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Can satellite-derived aerosol optical depth quantify the surface aerosol radiative forcing?

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ABSTRACT

Aerosols play an important role in the climate of the Earth through aerosol radiative forcing (ARF). Nowadays, aerosol particles are detected, quantified and monitored by remote sensing techniques using low Earth orbit (LEO) and geostationary (GEO) satellites. In the present article, the use of satellite-derived AOD (aerosol optical depth) products is investigated in order to quantify on a daily basis the ARF at the surface level (SARF). By daily basis we mean that an average SARF value is computed every day based upon the available AOD satellite measurements for each station. In the first part of the study, the performance of four state-of-art different AOD products (MODIS-DT, MODIS-DB, MISR, and SEVIRI) is assessed through comparison against ground-based AOD measurements from 24 AERONET stations located in Europe and Africa during a 6-month period. While all AOD products are found to be comparable in terms of measured value (RMSE of 0.1 for low and average AOD values), a higher number of AOD estimates is made available by GEO satellites due to their enhanced frequency of scan. Experiments show a general lower agreement of AOD estimates over the African sites (RMSE of 0.2), which show the highest aerosol concentrations along with the occurrence of dust aerosols, coarse particles, and bright surfaces. In the second part of this study, the lessons learned about the confidence in aerosol burden derived from satellites are used to estimate SARF under clear sky conditions. While the use of AOD products issued from GEO observations like SEVIRI brings improvement in the SARF estimates with regard to LEO-based AOD products, the resulting absolute bias (13 W/m^2 in average when AERONET AOD is used as reference) is judged to be still high in comparison with the average values of SARF found in this study (from −25 W/m^2 to −43 W/m^2) and also in the literature (from −10 W/m^2 to −47 W/m^2).

1. Introduction

Aerosols in the atmosphere play an important role in Earth's climate due to their effects on the global radiation budget of the Earth-atmosphere system. This is done in a direct way, through absorption and scattering of visible and infrared radiation (Kiehl and Briegleb, 1993; Bellouin et al., 2005), and also indirectly, by their effect over cloud microphysics due to their role as condensation nuclei (Forster et al., 2007). For instance, an enhanced presence of aerosols results in a decrease of downwelling direct solar radiation at the surface. This effect counteracts the global warming caused by greenhouse gases (Andreae, 1995). On the other hand, high aerosol loads increase the diffuse solar radiation due to aerosol scattering (Jayaraman et al., 1998). This feature has proven to amplify the vegetation photosynthesis as the bottom layers of dense canopies receive more solar light in this case (Niyogi et al., 2004).

The effect of aerosols upon climate is often investigated through the magnitude of the aerosol radiative forcing (ARF) estimated at the top of the atmosphere (TOA) (Boucher and Anderson, 1995; Xu, 2001; Giorgi et al., 2002). However, recent

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studies are focused on evaluating ARF at the surface level (SARF) where the impact of aerosols is higher, especially under clear sky conditions. For example, Garratt et al. (1998) suggested that the inclusion of aerosols in climate models would reduce the annual solar downward flux by 15–20 W/m^2 over non-polluted-land, which corresponds to 13–17 W/m^2 of SARF for a surface albedo of 0.15. This is in agreement with the theoretical study of Ramanathan et al. (2001), in which the average SARF under cloudless skies, with a higher aerosol load though, was estimated to range between −16 and −32 W/m^2 depending on the aerosol and surface properties. Studies based on ground measurements have also been carried out quantifying SARF to be between −11 and −52 W/m^2 (average of −30 W/m^2) over a mid-latitude region such as South Korea (Bush and Valero, 2003) and equal to −24 W/m^2 in average in the Mediterranean during a Saharan dust event (di Sarra et al., 2013). Likewise, Valenzuela et al. (2012) quantified the average SARF in the Spanish station of Granada to be within –(13–34) W/m^2 during the desert dust outbreaks from 2005 to 2010. The decrease of the net flux at the surface level due to the presence of aerosols can alter evaporation processes and thus modulate the hydrologic cycle (e.g., Miller et al., 2004). In the same matter, Kim et al. (2006) showed a decrease of snow melt due to SARF in temperate regions like the Sierra Nevada Mountains.

All the previous studies agree that accurate information on aerosol properties (aerosol content as a priority) is mandatory to properly quantify SARF. As a matter of fact, the impact of aerosols on the Earth's global radiation budget is still a matter of uncertainty due to the scarcity and insufficient quality of aerosol information (Forster et al., 2007; Bellouin et al., 2013). In this context, satellite remote sensing of aerosol optical depth (AOD) at continental scale is crucial to complement the ground aerosol measurements from networks like the Aerosol Robotic Network (AERONET) (Holben et al., 1998). In remote sensing, the main challenge to retrieve accurate AOD values is to yield a separation of the atmospheric and surface signals coexisting at the TOA level (Kokhanovsky et al., 2007; Carrer et al., 2010; Ceamanos et al., 2013). This task is rather challenging because the signal of each entity must be highly characterized. For example, the aerosol signal greatly varies with time and location due to its dependence on the aerosol content and chemical composition, which can have a natural, anthropogenic, or mixed origin (Ceamanos et al., 2014).

During the last decade, the characterization of aerosols from space observations has concentrated large efforts to make AOD products available to the user community. In this regard, observations taken by the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument aboard the low Earth orbit (LEO) Terra and Aqua satellites are used to disseminate two AOD products using the state-of-the-art Dark Target (Remer et al., 2005) and Deep Blue (Hsu et al., 2004) algorithms. Another relevant AOD product is generated from the Multi-angle Imaging SpectroRadiometer (MISR) aboard the Terra satellite using the method described by Diner et al. (2005). More recently, the potential of observations from the Spinning Enhanced Visible and Infra Red Imager (SEVIRI) aboard the geostationary Meteosat Second Generation (MSG) satellite to measure AOD — limited to Europe and Africa in this case — has been highlighted in the work by Carrer et al. (2010). The unique feature of SEVIRI is due to its high temporal resolution, which allows it to provide one observation of the Earth disk over the prime meridian every 15 min. Contrary to the limited repetivity of LEO satellites over a given point at the surface, the high number of observations per day acquired by the SEVIRI instrument allows the application of the method developed by Carrer et al. (2010) to provide a daily AOD product over all non cloudy regions within the SEVIRI Earth disk.

The aim of the present investigation is to determine the suitability of the previously cited satellite-derived AOD products to estimate SARF on a daily basis. As a first step, the strengths and flaws of the different AOD products are investigated based on their capability to catch up the maximum number of aerosol episodes and to report them with a satisfactory degree of magnitude. The dependability of all satellite AOD products is established through comparisons with coincident AERONET ground-based observations. In addition, we have analyzed the influence of aerosol properties, like particle size or type, on the agreement between satellite and AERONET derived AOD. In the second part, products of satellite-derived AOD are used to estimate direct SARF on a daily basis. Simulations are carried out using the radiative transfer code 6S (Vermote et al., 1997). In particular, the SARF bias introduced by using satellite-derived AOD values instead AERONET products is compared to average SARF values found in the literature. Special attention is paid to the limitation in temporal sampling of LEO-based AOD data with regard the GEO-based SEVIRI product.

This article is organized as follows. First, the materials considered in the present study are introduced in Section 2 along with the AOD retrieval methods. In Section 3, the adopted methodology to evaluate AOD products and SARF estimates is presented. Results of numerical experiments are detailed in Section 4. Section 5 concludes this work by discussing the outcomes of the experiments and drawing conclusions.

2. Materials

2.1. Area and period of investigation

Experiments in this article are conducted on a study area that spans from 0°N to 60°N in latitude and from 30°W to 50°E in longitude. A total of 24 sites are selected within the resulting geographical window. Each site corresponds to the location of one AERONET station as it is shown in Fig. 1. The selected area is limited to Europe and Africa to be in agreement with the spatial coverage of the AOD product obtained from the geostationary satellite MSG. The 24 locations are selected to encompass a broad range of environmental conditions where various aerosol properties and surface characteristics are found. Table 1 reports a list of all sites with their main characteristics. The time period of study goes from March 1st to August 31st in 2006. Indeed, the year 2006 was very rich in terms of aerosol activity, especially in the Sahara-Sahel region where strong dust events occurred (Redelsperger et al., 2006; Skonieczny et al., 2011).

2.2. Aerosol optical depth

2.2.1. Satellite-derived AOD products

Four AOD products from satellite observations are considered in this article. Two products are issued from the MODIS instrument, one from the MISR sensor, and last one from the