Journal of Aerosol Science 68 (2014) 46–57

Contents lists available at ScienceDirect

Journal of Aerosol Science

journal homepage: www.elsevier.com/locate/jaerosci

Impact of meteorological parameters on relation between aerosol optical indices and air pollution in a sub-urban area

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ARTICLE INFO

Article history:
Received 7 June 2013
Received in revised form
28 October 2013
Accepted 31 October 2013
Available online 13 November 2013

Keywords:
Aerosol optical depth
Particulate matter
Meteorological parameters
Angstrom exponent

ABSTRACT

Aerosol optical depth (AOD) provides a useful characterization of the total absorption and scattering effect of particles in direct or scattered sunlight, and can be derived from sun spectra measured directly by sun photometers. In this paper, atmospheric optical properties (e.g. $AOD_{440-1020\ nm}$, α and β, the coefficients in Angstrom formula) and meteorological conditions are presented for: summer (July–August–September) and winter (December–January–February–March) of 2009–2010 over Zanjan (36.41° N, 48.29° E) in northwestern Iran.

The diurnal variation of AOD in Zanjan is approximately 15%. An exponential dependence of α on AOD in winter indicates that dust aerosols are major contributions of atmospheric turbidity in this region. AOD regressed against PM_{10} to establish prediction models. The role of three meteorological parameters on the correlation of AOD and PM_{10} are analyzed. Results show that there is a high correlation between AOD_{440} and PM_{10} in wintertime, and β is a better indicator of air quality in winter than in summer for the study region considered here. Hourly analysis shows that this correlation is highest in the afternoon when the atmospheric mixed layer is at its highest thickness. A similar behavior for AOD–PM_{10} and a correlation between optical properties with NO_2 and PM_{10} are detected. A sensitivity study was designed to quantify the role of meteorological properties, such as relative humidity, wind speed, and temperature, on the correlation between AOD and PM_{10} concentration.

1. Introduction

The influences of atmospheric aerosols on the Earth's radiation balance are determined by the interaction of particles with electromagnetic radiation. Aerosols scatter and absorb solar radiation leading to atmospheric turbidity (Liou, 2002; Seinfeld & Pandis, 1998). Atmospheric aerosols include both natural (i.e. windblown dust, sea salt from the oceans, and volcanic eruptions) and anthropogenic sources (i.e. aerosols from biomass burning, combustion from automobiles and emission from power plants) (Kaufman et al., 2002). Aerosol optical depth (AOD) is a dimensionless parameter that characterizes the total absorption and scattering effect of particles in direct or scattered sunlight. AOD can be derived from sun spectra measured directly by sun-photometers at the ground or indirectly from reflected radiation of the surface received by satellite sensors (Sifakis & Deschamps, 1992; Hand et al., 2004). Studying the variability of AOD is important for a range of applications, including satellite aerosol data validation, radiative forcing computations, public health, and studies of aerosol interaction with clouds (Kaufman et al., 2002; Smirnov et al., 2003).

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0021-8502/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jaerosci.2013.10.008

Understanding the impact of particulate matter (PM) on AOD relies on monitoring PM at different time scales (Chu et al., 2003; Kacenelenbogen et al., 2006; Wang & Christopher, 2003). However, the relationship between PM and AOD depends on the season, meteorological variables, and the site location (Pelletier et al., 2007). Many studies have reported relationships between AOD and PM_{10} or $PM_{2.5}$ measurements for different parts of the world (e.g. Wang & Christopher, 2003; Hutchison, 2003; Chu et al., 2003; Engel-Cox et al., 2004, 2005; Al-Saadi et al., 2005; Kacenelenbogen et al., 2006; Koelemeijer et al., 2006; Kumar et al., 2007; Liu et al., 2003; Gupta et al., 2006; Pelletier et al., 2007; Mukai et al., 2008; Schaap et al., 2009; Retalis & Sifakis, 2010; Tsai et al., 2011; Wang et al., 2013). Variations in local meteorological conditions and aerosol chemical composition, as well as the occurrence of multiple aerosol layers, have significant impacts on determining the magnitudes of such correlations. Therefore, this relationship should be determined regionally. The limited number of such studies on the atmospheric optical properties in the Middle East leaves a gap that is worth investigating even for a local region (WMO/GAW, 2004-2005).

In this paper, we empirically determine the relationship between AOD and PM_{10} measurements for a semi-urban site in northwestern Iran, Zanjan. The correlation is investigated under different meteorological conditions in summer and winter from December 2009 to September 2010, focusing on the connection between PM_{10} and AOD.

2. Methodology and data collection

AOD, as measured by the ground-based sun-photometry, depends on the scattering and absorption by atmospheric constituents (e.g. gases and particles) along the optical path between the sun and the Earth's surface. A general definition of AOD implies effects such as extinction of the incident light due to atmospheric particles of different sizes (Liou, 2002). The relationship between micro-physical properties and the aerosol optics is described by the following Fredholm integral equation:

$$\mathrm{AOD}(\lambda) = \int \sigma_{ext}(\lambda, z)dz \tag{1}$$

Aerosol optical depth at wave length AOD(λ) is obtained by the vertical integration of the extinction coefficient (profile over the height z). The extinction coefficient is the part of light scattered or absorbed per unit distance in a particular medium (i.e. measuring the ability of scattering or absorption of light by a matter) and is defined as follows:

$$\sigma_{ext}(\lambda) = \int_{\log r} \pi r^2 Q_{ext}(r, \lambda, m) \frac{d\mathrm{N}(r)}{d \log r} d \log r \tag{2}$$

where λ is wavelength, r is radius and Q_{ext} is the extinction efficiency factor, being a function of the complex index of refraction (Kokhanovsky, 2008), also called Mie extinction cross-section. Q_{ext} depends on the particle size relative to the wavelength of radiation and the refractive index of particles, m. The extinction cross-section can be calculated on the basis of the Mie theory, if the particles are spherical (Hess et al., 1998; Malm & Hand, 2007). The extinction coefficient for a given aerosol ensemble depends on the geometrical size of the particles between the minimum and maximum radius as described by their number distribution, where N is the number of particle concentration/m^3.

The wavelength exponent α, in the spectral fit of the AOD is also calculated for each spectra recorded. Although α is not an explicit function of the size distribution, it provides information on the aerosol number distribution (Angstrom, 1929). The wavelength exponent is usually calculated according to the Angstrom formula,

$$\mathrm{AOD} = \beta \lambda^{-\alpha} \tag{3}$$

where β is the turbidity coefficient. Taking the natural logarithm of Eq. (3) yields:

$$\ln \mathrm{AOD} = \ln \beta - \alpha \ln \lambda \tag{4}$$

hence, the wavelength exponent may be calculated from the slope of a linear fit of ln AOD against ln λ. The value 1.3 for α represents an average value for the mean atmospheric conditions. An empirical relationship between the wavelength exponent and the dominant geometric diameter of the aerosol particles was found by Angstrom (1929). This empirical relation coupled with α, as determined from Eq. (4), is used to calculate the dominant radius for each measurement.

For the purposes of this study, AOD was measured using a sun-photometer at a ground station, located at the Institute for Advanced Studies in Basic Sciences (IASBS) of Zanjan (36.7° N, 48.5° E). This data is produced by a multi-channel (with wavelength range of 440–1020 nm) automatic optical instrument which measures the spectrum of direct solar irradiance. The instrument is made by the CIMEL Electronic Company and its technical information along with operational modes has been described in the CIMEL user manual (Rainwater & Gregory, 2005). The direct sun measurement is made in five spectral bands (440, 670, 870, 936, 1020 nm) and requires approximately 10 s. A sequence of three such measurements can be made 30 s apart creating a triplet observation per wavelength. The sampling interval is typically 15 min. More than 1000 measurements were taken by the CIMEL sun photometer in Zanjan during the period of study.

In order to eliminate the effects of cloud, a cloud-screening method is implemented according to Smirnov et al. (2000). The short-term variability is derived from triplets of three observations τ_1, τ_2, and τ_3 taken 30 s apart. Measurements are excluded if the triplet variability, $\Delta\tau = \max(\tau_{1,2,3}) - \min(\tau_{1,2,3})$, exceeds an empirical threshold value of 0.02 or 0.03 times the triplet average, whichever is larger at any wavelength. Since time periods with coincident rapid increase of AOD and rapid