Response to Reviewer1

"In my opinion the manuscript Direct radiative effects of intense Mediterranean desert dust outbreaks is acceptable for publication in ACP in its current state."

Thanks!

Before our paper being published in ACPD, the reviewer made the following comment and the Editor suggested that it should be answered in the current review process. Please find our response (regular font) below the reviewer's comment (bold font).

"My major concern is how the model takes into account the relative humidity to scale the optical (e.g. real and imaginary refractive indices) and the microphysical properties (e.g. size) of the aerosols. As authors well-know and say within the manuscript the water vapor influences SW and LW spectral ranges. It is not clear for me how the RRTMG considers this significant aspect (RH). An analysis the relative humidity (RH) in this area for these 20 desert dust cases would be very clarifying because it is huge important to go through how the RH changes from day to night times and how the desert dust optical and microphysical properties vary from day to night times. Relevant parameters in your calculations are the mass extinction efficiency, the single scattering albedo and the asymmetry parameter. The effect of the RH over them is well explained by Myhre et at. (1998)."

In the NMMB-MONARCH model, dust aerosols are externally mixed and hydrophobic. Therefore, no hygroscopic growth is considered and subsequently the RH effects are not taken into account in the RRTMG. This assumption, it is not expected to introduce large errors since it is well documented in literature that mineral particles are mainly hydrophobic and consisted of insoluble substances, particularly over desert regions. Of course, it is also known (e.g. Sullivan et al., 2009; Knippertz and Stuut, 2014) that dust hygroscopicity increases through mixing soluble of hygroscopic material with insoluble mineral particles, thus leading to the formation of internal mixtures of dust and sulfate, which can make mineral particles more soluble. Nevertheless, it should be noted that for such atmospheric processing to take place, time is needed and that this increase of dust hygroscopicity mainly occurs through aging. However, our study focuses on intense dust episodes above the Mediterranean, which basically transport fresh, and thus hygrophobic, dust particles. This clarification has been added in the revised manuscript (Lines 283-284). The paper of Myhre et al. (1998), regarding the effect of RH on optical properties, refers to sulfate and soot aerosols, and not dust.

Response to Reviewer2

We would like to thank the Reviewer for the useful comments that helped us to improve our manuscript. Below are given point by point answers to the comments (also provided in bold font).

"The paper addresses an important aspect of the Mediterranean radiation budget and climate. Intense Saharan dusts event may produce large perturbations to radiation, and affect surface temperature, heat exchange at the surface, circulation, etc. The study uses satellite data to identify intense events. Effects on radiation and different processes are investigated for the selected cases using a regional model which includes dust and radiation.

The paper is an interesting and useful contribution to the understanding of dust role and interactions in the Mediterranean.

A couple of aspects may be improved."

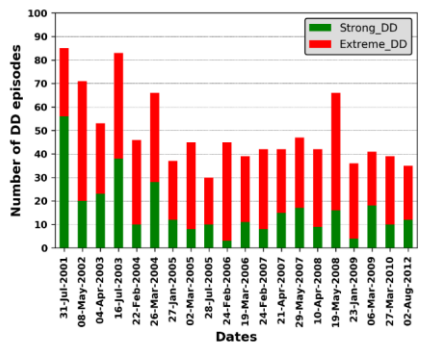
"The radiative effects are strongly related with the aerosol optical depth (AOD). A comparison of AOD values produced by the model versus those obtained from MODIS is presented in the paper. However, the comparison is qualitative and for a selection of cases. Given the large role of AOD in determining the radiative effects, a more detailed, possibly quantitative, comparison should be carried out. On the same point, some reference is made throughout the text to the inability of the model in reproducing the amount of dust. This should be better assessed."

As suggested by the Reviewer, we have made a more detailed comparison between the observed (MODIS) and simulated (NMMB) AODs. In order to eliminate the spatial inconsistencies between the two products, we have regridded the model outputs from their raw spatial resolution (0.25° x 0.25°) to 1° x 1° in order to match them the resolution of satellite retrievals. The new geographical distributions of the modelled AODs (dynamically calculated dust plus GOCART climatology for the other aerosol types), at coarse spatial resolution, have replaced the old ones presented in Figures 3 and S1 of the previous version of manuscript. In both MODIS and NMMB patterns a common colorbar is used making easier a visual intercomparison for the reader. Moreover, the model AODs have been compared against those of MODIS, considering only the grid cells where a DD episode (either strong or extreme) has been identified by the satellite algorithm. Note that NMMB-MODIS comparison all over the MSD is not possible because of the gaps (white areas) in MODIS AOD distributions, given that the operation of MODIS retrieval algorithm is impossible therein. The obtained results for each episode, in terms of overall computed correlation coefficient and bias (defined as NMMB-MODIS) are given in Fig. R1, while the stacked bars illustrate the number of strong, extreme and total DD episodes for each case (available also in Table 1).

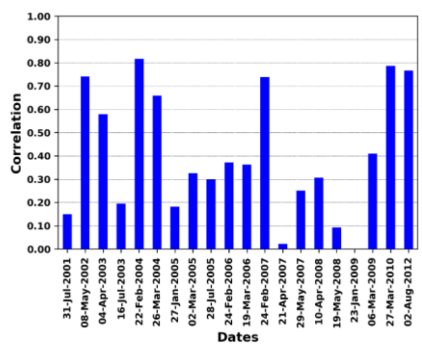
Among the studied cases, it is revealed a strong variation of R values (Figure R1-ii) which reflects the diversity of the model's capability in terms of capturing the spatial patterns of the desert dust outbreaks. These drawbacks rise mainly from displacements of the simulated dust patterns with respect to the observed ones (see Figs 3 and S1). The best performance is found on 22 Feb 2004 (R=0.82) while in 7 out of 20 cases R values are higher than 0.5. As it concerns the bias, in absolute terms, in all the events negative values are recorded ranging from -2.3 (24 Feb 2006) to -0.17 (19 May 2008). This finding shows that the model underestimates consistently the intensity of the desert dust outbreaks which have been analyzed in the present study.

According to the evaluation analysis, the model's ability in terms of reproducing satisfactorily the dust fields varies strongly case-by-case while the simulated intensity of the desert dust outbreaks is lower with respect to the satellite retrievals. It should be noted that the level of agreement between observed and simulated AODs (Lines 451-465) is not only associated with the model deficiencies, but also with other factors like the temporal inconsistency between the two products. More specifically, the satellite retrievals correspond to daily averages whereas the model products are representative for a specific forecast time (instantaneous fields). Considering the high variability of aerosols' loads, particularly under episodic conditions, this temporal discrepancy imposes a limitation when a quantitative comparison between MODIS and NMMB is attempted. This fact can explain the observed differences found either on the intensity or on the spatial patterns of the desert dust events. Also, it must be considered that artifacts of the satellite retrievals (e.g. clouds contamination, representativeness/homogeneity within the 1° x 1° grid cell) may lead to higher AODs as it has been shown in relevant evaluation studies (Gkikas et al., 2016). In the revised manuscript, the discussion in Section 5.1 has been updated presenting the quantitative comparison of NMMB-MONARCH versus MODIS-Terra as well as the reasons which lead to deviations between these two products.

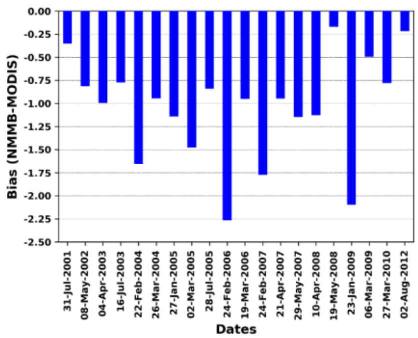
Finally, we would like to bring to the attention of the Reviewer that a detailed evaluation of the same version of the NMMB model for 2006 has been presented in Pérez et al. (2011), who compared the model products against MISR and AERONET retrievals. Based on their findings, for a domain including the Mediterranean, it is revealed that the model in general is able to reproduce satisfactorily the spatiotemporal features of the desert dust fields. Moreover, an evaluation of the NMMB AOD forecasts, along with similar forecasts from other models, against ground based AERONET and satellite MODIS retrievals, is available at the weblink of SDS-WAS System (https://sds-was.aemet.es/forecast-products/forecast-evaluation) to which reference is now made in the revised manuscript (lines 303-306).



(i)



(ii)

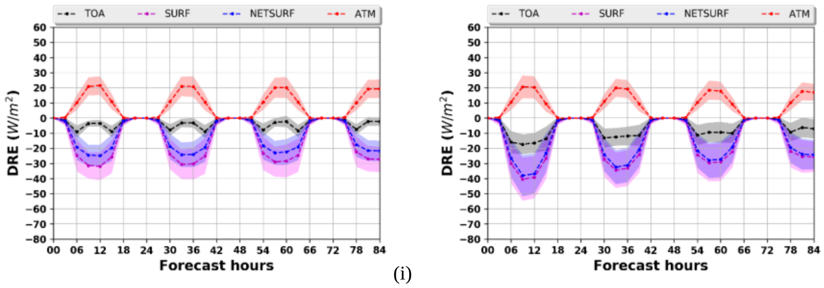


(iii)

Figure R1: (i) Number of strong (green bars), extreme (red bars) and total (entire bars) DD episodes identified by the satellite algorithm, (ii) Correlation coefficients (R) between satellite and model AODs, (iii) Regional average biases between the NMMB simulated and the MODIS retrieved AODs. Results are given for each studied case (given in x-axis) and are computed taking into account only pixels over which a DD episode (either strong or extreme) has been identified by the satellite algorithm.

"Some results, mainly in the shortwave spectral range, may be linked to differences in the surface albedo, in particular between ocean and land/desert. The discussion of this point may be somewhat improved. In some cases, averages over the Mediterranean Satellite Domain (MSD) have been used. The domain includes land and ocean surfaces. I would suggest separating the estimates of radiative effects obtained on land from those obtained over the ocean. Summing/compensation effects, also dependent on the fraction of surface type occurring in each event, may be present when the average includes land and ocean surface types."

The regional SW DREs for the MSD have been calculated separately over land and sea and the obtained results are illustrated in Figure R2. The temporal variation of SW DRE_{ATM}, DRE_{SURF} and $DRE_{NETSURF}$ values is similar with the one presented for the whole Mediterranean domain (Figure 5 in the revised document) over both land and ocean areas. However, a careful eye look reveals differences between land and ocean DREs. Thus, over dark (sea) surfaces DRE_{SURF} and $DRE_{NETSURF}$ values are almost equal (Fig. R2-ii) while over brighter (land) surfaces $DRE_{NETSURF}$ values clearly differ by DRE_{SURF} ones, i.e. they are smaller, due to the higher surface albedo, leading to increasing upward component and reducing the absorbed radiation. Another difference between land and ocean DREs is the larger magnitude of surface DREs over ocean than land areas, especially in early forecast times, due to higher AODs over ocean. The most noticeable difference between the Mediterranean land and sea DREs is evident at TOA, both in terms of temporal variation and magnitude, clearly reflecting the role of the surface albedo. In particular, over land, the DRE_{TOA} values are maximum (up to 9 Wm^{-2}) during early morning and afternoon hours, decreasing in magnitude between 9-12 UTC (values ranging from -3.6 to -2.2 Wm^{-2}) while such a decrease is not observed over sea areas. Also, the magnitude of ocean DRE_{TOA} values is smaller than over land, i.e. a stronger cooling of the Earth-atmosphere system is produced by aerosols over oceans than land due to the low sea water albedo below aerosols. The overall computed SW DREs presented in Figure 5 (without discriminating between land and sea grid points of the NMMB-MONARCH model) are mainly driven by the corresponding DREs over continental Mediterranean areas. The aforementioned result is also valid for the whole simulation domain (NSD) as well as for the Sahara domain (SDD). In the revised document a short sentence has been added (Lines 582-584).



(i) (ii)

Figure R2: Regional all-sky SW DREs calculated over the MSD above: (i) land and (ii) sea areas.

Minor points are outlined below.

"lines 17-19: please, indicate the AOD range attained during the selected events."

We have added in the text (lines 22-23) the range of the maximum dust AODs (2.5 – 5.5) simulated by the NMMB-MONARCH model.

"l.21-26: please, specify for what AOD and over what area these vary large radiative effects are found."

Done. Please see Lines 23-31.

"l. 66-68: the sentence is not clear; please, rephrase it"

The following sentence in the submitted document has been replaced with a new one (written below) in the revised text (Lines 73-76).

OLD (submitted manuscript)

"Through this chain of complex processes, it is described the indirect impact of mineral particles on the radiation and compared to the other two dust radiative effects (direct and semi-direct) is characterized by even larger uncertainties."

NEW (revised manuscript)

"This chain of complex processes, involving aerosol-cloud-interactions (ACI) and the subsequent modifications of the radiation fields, constitute the indirect impact of mineral particles on radiation, which is characterized by the largest uncertainties, even larger than those of the dust direct and semi-direct effects."

"l. 153: I would suggest specifying here that the dust outbreaks are identified using daily multi-sensor satellite data"

Done. Please see Lines 160-163 in the revised manuscript.

"l. 188-: please, clarify the difference between pixel and grid cell: are those the same?"

Both terms have the same meaning. In order to be clear we have added this clarification in Lines 200-202.

“table 1: are all the selected cases classified as "extreme" events? Are there "strong" events among them? Is there information on the time duration of the events?”

For each dust outbreak there are pixel-level episodes that are either strong or extreme, according to their AOD values. As suggested by the Referee, we have added in Table 1 two columns giving the number of strong and extreme DD episodes for each dust outbreak. Moreover, in the revised manuscript we have included this information by providing the ranges for the strong and extreme DD episodes that took place within the MSD (see Lines 224-228). No information is given about the duration of studied events because according to our analysis, the maximum duration (consecutive days satisfying the defined criteria, see sect. 2) is two (2) days, but in such cases we have decided to keep just the day for which the number of total pixel-level DD episodes is higher (see Lines 216-217).

Case	Date	Strong DD episodes	Extreme DD episodes	Total DD episodes	Intensity	Affected parts of the Mediterranean domain
1	31 July 2001	56	29	85	0.74	Western
2	8 May 2002	20	51	71	1.60	Central
3	4 April 2003	23	30	53	1.42	Eastern
4	16 July 2003	38	45	83	0.98	Western and Central
5	22 February 2004	10	36	46	2.18	Central and Eastern
6	26 March 2004	28	38	66	1.45	Central and Eastern
7	27 January 2005	12	25	37	1.36	Central and Eastern
8	2 March 2005	8	37	45	2.96	Central and Eastern
9	28 July 2005	10	20	30	1.08	Western and Central
10	24 February 2006	3	42	45	2.92	Eastern
11	19 March 2006	11	28	39	1.37	Eastern
12	24 February 2007	8	34	42	2.29	Central and Eastern
13	21 April 2007	15	27	42	1.65	Central
14	29 May 2007	17	30	47	1.40	Eastern
15	10 April 2008	9	33	42	1.58	Central
16	19 May 2008	16	50	66	1.45	Central
17	23 January 2009	4	32	36	2.65	Eastern
18	6 March 2009	18	23	41	1.41	Eastern
19	27 March 2010	10	29	39	1.43	Central
20	2 August 2012	12	23	35	1.20	Western

“l. 308: "quadratic" should be "quadrature"”

We have corrected it.

“l. 313: the correct web address seems to be: http://rtweb.aer.com/”

We have corrected this. Thanks for the note.

“l. 317: maybe "fraction" instead of "percentage"”

We have changed the text according to the reviewer’s suggestion.

"l. 324: it may be useful to add here information on the used refractive indices. They play a central role in the determination of the radiative effects, and the reader should be aware of which set of refractive index values are used in the calculations."

In Lines 331-336 of the revised manuscript, we have provided information on the refractive indices used in the model, as requested by the reviewer. More specifically, it is now specified that the refractive indices used in our simulations were taken by GADS (Koepke et al., 1997) and modified following Sinyuk et al. (2003), as described in Pérez et al. (2011).

"section 5.1: as discussed above, the comparison between satellite and modelled AOD seems qualitative. Given the stated limitations of the satellite dataset over land, a quantitative comparison might be carried out over the ocean. Also, the use of different colour scales in figure 3 does not allow a more detailed comparison."

Please see our response to your first main comment.

"l. 552: may the differences between the results over the MSD and SDD domains be partly due to the albedo differences? I would expect an effect, mainly for the NETSURF component."

In the shortwave spectrum, the surface albedo plays a critical role on the observed differences between the calculated DREs in the MSD and SDD. This is evident at noon when positive (planetary warming) and negative (planetary cooling) DRE_{TOA} values are found over the Sahara and the Mediterranean, respectively (Figure 5). In the former region, due to the higher surface albedo the atmospheric warming enhances (mineral particles do not absorb only the incoming SW radiation but also the reflected radiation from the ground) dominating over the surface (NETSURF) cooling which decreases since the upward component (reflected radiation from the ground) increases. On the contrary, over dark areas (maritime environments or vegetated land) the dust layers are brighter than the underlying surface resulting in negative perturbations (cooling effect) at TOA. Summarizing, the contrast between low- and high-reflective surfaces doesn't affect only the absorbed radiation at the ground (NETSURF) but also the atmospheric radiation budget and subsequently the perturbation of the Earth-Atmosphere system's radiation budget (Eq. 4).

"l. 596: does the model produce substantially different dust size distributions over the Sahara and along the coast and in the Mediterranean? It might be interesting to show this effect."

In Figure R3 is depicted the geographical distribution of the coarse-to-fine ratio of dust aerosols, at 12 UTC on 2nd August 2012, which has been calculated by dividing the aggregated dust concentrations for bins 5-8 (coarse particles) and bins 1-4 (fine particles). As expected, the maximum ratios (~ 19) are found over/close the dust sources (central Algeria) whereas considerably high values (> 10) are observed in the western parts of Sahara and over the Atlantic Ocean, both affected by the major dust plume (see Figure 4 in the manuscript).

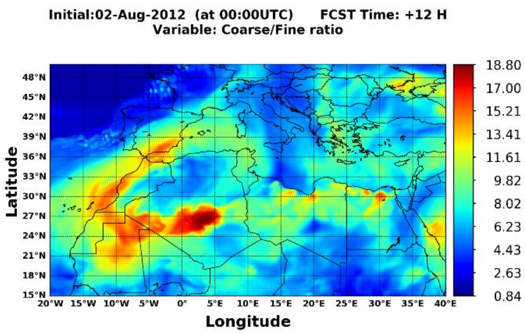


Figure R3: Geographical distribution of coarse-to-fine ratio of dust aerosols at 12 UTC on 2nd August 2012.

"section 5.3. the dust outbreak impact on SH and LE is investigated only over land. It may be worth including in this section the discussion on the SH and LE changes in the marine environment (l. 751-752). This is also needed to support the validity of the estimated temperature biases over the ocean discussed in section 5.4."

As stated in lines 664-665, in the utilized version of NMMB-MONARCH model the atmospheric driver is not coupled with an ocean model. Therefore, not a significant impact on SH and LE is expected over maritime areas, since the feedbacks from ocean are neglected. In addition, due to the larger heat capacity of sea (Lines 736 - 743), the perturbations of the SH and LE fields should be negligible at short temporal scales. The aforementioned reasons explain why we have investigated the induced impacts on heat fluxes (Section 5.3) only over land areas.

"l. 734-: it may be worth recalling the AOD value which corresponds with these cross sections."

We have inserted in the text the maximum dust AODs at 550nm simulated by the NMMB-MONARCH model along the cross-sections (see lines 732-733, lines 750-753).

"l. 858: although pyrgeometers are sensitive to the wavelength range 4-50 micron or similar, they are calibrated to provide LW irradiances integrated up to 100 micron."

We have taken this information from the specifications of the pyrgeometers (Eppley-PIR and Kipp & Zonen CGR4) that are installed at BSRN stations. The spectral ranges of the measured downwelling LW radiation at the ground span the wavelength range from 4 to 50 microns for Eppley-PIR and from 4.5 to 42 microns for Kipp & Zonen CGR4. Nevertheless, we haven't found any relevant reference regarding the calibration procedure that extends the upper bound to 100 microns.

"l. 796-803: how is the dust emission calculated? It should be mainly related to the wind intensity, and it seems to me that such a large day/night difference may be explained only if the emission is calculated as dust entrainment at some altitude above the ground"

We have avoided in our paper to provide much information about the dust emission scheme since a detailed description is given by Pérez et al. (2011). Briefly, the saltation of mineral particles is approximately proportional to the third power of the wind speed. The vertical dust flux (F_k), constrained by a tuning factor, is proportional to the horizontal flux. Based on F_k and turbulent regime, the concentration of the emitted dust particles is diagnosed at the top of a viscous sublayer extending between the assumed smooth desert surface and the lowest model layer. During day, due to thermal convection, the turbulence is enhanced resulting thus to an unstable atmosphere, higher wind speeds and subsequently to larger amounts of emitted dust. On the contrary, during night, the atmosphere is more stratified (less turbulence) leading to weaker wind speeds and less dust emission. The strong variability of dust emission throughout the day, presented in Figure 6-ii of our manuscript, has been also reported in previous studies (e.g. Schepanski et al., 2009).

“section 5.6: the verification of the data against surface radiation measurements is a very ambitious task. As the authors state, it would require a very good model description of the dust event evolution and spatial distribution, and a good reproduction of the observed AOD. I would suggest shortening this section, removing the discussion of specific cases and figure 10, and presenting the results as statistical means for all considered sites (a condensed version of table S1). Some of the selected events have been previously investigated using satellite/ground based measurements, and radiation transfer modelling (see e.g., Santese et al., 2010; Benas et al., 2011; di Sarra et al., 2011). The authors may consider if it may be reasonable to compare the radiativeeffect estimates, instead of the irradiances, obtained during some of these events.”

We would like to remind that the goal of this study is not to evaluate the model’s radiative fluxes against measurements, but to highlight the model improvement in terms of more adequately reproducing radiative fluxes when it takes into account dust in its simulations. Thus, we prefer to keep Figure 10 and the relevant discussion, since in both example cases (in Sede Boker) is nicely depicted (highlighted) the role of factors affecting the level of agreement between NMMB and BSRN, by taking advantage of the existing concurrent AERONET retrievals while the impact of clouds (relied on numerical simulations) is also considered. It is the first time that such an evaluation analysis of the NMMB-MONARCH is presented.
Regarding the last part of the reviewer’s comment, following his suggestion, we have compared our SW DREs with the corresponding ones calculated in Benas et al. (2011) and the results are presented in Table R1. The surface DREs (SURF, NETSURF) are comparable but lower (by up to 12 Wm^{-2} and 8 Wm^{-2}, respectively) in our analysis while the atmospheric warming in Benas et al. (2011) is 2.6 times higher than ours. At TOA, our SW DRE reach down to -35 Wm^{-2}, being higher, in absolute terms, by 59% with respect to Benas et al. (2011). A significant difference between the two studies, determining the DRE calculations, is that in our case the AOD (0.09) and SSA (0.87) are very low in contrast to Benas et al. (2011) where the corresponding values are equal to 0.44 and 0.95, respectively. Therefore, higher loads are considered in Benas et al. (2011) whereas the suspended particles are more absorptive in our analysis. Both facts interpret the differences found between the two studies. An additional source of differences is that DREs in our calculations are representative 60 hours after the initialization of the model (00 UTC 24-Feb-2006) while they have been spatially averaged around the FORTH-CRETE AERONET station (Latitude: 35º-36º N, Longitude: 25º-26º E). The increasing errors for increasing forecast time, as well as spatially averaged NMMB DREs against almost local (MODIS’ nadir view 10 x 10 km spatial resolution) estimates of DREs in Benas et al. produce differences when comparing our model to Benas et al. (2011) DREs.

In di Sarra et al. (2011), the SW DREs are presented for 25^{th} and 26^{th} March 2010 while in our study case the forecast run starts at 00 UTC on 27^{th} March 2010.

In Santese et al. (2010), the daily averages of DREs are presented for 17th July 2003. In the revised supplement document, we are providing the corresponding instantaneous (noon and night) DREs for the same date in Figure S6 (third and fourth row).

Table R1: SW DREs at 11:25 UTC on 26-Feb-2006 (Benas et al. (2011)) and at 12 UTC on 26-Feb-2006 (present analysis) over the FORTH-CRETE AERONET station (Crete, southern Greece).

	Benas et al. (2011) [11:25 UTC]	**Present study [12:00 UTC]**
TOA	-22 Wm^{-2}	-35 Wm^{-2}
SURF	-66 Wm^{-2}	-54 Wm^{-2}
NETSURF	-56 Wm^{-2}	-48 Wm^{-2}
ATM	34 Wm^{-2}	13 Wm^{-2}

"l. 859: I assume that emission from atmospheric gases and from the surface is not included in the way the SW radiation (up to 12.2. microns) is calculated. This might be clarified."

In the existing version of the NMMB-MONARCH model, only greenhouse gases and not the emitted short lived atmospheric gases are taken into account. We have added the relevant information in the text (Lines 267-268).

References

Benas, N., N. Hatzianastassiou, C. Matsoukas, A. Fotiadi, N. Mihalopoulos, and I. Vardavas (2011), Aerosol shortwave direct radiative effect and forcing based on MODIS Level 2 data in the Eastern Mediterranean (Crete), Atmos. Chem. Phys., 11, 12647-12662.

di Sarra, A., C. Di Biagio, D. Meloni, F. Monteleone, G. Pace, S. Pugnaghi, and D. Sferlazzo (2011), Shortwave and longwave radiative effects of the intense Saharan dust event of 25-26 March, 2010, at Lampedusa (Mediterranean Sea), J. Geophys. Res., 116, D23209, doi: 10.1029/2011JD016238.

Santese, M., M. R. Perrone, A. S. Zakey, F. De Tomasi, and F. Giorgi (2010), Modeling of Saharan dust outbreaks over the Mediterranean by RegCM3: Case studies, Atmos. Chem. Phys., 10, 133-156.

Response to Reviewer3

We would like to thank the Reviewer who helped us to improve our paper through his/her report. Below are listed our detailed responses (regular font) to each comment raised by the Reviewer (bold font).

The paper presents an interesting study for calculating DRE with the use of the NNMB-MONARCH model (NNMB). It is a well written paper which with the following revisions it could be published in the ACP journal. My main comments are:

- In order to accept the results of such a study, a more comprehensive validation of the presented outputs using real measurements and an analysis of the uncertainties introduces in several phases of the method have to be presented.

In the revised manuscript we have made a more detailed comparison between MODIS-NMMB for the cases (dust outbreaks) which are analyzed here. Regarding the validation of radiation and temperature fields, the discussion has been updated whenever is needed. Please see our responses to your comments below.

- A major aspect of the paper is not clarified. The abstracts talks about DRE and as the authors point out this is mostly aerosol optical depth (AOD) dependent. MODIS retrieves total (dust + other types) AOD while NNMB only dust AOD (that is what is shown throughout the text and in e.g. figure 3). So the authors have to clarify if they talk about Dust DRE or DRE. If someone assumes that these 20 events are purely dust events, an AOD comparison of MODIS AOD and NNMB AODs have to be included (not quantitevily as in fig. 3), in order try to assess the model results.

We have changed the title of our paper from "*Direct radiative effects of intense Mediterranean desert dust outbreaks*" to "*Direct radiative effects during intense Mediterranean desert dust outbreaks*" so that the goal of our study is more clear. This modification has been made since based on the configuration of the model the amount of dust aerosols is simulated dynamically (online) while for the other aerosol types the GOCART climatology is used (Lines 340-342). Moreover, the DREs are computed for days in which intense dust outbreaks prevail over the greater Mediterranean basin. Under such conditions, and over places where Saharan dust is transported, dust predominates and is the main contributor of AOD, even in MODIS AOD retrievals. Of course, in such cases all aerosol types exert a perturbation of the radiation budget, but the impact of mineral particles is predominant. A quantitative comparison between MODIS and NMMB has been made (suggested also by the Reviewer 2) and the obtained results are presented in Figure S2 (supplementary material) and discussed in Section 5.1.

- A major issue of the paper is the link between the NNMB results and the Gkikas et al., methodology (GM) for identifying dust episodes. Some questions that have to be clarified on the manuscript are the following:

(i) Are the domains seen in figure 3 and 1 have been used in the GM for all the episodes that are presented in the table 1? Is there a mix of surface and sea Modis pixels used?

The identification of DD episodes through the implementation of the satellite algorithm is made only for the Mediterranean Satellite Domain (MSD, red rectangle in Figure 1) as stated in the manuscript (see lines 192-194). The structure, methodology, and operational phases of the satellite algorithm have been presented in detail by Gkikas et al. (2013, https://www.atmos-chem-phys.net/13/12135/2013/). Briefly, the algorithm operates separately over land and sea surfaces by taking into account the MODIS AODs obtained by the dark target land and ocean retrieval algorithms. Therefore, the number of DD episodes presented in Table 1 corresponds to the number of grid cells (1° x 1° spatial resolution) where a desert dust (DD) episode has been recorded/identified within the geographical limits of the MSD. Please see lines 207-210 and the caption of Table 1 in the revised manuscript.

(ii) When GM identifies an episode (e.g. example of figure 3) are the DRE calculations of NNMB account only the relative (episodic) modis pixels? I think the answer here is no but it has to be clarified. So, If the answer is no (thus the whole domain (e.g. MSD) is used for NNMB) then the importance of the GM episode identification is only partially valid. (e.g. a lot of white in fig. 3 are used based only on NNMB and not on GM). As identifying an episode in a limited area in the MSD domain does not mean that this is valid for the whole domain.

We think that it is clear that the NMMB DREs calculations are made all over the Mediterranean basin and not only over the episodic MODIS pixels. This does not limit the validity and importance of GM dust episode identification. It is self evident that when talking about a dust episode over the Mediterranean, not the entire basin but just a significant part of it is expected to be dominated by dust, which is adequately ensured by GM. Therefore, having "a lot of white in Fig. 3" is not strange, unreasonable or problematic, but on the contrary it is expected and sound. Nevertheless, this does not prevent us from talking about Mediterranean dust episodes and radiative effects (DREs). The only issue that might be relevant to this comment, is averaging regionally over the Mediterranean, where dust and no dust dominated areas are considered together, but even in such cases DRE computations are meaningful. In the revised manuscript, the calculations of the regional DREs have been made taking into account all the grid points and therefore the spatial representativeness is consistent at each forecast step and among the studied cases.

(iii) If the whole domain is used are results of table 1 dependent in addition to dust AOD to the spatial extension of the event? Can a number of different episodes with different spatial extends and AODs, averaged (table 2)

In the revised manuscript (Table 1, lines 213-218) it is explained that the frequency and regional intensity, i.e. AOD of 20 dust outbreaks, is calculated from the total pixel-level DD episodes, therefore the results of Table 1, more specifically the intensity, are not dependent on the spatial extend of the episodes. As already answered in the previous comment, regional DREs can be computed for every dust episode. Therefore, as it concerns the second part (sentence) of this comment (e.g. Table 2 results) we believe that averaging DREs over the 20 different dust episodes is meaningful and representative of DREs during Mediterranean dust outbreaks.

Another example of the last point above is that modis GM detects a plume (high AOD) covering very few pixels in the western part of MSD (for example last row of figure 3). Then based on GM the whole MSD domain is considered as the one that will provide the DRE. In this case the link on GM used as a proxy in this work is very week as it covers only a small part of the domain, plus AODs are not compared. So also a number of episodic pixels should be included in these GM dust episode restrictions. Or simply dust outbreak identification can be based on NNMB spatial and NNMB-AOD absolute criteria as now the link with GM is really weak.

Most of the content of this comment has already been answered. However, we would like to note that of course intense dust outbreaks are not supposed to cover the entire Mediterranean, on the contrary, they always cover a part of it, this is logical. However, this does not prevent us of talking about dust episodic days over the Mediterranean basin whenever such dust outbreaks occur. And, moreover, it also does not prevent us from computing DREs all over the Mediterranean basin, even averaging over it. Therefore, there is not any problematic link in our concept and methodology combining the detection of dust outbreaks with GM and the DRE computation with NMMB. Concerning the last sentence and suggestion of the Referee, of course this is an option, i.e. dealing with detection of dust outbreaks and computing the associated DREs solely using the NMMB model. However, this would be purely theoretical. On the opposite, detecting intense dust outbreaks based on an observational approach, i.e. using MODIS products, is more appropriate. Finally, as already stated in our responses to this Referee's previous comments, a comparison of AODs has been made and it is discussed in the revised version of the manuscript.

In addition, in this case (and others e.g. west domain of fig. 3b) NNMB dust pixels cover less than 50% of the MSD. When averaging the 20 cases this percentage of pixels varies a lot. In the end you are averaging and provide a result e.g. SW = -9.7. So some of the outbreaks contribute much more and some others not, based on the dust coverage on the MSD only. Where can such statistics be used?

First, we would like to state that in the revised manuscript the regional DREs have been calculated considering all the grid points without setting any criterion on the simulated dust AOD or on clouds (this approach was initially followed). Therefore, at each forecast step and among the 20 desert dust outbreaks the number of grid points is constant. This ensures that the spatial representativeness of the regional DREs does not vary in time and among the studied cases (Figure 5).

To summarize, if GM is not used for AOD validation and GM identifies as "dust episodic pixels" only a fraction of the pixels used finally from NNMB for calculating dust DRE, then its use becomes not important for this study. So if someone trusts NNMB for DRE calculations, then it is much more easy to trust it also for dust outbreak identification.

We think that our previous responses give a sufficient answer to the reviewer's summary comment.

- There are more than 100 references and a lot of discussion about aerosol effects and model applications, but very few about NNMB validation on e.g. AOD retrievals. And only one (Ohmura) on BSRN radiation related validation. I think it is more essential to prove the validity of AOD NNMB output (e.g. radiation) and intermediate parameters (e.g. AOD), than a numerous studies cited here, with a very theoretical link to the paper.

It is not the first time that NMMB is used, so validation of its AOD has already been done. In our paper, we have included all the available studies regarding the evaluation of the simulated AODs relied on the same NMMB version which is used here (Lines 294-306). Moreover, in the revised manuscript we are providing the weblink of the SDS-WAS System (https://sds-was.aemet.es/forecast-products/forecast-evaluation) in which is presented the forecast evaluation of NMMB AODs, among other aerosol models, utilizing ground-based (AERONET) and satellite (MODIS) retrievals as reference.

Concerning BSRN, we would like to remind and underline that it provides just reference radiation measurements. The BSRN is considered the best global network of quality radiation measurements.

There is a very high number of scientific papers (http://bsrn.awi.de/other/publications/reviewed-scientific-papers-referring-to-bsrn/) or reports (http://bsrn.awi.de/other/publications/other-related-reports-and-papers/) referring to BSRN, so there is no need to make further reference to it than to the key paper of Ohmura et al. (1998) which is commonly used as reference for BSRN data. The validity of NMMB radiation fluxes is exactly proved through their comparison against BSRN measurements.

- The validation using BSRN is incomplete. In the document and in the abstract you are talking about this validation and 8 stations. Then in the manuscript only one station is shown. And from that only 4 days. In order to validate the results a more comprehensive analysis of long term periods of these 8 stations is needed. Probably Ohmura has answered some of the validation related questions, but this paper focuses on "intense dust outbreaks", and a specific model, so results might differ from the Ohmura related ones.

We would like to point out that the calculated biases (NMMB-BSRN) over the hindcast periods, for each case and for each station (6 in total), are given already for the SW and LW radiation in Tables S2 and S3, respectively and discussion (lines 882-887) refers to their results. In the main text, we have decided to present just as an example the obtained results for the SW (first row in Figure 10) and LW (second row in Figure 10) radiation for two dust outbreaks (22/2 -25/2/2004 and 21/4-24/4/2007) that affected the Sede Boker station, for which concurrent AERONET retrievals were available. This allows us to give a better insight regarding the factors that can affect the level of agreement between model and ground observations. We agree with the reviewer that a long-term evaluation is valuable (i.e. identification of systematic errors) but for our purpose focus is given only on specific desert dust outbreaks trying to investigate if the inclusion of dust-radiation interaction in the numerical simulations can improve the forecasting skills of the NMMB-MONARCH model.

- There are several issues that have to be clarified/commented on the input parameters of the model:

(i) Optical properties proposed in figure 2. Have been validated?

The optical properties have not been validated. The model dust optical properties are based on single-particle optical properties derived by the GOCART model (Chin et al., 2002) and refractive indices from the Global Aerosol Data Set (GADS) (Koepke et al.,1997). Both datasets are very well known and very much often used and cited in literature, and therefore we believe that there is no need for further validation here.

(ii) Water vapor, carbon dioxide, ozone, methane and oxygen. Where do you find these inputs?

Water vapor comes from the model simulations. We used a fixed value of CO_2 (350 ppm), methane (1.5 ppm) and oxygen; and a seasonal climatology for ozone.

(iii) Differences in dust optical properties of Sahara and middle East sources. What did you use and how much uncertain are they? and what is the contribution of this uncertainty in the final DRE budget?

The dust single-particle optical properties and the emitted size distribution are constant throughout the simulation domain without discriminating between different dust sources (Sahara, Middle East). At each forecast step, the aerosol optical depth (AOD), the single scattering albedo (SSA) and the asymmetry parameter (ASYM) have been produced based on the formulas presented in Pérez et al. (2006) utilizing the simulated mass concentration, the GOCART single-particle optical properties and the refractive indices from the Global Aerosol Data Set (GADS) which have been modified according to Sinyuk et al. (2003), as it has been described in Pérez et al. (2011) (lines 331-336). Regarding the last question of the reviewer, in order to be give an accurate answer a sensitivity analysis is required. More specifically, it must be investigated how the variation of key aerosol optical properties (AOD, SSA and ASYM) will affect the perturbations of the radiation budget and subsequently the associated impacts on dust AOD, dust emission, meteorological variables and radiation. This is something that has not been done in the present paper but it will be considered in a future work dedicated to all the aforementioned aspects considering also other parameters (e.g., dust layer vertical extension) which can affect DREs.

- BSRN and model differences in wavelength integrals of solar radiation. You mention: "These differences might contribute to the level of agreement between model and observations; however, are not discussed in our evaluation analysis". I think this is an important issue that have to be clearly discussed if a proper validation is included.

For solar radiation, the NMMB-BSRN SW flux departures, attributed to the different spectral coverage and integrals, are minor, varying from 1 to1.5 % (higher values for the model), therefore they do not affect substantially the agreement (in terms of biases) between model and measured fluxes.

- As already mentioned AOD comparisons from MODIS and NNMB could add value to this work. "The model's ability to reproduce correctly the spatial patterns and values of dust AODs is crucial for a successful computation of the dust DREs, since DREs are determined to a large extent by AOD". In addition you are mentioning modis uncertainty in section 2. Is this getting high (e.g. ~ 0.5) for both sea and mostly surface retrievals when you examine AODs in the order of 2-3 based on the table 1? And is this uncertainty already important for such outbreaks for the GM and indirectly for the DRE related uncertainty?

Actually, the uncertainty of C051 MODIS AOD retrievals is not reported in section 2, where only the detection of dust outbreaks is described. The uncertainty of MODIS AOD retrievals over ocean is ±0.03±0.05*AOD (Remer et al., 2002) while over land is higher and equal to ±0.05±0.15*AOD (Levy et al., 2010). The maximum MODIS retrieved AOD, over both continental and maritime areas, do not exceed 5, which means that the AOD uncertainties above sea and land, in absolute terms, are smaller than 0.28 and 0.8, respectively. In our cases, but also in general, these maximum AOD uncertainties are locally restricted and not recorded frequently (see Figures 3 and S1) while uncertainties are generally smaller, and thus do not affect the GM. Moreover, they neither affect DREs, since as already explained in our previous responses and in the manuscript, the DREs have been computed via the NMMB simulations without setting any constrain depending on MODIS retrievals (i.e., availability, magnitude).

- Table 2. These statistics are not referring to the model uncertainty but is an averaging of the episodes provided by the GM. NNMB DRE uncertainty is much more useful for any future user of these results. For example a systematic bias can not be identified here. This is also because the GM thresholds are mostly subjective as:

(i) Mean AOD values on dust related areas do not have an important statistical meaning due to the non normal distribution of AOD. It is clear that this is a published work and I have tried to follow the previous work by Gkikas et al and the relative open discussion, describing the method. However, as this is an open public statement I have to comment that AOD does not follow

necessarily a normal distribution so using the mean is not absolutely correct. Moreover, dust outbreaks related pixels/locations can be characterized more from a bimodal distribution of AODs when another (than dust) important AOD source is rarely present (e.g. most of the marine grids of Mediterranean domain).

First of all, as stated by the Referee, we would like to remind that the GM method has already been published (Gkikas et al., 2013; 2016) just after the discussion that took place concerning the way of computation of AOD thresholds, i.e. geometric versus arithmetic mean AOD values, which implies its validity against similar arguments cited in this comment. Nevertheless, we can remind the following. We agree with the Reviewer that AOD follows a log-normal rather than a Gaussian distribution, and that the arithmetic mean and standard deviation are not probably the best metrics for the calculation of the AOD thresholds, even though both primary statistics are widely applied in numerous aerosol studies. During the review process of Gkikas et al. (2013), following a similar comment raised by one of the referees, proposing to calculate the AOD thresholds based on the geometric mean and geometric standard deviation, we recomputed the AOD thresholds and compared them to the typical ones already used (based on arithmetic mean and standard deviation). Although there were found some differences in the thresholds' magnitude, in general, the geographical patterns of AOD thresholds were similar for both strong and extreme DD episodes. As for strong episodes, those differences were rather small, for example typical AOD thresholds varied within the range 0.4-1.2 and the geometrical thresholds ranged from 0.4 to 1.6. On the other hand, larger differences existed for extreme DD episodes, with the typical thresholds ranging from 0.6 to 2.2 while the geometric ones varying from 1 to more than 10. However, such extremely high AOD values are extremely rare and using them would be unrealistic from the physical point of view. For these reasons, it was decided to rely on GM methodology of Gkikas et al. (2013).

(ii) GM: By definition high mean AOD values per pixel are closer to dust sources. That makes possible that a pixel with high (in an absolute sense) AOD close to a dust source to be considered non episodic and a pixel with lower AOD, away from the sources to be considered episodic. This is ok, as it is just a matter of definition. But it gets more important when it is used for DRE calculations. So, the latest can be problematic when you calculate DRE in dust outbreaks or filter the outbreaks, as for the first example pixel (high AOD) it is not an outbreak and for the second (lower AOD) it is characterized as an outbreak. The results using this method for DRE calculations become not easily useful and applicable.

The issue of the identification method of DD outbreaks based on pixel-level AOD values, has already been addressed in our previous papers using the GM methodology, following similar comments to the one made by the Referee here. It has been shown that any differences in terms of AOD thresholds and dust outbreaks features (frequency, intensity) were not substantial.

However, the most important concerning the rest of Referee's comment referring to possible effects of this issue on computed DREs here, we would like to clarify again that DREs are computed by NMMB and have nothing to do with the AOD thresholds. It should be clear and kept in mind that GM methodology is only used for the determination of days with intense dust outbreaks for which NMMB then operates and makes computations of DREs all over the domain.

- Last but very important, the paper is very long and in various cases the discussion includes a lot of details that in the end confuse the reader on what is the important findings here and which are not. Even for scientists in the field it becomes difficult to read. Authors have to try to reduce the

length of the manuscript keeping the important aspects of the results presented. Basically for section 5 I would suggest to try to take out a lot of information that are secondary and to focus on the important results.

In the revised manuscript, following the suggestion of the Reviewer, we made an effort and reduced the paper length by removing some parts which can be considered as secondary information. However, at the same time, also following the Reviewers' suggestions, we added a discussion about the quantitative intercomparison between MODIS and NMMB as well as about the potential improvements on short-term forecasts of the temperature fields by the model. Therefore, the final length of the revised manuscript is similar to that of the original manuscript. We believe that any further shortening of the manuscript would be at the expense of its quality and scientific content.

Minor comments:

Line 141: it has already mentioned previously.

It has been modified.

Line 173: developed – improved

Done.

Table 1: episodes = grid cells

We think that is already clearly stated in the caption.

The overall approach of this paper is valuable and worth publishing. I strongly believe that after the above revisions, corrections and additional analysis it will be essentially upgraded and then it could be published in the ACP journal.

Direct radiative effects during intense Mediterranean desert dust outbreaks

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Abstract

The direct radiative effect (DRE) during 20 intense and widespread dust outbreaks that affected the broader Mediterranean basin over the period March 2000 – February 2013, has been calculated with the NMMB-MONARCH model at regional (Sahara and European continent) and short range temporal (84 h) scales. According to model simulations, the maximum dust aerosol optical depths (AODs) range from ~2.5 to ~5.5 among the identified cases. At midday, dust outbreaks induce locally a NET (shortwave plus longwave) strong atmospheric warming (DRE$_{ATM}$ values up to 285 Wm^{-2}; Niger-Chad; dust AODs up to ~5.5), a strong surface cooling (DRE$_{NETSURF}$ values down to -337 Wm^{-2}) whereas they strongly reduce the downward radiation at the ground (DRE$_{SURF}$ values down to -589 Wm^{-2} over the Eastern Mediterranean, for extremely high dust AODs, 4.5 – 5). During nighttime, reverse effects of smaller magnitude are found. At the top of the atmosphere (TOA), positive (planetary warming) DREs up to 85 Wm^{-2} are found over highly reflective surfaces (Niger-Chad; dust AODs up to ~5.5) while negative (planetary cooling) DREs down to -184 Wm^{-2} (Eastern Mediterranean; dust AODs 4.5 – 5) are computed over dark surfaces at noon. Dust outbreaks significantly affect the mean regional radiation budget, with NET DREs ranging from -8.5 to 0.5 Wm^{-2}, from -31.6 to 2.1 Wm^{-2}, from -22.2 to 2.2 Wm^{-2} and from -1.7 to 20.4 Wm^{-2} for TOA, SURF, NETSURF and ATM, respectively. Although the shortwave DREs are larger than the longwave ones, the latter are comparable or even larger at TOA, particularly over the Sahara at midday. As a response to the strong surface daytime cooling, dust outbreaks cause a reduction of the regional sensible and latent heat fluxes by up to 45 Wm^{-2} and 4 Wm^{-2}, respectively, averaged over

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land areas of the simulation domain. Dust outbreaks reduce the temperature at 2 meters by up to 4 K during daytime, whereas a reverse tendency of similar magnitude is found during nighttime. Depending on the vertical distribution of dust loads and time, mineral particles heat (cool) the atmosphere by up to 0.9 K (0.8 K) during daytime (nighttime) within atmospheric dust layers. Beneath and above the dust clouds, mineral particles cool (warm) the atmosphere by up to 1.3 K (1.2 K) at noon (night). On a regional mean basis, negative feedbacks on the total emitted dust (reduced by 19.5 %) and dust AOD (reduced by 6.9 %) are found when dust interacts with the radiation. Through the consideration of dust radiative effects in numerical simulations, the model positive/negative biases for the downward surface SW/LW radiation, with respect to Baseline Surface Radiation Network (BSRN) measurements, are reduced. In addition, they also reduce the model near-surface (at 2 meters) nocturnal cold biases by up to 0.5 K (regional averages), as well as the model warm biases at 950 and 700 hPa, where the dust concentration is maximized, by up to 0.4 K. However, improvements are relatively small and do not happen in all episodes because other model first order errors may dominate over the expected improvements, and the misrepresentation of the dust plumes' spatiotemporal features and optical properties may even produce a double penalty effect. The enhancement of dust forecasts via data assimilation techniques may significantly improve the results.

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1. Introduction

Dust aerosols through their interaction with the incoming solar (shortwave, SW) and the outgoing terrestrial (longwave, LW) radiation, perturb the radiation budget of the Earth-Atmosphere system and redistribute the energy therein. The induced perturbation of the radiation fields by dust particles, the so-called dust radiative effect, takes place through three processes of increasing complexity affecting the energy budgets at the surface, into the atmosphere and at the top of the atmosphere (TOA). The first one, known as direct radiative effect (DRE) and referred as REari (aerosol-radiation interactions) in the latest report of the Intergovernmental Panel on Climate Change (IPCC, Boucher et al., 2013), is caused by the absorption and scattering of the SW radiation (Sokolik et al., 2001) and the absorption and re-emission of the LW radiation by mineral particles (Heinold et al., 2008). Due to the perturbation of the radiation fields by dust aerosols, the energy budget both at the surface and into the atmosphere is modified and the signal of these impacts is evident in atmospheric stability/instability conditions associated with cloud development and precipitation. These rapid adjustments, which have been earlier referred as semi-direct effects (Hansen et al., 1997), are induced by the dust REari on surface energy budget and atmospheric profile (Boucher et al., 2013) contributing to the Effective Radiative Forcing (ERFari). Moreover, dust aerosols due to their ability to serve as cloud condensation nuclei (CCN) and ice nuclei (IN), modify the physical (Twomey, 1974; Albrecht, 1989) and optical properties of clouds (Pincus and Baker, 1994), which consist the major regulators of the Earth-Atmosphere system's radiation budget (Lohmann and Feicher, 2005). This chain of complex processes, involving aerosol-cloud-interactions (ACI) and the subsequent modifications of the radiation fields, constitute the indirect impact of mineral particles on radiation, which is characterized by the largest uncertainties, even larger than those of the dust direct and semi-direct effects. In the latest IPCC report (IPCC, 2013), the formerly known as indirect effects have been renamed to Effective Radiative Forcing (ERFaci) including the modification of radiation by clouds as well as the subsequent changes (rapid adjustments) of clouds' physical/microphysical/optical properties (Boucher et al., 2013).

Several studies have been conducted aiming at estimating the dust direct/semi-direct (e.g. Pérez et al., 2006; Helmert et al., 2007; Zhao et al., 2010; Nabat et al., 2015a) and indirect effects (e.g. Sassen et al., 2003; Seigel et al., 2013). Specifically, numerous studies have been carried out either by means of numerical modelling (e.g. Solmon et al., 2012; Woodage and Woodward, 2014) or through the synergy of observations and radiative transfer codes (Di Sarra et al., 2011; Valenzuela et al., 2012) or solely based on aerosol observations (e.g. Yang et al., 2009; Zhang et al., 2016) and their findings either referred to extended (e.g. Spyrou et al., 2013) or limited time periods (e.g. Nabat et al., 2015b) or to specific desert dust outbreaks (e.g. Pérez et al., 2006; Santese et al., 2010; Stanelle et al., 2010). The investigation of dust radiative effects is a scientific issue of great concern since it is documented that mineral particles, through their interaction with the radiation, can affect atmospheric processes from short (weather) to long (climate) temporal scales. To this aim, many research efforts were dedicated to the investigation of dust impacts on the convective activity (Mallet et al., 2009), sea surface temperature (Foltz and McPhaden, 2008), hydrological cycle (Miller et al., 2004b), hurricanes (Bretl et al., 2015), boundary layer dynamics (Heinold et al., 2008) and monsoons (Solmon et al., 2008; Vinoj et al., 2014).

The direct impact of dust aerosols is expressed by the sign and the magnitude of the DRE values, which are defined as the anomalies (perturbation) of the radiation fields attributed to dust-radiation direct interaction, considering as a reference (control) an atmospheric state where mineral particles are not a radiatively active substance. Based on this, negative and positive DREs indicate a cooling (loss of energy) and a warming effect (gain of energy), respectively. Nevertheless, the sign of the DREs varies between the SW and LW spectrum (Osborne et al., 2011) as well as within the Earth-Atmosphere system. More specifically, due to the attenuation (through scattering and absorption) of the SW radiation, dust aerosols warm the atmosphere and cool the surface (Huang et al., 2014), while reverse tendencies are revealed at

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The scientific importance of investigating the dust direct impacts on radiation has been notified in previous studies where it was shown that the consideration of the dust-radiation interactions may improve the forecasting ability of weather models (Pérez et al., 2006) and can reduce the observed biases of the LW radiation at TOA between models and satellite retrievals (Haywood et al., 2005). The dust direct impacts are highly variable both in space (e.g. Zhao et al., 2010) and time (e.g. Osipov et al., 2015) attributed to several parameters related either to dust aerosols' physical and optical properties or to external factors (e.g. surface type), which determine both the sign and the magnitude of the DREs (Liao and Seinfeld, 1998). One of the most important factor is the composition of mineral particles determining the spectral variation of the refractive index (Müller et al., 2009; Petzold et al., 2009; Perlwitz et al., 2015a, b; Pérez García-Pando et al., 2016) and subsequently their absorption efficiency (Mallet et al., 2009), which are both critical in radiation transfer studies, and are also dependent on the mixing state (either external or internal) of dust aerosols (Scarnato et al., 2015). Under clear skies, apart from mineral particles' optical properties, the shape (Wang et al., 2013a), the emitted dust size distribution (Mahowald et al., 2014), the surface albedo (Tegen et al., 2010) as well as the vertical distribution of dust aerosols (Mishra et al., 2015) have been recognized as determinant factors for the DRE calculation. On the contrary, when clouds are present, the position of dust layers with regards to clouds defines the sign and the magnitude of DREs at TOA (Yorks et al., 2009; Meyer et al., 2013; Choobari et al., 2014; Zhang et al., 2014).

The dust radiative effects become important under specific conditions of very high concentrations, so-called events or episodes or outbreaks. Such episodes occur frequently over the broader Mediterranean basin (Gkikas et al., 2013), due to its vicinity to the world's major dust sources situated across the northern Africa (Sahara) and Middle East deserts (Ginoux et al., 2012). Dust particles are mobilized over these areas by strong winds (Schepanski et al., 2009) being uplifted to the free troposphere due to strong convection in the boundary layer (Cuesta et al., 2009) and are transported towards the Mediterranean due to the prevailing synoptic circulation (Gkikas et al., 2015). Under these conditions, dust particles over the Mediterranean are recorded at very high concentrations as it has been confirmed either by satellite (e.g. Moulin et al., 1998; Guerrero-Rascado et al., 2009; Rémy et al., 2015) and ground retrievals (e.g. Kubilay et al., 2003; Toledano et al., 2007) or by surface PM_{10} measurements (e.g. Rodríguez et al., 2001; Querol et al., 2009; Pey et al., 2013).

Among the different aerosol types that co-exist in the Mediterranean (Lelieveld et al., 2002; Basart et al., 2009), dust is the one causing the greatest perturbation of the SW and LW radiation, especially during desert dust outbreaks (e.g. Di Sarra et al., 2008; Di Biagio et al., 2010). Thus, a number of studies focused on Mediterranean dust outbreaks' impacts on the SW (Meloni et al., 2004; Gómez-Amoet al., 2011; Antón et al., 2012; Di Sarra et al., 2013; Obregón et al., 2015), LW (Antón et al., 2014; Sicard et al., 2014a) and NET (Di Sarra et al., 2011; Romano et al., 2016) radiation. However, the obtained results were representative at a local scale and considering the high spatial variability of desert dust outbreaks, the optimum solution of assessing in a comprehensive way their impacts on weather and climate is provided by atmospheric-dust models. To this aim, the induced DREs by the Mediterranean desert dust outbreaks have been analyzed through short-term numerical simulations (Pérez et al., 2006; Santese et al., 2010; Remy et al., 2015) while similar studies have been conducted either at a seasonal (Nabat et al., 2015a) and annual scale (Nabat et al., 2012) or for extended time periods (Spyrou et al., 2013; Nabat et al., 2015b) pointing out the key role of desert dust aerosols in the Mediterranean climate.

The overarching goals of the present study are: (i) the assessment of the short-term direct radiative effects (DREs) on the Earth-Atmosphere system's radiation budget, induced during intense Mediterranean desert dust outbreaks, based on regional model simulations, (ii) the assessment of the associated impacts on temperature and sensible/latent heat fluxes, (iii) the investigation of possible feedbacks on dust AOD and dust emission and (iv) the assessment of the model's predictive skills, in terms of reproducing temperature and radiation fields, when dust-radiation interactions are taken into account in numerical simulations. To this aim, 20 intense and widespread desert dust outbreaks that affected the broader area of the Mediterranean basin, over the period March 2000 – February 2013, have been identified based on an objective and dynamic satellite algorithm, which utilizes daily multi-sensor satellite retrievals (Section 2). It must be highlighted that through the consideration of a large dataset of desert dust outbreaks is ensured the robustness of our findings, providing thus the opportunity to have a clear view of dust outbreaks' impacts on radiation as well as about the associated impacts on meteorological variables (e.g. temperature). For each dust outbreak, through short-term (84 h) numerical simulations of the regional NMMB-MONARCH model (Section 3), the DREs are calculated at TOA,

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surface and into the atmosphere, both at grid point (geographical distributions) and regional scale level (Section 5.2), for the SW, LW and NET (SW+LW) radiation. In addition, are examined the impacts of the Mediterranean desert dust outbreaks on the sensible/latent heat fluxes (Section 5.3) and on the surface temperature (Section 5.4) as well as the potential feedbacks on dust AOD and dust emissions (Section 5.5). The last part of the study (Sections 5.6 and 5.7) investigates the potential improvement of the model's forecasting ability in terms of reproducing the temperature and radiation fields when dust-radiation interactions are included in numerical simulations. A summary is made and conclusions are drawn in Section 6.

2. Selection of desert dust outbreaks

In the present study, 20 intense and widespread desert dust outbreaks that affected the broader area of the Mediterranean basin, over the period March 2000 – February 2013, are analyzed. The studied desert dust outbreaks have been identified using an objective and dynamic satellite algorithm introduced in Gkikas et al. (2013; flowchart in their Figure 2) and further improved in Gkikas et al. (2016). The algorithm utilizes daily 1° x 1° latitude-longitude resolution satellite retrievals, derived from MODerate resolution Imaging Spectroradiometer (MODIS; Remer et al., 2005), Total Ozone Mapping Spectrometer (TOMS; Torres et al., 1998) and Ozone Monitoring Instrument (OMI; Torres et al., 2007) observations. The MODIS-Terra (Collection 051) aerosol optical depth at 550 nm (AOD_{550nm}), Ångström exponent (α), fine fraction (*FF*) and effective radius (r_{eff}, available only over sea) products are used in the algorithm along with EP-TOMS and OMI-Aura Aerosol Index (*AI*). Using these products, the algorithm takes into account information regarding aerosols' load (*AOD*), size (*FF*, *a* and r_{eff}) and absorbing/scattering ability (*AI*) which is necessary for the identification of dust.

Only a brief discussion of the algorithm operation is given here, whereas a detailed description is provided in Gkikas et al. (2013). The satellite algorithm is applied to each individual 1° x 1° grid cell of the Mediterranean Satellite Domain (29° N - 47° N and 11° W - 39° E, MSD, red rectangle in Figure 1), separately over land and sea surfaces, during the period March 2000 – February 2013. For each grid cell, from the series (2000-2013) of daily AOD_{550nm} values, the mean (*Mean*) and the associated standard deviation (*Std*) of AOD_{550nm} are calculated. Based on these two primary statistics, two threshold (or cut-off) levels being equal to *Mean+2*Std* and *Mean+4*Std*, are defined. By comparing each daily AOD value to the two thresholds, the algorithm determines whether an aerosol episode (or event) occurs over an 1° x 1° grid cell (or pixel) in that day or not, and labels it as strong or extreme, depending on which AOD threshold is exceeded (lower or higher). Thereby, the term "aerosol episode" refers to pixel-level

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episodic (extremely high loading) aerosol conditions and it is used with this meaning henceforth. Subsequently, in order to characterize the identified pixel-level episodes as desert dust (DD) ones, appropriate thresholds for α, FF, r_{eff} and AI are used, based on existing knowledge about relevant physical properties (size and absorbing/scattering ability) of dust. According to the algorithm, a strong or extreme pixel-level DD episode occurs if $\alpha \leq 0.7$, $FF \leq 0.4$, $r_{eff} > 0.6 \mu m$ and $AI > 1$ (conditions should be met simultaneously).

Based on the satellite algorithm's outputs, for each day of the study period it is calculated the total number of grid cells over which a strong or an extreme DD episode has taken place. Subsequently, from the overall series of 4748 days over the study period, are kept only those in which at least 30 grid cells with a DD episode (either strong or extreme) have been recorded. This criterion was first adopted by Gkikas et al. (2015), who analyzed the atmospheric circulation evolution patterns favoring the occurrence of dust outbreaks over the broader Mediterranean basin, in order to keep and study the most extensive ones (in terms of the number of pixel-level DD episodes). In a next step, the days satisfying the defined criterion (i.e. days where at least 30 pixel-level DD episodes have been occurred) are ranked based on their regional MODIS-Terra AODs averaged over the "dust episodic" pixels within the geographical limits of the MSD. If two or more consecutive days are satisfying the defined criteria, then the day with the maximum number of DD episodes is selected. The final dataset consists of 20 intense Mediterranean desert dust outbreaks listed in a chronological order in Table 1.

The majority of the selected desert dust outbreaks (55 % or 11 out of 20) took place in spring (March-April-May) when massive dust loads originating in the Sahara Desert are transported towards the central and eastern parts of the Mediterranean (Gkikas et al., 2013; Pey et al., 2013). Four widespread desert dust outbreaks affected mainly the western sector of the MSD in summer (July, August), while five dust outbreaks were recorded across the central and eastern parts of the basin in winter (January, February). Among the selected cases, the number of pixel-level total (strong plus extreme) DD episodes in the MSD varies from 30 (28 July 2005, western-central Mediterranean) to 85 (31 July 2001, western Mediterranean). Almost in all cases, the number of extreme DD episodes is higher than those for the strong ones spanning from 20 (28 July 2005) to 51 (8 May 2002) and from 3 (24 February 2006) to 56 (31 July 2001), respectively. Likewise, the intensity (in terms of AOD at 550 nm) of total DD episodes ranges from 0.74 (31 July 2001) to 2.96 (2 March 2005), being in general higher in winter while moderate-to-high intensities are recorded in spring. Based on the information in Table 1, the selected study cases correspond to widespread and intense dust outbreaks that occurred in various parts of the

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Mediterranean, and therefore they are representative and appropriate for further studying their radiative effects.

3. Model description

In the present section, the main features of the meteorological driver (Section 3.1.1) and the dust module (Section 3.1.2) used in the regional NMMB-MONARCH (Multiscale Online Nonhydrostatic AtmospheRe CHemistry) model, previously known as NMMB/BSC-Dust, are described. The version (v1.0) of the NMMB-MONARCH model used here contributes to different model inter-comparisons like the International Cooperative for Aerosol Prediction (ICAP) initiative and the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS), a project developed under the umbrella of the World Meteorological Organization (WMO) with focus on improving capabilities of sand and dust storm forecasts. For brevity reasons, only the main characteristics of the model are discussed here since a thorough description is provided in Pérez et al. (2011, and references therein) as well as in recent publications presenting its developments and applications in gas-phase chemistry (Badia et al., 2017), volcanic ash dispersion (Marti et al., 2017) and data assimilation (Di Tomaso et al., 2017) studies. The spectral variation of the GOCART dust optical properties, utilized as inputs to the radiation transfer scheme, is presented in Section 3.2, whereas the model set up used in our experiments is given in Section 3.3.

3.1. The NMMB-MONARCH model

3.1.1. The NMMB atmospheric model

The Non-hydrostatic Multiscale Model NMMB (Janjic, 2004; Janjic and Black, 2007; Janjic et al., 2011) is a unified atmospheric model developed at the National Centers for Environmental Prediction (NCEP) (Janjic et al., 2001; Janjic, 2003). A powerful element of the model constitutes its non-hydrostatic dynamical core, activated depending on the resolution, providing the capability to be used for applications spanning at a wide range of temporal (from short- to long-term) and spatial (from regional to global) scales. An additional dynamic feature of the NMMB is the consideration of various parameterization schemes which can be incorporated into the numerical simulations. In our experiments, the parameterization schemes of Betts-Miller-Janjic (Betts, 1986; Betts and Miller, 1986; Janjic, 1994, 2000), Ferrier (Ferrier et al., 2002), Mellor-Yamada-Janjic (Janjic et al., 2001) and Monin-Obukhov

Deleted: The occurrence of intense desert dust outbreaks during the first half of the year is favored either by the predominance of intense low pressure systems across the Mediterranean basin (Varga et al., 2014; Gkikas et al., 2015) or by their eastwards shift (Saharan depressions) across the northern coasts of Africa (Alpert and Ziv, 1989).In both seasons, dust transport from the northern Africa deserts towards the Mediterranean is induced by the prevailing southerly or southwesterly airflow (Barkan et al., 2005; Meloni et al., 2008). Some of the identified desert dust outbreaks here, have been also analyzed in previous studies related to particulate matter levels (Kanakidou et al., 2010), chemical speciation (Theodosi et al., 2010), dust layers' vertical structure (Amiridis et al., 2009; DeSouza-Machado et al., 2010), dust radiative effects (Di Sarra et al., 2011), dust modelling (Carnevale et al., 2012) and prevailing synoptic conditionsfavoring the occurrence of dust events (Nastos, 2012).

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(Monin and Obukhov, 1954) have been utilized for the convection, cloud microphysics, turbulence and surface layer, respectively, as well as the NOAH land model (Ek et al., 2003). Moreover, only the greenhouse gases are taken into account and not the emitted short lived atmospheric gases. The model's dynamic equations, in the horizontal plane, are solved on the Arakawa B grid (Arakawa and Lamb, 1977) while in vertical the general hybrid pressure-sigma coordinate (Simmons and Burridge, 1981) is utilized. For regional simulations, a rotated longitude-latitude coordinated system is used (the Equator is running through the middle of the integration domain) enabling therefore more uniform grid distances.

3.1.2. The Dust component

The main components of the desert dust life cycle, regarding mineral particles' production in the source areas, transport and removal from atmosphere, are considered in the dust component of the MONARCH model, which is embedded into the NMMB model. The size intervals as well as the effective radii for each one of the 8 dust bins, representing clay-originated sub-micron (bins 1-4) and silt-originated coarse (bins 5-8) particles, that are considered in the dust module were adopted from Pérez et al. (2006). The mass of each bin is calculated at each time step, grid point and layer, while the median mass diameter and the geometric standard deviation of the sub-bin distribution are fixed to 2.524 μm and 2.0 μm, respectively. In the existing version of the NMMB-MONARCH model, dust aerosols are externally mixed and hydrophobic. All the required parameters regulating dust emission and mobilization namely the: (i) surface wind speed, (ii) turbulence, (iii) land use type, (iv) vegetation cover, (v) erodibility, (vi) surface roughness, (vii) soil texture and (viii) soil moisture, are considered in the dust emission scheme (Pérez et al., 2011). The vertical dust flux for each dust size bin is proportional to the horizontal sand flux while several parameters are tuned to match observations that are mainly available far away from the sources. Coarse dust aerosols are removed efficiently from the atmosphere through sedimentation, which is solved implicitly in each model layer. For the description of dust aerosols' wet removal, a mechanism which is more effective for fine mineral particles, parameterizations representing in- and below-cloud scavenging are included in the NMMB-MONARCH in which the grid-scale cloud microphysical scheme of Ferrier and the convective adjustment scheme of Betts-Miller-Janjic are utilized (Pérez et al., 2011). The ability of the NMMB-MONARCH model to reproduce accurately the dust aerosol fields has been confirmed through evaluation studies, relied on global and regional annual simulations (Pérez et al., 2011) as well as by utilizing measurements from experimental campaigns as reference data (Haustein et al., 2012). Moreover, the reliability of the model in terms of reproducing the Saharan dust patterns over Cape Verde as well as to simulate dust vertical profiles has been confirmed

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through the analyses made by Gama et al. (2015) and Binietoglou et al. (2015), respectively. In addition, the predictive skills of the NMMB-MONARCH model, in comparison with other regional models, have been assessed for a specific dust outbreak (Huneeus et al., 2016) that affected the western parts of the Mediterranean and Europe. Finally, in the framework of the SDS-WAS (https://sds-was.aemet.es/forecast-products/forecast-evaluation), the evaluation of the simulated dust fields (over Sahara, Middle East and Mediterranean) produced by 12 models, versus ground-based (AERONET) and spaceborne (MODIS) retrievals, reveals that the NMMB-MONARCH is ranked at the highest positions.

3.2. Radiative transfer model and dust optical properties

For the description of dust aerosols interaction both with the SW and LW radiation, the RRTMG (Rapid Radiative Transfer Model for Global Circulation Models, Iacono et al., 2008) radiative transfer model is coupled with the dust module. RRTMG consists a modified version of the RRTM which is a broadband radiative transfer model that includes the molecular absorption of the SW (by water vapor, carbon dioxide, ozone, methane and oxygen) and LW (by water vapor, carbon dioxide, ozone, methane, nitrous oxide, oxygen, nitrogen and halocarbons) radiation. Even though the basic physics and absorption coefficients utilized in RRTM (Mlawer et al., 1997) remain unchanged in RRTMG, several updates regarding computational efficiency and representation of subgrid-scale cloud variability have been implemented (Iacono et al., 2008). Through these adjustments, it has been improved the efficiency of the RRTMG in global circulation model (GCM) applications with a minimal loss of accuracy (Iacono et al., 2008). In the RRTMG, the total number of quadrature points (g points) used to calculate radiances has been reduced from 224 to 112 and from 256 to 140 for the shortwave and longwave spectrum, respectively. In addition, for the short wavelengths, the discrete ordinates algorithm DISORT (Stammes et al., 1998) has been replaced by a two-stream radiation transfer solver (Oreopoulos and Baker, 1999). All the updates applied in the RRTMG radiation transfer code are listed in the Atmospheric and Environmental Research (AER) radiative transfer web site (*http://rtweb.aer.com/*). Based on evaluation studies, the comparison of the RRTMG clear-sky SW and LW fluxes versus RRTM_SW and LBLRTM, respectively, has revealed that its accuracy at short wavelengths is within 3 Wm^{-2} whereas at long wavelengths is 1.5 Wm^{-2}. As inputs to the radiation transfer scheme, the aerosol optical depth (AOD, measure of the aerosol load), the single scattering albedo (SSA, expresses the fraction of scattering to total extinction) and the asymmetry parameter (ASYM, measures the degree of symmetry of the phase function between the forward and backward hemispheres) are required. In the present version (v1.0) of

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the model, the calculation of dust optical properties is made based on the formulas presented in Pérez et al. (2006), by using the mass concentration simulated by the NMMB-MONARCH model, the single-particle optical properties derived by the GOCART model (Chin et al., 2002) and the refractive indices from the Global Aerosol Data Set (GADS) (Koepke et al., 1997) which have been modified using Sinyuk et al. (2003), as described in Pérez et al. (2011). The spectral variation of the single-particle dust optical properties for each bin, namely the mass extinction coefficient, the single scattering albedo and the asymmetry parameter are shown in Figures 2-i, 2-ii and 2-iii, respectively. Their calculation for each dust size bin and at each spectral band is made based on the Mie code (Mishchenko et al., 2002) assuming homogeneous and spherical dust particles. For the other types of tropospheric aerosols (sulfate, organic carbon, black carbon, and sea salt), the GOCART monthly climatological AOD, SSA and ASYM values for the year 2000, are utilized.

3.3. Model set-up configuration

In our experiments, the simulation domain (NMMB-MONARCH Simulation Domain, NSD, outer domain in Figure 1) covers the Sahara (dust sources areas), the Mediterranean (mid-range dust transport areas) as well as most of the European continent (long-range dust transport areas). The horizontal resolution is equal to 0.25° x 0.25° degrees and 40 sigma-hybrid pressure levels up to 50 hPa are used in vertical. The atmospheric model's fundamental time step is set to 25 seconds. The simulations have been made for each one of the 20 identified Mediterranean desert dust outbreaks (see Section 2) considering a spin-up and a forecast period, using 1° x 1° NCEP final analyses (FNL) as initial and 6-h boundary conditions. More specifically, for each case, a hindcast period of 84 hours starts at 00 UTC of the day (see the second column in Table 1) when the desert dust outbreak has been identified according to the defined criteria (explained in Section 2). In order to ensure a more "realistic" initial state of the atmosphere, a 10-day spin-up before the initialization of the forecast period is simulated, where the model's meteorology is reinitialized every 24 hours. During the forecast periods, for the computation of the aerosol radiative effects, two configurations of the model were run. In the first one (RADON), all aerosol types interact with radiation while in the second one the corresponding interactions are deactivated (RADOFF). It must be clarified that in the RADON experiment, the perturbation of the radiation fields is mainly caused by dust aerosols, which are dynamically calculated, while the contribution of the other aerosol species depends on climatological optical properties derived from GOCART. However, since the selected cases refer to desert dust outbreaks, the term "dust-radiation interactions" instead of "aerosol-radiation interactions" is used throughout the manuscript.

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4. Calculation of the dust direct radiative effects

The direct radiative effects (DREs), expressed in Wm^{-2}, are computed at the top of the atmosphere (TOA), into the atmosphere (ATM), and at the surface, for the downwelling (SURF) and the absorbed (NETSURF) radiation, for the shortwave (SW), longwave (LW) and NET (SW+LW) radiation. The calculations are made according to the following formulas:

$DRE_{TOA} = F^{\uparrow}_{TOA,RADOFF} - F^{\uparrow}_{TOA,RADON}$ (Eq. 1)

$DRE_{SURF} = F^{\downarrow}_{SURF,RADON} - F^{\downarrow}_{SURF,RADOFF}$ (Eq. 2)

$DRE_{NETSURF} = \left(F^{\downarrow}_{SURF,RADON} - F^{\uparrow}_{SURF,RADON}\right) - \left(F^{\downarrow}_{SURF,RADOFF} - F^{\uparrow}_{SURF,RADOFF}\right) = F_{NETSURF,RADON} - F_{NETSURF,RADOFF}$ (Eq. 3)

$DRE_{ATM} = DRE_{TOA} - DRE_{NETSURF}$ (Eq. 4)

At TOA (Eq.1), DREs are calculated through the subtraction of the RADON (dust-radiation interaction is activated) from the RADOFF (dust-radiation interaction is deactivated) outputs of the upward (↑) radiative fluxes (*F*) and express the loss (cooling effect or planetary cooling) or the gain (warming effect or planetary warming) of energy within the Earth-Atmosphere system when are negative and positive, respectively. At the surface, DREs are computed for both the downwelling (↓) (SURF, Eq. 2) and the net (downward minus upward) radiation (NETSURF, Eq. 3). Both DREs indicate a dust-induced surface cooling or warming when they get negative or positive values, respectively. Finally, on energy within the Earth-Atmosphere system, the DRE_{ATM} is calculated by subtracting the $DRE_{NETSURF}$ from the DRE_{TOA} values (Eq. 4) and quantifies the impact (warming or cooling) of dust outbreaks on the atmospheric radiation budget. The DREs are based on the subtraction of two independent model runs. Therefore, our results represent the radiative anomalies induced by dust aerosols including both the direct effect and the rapid response of atmospheric constituents such as humidity and clouds (semi-direct effects).

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5. Results

5.1. Comparison of model and satellite AODs

Before dealing with the DREs, the ability of the model to reproduce satisfactorily the dust AOD fields is assessed using MODIS-Terra AOD$_{550nm}$ retrievals as reference data. The results of the intercomparison between the daily satellite AODs (left column in Fig. 3) and the modelled (right column in Fig. 3) AODs at 12 UTC (instantaneous fields) are presented here for three of the 20 identified desert dust outbreaks (see Section 2), which took place on 2nd March 2005 (upper row in Fig. 3), 19th May 2008 (middle row in Fig. 3) and 2nd August 2012 (bottom row in Fig. 3) and affected the eastern, central and western parts of the Mediterranean basin, respectively. The corresponding maps for the remaining 17 cases are illustrated in Figure S1. Note, that the evaluation of the model outputs versus the satellite measurements is restricted within the geographical limits of the MSD (red rectangle in Fig. 1), since the satellite algorithm used for identification of the desert dust outbreaks is applied only to this region (see Section 2). Moreover, in order to eliminate the spatial inconsistencies between the two products, we have regridded the model outputs from their raw spatial resolution (0.25° x 0.25°) to 1° x 1° matching them with the satellite retrievals.

According to the MODIS-Terra observations on 2nd March 2005, a dust plume extends from the Gulf of Sidra to the southern parts of Greece, with AODs up to 5 (Fig. 3 i-a). As shown in Fig. 3 i-b, the model on this day simulates high dust AOD$_{550nm}$ values (1-3.25) along a dust plume, extending from Algeria to the Black Sea, which affects the eastern parts of the Mediterranean Sea. Through the intercomparison of satellite and model AODs, it is revealed that the desert dust outbreak is slightly shifted eastwards while the maximum dust AODs are lower than those retrieved by the satellite sensor. The second desert dust outbreak occurred on 19th May 2008 and affected the central sector of the MSD. According to MODIS (Fig. 3 ii-a), the intensity of dust loads is maximized (up to 4) in the central parts of the Mediterranean Sea (southeastern of Sicily). This is also reproduced by the model, although somewhat higher AODs are found over the central and southern parts of Italy (Fig. 3 ii-b). In spite of this, however, there is a clearly good model performance in reproducing the dust event that hit the central Mediterranean. An ever better agreement between the model and satellite AODs, in terms of spatial variability and intensity of dust loads, is found for the desert dust outbreak of August 2nd 2012, that affected the westernmost parts of the Mediterranean, with highest AODs (up to 2-2.5) from the Alboran Sea down to the coastal areas of Morocco (Figs. 3 iii-a,b).

Apart from a qualitative comparison between MODIS and NMMB-MONARCH, the performance of the model has been assessed also quantitatively. More specifically, for each desert dust outbreak the spatial correlation coefficient (R) values as well as the absolute biases (defined as NMMB-MODIS) have been calculated considering only the grid cells where a DD episode (either strong or extreme) has been

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identified by the satellite algorithm. In Figure S2, are presented the computed regional R (Fig. S2-ii) and bias (Fig. S2-iii) scores while the stacked bars (Fig. S2-i) illustrate the number of strong, extreme and total DD episodes (available also in Table 1). Among the studied cases, it is revealed a strong variation of R values (Figure S2-ii) reflecting the diversity of the model's capability in terms of capturing the spatial patterns of the desert dust outbreaks. These drawbacks result mainly from displacements of the simulated dust patterns with respect to the observed ones. The best performance is found on 22 Feb 2004 (R=0.82) in contrast to 23 Jan 2009 where the correlation coefficient is zero. In 7 out of 20 cases, the R values are higher than 0.5 while in 7 cases vary between 0.2 and 0.4 indicating a weak-to-moderate performance of the model. In the remaining 6 dust events, the spatial agreement between MODIS and NMMB is characterized poor (R<0.2). As it concerns the bias, in absolute terms, in all the events negative values are recorded ranging from -2.3 (24 Feb 2006) to -0.17 (19 May 2008). This finding shows that the model underestimates consistently the intensity of the desert dust outbreaks which have been analyzed in the present study.

According to the evaluation analysis, the model's ability in terms of reproducing satisfactorily the dust fields varies strongly case-by-case while the simulated intensity of the desert dust outbreaks is lower with respect to the satellite retrievals. Therefore, both facts can raise questions regarding the accuracy of the computed DREs in some cases since the perturbations of the radiation fields are determined to a large extent by AOD (e.g. Hatzianastassiou et al., 2004; Pérez et al., 2006; Papadimas et al., 2012). Nevertheless, several factors affect/determine the level of agreement between observed and simulated AODs providing a reasonable explanation about the discrepancies found between MODIS and NMMB-MONARCH. The most important is the temporal inconsistency between the two products. More specifically, the satellite retrievals correspond to daily averages whereas the model products are representative for a specific forecast time (instantaneous fields). Considering the high variability of aerosols' loads, particularly under episodic conditions, this temporal discrepancy imposes a limitation when a quantitative comparison between MODIS and NMMB is attempted. This can explain the observed differences found either on the intensity or on the spatial patterns of the desert dust events. Also, it must be considered that artifacts of the satellite retrievals (e.g. clouds contamination, representativeness/homogeneity within the 1° x 1° grid cell) may lead to higher AODs as it has been shown in relevant evaluation studies (e.g. Gkikas et al., 2016). Moreover, due to the inability of the MODIS Dark Target (DT) algorithm to retrieve aerosol optical properties over desert areas as well as under cloudy conditions, in a significant part of the study region there are not available satellite observations (white areas in Figs. 3 i-a, ii-a and iii-a) restricting thus their comparison with the model outputs which provide full spatial coverage.

5.2. Direct radiative effects (DREs)

5.2.1. Geographical distributions

For each desert dust outbreak, the TOA, ATM, SURF and NETSURF DREs have been computed for the SW, LW and NET radiation, according to the formulas presented in Section 4. Just as an example, in Figure 4 are illustrated the geographical patterns of the instantaneous NET (SW+LW) DRE_{TOA} (second column), DRE_{ATM} (third column), DRE_{SURF} (fourth column) and $DRE_{NETSURF}$ (fifth column) values, at 12 h (first row), 24 h (second row), 36 h (third row) and 48 h (fourth row) after the initialization of the model forecast on 2nd August 2012 at 00 UTC, along with the simulated patterns of dust AOD at 550 nm on the same day and time (first column). For brevity reasons only the results for the allwave (NET) are given, while the SW and LW DREs and their contribution to NET DREs are discussed in the regional analysis (next sub-section). The corresponding patterns for each desert dust outbreak are given in Figures S3 – S21 in the supplementary material. Moreover, for each desert dust outbreak, the minimum and maximum clear-sky NET DREs at grid point level, during the simulation period, are presented in Table S1.

Based on the model outputs, at 12 h, an arc shaped dust plume affected the western parts of the Sahara, the Canary Islands, the maritime areas off the Moroccan coasts, the southern parts of the Iberian Peninsula and the western Mediterranean Sea (Fig. 4). During the forecast period, the spatial features of the desert dust outbreak do not reveal a remarkable variability, with maximum AODs (up to 3) across Mali, Mauritania, Western Sahara and in the Canary Islands. At a first glance, it is evident that the DRE patterns are driven by those of the desert dust outbreaks whereas small scale isolated features of extremely high/low DREs mainly result from slight "shifts" of clouds between the two independent model runs. Moreover, it is apparent that both the sign and the magnitude of DREs vary among TOA, surface and atmosphere as well as with time (day or night). During daytime (12 h and 36 h) the DREs are driven by their SW components which significantly exceed the LW ones. Through absorption and scattering of solar radiation by mineral particles, the downwelling radiation at the ground (SURF) is reduced by up to 308 Wm^{-2}, indicating a strong surface cooling (bluish colors) in areas where the dust AOD is maximized like Mauritania or south Algeria. During nighttime (24 and 48 h), the sign of the DRE_{SURF} values is reversed and their magnitude decreases compared to that at 12 and 36 h. This is because during the night the DRE_{SURF} values are identical to the LW DRE ones, which are positive,

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implying extra downwelling LW radiation at the surface, by up to 58 Wm^{-2}, emitted by the overlying dust. This effect, leading to night surface warming, is more visible over specific parts of Sahara that host high dust loads, e.g. in its western parts. The geographical patterns of $DRE_{NETSURF}$ are very similar to those of DRE_{SURF}, as expected, since they only differ by the net upward radiation at the surface, which in turn is determined by the surface albedo (for the SW radiation) and temperature (for the LW radiation). Based on our results, the negative (surface cooling) and positive (surface warming) $DRE_{NETSURF}$ values can reach down to -290 Wm^{-2} (eastern Atlantic Ocean) and up to 42 Wm^{-2} (western Sahara) during day and night, respectively. Among our studied cases (see Table S1) the instantaneous NET DRE_{SURF} and $DRE_{NETSURF}$ values at noon can be as large as -589 Wm^{-2} and -337 Wm^{-2}, respectively, in agreement with relevant results reported in previous studies dealing with the radiative impacts of dust intrusions in the Mediterranean (Pérez et al, 2006; Remy et al., 2015), in west Africa (Heinold et al., 2008; Mallet et al., 2009) and in Asia (Wang et al., 2009; Singh and Beegum et al., 2013).

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The occurrence of desert dust outbreaks results in a strong perturbation of the atmospheric radiation budget, attributed to the interaction of dust aerosols with the SW and LW radiation. More specifically, during daytime (i.e. 12 and 36 h), mineral particles absorb radiation at short wavelengths warming thus the atmosphere as indicated by the positive instantaneous NET DRE_{ATM} values in Figure 4 (third column), reaching up to 189 Wm^{-2} over the dust affected areas. Our calculated noon atmospheric DREs (Table S1) are comparable to those reported by Heinold et al. (2008; 2011) and significantly lower compared to those in Pérez et al. (2006), who found DRE_{ATM} values higher than 500 Wm^{-2} in land areas with dust AOD > 3 during a desert outbreak that affected the Mediterranean on 12th April 2002. We note that Pérez et al. (2006) used complex refractive indices taken from the Global Aerosol Data Set (GADS) that have been shown to be excessively absorbing, which may partly explain their high DRE_{ATM} values. During night, negative DRE_{ATM} values (down to -45 Wm^{-2} in Algeria and Mali) are computed in the dust affected areas indicating an atmospheric cooling because of the emission of LW radiation by mineral particles (Wang et al., 2013b).

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The sign and magnitude of DRE_{TOA} (Eq. 4) are regulated by $DRE_{NETSURF}$ and DRE_{ATM}. At noon and above cloud-free areas, there is a distinct change of DRE_{TOA} sign over oceanic and desert areas affected by dust loads (note for example the red colors over the dusty western Sahara Desert regions, e.g. Mauritania, against blue colors off the African coasts). This change of the DRE_{TOA} sign is due to the difference in surface albedo of the two types of surface (water and desert), in combination with dust high AODs and low-to-moderate single scattering albedo enhancing solar absorption by dust above highly multiple reflecting surfaces. Such a reverse of DRE_{TOA} sign has been also reported in previous studies (e.g. Santese et al., 2010; Nabat et al., 2012; Papadimas et al., 2012). Over highly reflective surfaces (i.e. deserts), the atmospheric warming is enhanced since dust aerosols absorb not only the incoming solar radiation but also the radiation reflected by the surface. At the same time, the amount of the absorbed radiation at the ground is reduced by the attenuation of the SW radiation and by the increase of the back reflected radiation at the surface. The combination of these processes results in a predominance of the atmospheric warming over surface cooling and subsequently to positive DRE_{TOA} values (planetary warming), which can be as large as 85 Wm^{-2} according to our simulations (Table S1). On the contrary, when dust aerosols are suspended over dark surfaces (i.e. maritime areas), the condition is reversed and negative DRE_{TOA} values down to -184 Wm^{-2} (Table S1) are calculated, revealing thus a strong planetary cooling. Nevertheless, the positive DRE_{TOA} values exceeding 300 Wm^{-2}, which are recorded in maritime areas off the western African coasts, are associated with the existence of absorbing dust aerosols superimposed over low- and mid-level clouds. During night, the atmospheric cooling offsets the surface warming, both induced by the desert dust outbreaks, and for this reason the DRE_{TOA} values are almost negligible (do not exceed 10 Wm^{-2} in absolute terms over cloud free areas) indicating an almost null dust direct radiative effect. Our model computed dust induced planetary warming above western Africa is comparable to similar results reported in previous studies focusing on the same or similar desert areas (e.g. Mallet et al., 2009; Pérez et al., 2006; Wang et al., 2010; Nabat et al., 2012; Kalenderski and Stenchikov, 2016).

5.2.2. Regional mean results

In order to show more clearly temporal patterns, DREs were also averaged over the NSD (outer NMMB Simulation Domain in Figure 1), SDD (Sahara Desert Domain, green rectangle in Figure 1) and MSD (Mediterranean Satellite Domain, red rectangle in Figure 1) domains, for each desert dust outbreak, separately for the NET, SW and LW radiation. Then, in a further step, DRE values have been averaged over the 20 dust outbreaks every three hours during the forecast period (84 hours). Thus, the time series of regional mean and associated standard deviation (shaded areas) all-sky TOA (black curve), SURF (purple curve), NETSURF (blue curve) and ATM (red curve) DREs are depicted in Figure 5.

The SW DREs (upper row in Fig. 5) are positive in the atmosphere (ATM, warming effect) and negative at the surface (SURF and NETSURF, cooling effect) throughout the entire forecast period, revealing a distinct diurnal cycle with marked maximum values around noon over all three domains. A careful look, however, reveals some differences between the sub-regions. Thus, in NSD (first column) and SDD (second column) the maximum DRE_{ATM} values increase slightly with time from 22.3 to 22.7

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Wm^{-2} and from 29.1 to 31.6 Wm^{-2}, respectively, while in contrast they decrease in MSD (third column) from 21 to 18.5 Wm^{-2}. Respectively, the negative DRE$_{SURF}$ values (surface cooling) reach down to -33.1 Wm^{-2} in the NSD and 45.3 Wm^{-2} in the SDD, while in the Mediterranean area reach down to -34.8 Wm^{-2}. In addition, the magnitude of DRE$_{SURF}$ and DRE$_{NETSURF}$ values in NSD and MSD slightly decrease while an increasing trend (in absolute terms) is recorded in the SDD. The opposite tendencies found for both sub-regions (i.e., SDD and MSD) for the atmospheric and surface DREs are attributed to the increase and decrease of dust AOD over the Sahara (Figure S22-ii) and the Mediterranean (Figure S22-i), respectively. As it concerns the SW DRE$_{NETSURF}$ values, their temporal variation is identical to the corresponding ones for DRE$_{SURF}$; however, the former ones are lower by up to 14.6 Wm^{-2}, in absolute terms. The most noticeable difference between the two sub-domains (i.e. SDD and MSD) is encountered for the DRE$_{TOA}$ at noon. Over bright desert surfaces, dust outbreaks warm the Earth-Atmosphere system as indicated by the positive DRE$_{TOA}$ values (up to 3.2 Wm^{-2}) while over the darker (mostly covered by sea) surfaces of the Mediterranean, the mineral particles induce a planetary cooling with DRE$_{TOA}$ values ranging from -12 to -4 Wm^{-2}. In both subdomains, the strongest planetary cooling is found at early morning and afternoon hours with negative SW DRE$_{TOA}$ values down to -11.9 Wm^{-2} and -11.6 Wm^{-2} over Sahara and Mediterranean, respectively. On the contrary, DRE$_{TOA}$ values decrease towards noon, due to increasing solar absorption and decreasing scattering by dust under smaller solar zenith angles. Finally, the regional SW DREs have been analyzed also separately over land and sea surfaces for the three subdomains (results not shown here) revealing that the computed DREs are mainly driven by the corresponding perturbations simulated over continental regions.

The regional all-sky DREs have been also computed for the LW spectrum (middle row in Figure 5) revealing reverse effects of lower magnitude (in absolute terms) with respect to the corresponding ones found at short wavelengths. Due to the emission of LW radiation by the mineral particles, desert dust outbreaks induce an atmospheric cooling (negative LW DRE$_{ATM}$ values) and increase the amount of the downward LW radiation at the surface (positive LW DRE$_{SURF}$ values). Both DRE$_{ATM}$ and DRE$_{SURF}$ levels do not reveal remarkable temporal variation ranging from -4.8 to -2.2 Wm^{-2} and from 1.4 to 3.7 Wm^{-2}, respectively, over the Sahara where the maximum values are found. On the contrary, from the timeseries of the LW DREs for TOA and NETSURF it is evident the existence of a diurnal cycle with maximum and minimum values around noon and during nighttime, respectively. Moreover, both DRE$_{TOA}$ and DRE$_{NETSURF}$ values are higher than zero, throughout the simulation period, indicating a warming LW radiative effect. More specifically, the regional LW DRE$_{TOA}$ ranges from 0.2 to 1.6 Wm^{-2} and DRE$_{NETSURF}$ varies between 1.7 and 4 Wm^{-2} for the whole simulation domain (NSD). The corresponding

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maximum DREs for the SDD and MSD are higher by up to 3.6 Wm^{-2} and lower by up to 1.1 Wm^{-2}, respectively. Dust aerosols act like greenhouse gases (Miller and Tegen, 1998) trapping the outgoing terrestrial radiation while at the same time emit radiation at longer wavelengths back to the ground explaining thus the positive LW DREs for TOA (planetary warming) and NETSURF (surface warming). In addition, the aforementioned LW DREs (TOA and NETSURF) covariate with time revealing that the sign and the magnitude of the LW DRE_{TOA} are determined by the perturbation of the surface radiation budget (LW $DRE_{NETSURF}$) since the LW DRE_{ATM} values are almost constant throughout the simulation period. This is in contrast to the corresponding finding for the SW radiation where the dust outbreaks' impact on the Earth-Atmosphere system's radiation budget is regulated by the perturbation of the radiation fields into the atmosphere (ATM) and at the surface (NETSURF). Finally, between SDD and MSD remarkably stronger LW DREs are found for the former domain due to the higher dust loads over the Sahara as well as due to the larger size of mineral particles close to the source areas.

As it has been shown from the above analysis, the dust DREs between short and long wavelengths are reverse (except at TOA over the Sahara around midday) and in order to assess the impact of desert dust outbreaks in the whole spectrum the regional all-sky NET (SW+LW) DREs have been also analyzed (bottom row in Fig. 5). During sunlight hours, the NET DREs result from the compensation of the SW and LW effects while during night the NET and the LW DREs are equal attributed to the absence of SW radiation. Based on our results, in the NSD, the DRE_{TOA}, DRE_{SURF}, $DRE_{NETSURF}$ and DRE_{ATM} range from -8.5 to 0.5 Wm^{-2}, from -31.6 to 2.1 Wm^{-2}, from -22.2 to 2.2 Wm^{-2} and from -1.7 to 20.4 Wm^{-2}, respectively. In the SDD, the corresponding NET DREs vary from -9.3 to 5.9 Wm^{-2}, from -42.2 to 3.5 Wm^{-2}, from -23 to 3.6 Wm^{-2} and from -3.5 to 27.2 Wm^{-2}, respectively. Over the Mediterranean, the DREs for TOA range from -10.7 to 0.5 Wm^{-2}, for SURF from -33.6 to 1.7 Wm^{-2}, for NETSURF from -26.7 to 1.7 Wm^{-2} and for ATM from -1.3 to 19.3 Wm^{-2}.

At noon, the SW planetary cooling dominates over the LW planetary warming resulting thus to negative DRE_{TOA} values over the simulation (NSD) and the Mediterranean (MSD) domains. On the contrary, in the SDD, both SW and LW DRE_{TOA} are positive due to the higher surface albedo and the trapping of the surface upward LW radiation by mineral particles, respectively, leading to a net warming of the Earth-Atmosphere system. In the atmosphere, for the three domains, the negative LW DREs offset by about 8-26% the positive SW ones resulting to an overall warming effect (positive NET DRE_{ATM}) around midday. Moreover, at noon, the increase of the absorbed LW radiation at the ground offsets the decrease of the absorbed SW radiation by about 14-18% resulting in a NET surface cooling (negative

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NET $DRE_{NETSURF}$) over the simulation domain. The corresponding levels for the SDD and MSD vary from 24 to 26% and from 9 to 13%, respectively.

Beyond the hourly and day-to-day variability of dust DREs, the results were averaged over the total 84-hour simulation period and the results are given, for the three domains, in Table 2, separately for the SW, LW and NET radiation. At TOA, desert dust outbreaks cause a net planetary cooling with all-sky NET DRE_{TOA} values equal to -2.6±3.2, -1.3±5 and -3.8±3.8 Wm^{-2} for the NSD, SDD and MSD, respectively. Note, that due to the very strong temporal variability of DREs at TOA, the computed standard deviations are higher than the averages in the NSD and SDD in contrast to MSD where are equal. The negative averaged NET DRE_{TOA} in SDD is attributed to the planetary cooling found at early morning and afternoon hours. Wang et al. (2011) showed that when solar altitude is low (i.e. high solar zenith angle) DRE at TOA is getting negative even over high-albedo deserts. Similar results reported also by Banks et al. (2014), who studied the daytime cycle of dust DREs during the Fennec campaign held in the central Sahara in June 2011. Our results for the DRE_{TOA} in the MSD are within the ranges reported in previous studies (e.g. Valenzuela et al., 2012; Sicard et al., 2014 a;b) dealing with dust intrusions in the Mediterranean. In the atmosphere, mineral particles cause an overall atmospheric warming with NET DRE_{ATM} levels varying from 6.9±8.3 (MSD) to 7.8±11.7 Wm^{-2} (SDD). On average, dust outbreaks reduce the downwelling NET radiation at the ground (DRE_{SURF}) by up to -14.7±14.6 Wm^{-2} (NSD), -18.0±19.3 Wm^{-2} (SDD) and -14.2±14 Wm^{-2} (MSD) while the corresponding $DRE_{NETSURF}$ levels are equal to -9.6±10.2 Wm^{-2}, -9.1±11.2 Wm^{-2} and -10.8±11.2 Wm^{-2}, respectively. Our results for the SW and LW radiation in the SDD are in a good agreement with the annual averages for the year 2008 presented by Nabat et al. (2012) over Northern Africa.

5.3. Impact on sensible and latent heat fluxes

As it has been shown in previous section, dust outbreaks exert a strong perturbation of the surface radiation budget by reducing and increasing the absorbed NET radiation at the ground during day and night, respectively. As a response to these disturbances, the surface heat fluxes, both sensible (SH) and latent (LE), associated with the transfer of energy (heat) and moisture between surface and atmosphere, also change in such a way trying to balance the gain or the loss of energy at the ground (Miller and Tegen, 1998). Subsequently, variations of SH and LE have impact on the components of the hydrological cycle (Miller et al., 2004b) as well as on the turbulent kinetic energy and momentum transfer which in turn affect near surface winds and dust emission (Pérez et al., 2006). Moreover, Marcella and Eltahir (2014) and Kumar et al. (2014) have shown that due to the presence of dust aerosols into the atmosphere, the

Deleted: 5… to 28…% and from 14… to 15…%, respectively. In addition, the increase of the downwelling LW radiation at the ground offsets by up to 8% the decrease of the downward SW radiation resulting in negative NET DRE_{SURF} values across the Sahara Desert (i.e. SDD). ...

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Formatted: No underline, Font color: Auto, English (United States) daytime surface sensible heat fluxes are reduced leading to a reduction of the planetary boundary layer (PBL) height.

Here, we are investigating the impact of desert dust outbreaks on SH and LE over the simulation domain (NSD). It must be clarified that our analysis is restricted only above land areas since we are looking at short range effects and the atmospheric driver is not coupled with an ocean model. The timeseries of the regional SH and LE values, over the forecast period, based on the RADON (red curve) and RADOFF (blue curve) configurations of the model are presented in Figures 6-i (for SH) and 6-ii (for LE). Each curve corresponds to the mean levels calculated from the 20 desert dust outbreaks while the shaded areas represent the associated standard deviations. According to our results, SH is characterized by a diurnal variation with maximum values (~ 350 Wm^{-2}) at noon and minimum ones (~ -30 Wm^{-2}) during nighttime (Fig. 6-i). Nevertheless, during sunlight hours, the surface sensible heat fluxes simulated in the RADON experiment are lower by up to 45 Wm^{-2} in comparison to the RADOFF outputs. At night, an opposite tendency is recorded and the RADON SH fluxes are higher by up to 2 Wm^{-2} than the corresponding fluxes based on the RADOFF configuration of the model. The reverse effects on SH levels, over the western parts of the Sahara, between daytime and nighttime as well as the diurnal variability of their magnitude have been pointed out by Zhao et al. (2011). Based on the paired t-test, the differences between RADOFF and RADON SH values are statistical significant at 95% confidence level throughout the forecast period. At local scale (geographical distributions), among the studied cases, in areas where the desert dust outbreaks' intensity is maximized, the SH fluxes are reduced by up to 150 Wm^{-2} during day and increased by up to 50 Wm^{-2} during night. Our findings are consistent with those presented by Mallet et al. (2009) and Rémy et al. (2015) who analyzed the impact of dust storms on sensible heat fluxes over W. Africa and Mediterranean, respectively, and substantially higher than the instantaneous perturbations of SH calculated by Kumar et al. (2014), who studied a dust outbreak that occurred in northern India (17-22 April 2010).

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The diurnal variation of the latent heat fluxes (Fig. 6-ii) is identical to that of sensible heat fluxes; however, LE levels are remarkably lower than the regional averages of SH. This is attributed to the lower soil water content and limited evaporation in arid regions (Ling et al., 2014). Based on our simulations, LE values at noon gradually decrease both for the RADOFF (blue) and RADON (red) experiments over the forecast period attributed to the too moist initialization of the model (Note that the model is initialized with FNL analysis produced by a different model (GFS)). Nevertheless, the latter LE values are lower than the former ones by up to 4 Wm^{-2} indicating that desert dust outbreaks reduce the latent heat fluxes leaving from the ground. The reliability of this finding is further supported by the fact that the RADOFF-

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RADON differences are statistically significant at 95% confidence level. During night, the RADON LE values are slightly higher (less than 0.5 Wm^{-2}) with respect to the corresponding ones simulated in the RADOFF configuration. The instantaneous reduction and increase of LE (results not shown here) can be as large as -100 Wm^{-2} and 20-30 Wm^{-2}, respectively. Finally, in contrast to SH, the spatial features of LE anomalies are not identical with those of $DRE_{NETSURF}$ since other parameters (e.g. soil moisture) regulate also the latent heat fluxes (Marcella and Eltahir, 2014).

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5.4. Impact on temperature fields

Through the perturbation of the radiation it is expected that desert dust outbreaks will affect also the temperature fields. In order to quantify these impacts, the temperature differences between the RADON and RADOFF simulations, both at 2 meters and in vertical, are analyzed. In Figure 7, are displayed the RADON-RADOFF anomaly maps of temperature at 2 meters at 12 (i), 24 (ii), 36 (iii) and 48 (iv) hours after the initialization of the forecast period on 2nd August 2012 at 00 UTC. At noon, the highest negative biases (down to -4 K) are observed over land areas where the intensity of dust loads is high (see the first and third row in the first column in Fig. 4) due to the strong reduction of the NET radiation reaching the ground by the mineral particles. Similar findings, under dust episode conditions, have been also reported by previous studies conducted for the Mediterranean (Pérez et al., 2006), across the Sahara (Helmert et al., 2007; Heinold et al., 2008; Stanelle et al., 2010) and in East Asia (Kumar et al., 2014; Ling et al., 2014). Over dust-affected maritime areas, due to the higher heat capacity of the sea, the temperature differences between the RADON and RADOFF experiments are almost negligible at these time scales. During nighttime, dust aerosols emit radiation at thermal wavelengths increasing thus the near surface temperature when the dust-radiation interactions are included into the numerical simulations (RADON experiment). For this reason, the RADON-RADOFF temperature differences at 2 meters become positive (up to 4 K) at 24 and 48 forecast hours over land areas where the "core" of the dust plume is observed. The reduction and the increase of the near surface temperature during daytime and nighttime, respectively, either solely or as a combined result indicate that the temperature diurnal range is reduced due to desert dust outbreaks.

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The vertical distribution of dust layers determines their impacts on radiation with altitude which in turn modify the temperature profiles (Meloni et al., 2015) and subsequently affect convection (Ji et al., 2015), cloud development (Yin and Chen, 2007), precipitation (Yin et al., 2002) and wind profiles (Choobari et al., 2012). In order to investigate the impacts of desert dust outbreaks on temperature fields into the atmosphere, we have reproduced the altitude-latitude cross sections (up to 8 km above mean sea level, m.s.l.) of RADON-RADOFF temperature differences on 4 April 2003 at 12 UTC along the meridional 30° E (Fig. 8 ii-a) and on 7 March 2009 at 00 UTC along the meridional 10° E (Fig. 8 ii-b). In addition, the corresponding cross sections of dust concentration (in kg m^{-3}) are shown in Figures 8 i-a and 8 i-b, respectively. At midday, an elevated dust layer extends from 1.5 to 6 km m.s.l., between 23° N and 33° N, with dust concentrations up to 0.8×10^{-6} kg m^{-3} while a low elevated dust layer extends from the surface up to 1.5 km m.s.l., between 27° N and 31° N, with concentrations up to 10^{-6} kg m^{-3} (Fig 8 i-a). Along the cross-section, the simulated columnar dust AOD at 550 nm reaches up to 1.21. Based on the cross section of temperature differences (Fig. 8 ii-a), dust aerosols via the absorption of solar radiation warm the atmospheric layers by up to 0.8-0.9 K between altitudes where the high-elevated dust layer is located. On the contrary, below the dust cloud, mineral particles cool the lowest tropospheric levels (by up to 1.3 K) by attenuating the incoming solar radiation. Note that between the parallels 31° N and 35° N, where dust loads are recorded at low altitudes (below 2 km), higher temperatures by up to 0.3 K are simulated in the RADON experiment with respect to RADOFF, revealing thus an atmospheric warming near surface. Also, it must be considered that in this area mineral particles are suspended over sea, where the impacts on sensible heat fluxes are negligible, making therefore evident the dust warming effect at low atmospheric levels in contrast to land areas (parallels between 27° N and 31° N), where the near surface temperature is reduced because of the reduction of the sensible heat fluxes, as it has been shown also by Pérez et al. (2006, Fig. 10). Therefore, the vertical distribution of dust loads plays a significant role regarding their impact on near surface temperature which in turn may affect winds and subsequently dust emission (Stanele et al., 2010; Huang et al., 2014). Above the high-elevated dust layer, negative RADON-RADOFF temperature differences (down to -0.3 K) are found indicating an atmospheric cooling attributed to the dust albedo effect (Spyrou et al., 2013).

In the second example, on 7th March 2009 at 00 UTC, a dust layer extends from the southern parts of the NSD domain to the northern parts of Tunisia, between surface and 4 km m.s.l. (Fig. 8 i-b). Along the dust plume, with AODs reaching up to 1.40, moderate concentrations (up to 0.5×10^{-6} kg m^{-3}) are simulated between 15° N and 20° N, low (less than 0.2×10^{-6} kg m^{-3}) between 20° N and 25° N while the maximum ones (higher than 2×10^{-6} kg m^{-3}) are recorded between 25° N and 35° N. Due to the emission of LW radiation by mineral particles, dust aerosols cool the atmospheric layers (Otto et al., 2007) in which they reside, by up to 0.8 K, and increase the temperature, by up to 0.4 K, just above the dust layer. Between the bottom of the dust layer and surface, positive RADON-RADOFF temperature differences (i.e. warming) up to 1.2 K are calculated as indicated by the red colors following the model topography

Deleted: (through scattering and absorption) (grey shaded). Nevertheless, this near surface warming is "interrupted", being null or even reverse (i.e. cooling), in areas where the dust layer abuts the ground.

5.5. Feedbacks on dust emission and dust aerosol optical depth

In the present section, focus is given on the investigation of the potential feedbacks on dust AOD (at 550 nm) and dust emissions attributed to dust radiative effects. To this aim, the timeseries of the regional averages and the associated standard deviations, throughout the forecast period (84 hours), calculated from the 20 desert dust outbreaks for both parameters, based on the RADON (red) and RADOFF (blue) experiments, are analyzed and the obtained results are shown in Figure 9. Over the simulation period, the RADOFF dust AOD_{550nm} gradually increases from 0.31 to 0.34 in contrast to the corresponding outputs from RADON that are gradually decreasing down to 0.29 (Fig. 9-i). The positive RADOFF-RADON differences of dust AOD, indicating a negative feedback when the dust-radiation interactions are considered into the numerical simulations, are getting evident 12 hours (0.005 or 2%) after the initialization of the forecast period and amplify with time (up to 0.036 or 12%), being also statistical significant (paired t-test, confidence level at 95%) at each forecast step. The observed negative feedbacks on dust AOD have been also pointed out in relevant studies (Pérez et al., 2006; Wang et al. , 2010) carried out for specific desert dust outbreaks. Through the comparison of the mean dust AOD levels, calculated over the 84-h simulation period, based on RADON (0.288) and RADOFF (0.308) simulations, it is revealed a statistical significant reduction by 0.02 (6.9 %) attributed to the dust radiative effects. Among the 20 desert dust outbreaks, these reductions vary from 1% (22 February 2004) to 12.5% (27 January 2005) and are statistical significant at 95 % confidence level in all cases.

A similar analysis has been also made for the dust emissions (in kg m^{-2}) aggregated over the whole simulation domain (NSD, outer domain in Figure 1) and the overall results are given in Figure 9-ii. Dust emissions are maximized around midday (Cowie et al., 2014) and are very weak during night. Based on the RADOFF simulation, the highest amounts of emitted dust are increased from 2 to 2.5 kg m^{-2} throughout the hindcast period. This increasing tendency is encountered also in the RADON experiment but the emitted dust amount is lower. The positive RADOFF-RADON anomalies during daytime range from 0.1 to 0.4 kg m^{-2} and are statistical significant at 95% confidence level based on the paired t-test. Therefore, desert dust outbreaks exert a negative feedback on dust emission explaining thus the reduction of dust AOD. The lower amounts of emitted dust, modelled based on the RADON configuration, result from a chain of processes triggered by the surface cooling which decreases the turbulent flux of sensible heat into the atmosphere, weakening the turbulent mixing within the PBL and the downward transport

Deleted: Mineral particles emit LW radiation and trap the outgoing terrestrial radiation explaining thus the warming effect of dust outbreaks close to the ground during nighttime.

Deleted: ; however, the reductionsof mineral particles' loads weresignificantly higher compared to our calculationscorresponding to averages of the 20 studied desert dust outbreaks. More specifically, Pérez et al. (2006) found a reduction of the regional dust AOD by up to 35-45 % and inWang et al. (2010) the corresponding reductions were ranging between 10 and 45%

Deleted: First, for each case and in each forecast step, the dust emissions from all grid points within the NSD are aggregated.Then, the mean and the standard deviation values are computed from the 20 desert dust outbreaks which are analyzed and the overall results are given in Figure 9-ii.Moreover, the total dust emissions at each forecast stepare added and the obtained results, separately for the RADON and RADOFF configuration of the model,are provided into the parentheses in the legend of Figure 9-ii.

Deleted: ; however, the dust emission is lower compared to the simulation in which the dust-radiation interactions are neglected (RADOFF) of momentum to the surface and subsequently reduces surface wind speed and dust emission (Miller et al., 2004a; Pérez et al., 2006).

During the simulation period, the total emitted amount of desert dust (parentheses in the legend of Figure 9-ii) is equal to 18.279 and 21.849 kg m^{-2} based on the RADON and RADOFF, respectively. Therefore, desert dust outbreaks cause a negative feedback on dust emissions reducing them by 3.57 kg m^{-2} (-19.5%). This reduction is consistent in all the studied cases of our analysis varying from 0.6 kg m^{-2} (~10%, 24 February 2006) to 6.6 kg m^{-2} (~34%, 2 August 2012). Negative feedbacks on dust AOD and dust emissions have been also pointed out in previous studies based on short- (e.g. Ahn et al., 2007; Rémy et al., 2015) and long-term (e.g. Perlwitz et al., 2001; Zhang et al., 2009) simulations. Woodage and Woodward (2014) relied on climatic simulations of the HiGEM model, found a positive feedback on global dust emissions which is in contradiction with findings reported in the majority of the existing studies. The authors claimed that this discrepancy could be explained by the absence of mineral particles with a radius larger than 10 μm in the emitted dust size distribution leading thus to an underestimation of the LW effects. It must be clarified that according to our results negative feedbacks on dust emission are found at a regional scale. Stanelle et al. (2010) showed that the vertical distribution of dust aerosols determines their impacts on atmospheric stability and wind patterns and subsequently the associated feedbacks on dust emissions which can be even positive at a local scale. This highlights the importance of studying the potential feedbacks on mineral particles' loads as well as on their emissions spatially by analyzing all the contributor factors.

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5.6. Assessment of the radiation at the ground

The performance of the NMMB-MONARCH model in terms of reproducing the downward SW and LW radiation is assessed using as reference data ground measurements derived from the Baseline Surface Radiation Network (BSRN, Ohmura et al., 1998). Through this analysis it is attempted to quantify objectively the potential improvements of the model's predictive skills attributed to the inclusion of the dust radiative effects into the numerical simulations. Globally, 59 BSRN stations are installed at different climatic zones providing radiation measurements (http://bsrn.awi.de/) of high accuracy at very high temporal resolution (1 min) (Roesch et al., 2011). For the evaluation analysis, we have used the global (direct and diffuse) shortwave and longwave downwelling radiation at the ground measured at 6 stations (magenta star symbols in Figure 1) located in Spain (Izana, Cener), France (Palaiseau, Carpentras), Algeria (Tamanrasset) and Israel (Sede Boker).

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In Figure 10, are presented the timeseries of the measured (red curve) SW (i-) and LW (ii-) radiation at Sede Boker and the corresponding model outputs based on the RADON (black curve) and the RADOFF (blue curve) experiments, for the periods 22 February 2004 00 UTC – 25 February 2004 12 UTC (-a) and 21 April 2007 00 UTC – 24 April 2007 12 UTC (-b). In the bottom row of Fig. 10 are also provided the temporal evolution of the model dust AOD_{550nm} and the Level 2 AERONET total AOD_{500nm} (red x symbols) retrieved via the O' Neill algorithm (O' Neill et al., 2003). Moreover, the AERONET Ångström exponent (alpha) retrievals (denoted with green x symbols) are used as an indicator of coarse or fine particles predominance into the atmosphere. For the comparison between model and observations, the nearest grid point to the stations' coordinates is utilized. In Sede Boker, the model's grid point elevation is 465 m being slightly lower than the AERONET (480 m) and BSRN (500 m) stations, and therefore these small altitude differences do not affect substantially the intercomparison results. Likewise, the SW and LW radiation are measured from 0.295 to 2.8 μm and from 4 to 50 μm, respectively, while the spectral intervals in the model's radiation transfer scheme span from 0.2 to 12.2 μm and from 3.3 to 1000 μm in the shortwave and longwave spectrum, respectively. These differences might contribute to the level of agreement between model and observations; however, are not discussed in our evaluation analysis.

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In both examples presented here, but also for the rest of our dataset, the model captures better the temporal variation of the downwelling SW in contrast to the LW radiation at the ground with correlation coefficients (R) higher than 0.96 and between 0.63 and 0.85, respectively. However, the model-BSRN biases vary strongly in temporal terms because of the inability of the model to reproduce adequately the amount of the suspended mineral particles. For the first desert dust outbreak (left column in Fig. 10), during the first forecast day, the maximum measured SW radiation is higher by about 150 Wm^{-2} than the simulated RADON outputs and slightly lower than the corresponding RADOFF levels. The former is explained by the facts that the model reproduces the dust peak earlier than actually recorded according to AERONET observations (see Figure 10 iii-a) and it develops low-level clouds (cloud fractions between 0.5 and 0.6) while the latter one is attributed to the absence of radiative effects. For the rest of the simulation period, the model overestimates and underestimates the shortwave and longwave radiation, respectively, due to its deficiency to reproduce (underestimation) the amount of dust aerosols. More specifically, based on AERONET retrievals, AOD and alpha levels vary from 0.2 to 0.4 and from 0.2 to 0.7, respectively, indicating the existence of dust loads of moderate intensity. On the contrary, the simulated dust AOD at 550 is less than 0.1 in both model configurations characterized by a "flat" behavior in temporal terms. Over the simulation period (22 February 2004 00 UTC – 25 February 2004

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12 UTC), the mean SW (LW) radiation based on BSRN, RADON and RADOFF is equal to 221.6 Wm^{-2} (290.0 Wm^{-2}), 255.4 Wm^{-2} (266.4 Wm^{-2}) and 272.7 Wm^{-2} (264.7 Wm^{-2}), respectively. Thanks to the consideration of the dust radiative effects, the positive model-BSRN biases in the shortwave spectrum are reduced from 51.1 Wm^{-2} (RADOFF-BSRN) to 33.9 Wm^{-2} (RADON-BSRN) while the negative model-BSRN biases in the longwave spectrum are reduced from -25.3 Wm^{-2} (RADOFF-BSRN) to -23.6 Wm^{-2} (RADON-BSRN).

In the second case which is analyzed (right column in Fig. 10), two peaks are simulated with dust AOD_{550nm} values up to 0.9 (midday on 23rd April 2007) and 0.5 (afternoon on 21st April 2007). For the major one, the model clearly overestimates aerosol optical depth with respect to AERONET retrievals in which AOD (red x symbols) varies between 0.2 and 0.3 and alpha (green x symbols) ranges from 0.3 to 0.5 while the second one cannot be confirmed due to the lack of ground observations. Note, that between 09 UTC and 15 UTC on 23rd April 2007, the model underestimates the SW radiation by up to 200 Wm^{-2} while overestimates the LW radiation by up to 150 Wm^{-2} (maximum overestimations throughout the simulation period) due to the misrepresentation of the dust AODs. Even higher model overestimations of the SW radiation are observed at 12 UTC on 22 April 2007 attributed mainly to the inability of the model to reproduce satisfactorily clouds, since the negative model-AERONET differences of AOD cannot explain these large discrepancies in radiation. Clouds play an important role in such comparisons, particularly when their features are not well reproduced by the model, leading to large overestimations or underestimations, by up to 600 Wm^{-2} in absolute terms among the studied cases of the present analysis, as it has been pointed out in previous studies (e.g. Spyrou et al., 2013). Finally, the model (RADON) overestimation of the SW radiation reaching the ground, by up to 200 Wm^{-2} at 09 UTC on 21 April 2007, is probably associated with underestimation of the simulated dust AOD since fair weather conditions are forecasted and confirmed by the true color MODIS-Terra images (http://modis-atmos.gsfc.nasa.gov/IMAGES/). For the SW radiation, the positive NMMB-BSRN biases during the simulation period (21 April 2007 00 UTC – 24 April 2007 12 UTC) are reduced from 69.0 Wm^{-2} to 40.9 Wm^{-2} when dust-radiation interactions are activated (RADON) while lower positive biases for the LW radiation are calculated (0.7 Wm^{-2}) when dust-radiation interactions are deactivated (RADOFF). Summarizing, in the majority of the studied desert dust outbreaks here, positive and negative model-observations biases are found for the downwelling SW (Table S2) and LW (Table S3) radiation, respectively, which are reduced when the dust-radiation interactions are activated. On the contrary, similar improvements are not evident on the correlation coefficients since are not found remarkable differences between RADON-BSRN and RADOFF-BSRN R values (results not shown).

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5.7. Assessment of the temperature fields versus analysis datasets

The forecasting performance of the NMMB-MONARCH model has been also assessed for the temperature fields, utilizing as reference final analyses (FNL) derived from the National Centers for Environmental Prediction database (http://rda.ucar.edu/). The evaluation of both model configurations (RADON and RADOFF) against FNL temperature at 2 meters and at 17 pressure levels into the atmosphere is made at a regional scale for the NSD. For the former intercomparison, only land grid points are taken into account, while for the latter one it is not applied any criterion regarding the surface type (land or sea). The evaluation of the model is made by considering grid points where the dust AOD is higher/equal than 0.1, 0.5 and 1.0, respectively. In order to overcome spatial inconsistencies between model and analyses, the model outputs have been regridded from their raw spatial resolution (0.25° x 0.25° degrees) to 1° x 1° degrees to match FNL. We note that analyses datasets are only "best" estimates of the observed states of the atmosphere and the surface produced by combining a model (in this case GFS) and available observations through data assimilation techniques. Analysis datasets are more poorly constrained by observations over certain regions including the arid and dusty ones, and more dependent on the model's behavior. This is even more relevant for surface variables such as 2-m temperature which may heavily depend on the underlying model's soil scheme.

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In Figure 11, are presented the regional biases (model-FNL) of temperature at 2 meters for the RADON (red curve) and RADOFF (blue curve) experiments, averaged from the 20 desert dust outbreaks every 6 hours of the hindcast period, considering only land grid points where the dust AOD is higher/equal than: (i) 0.1, (ii) 0.5 and (iii) 1.0. In order to avoid misleading interpretations, attributed to possible error compensations as a result of an erroneously representation of the dust patterns or optical properties (see Section 5.1), the corresponding root mean square error (RMSE) values have been calculated as well (Figure S23). The combination of these two skill scores (bias and RMSE) can provide information regarding the model departures (i.e., cold or warm biases) and how much "sensitive" is the level of agreement between NMMB-FNL due to large errors (outliers). Regardless the dust AOD threshold, cold biases are found during night and early morning hours, warm biases are calculated in the afternoon while the minimum biases in absolute terms appear at noon. According to our results, under low desert dust conditions (Fig. 11-i), the agreement between model and FNL is better when the dust radiative effects are neglected (RADOFF) during daytime, while slightly lower RADON-FNL biases compared to RADOFF-FNL ones are found during night. These trivial nocturnal "corrections" are not evident in the RMSE timeseries and therefore are not so trustworthy. At noon, the RADOFF-FNL biases

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are almost zero (less than 0.l K) whereas negative RADON-FNL biases (down to -0.27 K) are computed due to the surface cooling induced by the mineral particles. For moderate dust AODs (Fig. 11-ii), during night, the model-FNL temperature biases are lower, being in agreement also with the associated RMSE values (Fig. S23-ii), for the RADON configuration (less than 1 K) in contrast to the RADOFF simulation (less than 1.4 K) and these improvements are statistically significant at 95% confidence level. Nevertheless, at midday, the RADOFF-FNL biases are similar to those found for the lowest dust AOD threshold (Fig. 11-i), while the model cold biases, varying from -1.15 K (84 h) to -0.55 K (12 h), are amplified when the dust-radiation interactions are activated (RADON). The "corrections" of the near surface temperature forecasts during nighttime become more evident and statistically significant, when only land areas affected by intense dust loads (dust AOD ≥ 1.0) are considered in the NMMB-FNL comparison. Under these high dust AODs, the increase of air temperature at 2 meters due to the dust LW DREs reduces the existing cold biases and the RADON RMSE levels (Fig. S23-iii). Therefore, the improvements on model's predictability of temperature at 2 meters when accounting for dust-radiation interactions, are more evident when the intensity of dust loads increases.

The potential impacts of the dust radiative effects inclusion on the model's forecasting ability have been also investigated for the temperature fields in vertical. For this purpose, from the 20 desert dust outbreaks, the temperature model-FNL biases at 17 pressure levels (from 1000 to 100 hPa) have been calculated for the RADOFF (black curve) and RADON (red curve) and the obtained results are illustrated in Figure 12. The corresponding vertical profiles for the RMSE are given in Figure S24. The assessment results are presented only 24 (a) and 48 (b) hours after the initialization of the forecast period since are not found remarkable differences between the two model configurations at noon (i.e. 12 and 36 UTC).

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Based on our findings, model warm biases are found between 950 and 700 hPa where most of the dust is confined (brown curve). For the lowest dust AOD threshold, these positive model-FNL biases reach up to 0.245 K and 0.313 K at 24 and 48 forecast hours, respectively, when mineral particles are not treated as radiatively active substance (RADOFF). On the contrary, when dust-radiation interactions are activated (RADON) the corresponding biases are reduced down to 0.155 K and 0.239 K, respectively, indicating a better model performance which is further supported by the fact that these improvements are statistical significant (95 % confidence level). In addition, slightly lower RMSEs are also calculated for the RADON configuration between 925 and 700 hPa (Fig. S24-i). Similar but more evident results are found when the dust AOD threshold increases from 0.1 to 0.5 (middle row in Figures 12 and S24-ii). More specifically, at 24 forecast hours, the RADON-FNL temperature differences do not exceed 0.321 K in contrast to the corresponding biases between RADOFF and FNL which can be as high as 0.512 K.

At 48 forecast hours, between altitudes where the dust concentrations are maximized, the red curve (RADON-FNL) is close to the blue thick line which represents the ideal score (i.e. zero biases), while the RADOFF warm biases can reach up to 0.443 K. As it has been shown in Section 5.4 (see Fig. 8 ii-b), due to the emission of longwave radiation by the mineral particles there is a temperature reduction within the atmospheric layers in which they are confined and a slight warming above the dust layer. The former effect explains the statistically significant reduction of the model warm biases between 950 and 700 hPa whereas the latter one could explain the slight statistically significant reduction of the model cold biases recorded between 600 and 500 hPa (see Fig. 12 ii-a). According to the RMSE vertical profiles, between the two altitude ranges (950-700 hPa and 600-500 hPa), the better performance of the RADON configuration is evident only at pressure levels where the main amount of dust is simulated (Fig. S24 ii-a and ii-b). For the highest dust AOD threshold, at 24 forecast hours (Fig. 12 iii-a), the agreement of temperature profiles between RADON and FNL is better compared to RADOFF-FNL whereas at 48 forecast hours depends on altitude (Fig. 12 iii-b). Summarizing, thanks to the consideration of the dust radiative effects the predictive skills of the NMMB-MONARCH model in terms of reproducing temperature fields within the atmosphere are improved as it has been pointed also in previous relevant studies (Pérez et al., 2006; Wang et al., 2010; Wang and Niu, 2013). However, the improvements are relatively small. The consideration of dust-radiation interactions does not always lead to a better model performance since other model first order errors may dominate over the expected improvements. Also the representation of dust plumes' spatiotemporal features and optical properties, particularly the AOD and SSA, may produce double penalty effects. In this sense, the enhancement of dust forecasts via data assimilation techniques may significantly improve the results.

6. Summary and conclusions

In the present study, the direct radiative effects (DREs) during 20 intense and widespread Mediterranean desert dust outbreaks, that took place during the period March 2000 – February 2013, have been analyzed based on short-term (84 hours) regional simulations of the NMMB-MONARCH model. The identification of desert dust outbreaks has been accomplished via an objective and dynamic algorithm utilizing as inputs daily 1° x 1° satellite retrievals providing information about aerosols' load, size and nature. DREs have been calculated at the top of the atmosphere (TOA), into the atmosphere (ATM), and at the surface, for the downwelling (SURF) and the absorbed (NETSURF) radiation, for the shortwave (SW), longwave (LW) and NET (SW+LW) radiation. At a further step, the impacts on sensible and latent heat fluxes as well as on temperature at 2 meters and into the atmosphere have been

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investigated. Moreover, the potential feedbacks on dust emission and dust AOD have been assessed at regional scale representative for the simulation domain used in our experiments. In the last part of our study, focus was given on the potential improvements on model's predictive skills, attributed to the inclusion of dust radiative effects into the numerical simulations, in terms of reproducing the downward SW/LW radiation at the ground as well as the temperature fields. The main findings obtained from the present analysis are summarized below.

Direct Radiative Effects

- DREs into the atmosphere and at the surface are driven by the dust outbreaks' spatial features whereas at TOA, the surface albedo plays a crucial role, particularly under clear sky conditions.
- At noon, dust outbreaks induce a strong surface cooling with instantaneous NET DRE_{SURF} and $DRE_{NETSURF}$ values down to -589 Wm^{-2} and -337 Wm^{-2}, respectively.
- Through the absorption of the incoming solar radiation by the mineral particles, dust outbreaks cause a strong atmospheric warming effect (by up to 319 Wm^{-2}) around midday.
- At TOA, during daytime, positive DREs up to 85 Wm^{-2} (planetary warming) are found over highly reflective areas while negative DREs down to -184 Wm^{-2} (planetary cooling) are computed over dark surfaces.
- During nighttime, reverse effects of lower magnitude are found into the atmosphere and at the surface with maximum instantaneous NET DRE_{SURF}, $DRE_{NETSURF}$ and DRE_{ATM} values equal to 83 Wm^{-2}, 50 Wm^{-2} and -61 Wm^{-2} whereas at TOA due to the offset of the atmospheric cooling by the surface warming, the DRE_{TOA} values are almost negligible (less than 10 Wm^{-2}).
- The regional NET all-sky DREs for the NSD range from -8.5 to 0.5 Wm^{-2}, from -31.6 to 2.1 Wm^{-2}, from -22.2 to 2.2 Wm^{-2} and from -1.7 to 20.4 Wm^{-2} for TOA, SURF, NETSURF and ATM, respectively.
- The contribution of the LW DREs to the NET ones is comparable or even larger, particularly over the Sahara at midday.

Sensible and latent heat fluxes

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Deleted: <#>For the regional clear-sky NET DREs at TOA, the calculated positive DREs (7.1 Wm^{-2}) in the SDD and the negative DREs (-15 Wm^{-2}) in the MSD at noon indicate a planetary warming and cooling in the Sahara and in the Mediterranean, respectively.¶
<#>Over the 84 hours forecast period, the LW surface warming offsets by up to 37.7% the SW surface cooling whereas the LW atmospheric cooling offsets by 33.6% the SW atmospheric warming.¶
<#>At TOA, the corresponding LW/SW ratios vary from 15.4% (MSD) to 52.9% (SDD); however, t

- As a response to the surface radiation budget perturbations, desert dust outbreaks reduce the sensible heat fluxes (regional averages taking into account only land grid points) by up to 45 Wm^{-2} during daytime while reverse tendencies of lower magnitudes are found during night (2 Wm^{-2}).
- Locally, the aforementioned values can reach down to -150 Wm^{-2} and up to 50 Wm^{-2}.
- At noon, dust outbreaks reduce also the surface latent heat fluxes by up to 4 Wm^{-2} and 100 Wm^{-2} at a regional and grid point level, respectively. At night, the regional and the instantaneous LE levels are increased by up to 0.5 Wm^{-2} and 30 Wm^{-2}, respectively.

Impact on temperature fields

- Due to the attenuation of the incoming solar radiation and the emission of radiation at thermal wavelengths, both induced by dust aerosols, temperature at 2 meters reduces and increases during day and night, respectively, by up to 4 K in absolute terms in land areas where the dust loads are intense (AODs higher than 2).

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- At noon, dust outbreaks warm the atmosphere by up to 0.9 K between altitudes where elevated dust layers are located and cool the lowest tropospheric levels by up to 1.3 K, due to the reduced surface sensible heat fluxes.
- Due to the emission of LW radiation and the trapping of the outgoing terrestrial radiation by dust aerosols, the nocturnal temperature decreases by up to 0.8 K in atmospheric altitudes where mineral particles are confined, whereas between the bottom of the dust layer and the surface, the air-temperature increases by up to 1.2 K.

Feedbacks on dust AOD and dust emission

- The total emitted amount of dust is reduced by 19.5% (statistically significant at 95% confidence level) over the forecast period when dust DREs are included into the numerical simulations, revealing thus a negative feedback on dust emissions.
- Among the studied cases, the corresponding percentages range from -34% (2 August 2012) to -10% (24 February 2006) and are statistical significant (95% confidence level) in all cases.
- As a consequence of the lower amount of mineral particles emitted in the atmosphere, negative feedbacks are also found on the mean regional dust AOD_{550nm} which is decreased by 0.02 (6.9%) with respect to the control experiment (RADOFF).

- Statistically significant reductions of the regional dust AOD_{550nm}, varying from 1% (22 February 2004) to 12.5% (27 January 2005), are found in all the studied cases when dust-radiation interactions are activated (RADON).

Assessment of model's predictive skills

- Through the evaluation of the model's forecast outputs of the SW and LW downwelling radiation at the ground against surface measurements derived by the BSRN network, it is revealed a reduction of the modelled positive (for SW) and negative (for LW) biases attributed to the consideration of dust radiative effects. However, model's accuracy is critically affected by its ability to represent satisfactorily aerosols' and clouds' spatiotemporal features, highlighting thus their key role when such comparisons are attempted.

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- Under high dust load conditions (AODs higher/equal than 0.5), the nocturnal model-FNL negative regional biases of temperature at 2 meters are reduced by up to 0.5 K (95% statistically significant) in the RADON experiment. On the contrary, these temperature "corrections" are not evident during daytime revealing thus that other model errors (particularly those introduced by the soil model) can dominate over the expected improvements attributed to the consideration of dust-radiation interactions in the numerical simulations.
- The model regional warm biases found at 24 and 48 hours after the initialization of the forecast period, between pressure levels (950 and 700 hPa) where the dust concentration is maximized, are reduced by up to 0.4 K (95% statistically significant) in the RADON experiment.

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- In general, the bias and RSME reductions achieved are relatively small. We recall that the model simulations show underestimation and spatiotemporal mismatches compared to MODIS. A future study may consider the potential benefit of AOD data assimilation in the model to better reproduce the magnitude and spatial features of the events and therefore to further improve the weather forecast itself.

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Table 1: List of the Mediterranean desert dust outbreaks which have been identified based on the satellite algorithm. In addition, the number of DD episodes (number of satellite grid cells at 1° x 1° spatial resolution where a DD episode has been identified), the regional intensity (in terms of AOD_{550nm}) calculated from the DD episodes as well as the dust affected parts of the Mediterranean domain are provided. ¶
Case ...

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Table 1: List of the Mediterranean desert dust outbreaks which have been identified within the geographical limits of the MSD based on the satellite algorithm. In addition, the number of strong, extreme and total (strong plus extreme) DD episodes (number of satellite grid cells at 1° x 1° spatial resolution where a DD episode has been identified), the regional intensity (in terms of AOD_{550nm}) calculated from the total DD episodes as well as the dust affected parts of the Mediterranean domain are provided.

Case	Date	Strong DD episodes	Extreme DD episodes	Total DD episodes	Intensity	Affected parts of the Mediterranean domain
1	31 July 2001	56	29	85	0.74	Western
2	8 May 2002	20	51	71	1.60	Central
3	4 April 2003	23	30	53	1.42	Eastern
4	16 July 2003	38	45	83	0.98	Western and Central
5	22 February 2004	10	36	46	2.18	Central and Eastern
6	26 March 2004	28	38	66	1.45	Central and Eastern
7	27 January 2005	12	25	37	1.36	Central and Eastern
8	2 March 2005	8	37	45	2.96	Central and Eastern
9	28 July 2005	10	20	30	1.08	Western and Central
10	24 February 2006	3	42	45	2.92	Eastern
11	19 March 2006	11	28	39	1.37	Eastern
12	24 February 2007	8	34	42	2.29	Central and Eastern
13	21 April 2007	15	27	42	1.65	Central
14	29 May 2007	17	30	47	1.40	Eastern
15	10 April 2008	9	33	42	1.58	Central
16	19 May 2008	16	50	66	1.45	Central
17	23 January 2009	4	32	36	2.65	Eastern
18	6 March 2009	18	23	41	1.41	Eastern
19	27 March 2010	10	29	39	1.43	Central
20	2 August 2012	12	23	35	1.20	Western

Table 2: Mean and standard deviation of all-sky DRE_{TOA}, DRE_{SURF}, $DRE_{NETSURF}$ and DRE_{ATM} values, over the simulation period (84 hours), calculated in the NSD, SDD and MSD domains for the SW, LW and NET radiation. Blue and red background colors indicate negative (cooling effect) and positive (warming effect) DREs, respectively.

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		DRE_{TOA}	DRE_{SURF}	$DRE_{NETSURF}$	DRE_{ATM}
NSD	**SW**	-3.5±3.4	-16.3±14.3	-12.5±11	9.0±9.3
	LW	0.9±0.5	1.7±0.4	3.0±0.9	-2.0±0.4
	NET	-2.6±3.2	-14.7±14.6	-9.6±10.2	7.0±9.0
SDD	**SW**	-2.8±5	-20.8±18.8	-14.1±12.8	11.4±12.2
	LW	1.4±1.1	2.8±0.7	5.0±1.8	-3.6±0.8
	NET	-1.3±5	-18.0±19.3	-9.1±11.2	7.8±11.7
MSD	**SW**	-4.5±4	-15.4±13.8	-12.8±11.6	8.3±8.5
	LW	0.7±0.3	1.2±0.4	2.1±0.5	-1.4±0.3
	NET	-3.8±3.8	-14.2±14	-10.8±11.2	6.9±8.3

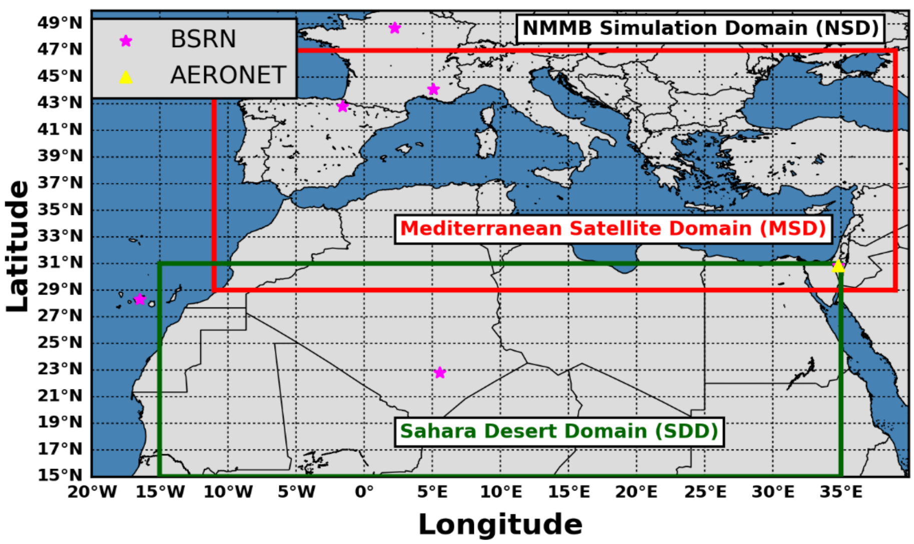
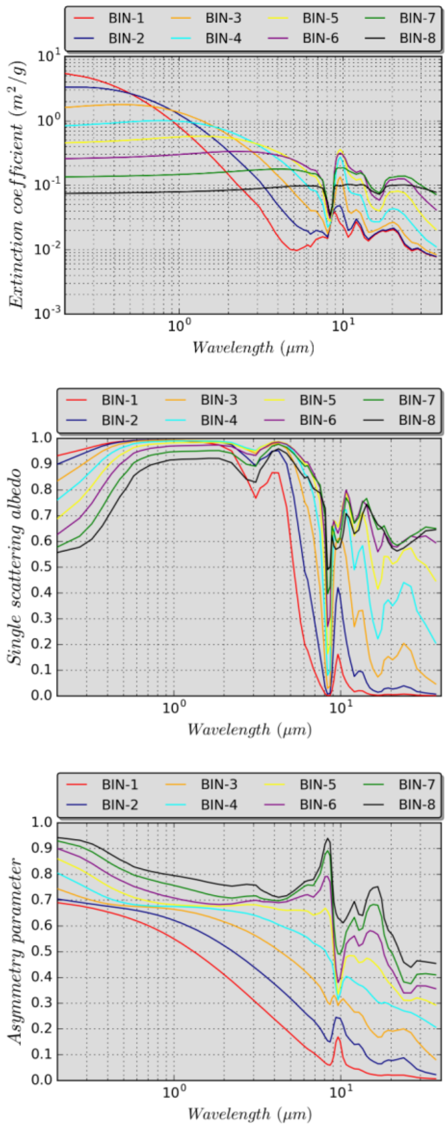


Figure 1: Geographical limits of the: (i) NMMB Simulation Domain (*NSD*, outer domain), (ii) Mediterranean Satellite Domain (*MSD*, red rectangle) and (iii) Sahara Desert Domain (*SDD*, green rectangle). With the magenta star symbols are depicted the locations of the BSRN stations and with the yellow triangle is denoted the location of the AERONET Sede Boker station.



(i) (ii) (iii)

Figure 2: Spectral variation of the GOCART: (i) extinction coefficient (in m^2/g), (ii) single scattering albedo and (iii) asymmetry parameter, for each one of the 8 dust bins which are considered in the dust module.

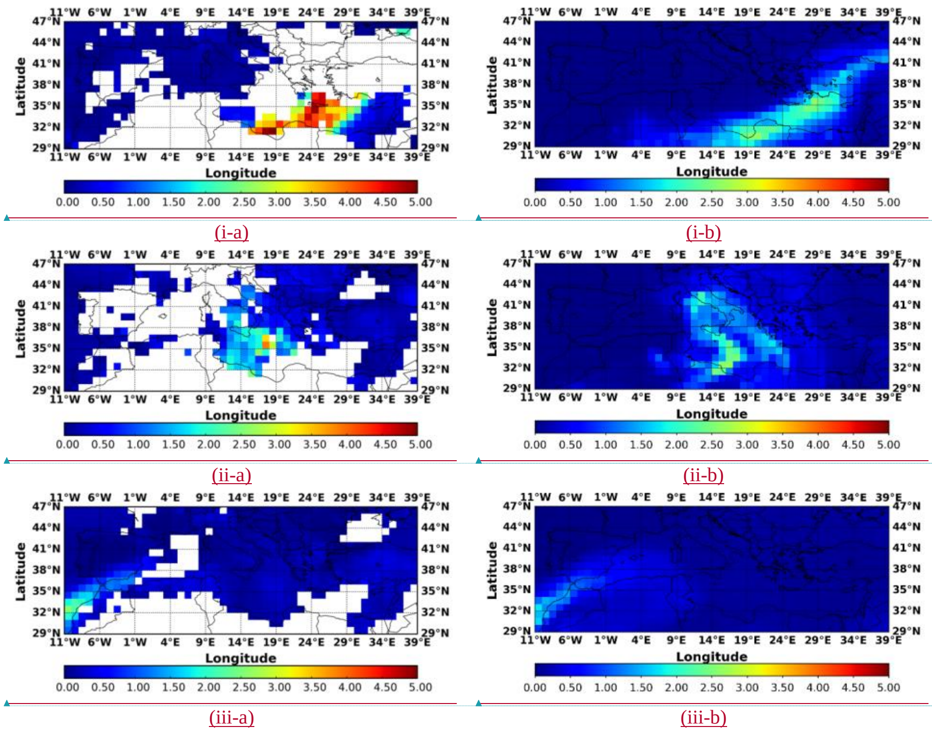


Figure 3: Geographical distributions of the aerosol optical depth (AOD) at 550 nm: (a) retrieved by the MODIS-Terra sensor and (b) simulated by the NMMB-MONARCH model at 12:00 UTC for the Mediterranean desert dust outbreaks that took place on: (i) 2[nd] March 2005, (ii) 19[th] May 2008 and (iii) 2[nd] August 2012.

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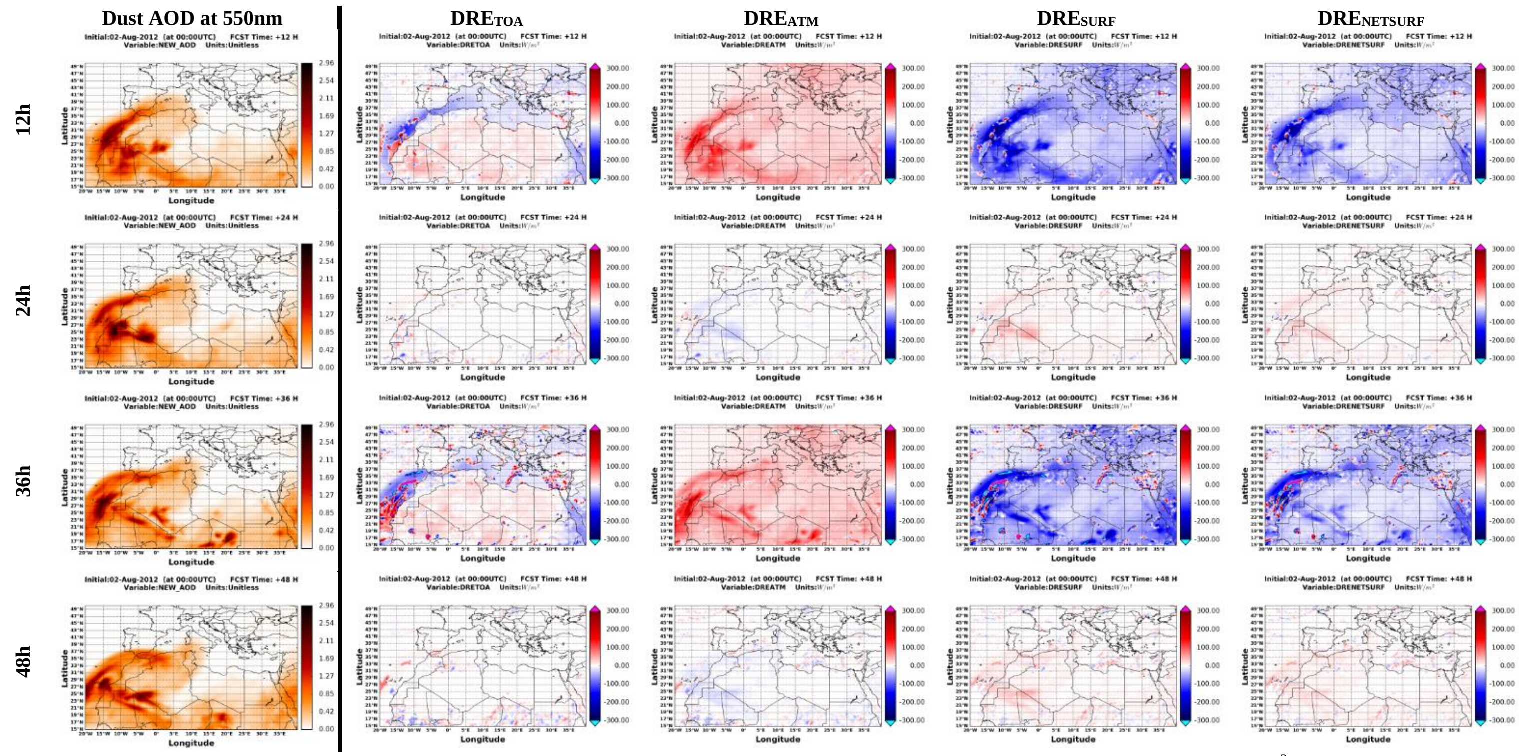

Figure 4: Spatial patterns of the simulated dust AOD_{550nm} and the instantaneous DRE_{TOA}, DRE_{ATM}, DRE_{SURF} and $DRE_{NETSURF}$ values, expressed in Wm^{-2}, at 12, 24, 36 and 48 hours after the initialization of NMMB-MONARCH model at 00 UTC on 2nd August 2012.

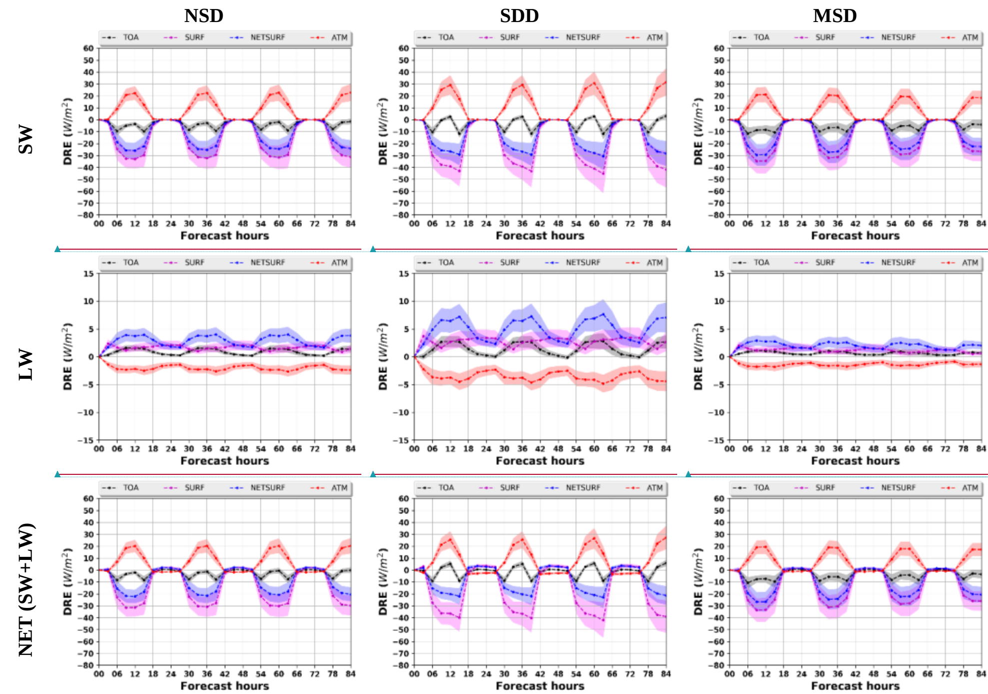

Figure 5: Regional all-sky SW (upper row), LW (middle row) and NET (SW+LW) (bottom row) DREs at TOA (black), SURF (purple), NETSURF (blue) and ATM (red) averaged over the NSD (left column), SDD (central column) and MSD (right column) domains. The calculated DREs correspond to the mean values calculated from the 20 simulated Mediterranean desert dust outbreaks and the shaded areas represent the associated standard deviation.

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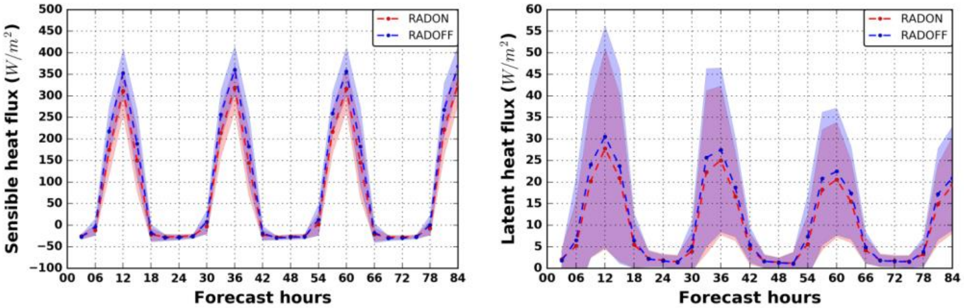

(i) (ii)

Figure 6: Regional averaged values, over land areas of the simulation domain affected by dust loads and under clear-sky conditions, of the: (i) sensible and (ii) latent heat fluxes, expressed in Wm^{-2}, based on the RADON (red) and the RADOFF (blue) configuration of the NMMB-MONARCH model. The dashed lines correspond to the mean values calculated by the 20 simulated Mediterranean desert dust outbreaks and the shaded areas represent the associated standard deviation.

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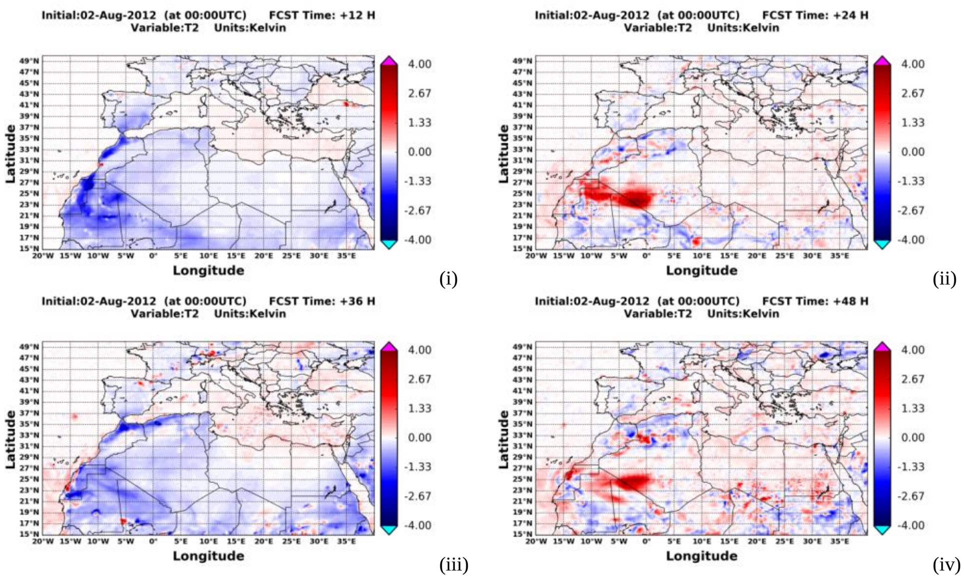


Figure 7: Spatial patterns of temperature differences at 2 meters, between the RADON and RADOFF configuration of the NMMB-MONARCH model, for the: (i) 12, (ii) 24, (iii) 36 and (iv) 48 hours forecast of the 00 UTC cycle on 2nd August 2012.

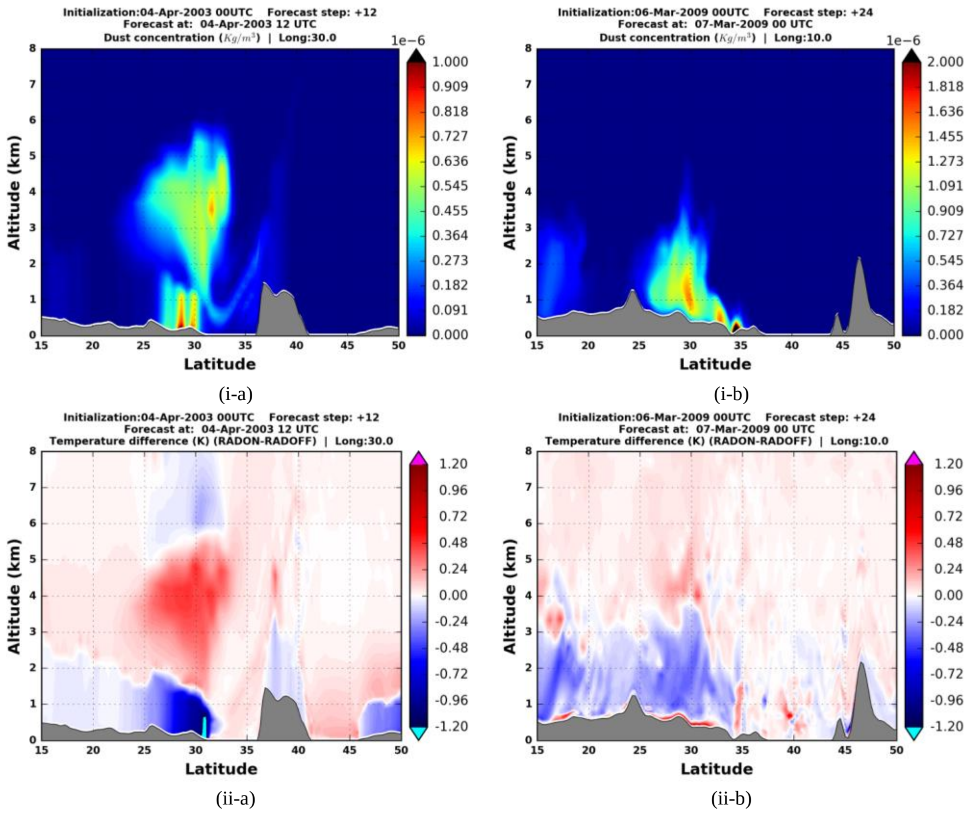
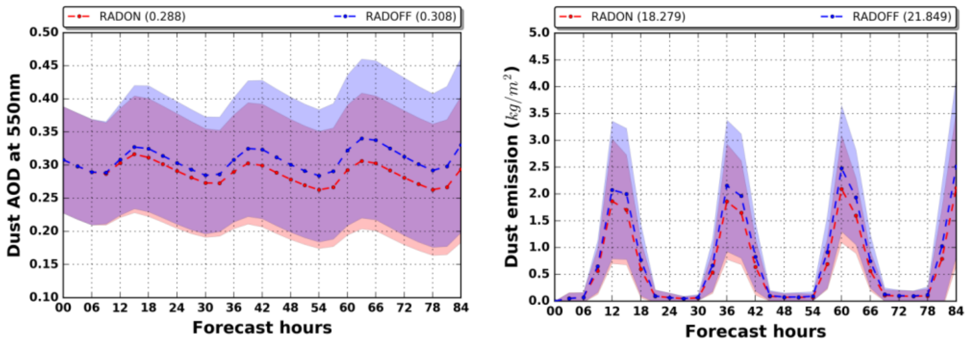


Figure 8: Altitude-latitude cross-sections (up to 8 km m.s.l.) simulated by the NMMB-MONARCH model of the: (i) dust concentration (in kg m^{-3}) and (ii) RADON-RADOFF temperature anomalies (in K) on: (a) 4 April 2003 at 12 UTC along the meridional 30° E and (b) 7 March 2009 00 UTC along the meridional 10° E.



(i) (ii)

Figure 9: (i) Regional dust AOD at 550nm averaged over the simulation domain (NSD) and (ii) Regional dust emission (in kg m^{-2}) aggregated over the simulation domain (NSD). Blue and red curves correspond to the mean values, calculated from the 20 desert dust outbreaks, for the RADOFF and RADON simulations, respectively, and the shaded areas represent the associated standard deviation.

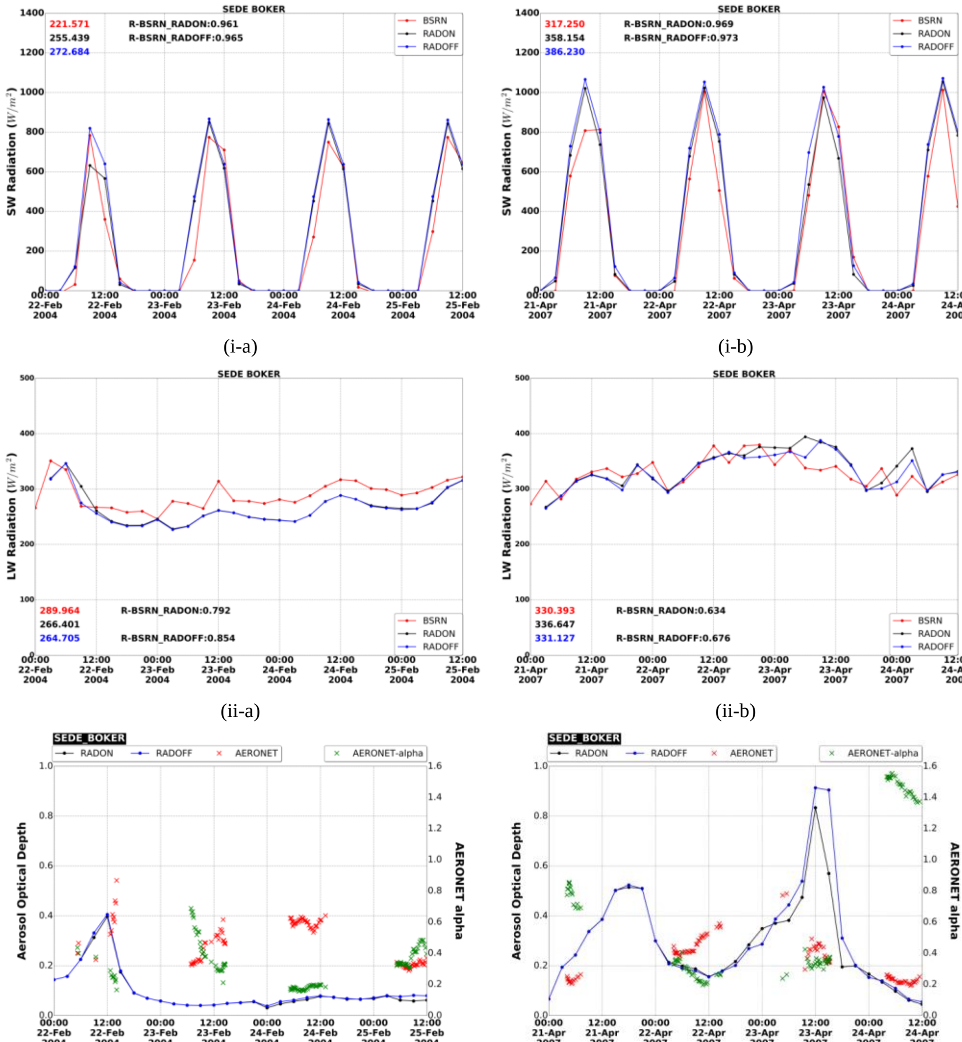


Figure 10: Timeseries of the downwelling: (i) SW and (ii) LW radiation measured at Sede Boker (red line) and simulated based on the RADON (black line) and RADOFF (blue line) configuration of the NMMB-MONARCH model during the periods: (a) 22 Feb. 2004 00UTC – 25 Feb. 2004 12UTC and (b) 21 Apr. 2007 00UTC – 24 Apr. 2007 12UTC. The mean ground and modelled values along with the computed correlation coefficients (R) between RADON-BSRN and RADOFF-BSRN, both calculated over the simulation periods, are also provided. (iii) Timeseries of the simulated dust AOD at 550 nm for the RADON (black line) and RADOFF (blue line) configuration of the NMMB-MONARCH model. Moreover, the AERONET total AOD at 500 nm (red) and AERONET alpha (green) values are provided.

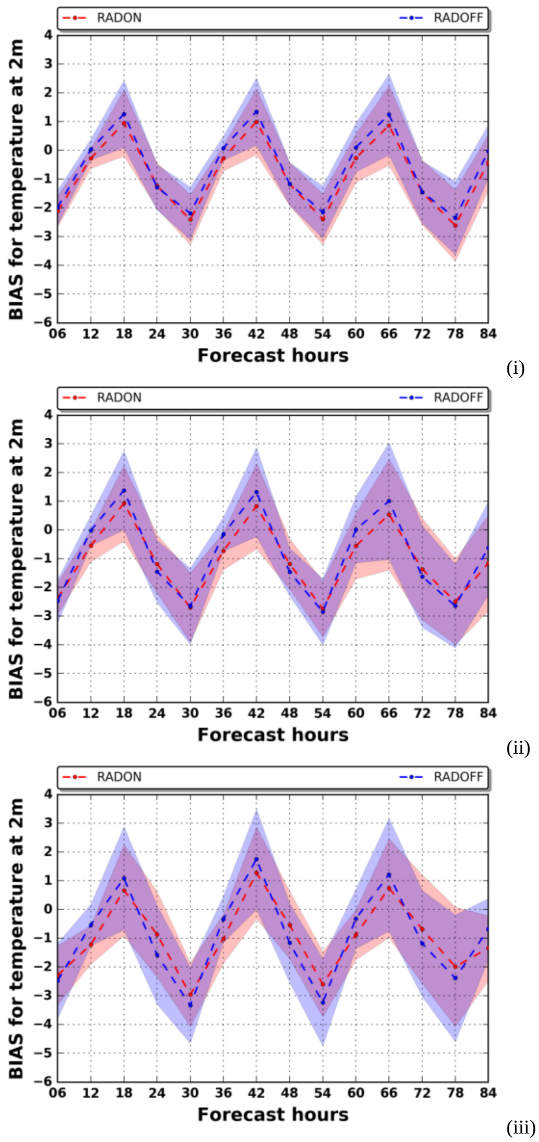


Figure 11: Regional biases of temperature at 2 meters between NMMB-MONARCH and FNL, at 1°x1° degrees spatial resolution, calculated over land grid points of the simulation domain (NSD) in which dust AOD at 550 nm is higher/equal than: (i) 0.1, (ii) 0.5 and (iii) 1.0.

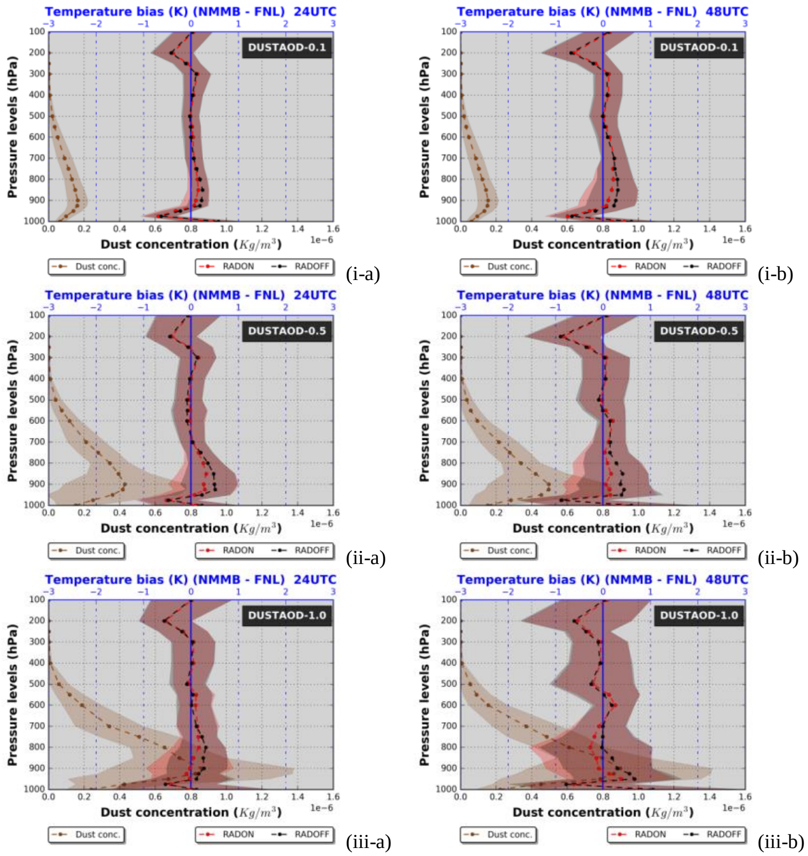


Figure 12: Vertical profiles of the regional temperature RADON-FNL (red curve) and RADOFF-FNL (black curve) biases calculated over grid points (1° x 1° degrees spatial resolution) where the dust AOD at 550 nm is higher/equal than: (i) 0.1, (ii) 0.5 and (iii) 1.0. In addition, the vertical profiles of the simulated dust concentration (in x10^{-6}kg m^{-3}) are provided (brown curve). Each profile corresponds to the mean value calculated from the 20 desert dust outbreaks which are considered while the shaded areas correspond to the associated standard deviations. The obtained results are valid: (a) 24and (b) 48 hours after the initialization of the forecast period.