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Impact of aerosol on surface reaching solar irradiance over Mohal in the northwestern Himalaya, India

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ABSTRACT

The present study, for the first time during 2007, is focused to examine the impact of aerosols on surface reaching solar irradiance over Mohal (31.9°N, 77.12°E, 1154 m amsl) in the northwestern part of the Indian Himalaya. The study also aims to estimate shortwave aerosol radiative forcing (SWARF) and its effect on regional climate. The multi-wavelength solar radiometer (MWR) is used to measure aerosol optical depth (AOD) over a wider spectrum, i.e. ultraviolet, visible and near-infrared. The AOD is obtained by analyzing the data from MWR following the Langley technique. The radiative transfer model is used along with Optical Properties of Aerosols and Clouds model to estimate the SWARF. Aerosol shows a great efficiency to reduce substantial fraction of energy from the surface reaching direct solar beam, i.e. 154 W m^{-2} μm^{-1} per unit AOD at 0.5 μm. The SWARF at the surface, top of the atmosphere and the atmosphere is estimated to be -18.5 ± 1.7, $+0.6 \pm 3.7$ and $+19.1 \pm 3.1$ W m^{-2}, respectively. The large SWARF at the surface stood during the summer (April–July), while small during the monsoon (August–September). Moderate SWARF is obtained in the autumn (October–November) and winter (December–March). The study estimates a notable extinction in incoming solar radiation relatively with lower atmospheric heating from 0.41 to 0.73 K day^{-1}. The potential effect of aerosol is found relatively higher on high aerosol loading days. On these days, the lower atmospheric heating increases by a factor 1.8 (during dust events) and 1.7 (during biomass burning). This study concludes that aerosols produce significant reduction in incoming solar radiation with substantial increase in lower atmospheric heating, leading to a remarkable effect on the atmospheric stability. In addition, as a subject of future interest, the present study has also important implications on the atmospheric circulation and regional climate.

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1. Introduction

The Earth's atmosphere is a medium which under the change of its composition brings significant changes to the surface reaching solar radiation (Dutton et al., 1991; Pinker et al., 2005; Wild et al., 2005). These changes are mainly brought by aerosols (Charlson et al., 1992; IPCC, 2007) by means of scattering and absorption (Charlson et al., 1992). The scattering and absorption of solar radiation by aerosol produces notable extinction in the direct solar radiation, as also increases their diffusion efficiency (McCartney, 1976). The changes in incoming solar radiation (direct and diffuse) alter the energy budget of the Earth-atmosphere, which result in many atmospheric phenomena (Ramanathan et al., 2001; Kumari et al., 2007). One of the major atmospheric phenomena of the 21st century is a break-down of the hydrological cycle (Ramanathan et al., 2001).

Many researchers from different parts of the world such as India (Kaiser and Qian, 2002; Soni et al., 2012; Guleria and Kuniyal, 2013), China (Liepert et al., 1994; Wang et al., 2012), Germany (Russak, 1990), the Baltic (Norris and Wild, 2007), the South Pole (Dutton et al., 1991), Europe (Ohmura, 2009), and other regions (Haywood and Shine, 1995; Wild, 2012) reported the aerosol optical depth (AOD) playing an important role to alter the incoming solar radiation. Despite AOD, the single scattering albedo (SSA) and asymmetry parameter (*g*) are also responsible to alter the radiation balance of the Earth-atmosphere (Hansen et al., 1997; Andrews et al., 2006). The changes in surface reaching solar radiation is not only influenced by aerosol parameters, but also by several others, such as, solar zenith angle, solar declination angle, geographical latitude, eccentricity of the Earth's orbit, atmospheric albedo, clouds and surface albedo (Iqbal, 1983).

The detailed pioneering studies on aerosols and their potential influence on earth atmosphere climate has been reported several decades ago (Twomey, 1977). In spite of these studies, the radiative effect of aerosol was not able to attract the scientific interest of the

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atmospheric scientists (IPCC, 1996). In recent times, the aerosol research has become advanced significantly using an integrated approach from the ground-based to the space-borne observations (IPCC, 2007; Guleria et al., 2012a, 2012b). Although, with these efforts, the exact estimation of SWARF is still a challenging task (IPCC, 2007). This is mainly due to lack of complete characterization of aerosol particles and their space and time evolution. The information on SWARF is useful in prediction of the climate change (IPCC, 2007). Thus, the study of the optical properties of aerosol and their potential effect on incoming solar radiation from different parts of the world is essential, particularly over the Indian region (Gautam et al., 2010).

India is the second most populated country in the world. Being a developing country, there has been a growing tendency of urbanization, industrialization and demand for energy, as a result the load of anthropogenic aerosol is gradually increasing (Kaskaoutis et al., 2011a). The occurrence of dust storms in the northern part of India mainly transports the desert dust from the arid regions. Due to this, Indian sub-continent is a representative of different types of aerosol, which present a large variation over India, both spatially and temporally. The long range transport of desert dust aerosol from the arid regions (e.g. the Sahara, the Arabian Peninsula, and the Thar Desert) is further mixed with anthropogenic emissions (Prasad et al., 2006) which is likely to increase the absorption efficiency of solar radiation along the elevated slopes of the Himalayas (Prasad and Singh, 2007a; Gautam et al., 2011, 2013). Earlier studies have shown that the transported dust influencing aerosol optical properties results in strong seasonal variation of aerosol loading and changes in aerosol properties over the northwestern part of India (Dey et al., 2004; Sarkar et al., 2006; Prasad and Singh, 2007a, 2007b; Gautam et al., 2007, 2009; Kaskaoutis et al., 2011b, 2012a, 2012b). In order to understand the climatic response of the extreme aerosol episode days over the northern India, the Indo-Gangetic Plain (IGP) in particular, has a significant importance (Kaskaoutis et al., 2013), as these aerosol episode lead to a large reduction in incoming solar radiation. Prasad et al. (2007) conducted the study over the northern part of India particularly during major dust storm events and found that during these events the average surface forcing is changed by $-23\ \mathrm{W\,m^{-2}}$. In response to desert dust aerosol loading over the northwestern India, Gautam et al. (2011) also reported reduction in surface reaching solar radiation in the range of 19–23 $\mathrm{W\,m^{-2}}$. The Indian Himalaya plays an important role to keep up the hydrological cycle. The snow peaks of the Indian Himalaya feed to the major rivers of world such as the Indus and the Ganges. These rivers are the lifeline of millions of people living in the downstream (Yanai et al., 1992). The recent studies reported that polluted dust accumulating in the foothills of the Indian Himalaya has been acting as an elevated heat source (Yanai et al., 1992; Lau et al., 2006; Lau and Kim, 2006; Gautam et al., 2010). These aerosols induce tropospheric temperature anomalies over the northern India. These anomalies result in many unexpected atmospheric incidences such as unequal distribution of Indian monsoon via the so-called "*Elevated Heat Pump mechanism*" (Lau et al., 2006; Lau and Kim, 2006).

In view of the importance and sensitivity of aerosol optical properties over the foothills of the Himalaya, the present study is carried out over Mohal (31.9°N, 77.12°E, 1154 m amsl) during 2007. Mohal is an important experimental site, surrounded by hills forming a valley like shape, in the northwestern part of the Indian Himalaya, under a nationwide program of the Aerosol Radiative Forcing over India (ARFI). Desert dust and anthropogenic aerosol are transported in addition to local emissions which accumulate over the experimental site and have been the major sources in the region (Guleria et al., 2011, 2012c). The present work aims to quantify the potential effect of aerosol on incoming solar radiation considering AOD, Ångström Exponent (α), turbidity coefficient (β), SSA and g as the main parameters. The study also aims to estimate SWARF and their effect on regional climate; the analyses of the potential effect of aerosol transport on the surface reaching solar radiation is also attempted by using satellite data. The study is also important as no such work in the northwestern part of Indian Himalaya has been done in the past.

2. Data and method

The multi-wavelength radiometer (MWR) is an automatic sun tracker radiometer operated at Mohal to measure aerosol optical depth (AOD) (Moorthy et al., 1999). In the present study, this radiometer is handled during cloud-free days. This instrument works on the principle as described in Shaw et al. (1973). The MWR is equipped with ten wavelength channels, i.e. 0.38, 0.4, 0.45, 0.5, 0.6, 0.65, 0.75, 0.85, 0.935, and 1.025 μm. The field of view of each wavelength channel is 2°. The sun radiometer collects solar radiation data corresponding to each wavelength channel following the Beer–Bouguer–Lambert law. The collected data is further analyzed using the application of Langley's technique to retrieve total optical depth (τ). This is a well known technique which is applied earlier (Shaw et al., 1973). τ is the sum of the optical depth arising due to molecular scattering (τ_r), aerosol extinction (τ_a), ozone (τ_o) and water vapor (τ_w) absorption (Moorthy et al., 1999). The AOD is estimated for each observation day by subtracting the non-aerosol contribution: $\tau_a = \tau - (\tau_r + \tau_o + \tau_w)$. The AOD obtained in the spectral band 0.38–1.025 μm is applied to the Ångström Power Law (Ångström, 1961). The application of the linear regression fit obtained after the Ångström Power Law is applied to obtain the Ångström parameters (α and β). α and β are important parameters, in general they are quantitative measure of aerosol size distribution and aerosol loading, respectively.

After examining the potential effect of aerosol on incoming solar radiation, it is essential to find the true position of the Sun in relation to the Earth. Solar zenith angle, geographic latitude of the observation site, hour angle and solar declination angle are some of the fundamental factors applied to find the position of the Sun. The trigonometric relations between these factors are expressed in Iqbal (1983). The incoming direct spectral irradiance ($F_{n\lambda}$) is inversely proportional to the square of its distance from the Sun. In the present context, $F_{n\lambda}$ is calculated following Bird and Riordan (1986). The extraterrestrial solar irradiance ($F_{on\lambda}$) values are taken from Fröhlich and Wehrli (1981) of the World Radiation Centre. The MWR measured values of optical depths arise due to air molecules, aerosol, ozone and water vapor which were used to derive transmittance functions. The diffuse spectral irradiance ($F_{d\lambda}$) on a horizontal surface of the Earth, is presented into three components namely Rayleigh scattering diffuse irradiance ($F_{dr\lambda}$), aerosol scattered diffuse irradiance ($F_{da\lambda}$) and multiple reflected diffuse irradiance ($F_{dm\lambda}$). The calculations of these components were performed following the equations given in the numerous literatures (e.g. Bird and Riordan, 1986; Kambezidis et al., 1997).

The optical properties of aerosols such as AOD, SSA and g are crucial in determining the SWARF. In this work, AOD, SSA and g in the spectral range 0.25–4.0 μm are derived from Optical Properties of Aerosols and Clouds version (OPAC) (Hess et al., 1998). Here, we used OPAC in a more robust manner such as matching absorption coefficient as well as the Ångström exponent in addition to AOD spectra, taking black carbon aerosol number concentration as the anchoring points. The number concentrations of black carbon aerosols are obtained using Aethalometer. In the OPAC database, the zero-order approximation is performed by adopting polluted continental aerosol (post-monsoon and winter) and desert aerosol (pre-monsoon and monsoon). The number densities of insoluble,

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