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Modeling Saharan Desert Dust Radiative Effects on Clouds

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Abstract — This work intends to study the Saharan desert dust storms effects on clouds. This is done through the estimation of the cloud radiative forcing in the presence of mineral desert dust aerosols during a strong desert dust event that occured in the end of May 2006. The assessment of the cloud radiative forcing is made at a regional scale both at the top of the atmosphere (TOA) and at the surface levels.

The results are obtained from numerical simulations with a mesoscale atmospheric model (MesoNH) over Portugal area and nearby Atlantic Ocean.

From the results obtained it is possible to observe that, for all days under study, a cooling effect is always found both at the TOA and surface levels. Also, for these two levels and for clouds developing in a dusty atmosphere, a more pronounced cooling effect (more negative cloud radiative forcing values) is found compared with the corresponding cloud radiative forcing values for clouds developing in a dust free atmosphere.

Keywords — Atmospheric modeling; Cloud and Aerosol radiative effects; Global Warming; Radiative Transfer

1 INTRODUCTION

Sahara desert is considered the most important dust source in the world, being responsible for up to half of the global dust emissions. Desert dust (DD) particles, present in the atmosphere, interact with solar and terrestrial radiation, modulating the Earth radiation balance and are responsible for large uncertainties in assessing climate forcing by atmospheric aerosols "[1], [2]". The magnitude and even the sign of DD radiative forcing (both direct and semi-direct or indirect through the effects on cloud formation and precipitation processes) are still difficult to evaluate"[3], [4] and [5]".

Clouds themselves are among the most important regulators of the Earth's radiation budget therefore among the most essential constituents for the climate change projections. However, the awareness of the contribution of clouds to radiative forcing is still limited [1]. Clouds may warm or cool the atmosphere depending on their microphysical properties and induce changes on these properties due to aerosol interaction.

Portugal represents an interesting location in Europe for the study of desert dust-cloud interactions, since this country is frequently on the pathway of the desert dust plumes advected from North Africa, particularly in spring and summer time [6] and on the pathway of cloud systems coming from the Atlantic Ocean and transported by the westerly and southwesterly winds.

In meteorological studies, clouds and aerosols, and their interactions, must be realistically considered. Regional atmospheric models are of significant utility, simulating several mesoscale circulations and aerosol-cloud interactions [7]. Currently, mesoscale models have associated schemes of transport and diffusion of aerosols "[8], [9] ".

The aim of this work is the study of the Saharan desert dust storm effects on clouds and on the modification of their optical properties. This is done through the assessment of the cloud radiative forcing in the presence of DD aerosols, for a case study corresponding to a three day episode that occurred between the 27 and 29 May 2006. The results are obtained from numerical simulations with a mesoscale atmospheric model over Portugal area and nearby Atlantic Ocean.

The next section briefly describes the method followed to estimate the cloud radiative forcing at the top of the atmosphere (TOA) and at the surface levels. Section 3 presents the results obtained and conclusions are given in section 4.

2 METHOD

The MesoNH model [10] is the atmospheric model implemented in this work. This mesoscale, nonhydrostatic model has been jointly developed by the Centre National de la Recherche Meteorologique (CNRM, Meteo France) and the Laboratoire d'Aeérologie (LA, CNRS). A full description of MesoNH model may be found at http://mesonh.aero.obs-mip.fr/. MesoNH is able to simulate atmospheric circulations from small to synoptic scales (horizontal resolution ranging from a

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few meters to several tens of kilometers) and it can run in a two way nested mode concerning up to 8 nesting stages.

Parameterizations are included for turbulence [11], shallow and deep convection [12] and cloud microphysics [13]. MesoNH is also coupled to an externalized surface model (SURFEX) which computes the fluxes between the atmosphere and the surface [14], taking into account the soil-vegetation-atmosphere exchanges [15].

The model uses the Morcrette and Fouquart “[16], [17]“ ECMWF (European Centre for Medium–Range weather Forecasts) radiative transfer model to compute both the short-wave and long-wave radiative fluxes. The Delta Eddington approximation [18] is used to compute the clouds and aerosols in the short-wave spectral region.

The dust emission processes are represented by the DEAD (Dust Entrainment and Deposition) Model [19], which computes dust fluxes taking into account the surface layer friction velocity, the soil wetness and the percentage of clay and sand in the soil. Dust advection and diffusion are quantified by the MesoNH transport model. The presence of dust aerosols are then taken into account in the radiation and in the cloud microphysical schemes used in the MesoNH model.

The desert dust episode corresponds to a strong desert dust storm that having left the African Continent to the Atlantic Ocean has reached the Iberian Peninsula from the South West direction.

In the simulations performed, the MesoNH were initiated and forced by ECMWF analyses. The simulations started at 0000 UTC on 26 May 2006 and ended at 0000 UTC 30 May 2006. The first day of simulation has been used as a model spin-up period.

For this work, MesoNH is running with the 50km (greatest area) and 10km (smallest nested area) horizontal resolutions, as shown in Fig. 1.

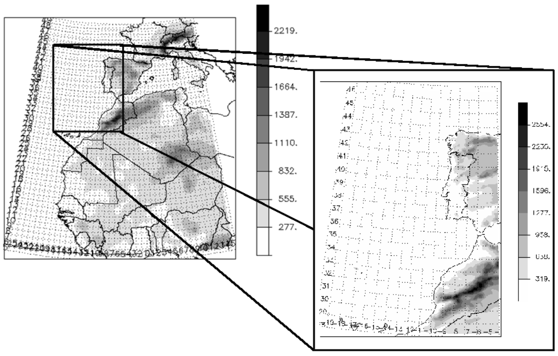


Fig. 1. MesoNH nested areas, used in this work, 50km (greatest area) and 10km (smallest nested area) horizontal resolutions, for the May 2006 period.

The largest domain is defined between 5°S and 50°N latitude and between 25°W and 15°E longitude (which contains the potential dust source) and the smallest domain is defined between 28° S and 47°N latitude and 20°W and 6° longitude. The vertical resolution used in this work, consists of 49 layers from the surface up to 24km altitude.

A set of two numerical simulations for the same case study were performed: one considering the dust emissions, through the activation of the DEAD model, and another one assuming the dust free situation.

The cloud radiative forcing (CRF) is calculated according to the following equation:

$$CRF = \left(N_{SW} + N_{LW}\right)^{Cloud} - \left(N_{SW} + N_{LW}\right)^{Clear} \qquad (1)$$

considering that the net shortwave $\left(N_{SW}\right)$ and longwave $\left(N_{LW}\right)$ fluxes are given by the differences between the downward and upward fluxes[1], respectively as $N_{SW} = F_{SW}^{\downarrow} - F_{SW}^{\uparrow}$ and $N_{LW} = F_{LW}^{\downarrow} - F_{LW}^{\uparrow}$. The N_{SW} and N_{LW} fluxes are obtained directly from the MesoNH model. In general, when negative values of CRF are found it indicates that clouds cause a cooling effect and when positive values of CRF are found, then it means that a warming effect is present.

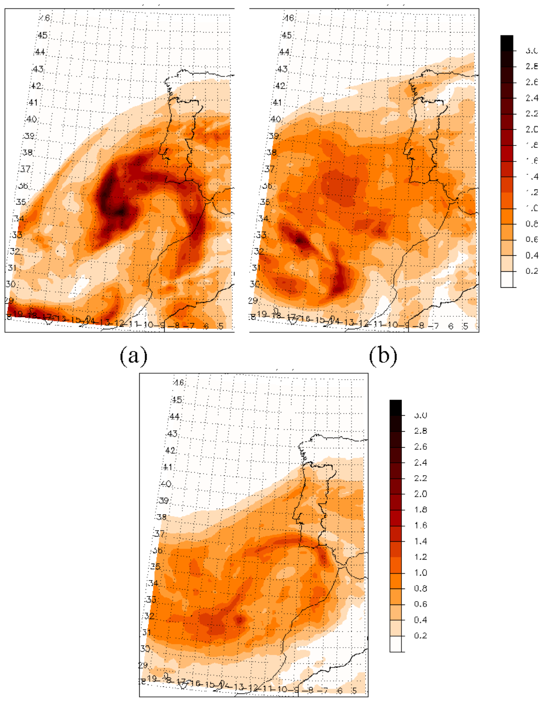
4 RESULTS AND ANALYSIS

The analysis prepared in this work is made for two situations: clouds developing in a dust free atmosphere (MesoNH DEAD dust scheme not activated) and cloud developing in an atmosphere where Saharan dust particles are present (DEAD dust scheme activated). The MesoNH simulated results, presented from now on, correspond to the smallest innermost domain (10km resolution).

Figs 2a, 2b and 2c present the simulated aerosol optical depth (AOD) values, respectively for the 27 (1200UTC), 28 (1400UTC) and 29 (1300UTC) May [20].

Taking into account the results for 27 May, showed in Fig. 2a, one can see that the AOD values are higher than the AOD values retrieved for the 28 and 29 of May (Figs 2b and 2c, respectively). From Figs. 2a, 2b and 2c, it can be observed that the dust plume, with its source in the North of Africa, travels through the Atlantic Ocean towards the south of Continental Portugal, dispersing all over the center of Continental Portugal and towards western Atlantic Ocean.

In order to investigate the effect of Saharan desert dust storms on clouds, an assessment of the cloud radiative forcing (Equation 1) due to the presence of desert dust aerosols, is made. Therefore, the regions free of this type of particles are not considered (Figs 3-8).

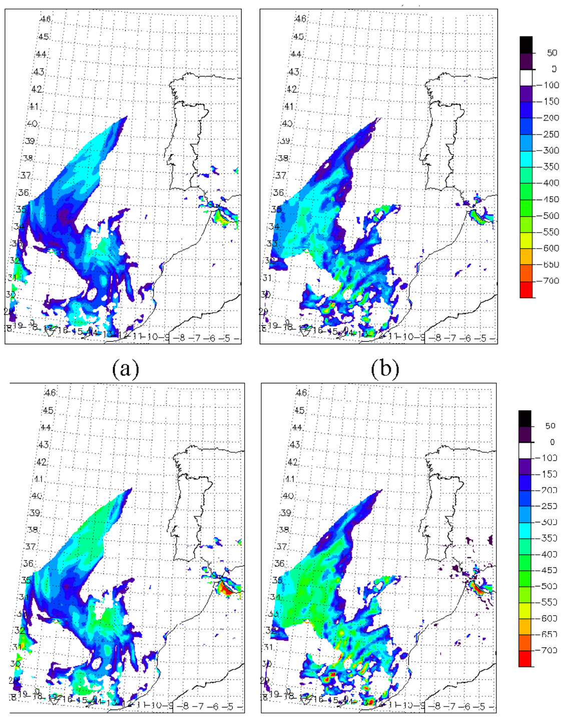


(a) (b)

(c)

Fig. 2. Simulated aerosol optical depth (AOD) for 27 May (a), 28 May (b) and 29 May (c).

The cloud shortwave (SW) radiative forcing is shown in Figs. 3, 4, and 5 and the cloud longwave (LW) radiative forcing is presented in Figs. 6, 7 and 8, obtained for the small nested area modeled for the May 2006 desert dust episode considered in this study.

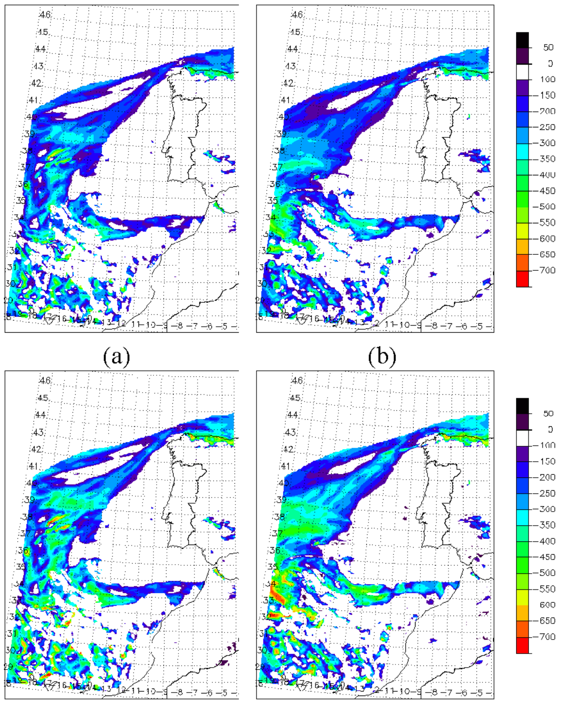


(a) (b)

(c) (d)

Fig. 3. TOA cloud SW radiative forcing and surface SW cloud radiative forcing, in Wm^{-2}, in the absence (a, c) and in the presence (b,d) of desert dust aerosols, for 27 May.

Figs. 3a, 3c, 4a, 4c, 5a, 5c, 6a, 6c, 7a, 7c, 8a and 8c illustrate the simulated cloud radiative forcing when desert dust aerosols are not present in the atmosphere and Figs. 3b, 3d, 4b, 4d, 5b, 5d, 6b, 6d, 7b, 7d, 8b and 8d exhibit the simulated cloud radiative forcing in the presence of desert dust aerosols in the atmosphere.



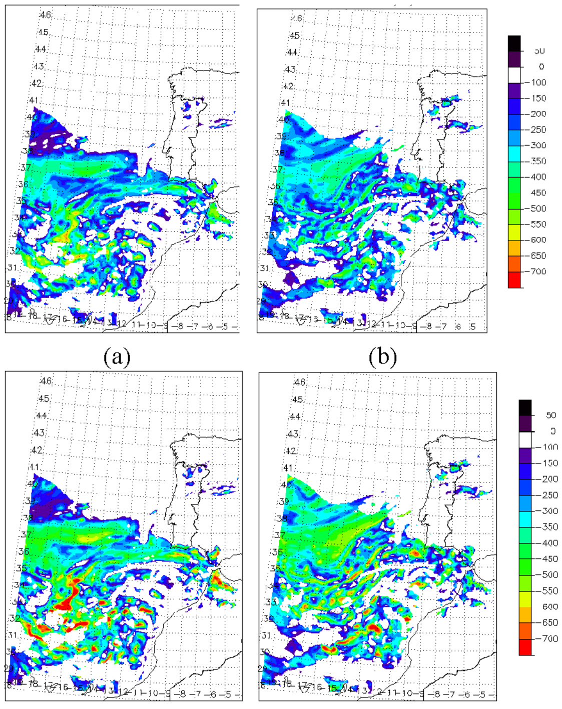
(a) (b)

(c) (d)

Fig. 4. Same as Fig. 3 for 28 May.

Comparing the simulated cloud SW radiative forcing, at the TOA (TOASWCRF) level, in the absence of DD in the atmosphere (Figs. 3a, 4a and 5a) with the simulated TOASWCRF values in an atmosphere where DD aerosols are present (Figs. 3b, 4b and 5b) it is possible to observe that, especially for the 27 and 28 May, the presence of DD provokes a more negative TOASWCRF in the majority of the cloud region. This situation is not evident for the 29 May, where more negative TOASWCRF values are found in the absence of DD aerosols.

A more prominent cloud cooling effect is also found at the surface level, for the 27 and 28 May, if the DD aerosols are present in the atmosphere, since a more negative cloud SW radiative forcing at the surface (SurfSWCRF) level is found (comparing Fig. 3c with Fig. 3d and Fig. 4c with Fig. 4d).

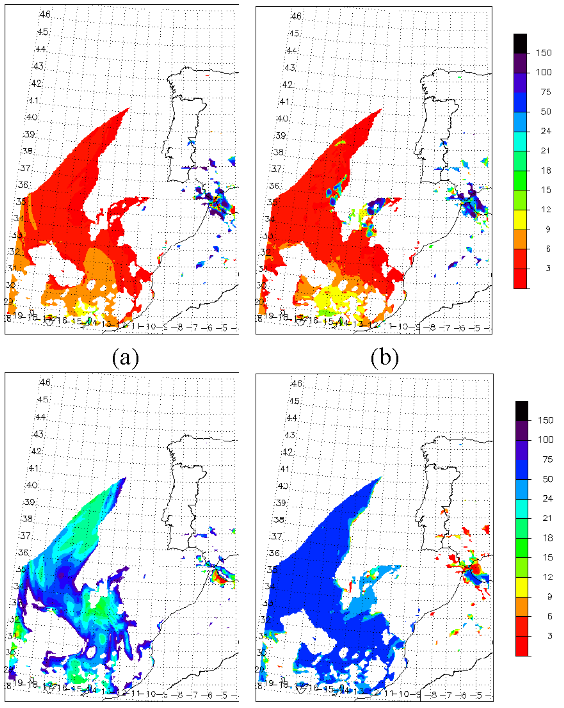


(a) (b)

(c) (d)

Fig. 5. Same as Fig. 3 for 29 May.

The presence of DD in the cloudy atmosphere seems to strength the reflection of SW radiation in the clouds.



(a) (b)

(c) (d)

Fig. 6. TOA cloud LW radiative forcing and surface LW cloud radiative forcing, in Wm^{-2}, in the absence (a, c) and in the presence (b,d) of desert dust aerosols, for 27 May.

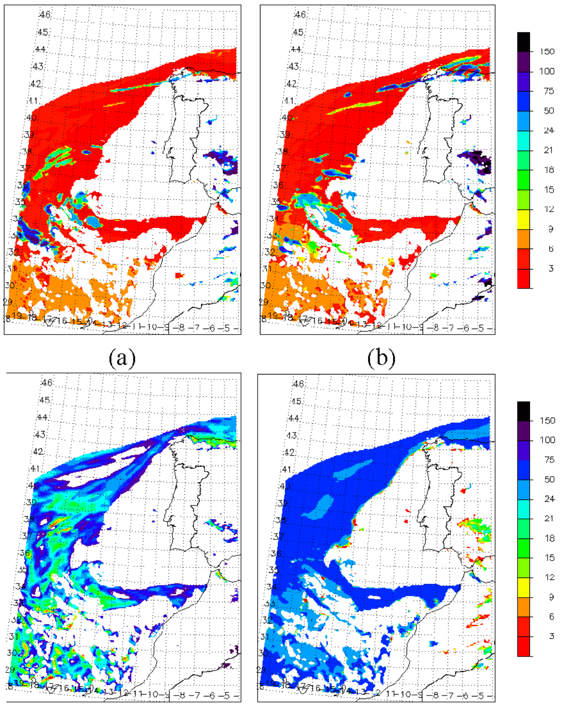
Considering now the TOASWCRF and the SurfSWCRF for 27, 28 and 29 May in the presence of DD aerosols (Figures 3b, 3d, 4b, 4d, 5b and 5d, respectively), it is possible to observe a SW cooling effect both at the TOA and at the surface levels, because negative values of TOASWCRF and SurfSWCRF are always found.

Nevertheless, comparing Fig. 3b with Fig. 3d, Fig. 4b with Fig. 4d, and Fig. 5a with Fig. 5b, it can be observed that the cooling effect is more pronounced at the surface level than at the TOA level, since cloud SW radiative forcing values are more negative at the surface level than at the TOA level.

Comparing now the simulated cloud LW radiative forcing at the top of the atmosphere (TOALWCRF, in the absence of DD in the atmosphere (Figs. 6a, 7a and 8a) with the simulated TOALWCRF values in an atmosphere where DD aerosols are present (Figs. 6b, 7b and 8b) it is possible to observe that, only for the 27 May (Figs. 6a and 6b), the presence of DD seem to induce a more pronounced LW warming effect.

For the other three days the presence of DD aerosols doesn't seem to interfere much in the cloud LW radiation balance at the TOA level.

Regarding now the cloud LW radiative forcing at the surface (SurfLWCRF) level, comparing Figs. 6c with 6d, 7c with 7d and 8c with 8d it can be observed that, especially for the 27 and 28 May, the presence of DD aerosols interacting with the cloud, induces a more pronounced LW warming effect at the surface.



(a) (b)

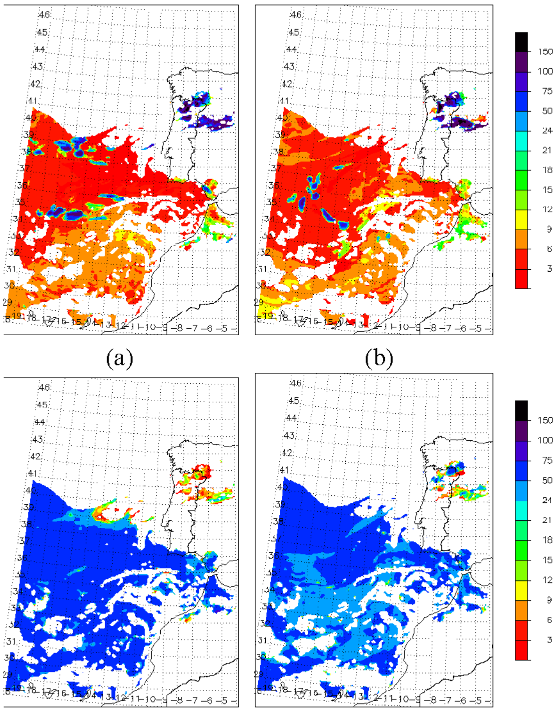
(c) (d)

Fig. 7. Same as Fig. 6 for 28 May.

Considering the TOALWCRF and the SurfLWCRF simulated values, for all the days under study, in the presence of DD (Figures 6b, 6d, 7b, 7d, 8b and 8d), it can be noted that a cloud LW warming effect is always found both at TOA and at surface levels.

Nevertheless, the LW warming effect at the surface level is more pronounced than at the TOA level, since more positive cloud LW radiative forcing values are found.

Also, when comparing the simulated values of SW forcing (Figs 3, 4 and 5) with the LW forcing simulated values (Figs 6, 7 and 8), one can see that the LW radiative forcing has a small impact on the total cloud radiative forcing, compared with the SW radiative forcing, both at TOA and surface levels.



(a) (b)

(c) (d)

Fig. 8. Same as Fig. 6 for 29 May.

Figs 9 and 10 present the total cloud radiative forcing at top of the atmosphere (TOACRF) and at surface (SurfCRF) levels, averaged over the region where a large quantity of DD aerosols are identified (higher AOD values in Fig. 2) .

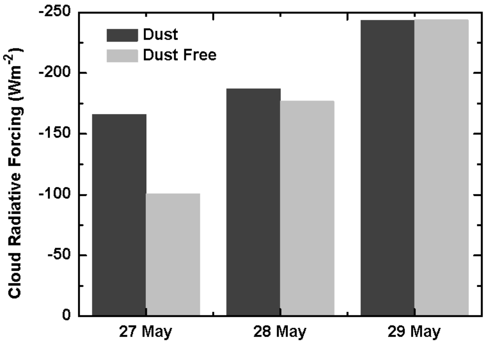


Fig. 9. Top of the atmosphere cloud radiative forcing (TOACRF), in the dust free (DF) atmosphere and in the dusty atmosphere (D), for 27, 28 and 29 May 2006.

All the TOACRF values for the three days and for the two situations (D and DF) under study, are negative, as it would be expected.

For the 27 and 28 May, the dusty atmosphere (D) TOACRF values are lower (more negative) than the dust free atmosphere TOACRF values (Fig. 9), meaning that the cloud with dust reflects more radiation than the cloud developing in a desert dust free atmosphere (DF). The aerosol layer interacting with the cloud, may reflect radiation, causing an increase of the cloud reflected radiation, explaining the more negative TOACRF value compared with the dust free TOACRF value.

Considering the TOACRF for the 29 May it is possible to observe (Fig. 9) that the TOACRF values for the two situations under study (D and DF) don’t differ much, meaning, for this specific case, that the clouds in the dusty and in the dust free atmosphere reflect approximately the same amount of radiation.

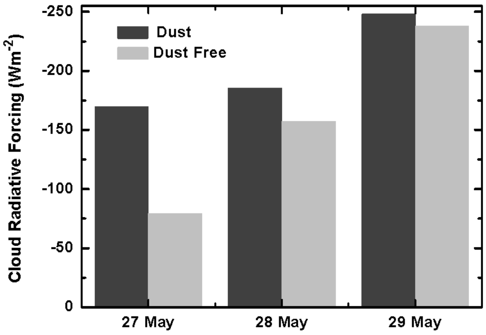


Fig. 10. Surface cloud radiative forcing (SurfCRF), in the dust free (DF) atmosphere and in the dusty atmosphere (D), for 27, 28 and 29 May 2006.

Once again and similarly to the results obtained for the top of the atmosphere, all the SurfCRF simulated values for the three days are negative, in the presence and in the absence of DD aerosols. Moreover, for the entire period the simulated surface cloud radiative forcing SurfCRF values (Fig 10) for the dusty atmosphere are also lower (more negative) than the dust free atmosphere SurfCRF values, meaning that, at the surface level, more radiation is reflected, when dusty clouds (D) are present in the atmosphere, than when clouds are not contaminated by DD aerosols (DF).

5 CONCLUSIONS

This work aimed at investigating the effects of strong Saharan desert dust storms on clouds.

These aerosols effects are analyzed through the assessment of the cloud radiative forcing, both at the top of the atmosphere TOACRF and at the surface SurfCRF levels, at a regional scale.

The method uses the results obtained from a mesoscale atmospheric model (MesoNH), in the region over Portugal area and nearby Atlantic Ocean, for the days 27, 28 and 29 May 2006.

As for the cloud radiative forcing, the simulations indicate that, for all the cases (dusty and dust free clouds) and for all days, the LW radiative forcing has a small impact on the total cloud radiative forcing, compared with the SW radiative forcing, both at TOA and surface levels. Also one can conclude that, in general, for clouds developing in a dusty atmosphere, a more negative cloud radiative forcing is found compared with the corresponding CRF values found for clouds developing in a dust free atmosphere, meaning that, when mineral dust aerosols are present in the atmosphere, a more pronounced cooling effect is observed due to DD aerosols-cloud interaction.

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