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Heating rate profiles and radiative forcing due to a dust storm in the Western Mediterranean using satellite observations

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HIGHLIGHTS

- We analyze the radiative impact of a dust storm though satellite observations and detailed radiative transfer modeling.
- We evaluate the sensitivity of dust radiative effects to changes in dust optical properties.
- Experimentally derived dust properties reduce its radiative effects with respect to prescribed dust models.

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ABSTRACT

We analyze the vertically-resolved radiative impact due to a dust storm in the Western Mediterranean. The dust plume travels around 3–5 km altitude and the aerosol optical depth derived by MODIS at 550 nm ranges from 0.33 to 0.52 at the overpass time (13:05 UT). The aerosol radiative forcing (ARF), forcing efficiency (FE) and heating rate profile (AHR) are determined throughout the dust trajectory in shortwave (SW) and longwave (LW) ranges. To do this, we integrate different satellite observations (CALIPSO and MODIS) and detailed radiative transfer modeling. The combined (SW + LW) effect of the dust event induces a net cooling in the studied region. On average, the FE at 22.4° solar zenith angle is -190.3 W m^{-2} and -38.1 W m^{-2}, at surface and TOA, respectively. The corresponding LW/SW offset is 14% and 38% at surface and TOA, respectively. Our results at TOA are sensitive to the surface albedo in the SW and surface temperature in the LW. The absolute value of FE decrease (increase) in the SW (LW) with the surface albedo, resulting in an increasing LW/SW offset, up to 76%. The AHR profiles show a net warming within the dust layer, with a maximum value of 3.3 Kd^{-1}. The ARF, FE and AHR are also highly sensitive to the dust optical properties in SW and LW. We evaluate this sensitivity by comparing the results obtained using two set of dust properties as input in our simulations: a) the prescribed dust model by Optical Properties of Aerosols and Clouds (OPAC) and; b) the dust optical properties derived from measurements of the size distribution and refractive index. Experimentally derived dust properties present larger SSA and asymmetry parameter in the SW than OPAC dust. Conversely, OPAC dust presents higher AOD in the LW range. These parameters drive the FE and AHR sensitivities in the SW and LW ranges, respectively. Therefore, when measured dust properties are used in our simulations: the ARF in the LW substantially reduces at surface and TOA (up to 57%); the absolute value of SW ARF is reduced by 15% at surface and an enhancement of 31% is observed at TOA; the AHR present less warming in the entire profile with deviations up to 53% within the dust layer, with respect to the results obtained using OPAC.

1. Introduction

Aerosols affects the Earth's radiative balance through the scattering and absorption of shortwave (SW) and longwave (LW) radiation, which is known as the direct radiative effect (e.g. Ramanathan et al., 2001; Boucher et al., 2013). Consequently, they may contribute to the temperature variations of the Earth-Atmosphere system and hence influence the climate at local, regional or global scale (Naeger et al., 2013). Moreover, aerosols may also influence the cloud formation modifying their radiative properties, altering both cloud albedo (first indirect or cloud albedo

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effect) and cloud lifetime (second indirect effect) (Forster et al., 2007). Aerosols may play a role in the hydrological cycle by changing the rainfall pattern (Lemaitre et al., 2010; Boucher et al., 2013). This is because they act reducing the cloud droplet size. As a result, the precipitation efficiency decreases and the cloud lifetime and cloud thickness increase (Albrecht, 1989; Pincus and Baker, 1994). Furthermore, complex vertical aerosol stratification with different layers showing different optical properties may impact locally the thermal profile of the atmosphere. This may also affect indirectly to the vertical stability, the dynamics of the boundary layer and the structure and cloud formation (e.g. Feingold et al., 2005; Barbaro et al., 2013; Ferrero et al., 2014; Gómez-Amo et al., 2014).

Aerosol effects are different for SW and LW spectral regions and are closely linked to the relationship between particle size and the wavelength of the incident radiation. In the SW, aerosols may either increase or decrease the local planetary albedo depending on the absorption-to-backscattering ratio, surface albedo, total aerosol optical depth and solar elevation, ordered approximately according to their importance (Grassl and Newiger, 1982). For a given aerosol load, the same aerosol layer may increase the planetary albedo when acting over a dark oceanic surface and decrease it over a bright sand desert. In addition, large size particles (as mineral dust) may considerably impact the LW radiation by reducing the LW radiation reaching the top of the atmosphere (TOA), since they are colder than the underlying surface (e.g. di Sarra et al., 2011; Naeger et al., 2013).

The greatest uncertainties in defining the aerosol radiative effect in the solar spectrum are associated with the difficulty to correctly determine the aerosol absorption properties (McComiskey et al., 2008) and its vertical distribution (Zarzycki and Bond, 2010). In fact, the lack of detailed knowledge of the aerosol optical properties point aerosols as one of the largest uncertainties sources in climate forcing assessments (IPCC, 2013). This is especially relevant in the LW, since there is a poor knowledge of the aerosol optical properties in the LW (e.g. Bharmal et al., 2009; Di Biagio et al., 2014).

The role of aerosols as modulators of solar irradiance has been widely studied (e.g. Di Biagio et al., 2009, 2010; García et al., 2012; Papadimas et al., 2012). Conversely, the works including the radiative effects in the LW, and the combined effect (SW + LW) on the heating rate profile are based on data collected during a few intensive measurement campaigns (e.g. Highwood et al., 2003; Perrone et al., 2012; Naeger et al., 2013; Gómez-Amo et al., 2014; Meloni et al., 2015). Consequently, the obtained results are valid mostly locally and makes the global mean of the net radiative impact difficult to estimate (e.g. Myhre et al., 2003, 2009; Feichter and Stier, 2012).

On the other hand, satellite measurements provide suitable spatial coverage and temporal resolution that may help to improve the determination of aerosol radiative forcing at regional or global scales (e.g. Chand et al., 2009; Myhre et al., 2009; Lemaitre et al., 2010; Henderson et al., 2013; Naeger et al., 2013; Thomas et al., 2013; Bhawar et al., 2016; Mallet et al., 2016). Operational satellite retrievals are usually based on a reduced set of aerosol optical models (e.g. Koepke et al., 1997; Hess et al., 1998). However, global aerosol observations indicate a significant variability of the aerosol properties for the same aerosol type due to different emission sources (e.g. Dubovik et al., 2002, Formenti et al., 2008, 2011; Di Biagio et al., 2014, 2016; Thomas et al., 2013). In particular, dust optical properties in the longwave are strictly controlled by its physicochemical properties (e.g. composition, size and shape) which vary in space and time depending on the soil mineralogy of the specific source area of emission (Sokolik et al., 1998; Jeong, 2008; Scheuvens et al., 2013). Therefore, to refine the accuracy of satellite retrieval algorithms, these aerosol optical models should be improved (Dubovik et al., 2002; Myhre et al., 2009; Kahn, 2012). Hence, research should move towards the use of regionally resolved aerosol optical properties to improve the uncertainties in the determinations of the dust radiative effect (Di Biagio et al., 2014).

This work is focused on the determination of the radiative forcing and heating rate profile due to a dust storm which took place on 23 June 2008 in the Western Mediterranean. To do that, we combine different standard satellite products with a detailed radiative transfer modeling. In addition, the sensitivity of our retrievals to different intensive dust optical properties has been addressed. This has been carried out by comparing the results obtained using aerosol measurements (in SW and LW) with those obtained using the dust model from the Optical Properties of Aerosols And Clouds (OPAC) database, (Hess et al., 1998).

2. Instruments and data

Our study area is the Western Mediterranean. The regional distribution of dust aerosols is described combining two complementary satellite products. The Moderate Resolution Imaging Spectroradiometer (MODIS; http://modis.gsfc.nasa.gov/) data, flying on EOS Aqua satellite and the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP, http://www-calipso.larc.nasa.gov/) data, aboard of CALIPSO. The MODIS-Aqua data corresponds to 13:05 UT and CALIPSO overpassed the studied region from 13:05 UT to 13:07 UT. Both platforms take part of the A-Train and its observations can be considered simultaneous, since they differ only in a few minutes. In addition, ground-based measurements from AERONET are also used.

2.1. MODIS

MODIS is a 36-band spectroradiometer measuring visible and infrared radiation. It provides a wide array of daily observations of land, ocean and atmosphere features at spatial resolutions of 250 m (2 bands), 500 m (5 bands) and 1000 m (29 bands), with a swath width of 2300 km at 110°. MODIS is aboard the Earth Science satellite Aqua (NASA, May 4, 2002), which flies in formation with the A-Train constellation. We use the MODIS Aqua product (MYD08). It is a LEVEL 3 atm gridded product with a 1° x 1° latitude-longitude equal-angle grid provided on a daily basis (Platnick et al., 2015). Measurements of aerosol optical depth at 0.550 nm (hereafter AOD) and Angström Exponent (AE) at 470–660 nm (over land) and 500–870 nm (over sea) have been used. The AOD and AE derived from MODIS have been validated against AERONET data in several worldwide locations. The AOD global uncertainties have been estimated as ±5% ± 0.03 over ocean and ±15% ± 0.05 over land (Remer et al., 2005; Levy et al., 2009, 2010). On the other hand, the global uncertainties for AE retrieval is ±0.5 over ocean and ±0.4 over land (Jeong et al., 2005; Levy et al., 2010).

These AOD and AE measurements allow identifying pixels characterized by the presence of the mineral dust within the MODIS image. Therefore, the dusty pixels are chosen in cases with AOD values greater than 0.2 and AE values below 0.5 (e.g. Marcos et al., 2015).

2.2. CALIOP

CALIOP is a nadir-pointing dual-wavelength polarization lidar, which provides information on the vertical distribution of aerosols and clouds and their optical and physical properties. The laser produces linearly-polarized pulses of light at 1064 nm and 532 nm, with a vertical resolution of 30 m (till 8 km) and a footprint spacing of 333 m along-track. CALIOP is aboard the Cloud-Aerosol Lidar and