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Seasonal variation of Angström turbidity from solar radiation data*

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The available solar radiation data (direct and diffuse components) and a nomograph are used to derive monthly variation of Angström turbidity coefficient, β, for a number of locations in India. The results show significant differences in the values of β for the summer and winter seasons (centered around June and December, respectively) when the locations are grouped under west coast, east coast, continental, industrial, high altitude and island areas.

1 Introduction

Atmospheric turbidity is a measure of total vertically integrated particulate load in the atmosphere and this is an important factor influencing the energetics of the solar radiation in the earth's atmosphere. Turbidity is a useful index of atmospheric pollution, particularly in the studies of long-term changes in the composition of atmosphere and resultant global climate changes. Despite its importance, there does not appear to be any universally adopted definition of turbidity or any unique technique for its measurement. Two parameters for turbidity, namely, Angström turbidity coefficient β and Schuepp's turbidity coefficient *B* are currently used. These parameters are measured using Angström pyrheliometer and Volz sun-photometer. Results of turbidity measurements (β and *B*) using sun-photometers from a network of stations have proved to be helpful in understanding climatic and meteorological factors and their variations over the years[1-5].

The parameter β is related to the aerosol optical depth (or extinction coefficient), τ_a, at the wavelength λ (in μm) by the relation $\tau_a = \beta\lambda^{-\alpha}$. The wavelength exponent α is related to aerosol size distribution, and β represents the amount of aerosol present in the vertical direction. The β values vary from 0 to 0.5 or even higher. Large values of α indicate relatively high ratio of small to large particles. Generally the value of α lies between 0.5 and 2.5 and it is customary to use $\alpha = 1.3 \pm 0.5$ (Ref. 6). The turbidity coefficient β thus refers to aerosol extinction at the wavelength $\lambda = 1$ μm. By definition, Schuepp's turbidity coefficient *B* is the decadic extinction coefficient and refers to the wavelength $\lambda = 0.5$ μm. The parameters β and *B* are related through $B = \beta 2^{\alpha} \log e$; and with $\alpha = 1.3$, we get $B = 1.07\ \beta$.

In all the turbidity measurements (β and *B*), the direct beam solar radiation is measured at selected wavelengths (using filters) in the visible region and such measurements have been specifically made at several locations covering low and middle latitudes. On the other hand, most of the meteorological stations, as a routine, measure the global solar radiation (*G*) and diffuse radiation (*D*). These are related by $G = D + I \cos\theta$, where θ is the solar zenith angle. From these, the direct radiation (*I*) has been computed and tabulated[7]. A nomogram method is available[8] for computing β from a knowledge of *D* and I_H, the solar radiation on a horizontal surface ($I_H = I \cos\theta$). We have used the available *D* and I_H values with the nomogram method to determine β for several Indian stations. This approach for β determination covers a large number of locations which have not been covered by sun-photometer measurements.

2 Methodology

Regular and reliable solar radiation data have been collected at a few (sixteen) meteorological stations in India by India Meteorological Department[7]. From these data and using a regression technique Mani and Rangarajan[7] have derived *G, D, I* and I_H values of solar radiation for 145 stations (covering all major climatic zones) in the country. Based on theoretical model computations, Rangarajan and Mani[8] have derived an expression for the ratio of diffuse to direct radiation (D/I_H) as a function of β and a special nomogram method is suggested to determine β from a knowledge of *D* and I_H. The nomogram gives β with respect to D/I_H with the relative air mass $m = \sec\theta$ as

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the running parameter. We have used the tabulated monthly values of D and I_H for clear sky noon conditions for 62 Indian stations listed in Table 1. The station abbreviations shown in Table 1 are the same as given in Ref. 7 and these are used for Figs 2-6. The latitude of the station and solar declination data corresponding to the middle of the month are used for obtaining the noon solar zenith angle (θ_{min}) of the station. We have generated the required nomogram of β vs (D/I_H) from the formula given by Rangarajan and Mani[8] to cover the local noon conditions ($m = \sec \theta_{min}$) for the stations considered in our study.

Table 1—List of Indian stations selected for this study

Name of station	Latitude ° 'N	Longitude ° 'E	Station code
	West coast stations		
Trivandrum	08 29	76 57	TRV
Kayamgulam	09 08	76 31	KLK
Kottayam	09 32	76 30	KTM
Ollukara	10 32	76 16	OLK
Pattambi	10 48	76 12	PTB
Kasargod	12 30	74 59	KSG
Mangalore	12 55	74 53	MNG
Vengurla	15 52	73 38	VNG
Ratnagiri	16 59	73 20	RTN
Bombay	19 07	72 51	BMB
Veraval	20 54	70 22	VVL
Surat	21 12	72 52	SRT
Bhavnagar	21 45	72 11	BHU
Okha	22 29	69 07	OKH
	East coast stations		
Kanyakumari*	08 05	77 30	KNK
Tuticorin*	08 48	78 09	TTC
Aduthurai	11 01	79 32	ADU
Annamali Nagar	11 24	79 41	ANM
Madras	13 00	80 11	MDS
Nellore	14 27	79 59	NLR
Gannavaram	16 32	80 48	GNV
Rajahmundry	17 00	81 46	RJM
Samalkot	17 03	82 13	SMK
Anakapalle	17 03	83 00	ANK
Visakhapatnam	17 43	83 14	VSK
Gopalpur	19 16	84 53	GPL
Calcutta	22 39	88 27	CAL
	Continental stations		
Kovilpatti	09 12	77 53	KPT
Kodaikanal	10 14	77 28	KDK
Vedasandur	10 32	77 57	VDS
Coimbatore	11 00	77 00	CMB
Ootacamund	11 24	76 44	OTC
Mandya	12 30	76 50	MDY
Bangalore	12 57	77 38	BNG
Hebbal	13 00	77 38	HBL
Nandhi Hills	13 22	77 41	NNH
Babbur	13 57	76 37	BBR
Hagari	15 10	77 04	HGR
Raichur	16 12	77 21	RCH
Solapur	17 40	75 54	SLP
Shakkarnagar	18 39	77 45	SKN
Golegaon	19 20	76 30	GLG
Akola	20 42	77 02	AKL
Hoshangabad	22 46	77 46	HSB
Guna	24 39	77 19	GNA
Gwalior	26 14	78 15	GWL
Agra	27 10	78 05	AGR
Aligarh	27 53	78 05	ALG
New Delhi	28 35	77 12	NDL
Dehradun	30 19	78 02	DDN
	Island stations		
Kondul	07 30	93 44	KDL
Minicoy	08 18	73 00	KNC
Car Nicobar	09 10	92 50	CNB
Amini Divi	11 07	72 44	AMN
Port Blair	11 40	92 43	PBL
	High altitude stations		
Kodaikanal (2345 masl)	10 14	77 28	KDK
Ootacamund (2218 masl)	11 24	76 44	OTC
Nandhi Hills (1479 masl)	13 22	77 41	NNH
Shillong (1598 masl)	25 34	91 53	SHL
Chaubattia (1962 masl)	29 45	79 40	CHB
Srinagar (1587 masl)	34 05	74 50	SRN
Leh (3514 masl)	34 07	77 34	LEH

*The seasonal variation of β for these two east coast stations are similar to the west coast stations TTC to PTB and hence discussed under west coast stations (see text).

3 Results

A preliminary examination of the seasonal variation of β for stations in the Indian subcontinent indicated a general trend of larger β values in summer months and lower β values in winter months. However, the ratio of peak to trough value of β and the nature of transition of β from high (summer) value to low (winter) value and vice versa and a few other features show significant differences among the stations grouped under five categories shown in Table 1. Some stations within the group also exhibit differences in the pattern of β variation as discussed later. The locations of these stations[7] are shown in Fig. 1.

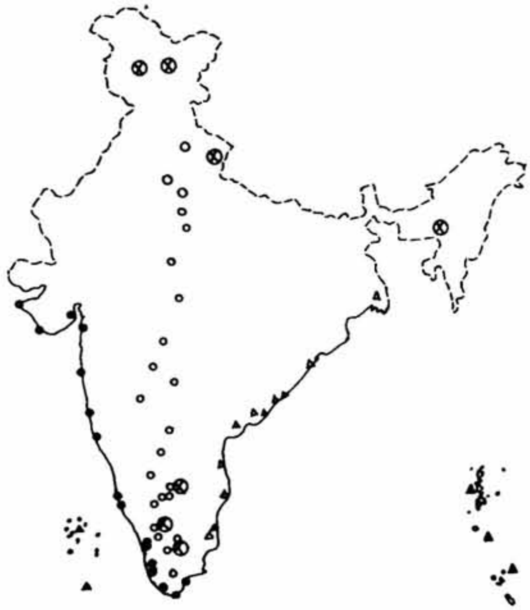

Fig. 1—Location of stations: west coast (●); east coast (△); continental (○); high altitude (⊗) and island (▲).

3.1 West coast stations

The latitudes of the stations selected vary from 08°29′N (Trivandrum) to 22°29′N (Okha) and the seasonal variation of β for these stations are shown in Fig. 2 [(a) and (b)]. The seasonal variation of β for the two east coast stations Tuticorin (TTC) and Kannyakumari (KNK) are found to be similar to those for the west coast stations Trivandrum (TRV) to Pattambi (PTB) and hence the results for TTC and KNK are shown in Fig. 2(a) along with the results for TRV to PTB. Similarly, β for these two stations (TTC and KNK) are grouped along with other west coast stations as shown in Fig. 6(b). It is likely that the meteorological factors influencing seasonal variation of β would be similar for the west coast stations TRV to PTB and the two east coast stations KNK and TTC. It is seen that the β values in Fig. 2(a) for stations KNK (8°05′N) to PTB (10°48′N) show a dip in the month of May, whereas for other west coast stations [Fig. 2(b)] a peak in the β values occurs in May. This feature is likely to be associated with the latitudinal variation of β as discussed later. The

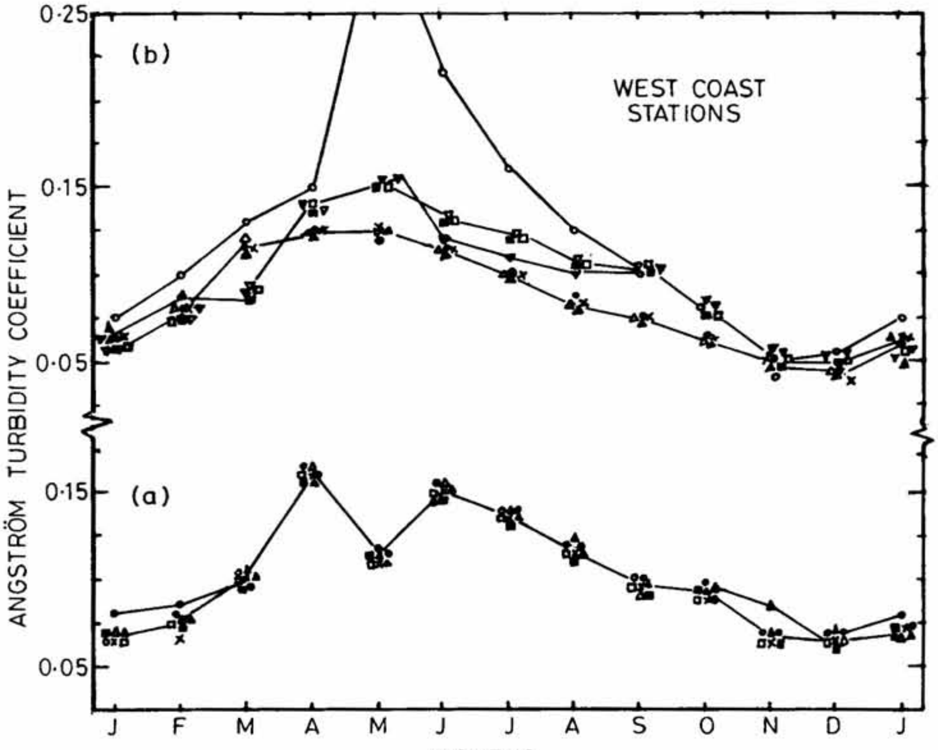

Fig. 2—Seasonal variation of Angström turbidity coefficient β for west coast stations [(a) TTC (●), KNK (×), TRV (△), KLK (▲), KTM (□), OLK (■), PTB (○); and (b) KSG (●), MNG (×), VNG (△), RTN (▲), BMB (○), SRT (■), BHU (□), VVL (▽), OKA (▼).]

largest summer peak in β values is seen for Bombay, an industrial city. The fall in β from summer maximum to the winter (November to January) minimum is gradual and similar for all the west coast stations (Fig. 2). Compared to this, the rise from winter (minimum) to the summer (maximum) values of β is more steep from February onwards [Fig. 2(a)] and from January onwards [Fig. 2(b)].

3.2 East coast stations

In this group we have considered the stations from Aduthurai (11°01'N) to Calcutta (22°39'N) and the β variations are shown in Fig. 3 [(a) and (b)].

The transitions from winter minimum (February) to summer maximum (May) are rather steep for all the east coast stations as in the case of west coast stations. A near-flat peak in β for summer months (May-September) is seen for the four stations, Aduthurai (ADU; 11°01'N) to Nellore (NLR; 14°27'N) in Fig. 3(a). Further, for these stations, β values show a sudden fall from the summer maximum in October with a dip in the month of December. This feature may be attributed to the atmospheric aerosol washout caused by NE monsoon rainfall. The stations Gannavaram (GNV; 16°32'N) to Gopalpur (GPL; 19°16'N) in Fig. 3(b), however, show a sudden fall in β from the summer peak in May to June value, then onwards a near-flat region in the β variation for the months June-October and then a decrease in β to a minimum value in December. The β variation from May to October [Fig. 3(b)] for stations above the latitude 16°32' (GNV) is not evident for any other groups of stations in the continent. Calcutta, an industrial location, shows variation similar to that of Bombay in the west coast.

3.3 Continental stations

Figure 4 [(a) and (b)] shows the seasonal variation of β for the group of continental stations. As observed with the east and west coast stations, here also significant differences and some interesting features are seen in β values for the two sub-groups of stations shown in Fig. 4 [(a) and (b)]. We note that in Fig. 4(a) three stations Nandhi Hills (NNH; 13°22'N), Kodaikanal (KDK; 10°14'N) and Ootacamund (OTC; 11°24'N) show a vastly different seasonal variation in β as compared to other stations in this group. In particular, the stations KDK and OTC show the lowest β values with very little summer to winter variation. These features of high altitude stations are further discussed later.

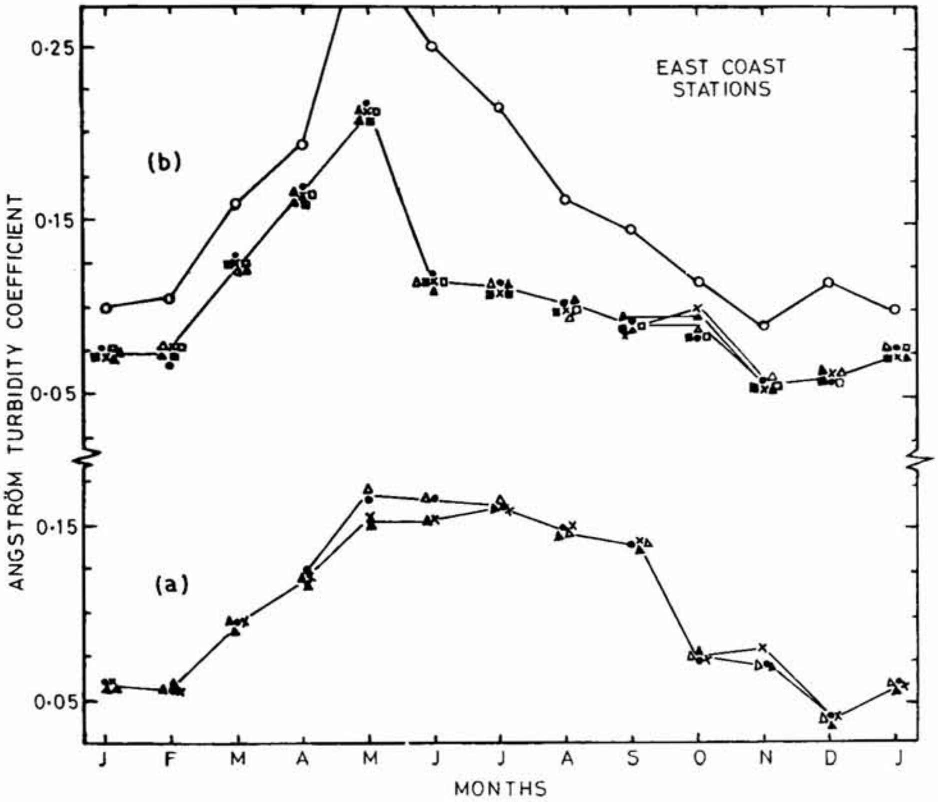

Fig. 3—Seasonal variation of Angström turbidity coefficient β for east coast stations [(a) ADU (●), ANM (×), MDS (△), NLR (▲), and (b) GNV (×), RJM (●), SMK (□), ANK (■), VSK (△), GPL (▲), CAL (○).]

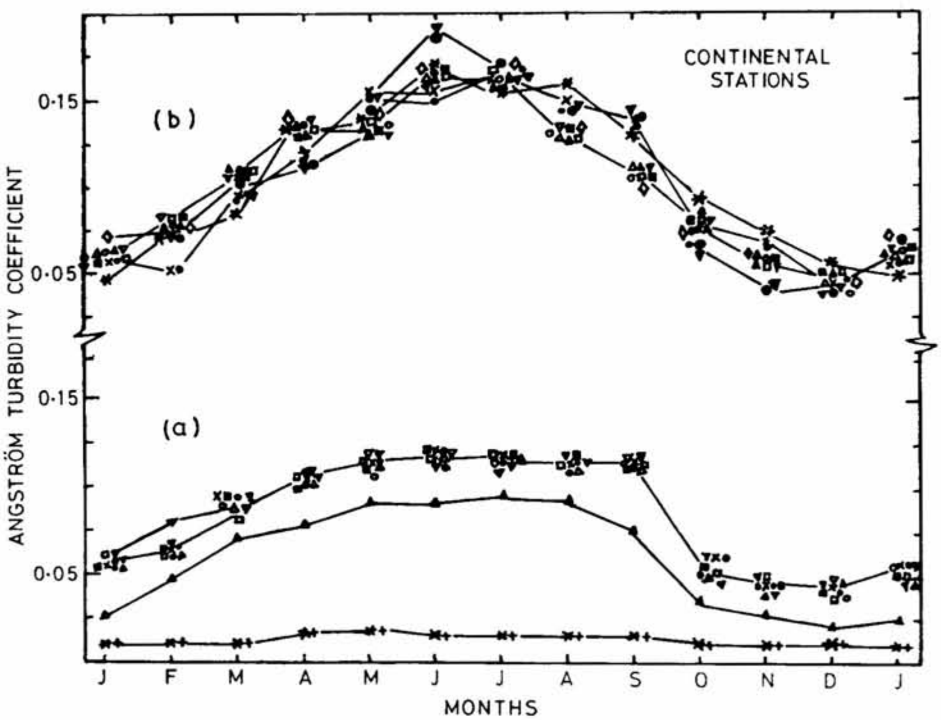

Fig. 4—Seasonal variation of Angström turbidity coefficient β for continental stations [(a) KDK (+), OTC (*), CMB (×), MDY (●), BNG (○), HBL (△), NNH (▲), BBR (□), HRG (■), RCH (▼), SLP (▽); and (b) KPT (×), VDS (●), SKN (○), GLG (△), AKL (▲), HSB (□), GNA (■), GPL (▽), AGR (◇), ALG (▼), NDL (*), DDN (●).]

It is of interest to note that all the stations in Fig. 4(a) showing similar features in β variation (except high altitude stations) are south Indian stations. A near-flat maximum of β value for the months April-September and then a sudden fall to minimum value for the months October-December are seen. It is noted that the flat feature in β variation for these continental south Indian stations (11°N-17°40′N) is similar to that noticed for the east coast stations [Fig. 3(a)] below the latitude 16°32′N. The near-constant low β (winter) value from October to January for this group of stations [Fig. 4(a)] is comparable to the similar features seen for the months November-February for the west coast stations [Fig. 2(a)]. The most striking feature is the β variation for the two southernmost stations Kovilpatti (KPT; 9°12′N) and Vedasandur (VDS; 10°32′N) which show similar variation as those for the north Indian continental stations [Fig. 4(b)], and hence β values for KPT and VDS are included in Fig. 4(b).

The ten north Indian stations Shakkarnagar (SKN; 18°39′N) to Dehradun (DDN; 30°19′N) in Fig. 4(b), and the above mentioned two stations (KPT and VDS) show exactly similar trend in β variation. The summer peak in β is in the month of June with no discernible flat feature as seen for the southern stations in Figs 3(a) and 4(a). The minimum β occurs in December and January. The transitions from summer (maximum) β to winter (minimum) β and vice versa are similar and gradual which are not seen for stations in the east and west coast and southern continental stations [Figs 2, 3 and 4(a)].

3.4 Island stations

The solar radiation data[7] are also available for the five island stations situated in the Andaman and Nicobar and Lakshadweep islands. These stations are listed in Table 1 and the seasonal variations of β for them are shown in Fig. 5(b). It is seen that the β variation for this group of stations is not similar to other groups discussed previously. A near-flat β variation for summer months from March to October, and then a gradual decrease to the winter minimum value from December to February are observed. The transition from winter to summer β values is also gradual as in the case of continental stations (Fig. 4).

3.5 High altitude stations

Seven stations are selected under this category (Table 1) of which three stations (KDK, OTC and NNH) are in southern India and the rest are in northern India. The altitudes of these stations (msl) are also given in Table 1. The seasonal variations of β

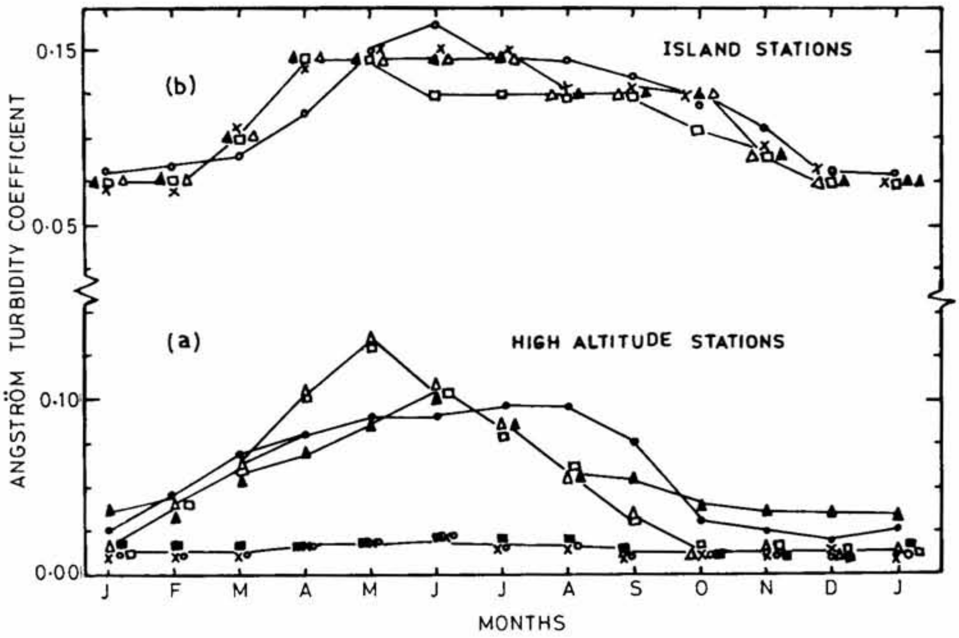

Fig. 5—Seasonal variation of Angström turbidity coefficient β for (a) High altitude stations: NNH (●), KDK (×), OTC (○), SHL (△), SRN (▲), CHB (□), LEH (■); and (b) Island stations: MNC (×), AMN (○), CNB (△), PBL (▲), KDL (□).

for the high altitude stations are shown in Fig. 5(a). The three stations KDK, OTC and LEH show the lowest β values with negligible seasonal variation. The other stations exhibit characteristics similar to their respective regional groups but with reduced β values. The β variation for NNH is similar to south Indian continental stations [Fig. 4(a)] and the seasonal variation of β for the stations Shillong (SHL), Srinagar (SRN) and Chaubattia (CHB) are similar to north Indian continental stations [Fig. 4(b)]. The altitude range covered by these seven stations is from 1400 to 3600 masl. The summer β (maximum) and winter β (minimum) are plotted against the altitude (masl) for these stations and is shown in Fig. 6(a). It is seen that the difference between summer and winter β values is negligible for altitudes above 2200 masl (approximately). For stations below this altitude, the larger β values in summer than in winter are similar to the general trend in β variation as seen for other locations. The significant variation in summer β (in the form of a peak) with altitude (for NNH, SRN, SHL and CHB) could be due to local meteorological factors. Such peak is not seen in the β variation for other high altitude stations.

3.6 Latitudinal variation of β

The latitudinal coverage of the stations under the three main groups, viz. east coast, west coast and continental, enables us to examine the latitudinal variation in β, if any. This is depicted in Fig. 6(b) where the maximum (summer) and minimum (winter) β values are plotted against latitude for stations in each group. We have excluded highly polluted locations (large β) like Bombay and Calcutta and high latitude stations (low β) in Fig. 6(b). Evidently a definite latitudinal variation is seen for summer β values for continental and west coast stations. This is in the form of a trough in the latitude range 10°32′N-18°39′N for continental stations and 10°32′N-20°54′N for west coast stations as indicated by the arrows in Fig. 6(b). The trough region for the west coast stations would have been more prominent if a few more locations above 17°N were available. Further, because of the absence of stations at latitudes below 11°N on the east coast, the left upper edge of the trough cannot be seen for this group. It is also seen [Fig. 6(b)] that the latitudinal variation in winter β values is either negligible as was with the continental stations or is not appreciable as was with the east and west coast stations. It is interesting to note that the west coast stations below the latitude 11°N which indicate a dip in β for May [Fig. 2(a)] are above the trough region of summer β values. Similarly the east coast stations (ADU-NLR) in Fig. 3(a) are in the trough region, whereas the stations (GNV-GPL) in Fig. 3(b) are above the trough region. Further, the low β values (~0.15) of the trough region for east coast are nearly the same as the large β values above the trough regions for west coast and

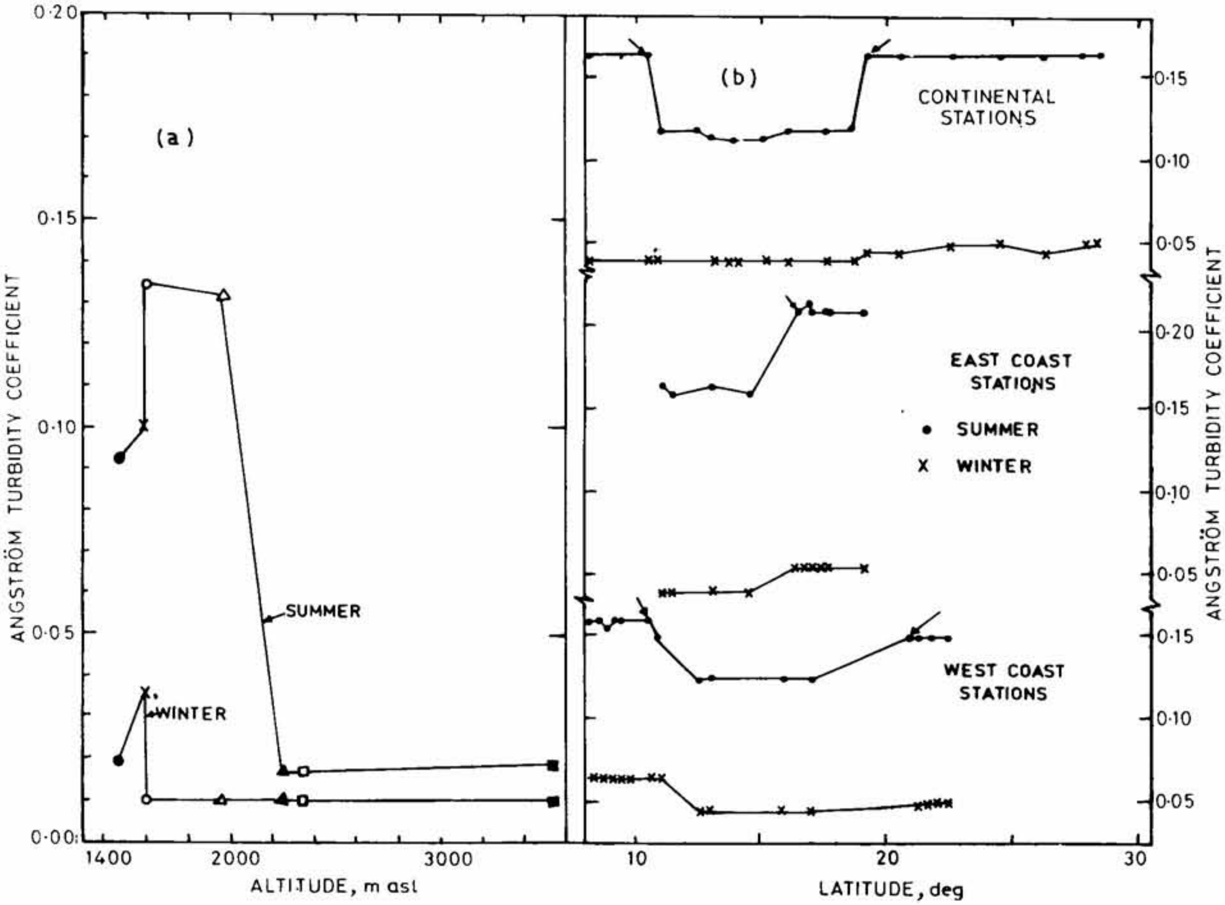

Fig. 6—(a) Variation of Angström turbidity coefficient β with altitude for NNH (●), SRN (×), SHL (○), CHB (△), OTC (▲), KDK (□), LEH (■); and (b) Latitudinal variation of Angström turbidity coefficient β.

continental stations. However, the peak to trough ratio (summer β values) for the three groups of stations are nearly the same (1.3-1.4). These features of latitudinal variations are to be viewed from the point of view of seasonal variation of rainfall data and other relevant meteorological parameters. This has not been attempted in the present study.

4 Discussion

The results presented in this paper show that the atmospheric turbidity variation with season for locations in the Indian subcontinent differs widely both in magnitude and nature. The only common feature for all the locations (except high altitude stations above 2000 masl) is the high turbidity in summer and low turbidity in winter months. The sharp dip in β for the month of May is seen for some of the west coast stations (8°N-11°N) and is not seen at any other location. The maximum turbidity seen in summer months for east and west coast stations in Figs 2(b) and 3(a), may be attributed to the increase in sea spray caused by the strong pre-monsoon winds. Also, there could be a large amount of aerosol input from dryland and vegetation during summer months. Atmospheric particulate removal processes, such as, wet scavenging and washout are weak during summer, but the monsoon rain forms a strong removal mechanism leading to the reduction in aerosol loading of the atmosphere during winter months. This explains the lower β values for all the stations in the subcontinent for the post-monsoon months, i.e. winter season. The varying degree of transition from maximum (summer) to minimum β (winter) values for the groups of stations considered could be due to the variation in the monsoon activity in these locations. The two unusual features, namely, (i) a dip in β for May for the west coast stations below the latitude of about 11°N [Fig. 2(a)] and (ii) the sudden fall of β from May to June and β remaining the same from June to October for the east coast stations above the latitude of about 16°N [Fig. 3(b)], are not seen for any other location. The reason for these could be due to local meteorological factors like the onset of SW and NE monsoons, thunder activity, etc.

The sources and sinks for the atmospheric aerosols have a strong influence on the atmospheric turbidity as seen in Fig. 4 for the continental stations in southern and northern India. The summer maximum in β values for southern stations [Fig. 4(a)] is about 0.125 and the corresponding β values for northern stations is around 0.175. Rajasthan desert is the main source of atmospheric particulates over north-west India. Dust storms and dust raising north westerly winds would bring in dust particulates into the atmosphere over central India which itself will be under convective activities during pre-monsoon season[9].

The two highly industrialized cities Bombay and Calcutta, although lie in west and east coast, respectively [Figs 2(b) and 3(b)], show the largest β for summer. The steep increase from February to May and a steep decrease from May to November are also similar for these two stations. The highly polluted industrial environment combined with the aerosol loading peculiar to sea coast and the rain washout of atmospheric particulates during heavy monsoon rains have resulted in the observed seasonal variation of β for these stations.

5 Conclusions

The nomogram method[8] of determining β is employed in the present study to cover 62 locations in our country and the results of our study show the usefulness of the method in identifying the geographic locations which show vastly differing seasonal variation in atmospheric turbidity. The yearly solar radiation data (on D and I_H), if made available, can be employed for establishing the seasonal variation of β over the years at these locations. The results of such a study will be useful in the studies of atmospheric pollution.

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