# Aerosol radiative forcing during African desert dust events (2005-2010) over south-eastern Spain.

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**Answers to Reviewer #3 comments:**

**We would like to thank the referee for the suggestions and corrections. All comments and recommendations have been taken into account. Please find in bold our point-by-point responses below.**

General comments

The paper addresses the shortwave radiative forcing of Saharan mineral dust, one of the most important atmospheric aerosols on the radiative balance of Earth-atmosphere system. The paper is well structured, clear and concise. The main concern is that the results of radiative forcing and efficiency do not justify a discussion according to source regions of Saharan mineral dust. The radiative forcing values obtained for each region are not significantly different, i.e., the mean values of a sector are within the uncertainty limits of any of the other two sectors. For example, the Table 2 and Figure 3 clearly show no significant differences among regions. Therefore, the authors should apply statistics tests (non-parameter tests like Mann-Whitney, Kolmogorov-Smirnov,: : :) that support whether there are significant differences among regions or the discussion in reverse, i.e., the differentiation by origin observed in the radiative properties of North Africa mineral dust does not translate into radiative forcing and efficiency.
I suggest this paper may be suitable for publication after major revisions regarding this issue and the specific ones listed below.

**According to referee's suggestions we have applied a Kolmogorov-Smirnov non-parametric test to the three ARF subsets in order to investigate if there are differences among the ARF for the three sectors. The test revealed that ARF at TOA for sector A (North Morocco; North West Algeria) was significantly different from the others two sectors. In addition, the test showed that ARF at TOA was not significantly different between sectors B (Western Sahara, Northwest Mauritania and Southwest Algeria) and C (Eastern Algeria, Tunisia). However, there were no significant differences in ARF at surface between the different origin sectors. A new table (Table 1 enclosed below) with the results of this test will be included in the revised version of the manuscript.**

Some minor comments:

1) Section 3.1: This study is mainly supported in the division in sources regions of Saharan mineral dust. So, please, the authors should include an explanation more in

details of the methodology used to select days with mineral dust. The authors properly reference the papers that support this classification, but a brief explanation of the methodology used would complement this work. Furthermore, it would be interesting a summary with the radiative properties for each sector and an explanation of meteorological transport in the region**.**

**The African dust events used in this paper have been confirmed by CALIMA network (www.calima.ws). For detecting the African desert dust intrusions over Iberian Peninsula, CALIMA network uses models as SKIRON, BSC-DREAM and NAAPs as well as back-trajectories analysis by HYSPLIT4 model (Draxler et al., 2003), synoptic meteorological charts, satellite images, and surface data (PM10 levels recorded at regional background stations from air quality monitoring). The air masses back trajectories during the analyzed desert dust events have been classified according to the desert dust potential origin sources by Valenzuela et al. (2012). This method assumes that the dust particles are confined in the mixed layer at the potential source region, and that the air mass is loaded by desert dust when the air mass altitude is lower or close to the altitude of the mixed layer at potential source. According to this criterion three source regions were identified; 1) Sector A (North Morocco, Northwest Algeria) where the more frequent meteorological scenario favoring dust transport from this source was the low pressure over Atlantic and high pressure systems over Mediterranean Sea or northeast Africa, 2) Sector B (Western Sahara, Northwest Mauritania and Southwest Algeria) where the desert dust transport was favored by a high pressure over northern African continent, and 3) Sector C (Eastern Algeria, Tunisia) where the synoptic scenario favoring dust transport from this source was the low pressure over Morocco and high pressure over northeast Africa. This information has been included in the new version of the manuscript.**

**Moreover, we have added in the revised manuscript a new table (Table 2 enclosed below) with number of desert dust days, number of observations during desert dust days, and optical and microphysical properties for each sector.**

2) Section 3.2: It is necessary an explanation more in detail of the methodology used to calculate the radiative forcing. For example: a) throughout the text it is not clear how the authors calculated the mean radiative forcing values for each region. As shown in Figure 3, it is necessary to take into account the behavior with the solar zenith angle, so that the forcing must be calculated daily integrating over the solar zenith angle. Furthermore, the daily averages of aerosol radiative forcing are more climatologically significant, especially for evaluating climate aerosol effects and comparing to other studies. Therefore, please consider to calculate daily values instead of instantaneous ones. b) The radiative forcing is calculated using spectral values of AOD, ssa, asymmetry factor, etc., but the authors do not mention how these values are obtained outside the spectral range 440-1020 nm (inversion range). For example, are they extrapolated at a constant value? c) The surface albedo is a crucial parameter for assessing the radiative forcing, especially at TOA. So, please justify the value set at 0.15.

**We thank the reviewer to give us the opportunity to clarify these issues. In the new manuscript, we have computed the daily mean aerosol radiative forcing (24 hour averages), according to the reviewers' suggestions and we have recomputed the mean radiative forcing values for each region from mean daily values. In the revised manuscript, we clarified this point and provided the new ARF values. The aerosol optical and microphysical properties used as input in SBDART code have been extrapolated for wavelengths outside the spectral range 440-1020 nm. Logarithmic interpolation (or extrapolation for λ < 414 nm or λ > 860 nm) was used to supply SBDART with aerosol optical depths covering the entire wavelength range (310–2800 nm). Linear extrapolation is used for single scattering albedo and asymmetry parameter. On the other hand, taking into account the spectral dependence of the surface albedo at the study site, we have re-calculated all simulated values of the aerosol radiative forcing. For that, we used as input in the SBDART code the surface spectral albedo provided by the AERONET algorithm, which is based on a dynamic spectral and spatial model estimation at four wavelengths: 0.05 at 440 nm, 0.16 at 675 nm, 0.31 at 870 nm and 0.32 at 1020 nm. This algorithm was adopted the Lie-Ross model for land surface covers (Lucht and Roujean, 2000), considering the bidirectional reflectance distributions taken from MODIS (Moody et al., 2005). All this new information and results have been added to the revised version of the manuscript.**

3) Section 4: a) A division of this section into subsections would help to readers. For example, 4.1: Comparison between model and measurements, 4.2. Radiative Forcing; 4.3: Radiative Forcing Efficiency or something similar. b) The comparison between simulations and measurements (CM-11 pyranometer) is quite satisfactory, but why was not it performed in the same spectral range? The difference is less than 1%, but it is an additional uncertainty. Is there any difference in comparing between clean and dust situations? c) It would be convenient that the authors discuss the scatter observed in the radiative forcing, especially at TOA (Figure 4). d) It is interesting to discuss what component of solar radiation is more affected by mineral dust. Nonetheless, the discussion of Table 1 in clean and dust conditions is equivalent to the discussion of radiative forcing. Please, consider to calculate radiative forcing by component (direct and diffuse). Exclude table 1 or modify it in terms of radiative forcing. e) The radiative efficiency is calculated by the slope method, but the figure 4 only shows the slopes and not the bias and the respective errors. The bias can give us an estimate of radiative forcing error. f) Justify the limitation of the study at solar zenith angles lower than 65. g) Clarify in which conditions is performed the comparison with AERONET data (for example, the solar zenith angle). h) In general, many values are given without error bounds. For example, ssa, AOD, etc. Furthermore, the authors do not clarify what error type is been (standard error of the mean or standard deviation of the distribution).

**According to the referee's suggestions we have restructured the results section. In this sense, we have divided this section in two subsections. The first one has been named `` *Model Output fluxes comparison against ground-based measurements and AERONET data´´*. In this section we have added more information about the comparison between the instantaneous global irradiances simulated by SBDART and ground-based measurements by CM-11. In addition, the comparison of**

**instantaneous global irradiances simulated by SBDART against AERONET fluxes was included in this section. The second subsection has been named ``*Aerosol radiative forcing and aerosol radiative forcing efficiency during desert dust events´´*. This subsection in turn has been structured in three parts. In the first part we showed and discussed the monthly temporal evolution of aerosol radiative forcing. In the second part we included the aerosol radiative forcing analysis according to the desert dust origin sources. In the last part we compared the aerosol radiative forcing results with those obtained by other authors during desert dust events.**

**The given spectral range of the pyranometer in old version was incorrect. The correct spectral range is 310-2800 nm. The global irradiance simulations were done in 310 - 2800 nm spectral range. Therefore, there were no differences between the spectral range of the pyranometer and that used for simulations. We have corrected these typographical errors in the new version of the manuscript.**

**The poor correlation of the instantaneous aerosol radiative forcing, especially at TOA, could be related to the high dependence of this parameter on solar zenith angle, although we have only considered solar zenith angles lower than 65º. Also, other important factor could be the high dependence of the aerosol radiative forcing with surface albedo, being more important at TOA. In order to avoid these dependencies we have computed the daily mean aerosol radiative forcing, and also we have used the SBDART model with a spectral surface albedo. Nevertheless, according to reviewers' suggestion, we have removed the figure 4 from the new version of the manuscript. Furthermore, we have computed daily aerosol radiative forcing efficiency (ARFE) as the ratio of daily aerosol radiative forcing by the corresponding daily mean AOD (440 nm). Using these daily ARFE we also computed the ARFE for each desert dust sector origin. The new ARFE results were included in Table 5 in the new version of the manuscript.**

**According to the referee's suggestion we have removed the old Table 1.**

**AERONET forcing calculations are done in 0.2-4.0 μm spectral ranges. However, the AERONET procedure used to compute the aerosol radiative forcing at surface is different to our method at surface. In AERONET methodology the aerosol radiative forcing is computed as:**

$$\Delta F_{surface} = F^{\downarrow A}{}_{surface} - F^{\downarrow c}{}_{surface}$$

**where $F^{\downarrow A}{}_{surface}$ indicates the downward global irradiance at surface with aerosol presence and $F^{\downarrow c}{}_{surface}$ indicates the downward global irradiance at surface without aerosol presence.**

**Therefore, we can not directly compare our aerosol radiative forcing results at surface to those given by AERONET. However, we can compare the instantaneous global irradiances simulated with SBDART model and the corresponding instantaneous global irradiances provided by AERONET. So, for comparisons we have run SBDART model in the same spectral range as used in AERONET. The analysis shows that the relative differences between upwelling global irradiances at**

**TOA and down welling global irradiances at surface simulated with SBDART model and the provided by AERONET are of 0.8% and 2.4%, respectively. Thus, we have included in the revised paper the scatter plots of the instantaneous global irradiances using SBDART model against corresponding AERONET fluxes (Figure 1 enclosed below). These results will be added to the revised manuscript.**

Figures and Tables: 1) Table 3: In order to properly compare the studies given in table 3, some additional details should be added. For example, instantaneous (solar zenith angle range) or daily values, wavelength used to calculate the radiative efficiency,: : :

**According to the referee suggestion we have added some information about each study in this table (e.g. the wavelength range where the radiative forcing was calculated and the used surface albedo) and we only included studies that reported daily mean aerosol radiative forcing (24 hours averages) during desert dust episodes in this table (Table 3 enclosed below).**

2) Figure 2: Include the error bars. Furthermore, a subplot with the monthly evolution of AOD and ssa would support the discussion. 3) Figure 3: Include error bars and the y-label. 4) Figure 4: Correct legend

**These suggestions have been included in figures. According to reviewers' suggestion, we have removed the figure 4 from the new version of the manuscript.**

**REFERENCES**

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**Moody, E.G., King, M. D., Platnick, S., Schaaf C.B., Gao F.: Spatially complete global spectral surface albedos: value-added datasets derived from Terra MODIS land products, IEEE Transactions on Geoscience and Remote Sensing, 43, 144-158, 2005.**

**Valenzuela, A., Olmo, F.J., Lyamani, H., Antón, M., Quirantes, A., Alados-Arboledas, L.: Classification of aerosol radiative properties during African desert dust intrusions over southeastern Spain by sector origins and cluster analysis, J. Geophys. Res., 117, D06214, doi:10.1029/2011JD016885, 2012.**

**Table 1:** The p values of the Kolmogorov-Smirnov non-parametric test for each pair of origin sectors, with *ARF* at TOA tests above the diagonal and *ARF* at surface tests below it. Values p< 0.05 indicates statistical significant differences between means at the 95% confidence level.

| | Sector A | Sector B | Sector C |
|---|---|---|---|
| | *ARF* at TOA | | |
| Sector A | --------- | **0.008** | **0.009** |
| Sector B | 0.493 | -------- | 0.601 |
| Sector C | 0.555 | 0.084 | --------- |
| | *ARF* at surface | | |

**Table 2**: The number of desert dust days, number of measurements recorded by sun-photometer and the daily mean $AOD(\lambda)$, $\omega(\lambda)$ and $g(\lambda)$ values.

| | Sector A | Sector B | Sector C |
|---|---|---|---|
| Days | 86 | 56 | 41 |
| Measurements | 426 | 287 | 195 |
| | | | |
| $AOD(440nm)$ | 0.28±0.18 | 0.30±0.13 | 0.28±0.13 |
| $\omega_0(440nm)$ | 0.89±0.03 | 0.89±0.03 | 0.90±0.03 |
| $\omega_0(1020nm)$ | 0.90±0.03 | 0.92±0.03 | 0.92±0.03 |
| $g(440nm)$ | 0.69±0.01 | 0.70±0.01 | 0.68±0.01 |
| $g(1020nm)$ | 0.67±0.01 | 0.67±0.01 | 0.67±0.01 |

**Table 3**: Daily aerosol radiative forcing (W/m$^2$) and daily aerosol radiative forcing efficiency (W/m$^2$ per unit of $AOD(\lambda)$) at surface, TOA and in the atmosphere observed over different locations during desert dust events. The second column ($\lambda$) indicates the spectral range considered and third column shows the surface albedo ($\alpha$) used in each study.

| Reference | $\lambda$(µm) | $\alpha$ | DARF $_{TOA}$ | DARF $_{Surface}$ | DARF $_{Atmosphere}$ | DARFE $_{TOA}$ | DARFE $_{Surface}$ | Location |
|---|---|---|---|---|---|---|---|---|
| Meloni et al. (2005) [1] | 0.4 - 0.7 | 0.02-0.37 | -5.1 to -8.7 | -11.0 to -14.2 | 3.7 to 9 | -15.0 to -16.4 | -28.4 to -30.1 | Lampedusa, Italy |
| Derimian et al.(2006) [2] | 0.175 – 2.270 | 0.23-0.35 | -2.1 | -6.4 | --------------- | -22 | -65 | Negev, Israel |
| Derimian et al.(2008) [3] | 0.2 – 4.0 | spectral depen. | - 8.1 | -29.1 | 21.0 | -15.7 | -56.4 | M'Bour, Senegal |
| Prasad et al.(2007) [4] | 0.3 – 3.0 | 0.25 | - 2.9 to -26 | -29.5 to -87.5 | --------------- | -17±3 | - 46±3 | Kanpur, India |
| Lyamani et al. (2006) [5] | 0.4 – 0.7 | 0.15 | -4.0 | -20.4 | 16.4 | -14.5 | -73.4 | Granada, Spain |
| Di Sarra et al. (2011) [6] | 0.3 – 3.0 | 0.07 | ----------- | -69.9±3.4 | --------------- | -------------- | -59.9±2.6 | Lampedusa, Italy |
| Huang et al. (2009) [7] | 0.175 – 4.0 | spectral depen. | 14.11 | -64.72 | 78.8 | -------------- | -------------- | Taklimakan Desert China |
| Saha et al.(2008) [8] | 0.28 – 2.8 | spectral depen. | -7.7 to -9.8 | -61.8 to -64.4 | 54.1 to 54.6 | -9.7 to -12.4 | - 78.2 to -81.5 | Toulon, France |
| Present study | 0.31 – 2.8 | spectral depen. | -5±5 | -20±12 | 15±9 | -17±7 | -74±12 | Granada, Spain |
| Present study | 0.31 – 2.8 | spectral depen. | -7±5 | -21±9 | 14±7 | -20±9 | -70±14 | Granada, Spain |
| Present study | 0.31 – 2.8 | spectral depen. | -6±5 | -18±9 | 12±8 | -22±10 | -65±16 | Granada, Spain |

Method: [1] Surface albedo varies between 0.02 at 20º and 0.37 at 90º SZA. Unit for DARF is W m$^{-2}$ AOD$^{-1}$ (500 nm). [2] Mixture of desert dust and anthropogenic aerosol. Unit for DARF is W m$^{-2}$ AOD$^{-1}$ (550 nm). [3] Takes into account the non-sphericity of dust particles for simulating radiative effects. Unit for DARF is W m$^{-2}$ AOD$^{-1}$ (440 nm). [4] Unit for DARF is W m$^{-2}$ AOD$^{-1}$ (500 nm). [5]Fixed surface albedo of 0.15. Unit for DARF is W m$^{-2}$ AOD$^{-1}$ (675 nm). [6] The surface albedo has been calculated as the weighted average of land and ocean albedo over a 10 Km diameter area around the measurement site. [7] Takes into account the vertical distributions of the dust aerosol extinction coefficient. [8] Unit for DARF is W m$^{-2}$ AOD$^{-1}$ (440 nm).

**Figure 1**: Scatter plots of the instantaneous global irradiances using SBDART model against corresponding AERONET fluxes for a) downward fluxes at surface and b) upward fluxes at TOA. The black lines are the linear fits, with the equations regression and correlation coefficients and biases.