Remote Sensing of Environment 166 (2015) 154–162

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Impact of Sahara dust on solar radiation at Cape Verde Islands derived from MODIS and surface measurements

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ARTICLE INFO

Article history:
Received 3 December 2014
Received in revised form 19 May 2015
Accepted 29 May 2015
Available online 24 June 2015

Keywords:
Sahara dust
Radiation
MODIS
Aeronet
AOD

ABSTRACT

Based on radiometer measurements of solar irradiance (direct and diffuse light) and Aeronet-based aerosol optical depth (AOD) obtained at the Cape Verde atmospheric observatory during a major cloud-free dust outbreak event on February 7, 2012, the relationship between Saharan mineral dust outbreaks and a reduction of solar irradiance is quantified. The investigation is representative of the eastern subtropical North Atlantic region where the wind mobilization of mineral desert dust from the Sahara results in aerosol signals that are large enough to outweigh those from other aerosol types such as anthropogenic and marine aerosols. Ground-based estimates of AOD show frequency dependence as is expected from Mie theory. Our AOD signals agree well with satellite-based MODIS products and reveal AOD values exceeding 2.5 during the investigated dust storm event. We also demonstrate the use of satellite imagery with an atmospheric trajectory model to simulate time series of measurements at a given location. Using this approach, variations in AOD observed during February 7, 2012 can be rationalized as spatial inhomogeneities in the atmospheric dust load being advected laterally over the observing site. Our measurements suggest a dust forcing efficiency of around −90 W/m^2/AOD at a wavelength of 380 nm, which is about 10–15% greater than reported in the literature indicative of a possible non-linear behavior at high AODs.

1. Introduction

The radiation budget of the Earth's atmosphere is greatly influenced by the amount and type of atmospheric aerosols (Kaufman, Tanre, & Boucher, 2002). Atmospheric aerosols modify the incoming and outgoing radiation (Tegen et al., 1997) directly through scattering and absorption and indirectly by impacting cloud formation processes, and subsequently the precipitation characteristics (Albrecht, 1989; Kaufman et al., 2002; Rosenfeld, Rudich, & Lahav, 2001; Sokolik et al., 2001; Twomey, 1977). For the sign and magnitude of the mineral dust radiative forcing, however, the most important factor for the shortwave radiative forcing is the single scattering albedo (related to atmospheric opacity) whereas the longwave radiative forcing is dependent on the vertical profile of the dust concentrations (Forster et al., 2007; Vogelmann, Flatau, Szczodrak, Markowicz, & Minnett, 2003). In addition to the dust types/size(s) and the geographical location, their complex mineral composition leads to highly uncertain effects on dust-related radiative forcing. Despite of being a core element of radiation and climate forcing, the knowledge of dust–radiation–climate impacts are still rudimentary (Chiapello, Moulin, & Prospero, 2005; Forster et al., 2007; Prospero, 1999; Prospero & Carlson, 1972). According to the Intergovernmental Panel on Climate Change (IPCC) AR5 report, the radiative forcing from aerosol–radiation interactions contribute to a major part of the largest uncertainty in quantifying the earth's radiation budget (IPCC AR5, 2013).

The Saharan region is a major source of mineral dust aerosols for the Atlantic atmosphere. After being advected across the North Atlantic Ocean (Kaufman et al., 2005) via large scale atmospheric circulation those mineral dust particles are a prime aerosol constituent of the lower atmosphere downwind of the Saharan region. As a consequence, they have a substantial influence on the solar and infrared radiation budget at sea level over the eastern subtropical North Atlantic (Evan, Foltz, Zhang, & Vimont, 2011; Lau & Kim, 2007). Studying the interaction of Sahara mineral dust with solar incoming shortwave radiation provides an important opportunity to determine its climate forcing efficiencies. Related previous studies showed multiple instances of enhanced dust concentration over the west African coast that led to a relative cooling of the ocean surface by scattering of solar radiation (Lau & Kim, 2007; Li, Vogelmann, & Ramanathan, 2004; Zhu, Ramanathan, Li, & Kim, 2007). Although many model and satellite based studies have been performed showing the absorption of solar radiation by dust (Chin et al., 2002; Evan et al., 2011; Kaufman, Tanre, Dubovik, Karnieli, & Remer, 2001; Kaufman et al., 2002; Li et al.,

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http://dx.doi.org/10.1016/j.rse.2015.05.026
0034-4257/

2004), ground-based radiation measurements are still the basic method for the validation of the surface aerosol radiative forcing estimates (Holben et al., 2001).

Using a synthesis of recently obtained ground based observations of radiation and aerosol optical thickness estimates at the Cape Verde Islands, the present study revisits the question of the impact of Saharan dust on the solar incoming radiative forcing in the eastern subtropical Atlantic Ocean. In detail, we investigate the dust aerosol optical properties in a cloud-free atmosphere during a Saharan dust outbreak and quantify the dust forcing efficiency. In addition, we use the ground based results to test MODIS (moderate resolution imaging spectroradiometer) retrievals of the atmospheric aerosol optical thickness. The volcanic archipelago of Cape Verde Islands, located about 600 km west of Senegal, is specifically suited for these studies since these islands are located within the primary dust transport area over the tropical Atlantic (Chiapello et al., 1997; Schütz, 1980) and because the dust load over this area is therefore relatively abundant in comparison to the non-sea salt sulfate aerosols leading it to be the dominant light scattering aerosol for this region (Li, Mating, Savoie, Voss, & Prospero, 1996).

2. Radiation measurements at Cape Verde Islands

All in situ measurements analyzed here were taken at the Cape Verde Atmospheric Observatory *Humberto Duarte Fonseca* located at Calhau on a northwest facing sandy beach on São Vicente at 24.9°W–16.8°N, adjacent to the ocean, with the prevailing trade winds blowing directly off the ocean (Fig. 1a). Our instrumentation consists of two stand-alone highly integrated ultraviolet (UV)–visible (VIS) hyper-spectral radiometers (RAMSES–ACC–VIS hyper-spectral radiometer manufactured by TriOS) and an automatic sun photometer CIMEL CE-318 (Fig. 1b). The sensors measure radiance in the UV–VIS spectral range and irradiance in the UV–VIS and UVA/UVB spectral ranges. Direct solar radiance is radiation that comes from the sun, without scattering or reflection by clouds, atmospheric dust, the ground or other objects. In contrast, irradiance includes diffuse light that is scattered sunlight. The radiometers measure direct radiance and hemispheric irradiance spectra every 5 min starting from 06:00 UTC to 22:00 UTC (producing about 192 spectra per day). The measurement wavelength range is 320 to 950 nm with a spectral resolution of 3.3 nm and a wavelength uncertainty of 0.3 nm. The presently available data are from March 29, 2008 to January 31, 2010, and from March 10, 2011 to present.

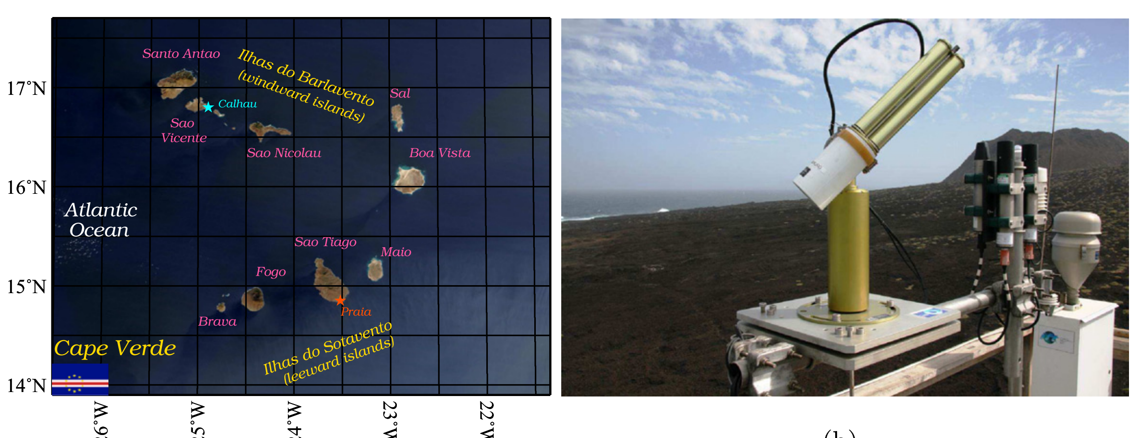
Through this project, the automatic sun photometer CIMEL CE-318 deployed at the Cape Verde atmospheric observatory at Calhau, became part of the aerosol robotic network (Aeronet), starting in February 2012. The photometer measures the direct sun radiances in eight channels within the spectral range of 340–1640 nm and sky radiances in four spectral channels (Holben et al., 2001). The ground observations of the raw sun-photometer are processed and stored at the Aeronet archive (http://aeronet.gsfc.nasa.gov/). The spectral channels of 380 nm and 870 nm are used in this study, with AOD level 1.5 data (cloud-screened and quality checked as detailed in Smirnov, Holben, Eck, Dubovik, and Slutsker (2000)) from the Aeronet archive for the Calhau site.

Aerosol optical depth (AOD) is calculated from spectral extinction of direct beam radiation at each wavelength based on the Beer–Bouguer Law. AOD time series provide a measure of Saharan mineral dust concentrations and can be used to compute the anomaly of solar shortwave irradiance at sea level underneath the dust layer (Li et al., 2004; Martínez Avellaneda, Serra, Minnett, & Stammer, 2010; Yoon, Won, Omar, Kim, & Sohn, 2005). Typically, the uncertainty in AOD estimates derived from a newly calibrated field instrument is smaller than 0.02 under cloud-free conditions. Along with the AOD data provided at every 15 min for the sunlit time of the day, single scattering albedo, and refractive indices of the aerosols are computed via Aeronet inversion algorithm (Dubovik & King, 2000). The Ångström exponent is computed from AOD at the available wavelengths by Aeronet (Holben et al., 1998).

3. Results

3.1. Radiation measurements

Time series of integrated shortwave (SW) radiation computed at top of atmosphere (Q_{TOA}, shown in blue) and measured at sea level (Q_{SL}, shown in red) in the visible spectrum are shown in Fig. 2a for the dust outbreak period of 5 days in Feb 2012. The values of Q_{TOA} were calculated for the position of the sun at the site location and local measurement times using the equations given in the Astronomical Almanac (Astronomical Applications Department, 1990) with the



(a) (b)

Fig. 1. (a) Map of the Cape Verde archipelago in the eastern subtropical North Atlantic showing the locations of individual islands. The blue star shows the location of the Cape Verde atmospheric Observatory Humberto Duarte Fonseca in São Vicente. (b) The Cape Verde atmospheric observatory tower platform with the instrumentation that consists of a CIMEL sun-photometer measuring AOD at multiple wavelengths (340–1640 nm) together with other columnar optically effective aerosol properties and hyperspectral radiometers measuring solar irradiance in visible and UV spectrum. Also visible are the RAMSES–ACC–VIS hyperspectral radiometers.