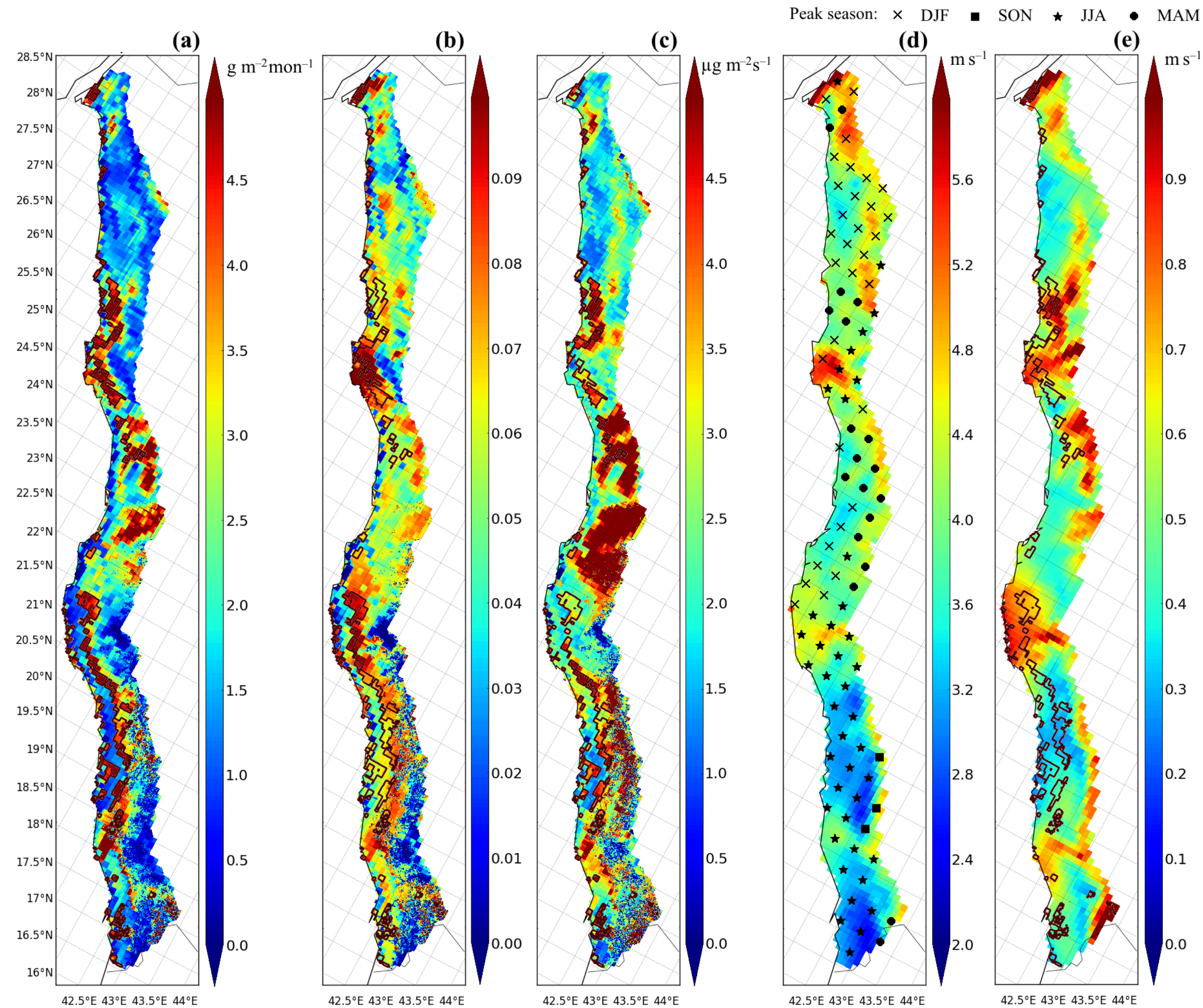

Figure 6. Standard deviations of monthly (a) total dust emission (g m^{-2} mon^{-1}); (b) dust event frequency; (c) average emission intensity (μg m^{-2} s^{-1}) in 1kmALL experiment with SEVIRI source function. Average 2009–2011 WRF forcing (d) wind speed (m s^{-1}), and (e) its monthly standard deviation (m s^{-1}). Peak season is shown by marks (see figure legend).

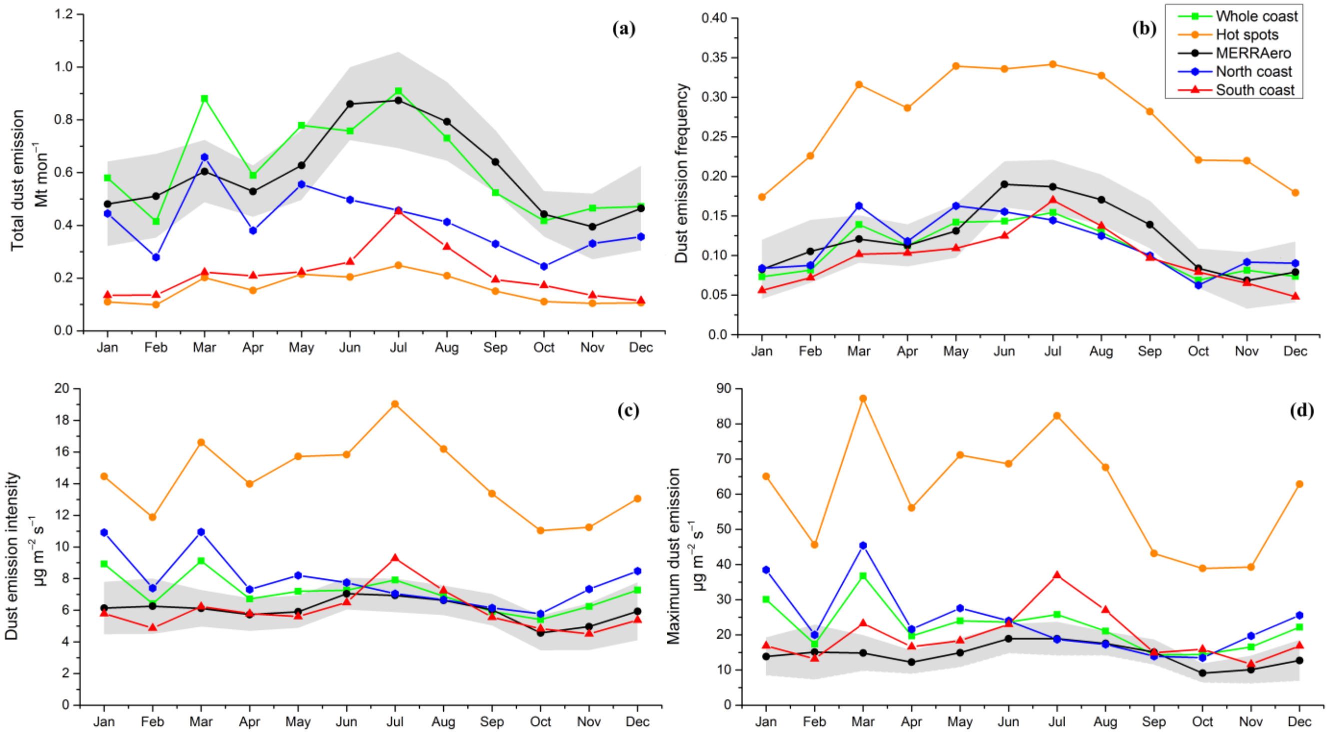

Figure 7. Average seasonal cycles of monthly (a) total dust emission (Mt mon^{-1}); (b) dust event frequency; (c) average emission intensity (μg m^{-2} s^{-1}); (d) maximum emission rate (μg m^{-2} s^{-1}) in 1kmALL experiment with SEVIRI source function (2009–2011) and MERRAero reanalysis (2003–2015). MERRAero Standard deviation intervals are shown by shading.

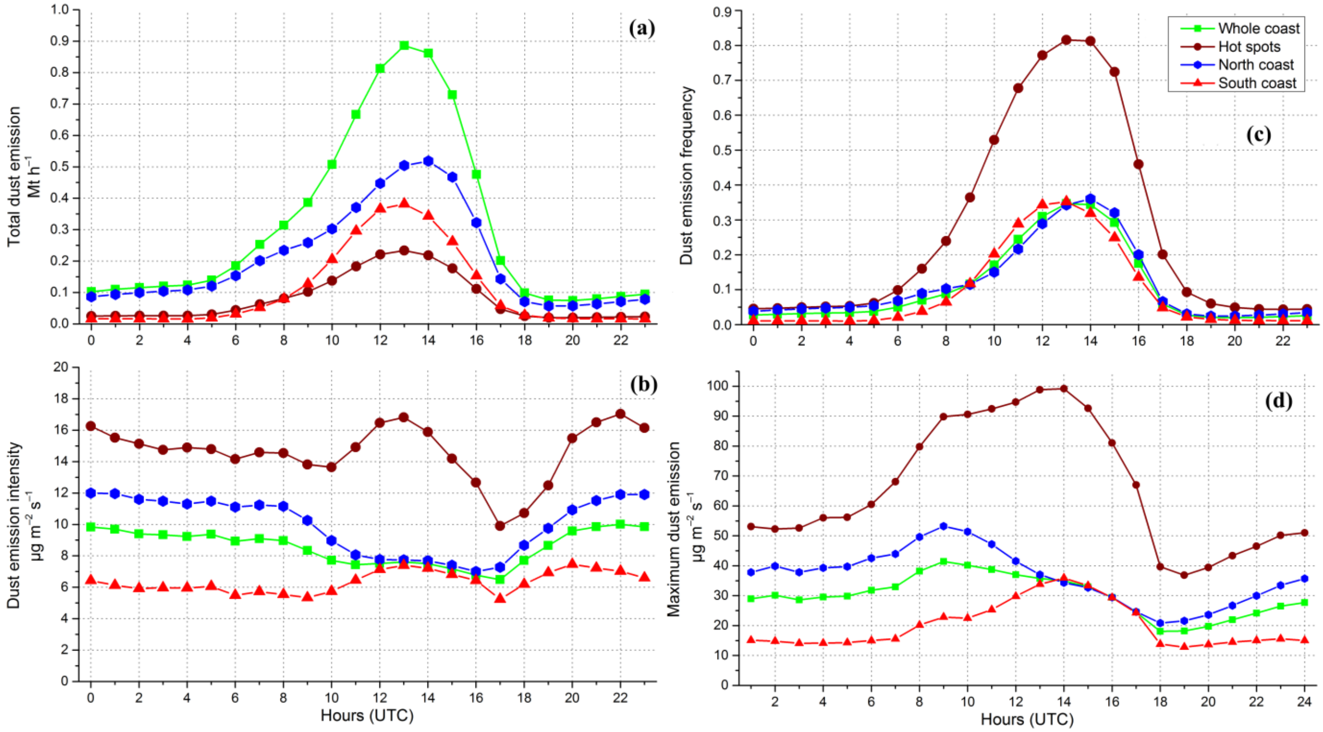

Figure 8. Annual mean diurnal cycles of (a) total dust emission (Mt h^{-1}); (b) dust event frequency; (c) average emission intensity (µg m^{-2} s^{-1}); (d) maximum emission rate (µg m^{-2} s^{-1}) in 1kmALL experiment with SEVIRI source function (2009–2011).

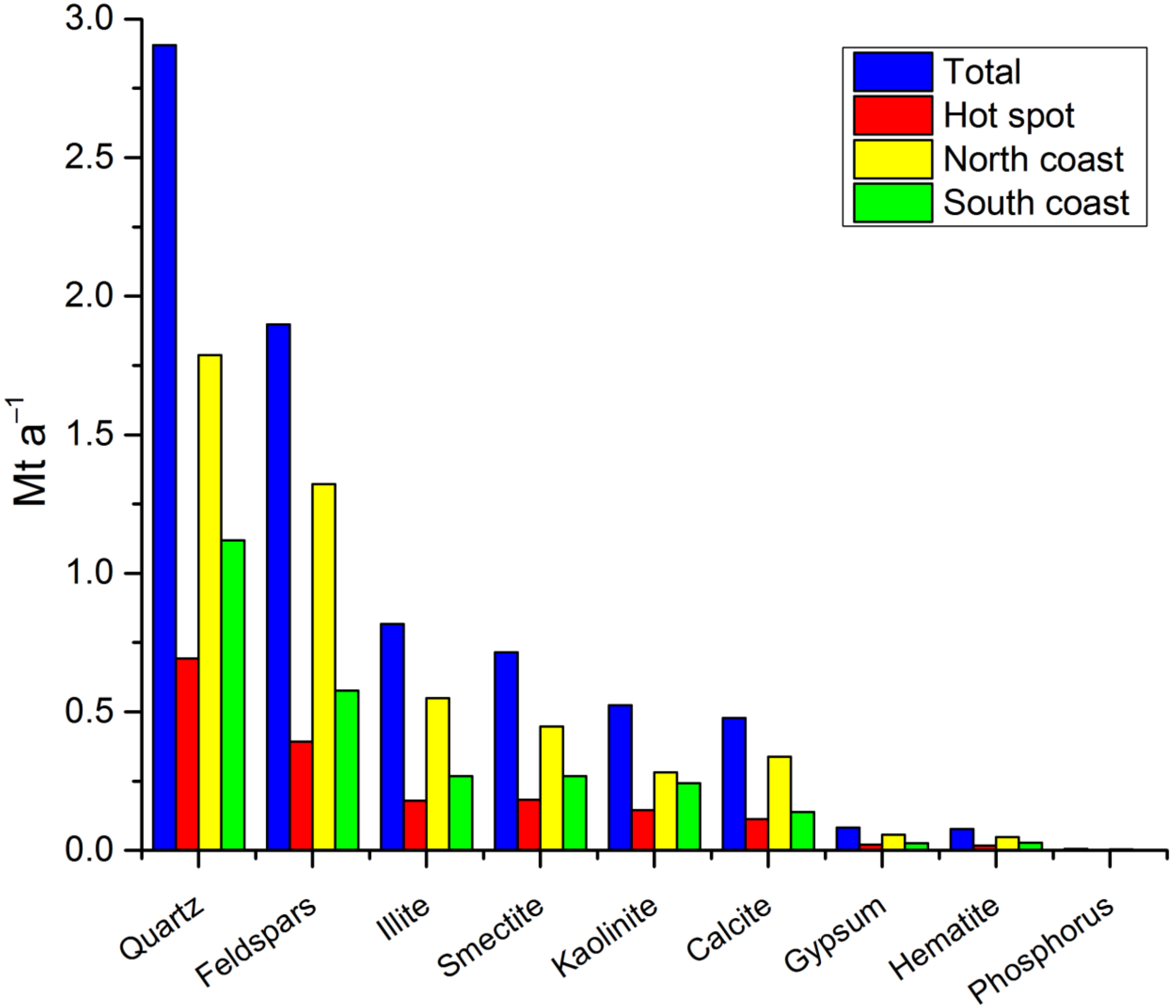

Figure 9. Annual mineral emission fluxes (Mt a^{-1}) in 1kmALL experiment with SEVIRI source function (2009–2011).