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Aerosol optical depth in a western Mediterranean site: An assessment of different methods

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ABSTRACT

Column aerosol optical properties were derived from multifilter rotating shadowing radiometer (MFRSR) observations carried out at Girona (northeast Spain) from June 2012 to June 2014. We used a technique that allows estimating simultaneously aerosol optical depth (AOD) and Ångström exponent (AE) at high time-resolution. For the period studied, mean AOD at 500 nm was 0.14, with a noticeable seasonal pattern, i.e. maximum in summer and minimum in winter. Mean AE from 500 to 870 nm was 1.2 with a strong day-to-day variation and slightly higher values in summer. So, the summer increase in AOD seems to be linked with an enhancement in the number of fine particles. A radiative closure experiment, using the SMARTS2 model, was performed to confirm that the MFRSR-retrieved aerosol optical properties appropriately represent the continuously varying atmospheric conditions in Girona. Thus, the calculated broadband values of the direct flux show a mean absolute difference of less than 5.9 W m^{-2} (0.77%) and R = 0.99 when compared to the observed fluxes. The sensitivity of the achieved closure to uncertainties in AOD and AE was also examined. We use this MFRSR-based dataset as a reference for other ground-based and satellite measurements that might be used to assess the aerosol properties at this site. First, we used observations obtained from a 100 km away AERONET station; despite a general similar behavior when compared with the in-situ MFRSR observations, certain discrepancies for AOD estimates in the different channels (R < 0.84 and slope < 1) appear. Second, AOD products from MISR and MODIS satellite observations were compared with our ground-based retrievals. Reasonable agreements are found for the MISR product (R = 0.92), with somewhat poorer agreement for the MODIS product (R = 0.70). Finally, we apply all these methods to study in detail the aerosol properties during two singular aerosol events related to a forest fire and a desert dust intrusion.

1. Introduction

Aerosols are small particles suspended in the atmosphere that occur naturally (e.g., originating from volcanoes, dust storms, sea spray) or are generated by human activities (e.g., burning of fossil fuels). They have a profound impact on the climate system: the aerosol influence on the Earth radiative budget is related to a direct effect, due to scattering and absorption of solar and terrestrial radiation (e.g., Charlson et al., 1992; Hansen et al., 1997) and to an indirect effect connected to interaction with clouds (e.g., Ramanathan et al., 2001; Rosenfeld et al., 2014; Twomey, 1977).

In spite of these well-known mechanisms, and compared with greenhouse gases, aerosols still present a major uncertainty when estimating their radiative forcing of climate due to their non-uniform chemical and physical properties, and spatial and temporal variations in the atmosphere (Boucher et al., 2013). Improved knowledge of the aerosol loading and properties will help to reduce the uncertainties associated with aerosol effects in climate models and, in consequence, to improve climate change projections. Many studies are devoted to understanding the effects of aerosols on the climate system both from ground-based networks (see Table 1 in Michalsky et al., 2010) and satellite platforms (see Table 1 in Lee et al., 2009). Both methods are based on radiative measurements to retrieve values of aerosol properties.

The most important of the aerosol radiative properties that can be retrieved from either ground or satellite-based methods is the aerosol optical depth (AOD), which is the degree to which aerosols prevent the transmission of light by absorption or scattering, and is much linked to the total aerosol burden in the atmosphere. The spectral dependence of AOD, typically described by the Ångström exponent (AE), is an indicator of particle size, with large particles having AE values near zero (e.g. desert dust) and smaller particles exhibiting larger AE values (e.g. urban, industrial, or biomass burning aerosols).

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Among satellite onboard instruments, it is worth mentioning the multi-angle imaging spectroradiometer (MISR) and the moderate resolution imaging spectroradiometer (MODIS). Both instruments give a very complete set of variables related to atmospheric aerosol (including AOD and AE), which are derived from various measurement channels. Specifically, MISR is an instrument onboard the Terra satellite operated by NASA that measures in four spectral bands between 0.45 and 0.87 μm (Diner et al., 1998, 2005). On the other hand, MODIS is an instrument onboard two satellites of NASA's Earth Observing System (Terra and Aqua), and its detectors measure in 36 spectral bands between 0.40 and 14.39 μm (King et al., 1992; Salomonson et al., 1989). Despite the satellite instruments providing global coverage, they give low temporal resolution as compared to ground based observations; the latter being generally regarded as more accurate aerosol retrievals for the place they are performed.

Ground-based optical observations of atmospheric aerosols usually involve measurements of direct solar radiation in distinct spectral bands using pyrheliometers or sunphotometers (Iqbal, 1983). These measurements may be used to obtain AOD and AE (Ångström, 1929, 1964; Masmoudi et al., 2003; Ramachandran and Jayaraman, 2003). For example, we can highlight the Aerosol Robotic Network (AERONET) of ground based Cimel sunphotometers that measure in eight different channels between 0.34 and 1.64 μm (Dubovik and King, 2000; Holben et al., 1998). In our research, we use the multifilter rotating shadowband radiometer (MFRSR), which continuously measures the global and diffuse solar horizontal irradiance in six narrowband wavelengths (Harrison et al., 1994), using five of these to derive AOD and AE (Alexandrov et al., 2002; Harrison and Michalsky, 1994; Michalsky et al., 2001).

The MFRSR instrument has been extensively used to retrieve aerosol properties and study their climatology at different sites in the USA (e.g. Augustine et al., 2008; Michalsky and LeBaron, 2013; Michalsky et al., 2010), Europe (e.g. Ciardini et al., 2012; Mazzola et al., 2010; Pace et al., 2006), Asia (e.g. Janjai et al., 2008; Lee et al., 2010), and Oceania (e.g. Bouya and Box, 2011; Bouya et al., 2010; Liley and Forgan, 2009); including the study of AOD and AE during fire and dust episodes (e.g. Augustine et al., 2008; Ge et al., 2010). Nevertheless, it is worth noting that there are relatively few studies using this instrument in the western Mediterranean and in Spain in particular, where studies based upon Cimel sunphotometer measurements are much more common (e.g. Bennouna et al., 2011, 2013; Obregón et al., 2014; Toledano et al., 2007).

Ground measurements present the inconvenience of their scarcity. Thus, for the western Mediterranean (Iberian Peninsula, southern France, Italy and North Africa), an area covering more than 1.5 million km^2, about 30 stations are currently measuring aerosol characteristics, with distances of hundreds of km between them. Given the geographical and meteorological complexity of the area (Fig. 1), and the variability in the processes driving the aerosol behavior (emissions from different sources, transport subject to both synoptic and mesoscale meteorology), it can be argued that the network density should be improved in order to correctly describe the aerosol conditions in that area. On the other hand, the increasing spatial resolution of satellite instruments should help for a better characterization of the regional conditions, but the low temporal resolution of their measurements is an issue, besides the fact that satellite-derived records must be validated against reliable references (that is ground based).

This evident need of comparing the variety of methods and instruments usable to obtain information on aerosols has been partially covered by a number of studies. Comparisons between MFRSR and AERONET optical depth retrievals have been performed in the past giving good agreement between both devices (e.g. Alexandrov et al., 2008; Augustine et al., 2008). However, comparison studies between MFRSR and satellite products are scarce (while there are a number of studies that relate AERONET data with MODIS and MISR retrievals, e.g. Cheng et al., 2012; Kanniah et al., 2014; Qi et al., 2013). As satellite products are on the rise, it is important to compare satellite instruments with ground based aerosol observations in order to understand deviations, if any, between the two kinds of measurements (Kharol et al., 2011). In the case of Spain, there are several articles that compare AERONET data with MODIS (e.g. Bennouna et al., 2011, 2013; Segura et al., 2015) and a few include a comparison with MISR (e.g. de Meij and Lelieveld, 2011), but no one for the specific region of the northeast corner of Spain (a region which, unlike other regions of Spain, is rarely affected by desert dust intrusions) and using MISR data.

In the present study, we use two years of MFRSR measurements taken at Girona, northeast Spain, to establish a reference dataset for AOD and AE for this area. A closure experiment is performed to help the assessment of the quality of the AOD and AE retrievals: we use the MFRSR retrieved aerosol properties as input of a radiative transfer model to determine the direct irradiance and compare it with pyrheliometer measurements (McFarlane et al., 2009; Michalsky et al., 2006; Ricchiazzi et al., 2006). The MFRSR-based dataset is then used as a reference for other alternative methods (ground and satellite-based) in order to assess the aerosol properties in the area, taking measurements from: (1) a 100 km away AERONET station (Barcelona), (2) MISR onboard Terra, and (3) MODIS onboard Terra and Aqua. The comparison is performed for the two years covered by the dataset, but particular attention is given to a wildfire event and a Saharan dust outbreak that occurred in Girona in July 2012. The general aim of the study is to add some knowledge about the performance of the methods when assessing aerosol behavior at some specific site.

Section 2 describes the characteristics of the site, the instruments used in this research, and the method applied to the raw measurements (including calibration, AOD and AE determination, cloud screening, and the evaluation of uncertainties). A detailed examination of the MFRSR retrieved AOD and AE is presented in Section 3.1; the radiative closure experiment in Section 3.2; a comparison with other products available to estimate aerosol properties in the area (AERONET, MISR, and MODIS data) in Section 3.3; and the episode with smoke and dust is examined in Section 3.4. Finally, conclusions of this study and suggestions for further research are presented in Section 4.

2. Data and method

The reference measurements were carried out in Girona, which is a small city located in northeastern Spain (Southern Europe), about 30 km from the Mediterranean Sea, 100 km northeast of Barcelona, and 40 km from the Pyrenees (Fig. 1). It has a population of almost 100,000 inhabitants and an average elevation of 75 m above sea level (asl). Girona enjoys a Mediterranean climate, with mild winters and hot summers, and maximum precipitation during autumn and spring. The measurements for the present work are performed at the weather and radiometric station (41.96° N, 2.83° E, 115 m asl) located on the roof of a building of the University of Girona.

Data used cover the period from June 2012 to June 2014. The MFRSR, which is fully described in the work of Harrison et al. (1994), measures global and diffuse irradiances at six channels with nominal wavelengths 415, 500, 615, 673, 870 and 940 nm, and with 10 nm full width at half maximum. The radiometer also has a sensor for the measurement of the broadband solar irradiance (300–1100 nm). Measurements of the global and diffuse components are performed every 15 s and averaged over 1 min intervals. As both irradiances are measured using the same detector for a given wavelength, this guarantees that the calibration coefficients apply for both components. The direct normal irradiance is obtained by subtracting the diffuse from the global irradiance, and is used to derive AOD for all narrowband channels, with the exception of the 940 nm channel, which is strongly influenced by water vapor.

At the station, global, diffuse, and direct broadband irradiances are also measured with thermopile sensors (CM11 pyranometers and CH1 pyrheliometer from Kipp & Zonen). Images from a Whole Sky Camera