Premonsoon aerosol characterization and radiative effects over the Indo-Gangetic Plains: Implications for regional climate warming

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Received 6 January 2010; revised 1 April 2010; accepted 12 April 2010; published 10 September 2010.

[1] The Himalayas have a profound effect on the South Asian climate and the regional hydrological cycle, as it forms a barrier for the strong monsoon winds and serves as an elevated heat source, thus controlling the onset and distribution of precipitation during the Indian summer monsoon. Recent studies have suggested that radiative heating by absorbing aerosols, such as dust and black carbon over the Indo-Gangetic Plains (IGP) and slopes of the Himalayas, may significantly accelerate the seasonal warming of the Hindu Kush–Himalayas–Tibetan Plateau (HKHT) and influence the subsequent evolution of the summer monsoon. This paper presents a detailed characterization of aerosols over the IGP and their radiative effects during the premonsoon season (April–May) when dust transport constitutes the bulk of the regional aerosol loading, using ground radiometric and spaceborne observations. During the dust-laden period, there is a strong response of surface shortwave flux to aerosol absorption indicated by the diurnally averaged forcing efficiency of $-70 \text{ Wm}^{-2}$ per unit optical depth. The simulated aerosol single-scattering albedo, constrained by surface flux and aerosol measurements, is estimated to be $0.89 \pm 0.01$ (at $\sim 550 \text{ nm}$) with diurnal mean surface and top-of-atmosphere forcing values ranging from $-11$ to $-79.8 \text{ Wm}^{-2}$ and $+1.4$ to $+12 \text{ Wm}^{-2}$, respectively, for the premonsoon period. The model-simulated solar heating rate profile peaks in the lower troposphere with enhanced heating penetrating into the middle troposphere (5–6 km), caused by vertically extended aerosols over the IGP with peak altitude of $\sim 5 \text{ km}$ as indicated by spaceborne Cloud-Aerosol Lidar with Orthogonal Polarization observations. On a long-term climate scale, our analysis, on the basis of microwave satellite measurements of tropospheric temperatures from 1979 to 2007, indicates accelerated annual mean warming rates found over the Himalayan–Hindu Kush region ($0.21^\circ \text{C/decade} \pm 0.08^\circ \text{C/decade}$) and underscores the potential role of enhanced aerosol solar absorption in the maximum warming localized over the western Himalayas ($0.26^\circ \text{C/decade} \pm 0.09^\circ \text{C/decade}$) that significantly exceed the entire HKHT and global warming rates. We believe the accelerated warming rates reported here are critical to both the South Asian summer monsoon and hydro-glaciological resource variability in the Himalayan–Hindu Kush snowpack and therefore to the densely populated downstream regions.


1. Introduction

[2] Atmospheric aerosols are of great importance to global climate because of their scattering as well as absorbing properties and in turn significantly influence the Earth’s radiation budget [Ramanathan et al., 2001; Haywood and Boucher, 2000; Bellouin et al., 2005]. In general, aerosols could offset the regional greenhouse warming by directly scattering the sunlight back to space and by indirectly enhancing cloud albedo, thereby cooling the climate. However, it is also known that aerosols (such as soot) heat the atmosphere because of their absorption of sunlight, which in turn enhances the greenhouse effect [Jacobson, 2001]. Naturally occurring aerosols such as windblown mineral dust are a major contributor to the aerosol loading in the troposphere and influence the seasonal variability of aerosol optical properties and radiative forcing [Tegen and Lacis, 1996]. Over polluted regions, long-range transport of mineral dust mixed with anthropogenic species could induce significant changes in optical and
physical properties of aerosols and alter the radiation budget [Seinfeld et al., 2004].

[1] Through perturbations to the radiative energy balance, mineral dust may also potentially cause changes in the global hydrological cycle [Miller et al., 2004], especially over Asian monsoon regions, together with absorbing aerosols such as soot [Lau et al., 2006]. In recent years, a number of global circulation modeling (GCM) studies have suggested the importance of aerosol solar absorption in modulating the monsoon rainfall distribution [Menon et al., 2002; Ramanathan et al., 2005; Chung and Ramanathan, 2006; Lau et al., 2006a; Meehl et al., 2008; Randel and Ramsawy, 2008; Collier and Zhang, 2009; Sud et al., 2009; Wang et al., 2009]. Additionally, another recent GCM study suggested a net warming of about 1.2°C in the lower atmosphere (below 5 km) over the Himalayan monsoon region, as referred earlier, recently such arguments are in context and pose concerns particularly to the South Asian region as the Himalayas contain one of the largest ice-covered regions on the Earth’s surface, and their glaciers form headwaters of major rivers such as the Indus and the Ganges that serve millions of people downstream (south of the Himalayas) in the highly agriculturally productive Indo-Gangetic River Basin.

[2] Both the summer monsoon and the seasonal snow melt from the Himalayan glaciers and snowpacks are indispensable to the livelihood of the downstream densely populated Indo-Gangetic Plains (IGP). In addition to the heavy particulate pollution comprising of sulfates, soot, and other anthropogenic aerosol species [Guttikunda et al., 2003; Bond et al., 2004], the IGP has long been recognized to be strongly affected by seasonal (premonsoon) mineral dust transport from various Southwest Asian arid regions including the swath of desert that stretches from Iran through Afghanistan and Pakistan, northwestern India (Thar desert), and the Arabian Peninsula [Grigoryev and Kondratyev, 1981; Middleton, 1986; Prospero et al., 2002], which strongly influences the regional aerosol optical properties [Dey et al., 2004; Singh et al., 2004; Singh et al., 2005; Prasad and Singh, 2007; Pandithurai et al., 2008; Gautam et al., 2009c]. As a result, the atmospheric column aerosol loading during the premonsoon season is highest over the IGP, annually [Singh et al., 2004; Jethva et al., 2005; Gautam et al., 2007].

[3] The premonsoon period is also crucial to the summer monsoon onset and rainfall through large-scale land–ocean-atmosphere coupled dynamical processes, i.e., the rapid heating of the Indian landmass and the elevated heat source over the Himalayas–Tibetan Plateau cause overturning of the meridional tropospheric temperature gradient resulting in moist air influx and rainfall over the continent. The regional tropospheric temperature distribution, particularly the premonsoon heating over the Himalayas–Tibetan Plateau, is important in modulating the onset and intensity of the Indian summer monsoon and has long been recognized in influencing the monsoon circulation and rainfall [Flohn, 1957; Yanai et al., 1992; Webster et al., 1998]. Along with the various modeling efforts on the subject of aerosol–monsoon water cycle coupling (as referred earlier), recently a few studies also investigated the aerosol-precipitation linkages and feedbacks in the critical premonsoon and monsoon periods through means of various observational and reanalysis parameters, with emerging patterns found in the interannual variability and trends of aerosol loading, rainfall, and tropospheric temperatures over South Asia and particularly over the IGP and Himalayan region [Lau and Kim, 2006; Bollasina et al., 2008; Bollasina and Nigam, 2009; Gautam et al., 2009a, 2009b; Shrestha et al., 2010].

[4] However, both the climate modeling and long-term mechanistic observational analyses can benefit from an in-depth understanding of the aerosol properties, vertical characterization, solar absorption, and radiative effects over the source region, e.g., IGP in this case. Thus, in this paper we focus on the IGP and utilize various spaceborne Moderate Resolution Imaging Spectroradiometer (MODIS), Clouds and the Earth’s Radiant Energy System (CERES), and CALIPSO) and ground-based measurements (Sun photometer, solar flux pyranometer) together with a one-dimensional radiative transfer model to characterize the heavy premonsoon aerosol loading and associated solar radiative effects at top-of-atmosphere (TOA) and surface (including estimation of single scattering albedo (SSA) and shortwave heating rates) over the Gangetic Plains, where dust transport occurs at elevated altitudes. We also investigate temperature trends of the free troposphere over the Hindu Kush–Himalayas–Tibetan Plateau (HKHT) from long-term satellite microwave measurements (1979–2007), which is important to the onset and intensity of the summer monsoon and in general for the regional hydro–glaciological resource and climate.

2. Data Sets
2.1. AERONET-Retrieved Aerosol Optical Properties
[5] In this study, we use the Version 2 retrievals of aerosol properties from a CIMEL Sun photometer over Kanpur in the central IGP, part of the Aerosol Robotic Network (AERONET) project [Holben et al., 1998] for the period 2001–2006. This data set is in the form of Level 2.0 quality-assured product after cloud screening and necessary post calibration adjustments. Radiometric measurements of the direct sun and diffuse sky radiance are made within the spectral range 340–1020 nm. The direct sun measurements are made at eight spectral channels (340, 380, 440, 500, 670, 870, 940, and 1020 nm) and sky radiance measurements are made at four spectral channels (440, 670, 870, and 1020 nm). The aerosol optical depth (AOD) is retrieved at all channels [Holben et al., 1998] other than the 940 nm channel, which is used to retrieve atmospheric water vapor content. The CERES sky radiance measurements together with the direct sun measurements of optical depths are used to retrieve optical equivalent aerosol size distributions and refractive indices and hence deduce the spectral dependence of SSA. Version 2 retrievals utilize the enhancements described by Dubovik et al. [2006] over the Version 1 algorithm of Dubovik and King [2000].

2.2. CERES Top-of-Atmosphere Shortwave Flux
[6] In order to understand the effect of aerosols on the radiant energy flux, we use the TOA flux observations from the spaceborne CERES instrument. The CERES provides
broadband radiance measurements at the TOA, both in the longwave and shortwave [Wielicki et al., 1996]. We use the Single Scanner Footprint (SSF) data product that contains aerosol and cloud properties from the MODIS for each CERES footprint and reports measured TOA radiances, which are converted to fluxes using angular distribution models (ADM) derived from CERES radiance measurements [Loeb and Kato, 2002]. An ADM is a set of anisotropic factors and represents the CERES radiance dependence on different scene types associated with angular variations. The clear land and desert ADMs account for seasonal variations in surface type and are defined for a 1° by 1° equal area region with a temporal resolution of 1 month [Loeb et al., 2005]. The best estimate of the error in CERES TOA flux due to the radiance-to-flux conversion is 3% (10 Wm−2) in the shortwave (SW). The overall bias in regional monthly mean SW TOA flux is less than 0.2 Wm−2 and the regional RMS error ranges from 0.70 to 1.4 Wm−2. In this study, we use the SW flux data product with spatial resolution of ~20 km nadir.

2.3. CALIOP Backscatter Profile

[9] Aerosol vertical information is obtained from the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument that provides global vertically resolved measurements of aerosol and cloud distribution in the atmosphere [Winker et al., 2007]. CALIOP can observe aerosols over bright surfaces and beneath thin clouds as well as in clear sky conditions. We use the Level 1B data that contain high-resolution lidar profiles, including 532 nm and 1064 nm attenuated backscatter and depolarization ratio at 532 nm. The vertical resolution for both the profile-specific and fixed altitude arrays is 30 m.

2.4. Microwave Sounding Unit Tropospheric Temperature

[10] Long-term analysis of tropospheric temperatures is carried out using data from the Microwave Sounding Unit (MSU) sensor for the period 1979–2007. The MSU operating on NOAA satellites makes measurements of microwave radiance in four channels ranging from 50.3 to 57.95 GHz. These four channels measure the atmospheric temperature in four thick layers spanning the surface through the stratosphere. The brightness temperature for each channel corresponds to an average temperature of the atmosphere averaged over that channel’s weighting function. For example, in the case of channel 2, Temperature Middle Troposphere (TMT), the majority of the signal is from a thick layer in the middle troposphere at altitudes from 4 to 7 km, with some contributions from the surface and the stratosphere. The MSU data set is corrected for long-term drifts in the measurements that arise from drifts in local measurement time that can alias the local diurnal cycle into the long-term record [Mears et al., 2003]. We use the Version 3.2 MSU gridded monthly mean atmospheric temperature products (with spatial resolution of 2.5 degrees available from the Remote Sensing Systems (RSS) (http://www.ssmi.com). In addition, we use the methodology of Fu et al. [2004] to minimize the cooling influence of the stratosphere penetrating into the tropospheric signal. Further details are provided in section 4 in relation with the tropospheric temperature trend analysis.

2.5. Radiative Transfer Model

[11] We used a one-dimensional delta-four-stream radiative transfer program for plane-parallel atmospheres [Liou et al., 1988; Fu and Liou, 1993] to estimate the SSA and radiative heating of the aerosol-laden atmosphere during premonsoon season. The SW spectrum (0.2–4.0 µm) is divided into 6 bands: 0.2–0.7 µm, 0.7–1.3 µm, 1.3–1.9 µm, 1.9–2.5 µm, 2.5–3.5 µm, and 3.5–4.0 µm. The visible band is further divided into 10 subvisible bands. Standard mid-tropical atmosphere was adopted in the Fu-Liou radiation scheme with instantaneous column AOD and water vapor measurements from a CIMEL Sun photometer. Spectrally equivalent SW surface albedo, with the Fu-Liou bands, was obtained from a compilation of the Surface and Atmospheric Radiation Budget working group (http://www-surf.larc.nasa.gov/surf/pages/bbalb.html), which uses several scene types defined by the International Geosphere Biosphere Programme [Briegleb et al., 1986]. These surface types are assumed on a 10 min (one-sixth of a degree) equal angle map covering the globe. Cropland land cover type was selected on the basis of the spectral curve source of Briegleb et al. [1986] and solar zenith angle adjustments were applied to the spectral surface albedo.

3. Results

3.1. Premonsoon Aerosol Characterization

3.1.1. Optical Properties

[12] The aerosol loading, in terms of the aerosol type and optical depth, undergo strong seasonal variation over the IGP with dust aerosols (coarse mode) dominating during premonsoon and monsoon seasons while fine mode anthropogenic pollution particles result in dense haze during postmonsoon and winter months [Dey et al., 2004; Singh et al., 2004; Girolamo et al., 2004; Gautam et al., 2007]. Figure 1a shows the climatology of AOD and Angstrom exponent (AE) for the six months of 2001–2006 in central IGP over Kanpur (26.5°N, 80.2°E), from the CIMEL Sun photometer data. Combined with the spectral behavior of AOD, the AE can be considered as a first-order indicator of size of the particles where low values (<1) correspond to large-sized particles and higher values indicate the presence of fine mode particles. The column aerosol loading is highest during the May–June period with peak mean value of 0.8 in May. Grey bars in Figure 1a show progressive increase in particle size from the winter period (AE ~1.3) to the premonsoon period with minimum value of AE (0.36) in May. Greater solar extinction during dust events (in May and early June) is frequently observed in daily data with significant drop in AE (where AE is often close to zero).

[13] In addition to the AOD and the associated wavelength exponent, the aerosol size distribution can also be used to infer the size of particles. Winter months (November–December–January) mark the prevalence of anthropogenic pollution, with minimum dust influence, where the predominant fine mode peak is found to be 0.058 µm2/µm2 and centers around 0.19 µm (Figure 1b). It should be noted that the typical winter period in northern India is December through February, however we include the month of November in the analysis since distribution retrieval is generally more reliable for high aerosol-loading conditions.
Size distribution is highest in the coarse mode during the dust-laden premonsoon period and follows a bimodal log normal distribution with six-year mean values of 0.29–0.3 μm³/m² centered around 2.2–2.9 μm radius (Figure 1b). The small mode peak around 0.11 μm is most likely due to the anthropogenic aerosol content in the regional atmosphere. Consistent with the ground-based characterization of increased dust loading from March through June, spatial distribution of the climatological mean AOD, from daily Level 2 Aqua MODIS dark target [Levy et al., 2007] and deep blue [Hsu et al., 2004] aerosol products for the period 2003–2009, indicate buildup of enhanced premonsoon aerosol loading (April to June) from the northwestern arid regions of India and Pakistan stretching into the IGP and the Himalayan foothills (Figure 2). Long-range transport of dust from the Arabian Peninsula also contributes to the net regional aerosol loading with marked increase in AOD over the northern Arabian Sea in May–June relative to April. It should be noted that the northern parts of India receive monsoon rainfall in the latter half of June, and therefore, both the MODIS and AERONET monthly mean June AOD is likely to be biased because of increased cloudiness during this period and other monsoon months (July–September), compared to the relatively cloud-free and dry April–May period.

3.1.2. Vertical Distribution

While the radiometric measurements provide valuable data, the derived information only indicates the column-integrated heavy aerosol loading. Vertical distribution of aerosols is much required for inferring regional aerosol-induced climate perturbations. It was recently shown that Asian dust originating in China can transport to great distances around the globe and can extend to elevated altitudes in the upper troposphere potentially affecting the Earth’s radiation budget [Uno et al., 2009]. Over the Gangetic-Himalayan region, dust transport reaches up the slopes of the Himalayas and is further vertically elevated to higher altitudes because of the strong westerly premonsoon winds coupled with enhanced convection and pressure gradient resulting from large topographic differences. Regional and long-range dust transport reaching the IGP has been modeled in back-trajectory analyses [Dey et al., 2004; Prasad and Singh, 2007] with satellite observations also indicating the spatial extent of the enhanced aerosol loading over the foothills of the Himalayas during premonsoon season [Gautam et al., 2009c]. In addition, surface observations of aerosol properties indicate episodic dust transport from the

Figure 1. (a) Aerosol optical depth and Angstrom exponent climatology over Kanpur AERONET in central IGP during 2001–2006. The strong seasonal variability in the aerosol loading and the size of particles across the seasons is evident. (b) Aerosol volume size distribution for premonsoon period (April–May–June) and winter period (November–December–January) during 2001–2006 from AERONET Sun photometer observations over Kanpur.

Figure 2. Climatology of monthly mean aerosol optical depth for April, May, and June from daily Level 2 Aqua MODIS aerosol products (dark-target and deep blue) for the period 2003–2009.
Thar desert reaching up the central Himalayas resulting in significant increase in the aerosol number concentrations in coarse modes and influencing other aerosol optical properties [Hegde et al., 2007]. Furthermore, recently, a series of papers has shown that the westerly–windblown mineral dust transport is critical to the interannual variation of the enhanced premonsoon aerosol loading and largely influences the aerosol optical properties and chemical composition at various elevated sites along the southern slopes of the Himalayas [Hyvärinen et al., 2009; Komppula et al., 2009; Kuniyal et al., 2009; Bonasoni et al., 2010; Gobbi et al., 2010; Ram et al., 2010]. Although a rarity, the trans-Himalayan transport of aerosols from the foothills in Nepal advected into Tibet has also been observed using a sequence of surface meteorological and condensation nuclei measurements [Hindman and Upadhyay, 2002].

[15] Here we utilize the vertically resolved capability of CALIOP backscatter measurements to study aerosol vertical distribution over the IGP from Level 1b attenuated backscatter profiles. Figure 3a shows an example backscatter image of a CALIOP transect (indicated in the inset) on 9 May 2008 from southern India across the IGP and the Himalayas–Tibetan Plateau region. The total attenuated backscatter from aerosols is indicated in the green-yellow-red color scale and clouds are marked by pink, grey and white colors. Vertically extended aerosols (up to 5 km) along the slopes of the Himalayas and over the IGP are clearly captured by the attenuated backscatter associated with aerosols. Extinction-derived depolarization ratios from the CALIOP data suggest the presence of greater concentration of non-spherical particles over the IGP and the slopes (25°N–29°N) indicated by higher depolarization ratio values, compared to the relatively fine mode dominated aerosol loading over southern India (12°N–20°N) (Figure 3b). This pattern was also shown in a recent paper such that the aerosol loading over northern India during the 2008 premonsoon season was associated with significantly greater dust contribution compared to southern India where fine mode anthropogenic aerosols were prevalent [Gautam et al., 2009c]. On the basis of particle sphericity inferences from the depolarization ratio, the study suggested that the AOD from CALIOP (from March to May) was associated with ∼50% dust contribution over northern India with the month of May being the dust-dominant period.

[16] In order to understand the regional aerosol vertical extent, backscatter profiles were obtained over the Indian subcontinent from 70°E to 85°E and 5°N to 30°N for the period April–May 2008. Since the western subcontinent is influenced by greater dust transport, the coverage for CALIOP data analysis was restricted to 85°E in order to focus on the dust source and transport. Cloudy profiles in CALIOP Level 2 cloud layer products are identified on the basis of the cloud-aerosol discrimination method developed by Liu et al. [2004], recently used in a global study for aerosol vertical characterization [Liu et al., 2008]. The individual profiles were subjected to cloud screening by using Level 2 cloud-layer products, where cloud top and bottom are reported for each cloud layer found in a single vertical profile. In order to make the vertical resolution of the Level 1b measurements consistent with the 5 km resolution cloud-layer product, backscatter profiles were averaged to a 5 km horizontal resolution (15 lidar shot averaging) to screen the signal associated with attenuation by clouds. In addition, the profiles were further screened for residual cloud signals based on a fixed threshold value (from visual inspection of CALIOP profiles) where aerosol-attenuated backscatter usually lies less than 0.005/km/sr, while the backscatter due to clouds is typically greater than 0.006/km/sr.

[17] Figure 4 shows the latitudinal mean of all cloud-free profiles over 70°E–85°E from surface to ∼8 km obtained from the daytime and nighttime CALIOP data for the period April–May 2008. There is a difference of 12 h in the two temporally separated lidar scans with the daytime overpass taking place around 1340 local time. Although there is a conspicuous difference in the daytime (Figure 4a) and nighttime (Figure 4b) plots because of the large influence of noise embedded in the daytime data, both plots show similar latitudinal variation patterns over the northern and southern India. There is a sharp contrast in the aerosol-induced backscatter across northern and southern India with significantly higher backscatter over northern India encompassing the Thar desert and the IGP around 25°N. The desert dust lifting over the Thar desert is characterized by near-surface high backscatter and a well mixed turbulent boundary layer in general over northern India. On the other hand, central India is associated with peak lidar intensity above the boundary layer around 3–3.5 km. The largest backscatter...
over northern India is found in the lower troposphere indicating the transport of dust into the IGP (most likely mixed with local heavy pollution) steered aloft by the enhanced convection during premonsoon season.

[18] In addition to differences in aerosol-induced backscatter, the aerosol vertical extent also significantly varies with aerosols over southern India confined around 3–4km (consistent with aircraft measurements over southern India reported by Satheesh et al. [2008]) while the CALIOP data indicate the aerosol layer top extending to ∼5km over northern India. We restricted the data analysis to 30°N in order to focus over the IGP and foothill region, and therefore eliminate the steep topography of the Himalayas to avoid misrepresentation of the aerosols aloft. Over our focus region where dust transport occurs, i.e., in the IGP centered over Kanpur (25°N–27°N, 78°E–82°E), the daytime aerosol-induced backscatter peaks around 3 km, whereas the nighttime backscatter peak is confined within the boundary layer, an indication of the effect of daytime convection compared to relatively stable atmospheric conditions during night (Figure 5).

3.2. Radiative Effects

3.2.1. Aerosol Forcing Efficiency at TOA From CERES

[19] The direct aerosol shortwave radiative forcing at TOA in cloud-free conditions is defined as

\[ F = F_{\text{aer}} - F_{\text{clr}}, \]

where \( F_{\text{clr}} \) is the broadband shortwave flux in cloud-free conditions with no aerosols in the atmosphere, while \( F_{\text{aer}} \) is the broadband flux scattered upward in the presence of cloud-free aerosol-laden atmosphere. The aerosol radiative forcing efficiency is defined as the change in direct shortwave flux per unit AOD, i.e., \( \text{Wm}^{-2}/\text{AOD} \). The efficiency is given by the slope of the linear regression between shortwave flux and AOD. The slope, which represents the efficiency at TOA (in this case), also indicates the absorbing nature of the column aerosol loading. Previous studies have demonstrated the success and feasibility of using this approach for the estimation of aerosol forcing from satellite-derived TOA SW flux such as from the spaceborne Earth Radiation Budget Experiment (ERBE) and CERES sensors [Hsu et al., 2000; Zhang et al., 2005].

[20] In this study, we use the TOA flux to derive the aerosol forcing efficiency for the premonsoon period (April–May–June) during 2001–2006. The last two weeks worth of data from June was not considered in the analysis since the IGP receives monsoon rainfall around this period and is influenced by increased cloudiness. The spatial resolution of each SSF pixel is 20 km × 20 km at nadir, and the TOA flux data were gridded into 0.25° × 0.25° format. An essential preprocessing step prior to the estimation of aerosol forcing was to screen the CERES data for cloud contamination by using the colocated MODIS cloud fraction information (from the same platform) in the SSF product. A stringent cloud-screening scheme is employed with CERES pixels
associated with cloud fraction higher than 1% being filtered out and not considered in further analysis. It is likely that cases of thick dust/haze plumes were filtered out from the analysis, however relaxing the threshold may add to uncertainties in the estimation of forcing efficiency and may also affect accurate knowledge of aerosol absorption.

Figure 6 shows the CERES TOA flux from Terra collocated with AOD from the AERONET Sun photometer at Kanpur. The instantaneous TOA forcing efficiency between the AOD (±30 min of the Terra overpass and within 20°–30° solar zenith angle interval) collocated with flux observations is given by the slope as 19.09 ± 6.4 W m⁻² per unit optical depth. Additionally, the instantaneous forcing can be calculated by using the intercept (213.2 ± 4.9 W m⁻²), obtained from linear regression between TOA flux and AOD, as an approximation of clear-sky flux value ($F_{\text{clr}}$). The impact of aerosol loading is observed in the increase in forcing value ($F$) from −13.5 to 45.1 W m⁻² with respect to an increase of AOD from 0.34 to 1.25, respectively. However, the instantaneous TOA forcing and the forcing efficiency in Figure 6 is derived from a relatively loose scatter of points ($r^2 = 0.17$) with a large standard error (6.4 W m⁻²) and thus represents a weak response of aerosol forcing at TOA, most likely caused by the impact of underlying higher surface albedo (especially at low aerosol-loading conditions). Hence, the CERES-derived TOA forcing over the IGP during the premonsoon period may not be sufficient to quantify the aerosol forcing and solar absorption, and therefore, surface forcing measurements as described in the following section are used to better understand the aerosol radiative effects.

### 3.2.2. Surface Flux Measurements

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### Surface Flux Measurements

Broadband surface flux measurements are used to assess the solar flux attenuation due to aerosols from a Kipp and Zonen CM 21 pyranometer that measures the total solar spectrum. The pyranometer is part of the Solar Radiation Network (Solrad-Net), a companion to the AERONET, colocated with the CIMEL Sun photometer at Kanpur in central IGP and records instantaneous downwelling irradiance at 2 min intervals. Instantaneous flux measurements were subjected to a cloud screening procedure similar to the methodology of Conant [2000] and Schafer et al. [2002], wherein a time variability filter was required to eliminate scattered and peripheral clouds in the hemispherical field of view. Flux measurements temporally colocated with concurrent CIMEL Sun photometer measurements within a ±2 min time frame were selected for further analysis. Data points were restricted to a narrow interval between 25° and 35° solar zenith angle in order to focus on the aerosol attenuation of flux.

The instantaneous aerosol radiative forcing efficiency at the surface is estimated to be $-187.6 \pm 17.4$ W m⁻² (Figure 7a). In comparison to the TOA forcing estimated from CERES observations, surface forcing efficiency from pyranometer measurements is derived from a close-fit scatter ($r^2 = 0.6$) suggesting greater confidence in the surface forcing values. The combination of large surface forcing efficiency and weak TOA forcing is an indication of strong absorption associated with the high aerosol loading over this region. Model-calculated and pyranometer observations of surface forcing efficiency per unit optical depth in Delhi, ∼350 km northwest of Kanpur, during the entire premonsoon period (April to June) of 2003 were reported to be $-161.5$ and $-136.3$ W m⁻², respectively [Singh et al., 2005]. These values are less than that over Kanpur since the mixture model for radiative transfer calculations over Delhi consisted of desert dust and urban aerosols,

![Figure 5](image5.png)

**Figure 5.** Cloud-screened mean daytime (dotted black) and nighttime (dotted grey) backscatter ($\text{km}^{-1} \text{sr}^{-1}$) profile centered over Kanpur in the IGP (25°N–27°N, 78°E–82°E). Smoothed profile after a seven-point moving average filter for daytime (black solid) and nighttime (grey solid). The daytime attenuated backscatter peaks around 3 km, whereas the nighttime backscatter peak is confined within the boundary layer.

![Figure 6](image6.png)

**Figure 6.** Instantaneous aerosol forcing efficiency at TOA from CERES Single Scanner Footprint (SSF) data colocated over Kanpur Sun photometer AOD during premonsoon season for the period 2001–2006. The instantaneous forcing efficiency ($f_e$) is estimated to be $+19$ W m⁻².
whereas additional soot may be present and mixed with other aerosol species over Kanpur (as discussed in the next section).

3.2.3. Single Scattering Albedo Estimation

[25] The instantaneous AERONET-retrieved AOD values over Kanpur, along with column water vapor retrievals, were provided as input to the Fu–Liou radiation model. The intrinsic aerosol profile in the Fu–Liou code is assumed as exponential with the aerosol extinction scale height as an indicator of vertical distribution. In this study, aerosol profile from the daytime cloud-screened CALIOP observations was provided as input to the radiative transfer model inferred as discussed in section 3.1.2. Mixing ratios of the different aerosol models were varied iteratively until a close agreement was achieved in the relationship between the observed and model-simulated flux (at surface) with AOD. The final calculated external mixture comprised 45% dust, 48% water soluble aerosols with an addition of 7% soot and was used as input to the Fu–Liou radiation model. This step is essentially a tuning procedure, geared toward matching the model simulations close to the observations, as a means to constrain the model inputs and thus provide an estimate about the aerosol solar absorption and heating rates. The SSA of the calculated aerosol mixture, at ~550 nm, is estimated to be 0.89 ± 0.01, and a close agreement was found between the spectral SSA from AERONET and model-derived SSA with only a difference of 2%–3% (Figure 8a). In addition, the model-simulated forcing efficiency at surface is also in close agreement with the observed pyranometer-derived forcing efficiency (Figure 7b). The modeled forcing efficiency slightly overestimates that of observations indicated by the slope value of ~1.05. The diurnal mean surface forcing efficiency (24 h average integrated over each solar zenith angle) is estimated to be −70 W m⁻² from observations of 27 d during the April–June 2006–2007 period. Additionally, the diurnal surface and TOA forcing values (for the same period) range from −11 to −79.8 W m⁻² and +1.4 to +12 W m⁻², while the mean forcing value for the entire period is −44 W m⁻² and +6.8 W m⁻² for surface and TOA, respectively. Our calculated surface forcing values, constrained with solar flux measurements, are in close agreement with previous model–based estimates over the IGP [Dey and Tripathi, 2008; Pandithurai et al., 2008].

[26] It should be noted that the AERONET SSA is not a direct retrieval and is obtained from inversion of sky radiance measurements [Dubovik and King, 2000] and therefore should not be treated as ground truth as with the case of their most reliable AOD product. However, the close agreement between our model calculations with the spectral SSA from AERONET as well as the surface forcing efficiency from the model and observations provides greater confidence in the derived aerosol solar absorption and the calculated external mixture. On the other hand, the TOA forcing efficiency calculated from the model (13.3 ± 1.9 W m⁻²) is not in close agreement with the relatively weak aerosol-induced response of observed CERES shortwave flux at TOA (19.09 ± 6.4 W m⁻², r² = 0.17) (Figure 6). It is also noted that the CERES observations used in this study are for the period 2001–2006, whereas the surface forcing analysis is carried out for the two-year premonsoon period 2006–2007 when the pyranometer data is available. Nevertheless, the combination of strong surface forcing and weak TOA response
to changes in AOD is consistent with the signature of absorbing aerosols over land.

[27] The instantaneous shortwave heating rate of the computed external mixture, with other input parameters as described above, was also estimated using the radiative transfer model. The heating rate profile is found to have a peak value of ∼6 K/d around 3 km (Figure 8b) and appears to penetrate well into the midtroposphere leading to increased heating rates in the 5–6 km altitude range. The daily average solar atmospheric heating (24 h) also follows a similar profile throughout the troposphere, peaking around 3 km with a mean value of ∼2 K/d. We also found strong temperature enhancement signal in instantaneous profiles, associated with heavy dust-loading conditions, from the Atmospheric Infrared Sounder (AIRS) aboard Aqua satellite. Temperature profiles from the AIRS instrument (using microwave retrieval) were colocated over AERONET measurements at Kanpur for a four-year period from 2003 to 2006 in May–June and were subsequently grouped on the basis of high dust-loading and low dust-loading days with respect to AE. The AIRS temperature profiles during the four-year period reveal a significant temperature difference of 2–2.4 K in the middle troposphere (4–7 km altitude range) associated with high dust loading compared to that of low dust-laden atmosphere (not shown here). It is very likely that the observed temperature enhancement may simply be a consequence of the hot air mass transport from the northwestern desert/arid region into the IGP. However, it has been demonstrated in previous studies such as by Alpert et al. [1998] that dust forcing increases tropospheric temperatures, as indicated in their observational and modeling study over the Sahara, and therefore, the association of the observed temperature enhancement due partially to aerosol solar absorption (dust mixed with absorbing aerosols such as soot over the IGP) may not be ruled out. A more rigorous approach involving extensive analysis of air mass coupled with enhanced dust loading as well as isolating the meteorology and including uncertainty analysis of dust impact on AIRS profiles is required to further construe the temperature enhancement in instantaneous profiles.

4. Tropospheric Temperature Trends

[28] In this section, we analyze long-term tropospheric temperature trends from the MSU data over the Indian monsoon region (40°E–100°E, 0°N–40°N) for the period 1979–2007. First, the brightness temperatures for the two channels, namely, midtropospheric temperatures (TMT or channel 2) and the lower stratospheric temperatures (TLS or channel 4), were obtained from the MSU data archive of the RSS [Mears et al., 2003]. We then use the channel 4 temperature to minimize the stratospheric cooling influence in channel 2 following the methodology of a previous study [Fu et al., 2004] as channel 4 is sensitive mainly to stratospheric temperature changes. Fu et al. [2004] define the free tropospheric temperature as the mean temperature between
850 and 300 hPa (T850−300). Using a global network of surface radiosonde observations, they derived this temperature from the measured brightness temperatures of MSU channels 2 and 4. The resulting temperature (T850−300) peaks at the same level as channel 2 but is 15% larger. Enhancement of the tropospheric temperature signal and its long-term global trends compared to earlier methodologies are discussed by the Intergovernmental Panel on Climate Change (IPCC) [2007, chap. 3].

The tropospheric temperature trends during the premonsoon period were the subject of a recent study indicating a widespread temperature rise in the Gangetic-Himalayan region in the past three decades [Gautam et al., 2009a]. The western Himalayas, in particular, were found to have experienced a large sustained warming in May with appreciable warming also observed over the Tibetan Plateau in the three-decade long MSU data set. The enhanced premonsoon warming trend (and the strengthened meridional land-sea temperature gradient) was studied in relation with increased loading of absorbing aerosols during the premonsoon season. Plausible amplification of the observed premonsoon warming is partly attributed to the Elevated Heat Pump effect [Lau et al., 2006; Lau and Kim, 2006] of aerosols, particularly, enhanced dust loading over northern India mixed with heavy soot emissions in the IGP.

Here, we further report that the Himalayas have experienced significant annual mean tropospheric warming in the past three decades. During the period 1979–2007, there is an area average warming trend of 0.21°C/decade ± 0.08°C/decade (ranging from 0.15°C/decade to 0.34°C/decade at pixel level) in annual mean, found over the Himalayan–Hindu Kush snowpack region with large warming spanning the western central Himalayas compared to a relatively smaller positive trend over the Hindu Kush region, eastern Himalayas, and the Tibetan Plateau (Figure 9). The maximum area-average warming over the western Himalayas was also found previously in the premonsoon season, potentially amplified by aerosol solar absorption associated with enhanced regional dust loading and transport from over the northwestern arid region in India, in close proximity to the western Himalayas compared to the Hindu Kush region and eastern Himalayas [Gautam et al., 2009a]. The tropospheric warming over the western Himalayan region, both in annual mean (0.026°C/yr ± 0.009°C/yr) and May (0.067°C/yr ± 0.033°C/yr), significantly exceeds the warming associated with the Hindu Kush region (annual mean, 0.02°C/yr ± 0.008°C/yr; May, 0.039°C/yr ± 0.028°C/yr) and eastern Himalayas (annual mean, 0.018°C/yr ± 0.008°C/yr; May, 0.034°C/yr ± 0.023°C/yr) (Figure 10). Table 1 shows the 29-year period trends (with related error and statistics) in the annual mean and May over the Hindu Kush and western and eastern Himalayan regions. Trends are calculated after removing the climatological monthly mean in order to minimize the effect of seasonal variation in the time series. In terms of percentage, the annual mean western Himalayan warming is 43% and 30% higher than the eastern Himalayan and Hindu Kush, respectively, with large warming in May (97% and 71% higher than the eastern Himalayan and Hindu Kush, respectively).

![Figure 9. Linear trend of annual mean tropospheric temperature (calculated from the anomaly) over South Asia from MSU data from 1979 to 2007. Dotted black ellipses denote the Hindu Kush and eastern and western Himalayan snowpack regions as indicated by their labels.](image-url)
We also provide temperature trends obtained directly from the RSS data (Table 1), i.e., before correcting for stratospheric cooling influence. The RSS trend values also show similar characteristic large western Himalayan warming compared to smaller trend (positive) over the eastern Himalayan and the Hindu Kush region, e.g., the annual mean (May) trend is 58% (107%) and 26% (80%) higher than the eastern Himalayan and Hindu Kush, respectively. It should be noted that, in general, the RSS trend values are substantially lower than the stratospheric cooling corrected values (following Fu et al., 2004) and can be partially attributed to the stratospheric cooling influence in the MSU channel 2 weighting function. However, the trends reported here are not carried out to highlight the differences or reconcile the two temperature data sets but simply show that the concentrated western Himalayan warming is of local scale and not representative of a widespread tropospheric temperature trend over the entire HKHT region. This strengthens the observation that, in addition to the greenhouse warming signal, the enhanced western Himalayan–Gangetic warming is a likely response of a localized phenomenon, e.g., aerosol solar absorption. Here,

Figure 10. Time series of the area-average annual mean (top panel) and May (bottom panel) tropospheric temperature anomaly from 1979 to 2007 over the Hindu Kush (solid blue), eastern Himalayan (solid black), and western Himalayan (solid red) regions after correction for the stratospheric cooling influence in the MSU data [Fu et al., 2004]. The linear trend lines (dotted) and the regression equation are also shown for the three regions with same color.
it is worth pointing out that the warming trend observed over the HKHT region may also be influenced by increased snow surface emissivity associated with the premonsoon snow melt period and declining snow cover, as observed in the period 1979–2001 [Goes et al., 2005]. However, this important factor would also depend on any existing spatial patterns in the declining snow cover information, which is not clear at this time and remains to be investigated further.

[32] On the basis of model simulations, Ramanathan et al. [2007] estimated an annual mean lower-tropospheric (less than 5 km) warming rate of 0.24°C/decade over the Himalayan–Hindu Kush region from the 1950s due to the combined forcing (with equal contributions) of aerosols and greenhouse gases. Their model simulations mainly accounted for the increasing soot, sulfate, and greenhouse gases since the 1930s over India [Novakov et al., 2003]. Our observational results largely represent the 4–7 km layer from the MSU data, including surface contribution over the elevated Himalayas, and thus reveal enhanced warming of the middle troposphere over the Himalayan–Hindu Kush region (0.21°C/decade ± 0.08°C/decade) with the most pronounced warming over the western Himalayas (0.26°C/decade ± 0.09°C/decade). Thus, it appears that the observed warming in the past three decades, as shown here, may be amplified by the solar absorption caused not only by soot and greenhouse gases but caused also by the heavy premonsoon mineral dust transport (and mixing with other carbonaceous aerosols) in the Gangetic–Himalayan region. This anomalous warming at elevated altitudes could as well be partially attributed to the vertically extended aerosols, particularly the influence of dust loading (up to 5 km over the Gangetic–Himalayan region as clearly shown here using the spaceborne CALIOP data) associated with enhanced convection and well-mixed turbulent boundary layer in the premonsoon season. On the contrary, the vertical extent of aerosol plume was confined within the surface and 3 km in the GCM simulations of Ramanathan et al. [2007], on the basis of observations over the Arabian Sea from the Indian Ocean Experiment.

5. Concluding Remarks

[33] Climate warming has also been previously observed over the Tibetan Plateau, using surface observations [Liu and Chen, 2000], with a temperature increase of 0.16°C/decade for the period 1955–1996, which is less than that over the Himalayas found from our study based on MSU data. However, the highest warming reported by Liu and Chen [2000] over elevated sites (~0.34°C/decade) is close to our finding over the Himalayas. Globally, the tropospheric warming rate from MSU observations (from previous studies) indicate an increasing trend of 0.04°C–0.20°C per decade for the period 1979–2004 [IPCC, 2007, and references therein]. Over the foothills and middle Himalayan regions in Nepal, the warming rate is even faster, estimated at 0.6°C–1.2°C per decade for the period 1977–94 [Shrestha et al., 1999]. Recently, Prasad et al. [2009] also reported the spatiotemporal variability in warming trends over the Himalayas and the western–eastern gradient which was previously shown to be most pronounced during the premonsoon dust-laden season [Gautam et al., 2009a]. On the basis of these differences in warming rates, it may be argued that local forcing and feedback processes, in addition to global warming, could play an important role in causing the accelerated warming rate. Thus, as reported here, the maximum warming rate found over western Himalayas (0.26°C/decade ± 0.09°C/decade) in particular, and the area average warming over the Himalayan–Hindu Kush region (0.21°C/decade ± 0.08°C/decade) in general, significantly exceed the global rate. We interpret the large amplification of the western Himalayan warming to be not likely due to aerosol radiative heating alone, especially during premonsoon season, but also due to other atmospheric feedbacks stemming from enhanced convection, accelerated snow melt [Lau et al., 2006; Lau et al., 2010], and water vapor enhancement [Kim et al., 2004; Prasad and Singh, 2007].

[34] In summary, this paper focuses on the satellite and ground-based characterization of the premonsoon dust transport from the western arid/desert regions in the Arabian Peninsula and the Thar desert in India into the IGP and over the foothills of the Himalayas. The bulk of the net aerosol loading during premonsoon is contributed by dust aerosols, observed in the optical properties including particle size distribution, optical depth and Angstrom exponent, as indicated by radiometric measurements in central IGP. The heavy aerosol loading over northern India, dominated by dust, is found to be vertically extended to elevated altitudes (~5 km) as indicated by CALIOP observations during April–May 2008 and is in sharp contrast with the aerosol vertical extent over southern India (up to 3–4 km) and the northern Indian Ocean. We used Sun photometer measurements, CALIOP-derived backscatter profiles, and surface solar flux measurements to derive the aerosol absorption and heating rates by utilizing a radiative transfer model. The premonsoon aerosols are found to be significantly absorbing suggested by the model-calculated SSA value of 0.89 ± 0.01, which is in close agreement with the AERONET-derived SSA over Kanpur in
central IGP. Model-simulated solar heating peaks in the lower troposphere with enhanced heating penetrating into the middle troposphere (5–6 km) caused by vertically extended aerosols over the IGP.

[35] As reported here over the IGP and by others over elevated Himalayan sites [Ramana et al., 2004; Pant et al., 2006; Dumka et al., 2006; Gobbi et al., 2010; Bonasoni et al., 2010], the aerosol solar absorption in the Gangetic-Himalayan region plays a particularly important role on radiation budget, and more so because of its potential effects on the Indian summer monsoon circulation and rainfall [Menon et al., 2002; Ramanathan et al., 2005; Lau et al., 2006; Meehl et al., 2008]. The problem of the radiative-dynamical interactions via which aerosols may affect hydrological cycle processes becomes even more complex because of mineral dust transport that could cause significant solar absorption when mixed with other absorbing aerosol species such as soot. Over densely populated and heavily polluted source regions in the realm of monsoons such as South and East Asia, more observational studies are required to constrain climate models to simulate the response of both natural and anthropogenic aerosols on the net radiation balance and to better understand the associated potential effects of tropospheric warming and surface dimming on the monsoon and hydro-geologic resource variability in the Himalayan-Hindu Kush snowpack region.

Acknowledgments. This work is supported by grant from the NASA EOS Program, managed by Hal Maring. We thank the various agencies, portals, and science teams for making the ground and satellite data used in this study available in public domain, namely, AERONET, CALIPSO, CERES, MODIS, and MSU/RSS. Efforts of the AERONET PIs (B. Holben and R. Singh) in establishing and maintaining the Kanpur site are also acknowledged. We thank the anonymous reviewers for the useful comments in improving an earlier version of the manuscript.

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