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Long-term changes in the radiative effects of aerosols and clouds in a mid-latitude region (1985–2010)

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ABSTRACT

As clouds and aerosols are the main sources of uncertainty in the determination of the energy balance of the Earth, there is a growing interest in the evaluation of their radiative effects. Hence, in this work, long-term data of shortwave radiation from 13 locations over Spain (South-Western Europe) are used to investigate, for the first time, the radiative effects of clouds and aerosols in the period 1985–2010. In particular, monthly radiation data from ground-based observations and radiative transfer simulations fed with reanalysis data of ozone, water vapour and surface albedo, are used to evaluate the cloud and aerosol radiative effect (CARE). Annual values of the CARE become less negative from Northern to Southern stations. For instance, the annual CARE values for Bilbao (North), Valladolid (Centre), and Murcia (South) are −82, −46, and −42 Wm^{-2}, respectively. CARE averages exhibit a clear seasonal pattern with the strongest contribution during spring and summer months. Particularly in these seasons, there is a very high correlation between CARE values and sunshine duration, number of cloud-free days, and temperature. Additionally, a significant decrease of the radiative effects of the clouds and aerosols is observed over Spain in the last 26 years. Overall, the linear trend of the mean annual CARE series over Spain is statistically significant with positive sign, 3.1 Wm^{-2} per decade. The significant trend values at individual stations range between 2.9 and 5.2 Wm^{-2} per decade. Seasonal trends in summer and spring are larger than in autumn and winter. Finally, the radiative effects of water vapour and ozone were also evaluated showing an annual mean over Spain of about −10 Wm^{-2} and −1 Wm^{-2}, respectively. However, no significant trends were observed for these two variables between 1985 and 2010.

1. Introduction

The knowledge of the amount of solar radiation reaching the surface is essential for the planetary climate system, since it plays a key role in the global energy balance. There are several socioeconomic sectors interested in a good characterization of solar shortwave radiation (SW), 280–3000 nm, at the surface. For instance, the renewable energy sector needs a full description of SW radiation because it is directly linked with sunshine duration, temperature, and wind formation, among others. Hence, the interannual variations of SW radiation due to atmospheric components have been addressed by many studies in the last decades (e.g., Palancar and Toselli, 2004; Antón et al., 2008; Jacovides et al., 2009; de Miguel et al., 2011a). Equally, the temporal trends of the SW radiation have been studied by several authors. Since the second half of 20th century, two opposite trends have been observed. From the 1950s to the 1980s, a reduction in SW radiation (also known as the global dimming phenomenon) has been documented (e.g., Stanhill and Cohen, 2001); while since the 1980s an increase in the levels of SW radiation (the brightening phenomenon) is noticed (e.g., Wild et al., 2005). The causes of the dimming/brightening have been mainly attributed to changes in anthropogenic aerosol emissions and variations in cloud properties (e.g., Stanhill and Cohen, 2001; Philipona et al., 2009; Wild, 2009; Lachat and Wehrli, 2013).

The surface radiative effect of an atmospheric factor is defined as the difference between the actual net flux at the surface and the equivalent flux when this factor is absent in the atmosphere. For instance, there are many studies dealing with the cloud radiative effect at the surface, CRE (e.g., Dong et al., 2006; Taylor, 2012; Mateos et al., 2013). However, the high spatial and temporal variability of cloud optical and microphysical properties makes it difficult to study the global trends of cloud cover, cloud optical thickness, and cloud types. The aerosol radiative effect at the surface (ARE) is usually studied under cloud-free conditions (e.g., Di Biagio et al., 2009; Valenzuela et al., 2012). However, long-term analyses of the radiative effects are very sparse in the literature, because of the lack of ground-based measurements and their non-homogeneous distribution over the Earth's surface. Thus, currently there are no more than 100 stations in Europe with SW radiation series over 25–30 years in the Global Energy Balance Archive (GEBA), a central archive for the worldwide measured surface energy fluxes, and they are

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mostly placed over Central Europe (e.g., Gilgen et al., 1998; Sanchez-Lorenzo et al., 2013b).

Allan (2011) evaluated the net anomalies of the CRE over the near-globe (60ºS to 60ºN) from reanalysis data. He found no change at the surface in net radiation between 1985 and 2010. Some exceptions were attributed by this author to the effects caused by volcanic eruptions. Su et al. (2008) analysing 4-year mean CRE data at the surface found that the cloud cooling effect at the top of the atmosphere (TOA) decreases more than 50% when Asian dust aerosols are present in the atmosphere. Urankar et al. (2012) analyzed 30 years of reanalysis to establish the annual cycle of aerosol and cloud effects separately, in four Indian areas. Both variables show a clear pattern with maximum effects occurring in the spring or summer months. They obtained maximum CRE values of about $-120\ \mathrm{Wm}^{-2}$, while ARE showed values of less than $-28\ \mathrm{Wm}^{-2}$. Dong et al. (2006) analyzed 6 years of ground-based data to establish the seasonal dependence of CRE on SW radiation in Central USA. They observed clear differences among the four seasons, with maximum and minimum effects in spring and winter, respectively. SW surface cloud radiative effects varied from -38.2 to $-90.6\ \mathrm{Wm}^{-2}$ during La Niña and El Niño conditions in Australia (McFarlane et al., 2013).

As noted by Wild (2009), more research about the impact that the aerosol–cloud system produces on the radiative levels at the surface is required. Therefore, the main aim of this study is to provide, for a first time, a complete characterization of the cloud and aerosol radiative effect (CARE) of the SW radiation at the surface in Spain (South-Western Europe), evaluating the temporal trends over 26 years (period 1985–2010). We also analyze water vapour radiative effect (WRE) and ozone radiative effect (ORE) for the same period. Data from different Spanish ground-based stations are used together with radiative transfer simulations to obtain monthly CARE, WRE, and ORE values. Specifically, the libRadtran (Mayer and Kylling, 2005) model is fed with monthly reanalysis data of ozone, water vapour, and surface albedo.

This article presents the following outline: Section 2 includes a detailed description of the ground-based stations, the reanalysis data, and the methodology used in this study. Section 3 shows the climatology of CARE values in Spain, whereas the analysis of its temporal trends is performed in Section 4. Finally, the conclusions of this article are summarised in Section 5.

2. Data and methods

2.1. Ground-based measurements

The ground-based database of SW radiation measurements on a monthly basis was extracted from Sanchez-Lorenzo et al. (2013a), which were originally provided by the Spanish Meteorological Agency (AEMET). The 13 stations used in this study are shown in Fig. 1. As can be seen, they are distributed in the North, Central, and South of the Iberian Peninsula, with one station located in the Balearic Islands. Table 1 shows the main details of the 13 stations used in this study. SW radiation measurements were performed by Kipp & Zonen pyranometers (models CM-11 and CM-21), which were periodically calibrated according to the standards for measurements of the World Radiation Centre in Davos (Switzerland). For more information about the dataset used in this study we refer to Sanchez-Lorenzo et al. (2013a), where more details about the original AEMET data, quality control cheques, and the homogenization and gap filling procedures of the monthly series, can be consulted. A monthly resolution is adequate to establish the temporal trends of SW radiation over the Iberian Peninsula (see, e.g., Sanchez-Lorenzo et al., 2007).

Climatological tables of several variables are freely-available from AEMET on the website www.aemet.es. Monthly mean values for variables such as sunshine duration, number of cloud-free days, temperature, precipitation, and relative humidity, among others, can be obtained for a large number of Spanish ground-based stations (Instituto Nacional de Meteorología, 2007). For this study, data of sunshine duration, maximum temperature average, and number of cloud-free days in the 13 ground-based stations mentioned above were used.

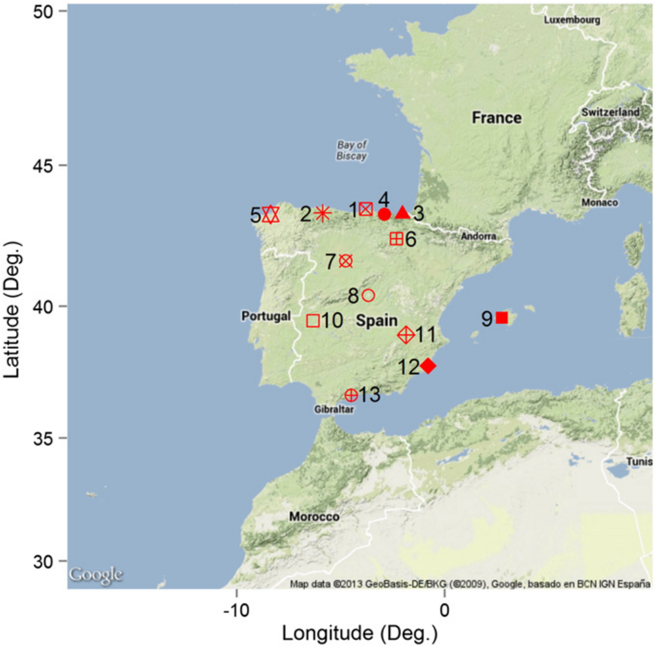

Fig. 1. Location of the 13 ground-based stations used in this study. The numbers correspond to those in Table 1.

2.2. Reanalysis data

Total ozone column (TOC) and precipitable water column (PWC) data were obtained from the ERA-Interim reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). This reanalysis covers the period from 1979 to present day. The ERA-Interim data assimilation system contains many improvements relative to previous reanalysis as was explained by Dee et al. (2011). The atmospheric model and reanalysis system are configured with 60 levels in the vertical to produce data every 6 h. Hence, data of TOC and PWC were downloaded from the ECMWF data server on a fixed grid of 1.5°. To obtain data for each station, the 6-hour values were bi-linearly interpolated (with the four closest points) to the selected coordinates being daily and monthly averaged afterwards.

Table 1
Information about the 13 ground-based stations used in this study: geographical coordinates, time period, and number of monthly data. The ID numbers correspond to those in Fig. 1.

ID	Station	Latitude (°N)	Longitude (°E)	Altitude (m)	Time Period	Monthly data
1	Santander	43.49	−3.80	52	1983–2010	336
2	Oviedo	43.35	−5.87	336	1972–2010	459
3	San Sebastián	43.31	−2.04	251	1983–2010	336
4	Bilbao	43.30	−2.91	42	1985–2010	312
5	Coruña	43.30	−8.38	58	1984–2010	314
6	Logroño	42.45	−2.33	353	1984–2010	324
7	Valladolid	41.65	−4.77	735	1975–2010	427
8	Madrid	40.41	−3.68	664	1973–2010	456
9	Palma de Mallorca	39.57	2.74	8	1975–2010	428
10	Cáceres	39.47	−6.34	405	1983–2010	336
11	Albacete	38.95	−1.86	674	1983–2010	333
12	Murcia	37.79	−0.80	61	1972–2010	464
13	Málaga	36.67	−4.49	60	1975–2010	421