Hindawi Publishing Corporation
Advances in Meteorology
Volume 2014, Article ID 202868, 5 pages
http://dx.doi.org/10.1155/2014/202868

Research Article

Aerosol Modulation of Ultraviolet Radiation Dose over Four Metro Cities in India

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Received 12 September 2013; Revised 20 November 2013; Accepted 21 November 2013; Published 2 January 2014

Academic Editor: Pavan S. Kulkarni

This paper discusses the influence of aerosols on UV erythemal dose over four metro cities in India. Tropospheric Emission Monitoring Internet Service (TEMIS), archived UV-index (UV-I), and UV daily erythemal dose obtained from SCIAMACHY satellite were used in this study during June 2004 and May 2005 periods covering four important Indian seasons. UV-Index (UV-I), an important parameter representing UV risk, was found to be in the high to extreme range in Chennai (8.1 to 15.33), moderate to extreme range in Mumbai and Kolkata (5 to 16.5), and low to extreme over Delhi (3 to 15). Average UV erythemal dose showed seasonal variation from 5.9 to 6.3 KJm^{-2} during summer, 2.9 to 4.4 KJm^{-2} during postmonsoon, 3 to 4.5 KJm^{-2} during winter, and 5.1 to 6.19 KJm^{-2} during premonsoon seasons over the four cities. To estimate the influence of aerosols on reducing UV dose, UV aerosol radiative forcing and forcing efficiency were estimated over the sites. The average aerosol forcing efficiency was found to be from -1.38 ± 0.33 to -3.01 ± 0.28 KJm^{-2} AOD^{-1} on different seasons. The study suggests that aerosols can reduce the incoming UV radiation dose by 30–60% during different seasons.

1. Introduction

Ultraviolet radiation, in spite of its nominal presence in solar spectrum, is important in human health perspectives. The UV region of the spectrum mainly consists of UV-C (200–280 nm), UV-B (280–315 nm), and UV-A (315–400 nm). Out of these UV-B is the most important spectral range, as it directly influences the human health. Enhanced exposure to UV-B can damage both terrestrial and oceanic organisms and also results in increases in the incidences of cataracts and skin cancer in humans [1, 2]. Very high levels of UV radiation also are reported to result in the extinction of minute biological species [3]. The impact of UV irradiance on human skin is characterized with UV erythemal dose. UV-index (UV-I) serves as a primary indicator of impact of UV radiation on human health. The UV radiation reaching the earth surface is modulated by the ozone concentration, cloud cover, solar zenith angle, and aerosols. The influences of ozone on UV radiation are well documented [4]. Several studies report the influence of cloud cover on UV radiation. Reference [5] reported that, for a solar zenith angle of 50°, average UV-B transmission was observed to be 30% for overcast skies and found to be ranging between 61 and 79% according to cloud amount. The paper [6] has shown that the effect of cloud for UV wavelengths is less than that for the whole solar spectrum and less than that for the visible part of the spectrum. However studies on influence of aerosols on UV are sparse, especially across Indian subcontinent [7–9]. A few studies reported the variation of UV radiation and UV-index over Indian region [10, 11]. However most of the studies ignore the aerosol component and its influence on UV radiative transfer. The role played by aerosols on the UV radiative transfer in the atmosphere is also uncertain [9]. Reference [12] has suggested that aerosol vertical (height) distribution can also affect surface UV irradiances by 2–5% for optical depth observations at visible wavelengths. And [13] has shown that the increase of anthropogenic aerosols has significantly decreased the biologically active UV radiation (5 to 18%) in nonurban areas of industrialized countries. It is suggested that aerosols are partially efficient to reduce UV radiation increase due to ozone depletion [14, 15]. Hence in this paper, the modulation of UV radiation by aerosols, quantified through aerosol forcing efficiency over four metro cities in India (Chennai, Mumbai, Delhi, and Kolkata), is discussed. The data and methodology are explained in Section 2. A detailed description of variations of UV erythemal dose, UV-I, AOD, and forcing estimates is explained in Section 3 and conclusions are provided in Section 4.

2. Data and Methodology

The locations selected for this study are four metro cities in India, which are characterized with high industrialization and high population density. Chennai (13.08°N; 80.27°E) is situated in south of India and is characterized with typical tropical conditions, namely, high solar irradiance and high humidity, throughout the year. Mumbai (18.97°N; 72.83°E) is in the western part of India and is the financial capital of India. It is a highly urbanized and industrialized area and is a peak point of air pollution. Kolkata (22.57°N; 88.37°E) is in the eastern part of India, located on the bank of river Ganges. New Delhi (28.61°N; 77.23°E) is the political capital of India and is characterized by extreme weather events especially during premonsoon and winter seasons.

The Tropospheric Emission Monitoring Internet Service (TEMIS) archived daily datasets of UV erythemal (UVE) dose rate and UV-index (UV-I) are used in this study. TEMIS (http://www.temis.nl/general/index.html) provides global datasets of trace gases, aerosols, and UV products obtained from satellite instruments such as SCHIAMACHY (SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY), GOME (Global Ozone Monitoring Experiment), and ATSR (Along-Track Scanning Radiometer). UV-I and UVE used in the study are obtained from SCHIMACHY satellite products. The data are available for selected specific locations on http://www.temis.nl/uvradiation/SCIA/stations_uv.html. UV-I is a measure of UV risk to human health. The clear-sky UV-I is the effective UV irradiance (1 unit equals 25 mWm^{-2}) reaching the Earth's surface. The clear-sky UV-I is based on the CIE action spectrum for the susceptibility of the Caucasian skin to sunburn (erythemal) and it is valid for cloud-free conditions. The convention regarding UV-I is that, index values between 1 and 2 (minimal), between 3 and 4 (low), 5 and 6 (moderate), 7 and 9 (high) and above 10 (very high or extreme), which may be vulnerable to sensitive skin [9, 16]. UV erythemal dose (UVE) represents the UV irradiance weighted to represent the incoming UV radiation affecting human skin. It is the integration of the erythemal UV-I from sunrise to sunset, with a time step of 10 minutes. The integration takes cloud cover into account and hence estimates the daily erythemal UV dose, the total amount of UV radiation absorbed by human skin during the day, and is expressed in KJm^{-2}. Aerosol concentration is generally represented by aerosol optical depth (AOD) [17]. We used AOD at 550 nm obtained from MODIS level-3 products at a resolution of 1° × 1° over the study regions for this analysis.

There are several methods suggested in the literature to estimate radiative forcing [18–23]. To estimate the UV radiative forcing and hence forcing efficiency, we used the differential method suggested by [21]. In this method, the day with lowest AOD (highest UVE) is selected as a clear-sky day (no aerosol condition). The UV radiative forcing (UVRF) is estimated for each day using the equation as suggested in [24]:

$$\text{UVRF} = [F \downarrow - F \uparrow]_{\text{UVEeachday}} - [F \downarrow - F \uparrow]_{\text{UVEclearday}}, \quad (1)$$

where downward fluxes were obtained from TEMIS archived UVE irradiances. Upward fluxes were derived as product of average albedo in UV region (0.07) [25, 26] and downward UV erythemal radiation. The downward flux during day with minimum AOD (maximum UVE) was chosen as "clear-sky day" and upward fluxes for clear-sky day also were derived using albedo as explained above. The difference is calculated to obtain radiative forcing for each day as shown in the equation. In a month, we used only days whose AOD observations lie in condition suggested by [27] that is, AOD values falling within mean AOD ± 3σ condition. The UVE also was considered only for the corresponding days.

Since radiative forcing estimates in each day differ according to AOD conditions, it is standardized by estimating forcing efficiency (F_{eff}), defined as radiative forcing per unit increase in AOD [19, 21]. Generally F_{eff} is estimated by regressing between daily radiative forcing and daily mean AOD. However this method may not provide a representative value of surface forcing because of the day-to-day variation in the aerosol absorbing characteristics and scattering direction changes [21]. Hence we used the ratio method suggested by [19] by taking ratio of daily mean radiative forcing and AOD, to estimate forcing efficiency from radiative forcing over the four experimental locations.

3. Results and Discussions

3.1. Variations of UV Erythemal Dose, UV-Index, and AOD. Figure 1 shows the monthly variation of UV erythemal dose and UV-I over different metro cities in India. UVE dose and UV-I were found to be high during June over all the four sites. The reason for this high UV irradiance could be associated with the lower solar elevation during summer periods. The minimum values of UV-I and UVE were observed during December-January. This also could be mainly associated with high solar elevation angles of irradiance during winter compared to other factors such as cloud cover or ozone concentration variation [3]. The highest value of UVE was found to be up to 6.85 KJm^{-2} during June 2004 (over Mumbai). It steadily decreased and reached its minimum during December. The erythemal dose showed a steady increase from January 2005 and was found to reach a value of 6.7 KJm^{-2} (over Mumbai) during the month of May in 2005. The seasonal mean UVE was found to be 5.95 to 6.4 KJm^{-2} during monsoon months over the four locations. The seasonal mean UV erythemal dose values ranged between 2.86 and 4.36 KJm^{-2}, 2.04 and 4.45 KJm^{-2}, and 5.11 and 6.26 KJm^{-2}, respectively, during post-monsoon, winter and premonsoon over different locations (Table 1). In all seasons, Chennai showed higher UV

Table 1: Variation of UV erythemal dose, UV-aerosol forcing efficiency, and percentage of UVE reduction over Chennai, Mumbai, Kolkata, and Delhi.

Station	UV erythemal dose (KJm^{-2})			F_{eff} (KJm^{-2} AOD^{-1})			UVE reduction in %		
	Postmonsoon 04	Winter 04-05	Premonsoon 05	Postmonsoon 04	Winter 04-05	Premonsoon 05	Postmonsoon 04	Winter 04-05	Premonsoon 05
Chennai	4.36 ± 0.34	4.45 ± 0.77	6.19 ± 0.06	−2.06 ± 0.44	−1.31 ± 0.34	−2.07 ± 0.33	47.1	30	33.5
Mumbai	4.08 ± 0.58	3.82 ± 0.71	6.26 ± 0.54	−1.67 ± 0.23	−1.56 ± 0.32	−1.93 ± 0.23	41	41	31
Delhi	2.86 ± 0.39	2.04 ± 0.51	5.11 ± 0.99	−1.38 ± 0.33	−1.21 ± 0.34	−1.78 ± 0.3	48.3	60	35
Kolkata	3.72 ± 0.14	3.06 ± 0.67	5.48 ± 0.77	−1.86 ± 0.33	−1.71 ± 0.34	−3.01 ± 0.28	50.3	55.8	54.9

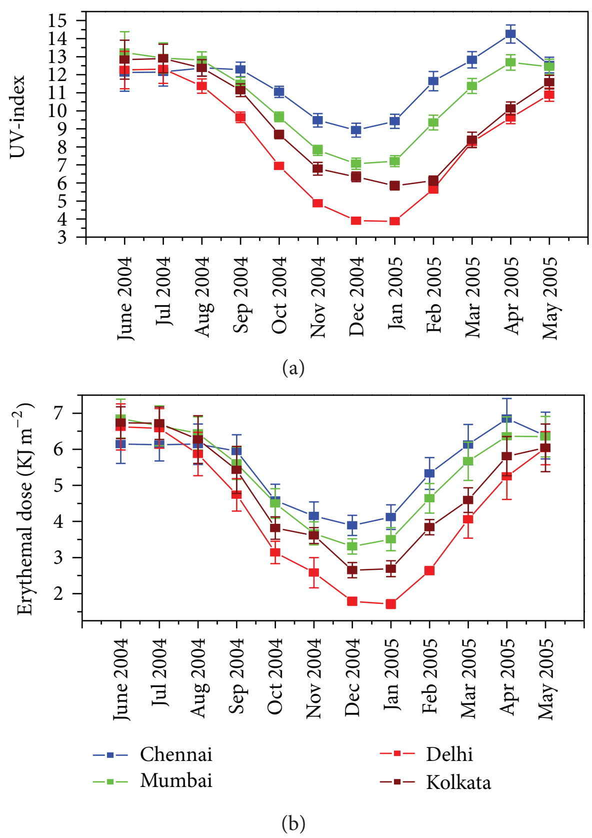

Figure 1: Monthly variation of (a) UV-index and (b) UV erythemal dose irradiance over Chennai, Mumbai, Kolkata, and Delhi.

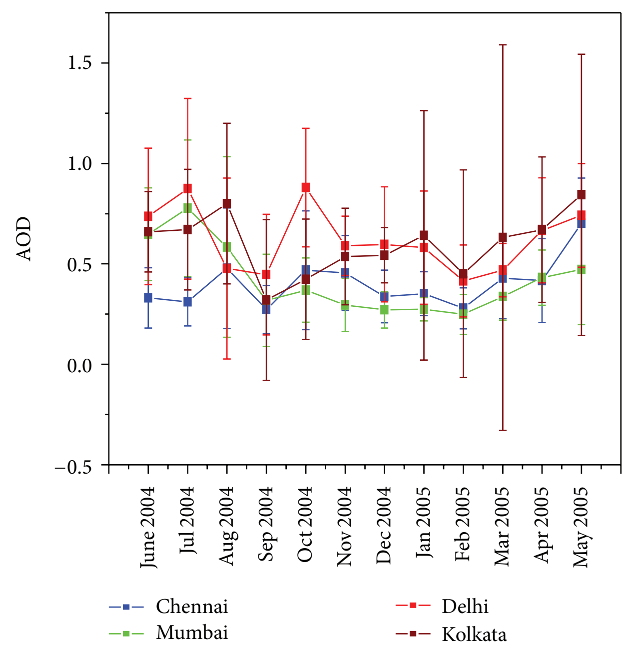

Figure 2: Monthly variation of AOD over Chennai, Mumbai, Kolkata, and Delhi.

erythemal values (except during winter) and Delhi showed lower values. This implies that solar inclination is the major factor for variation of UVE in various selected locations.

UV-I also followed the same pattern as of UV erythemal dose (Figure 1). UV-I was found to be in extreme range (greater than 10) in premonsoon (March–May) and in early monsoon months (June, July). It steadily decreased and was found to be in high range (7–9) during postmonsoon (October and November) (except over Delhi). The UV-I was found to be lowest in December. The UV-I over Delhi was found to be in moderate to low range in postmonsoon and winter (December–February) months. However it still pertained in moderate to high range over the other three locations, indicating high UV risk throughout the year.

The variation of aerosol loading represented by AOD is shown in Figure 2. AOD showed higher values in the months of June and July and then showed a sharp decrease in August and September over all the four locations. It is expected to have lower AOD in monsoon due to rain and washout. However, 2004 was a below-normal monsoon year [28] and rains intensified in August and September over the subcontinent. This could be the major reason for higher aerosol loading in early monsoon months. The AOD showed a substantial increase in postmonsoon seasons. Lower AOD values were observed during winter season (except over Kolkata). High AOD values in premonsoon season are majorly associated with the high convection and associated surface lifting of particles [29–31].

3.2. Aerosol—UV Forcing and UV Reduction. Aerosol UV radiative forcing and forcing efficiency were calculated as explained in Section 2. We confined our forcing calculations to post-monsoon, winter, and premonsoon seasons only, as the AOD in monsoon season could be contaminated due to cloud cover in active monsoon conditions. The estimated radiative forcing efficiency (UV radiative forcing per

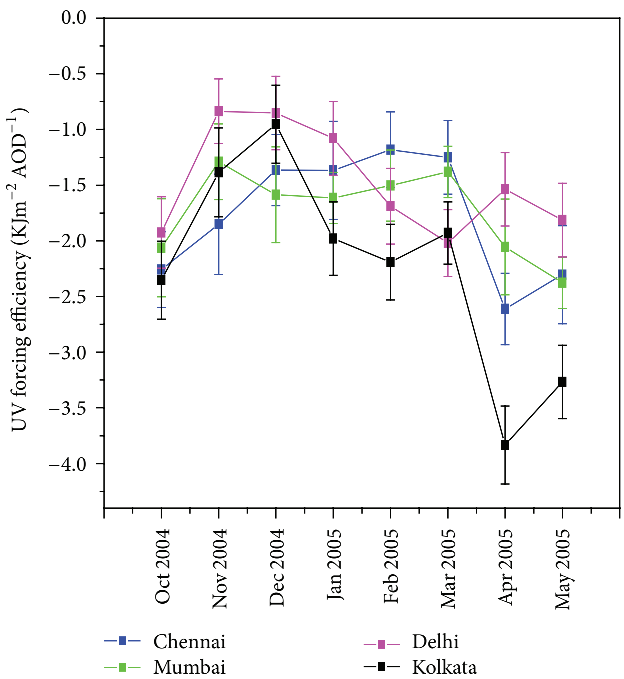

FIGURE 3: Monthly variation of aerosol-UV forcing efficiency over Chennai, Mumbai, Kolkata, and Delhi.

unit optical depth) is depicted in Figure 3. Monthly mean F_{eff} ranged from −0.75 to −3.9 KJm^{-2} AOD^{-1} on different seasons. Table 1 depicts the total erythemal dose variations and aerosol forcing efficiency values in different seasons. The forcing efficiency was found to be varying proportional to AOD. The F_{eff} over Chennai was up to −2.07 ± 0.33 KJm^{-2} AOD^{-1} during premonsoon. The F_{eff} varied between −1.56 and −1.93 KJm^{-2} AOD^{-1} over Mumbai, −1.21 and −1.78 KJm^{-2} AOD^{-1} over Delhi, and −1.71 and −3.01 KJm^{-2} AOD^{-1} over Kolkata. It can be seen from Table 1 that the total UV erythemal dose over Chennai during postmonsoon was 4.36 ± 0.34 KJm^{-2}, and it can be observed that F_{eff} was −2.06 KJm^{-2} AOD^{-1}. This implies that a unit increase in AOD is able to reduce the UV erythemal dose rate by 47.1%. The lower reduction in UV erythemal in winter over Chennai (30%) is associated with lower AOD observed during the season. Over Mumbai, it can be seen that unit increase in AOD can reduce the UV erythemal dose rate by 31 to 41% during different seasons proportional to aerosol loading. The UV reduction was found to be highest over Delhi during postmonsoon (60%). It varied between 35 and 60% over Delhi on different seasons. The aerosol-induced UV reduction was 50.3 to 55.8% over Kolkata during different seasons. The results obtained here are in accordance with the earlier findings. Reference [32] suggested that aerosols can reduce UV radiation with more than 50% in cloud-free conditions. Reference [33] found a reduction of UV by 40–50% caused by smoke aerosols. Reference [9], using a hybrid method, has reported a UV reduction of 40–56% over another Indian city, Pune, during 2004-2005. Reference [3] found a reduction of 40–50% in UV-B on biomass burning days and a reduction of UV-B by 35–40% on dusty days over Hyderabad, another urban location in India.

4. Conclusions

(1) Tropospheric Emission Monitoring Internet Service (TEMIS) archived UV-index, UV daily erythemal dose obtained from SCIAMACHY satellite, and AOD from MODIS satellite were used to study the variation of UV parameters and its aerosol-induced reduction.

(2) The analysis was carried out over four highly urbanized metro cities of India, namely, Chennai, Mumbai, Delhi, and Kolkata.

(3) UV erythemal dose and UV-index were found to be high during June over all the sites and were found to be minimum in December-January. The reason for this UV irradiance variation could mainly be associated with the lower solar elevation during summer periods than other factors such as aerosol, cloud cover, or albedo.

(4) Over the four locations, UV-Index was found to be in extreme range (greater than 10) in premonsoon (March–May) and in early monsoon months (June, July). It steadily decreased and was found to be in high range (7–9) during postmonsoon (October, November) (except over Delhi).

(5) The aerosol UV radiative forcing and forcing efficiency (forcing per unit AOD) were estimated using differential method that is, utilizing observed fluxes and minimum AOD conditions.

(6) The average aerosol forcing efficiency was found to be varying from −1.38 to −3.01 KJm^{-2} AOD^{-1} on different seasons.

(7) Our study suggests that aerosols can reduce the incoming UV radiation dose by 30–60% during different seasons.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The authors acknowledge Professor B. N. Goswami, Director IITM, for encouragements. IITM is funded by the Ministry of Earth Sciences, Government of India. This work is supported by the National Research Foundation of Korea (NRF) through a Grant provided by the Korean Ministry of Education, Science & Technology (MEST) 2013 (no. 200603874).

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