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An empirical equation to estimate mineral dust concentrations from visibility observations in Northern Africa

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ABSTRACT

This paper presents a new empirical equation relating horizontal visibility and PM_{10} dust concentrations. The new empirical equation (IZO-Eq) is derived from observations performed at the Izaña Atmospheric Observatory (IZO, 28.30°N, 16.49°W, 2367 m a.s.l., Tenerife, Spain), recorded during Saharan dust outbreaks from 2003 to 2010. A filter based on relative humidity, present-weather and aerosol optical properties is applied to identify dust events. IZO-Eq is validated in the Sahel region during the dry and wet seasons (2006–2008) using data from two PM_{10} monitoring stations from the African Monsoon Multidisciplinary Analysis (AMMA) International Project, and data from the nearest meteorological synoptic stations. The estimated PM_{10} derived from IZO-Eq is compared against that those obtained by other empirical equations and dust surface concentrations from NMMB/BSC-Dust model. IZO-Eq presents better performance than the other equations in both dry and wet seasons when compared with observed PM_{10} at two Sahelian sites. IZO-Eq is also able to reproduce the surface concentration variability simulated by NMMB/BSC-Dust. Above 10 km of horizontal visibility, empirical equations cannot be used to estimate PM_{10}, since above this threshold equations estimate a nearly constant PM_{10} value, regardless of the visibility range. A comparison between the PM_{10} spatial distributions derived from visibility SYNOP observations through IZO-Eq, the modelled values from the NMMB/BSC-Dust model and aerosol optical depth (AOD) retrieved from MODIS is performed for the 2006–2008 period. The different spatial distributions present a rather good agreement among them as well as to reproduce the characteristic seasonal dust features over North Africa.

1. Introduction

Mineral dust has a strong interaction with the climate system through direct and indirect impacts (IPCC, 2007, 2014). Directly, mineral dust influences the Earth's radiative budget by affecting the processes of absorption and scattering of solar and infrared radiation (Tegen, 2003; Pérez et al., 2006; Balkanski et al., 2007; Heinold et al., 2008) and indirectly, it affects the clouds condensation nuclei (Hoose et al., 2008) and ice nuclei (Klein et al., 2010), optical properties and lifetime of clouds, causing an indirect radiative forcing (Ramanathan et al., 2001; IPCC, 2007). Mineral dust can be transported in large plumes many thousands of kilometers away from their source regions causing changes in the biogeochemical processes of terrestrial and marine ecosystems (Maher et al., 2010) and, being an important source of primary nutrients such as nitrogen, phosphorus or potassium (Jickells et al., 2005).

Mineral dust emissions into the atmosphere have a negative impact on human health, causing or aggravating allergies, respiratory diseases and eyes infections (Griffin and Kellogg, 2004; WHO, 2005). During Saharan dust intrusions in Spain, Díaz et al. (2012)

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observed effects of PM_{10} (mass concentration of particulate matter with aerodynamical diameter less than 10 μm) on mortality due to respiratory causes in the cold season and to circulatory causes in the warm one. Griffin (2007) summarized the current state of knowledge of desert dust microbiology and the health impact that desert dust and its microbial constituents may have on downwind environments, both close and far from their sources. Saharan dust seems to be related with meningitis epidemics in the Sahel region (Thomson et al., 2006; Cuevas et al., 2011; Pérez et al., 2014) and increased incidence of pediatric asthma crisis in the Caribbean region (Gyan et al., 2005). Stefanski and Sivakumar (2009) summarized the negative impacts of sand and dust storms on agriculture. High dust concentrations increase significantly light extinction affecting negatively aircraft operations and ground transportation. Ohde and Siegel (2012) and Schroedter-Homscheidt et al. (2012) assessed the impact of Saharan dust on solar irradiance in concentrated photovoltaic plants.

There is an increasing interest in quantifying the mineral dust concentration over North Africa, which is the most important dust source of the world (Prospero et al., 2002; Washington et al., 2003; Shao et al., 2011; Ginoux et al., 2012; Hsu et al., 2012). However, air quality monitoring stations in rural sites or near dust sources over Northern Africa are almost inexistent. A variety of global and regional dust models have been used to characterize the dust cycle over main source regions (Nickovic et al., 2001; Morcrette et al., 2009; Pérez et al., 2011), but there are significant differences in the results among models (Uno et al., 2006; Todd et al., 2008; Huneeus et al., 2011). Satellite remote sensing has been used for dust detection, but the high reflectivity of the desert ground in the visible channels supposes a severe limitation to retrieve quantitative aerosol data from satellite (Hsu et al., 2004; de Paepe and Dewitte, 2009). The AErosol RObotic NETwork, (AERONET, Holben et al., 1998) has also been used to derive dust content in the atmospheric column and to characterize the optical properties of mineral dust near source regions. However, AERONET observations are very scarce in- near-dust source regions, and the available time series are relatively short, presenting many gaps. It is worthily to note that column aerosol data often do not have a clear correspondence with surface concentration. Moreover, such measurements integrate different types of particles.

In order to overcome this strong observational limitation, horizontal visibility obtained from meteorological reports (SYNOP) has been used to infer surface dust concentration (D'Almeida, 1986; Ben Mohamed et al., 1992; Ozer et al., 2006; Mahowald et al., 2007; Dayan et al., 2008). The horizontal visibility is an indication of the intensity of attenuation of solar radiation by the suspended particles (N'Tchayi Mbourou et al., 1997). It is strongly influenced by dust particle size distribution (Tegen, 2003) and also has a clear dependence on the ambient humidity (Shao and Dong, 2006; Cabello et al., 2012). However, many studies have shown that horizontal visibility is a good indicator of dust storms (e.g., N'Tchayi Mbourou et al., 1997; Shao and Wang, 2003; Shao and Dong, 2006; Mahowald et al., 2007; Klose et al., 2010; Hamidi et al., 2013). Several empirical equations relating surface dust concentrations and visibility have been proposed in dust regions, such as North America (Chepil and Woodruff, 1957; Patterson and Gillette, 1977), Australia (Tews, 1996; Leys et al., 2002), Asia (Shao and Wang, 2003; Wang et al., 2008; Judger et al., 2014), West Asia (Dayan et al., 2008) and in West Africa (D'Almeida, 1986; Ben Mohamed et al., 1992).

In the present study we propose a new empirical equation relating horizontal visibility and PM_{10} using high quality data obtained at the high-mountain Izaña Global Atmospheric Watch (GAW) observatory (IZO, Tenerife, The Canary Islands), located at the subtropical eastern North Atlantic, near Africa and under environmental conditions ensuring that practically all PM_{10} recorded corresponds to mineral dust coming from the Sahara. Results are validated through the comparison of independent in situ measurements at two PM_{10} stations located in the Sahel with visibility observations, with surface dust concentration from the NMMB/BSC-Dust model and with PM_{10} estimations from other referenced empirical equations derived for West Africa, Middle East and East Asia.

The paper is structured as follows: data and methods used to derive the empirical equation at IZO and to validate it over the Sahel region are described in Section 2, results are presented in Section 3, and in Section 4 the main conclusions are summarized.

2. Data and methods

2.1. PM_{10} and TSP

The present analysis includes PM_{10} and Total Suspended Particles (TSP) (μg/m^3) measured at IZO (28.30°N, 16.49°W, 2367 m a.s.l.,) during the period spanning from January 2003 to January 2010. IZO station is managed by the Izaña Atmospheric Research Center (IARC), from the Meteorological State Agency of Spain (AEMET). Quasi-permanent subsidence conditions in the free troposphere together with frequent trade winds flow in the lowest troposphere resulting in a strong and stable temperature inversion (located at 1400 m a.s.l. on average) that separates a dry free troposphere from a relatively fresh and humid oceanic boundary layer (Torres et al., 2002). Given its close proximity to the western Africa coast, IZO is an excellent site to study and characterize almost pure mineral dust released from African source regions and its transport over the subtropical North Atlantic (Alonso-Pérez et al., 2007, 2011; Basart et al., 2009; Rodríguez et al., 2011). Details of the methodology to determine PM_{10} and TSP mass concentrations at IZO station can be found in Rodríguez et al. (2009, 2011, 2012). Simultaneous PM_{10} measurements and visibility observations from 06 to 18 UTC every 3 h have been used to obtain daily means and to derive the empirical relationship between both parameters. Since some empirical equations considered in this paper use TSP instead of PM_{10}, an averaged PM_{10}/TSP ratio has been computed from a set of simultaneous values of these variables.

The empirical equation obtained at IZO (IZO-Eq) has been validated using daily PM_{10} averages at two monitoring stations from the African Monsoon Multidisciplinary Analysis (AMMA) International Project (Marticorena et al., 2010) in the Sahel region from January 2006 to December 2008. The AMMA stations are M'Bour (Senegal, 14.39°N, 16.96°W, 13 m a.s.l.), located near the Atlantic coast and Banizoumbou (Niger, 13.54°N, 2.66°E, 191 m a.s.l.), representative of the inland Sahel. Both stations are aligned

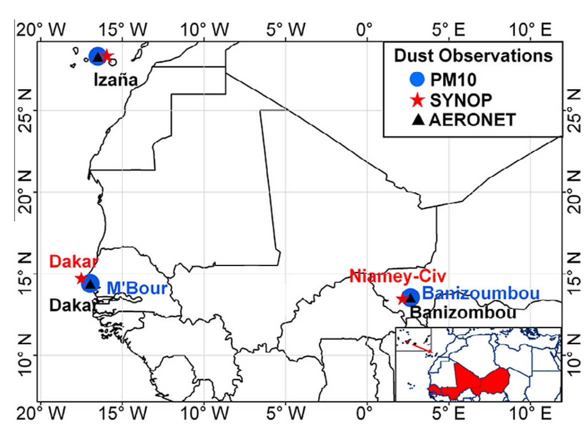

Fig. 1. Location of the PM_{10} monitoring sites (blue circles), meteorological stations (red starts) and AERONET stations (black triangles) near PM_{10} monitoring sites used in the present analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)