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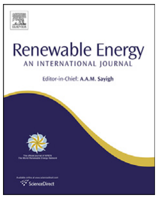

The aerosol effect on direct normal irradiance in Europe under clear skies

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The effect of spatial and temporal variability of aerosol optical depth (AOD) on direct normal irradiance (DNI) under clear skies is studied, with the synergetic use of satellite and ground-based data as well as calculations from a radiative transfer model. The area of interest is Europe; data from May to September during 13 years (2000–2012) are analyzed. The aerosol effect on DNI is high in areas influenced by desert dust intrusions and intense anthropogenic activities, such as the Mediterranean basin and the Po Valley in Italy. In May, the attenuation of DNI from aerosols, over these areas, can reach values up to 35% and 45% respectively, which corresponds to 4 and 6 kWh m^{-2} per day. In most areas, even for periods with lower values of AOD, the attenuation of DNI is found to be around 20%, which corresponds to about 2–3 kWh m^{-2} less received DNI per day, compared to the corresponding value on an aerosol clean day. However, the DNI has increased during the recent years, due to the decreasing tendency of AOD over most areas of Europe. The increase is around 6–12%, which corresponds to an amount of 0.5–1.25 more kWh m^{-2} received per day, compared to a clean day. The percentage differences of daily DNI from the corresponding monthly climatological value reveals that day-to-day differences (due to AOD changes) from the monthly mean, by ±20%, can occur. The significance of the aerosol changes in Europe reveals the necessity for near real-time measurements or forecasts of AOD when reliable estimations of DNI are required.

1. Introduction

Aerosols are one of the most important constituents in the atmosphere that affect the incoming solar radiation, either directly through absorbing and scattering processes or indirectly by changing the optical properties and lifetime of clouds. Even though aerosols have been in the center of scientific research for years; their high spatiotemporal variability and complex atmospheric interactions induce challenges in the determination of their radiative forcing, which still holds high uncertainties [1].

Many studies focus on the spatiotemporal distribution of aerosol properties in Europe. Chubarova [2] studied the seasonal distribution, using data from the MODIS instrument and the AERONET network. The highest aerosol loads were observed in south and southeastern parts of Europe during the warmer months of the year. Over these areas, permanent high values of the Ångström α coefficient were found indicating the presence of anthropogenic aerosols. Marmer and Langmann [3] studied the interannual variability of the aerosol distribution over Europe, using a regional atmospheric chemistry model. They highlighted the role of meteorological conditions which can induce a variability of up to 100% in the monthly mean of the aerosol load. The weekly variability of aerosols in Europe presents the lowest values during the weekend due to the decrease in transport and other anthropogenic activities [4–6]. As a result of legislations regarding atmospheric pollution, negative trends in aerosol amounts have been observed during the last years in many areas of Europe, the so-called "brightening effect" [7–11].

In order to complement the ground measurements and account for their limited spatial coverage, satellites have been employed for Earth's and atmosphere's observation. Satellites can provide global coverage and produce long-term datasets. The MODerate resolution Imaging Spectroradiometer (MODIS), on board the NASA Terra satellite, has been in operation since February 2000. The sun-synchronous satellite provides global coverage every 1–2 days and acquires data in 36 spectral bands (http://modis.gsfc.nasa.gov/) [12]. The Collection 005 (C005) is the dataset of MODIS products

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provided by the version 5.2 of the algorithm, which has replaced older versions [13,14]. The prelaunch expected error in AOD retrievals over land is ± (0.05 + 0.15 AOD), while AOD is estimated to within this expected error in more than 60% and 72% of the cases over ocean and over land respectively [15]. The MODIS data have been extensively validated against ground-based measurements [16–19] and used to calculate, amongst others, the aerosol trends and events [7,20,21], as well as the surface shortwave, ultraviolet [22–24] and visible solar irradiance [25].

The accurate knowledge of the amount of solar irradiance reaching a surface on the Earth and its temporal variability is essential for the efficient performance of solar power applications. The most important constituent of solar radiation is the Direct Normal Irradiance (DNI), which is the radiation received by a surface perpendicular to the direction of the sun. Although systems measuring the Global Horizontal Irradiance (GHI) are abundant, DNI measurements are not so common and these data are usually estimated indirectly with the use of radiative transfer or decomposition models [26–28]. Under clear skies, aerosols become the dominant factor that affect the intensity of solar irradiance reaching the ground. It has been shown that the variability in DNI due to aerosols is more important than the one induced in GHI [29], while the uncertainty in its calculation is dominated by uncertainties in the aerosol optical properties [30]. Suri et al. [31] studied the DNI over Europe as this is provided by 5 different datasets. The annual sum was found to reach the highest values in areas of the Mediterranean, Southern and Central Spain, Portugal, Sicily, Sardinia and Provence. Gueymard [29] used AOD measurements from 180 stations of the AErosol RObotic NETwork (AERONET) over the world to study the variability of AOD and its effect on DNI and GHI. He concluded that some areas experience a high variability that makes resource assessments potentially too optimistic for bankability if based only on limited data series.

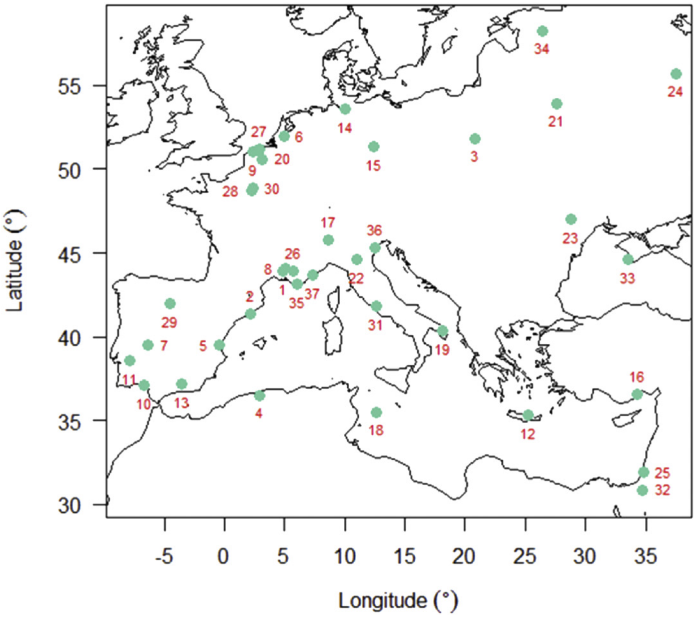
In this study, the effect of AOD on DNI under clear skies is studied, with the synergetic use of satellite data from the MODIS instrument, complementary data from the AERONET network and calculations from a radiative transfer model. The area of interest is Europe and data from a 13-year period (2000–2012) are analyzed. The DNI temporal and spatial variability due to aerosols is examined, as well as the increase induced by the observed decreasing tendency of AOD over Europe. The uncertainties of DNI estimations induced by the use of aerosol climatological values are investigated.

2. Data and methodology

The AOD at 550 nm is taken from the MODIS Terra daily Level-3 data (Collection 5.1) which have a spatial resolution of 1° × 1° (100 × 100 km). Terra was launched in December 1999 and started providing MODIS data in March 2000. The MODIS AOD at 550 nm, from the Terra satellite is used in this study from the beginning of operation (March 1st, 2000) until the end of 2012. The AOD wavelength dependence, described by the Ångström-α exponent, is provided by MODIS but is not used in this study since it still presents considerable errors when compared with ground-based measurements [14,18].

For the Ångström-α exponent, the level 2.0 climatological data from AERONET were used. The level 2.0 data are pre- and post-field calibrated, automatically cloud-screened and manually checked. The monthly climatological values of Ångstrom α exponent (440–870 nm) were chosen for 37 stations in Europe, which present data availability longer than 3 years during the period 2000–2013. These data were then interpolated for the region of our study in order to obtain the spatial resolution of MODIS (1° × 1°). The interpolation was performed using the method of Ordinary Kriging, combined with a linear semi-variogram model. The AERONET sites used in this study are shown in Fig. 1. The area examined (latitude: 29.5°N – 59.5°N, longitude: 9.5°W – 38.5°E) covers Europe, with the exception of the northern latitudes of Scandinavia, the northern coasts of Africa and the Mediterranean coasts of Middle East.

In order to estimate the DNI on the surface, the radiative transfer model SBDART was used [32], which is included in the LibRadtran package [33] (www.libradtran.org). Typical vertical profiles for the basic atmospheric gases, pressure and temperature, for the mid-latitudes, were used [34]. The surface albedo was set at 0.2 for the shortwave (SW) range (280–3000 nm) [35]. The aerosol vertical profile is described by Shettle [36]. The AOD is described by the



	Station	19	Lecce University
1	Avignon	20	Lille
2	Barcelona	21	Minsk
3	Belsk	22	Modena
4	Blida	23	Moldova
5	Burjassot	24	Moscow
6	Cabauw	25	Nes Ziona
7	Caceres	26	OHP OBSERVATOIRE
8	Carpentras	27	Oostende
9	Dunkerque	28	Palaiseau
10	El Arenosillo	29	Palencia
11	Evora	30	Paris
12	FORTH Crete	31	Rome Tor Vergata
13	Granada	32	Sede Boker
14	Hamburg	33	Sevastopol
15	IFT Leipzig	34	Toravere
16	IMS-METU Erdemli	35	Toulon
17	Ispra	36	Venise
18	Lambedusa	37	Villefranche

Fig. 1. AERONET stations used for the retrieval of the gridded monthly averages of Ångström α exponent.