



Proceeding Paper Vertically Resolved Direct Radiative Effects of Intense Mediterranean Dust Episodes during the Period 2005–2018⁺

Maria Gavrouzou ^{1,*}, Nikos Hatzianastassiou ¹, Marios Bruno Korras-Carraca ^{1,2}, Michalis Stamatis ¹, Christos J. Lolis ¹, Christos Matsoukas ³, Nikos Mihalopoulos ^{4,5} and Ilias Vardavas ⁶

- ¹ Laboratory of Meteorology and Climatology, Department of Physics, University of Ioannina, 45110 Ioannina, Greece; nhatzian@uoi.gr (N.H.); koras@env.aegean.gr (M.B.K.-C.); m.stamatis@uoi.gr (M.S.); chlolis@uoi.gr (C.J.L.)
- ² Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, 11810 Athens, Greece
- ³ Department of Environment, University of the Aegean, 81100 Mytilene, Greece; matsoukas@aegean.gr
- ⁴ Institute for Environmental Research and Sustainable Development (IERSD), National Observatory of Athens, 15236 Athens, Greece; nmihalo@noa.gr
- ⁵ Environmental and Chemical Processes Laboratory, Department of Chemistry, University of Crete, 71500 Crete, Greece
- ⁶ Department of Physics, University of Crete, 70013 Crete, Greece; vardavas@uoc.gr
- * Correspondence: m.gavrouzou@uoi.gr
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Abstract: In the present study, the all-sky Dust Direct Radiative Effect (DDRE) is estimated during intense Dust Aerosol (DA) episodes that took place from 2005 to 2018 over the broader Mediterranean Basin (MB). DA episodes are identified using a satellite algorithm, which is based on aerosol optical properties. The DDREs are estimated using a vertically resolved version of the FORTH spectral radiative transfer model (RTM). The RTM ran on a 3-hourly temporal and $0.5^{\circ} \times 0.625^{\circ}$ horizontal spatial resolution for each of the 162 identified DA episode days (DAEDs), initialized with 3D dust and total (all) aerosol optical properties, namely optical depth, single scattering albedo, and asymmetry parameter from the MERRA-2 reanalysis. Cloud data (cloud amount, optical depth, and top pressure) are taken from the ISCCP-H. The RTM computes the upwelling and downwelling solar fluxes at TOA, at the surface, and at 50 levels in the atmosphere. The runs were made with all aerosols, and all but DA. The DDREs were calculated by the difference between the two sets of output fluxes. According to the model results averaged over the 162 studied episodes, DA reduces the net surface solar radiation over the MB, causing a cooling effect as large as -77 W/m^2 (climatological mean value at 12:00 UTC) over areas with high dust optical depth. On the contrary, they increase the atmospheric absorbed solar radiation, resulting in considerable (up to 79 W/m^2) atmospheric radiative heating. At TOA, either heating (up to 30 W/m² over desert areas) or cooling (as strong as -21 W/m^2 over oceanic areas) are found, depending on the significantly different underlying surface albedos. DDREs are even higher during single episodes, with a surface cooling effect as large as -200 W/m^2 and a corresponding atmospheric heating effect of up to $+187 \text{ W/m}^2$.

Keywords: aerosols; dust episodes; direct radiative effect; Mediterranean



Mediterranean Dust Aerosol Episodes (DAEs) have been extensively investigated during the last decades. According to the bibliography, they mainly originate from the deserts of N. Africa, but also from those of the Middle East, and they take place yearround with maximum frequency in spring (over the central and eastern basin) and summer (over the western basin) [1]. Some efforts have been made to estimate the DRE of such



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). episodes, first on a local [2–4] and later on a regional [5] basis. Specifically, ref. [5] calculated aerosol DREs for the first time over the entire MB and on a monthly and 2.5° latitude-longitude resolution using satellite and reanalysis data as input to the FORTH (Foundation for Research and Technology-Hellas) radiative transfer model (RTM). However, that study dealt with total aerosol DREs under background aerosol conditions. Except for [6], who estimated the DA DRE during 20 Mediterranean cases of DAEs (DAECs), all other works were conducted for specific case studies [7,8].

In the present study, all-sky Dust DREs (DDREs) under episodic conditions (namely DAECs) are calculated for the first time over the entire MB and for a considerable number of DA episodes (162 DAEDs), which cover the 15-year period of 2005–2018, thus yielding an unprecedented climatology of DDREs. For this purpose, a new version of the FORTH RTM, which incorporates analytical vertical aerosol profiles from the MERRA-2 reanalysis product, is utilized. In addition, thanks to the use of contemporary reanalysis and satellite data (i.e., MERRA-2 and ISSCP-H), the model provides results on high horizontal ($0.500^{\circ} \times 0.625^{\circ}$), vertical (50 levels) and temporal (3 h) resolution.

2. Data and Methodology

2.1. Dust Episodes Identification

The Dust Aerosol Episode Cases (DAECs) that are studied here have been identified using a satellite algorithm, which ran from 2005 to 2018 over the Mediterranean Basin (MB) and is fully described in [9]. The algorithm relies on aerosol optical properties, namely spectral AOD, Aerosol Index (AI), and Angstrom Exponent (AE). The first two parameters are retrieved by Moderate Resolution Imaging Spectroradiometer (MODIS) and Ozone Monitoring Instrument (OMI) measurements, respectively, while the third is calculated based on MODIS spectral AOD. All input data are daily level-3 data obtained from the latest available collections of each database (MODIS C6.1 and OMI OMAERUV) and are available on a $1^{\circ} \times 1^{\circ}$ spatial resolution at https://disc.gsfc.nasa.gov/ (accessed on 23 August 2023). The algorithm ran for all days during the period 2005–2019 and detected 166 Dust Aerosol Episode Days (DAEDs). From these DAEDs, only 162, which took place from 2005 to 2018, are studied here due to the absence of available cloud data from ISCCP-H for 2019.

2.2. MERRA-2 Data

The FORTH RTM requires three key aerosol optical properties as input, namely aerosol optical depth, single scattering albedo, and asymmetry parameter. These, along with other properties of surface and atmosphere, were taken from MERRA-2 (Modern-Era Retrospective analysis for Research and Applications, Version 2) reanalysis, which is produced using the fifth version of the Goddard Earth Observing System (GEOS-5) Model, along with its Atmospheric Data Assimilation System (ADAS), version 5.12.4 [10]. The MERRA-2 data are gridded at $0.625^{\circ} \times 0.500^{\circ}$ latitude-longitude spatial resolution, given at 72 atmospheric layers, and cover the years from 1980 to date. They are available at different time scales (namely 1 h, 3 h, and 6 h) via NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC) website (https://disc.gsfc.nasa.gov/, accessed on 23 August 2023).

2.3. ISCCP-H Data

The RTM-required input cloud properties (i.e., cloud amount, optical depth and top pressure) were taken from the International Satellite Cloud Climatology Project (ISCCP) H-series climate data record, which is produced using both geostationary and polar-orbiting satellite imaging radiometers, having one visible (VIS $\approx 0.65 \pm 0.05$ –0.20 μ m) and one infrared (IR $\approx 10.5 \pm 0.5$ –0.75 μ m) channels. In the present study, the level-3 data gridded at $1^{\circ} \times 1^{\circ}$ spatial and 3 h temporal resolution are used (https://doi.org/10.7289/V5QZ281S, accessed on 23 August 2023).

2.4. The FORTH RTM

The dust DREs, during the detected DAECs, are estimated using the FORTH spectral RTM [11]. This has evolved from a radiative-convective model developed by [12] and has been applied to calculate radiation fluxes and DREs at different spatial scales [2,5,13–17]. The utilized version of the FORTH RTM here ran on a 3 h temporal and $0.500^{\circ} \times 0.625^{\circ}$ spatial resolution using 3D aerosol optical properties from MERRA-2 and cloud properties from ISCCP-H (see 2.2 and 2.3). The DDREs are calculated by subtracting the model output fluxes computed considering all aerosol types except for aerosols, from the corresponding fluxes, as well as the DDREs, are computed at TOA, at the surface, and at 50 levels in the atmosphere.

3. Results and Discussion

The geographical distributions of the climatological mean (averaged over the 162 DAEDs that took place from 2005 to 2018 over the MB) MERRA-2 DOD and ISCCP-H Cloud Amount (CA) at 12:00 UTC, are presented in Figure 1. DOD is high (up to 0.58) over Algeria and Tunisia, as well as over the Libyan coasts (Figure 1a). Secondarily high values (up to 0.36) are noted over the southern parts of the central and eastern Mediterranean Sea and especially over the Libyan Sea and off the Gulfs of Gabes and Sidra. Minimum values (<0.03) exist over the Iberian Peninsula and the northeastern Atlantic Ocean. Over the rest of the study area, DOD values vary between 0.17 and 0.23. The CA is maximum (CA = 1) over the Aegean Sea, Crete, and N. Algeria. High CA values (>0.7) are also observed over the most of land areas, namely the Iberian Peninsula, Central Italy, the Balkans, and Turkey. In contrast, minimum cloudiness occurs over the southeastern MB (Arabian Peninsula, Levantine Sea, Cyprus, and Egypt).



Figure 1. Geographical distribution of climatological mean (**a**) MERRA-2 DOD and (**b**) ISCCP cloud amount, during 162 dust aerosol episode days (DAEDs) that took place over the Mediterranean basin from 2005 to 2018, at 12:00 UTC.

The climatological mean geographical distributions of the DDREs within the atmosphere, at the Earth's surface, and at the top of the atmosphere (TOA), during the 162 DAEDs that took place over the Mediterranean basin from 2005 to 2018 at 12:00 UTC, are given in Figure 2a–c, respectively. In the atmosphere, DA increases the absorption of SW solar radiation over the entire MB (Figure 2a). This enhancement varies from very small values over the northern parts of MB, where very weak DA loads exist, up to $+79 \text{ W/m}^2$ over Algeria and across Tunisian and Libyan coasts, where DOD is also maximum, and CA is relatively low (Figure 1). These values are much larger than those found in [5], where an annual climatological aerosol SW atmospheric heating effect up to $+11 \text{ W/m}^2$ was estimated. On the contrary, the climatological mean values reported here are almost half of those reported in case studies of dust episodes. For instance, ref. [8] who used the WRF-Chem model to estimate the DDREs during a DAEC that took place on 1 and 2 February 2015, found an increase in atmospheric absorption up to 147 W/m². However, it should be noted that apart from averaging over numerous episodes, which reduced the magnitude of the estimated climatological DDREs compared to those caused during a single episode, the values reported in [8] refer to clear-sky conditions. At the Earth's surface, negative DDREs (reduction in the net surface solar radiation) occur over the entire MB (Figure 2b). Maximum reduction (down to -77 W/m^2) is noted over the Tunisian and Libyan coasts, where both DOD and CA are high (Figure 1). The corresponding values of total aerosol DREs under background conditions are less than -14 W/m^2 [5]. Last, at TOA, both cooling and heating SW effects of DA are observed. Specifically, an increase in the net TOA incoming solar radiation (up to 30 W/m^2) takes place over desert areas and the Alps (red colors in Figure 2c), while a decrease (down to -21 W/m^2) is observed over the Mediterranean Sea and most of the land areas (blue colors in Figure 2c). This change in the sign of the TOA DDREs is attributed to differences in surface albedo.



Figure 2. Geographical distribution of 14-year (2005–2018) mean dust Direct Radiative Effects: (a) within the atmosphere (absorbed solar radiation), (b) at the Earth's surface (net incoming solar radiation), and (c) at the top of atmosphere (net incoming solar radiation), during 162 dust aerosol episode days (DAEDs) that took place over the Mediterranean basin, at 12:00 UTC.

4. Summary and Conclusions

In the present study, the climatological mean all-sky DDREs at 12:00 UTC caused by 162 DAEDs that took place from 2005 to 2018 over the MB are estimated using a vertically resolved version of FORTH RTM. According to the results, DAEDs:

- Results in a heating of the regional atmosphere (an increase in atmospheric solar absorption), which at 12:00 UTC varies from near zero values where DOD is very low up to +79 W/m² over Algeria, where DOD is maximum (up to 0.58), and CA is relatively low (<0.5).
- Reduce the net surface downward solar radiation over the entire study area. This
 reduction is maximum (-77 W/m²) over the Tunisian and Libyan coasts, where DOD
 is high, and CA is relatively low.
- Cause, at TOA, either heating (up to 30 W/m² over desert areas) or cooling (as strong as -21 W/m² over oceanic areas), the change in sign being attributed to differences in surface albedos.

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References

- Gkikas, A.; Hatzianastassiou, N.; Mihalopoulos, N.; Katsoulis, V.; Kazadzis, S.; Pey, J.; Querol, X.; Torres, O. The Regime of Intense Desert Dust Episodes in the Mediterranean Based on Contemporary Satellite Observations and Ground Measurements. *Atmos. Chem. Phys.* 2013, 13, 12135–12154. [CrossRef]
- Benas, N.; Hatzianastassiou, N.; Matsoukas, C.; Fotiadi, A.; Mihalopoulos, N.; Vardavas, I. Aerosol Shortwave Direct Radiative Effect and Forcing Based on MODIS Level 2 Data in the Eastern Mediterranean (Crete). *Atmos. Chem. Phys.* 2011, 11, 12647–12662. [CrossRef]
- Granados-Muñoz, M.J.; Sicard, M.; Román, R.; Benavent-Oltra, J.A.; Barragán, R.; Brogniez, G.; Denjean, C.; Mallet, M.; Formenti, P.; Torres, B. Impact of Mineral Dust on Shortwave and Longwave Radiation: Evaluation of Different Vertically Resolved Parameterizations in 1-D Radiative Transfer Computations. *Atmos. Chem. Phys.* 2019, 19, 523–542. [CrossRef]
- Nabat, P.; Somot, S.; Mallet, M.; Michou, M.; Sevault, F.; Driouech, F.; Meloni, D.; Di Sarra, A.; Di Biagio, C.; Formenti, P. Dust Aerosol Radiative Effects during Summer 2012 Simulated with a Coupled Regional Aerosol–Atmosphere–Ocean Model over the Mediterranean. *Atmos. Chem. Phys.* 2015, 15, 3303–3326. [CrossRef]
- 5. Papadimas, C.; Hatzianastassiou, N.; Matsoukas, C.; Kanakidou, M.; Mihalopoulos, N.; Vardavas, I. The Direct Effect of Aerosols on Solar Radiation over the Broader Mediterranean Basin. *Atmos. Chem. Phys.* **2012**, *12*, 7165–7185. [CrossRef]
- Gkikas, A.; Obiso, V.; Perez Garcia-Pando, C.; Jorba, O.; Hatzianastassiou, N.; Vendrell, L.; Basart, S.; Solomos, S.; Gassó, S.; Baldasano, J.M. Direct Radiative Effects during Intense Mediterranean Desert Dust Outbreaks. *Atmos. Chem. Phys.* 2018, 18, 8757–8787. [CrossRef]
- Kosmopoulos, P.G.; Kazadzis, S.; Taylor, M.; Athanasopoulou, E.; Speyer, O.; Raptis, P.I.; Marinou, E.; Proestakis, E.; Solomos, S.; Gerasopoulos, E. Dust Impact on Surface Solar Irradiance Assessed with Model Simulations, Satellite Observations and Ground-Based Measurements. *Atmos. Meas. Tech.* 2017, 10, 2435–2453. [CrossRef]

- Gkikas, A.; Giannaros, T.; Kotroni, V.; Lagouvardos, K. Assessing the Radiative Impacts of an Extreme Desert Dust Outbreak and the Potential Improvements on Short-Term Weather Forecasts: The Case of February 2015. *Atmos. Res.* 2019, 226, 152–170. [CrossRef]
- 9. Gavrouzou, M.; Hatzianastassiou, N.; Gkikas, A.; Lolis, C.J.; Mihalopoulos, N. A Climatological Assessment of Intense Desert Dust Episodes over the Broader Mediterranean Basin Based on Satellite Data. *Remote Sens.* **2021**, *13*, 2895. [CrossRef]
- Gelaro, R.; McCarty, W.; Suárez, M.J.; Todling, R.; Molod, A.; Takacs, L.; Randles, C.A.; Darmenov, A.; Bosilovich, M.G.; Reichle, R. The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). J. Clim. 2017, 30, 5419–5454. [CrossRef] [PubMed]
- Hatzianastassiou, N.; Matsoukas, C.; Drakakis, E.; Stackhouse, P., Jr.; Koepke, P.; Fotiadi, A.; Pavlakis, K.; Vardavas, I. The Direct Effect of Aerosols on Solar Radiation Based on Satellite Observations, Reanalysis Datasets, and Spectral Aerosol Optical Properties from Global Aerosol Data Set (GADS). *Atmos. Chem. Phys.* 2007, 7, 2585–2599. [CrossRef]
- 12. Vardavas, I.; Carver, J.H. Solar and Terrestrial Parameterizations for Radiative-Convective Models. *Planet. Space Sci.* **1984**, 32, 1307–1325. [CrossRef]
- Hatzianastassiou, N.; Fotiadi, A.; Matsoukas, C.; Pavlakis, K.; Drakakis, E.; Hatzidimitriou, D.; Vardavas, I. Long-Term Global Distribution of Earth's Shortwave Radiation Budget at the Top of Atmosphere. *Atmos. Chem. Phys.* 2004, *4*, 1217–1235. [CrossRef]
- Korras-Carraca, M.; Pappas, V.; Hatzianastassiou, N.; Vardavas, I.; Matsoukas, C. Global Vertically Resolved Aerosol Direct Radiation Effect from Three Years of CALIOP Data Using the FORTH Radiation Transfer Model. *Atmos. Res.* 2019, 224, 138–156. [CrossRef]
- 15. Korras-Carraca, M.-B.; Gkikas, A.; Matsoukas, C.; Hatzianastassiou, N. Global Clear-Sky Aerosol Speciated Direct Radiative Effects over 40 Years (1980–2019). *Atmosphere* **2021**, *12*, 1254. [CrossRef]
- Matsoukas, C.; Hatzianastassiou, N.; Fotiadi, A.; Pavlakis, K.; Vardavas, I. The Effect of Arctic Sea-Ice Extent on the Absorbed (Net) Solar Flux at the Surface, Based on ISCCP-D2 Cloud Data for 1983–2007. *Atmos. Chem. Phys.* 2010, 10, 777–787. [CrossRef]
- 17. Pyrina, M.; Hatzianastassiou, N.; Matsoukas, C.; Fotiadi, A.; Papadimas, C.; Pavlakis, K.; Vardavas, I. Cloud Effects on the Solar and Thermal Radiation Budgets of the Mediterranean Basin. *Atmos. Res.* **2015**, *152*, 14–28. [CrossRef]

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