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Turbidity coefficients from normal direct solar irradiance in Central Spain

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ABSTRACT

Atmospheric turbidity causes attenuation of solar radiation reaching the earth's surface under a cloudless sky. The Ångström turbidity coefficient and the aerosol optical thickness, AOD550, were obtained from 10-minute direct normal solar irradiance measurements recorded in a rural area of Castilla y León region, Spain, from July 2010 to December 2012. During the study period, the diurnal variation of the mean monthly 10-minute turbidity coefficient increased in early morning, remained with fluctuations around noon, and increased or diminished in the evening, near sunset. The monthly turbidity coefficient shows an annual cycle with minimum values in winter and maximum values in summer, varying between 0.04 in winter and 0.16 in summer. The frequency distribution of 10-min Ångström turbidity coefficient on cloudless days shows that 0.65% of values are below 0.02, 84.50% between 0.02 and 0.15, and 14.85% above 0.15. Comparing at solar noon AOD550nm retrieved from MODIS (MODerate resolution Imaging Spectroradiometer on-board the Terra satellite) with those estimated from direct normal solar radiation measurements shows a good correlation coefficient of 0.78, although MODIS values are lower than estimated ones. High turbidity situations were investigated depending on the season and air-mass origin; the results show that they might be attributed to aerosol dust from the Sahara desert.The most significant high turbidity situations were investigated on base of wind at 700 mb and air-mass origin; the result shows that this might be attributed to aerosol dust from the Sahara desert.

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1. Introduction

Solar radiation is attenuated by absorption and scattering processes when passing through the earth's atmosphere; the main gaseous absorbers are ozone, oxygen, water vapour, and carbon dioxide. All atmospheric gases and aerosols scatter solar radiation at all wavelengths although absorption by aerosols is smaller than by scattering. It is known that under cloudless conditions, ozone, water vapour, and aerosols are the most variable atmospheric components although aerosols show a diverse composition, size, and distribution that make them being the greatest attenuators of solar radiation in the visible and near-IR wavelengths on cloudless days.

Aerosols are small solid or liquid particles suspended in the air that follows air mass motion within certain broad limits. These particles are either of terrestrial origin (industrial smoke, pollen, volcanic eruptions, sandstorms, forest fires, as well as agricultural and slash burning), or of marine origin, and range in size from 10^{-3} μm to several tens of microns (López and Batlles, 2004). There are two dominant aerosol layers in the atmosphere, one near the earth's surface (0–4 km), which is affected by natural dust storms and anthropogenic activities, and another stratospheric dust layer (15–25 km) above sea level (Hess et al., 1998) affected by volcanic action and cosmic sources.

Aerosols play a role in the earth's energy balance, in cloud formation, precipitation, and in atmospheric chemical reactions. In order to estimate aerosol climatic effects, the physical–chemical and optical properties need to be known (Adamopoulos et al., 2007). Aerosol turbidity is an essential atmospheric variable which conditions the magnitude and variability of solar radiation (Gueymard, 2012). An atmosphere with aerosols is called turbid and the effects that those aerosols produce on solar radiation are known as turbidity (Pedrós et al., 1999). The presence of aerosols in the atmosphere can be quantified by different parameters related to the chemical, physical and optical properties of the particles (D'Almeida et al., 1991; Hess et al., 1998).

The parameters that characterized the atmospheric turbidity are called turbidity coefficients. The most commonly used coefficients are the Ångström turbidity coefficient β, the Linke turbidity factor T_L, and the Unsworth–Monteith turbidity coefficient T_{UM} (Kambezidis et al., 1993, 1998, 2000; López and Batlles, 2004) and the Ångström turbidity coefficient represents the amount of aerosols in the atmosphere (Iqbal, 1983). The Ångström turbidity formula incorporates the number of particles and particle size, and is given by the following expression

$$\tau_a(\lambda) = \beta\lambda^{-\alpha} \tag{1}$$

where λ is the wavelength (in μm), and the Ångström exponent, α, is related to the size distribution of the aerosols (large values of α indicate a relatively high ratio of small particles to large particles), $\tau_a(\lambda)$ is the monochromatic aerosol attenuation coefficient, known as aerosol optical depth, AOD and β is the AOD at 1 μm wavelength.

Like many other climate variables, β and α can vary throughout the day due to photochemical activity, local emissions, mesoscale circulation, ventilation by wind, and changes in temperature that cause evaporation or condensation of moisture in the atmosphere. These changes can decrease or increase the value of these coefficients.

The coefficients α and β can be determined by sun-photometers and spectral radiometers. Moreover β and α can be retrieved using solar broadband sensors. Several methods are based on broadband measurements of solar radiation. Louche et al. (1987) determined the value of β with direct solar irradiance data from Ajaccio (France), assigning a fixed value to α. Gueymard and Vignola (1998) evaluated turbidity from a proposed semi-physical method that demonstrated the utility of diffuse broadband irradiance data for estimating atmospheric turbidity.

In Spain, Cañada et al. (1993) estimated β in Valencia and the results were compared with those from Ajaccio, Avignon, and Dhahran, and they kept α equal to 1.3. López and Batlles (2004) compared different methods for evaluating turbidity and precipitable water, and reported that the most exact method is the one proposed in Gueymard and Vignola (1998). Based on spectral measurements, Adamopoulos et al. (2007) determined the aerosol particle radii in the atmosphere over Athens from spectral solar direct irradiance on 42 cloudless days and air-mass trajectories were used to reveal certain specific events. Power (2001) proposed a model for Ångström β evaluation from readily available surface-weather data, regardless of cloud cover.

The Aerosol Robotic Network (AERONET) was set up to monitor global aerosols and their optical and physical properties (e.g. size distribution, single scattering albedo, asymmetry factor, and refractive index) are obtained through the Dubovik et al. (2006) algorithm.

The present paper aims to analyse the Ångström turbidity coefficient and AOD at 550 nm, AOD_{550}, in Central Spain. The method proposed by Louche et al. (1987) has been run here with the Ångström exponent input equal to the measured value retrieved from MODIS on board the Terra and Aqua satellites. According to Levy et al. (2013), the Ångström exponent between 470 and 660 nm derived over land presents some limitations concerning its reliability. But we have considered that the Ångström exponent values used here are the most practical ones when no better values can be obtained without appropriated instrumentation. On the other hand it has been observed that the tendency of the Ångström exponent values used in this study is similar to the ones recorded at the nearest Aeronet station Autilla (41°N, 4 W), Spain.

AOD_{550} values estimated by direct normal solar irradiance and satellite retrieved ones are compared. The turbidity dependence on atmospheric conditions is studied relating daily and monthly turbidity with meteorological data and taking into account air mass trajectories. High aerosol load (e.g. that on 7th April 2011and other days) was analysed using the HYSPLIT (HYbrid Single Particle Lagrangian Integrated Trajectory) model and synoptic conditions at the measuring station. Results and analysis should contribute to increasing knowledge of atmospheric and climatic characteristics of the geographical area and could be used to improve the accuracy of solar radiation modelling over regions of interest for solar applications (Gueymard, 2005).

By means of the proposed method, it will be possible to evaluate turbidity in areas where normal direct solar irradiance measurements are available, and by using the exponent coefficient α, precipitable water vapour, and AOD_{550} data from satellite measurements.