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Trends in atmospheric turbidity over India

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सार— 1973–1980 और 1981–85 की अवधियों के लिए भारतीय "पृष्ठभूमि वायुप्रदूषण मानीटरन संजाल" (बेपमन) में आविलता सह-संबंध के वार्षिक माध्य मानों की तुलना की गई थी । यह पाया गया था कि पुणे और कोडाईकनाल के अलावा सभी स्टेशनों पर बाद की अवधि के दौरान आविलता में सामान्य वृद्धि हुई है, जो प्रदूषण के मानवोद्‌भवी स्त्रोत के प्रभाव को बताती है । कोडाईकनाल के प्रेक्षणों से ज्वालामुखीय उद्‌भेदनों के लघु अवधि के प्रभाव को भी दर्शाती थी । इन स्टेशनों के स्पेक्ट्रल विश्लेषण (एफ. एफ. टी.) ने प्रमुख विधियां निकाली हैं जो कि जलवायु विज्ञान और वायुविलय विसर्जन विशेषताओं के आधार पर समझाई जा सकती हैं । इस शोध पत्र में प्रस्तुत दीर्घ अवधि वायुमंडलीय आविलता प्रेक्षण (1973-1985) विकिरण जलवायु पर वायुविलय के प्रभाव के मूल्यांकन के लिए विश्वसनीय आंकड़ा समुच्चय प्रदान करता है ।

ABSTRACT. Annual mean values of the turbidity coefficients at Indian 'Background Air Pollution Monitoring Network' (BAPMoN) were compared for the periods 1973-1980 and 1981-1985. It was found that there is a general increase of turbidity during the latter period at all the stations except at Kodaikanal and Pune, suggesting the effect of anthropogenic sources of pollution. Short term influence of volcanic eruptions were also discernible from the observations at Kodaikanal. Spectral analysis (FFT) at these stations brought out the predominant modes which could be explained on the basis of climatology and aerosol dispersion characteristics. The long term atmospheric turbidity observations (1973-1985) presented in this paper provide reliable data set for assessing the aerosol impact on radiation climate.

Key words — Aerosols. Trend, Climate change, Volcanic eruptions, Anthropogenic, Spectral analysis, Atmospheric turbidity.

1. Introduction

Global climate change is one of the most important issues of present times. Unlike the green house gases which have predominantly warming effect, atmospheric aerosols could either warm or cool the atmosphere depending upon the size distribution and optical properties and also the reflectivity of the underlying surface.

The major constituents of the atmospheric aerosols are the sea spray particles and the finer fractions of crustal particles. Volcanic eruptions provide large transient tropospheric populations but their residence times in the stratosphere are relatively larger enabling them to influence the shortwave radiation input to the atmosphere. Loginov *et al.* (1983) has correlated the volcanic cloud induced direct solar radiation variability to surface cooling for short periods. In the recent times anthropogenic inputs of aerosols have not only become significant in terms of total aerosol loads but also by virtue of their distinct optical properties.

Over the Indian continent which has large intrusions of maritime air during the southwest and northeast monsoons and where industrial activity and human interference with the state of vegetative cover is rapidly on the increase, significant influences of all the above mentioned sources are likely to be experienced. Khemani *et al.* (1982) have observed that a bimodal distribution of aerosols with one mode in the size range of 4-5.0 μm and the other mode at less than 0.3 μm is characteristic of the background aerosol. The larger size fraction is likely to be a result of growth of hygroscopic particles under humid conditions and would not contribute substantially to the long term average atmospheric turbidity. Patters and Grams (1981) also detected a bimodal haze layer over the Arabian Sea during the summer MONEX-79 but with the higher modal class around slightly less than 1.0 μm. Electron microscopic analysis showed that these were crustal aerosol, which would have been transported from desert areas.

In the past, several authors Rao and Ganesan (1972), Iyer (1985), Mani *et al.* (1973) have reported the turbidity coefficients for the Indian region using broad band pass filters (OG1,RG2 and RG8) with pyrheliometers, covering the range of wavelengths from 0.525-2.900 μm. Such a wide coverage incorporates particles of extremely varied characteristics and size number distributions. It is difficult to distinguish the relative significances of aerosols from different types of sources. Nevertheless one finds a common pattern from all these studies, *i.e.*, summer season maxima in atmospheric turbidity for all continental stations.

In 1973, the Background Air Pollution Monitoring Network (BAPMoN) was established in India. Krishnanand and Maske (1983) studied decadic turbidity coefficients of a few of these stations based on limited data available till then and concluded that soil derived aerosols are the most significant contributors to atmospheric

TABLE 1

Mean turbidity coefficient $B\,(0.5\ \mu m)$ and standard deviation computed from annual averages

Station	Elevation (m)	Station classification	$B\ (0.5\ \mu m)$			
			1973-1980	No. of years	1981-1985	No. of years
Allahabad	98	Continental, alluvial	0.145 ± 0.014	4	0.179 ± 0.023	-
Jodhpur	217	Continental, arid	0.112 ± 0.030	6	0.122 ± 0.037	
Kodaikanal	2343	Tropical, high altitude	(0.058 ± 0.040)	3	0.040 ± 0.010	3
Minicoy	02	Arabian Sea, marine	(0.136 ± 0.080)	2	0.162 ± 0.070	3
Mohanbari	111	Humid, alluvial	(0.120 ± 0.026)	3	0.186 ± 0.050	5
Nagpur	310	Continental	(0.111 ± 0.017)	2	0.146 ± 0.026	5
Port Blair	79	Bay of Bengal, marine	(0.113 ± 0.071)	2	0.101 ± 0.021	5
Pune	559	Deccan Traps Semi-arid	0.123 ± 0.024	4	0.120 ± 0.020	5
Srinagar	1587	Extra tropical, elevated valley	0.080 ± 0.040	4	0.096 ± 0.030	5
Visakhapatnam	72	Coastal	(0.105 ± 0.032)	2	0.125 ± 0.026	5

Note — Mean $B(0.5\ \mu m)$ and the S.D. of B : values are indicated in parentheses for those stations for which data series is not continuous, *e.g.*, Minicoy (0.136 ± 0.080).

turbidity. In these studies the anthropogenic influence were not studied. The object of this paper is to examine the long term data sets for about 12 years, and results of a detailed statistical analysis to obtain informaion regarding any significant changes in turbidity values during the two epochs 1973-80 and 1981-85. Analysis on frequency distributions of turbidity coefficients have been made. Power spectra analysis of the time series has also been carried out using the Fast Fourier Transform (FFT) technique. The temporal and seasonal variations have been discussed in the light of anthropogenic and natural perturbations.

2. Methodology

The method used in making sunphotometric measurements is described in WMO (1978). The sunphotometers employed in the present network are calibrated using the Langley method. They have a narrow band pass filter at 0.50 μm, thereby directly yielding the decadic turbidity coefficient. At Pune, a double filter equipment is used (0.44 μm, 0.64 μm) and the Angström wavelength exponent is computed from the observed data which in turn is used to calculate the turbidity coefficient. Six to seven observations are made on cloud free days. During clouded conditions observations are suspended when the sun is not visible.

Turbidity is a measure of spectral extinction of extra-terrestrial solar irradiance and is computed from ratio of irradiance measured to the corresponding extra-terrestrial values. Hence, the turbidity can be computed for any arbitrarily chosen unit of radiation, may it even be the current recorded by the sensor. Clearly, the extra-terrestrial value would be a constant for completely clear atmosphere, when the earth is at the mean earth-sun distance. Let this constant be called the instrument constant, J_0, since its magnitude would depend on the characteristics of the instruments. The Beer- Lambert Law states that for an observed irradiance of J at the ground the variation of J due to the extinction coefficient, τ and relative air mass, M, is given by :

$$J = (J_0 / S) \exp (\tau M)$$

where, S is a factor that reduces the actual distance between the earth and sun to its mean value. M depends of the solar zenithal angle, Z, and is "1" for the solar zenithal position, implying that one unit thickness of the atmosphere is traversed by sunlight. In the above equation $J.S$ becomes equal to J_0 when $M=0$ which again notionally implies that the scattering atmosphere does not exist. This is employed as a method of determining J_0. For a very clear day several values of $J.S$ are plotted against corresponding values of M. The line extrapolated to $M=0$ cuts off the $J.S$ axis at J_0. This is known as the Langley method.

It is obvious that the choice of a perfectly clear day introduces errors in determination of J_0, which is ultimately the principal source of error in determination of turbidity. Moreover, if we are to neglect the contributions due to very small amount of aerosols on a clear day we must know what could be its contribution compared to the Rayleigh optical depth. Laulainen and Taylor (1974) have shown that error in turbidity could be even up to 10% of Rayleigh optical depth. This would mean that turbidity variation smaller than about 0.015, at sea level and 0.005 at an elevation of 2000 m would not be reliably detected by this technique. In addition to this, it has been seen with this data that due to an error in reporting time (up to 30 sec) an error of 10% in turbidity coefficient can occur, if the M value is more than 5. Hence for all those days when observations were taken with only $M\geqslant5$, the values have not been considered for averaging.

A standard FFT routine has been employed to study the power spectra of the time series of monthly values.

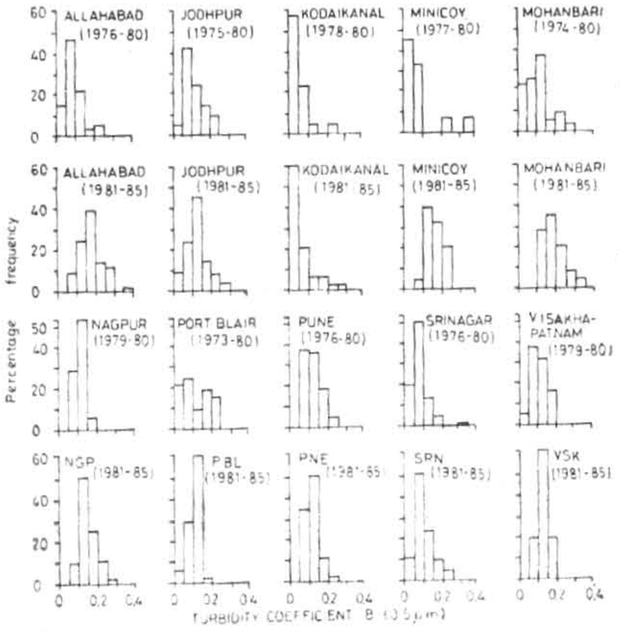

Fig. 1. Percentage frequency of occurrence of turbidity coefficient B (0.5 μm)

The length of the data at Jodhpur and other stations (except Port Blair) is 128 and 64 months respectively, while for Port Blair, 32 months only. Stations with discontinuous data sets due to overcast conditions could not be considered for spectral analysis.

3. Results

3.1. *Trend of turbidity coefficient, B* (0.5 μm) *value at the Indian BAPMoN stations*

The mean values of B (0.5 μm) for the periods 1973-80 and 1981-85 have been given in Table 1. The bracketed values of the turbidity coefficient are those for which full monthly average data were not available on account of some discontinuity in the data set of monthly means. It may be seen that although higher elevation from sea level in a flat terrain does not cause much decrease in turbidity, yet generally the stations located on higher altitude ridges are seen to have the lowest turbidities. Secondly, river basins with thick alluvial deposits (Allahabad, Mohanbari) seem to have higher turbidities than desert regions (Jodhpur) or non-alluvial continental regions (Nagpur). However, the two oceanic stations provide interesting contrast. Minicoy, an island in the Arabian Sea, is substantially more turbid than Port Blair in the Bay of Bengal.

A relatively higher degree of variability of the turbidity coefficient is evident over desert areas as well as over Minicoy. High variability of turbidity over Port Blair could possibly be attributed to settlement activities and a shift in the land use pattern that brought about a significant change in aerosol load in the later period.

Comparing the shifts in the periodic means over the peroids 1973-80 and 1981-85, as shown in Table 1, it may be noticed that with the distinctive exception of Kodaikanal, most other stations show an upward trend. However, such an upward shift in the means is found to be significant at 5% level only at Mohanbari. Kodaikanal has shown a marginal drop while the reduction over Pune could be considered as only nominal. The standard deviations of the values do not show one to one correspondence with the means suggesting that source characteristics are liable to minor adjustments from time to time.

3. 2. *Distribution of turbidity values*

Fig.1 shows the comparative percentage frequency of occurrence of turbidity coefficient (B) at different stations for the periods 1973-80 and 1981-85 respectively.

It is noticed that Minicoy, Mohanbari and Port Blair have undergone drastic changes in their distributions. At Minicoy and Mohanbari a large percentage of occurrences (at least 50%) were confined in the earlier epoch within the first two class intervals with B (0.5 μm) ranging up to a value of 0.10, whereas in the later epoch at least 60% occurrences have taken place in a range 0.10 to 0.20. Port Blair is distinctive with a change in aerosol characteristics, *i.e.*, a change from a relatively flat distribution to a peaked one, the erstwhile median class around $B = 0.075$ later became the prominent modal class around $B = 0.125$ accounting for 60% of all occurrences. This change has occurred

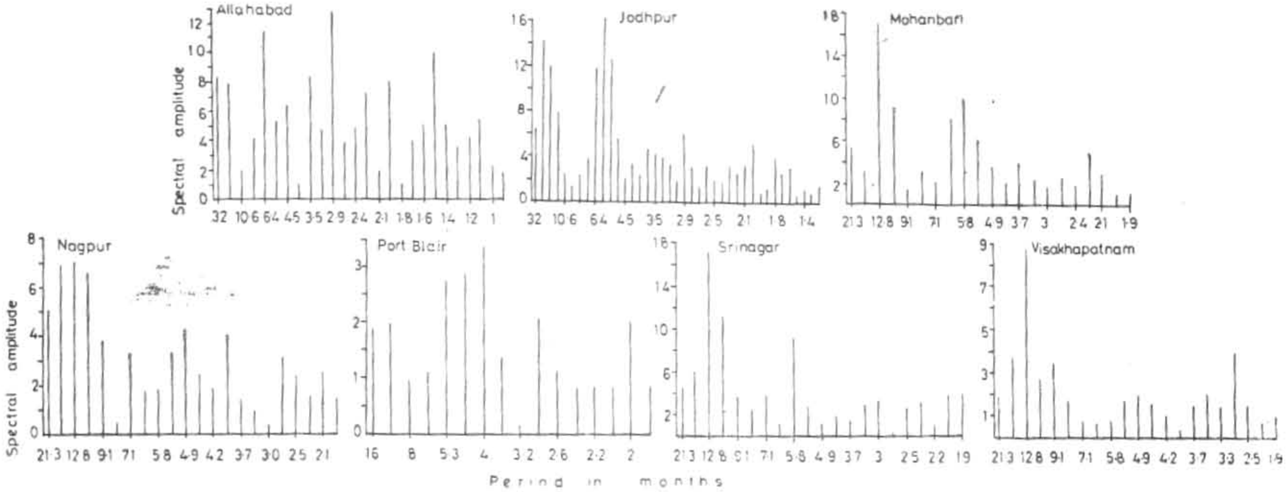

Fig. 2. Power spectrum of turbidity

with reduction in frequency of higher values of turbidity. Allahabad, Nagpur and to a lesser extent Srinagar have also shown an increasing bias towards higher values of *B*, although broadly retaining the shapes of the distribution curves. Among these stations, Allahabad has shown a shift of its modal class from 0.05-0.10 to 0.15-0.20. Visakhapatnam, too, may be considered to have a similar trend as Allahabad with the only difference that the distribution has become further peaked at the expense of lower values of turbidity.

Pune stands out among the above stations by essentially retaining its mean values for the two epochs with a marginal shift of its modal class towards higher side.

Kodaikanal, which is a high altitude station, not having seen any change in its population characteristics over the entire period, has emerged unscathed and there is no detectable increase in the atmospheric turbidity. The cleanest of all stations to start with, it continues to remain so.

3.3. *Power spectrum of turbidity time series*

The relative contributions of different frequency modes to the over all variability based on FFT analysis at some of the stations for which continuous data is available (monthly mean data), are shown in Fig.2.

Jodhpur and Srinagar show two clear pronounced peaks in their respective spectra. Mohanbari also has two peaks but amidst a higher level of base noise. Allahabad contains several peaks and a very high level of base noise. Port Blair and Nagpur do not show clear-cut modes but a cluster of peaks and also a high level of noise. In interpreting the spectra, it may be noticed that a six monthly cycle is prevalent at Allahabad, Jodhpur, Mohanbari and Srinagar. An annual cycle is seen at Nagpur, Srinagar, Visakhapatnam and Mohanbari. Allahabad and Jodhpur show a slightly longer cycle than one year which at the same time is relatively weaker than the semi-annual cycle. In addition to this feature, Allahabad and Nagpur show a weak 3-4 month cycle.

The annual cycle is related to the fact that there is one single 'driest' season that renders the top-soil most susceptible to dust raising by wind. The semi-annual cycle corresponds to two dry seasons of comparable dryness separated by two seasons of rainfall. The higher frequency cycles are a reflection of the capacity of soil to rapidly recover from wetting due to rain to be able to provide substantial aerosols for increasing the turbidity within a short interval of time. The spectra in which there are no sharply peaked features suggest a sub-dued contrast in the seasonal patterns as at Port Blair.

3. 4. *Seasonal variations of turbidity coefficient*

The long term monthly means of the entire data sets for each station are given in Table 2.

In Allahabad and Jodhpur, which are continental stations having onset of monsoon in late June and July respectively, the turbidity values increase steadily during the pre-monsoon months which are relatively drier and are associated with radiationally induced convective phenomena. The values reduce sharply after the onset of monsoon rains. With cessation of rains, turbidity again increases in post-monsoon only to decrease once again in late winter which is characterised by stable atmospheres and occasional rains associated with the western disturbances. These stations also show a semi-annual turbidity spectrum as mentioned earlier. It may be noticed that none of the two minima at Allahabad come up with large contrasts thereby reducing the sharpness of the spectrum as shown in Fig.2. At Nagpur, the frequency of rainy days in late winter is less than that at Allahabad, hence the frequency values do not register a fall. In addition, the post-monsoon wetness seems to carry half way into winter. Thus as a result, the post-monsoon secondary maxima is not seen as in the earlier cases. Subsequently the semi-annual mode is not strong at this station.

Mohanbari is the fourth typically continental station pre-monsoon rain in May almost merges with the monsoon rains. Hence the turbid season is restricted to February-April. The annual cycle of turbidity is derived from this local dry convective dust raising phenomenon. The month of February not having a minima which is shifted to early winter broadens the secondary cycle to 5.5-6.5 months, which is easily discernible in Fig. 2. Visakhapatnam shows an annual pre-monsoon maxima which predominates over other periodicities. The semi-annual cycle which is normally generated due to a post-monsoon rise does not occur here because of onset of northeasterly monsoon rains.

Pune follows a seasonal pattern characterised by pre-monsoon high values of turbidity and a monsoon low with values increasing during post-monsoon when air mass of continental origin begin to take over. The December low as seen in Allahabad, Jodhpur, Nagpur and to a certain extent at Visakhapatnam which is probably associated with reduced thermal convection and lack of other sources is very weak in Pune, apparently due to anthropogenic contribution to turbidity. It may be recalled that Pune is a fast developing city among the other BAPMoN stations.

January maxima in all the continental stations could be explained by anthropogenic pollutants being trapped in low level inversions. Jodhpur being less affected by such sources and also having soil particles in the coarser mode (being essentially sand) does not show this aspect.

Among the island stations, it may be seen that the behaviour at Port Blair is in accordance with the suppression of turbidity during the southwest monsoon month but that at Minicoy is completely different from that at other stations. The turbidity is low only during the months of northeast trade wind regime. With the reversal of winds to the westerly regime the transport of aerosol from African coast and even Arabia could be a major factor for increasing turbidity values. Patterson and Grams (1981) had earlier detected the presence of mineral aerosols over the Arabian Sea during the summer MONEX-1979. The fact that emerges from the Minicoy turbidity data is that these mineral aerosols are carried even up to south Arabian Sea.

The only extra-tropical type of station is Srinagar which shows low values of turbidity from April to Octber. It may be noted that it is relatively higher in the rainy months of January and February. A closer scrutiny of the daily data reveals that a greater contribution to the mean monthly turbidities is from morning and afternoon observations when under the influence of strong valley type inversions a larger number of aerosols remain trapped. However, occasional occurrences of high values of mid-day turbidity during December to February, suggest westerly transport of dust from upstream desert locations in Iran and Afghanistan.

4. Discussion

The turbidity values at Indian BAPMoN stations and their seasonal variations are well explained by rainfall climatology. During the cleanest months, the typical average maritime atmosphere can have a turbidity coefficient of around 0.09 which is lower than a typical continental station at around 0.10 and higher than a desert station at around 0.08. The low desert value are because of the coarse mode sand particles which settle rapidly and thus contribute to a lesser extent to the turbidity during stable conditions of the atmosphere.

The high elevation stations have significantly lesser turbidity because of a lesser capacity of the atmosphere to hold aerosol loads. That is why the highest mean monthly turbidity value at Kodaikanal is only around 0.09. The decrease of turbidity with altitude is also reported by Chen and Bai (1987). Since the boundary layer contribution to the turbidity reduces with height, a high altitude station is likely to provide an ideal condition for ground based monitoring of the stratospheric aerosol. In the case of Kodaikanal four yearly averages (excluding 1982) are given below, along with the corresponding 1982 values in brackets : May 0.050 (0.158), June 0.037 (not available), July 0.036 (not available), August (not available), September 0.018 (0.260), October 0.028 (0.185), November 0.025 (0.125), December 0.022 (0.063).

It may be noted that a manifold increase during 1982 is in accordance with the results of d'Almeida (1987) for a few north African stations for the same period which could be attributable to the El Chichon (17° N, 146° E) volcanic eruption of April 1982. The Ulawun eruption (5° N, 151° E) in October 1980 is also seen to be associated with a sudden increase of turbidity in December 1980 (0.248) and January 1981 (0.213).

The effect of the eruptions of Mt. St. Helena (46° N, 122°E) in May 1980, Nyamuragira (1° S, 29° E) in December 1981 could not be ascertained as observations were suspended after February 1981 due to equipment failure which were recommenced only in 1982. However, the effect of another southern hemispheric eruption of Sierra Negra (1° S, 91°W) in November 1979 did not cause any detectable change in turbidity at Kodaikanal. There is a possibility that meridional transport of stratospheric aerosol caused by volcanic injection could be small and hence eruptions occurring at distant latitude belts could cause only minor changes in the turbidity. It would also be seen from the data that the residence time of a major

TABLE 2

Monthly means of turbidity (1976-1985)

Month	ALB	JDP	KDK	MHB	MNC	NGP	PNA	PBL	SRN	VSK
Jan	0.155	0.081	0.057	0.158	0.126	0.125	0.115	0.114	0.139	0.120
Feb	0.128	0.080	0.058	0.216	0.147	0.139	0.102	0.091	0.113	0.115
Mar	0.142	0.114	0.052	0.260	0.155	0.154	0.124	0.099	0.091	0.152
Apr	0.197	0.127	0.052	0.208	0.166	0.144	0.137	0.100	0.069	0.152
May	0.229	0.160	0.076	0.171	0.159	0.164	0.136	0.123	0.066	0.147
Jun	0.264	0.165	0.037	0.134	0.199	0.165	0.103	0.099	0.067	0.150
Jul	0.138	0.142	0.036	0.104	0.232	0.159	0.092	0.108	0.061	0.112
Aug	0.134	0.129	0.015	0.126	0.202	0.144	0.060	0.129	0.056	0.113
Sep	0.139	0.126	0.090	0.145	0.150	0.144	0.112	0.124	0.055	0.110
Oct	0.145	0.117	0.065	0.130	0.135	0.123	0.115	0.094	0 068	0.110
Nov	0.157	0.082	0.045	0.101	0.126	0.116	0.108	0.103	0.110	0.096
Dec	0.147	0.082	0.073	0.132	0.123	0.107	0.108	0.098	0.190	0.100
Annual means	0.164	0.117	0.055	0.157	0.160	0.140	0.109	0.107	0.090	0.123
S.D.	0.041	0.029	0.019	0.048	0.033	0.018	0.020	0.012	0.039	0.020
Lat. (°N)	25.27′	26.18′	10.14′	27.29′	08.18′	21.06′	18.32′	11.40′	34.05′	17.41′
Long. (°E)	81.44′	73.01′	77.28′	95.01′	73.00′	79.03′	73.51′	92.43′	74.50′	83.18′

BAMPoN stations in India : (1) Allahabad (ALB), (2) Jodhpur (JDP), (3) Kodaikanal (KDK), (4) Mohanbari (MHB), (5) Minicoy (MNC), (6) Nagpur (NGP), (7) Pune (PNA), (8) Port Blair (PBL), (9) Srinagar (SRN), (10) Visakhapatnam (VSK).

fraction of these particles is not likely to be more than a few months in the Indian region which could be used in climate modelling studies.

The shift towards a gradual increase in the monthly means of turbidity values may be noted from Fig. 2. It is due to an alteration of the distribution of turbidity coefficients. On comparing the monthly pattern of Table 2 with the data published by India Met. Dep. (1982) for the period 1973-80, it is found that a major contribution for the increase in the overall means arises during the months of November-January at Allahabad and November-February at Mohanbari. These are attributed to the more obvious local sources of pollution being amplified by the influence of winter inversions. Among the other stations showing overall increase in long term means at Nagpur, Visakhapatnam, Jodhpur and Minicoy, there is no noticeable seasonal influence. The data of Port Blair shows that the highest contribution to the overall means of the 1973-79 period for that station was from the years 1973 and 1974. It had been pointed out earlier that a flat type of distribution at this station later changed into a peaked one and caused reduction in both the means and the standard deviation. This could be attributed to major changes in land use patterns. Massive growth of settlements in the early seventies had caused clearance of large tracts of tropical forest land. The exposed soil along with spurt in construction activities might have caused increased loads of atmospheric dust. Thereafter stabilization of the settlements and an effort to arrest deforestation could have reduced the turbidity values later. An increase in the relative proportion of turbidity values in the range of 0.10 to 0.15 which can be seen in Fig. 2 to be a common phenomenon in an almost all the stations holds good for Port Blair as well. However, no specific conclusion can be drawn about the size distribution of aerosols and the identity of their sources. However, since prevalent turbidity values at all the BAPMoN stations now lie in the 0.10 to 0.15 interval, which was confined to less than 0.10 in the earlier period from 1973-80, the role of possible anthropogenic influence cannot be ruled out. This is supplemented by the fact that Kodaikanal, which has not been affected by any growth in settlements, remains almost totally unaffected despite a brief period of higher values in the year 1982.

Rangarajan and Mani (1984) have reported turbidity values, by using a diffuse to direct radiation ratio as index, for two of the BAPMoN stations, *viz.*, Visakhapatnam and Jodhpur for the period 1958-75. It appears that the monthly variation pattern as well as the long term means did not change significantly in the subsequent ten years for which the present study was conducted. However, since their observations were based on total radiation and not spectral and measurements were made within a 2° solid angle exposure, an approximate anisotropy factor of dust scatter had to be invoked to derive the turbidity values. It is natural to expect a slightly higher proportion of diffuse radiation scattered from distant cumulus towers especially in the pre-monsoon season. Indeed, Visakhapatnam showed somewhat higher pre-monsoon turbidity values compared to the present observations. On the other hand, Jodhpur values agree well with Volz sunphotometric observations. In another study, Prabhu (1989) has reported Scheupp's turbidity coefficient from pyrheliometric observations for Pune for the period 1986-88. An interesting feature is the difference in seasonal pattern for turbidity at different airmass factors. Turbidity values at low solar elevations appear to be relatively higher during winter months in comparison to the turbidity values at low solar elevations during the other months. This could be a result of low level inversions being prevalent in winter months during the morning and the evening hours.

Based on mean monthly vertical profiles at Pune for the years 1986-89 obtained from Lidar observations, Devara and Ernest Raj (1990) show that the number density of aerosols falls drastically beyond a height of 1-1.5 km, and that this boundary height shrinks to a minimum during post-monsoon and winter, and rises to a maximum in summer. This explains to a certain extent the higher turbidity of low solar elevation observations than overhead observations during winter months.

Iyer (1985) presented the seasonal variation of atmospheric turbidity (Angström coefficient) at some stations using broad band pass filters and found the lowest values at Shillong and the lowest amplitude of seasonal variations at coastal stations, which are corroborated from the present studies of narrow band pass measurements. Rao and Ganesan (1972) and Mani *et al.* (1973) reported hightest mean turbidity, using the same method as Iyer, during the summer season when dust is raised from the dry topsoil by convective turbulence. Since similar results are obtained in the present study for wavelength of $0.5\mu m$, it is evident that the stable populations of crustal aerosols are in the sub-micron range as reported by Patternson and Grams (1981) over South Arabia and Arabian Sea having imaginary index of refraction around 0.009-0.02 for the entire range of wavelengths from $0.3\mu m$-$0.7\ \mu m$. Their model computations for radiative heating over the Arabian Peninsula yielded a heating rate of 1° K/day. The absorption to back scatter ratio, equal to $(1-\alpha)^2/2\alpha$ defines the demarcation between, warming and cooling, α being the ground albedo. From results of Kellog (1980), it may be inferred that the haze layer characterised by Patterson and Grams would lead to a marginal cooling of the layers 0-6 km over Arabian Sea. The Arabian Sea dust is transported right up to Minicoy, as inferred earlier and, therefore, this cooling effect could probably be a feature of the entire Arabian Sea.

5. Conclusions

The long term and seasonal variations of the atmospheric turbidity values derived from the observations made at the Indian BAPMoN stations, bring out the following results :

(*i*) A general increasing trend in the turbidity values has been found at all the stations except at Port Blair and Pune, and significantly so at Mohanbari, over the entire period from 1973 to 1985. The modal class seems presently to cluster around a turbidity range of 0.10–0.15 at all the stations except Kodaikanal where it shows a lower value of 0.00–0.10. The higher values observed during the period 1981-85 are attributed to the anthropogenic influence.

(*ii*) Evidence of long distance transport of crustal aerosol is obtained from the turbidity data of Minicoy which registers high values during westerly wind flow and drops when the wind regime reverses direction. However, transport of dust from the deserts of Rajasthan to further east is difficult to detect since alluvial soils of northcentral India are rich sources of clay size fractions which when raised locally become the predominant factor for turbidity variations.

(*iii*) This study mainly presents the results of long term observations (1973-85) of atmospheric turbidity made over the Indian sub-continent and adjoining areas and discusses spatial and temporal variation in B (0.5 μm) in relation to the distribution of sub-micron size aerosol particles which are known to significantly influence the radiation climatology and monsoon dynamics of the region, through radiative cooling heating of the atmosphere over sea/land.

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