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."

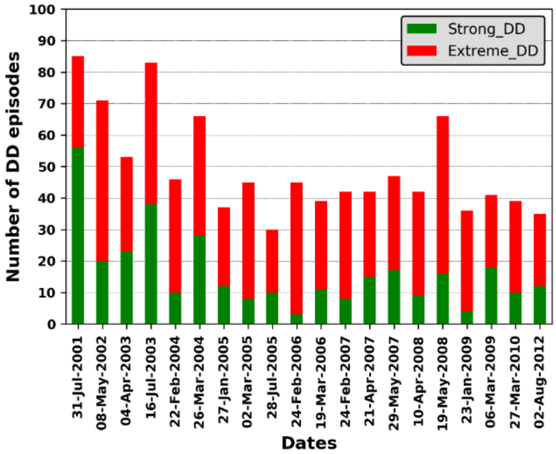
"The radiative effects are strongly related with the aerosol optical depth (AOD). A comparison of AOD values produced by the model versus those obtained from MODIS is presented in the paper. However, the comparison is qualitative and for a selection of cases. Given the large role of AOD in determining 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).

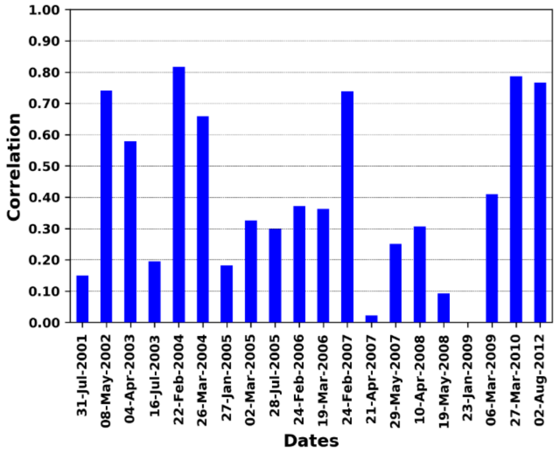
Among the studied cases, it is revealed a strong variation of R values (Figure R1-ii) which reflects the diversity of the model's capability in terms of capturing the spatial patterns of the desert dust outbreaks. These drawbacks rise mainly from displacements of the simulated dust patterns with respect 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.

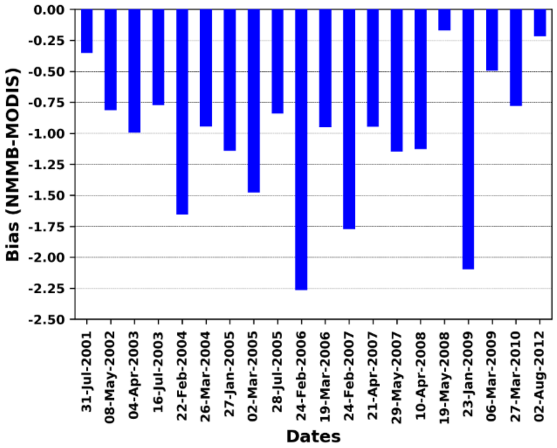
Finally, we would like to bring to the attention of the Reviewer that a detailed evaluation of the same version of the NMMB model for 2006 has been presented in Pérez et al. (2011), who compared the model products against MISR and AERONET retrievals. Based on their findings, for a domain including the 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)

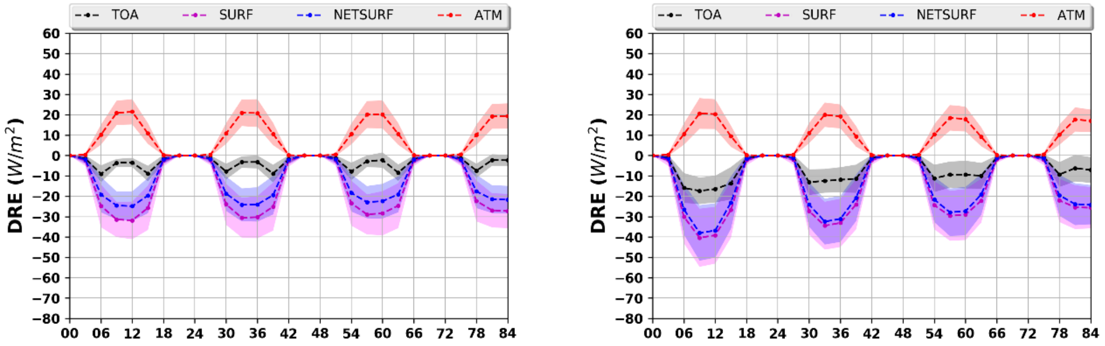


(iii)

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).

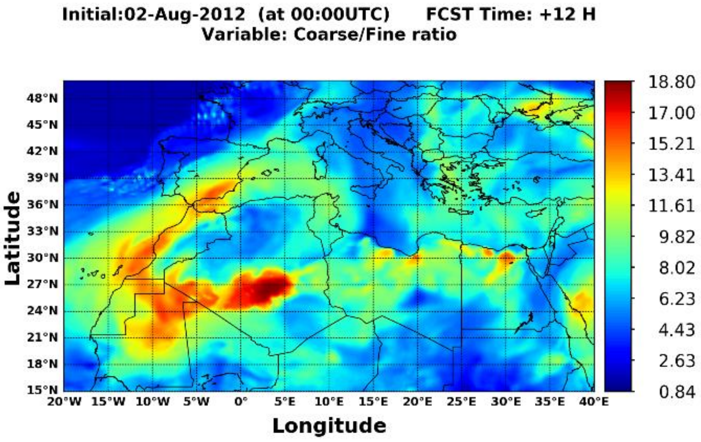


Figure R3: Geographical distribution of coarse-to-fine ratio of dust aerosols at 12 UTC on 2nd August 2012.

“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 25th and 26th March 2010 while in our study case the forecast run starts at 00 UTC on 27th 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.