Atmósfera 25(2), 199-215 (2012)

Optical properties and meteorological correlations of aerosol parameters during 2007-08 over Mohal in the Kullu Valley of northwestern Himalayan region, India

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Received November 20, 2010; accepted November 29, 2011

RESUMEN

Las observaciones de un radiómetro de longitud de onda múltiple (MWR, por sus siglas en inglés) ubicado en tierra en el valle Kullu en la región noroccidental del Himalaya, de abril de 2007 a marzo de 2008, muestran que la profundidad óptica espectral del aerosol (AOD, por sus siglas en inglés) y el coeficiente Ångstr?m de turbidez (β) son altos durante la estación del monzón, ligeramente menores en el verano, bajos en invierno y los más bajos en otoño, para días claros, neblinosos y parcialmente claros, mientras que el exponente Ångstr?m de longitud de onda (α) tiene una tendencia opuesta. Los valores promedio anuales de AOD a 5000 nm son 0.25 ± 0.01, 0.46 ± 0.02 y 0.28 ± 0.02, para días de cielos claros, nebulosos y parcialmente claros, respectivamente. Los valores correspondientes para β son 0.13 ± 0.01, 0.22 ± 0.01 y 0.15 ± 0.01 y los de α 1.09 ± 0.04, 1.18 ± 0.03 y 0.89 ± 0.05. La α es ligeramente mayor pero la β es considerablemente más alta en los días nebulosos que en los claros, indicando que la niebla montañosa es rica en partículas gruesas. Hay una buena concordancia entre los valores MWR y los AOD satelitales de MODIS, con coeficientes de correlación anuales de 0.89, 0.70 y 0.81 para días claros, nebulosos y parcialmente claros, respectivamente. La correlación entre AOD a 500 nm y el coeficiente β con la temperatura, velocidad del viento y humedad es significativamente positivo, mientras que el del exponente α es negativo para la mayoría de los días, lo que sugiere alto AOD y turbidez pero baja concentración de partículas finas en días calientes, húmedos y con viento y viceversa. Asimismo, la correlación entre AOD a 500 nm y el coeficiente β con la dirección del viento es la mayoría de las veces negativa, mientras que la del exponente α es positiva, indicando que AOD y la turbidez disminuyen pero la concentración de partículas finas aumenta al cambiar la dirección del viento más hacia el sur de nuestro sitio. Así, durante el periodo analizado, los vientos que se dirigen hacia nuestro sitio desde las planicies indogangéticas son ricos en partículas gruesas, mientras que los vientos de la dirección sur o del desierto Thar transportan principalmente partículas finas.

ABSTRACT

Observations from a ground based multi-wavelength radiometer (MWR) in the Kullu valley of the North Western Himalayan region from April 2007 to March 2008 show that the spectral aerosol optical depth (AOD) and the Ångström turbidity coefficient (β) are high during the monsoon season, slightly less in summer, low in winter and lowest during the autumn for clear, hazy and partially clear days while the Ångström wavelength exponent (α) has an opposite trend. Average annual values of the AOD at 500 nm are 0.25 ± 0.01, 0.46 ± 0.02 and 0.28 ± 0.02, for clear, hazy and partially clear sky days, respectively. The corresponding values of the β are 0.13 ± 0.01, 0.22 ± 0.01 and 0.15 ± 0.01 and those of α are 1.09 ± 0.04, 1.18 ± 0.03 and 0.89 ± 0.05. The α is slightly high, but the β is considerably higher on hazy days than on clear days, indicating that mountain haze is rich in coarse particles. There is a good agreement between MWR and satellite-based AOD values from MODIS, with annual correlation coefficients of 0.89, 0.70 and 0.81 for clear, hazy and partially clear days, respectively. The correlation of the AOD at 500 nm and the β coefficient with temperature, wind speed and humidity is significantly positive while that of the α exponent is negative for most of days suggesting high AOD and turbidity but low concentration of fine particles on hot, humid and windy days and vice versa. Also, the correlation of AOD at 500 nm and β coefficient with wind direction is mostly negative while that of the α exponent is positive, indicating that AOD and turbidity decrease but the concentration of fine particles increases as wind direction veers to become more southwardly at our site. Thus, winds heading toward our site from the Indo-Gangetic plains brought air rich in coarse particles while winds from more southward direction or from the Thar-Desert advected mostly fine particles during the period analyzed here.

Keywords: Aerosol optical depth, multi-wavelength radiometer, Ångström coefficients.

1. Introduction

It is well known that aerosols, through scattering and absorption, play a major role in Earth's radiation budget and produce climate forcing (Charlson *et al.,* 1992; Ramanathan *et al.,* 2001) both at regional and global scale. The size, refractive index and total concentration of these aerosols in the atmosphere not only influence the formation of fog, mist and clouds (Ramanathan *et al.,* 2003), but are also deciding factors to adversely impact human health (Oberdorster *et al.,* 1990; Dockery and Rope, 1994) and ecosystems. The increased concentration of aerosol in the atmosphere is responsible for modifying regional as well as global radiation budgets and is thus disturbing climatic balance (Seinfeld and Pandis, 1998). All these optical characteristics of aerosols are under considerable investigation worldwide.

In India, the studies related to atmospheric aerosols are vigorously pursued under the Indian Space Research Organization's Geosphere Biosphere Program (ISRO-GBP). It has been instrumental in the study of atmospheric aerosols in different regions of India (see Subbaraya *et al.,* 2000 and references therein) and surrounding oceans, including the delicate Himalayan regions (Moorthy *et al.,* 1998, 2007, 2008). The measurements of aerosol parameters such as spectral aerosol optical depth (AOD) and Ångström coefficients (α and β) in the background hilly regions are important, not only in the sense that against it we can compare the urban results but also we can investigate impacts of anthropogenic activities (Jayaraman, 2001) on the clean environment of Himalayan region. In this study, we analyze the measured AOD and calculated Ångström coefficients at a remote site in the Himalayan region of India, from April 2007 to March 2008 during clear, hazy and partially clear sky days, in order to characterize the aerosol contribution to the air quality.

2. Experimental

2.1 Location of site

The present study is carried out at the G. B. Pant Institute of Himalayan Environment and Development, in Mohal (31º 54’ N, 77º 07’ E, 1154 mamsl) in the Kullu district of the Himachal Pradesh (HP) state of India (Fig. 1a) with the help of ground based multi-wavelength radiometer (MWR). It is one of the stations of the ISRO-GBP and carries out the projects on Aerosol Radiative Forcing over India (ARFI) and Integrated Campaign for Aerosol Radiation Budget (ICARB) (Fig. 1b). It is a semi-rural location with a population of about 18 300, while the population of entire Kullu valley is 221 858 (Government of Himachal Pradesh, 2001).

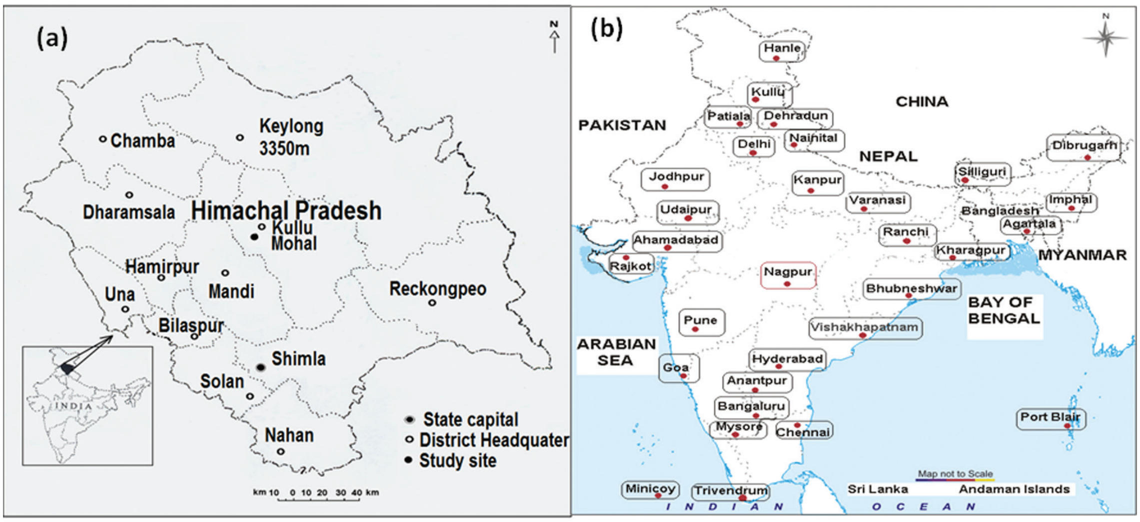

Fig. 1. (a) Location of experimental site, (b) MWR network stations under ISRO-GBP.

The Kullu valley begins from Larji (957 m) in the lower Beas basin and stretches up to Rohtang Crest (4038 m) under upper Beas basin (Gajananda *et al.,* 2005). It is an important tourist destination of the western Himalayas. It has witnessed tremendous growth in tourism (Kuniyal *et al*., 2004) as well as local vehicles over last decade. It is evident from the fact that from 2004 to 2008 the total tourist traffic to the entire state of HP increased from 6.55 million to 9.75 million, out of which the Kullu Manali alone hosted 2.12 million tourists in 2008 (Sharma *et al*., 2009). The valley which earlier was clean and serene has become a conglomeration of large anthropogenic activities, such as road constructions, mining, hydro-power generation and tourist activities.

2.2 Methods

The AOD are obtained using a MWR designed by Space Physics Laboratory (SPL), Thiruvanthapuram, Kerala, India. This MWR contains ten filters of wavelengths 380, 400, 450, 500, 600, 650,750, 850, 935, 1025 nm. The solar radiation from UV to NIR is passed through an automatic filter wheel. It works on the principle that aerosols reduce the intensity of solar radiation due to scattering and absorption processes. Using the Lambert-Beer law (Shaw *et al.,* 1973), the flux of solar radiation at the surface of Earth can be given as Moorthy *et al.* (1998):

$$F_\lambda = F_{0\lambda}\left(\frac{r_0}{r}\right)^2 e^{-m\,\tau_\lambda} \tag{1}$$

where F_λ and $F_{o\lambda}$ represents solar flux at the surface of the Earth and at the top of atmosphere (TOA) respectively. r_o and r denote mean and instantaneous Sun to Earth distance, while m denotes relative air mass, representing relative increase in optical path with increase in zenith angle. τ_λ is wavelength dependent optical depth. Neglecting refraction and curvature effects, 'm' can be approximately written as

$$m = \sec \chi \tag{2}$$

MWR converts the incident flux into voltage through:

$$V_\lambda = V_{0\lambda}\left(\frac{r_0}{r}\right)^2 e^{-m\,\tau_\lambda} \tag{3}$$

Taking natural log on both side of Eq. (3)

$$\ln V_\lambda = \ln V_{0\lambda} + 2 \ln \frac{r_0}{r} - m\,\tau_\lambda \tag{4}$$

The optical depth τ_λ is determined from the graph of ln V_λ with m (called Langley plot), as the slope of the best fit line. Menu driven software devised by SPL, yields one set of AOD at ten wavelengths for forenoon part and one set of AOD for evening part of the measurement day. Additional details of the instrument, data analysis and calibrations used in the present study have been published elsewhere (Moorthy *et al*., 2007; Aloysius *et al.,* 2008). The data are collected on days when no clouds are near the solar disc and are grouped into clear days (when morning till evening the sky is clear), hazy days (when sky appears clear but is obscured due to haze) and partially clear days (when only forenoon (FN) or afternoon (AN) part of a day is clear).

During rainy days, the ground based MWR observations could not be carried out and so they alone are not sufficient in assessing the regional distribution of aerosols. To get a more homogeneous picture of the aerosol environment over this region, we compared our data with satellite derived observations. The Moderate Resolution Imaging Spectro-Radiometer (MODIS) is a key instrument present on board polar Earth Observing System (EOS) Terra and Aqua satellites, sensing FN and AN part of each day (Levy *et al.,* 2007). It provides valuable information about the global distribution of aerosols and their properties. The MODIS derived AOD at 550 nm can be compared with ground based AOD interpolated to 550 nm using Ångström formula **(**Ångström, 1961**).**

$$\tau_{550} = \tau_{500}\left(\frac{550}{500}\right)^{-\alpha} \tag{5}$$

The substitution of τ_{500} (optical depth at 500 nm) and α exponent, both measured by ground based MWR will give τ_{550} (the calculated value of ground based AOD at 550 nm). Also, the correlation between AOD at 500 nm, α and β with corresponding meteorological parameters retrieved from an automatic weather station at our site, was estimated using Student's t distribution formula. The t thus calculated is used to find the probability Ps of correlation outside the region of significance under two tailed column in T- Table. The Ångström coefficients α and β are calculated using Ångström relation as

$$\tau_\lambda = \beta\lambda^{-\alpha} \tag{6}$$

The α exponent, is often used as a qualitative indicator of aerosol particle size or fine mode fraction and coefficient β is indicator of coarse mode fraction of aerosols (Angstrom, 1964). Further, by taking log of Eq. (6) we get

$$\ln \tau_\lambda = \ln \beta - \alpha \ln \lambda \tag{7}$$

The best fit between observed τ_λ and λ determines β and α (Schuster *et al.,* 2006). For the calculation of α and β, one set of AODs at ten wavelengths for FN and AN part of a particular measurement day are used. The AOD value at 850 nm is not considered due to instability of this filter and AOD at 935 nm is discarded, due to its link to water vapor in the atmosphere (Moorthy *et al*., 1991).

3. Results and discussion

3.1 Meteorology during study period

The Kullu valley is a bowl shaped valley surrounded by mountain ranges from all sides. It receives most of its rains during the winter months while heavy snow fall is observed during winter along the adjoining hilltops. Figure 2 shows monthly meteorological conditions during all MWR operating days of the entire study period. It shows on average, temperature rising from 25.8º C in April to 29.7º C in August, then decreasing gradually to 10.7º C in January and finally rising again to 21.1ºC in March. Wind speed has almost same trend as temperature, showing an increase from 0.94 m/s in April to 1.33 m/s in September, then gradually decreasing to 0.71 m/s in December and then increasing gradually to 0.92 m/s in March. The wind direction shows a fluctuating clockwise veer from 158ºN (east of north) in April to 165ºN in June. It then backs slightly in July to 138ºN and thereafter again a have a gradual veer to 191ºN in February. So, on average, the wind direction has a veering trend from 138ºN to 191ºN during the entire period showing that the wind is gradually changing direction from the south-east (the Gangetic plains) in summer, to south (Thar-Desert of India) in winter. The humidity increases from 35.5% in April to 52.9 % in August and then decreases gradually to 30.2% in March, with some exceptionally higher values during the rainy winter month of January. These meteorological conditions suggest that the climate of this region has four distinct seasons (Kuniyal *et al.,* 2007): summer (April to June), monsoon (July to September), autumn (October and November) and relatively longer and harsh winter (December to March).

3.2 Aerosol optical depth

3.2.1 Temporal variations

Figure 3 shows the variation of monthly mean AODs at 500 nm for all the measurement days of 2007-08: full clear (71 days), hazy (49) and partially clear days (45) of 2007-08. AOD increases

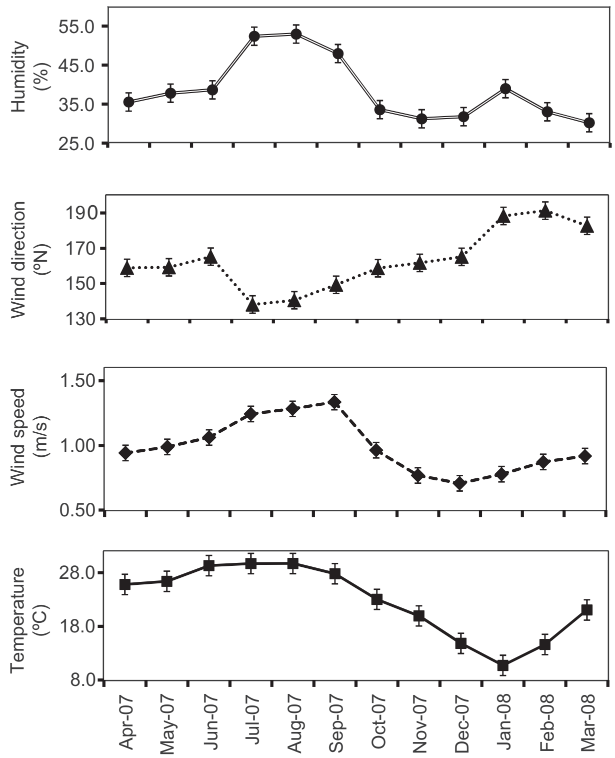

Fig. 2. Meteorological conditions during MWR measurement days at experimental site.

in summer from April to June, decreases in the monsoon months to become lowest in October. Thereafter, it starts increasing again in winter months for almost all types of days, with the exception of slightly more increase in January. It shows that AOD on hazy days are higher than on partially clear days, whereas AOD on clear days are lowest. Also, AOD are high in summer and monsoon, lowest in autumn and low in winter; a trend found at many locations (Holben *et al.,* 2001; Wang *et al*., 2008). On average during full clear sky days, the AOD at 500 nm is 0.30 ± 0.02 in summer, 0.31 ± 0.02 in monsoon, 0.21 ± 0.01 in autumn and 0.23 ± 0.01 in winter season.

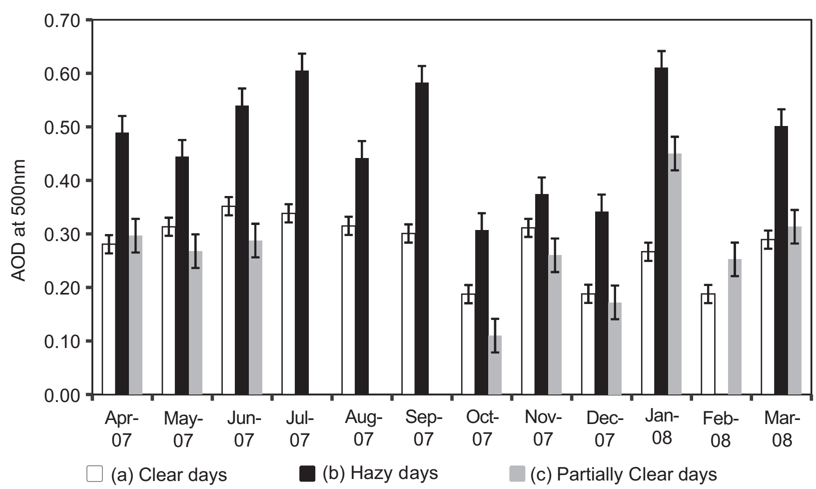

Fig. 3. Variations of monthly mean AOD at 500 nm for (a) clear days (b) hazy days (c) partially clear days.

These values are large when compared to sloppy hill sites like Nainital and Hanle (Dumka *et al.,* 2008; Verma *et al*., 2010) but are less than valley sites like Dibrugarh (Gogoi *et al*., 2008).

For hazy days, AOD at 500 nm on average is 0.49 ± 0.02 during summer, 0.55 ± 0.04 during monsoon, 0.35 ± 0.02 during autumn and 0.47 ± .04 during winter. And for partially clear days, which mostly occurred for FN part of a day, the FN-AOD at 500 nm is 0.28 ± 0.02 during summer, for monsoon months this value is not available due to overcast sky conditions. In autumn, the FN-AOD value is 0.20 ± 0.04 and during winter months, it is 0.29 ± 0.03. Annual mean AOD at 500 nm for entire study period comes out to be 0.25 ± 0.01 for clear days, 0.46 ± 0.02 for hazy days and 0.28 ± 0.02 for partially clear days of present study period.

3.2.2 Spectral features of AODs

The spectral graphs for clear, hazy and partially clear days are shown in Figure 4, indicating a gradual decrease in the AOD with increasing wavelength, suggesting an abundance of fine over coarse particles in atmosphere (Kumar *et al*., 2009). The slight less slope at first filter indicates either non applicability of Mie scattering theory in the low wavelength region or a relatively low production of ultra fine particles in the hilly regions than in the plains. The increase in AOD at 1025 nm indicates relatively more concentration of coarse particles of large sizes. Also, the FN-AOD is almost the same as the AN-AOD during clear days showing that concentration of aerosols of all sizes is the same from morning till evening during those days. But during hazy days there is a large difference between the two, suggesting that the concentration of aerosol particles of all sizes increases from morning to evening due to windblown dust and other human activities.

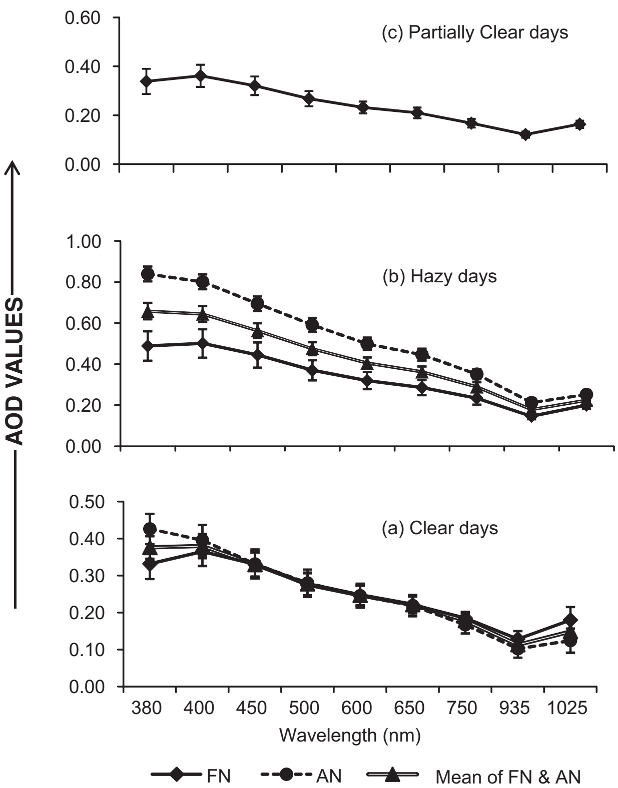

Fig. 4. Annual spectral average FN, AN and mean AOD for (a) clear (b) hazy and (c) partially clear days.

3.2.3 Comparison with MODIS data

MODIS on Terra and Aqua satellites has proved efficiency in space based monitoring of aerosols over land. In the Indian context, validation of MODIS derived AOD has been attempted by many studies (Tripathi *et al.*, 2005; Gogoi *et al.,* 2008; Sharma *et al.,* 2010). We used latest level 3 MODIS data to assess validity and efficacy of both MODIS as well as ground based instruments like MWR. Figure 5 shows a bar graph of the monthly mean AOD at 550 nm over Mohal, derived from MODIS and MWR for various types of days, showing good agreement in the trend as well as in the magnitude.

MODIS mostly underestimates values and except the noticeable difference in few cases, mostly there is a close agreement between MODIS and MWR values with mean absolute difference (MABD) of 0.08 and root mean square difference (RMSD) of 0.14. The two sets of daily mean AOD has been found to have a correlation of 0.75 for clear days, 0.65 for hazy days and 0.57 on partially clear days, whereas on a monthly mean basis, a better correlation between the two has been found: 0.89 ($P < 0.01$) on clear days, 0.70 ($P < 0.05$) on hazy days and 0.81 ($P < 0.01$) on partially clear days. The time-averaged MODIS derived (on board Aqua platform) AODs at 550 nm over

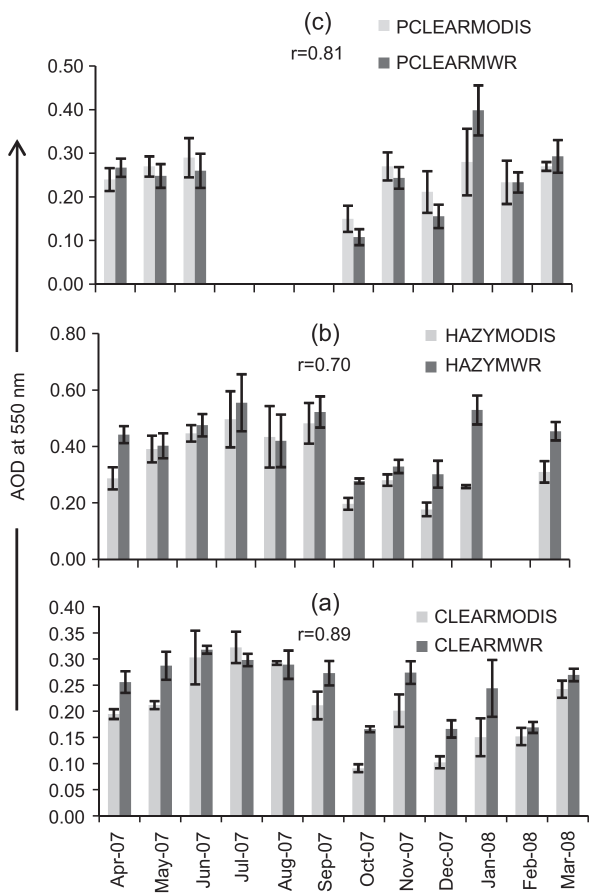

Fig. 5. Monthly mean values of AODs at 550nm for (a) clear, (b) hazy and (c) partially clear days.

the Indian zone from 01 April-2007 to 31 March-2008 are shown in Figure 6a. Figure 6b shows scatter plot of all 165 diurnal AODs at 550 nm values derived from MODIS and interpolated from ground based MWR present at our site. It shows a good correlation between MODIS and MWR retrieved AOD at 550 nm with correlation coefficient of 0.76 and level of confidence $P < 0.01$. The slope of 0.79 toward MODIS derived AOD shows underestimation of AOD by MODIS. This indicates that the algorithm used in MODIS requires improvement to assess correctly the pollution in hilly and snowy areas.

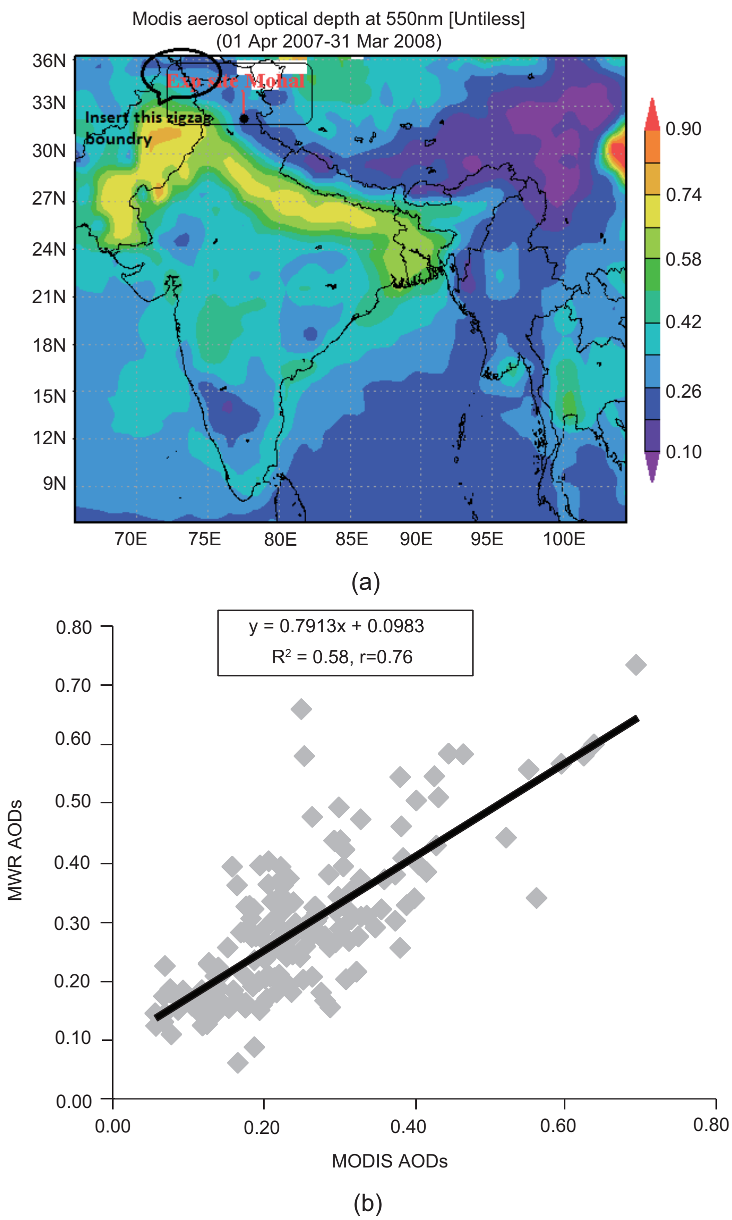

Fig. 6. (a) Time averaged MODIS AODs at 550 nm over entire Indian zone and (b) scatter plot of MWR vs MODIS AODs.

3.2.4 Correlation between AODs and meteorological parameters

The confidence level of the correlation between monthly mean AODs at 500 nm and corresponding values of meteorological parameters during FN, AN and whole of day are shown in Table I. This correlation analysis shows a positive mean correlation coefficient of confidence level (CL) greater than 98 and 30% between temperature and AOD at 500 nm during clear and hazy days, respectively. The comparison suggests that this positive correlation is strong on clear days but not on hazy days. Also, the AN correlation is stronger than the FN correlation during clear days. Between wind speed and AOD, there is a strong positive correlation of CL > 90% during clear days and CL > 30% on hazy days. Thus, high wind speed increases AODs by transporting dust from the adjacent plains during clear days. Again, the comparison suggests that this positive correlation is stronger during FN of clear days compared to hazy days and for both types of days, the correlation is stronger during FN than during AN of measurement days.

Further, for entire study period, between wind direction and AOD at 500 nm, there is a strong negative mean correlation of CL > 90% during clear days, and very weak negative correlation of CL > 10% during hazy days. This correlation is stronger during FN than during AN of clear days. Finally, between humidity and AOD, there is a strong positive correlation of CL > 90% for clear and hazy days and this correlation is stronger during FN than during AN part of these days. This positive correlation suggests increase of AOD with humidity and vice versa due to deposition of moisture on fine aerosol particles increasing particle size and hence AOD.

Table I. Confidence level of correlation between monthly mean AODs at 500nm and meteorological parameters (letters in bold represents significant correlation).

		Clear days			Hazy days			Partially clear days		
Met parameters		r	Ps	%CL	r	Ps	%CL	r	Ps	%CL
Temperature	FN	0.4367	**<0.20**	**>80**	0.2968	<0.40	>60	–0.2550	<0.70	>30
	AN	0.7051	**<0.01**	**>99**	0.1788	<0.60	>40			
	Mean	0.6755	**<0.02**	**>98**	0.1439	<0.70	>30			
Wind speed	FN	0.5584	**<0.05**	**>95**	0.3973	**<0.30**	**>70**	–0.4206	**<0.30**	**>70**
	AN	0.4993	**<0.10**	**>90**	0.1480	<0.70	>30			
	Mean	0.4943	**<0.10**	**>90**	0.1380	<0.70	>30			
Wind direction	FN	–0.1795	<0.40	>60	0.2209	<0.60	>40	0.3480	<0.40	>60
	AN	–0.5440	**<0.05**	**>95**	0.0129	<0.90	>10			
	Mean	–0.4880	**<0.10**	**>90**	–0.0507	<0.90	>10			
Humidity	FN	0.4453	**<0.20**	**>80**	0.6136	**<0.05**	**>95**	–0.2344	<0.60	>40
	AN	0.2993	**<0.30**	**>70**	0.1132	<0.70	>30			
	Mean	0.4939	**<0.10**	**>90**	0.5849	**<0.10**	**>90**			

3.3 Ångström parameters

3.3.1 Temporal variations

The monthly mean values of α and β calculated using Eq. (7) are shown in Figure 7. It confirms the universal fact that as α increases, β decreases and vice versa. Panel (a) of this figure depicts α

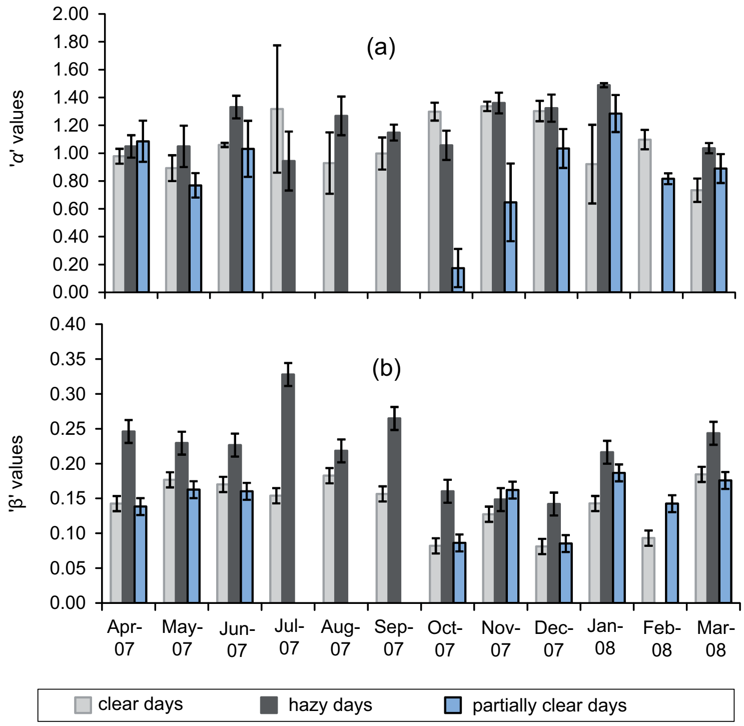

Fig. 7. Monthly mean values of (a) α and (b) β for various types of days.

small during the summer months, having smallest value in May. It then increases in the monsoon months and becomes largest in autumn and in early winter months. Finally, it again starts decreasing in later winter. The relatively higher value of α during June can be attributed to the peak vehicular flow due to tourists in this month increasing ultrafine/fine particles through their exhausts (Sharma *et al*., 2009). In July, the reason could be continental convective drift of fine dust by pre-monsoon winds. For clear days, the average seasonal value of α is 0.98 ± 0.05 in summer, 1.08 ± 0.12 in monsoon, 1.32 ± 0.02 in autumn and 1.01 ± 0.12 in winter season, while during hazy days these values are 1.14 ± 0.09 in summer, 1.12 ± 0.09 in monsoon, 1.21 ± 0.15 in autumn and 1.28 ± 0.13 in winter season. During partially clear days, the seasonal value of α are 0.96 ± 0.03 in summer, no data available in monsoon, 0.41 ± 0.19 in autumn and 1.01 ± 0.10 in winter. Such a trend is found at many sites in India and abroad (Devara *et al*., 2005; Wang *et al*., 2008). An important aspect of this bar graph is that α values are almost the same during hazy and clear days, showing that mountain haze does not contain large amount of fine particles.

Similarly, Figure 7b shows β increasing in summer months, becoming largest in May. It then decreases in the monsoon months due to washout/rainout effects and becomes small in autumn and early winter. Finally, it starts again increasing in the later winter months. For clear days, the average seasonal value of β is 0.15 ± 0.01 in summer, 0.16 ± 0.01 in monsoon, 0.10 ± 0.02 in autumn and 0.13 ± 0.02 in winter, while during hazy days the values are 0.23 ± 0.01 in summer, 0.27 ± 0.01 in monsoon, 0.15 ± 0.01 in autumn and 0.20 ± 0.03 in winter. During partially clear days, the seasonal value of β is 0.15 ± 0.01 in summer; no value is available in monsoon, in autumn it is 0.12 ± 0.03, while in winter it is 0.14 ± 0.02. Also, this figure shows considerably higher values of β during hazy days compared to clear days, indicating that haze contain coarse particle in large amount. The annual whole day α is 1.09 ± 0.05, 1.18 ± 0.03 and 0.89 ± 0.04 for clear, hazy and partially clear days; while the annual whole day value of β for these types of days, are 0.13 ± 0.02, 0.22 ± 0.01 and 0.15 ± 0.02, respectively.

3.3.2 α vs β correlation

We analyzed the correlation between mean α and mean β of various days of different months during the period studied and found it mostly negative, a result consistent with other studies **(**Gogoi *et al.,* 2008; Devara *et al*., 2005). Table II depicts these correlation coefficients on a monthly basis. It shows that during clear days, there is a negative correlation between α and β for almost all months except May, while during hazy days there is a negative correlation for all months, except January and March. During partially clear days, the correlation between α and β is negative, except in February and March. The positive anomalous correlation found mostly during the summer month in clear days and fall winter months in hazy and partially clear days, suggests that during these months both fine and coarse particle strength is of supplementary nature, i.e more fine particles as well as turbidity which in most of other months is of complementary nature, i.e. more fine particle, less turbidity and vice versa. The reason for this anomalous positive correlation between α and β could be convective airmass transport from far off places in these months raising coarse particles, which otherwise is less in these months due to less anthropogenic activities. On an annual basis, the correlation between monthly mean α and monthly mean β is slightly positive (0.07) during FN, –0.76 during AN and –0.69 during clear days. During hazy days, α vs. β correlation value is 0.68 during FN, –0.85 during AN and –0.54 during whole of the day, showing that the correlation coefficient is larger in the AN part than in FN part of clear days as well as hazy days. During partially clear days, for the entire period there is again a positive correlation of value 0.48 between α and β.

Table II. Confidence level of month wise correlation between α and β (letters in bold represent significant correlation).

Months	Clear days				Hazy days				Partially clear days			
	r	n	P	CL %	r	n	P	CL %	r	n	P	CL %
Apr-07	–0.7337	7	<0.05	**–95**	–0.7103	7	<0.10	**–90**	–0.6704	6	<0.20	**–80**
May-07	0.4735	3	<0.70	30	–0.9053	4	<0.10	**–90**	–0.0742	9	<0.90	–10
Jun-07	–0.7510	3	<0.10	**–90**	–0.4576	5	<0.40	–60	–0.5342	4	<0.40	–60
Jul-07	–0.9826	3	<0.10	**–90**	–0.9064	3	<0.30	**–70**	No data			
Aug-07	–0.9630	3	<0.20	**–80**	–0.9410	3	<0.20	**–80**	No data			
Sep-07	–0.5250	7	<0.20	**–80**	–0.7157	5	<0.20	**–80**	No data			
Oct-07	–0.7870	16	<0.01	**–99**	–0.9464	5	<0.02	**–98**	–1.0000	2	<0.01	**–99**
Nov-07	–0.6831	4	<0.30	**–70**	–0.9339	8	<0.01	**–99**	–0.8321	3	<0.40	–60
Dec-07	–0.8685	5	<0.05	**–95**	–0.8941	3	<0.30	**–70**	–0.3130	5	<0.80	–20
Jan-08	–0.7559	3	<0.50	–50	1	2	<0.01	**99**	–0.5736	3	<0.70	–30
Feb-08	–0.6277	9	<0.10	**–90**	No		data		0.6670	4	<0.30	**70**
Mar-08	–0.7736	8	<0.02	**–98**	0.4942	4	<0.50	50	0.3628	9	<0.30	**70**

3.3.3 Correlation of α and β with meteorological parameters

The correlation of daily mean α as well as of daily mean β with daily mean meteorological parameters is not consistently of the same sign as well as of sufficient confidence level for different months. It is found that the correlation between daily mean α and daily mean meteorological parameter for different months is different. The correlation between β and temperature is mostly positive for all types of days indicating that coarse particle concentration increases on hot days. Between β and wind speed, there is a significant positive correlation, for most of the months, and almost all types of days. It shows more concentration of coarse particles brought or produced on windy days. Between β and wind direction, a significant negative correlation for most of months is found for all types of days indicating that, as wind direction veers or heads to our site from the south, the coarse particle concentration decreases and vice versa. In other words, the wind coming from the Indo-Gangetic plains brought more coarse particles to our valley than that coming from Thar-Desert of India. Finally, between β and humidity, there is a positive correlation for most of months indicating the expected trend that coarse particle strength increases with increase in humidity and vice versa, due to condensation of water vapors on fine particles growing their size and hence turbidity increases.

On a monthly basis, the correlation between α and temperature is significantly negative during most of the months, for all types of days. It indicates that the concentration of fine particles decreases with increase in temperature and vice versa. Similarly, the correlation between α and wind speed is significantly negative for most of months, for all types of days. It also indicates the decrease of fine particle concentration when wind speed increases and vice versa. The correlation between α and wind direction is significantly positive for most of months of all types of days. It shows that fine particle concentration increases as wind direction veers, coming from a more southwest direction (Thar Desert side of India) and vice versa. Finally, the correlation between α and humidity is significantly negative for most of months of all types of days. It suggests that fine particle concentration decreases with the rise in humidity and vice versa.

The monthly trend of correlation seen for most of months is confirmed by the annual trend. On annual basis, the correlation coefficients of monthly mean α and monthly mean β with corresponding monthly mean meteorological parameters is shown in the Table III. It shows that there is a good positive correlation of CL >95% between whole day β and temperature, and a negative correlation of CL >90% between whole day α and corresponding temperature, during clear and hazy days, respectively. This correlation is stronger during hazy days than during clear days. Again, whole day β vs wind speed correlation is strongly positive with CL >90% during clear and hazy days, while the whole day α vs wind speed correlation is negative although it is weak (CL >60%) during clear days and strong (CL >90%) during hazy days. This correlation is stronger in the AN part of day than in the FN part of a day. The Table also shows a moderate negative correlation of CL >80% between β and wind direction for clear as well as hazy days. Between whole day α and wind direction, it shows a weak negative correlation of CL >70% on clear days but a strong positive correlation of CL >90% on hazy days. Finally, the β vs humidity correlation coefficient are significantly positive (CL >70 to 90%) during clear and hazy days, while it shows a weak negative correlation during partially clear days, but α and humidity have a weak negative correlation for hazy and partially clear days, while on clear days it is weakly positive.

4. Conclusions

The temporal study of AOD and Ångström parameters and their correlation with meteorological parameter during clear, hazy and partially clear days, results in the following conclusions:

Table III. Confidence level of correlation between β and α with meteorological parameters (letters in bold represent significant correlations).

		‘β’ vs. Meteorological parameters								
		Clear days			Hazy days			Partially clear days		
Met parameters		r	Ps	%CL	r	Ps	%CL	r	Ps	%CL
Temperature	FN	0.4290	**<0.20**	**>80**	0.5540	**<0.10**	**>90**	–0.0099	<0.95	>5
	AN	0.5943	**<0.05**	**>95**	0.4913	<0.10	>90			
	MEAN	0.5835	**<0.05**	**>95**	0.5089	**<0.10**	**>90**			
Wind speed	FN	0.5527	**<0.10**	**>90**	0.5976	**<0.05**	**>95**	–0.4448	**<0.20**	**>80**
	AN	0.5153	**<0.10**	**>90**	0.5193	**<0.10**	**>90**			
	MEAN	0.5287	**<0.10**	**>90**	0.4990	**<0.10**	**>90**			
Wind Direction	FN	–0.093	<0.80	>20	–0.0028	<0.95	>5	0.3704	**<0.30**	**>70**
	AN	–0.203	<0.60	>40	–0.2257	<0.50	>50			
	MEAN	–0.234	<0.50	>50	–0.4437	**<0.20**	**>80**			
Humidity	FN	0.4815	**<0.20**	**>80**	0.7928	**<0.01**	**>99**	–0.0388	<0.95	>5
	AN	0.1098	<0.80	>20	0.2510	<0.50	>50			
	MEAN	0.3980	**<0.30**	**>70**	0.7146	**<0.02**	**>98**			

		‘α’ vs. Meteorological parameters								
		Clear days			Hazy days			Partially clear days		
Met parameters		r	Ps	%CL	r	Ps	%CL	r	Ps	%CL
Temperature	FN	–0.1562	<0.70	>30	–0.0103	<0.95	>5	–0.2370	<0.50	>50
	AN	–0.1687	<0.70	>30	–0.5553	**<0.10**	**>90**			
	MEAN	–0.0781	<0.90	>10	–0.5271	**<0.10**	>90			
Wind speed	FN	–0.0533	<0.90	>10	0.0968	<0.80	>20	–0.5286	**<0.10**	**>90**
	AN	–0.2416	<0.50	>50	–0.6440	**<0.05**	**>95**			
	MEAN	–0.2792	<0.40	>60	–0.4955	**<0.10**	**>90**			
Wind Direction	FN	–0.0342	<0.90	>10	0.3886	<0.30	>70	0.1672	<0.70	>30
	AN	–0.3201	<0.40	>60	0.3601	**<0.30**	**>70**			
	MEAN	–0.3809	**<0.30**	**>70**	0.5142	**<0.10**	**>90**			
Humidity	FN	–0.0017	<0.90	>10	0.2491	<0.50	>50	–0.3582	<0.30	>70
	AN	0.2402	<0.50	>50	–0.2832	<0.40	>60			
	MEAN	0.0448	<0.90	>10	–0.2500	<0.50	>50			

The AODs are high in monsoon, slightly less in summer, low in winter and lowest in autumn months for almost all types of days. Annual average AODs at 500 nm for the entire period are 0.25 ± 0.01 for clear days, 0.46 ± 0.02 for hazy days and 0.28 ± 0.02 for partially clear days.

The spectral analysis of AODs indicates that during clear days, FN-AODs are almost the same as AN-AODs at almost all wavelengths, but during hazy days at all wavelengths AN-AODs are higher than FN-AODs, indicating less production of pollutants during clear days but more production during hazy days from morning till evening.

There is a good agreement between ground based MWR and satellite based MODIS-AODs having correlation coefficient of 0.89, 0.70 and 0.81 during clear, hazy and partially clear days, respectively.

The AOD at 500 nm has significantly positive correlation with temperatures as well as with wind speed for most of months as well as on annual basis for clear days, while during hazy days it is weakly positive. With wind direction, AOD has a strong negative correlation for clear days and with humidity, the correlation of AOD is strongly positive during clear as well as on hazy days. During partially clear days, the correlation coefficients of AOD with all meteorological parameters are too small and insignificant to draw any conclusion.

The monthly averaged α decreases from April to May, then increases during the monsoon months becoming largest in autumn and early winter months and then again starts decreasing in the later winter months, while β has an opposite trend. The annual whole day α is 1.09 ± 0.05, 1.18 ± 0.03 and 0.89 ± 0.04 during clear, hazy and partially clear days, while annual value of β are 0.13 ± 0.02, $0.22 \pm .01$ and 0.15 ± 0.02, respectively.

The correlation between α and β is found mostly negative with few exceptions of positive correlation. It is found to be positive during a few summer and winter months.

The correlation of α with temperature as well as with wind speed is found to be negative while that of β is found to be positive, on monthly as well as on annual basis. This correlation is weak during clear days, but strong during hazy days. With wind direction, a positive correlation of α and a negative correlation of β is found, during most of months. This correlation is also confirmed on an annual basis, except during clear days for α. With humidity, a negative correlation of α and a strong positive correlation of β is found for most of months. This correlation on an annual basis is strong only for β while for α it is mixed type.

Acknowledgements

Authors are thankful to the Director of the G. B. Pant Institute of Himalayan Environment and Development, Kosi-Katarmal, Uttarakhand, India for providing facilities at Himachal Unit of the Institute. Thanks are also due to ISRO, Bangalore, for providing MWR and financial support through Space Physics Laboratory, Thiruvanthapuram, for encouraging inter-institutional collaborative research program. This research is supported by NASA's Giovanni, an online data visualization and analysis tool maintained by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC), a part of the NASA Earth-Sun System Division.

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