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Temporal variations and the effect of volcanic eruptions on atmospheric turbidity over India

VIJAY KUMAR SONI and P. S. KANNAN

Meteorological Office, Pune – 411 005, India

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सार – इस शोध–पत्र में समय की भिन्नताओं के प्रमुख कारणों का पता लगाने के लिए भारतीय भूमंडल वायुमंडलीय निगरानी केन्द्रों में लगभग 23 वर्षों (1975–97) की अवधि के एकत्रित किए गए वायुमंडल आविलता आँकड़ों का विश्लेषण किया गया है। अप्रेल 1982 में एल शियोन, मेक्सिको (17° उ., 146° पू.) तथा जून 1991 में माउंट पाइवाट्यूबों, फिलीपीन (15° उ., 120° पू.) में आए उल्लेखनीय ज्वालामुखी विस्फोटों के साथ अत्यंत तीव्र विक्षोभ से संबंद्ध है। इन ज्वालामुखी विस्फोटों के बाद वायुमंडलीय आविलता मानों में वृद्धि, विस्फोट के बाद 1.5 - 2 वर्षों तक देखी गई है। लगातार दो दशकों, अर्थात 1976–85 और 1986–95 में आकलित किए गए आविलता गुणांकों के वार्षिक माध्य मानों से कोडाईकनाल को छोड़कर सभी केन्द्रों पर परवर्ती युग के दौरान आविलता में मामूली वृद्धि देखी गई है। दीर्घावधि मासिक मानों के विश्लेषण से आविलता गुणांको में मौसमी भिन्नताओं और मानसून के प्रभाव का पता चलता है। प्रतिशत आवृतिता विश्लेषण द्वारा निम्न बैंड मानों (0.0-0.1) से उच्चतर बैंड (0.1-0.2) तक होने वाले वायुमंडलीय आविलता मानों में उल्लेखनीय परिवर्तन भी देखा गया है।

ABSTRACT. Atmospheric Turbidity data collected over a period of about 23 years (1975-97) at Indian 'Global Atmospheric Watch' stations have been analysed to determine the major causes of time variation. The most extreme perturbations have been associated with significant volcanic eruptions of El-Chichon, Mexico (17° N, 146° E) in April, 1982 and Mt. Pinatubo, Philippines (15° N, 120° E) in June, 1991. The increase in atmospheric turbidity values following these eruptions was discernible for 1.5 - 2 years after the eruption. Annual mean values of the turbidity coefficients computed for the two consecutive decades, 1976-85 and 1986-95, show a general increase of turbidity during the later epoch at all stations except Kodaikanal. Analysis of long-term monthly means shows the seasonal variations and influence of monsoon over turbidity coefficients. A considerable shift of atmospheric turbidity values from the lower band values (0.0 - 0.1) to higher band (0.1 - 0.2) also witnessed from the percentage frequency analysis.

Key words – Atmospheric turbidity, Volcanic eruption, Aerosol, El-Chichon, Mt. Pinatubo.

1. Introduction

The effect of the aerosol load in the troposphere and stratosphere and its interaction with the Sun's radiation on the earth's energy budget and on the local and global climate is known for a long time. Turbidity measurements are useful in deriving information about the vertically integrated aerosol content of the atmosphere.

Considerable increase in atmospheric turbidity during the last few decades has been reported by several authors (Mani *et al*., 1973; Krishnanand and Maske, 1983; Srivastava *et al*., 1992, Subbaraya *et al*., 2000). A few groups in India have been making atmospheric aerosol measurements using *in situ* and remote sensing techniques (Devara, 1999). Under ISRO's Geosphere Biosphere Program a network of multi-wavelength radiometer stations has been set up. Studies from this network from locations such as Trivandrum, Mysore, Pune, Visakhapatnam and Ahmedabad indicate significant increase in aerosol optical depths over the last one to one and a half decade and the increasing trend is more significant at shorter wavelengths (Moorthy, 1999, 2001, Prasad *et al*., 1999). A program of monitoring atmospheric aerosols using lidar technique has been in progress at IITM, Pune since 1986. A small increasing trend of about 3% is seen in aerosol column content for 12 years from 1986 which is attributed to the increase in human activity in the urban area of Pune and also due to change in land use pattern (Earnest Raj *et al*., 1999). The same data showed an increasing trend of almost 20% for 9 year period upto 1995. The aerosol loading is found to be maximum in summer and minimum during the SW monsoon (Earnest Raj *et al*., 1997).

The observed atmospheric turbidity values at all the Indian Global Atmospheric Watch (GAW, formerly known as BAPMoN) stations show systematic seasonal as well as long-term variation apart from random fluctuations. However, the nature of variation is station

TABLE 1

Geographical locations of GAW stations

Stations	Latitude (°N)	Longitude (°E)	Altitude (m)	Aerosol Environment
Allahabad	25° 27′	81° 44′	98	Mid-latitude, Continental & Urban
Jodhpur	26° 18′	73°01′	217	Mid-latitude, Arid & Rural
Kodaikanal	10° 14′	77° 28′	2343	Tropical, High altitude
Minicoy	08° 18′	73° 00′	2	Tropical maritime & Natural
Mohanbari	27°29′	95°01′	111	Tropical, Humid
Nagpur	21°06′	79°03′	310	Continental, Urban
Portblair	11°40′	92°43′	79	Tropical maritime & Natural
Srinagar	34°05′	74°50′	1587	Extra-tropical & Elevated valley
Visakhapatnam	17°41′	83°58′	72	Tropical Coastal, Industrial & Urban

dependent. Singh *et al*. (1997) have found that surface wind, surface maximum temperature and negative lapse rate are positively correlated with atmospheric turbidity. Significant short term and long term variations in the atmospheric transmission are common. These variations are mainly a function of the vertical distribution and total loading of aerosol in the troposphere and stratosphere, the aerosol size distribution and concentration, the optical qualities of the aerosol and the total precipitable water (Junge, 1971).

Explosive volcanic eruptions are the major source of aerosol in the stratosphere, which influences the atmospheric transmission. Tropospheric aerosols have short residence time due to gravitational settling, rainout and washout and produce only local and seasonal effects. But stratospheric aerosols have lifetime of the order of 2-3 years and can get transported by atmospheric circulations and produce long-term effect. Observations following the eruption of Mt. Pinatubo in Philippines in June 1991 have offered large details regarding forcing and response characteristics associated with stratospheric aerosols (McCormick *et al*., 1995). Long-term measurements for the period from 1956 to 1992 from coastal Antarctica showed the influence of Mt. Agung, El-Chichon and Mt. Pinatubo volcanic eruptions on aerosol optical depth (Herber *et al*., 1993).

Mani *et al*. (1973) noticed marked decrease in direct solar radiation and increase in Angstrom turbidity in 1963 and 1965 associated with Mt. Agung and Taal volcanic eruption. Srivastava *et al*. (1992) have reported a sudden increase in turbidity over some Indian stations during 1980 and 1982 associated with Ulawun and El-Chichon volcanic eruptions. Under the ISRO's Geosphere Biosphere Programme, the measurements during 1991 and 1992 show highest aerosol optical depth ever measured at Hyderabad over a fifteen year period of observation, which is attributed to Mt. Pinatubo volcanic eruption (Subbaraya *et al*., 2000). The long-term sun photometric turbidity observations from Indian GAW Stations have been analysed in this paper to examine the long-term variations and the effect of volcanic eruptions. During the period of study the eruptions of El-Chichon in 1982 and Mt. Pinatubo in 1991 have had greatest impact on turbidity over Indian stations. Both were low northern latitude and sulphur rich volcanic injections of large magnitude.

2. Data and methodology

Sun photometric observations at 500 nm wavelength made at nine stations of GAW network of the India Meteorological Department (IMD) for the period 1975-97 are considered for the present study. Geographical locations of these stations are given in Table 1. The Indian GAW network contains Allahabad, Jodhpur, Kodaikanal, Mohanbari, Minicoy, Nagpur, Portblair, Pune, Srinagar and Visakhapatnam. Due to the lack of continuity in the data set, the station Pune was excluded for the present study. As turbidity observations are taken only under cloud free sky conditions, very less number of observations is generally possible during the rainy season. The method used to calculate turbidity coefficient is described in WMO (1978). The mean and standard deviation of turbidity coefficients for two consecutive decades 1976-85 and 1986-95 have been calculated to find out the decadal variations and dispersion nature. Annual means for the period 1975-97 for all the stations have been worked out and used for finding the long-term trend pattern. In order to analyse the seasonal variations, long-term monthly means were calculated and plotted.

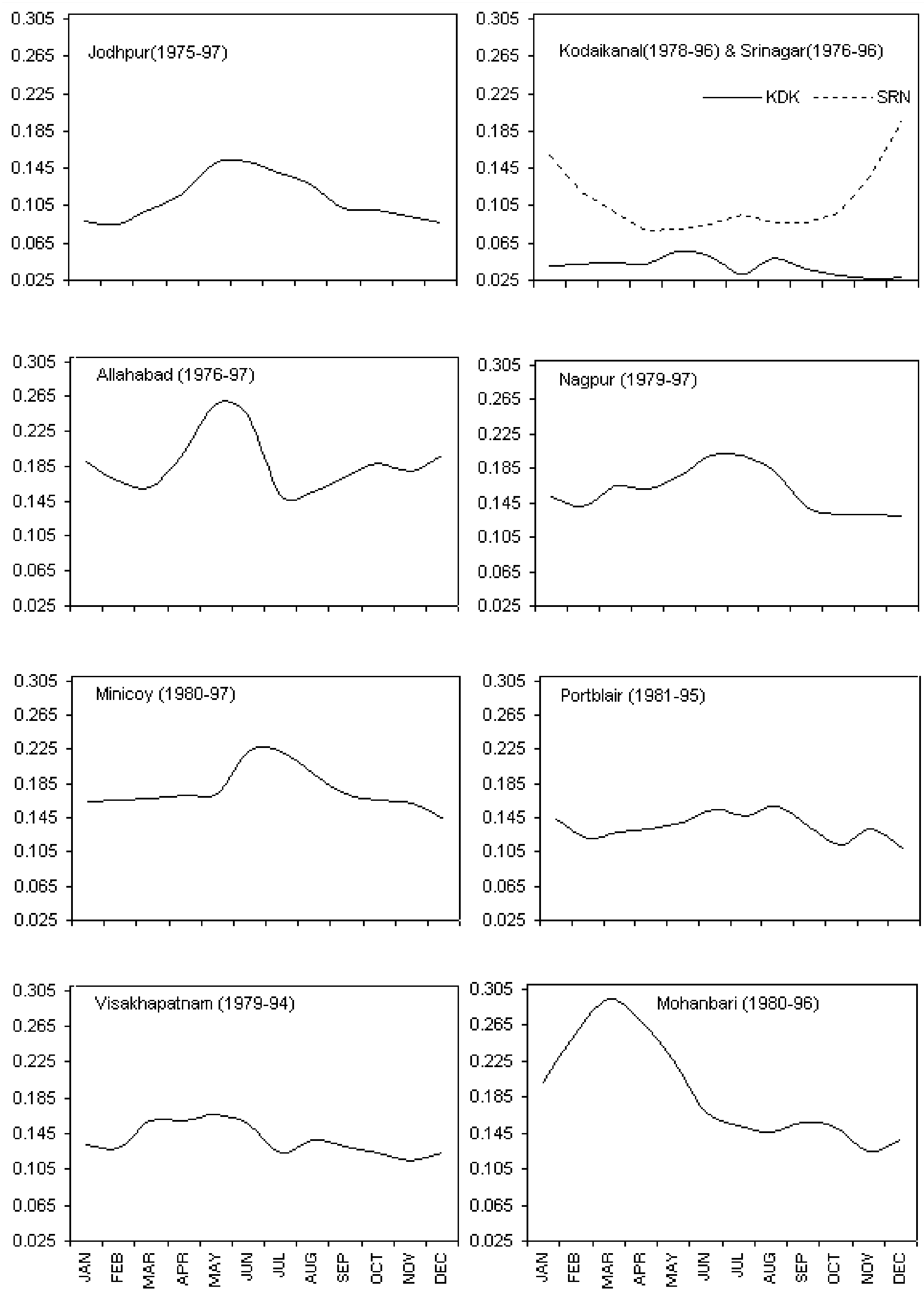

Fig. 1. Monthly variation of turbidity coefficient B (0.5 µm)

Percentage of frequency of occurrences of turbidity coefficients was computed for two consecutive five years periods 1986-90 and 1991-95. The effect of volcanic eruptions on turbidity is discussed in detail for Visakhapatnam, Jodhpur and Nagpur stations where clear sky days are more in comparison to the other stations. However, the effect of volcanic eruptions was noticed at all the stations. Total suspended particulate matter (TSPM,

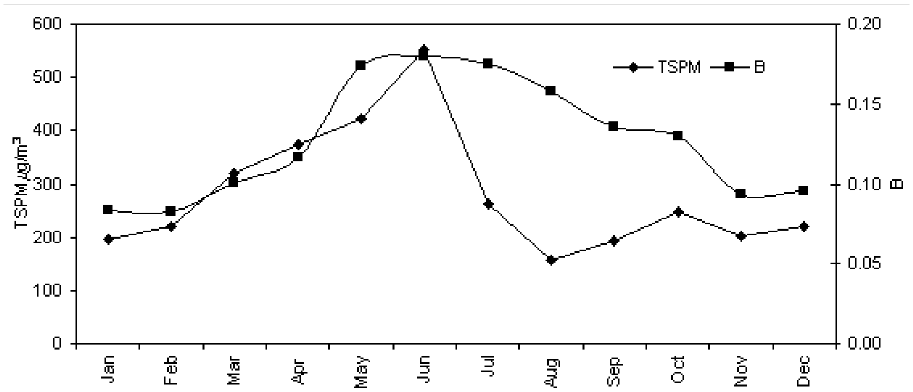

Fig. 2. Variation of turbidity coefficient (B) with TSPM

TABLE 2

Long term mean of atmospheric turbidity and standard deviation

Stations	No. of days per year with PPT / TS / DS	Annual R/F (cm)	Mean turbidity coefficient ± Standard deviation	
			1976 - 85	1986 - 95
Allahabad	68.0 / 55.2 / 6.4	102	0.158 ± 0.058 (10)	0.242 ± 0.053 (10)
Jodhpur	(35.0 / 27.0 / 6.0)*	38	0.103 ± 0.041 (10)	0.118 ± 0.046 (10)
Nagpur	87.7 / 63.3 / 0.0	113	0.126 ± 0.035 (7)	0.166 ± 0.044 (10)
Mohanbari	168.8 / 91.8 / 0.6	259	0.192 ± 0.059 (6)	0.212 ± 0.083 (9)
Kodaikanal	156.0 / 67.1 / 0.4	167	0.039 ± 0.026 (7)	0.041 ± 0.024 (9)
Srinagar	93.0 / 36.3 / 0.3	66	0.083 ± 0.039 (10)	0.126 ± 0.054 (5)
Minicoy	137.2 / 35.4 / 0.0	167	0.163 ± 0.059 (6)	0.183 ± 0.067 (10)
Portblair	179.7 / 66.3 / 0.2	317	0.107 ± 0.029 (5)	0.142 ± 0.050 (10)
Visakapatnam	81.8 / 62.3 / 0.1	97	0.122 ± 0.029 (7)	0.148 ± 0.043 (9)

Note : No. of years of available data is given within the bracket.
PPT : Precipitation, TS : Thunderstorm, DS : Duststorm, R/F : Rainfall taken from "Climatological Table 1951-80" published by India Meteorological Department. * Climatological Table 1931-60

in $\mu g/m^3$) data from Jodhpur, obtained using high volume air sampler between 1982-91, have been also utilized to establish the relation between turbidity and TSPM.

The volcanic eruptions of El-Chichon and Mt. Pinatubo resulted in unusually large turbidity values. Turbidity values during volcanically perturbed period of May 1982 to December 1983 and June 1991 to December 1992 are not considered in calculating long term trend and decadal variations.

3. Results and discussion

3.1. *Seasonal variation*

The graphical representation of long-term monthly means for all the stations is shown in Fig. 1. Most of the monthly mean turbidity coefficients lie within the range of 0.10 - 0.35 for the continental stations, for the islands and coastal stations, the range is 0.10 - 0.25, while hill stations Kodaikanal and Srinagar have a lower value of 0.05-0.15.

The continental stations Allahabad and Jodhpur are having onset of monsoon in late June and July respectively. Hence, the turbidity values increase steadily during the pre-monsoon season, which is relatively drier, but reduce considerably after the onset of monsoon. For Jodhpur, this decreasing tendency found to continue till late winter because of the stable atmosphere and occasional rains associated with the Western Disturbances. Since the frequency of rainy days in late winter is less at Nagpur, the turbidity values do not show a considerable fall in the post-monsoon and winter seasons. At Mohanbari, as the pre-monsoon rains almost merge with the monsoon rains, the turbid season is restricted to January-March after that turbidity values decrease

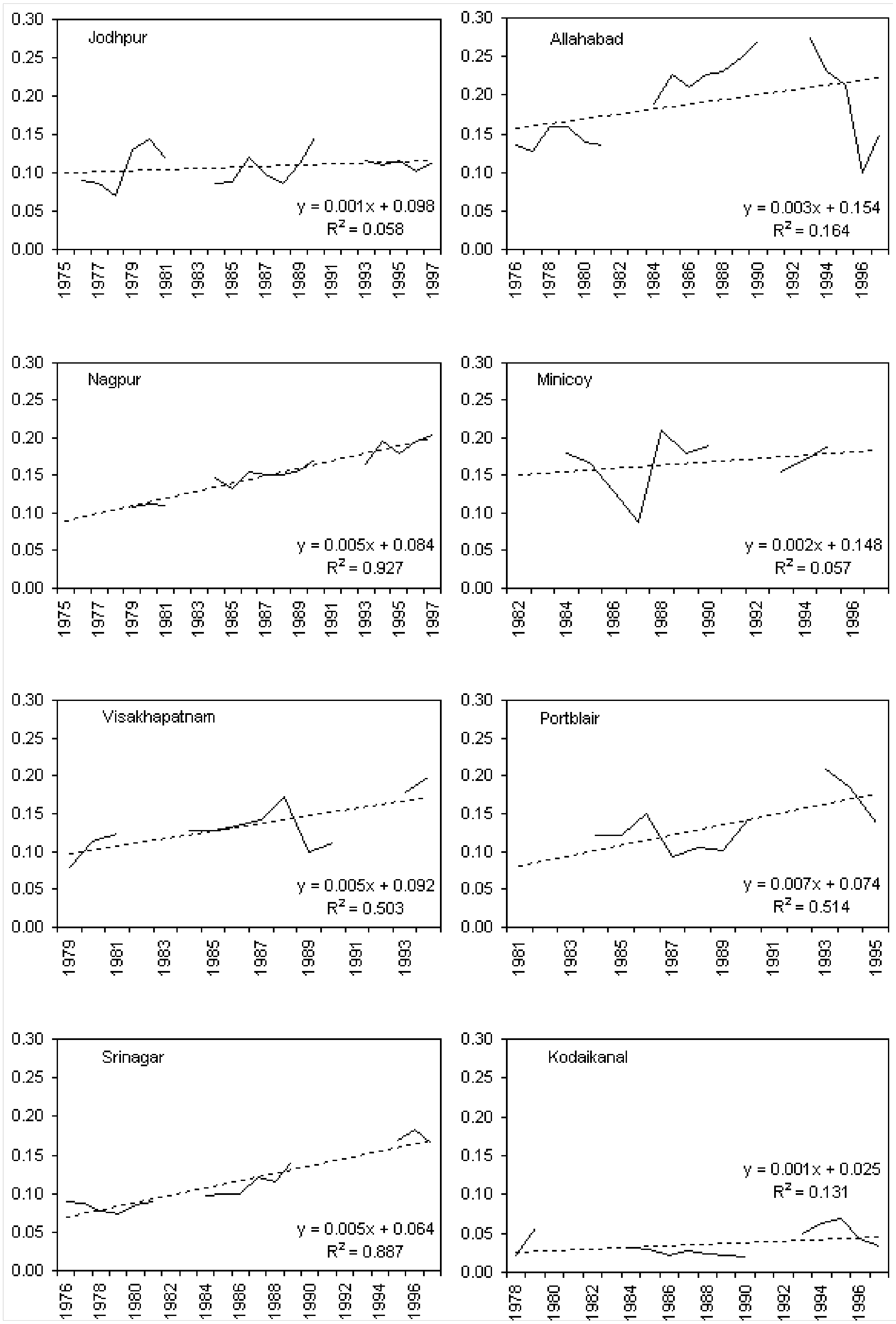

Fig. 3. Annual mean turbidity coefficient over Indian GAW stations. The gaps correspond to volcanically perturbed period

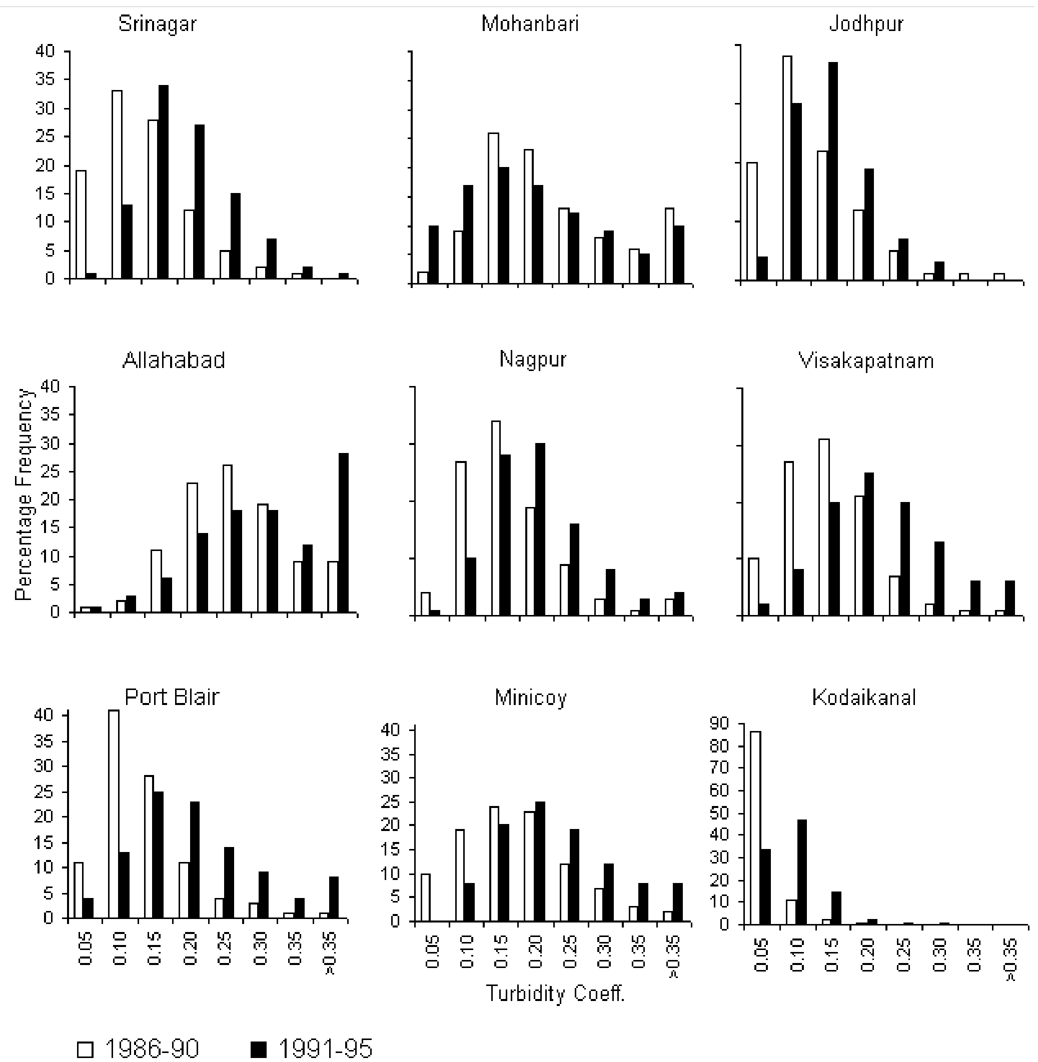

Fig. 4. Frequency of occurrence histogram of turbidity coefficient

considerably and remain more or less constant from June to December. Visakhapatnam shows annual pre-monsoon maxima, which is predominant over other periodicities. Due to the onset of northeasterly monsoon rains, the secondary maxima that generally occurs in the post-monsoon does not occur at Visakhapatnam.

Turbidity values over Minicoy are found to be higher than Portblair throughout the year. At Minicoy, turbidity values are found to have slight variation from January-May during the months of northeast trade wind regime and increasing during June-July with the reversal of winds to the westerly regime. This can be attributed to the aerosol transported from African coast and even from Arabia to India. Patterson and Grams (1981) had earlier detected the presence of mineral aerosols over the Arabian Sea during the summer MONEX-1979. Using “tagged radon” species to track the air masses, Rasch *et al.* (2000) during INDOEX found that in the northern Arabian Sea, most of the air near the surface originates from Arabia and India and at the higher altitude (2.5 km) air of African origin makes a much larger contribution to the air in the Arabian Sea.

Srinagar is an extra-tropical type of station, which shows low values of turbidity from April to October. Higher values of turbidity found during December-February. Srivastava *et al*. (1992) attributed higher turbidity values during winter months due to westerly transport of dust from upstream desert locations in Iran and Afghanistan. In case of Kodaikanal, the values are found to have the range 0.03 - 0.07 with slight variation. Kodaikanal shows two pronounced maxima, one before the monsoon season in May and other in September.

The winter months have narrowest distribution of turbidity values at all the stations. Seasonal rains affect the atmospheric turbidity in two ways. Firstly, rains are very effective in cleansing the atmosphere by rainout and washout processes. Secondly, during monsoon season soil becomes moist and vegetation cover develops over extended areas due to which soil derived aerosol in the atmosphere decrease. Thus aerosol input decreases during monsoon season and increases progressively in the post-monsoon period until the next monsoon season. This is evident from the total suspended particulate matter (TSPM) data obtained from Jodhpur (Fig. 2). TSPM values are significantly correlated (c.c. 0.52 significant at 5% level) with atmospheric turbidity in all the months except in monsoon months at Jodhpur. In monsoon months TSPM values decrease sharply as compared to turbidity coefficient.

3.2. *Long term and decadal variations*

On an annual basis, the lowest turbidity is observed at Kodaikanal and Srinagar and highest in the north and central India. The effect of heavily industrialized cities on turbidity is apparent from the Fig. 1 especially those for Allahabad and Nagpur which are more turbid as compared to other stations. The mean values and standard deviations of turbidity values during the two epochs 1976-85 and 1986-95 have been given in the Table 2. Comparing the shifts in the mean values, the increase in atmospheric turbidity over Jodhpur, Kodaikanal, Minicoy and Mohanbari could be considered as nominal. The other stations show an upward shift in the means, which is significant at 5% level of significance. The high altitude stations concerned, Kodaikanal has remained almost unaffected by this trend pattern despite the brief period of high turbidity during 1982-83 and 1991-92, but Srinagar has shown a significant increasing trend. Allahabad, Nagpur, Portblair, Visakhapatnam and Srinagar show significant secular increasing trends with higher values of turbidity in all the months of the later epoch.

The increasing trend of the turbidity at short wavelength (500 nm) indicates that it is caused more by fine size range aerosol, which are the product of primary and secondary production processes associated with anthropogenic activities. The large prolonged departures from background turbidity levels are associated with the major volcanic eruptions. Fig. 3 shows the variation of annual turbidity values and the associated trend lines for some of the stations.

3.3. *Distribution of turbidity coefficients B (0.5 μm)*

The frequency of occurrence histogram of turbidity coefficient B(0.5μm) at different stations for the periods 1986-90 and 1991-95 are presented in Fig. 4.

Aerosol distributions at Allahabad and Visakapatnam have undergone drastic change. At Srinagar, Jodhpur and Port Blair a large percentage of occurrences (at least 52%) were confined in the earlier epoch within the first class intervals with B(0.5μm) ranging upto a value of 0.10, whereas in the later epoch at least 50% occurrences have taken place in the range 0.10 to 0.20. Jodhpur, Nagpur and Minicoy have shown an increasing bias towards higher values of B, although broadly retaining the shapes of the distribution curves. Almost all the stations except Mohanbari, have a trend of shifting their model class to higher values at the expense of lower values of turbidity. Kodaikanal, which is a higher altitude station, too have changed in its distribution pattern where, the class 0.0 to 0.05 that had 85% of occurrences in the first epoch, is reduced to 35% in the second epoch. It is to be noted that the later epoch had a large volcanic eruption which contributed significantly to the shift of B(0.5μm) towards higher values. However, the role of possible anthropogenic influence cannot be ruled out.

3.4. *Effect of volcanic eruptions on atmospheric turbidity*

The impact of volcanic eruptions on the atmosphere depends not only on the strength of the eruption but also on the geographic location. A large volcanic eruption establishes a reservoir in the lower stratosphere at the latitude of injection, moving with and stretching out in the direction of the zonal circulation. Equatorial reservoirs have a residence time of about two years while, middle and high latitude injections have a residence time of about three to nine months according to the latitude and time of injection in the annual cycle of stratospheric transport (Dyer, 1974). Aerosol observations suggest that two transport regimes exist in the lower tropical stratosphere. A lower transport regime is suggested by the rapid poleward and downward movement of volcanic material deposited within a layer several kilometers above the tropopause (Kent and McCormick, 1984). In the upper transport regime, detrainment of aerosol from the upper equatorial reservoir depends upon the intensity of planetary wave activity and on the phase of quasi-biennial oscillations (QBO). During the westerly phase of the QBO, the stratospheric surf zone is able to penetrate deeper into the tropics and eddy mixing can tap the core of the aerosol reservoir lying near the equator. On the other hand during the easterly phase of the QBO, planetary waves are shielded from the equator and only aerosol

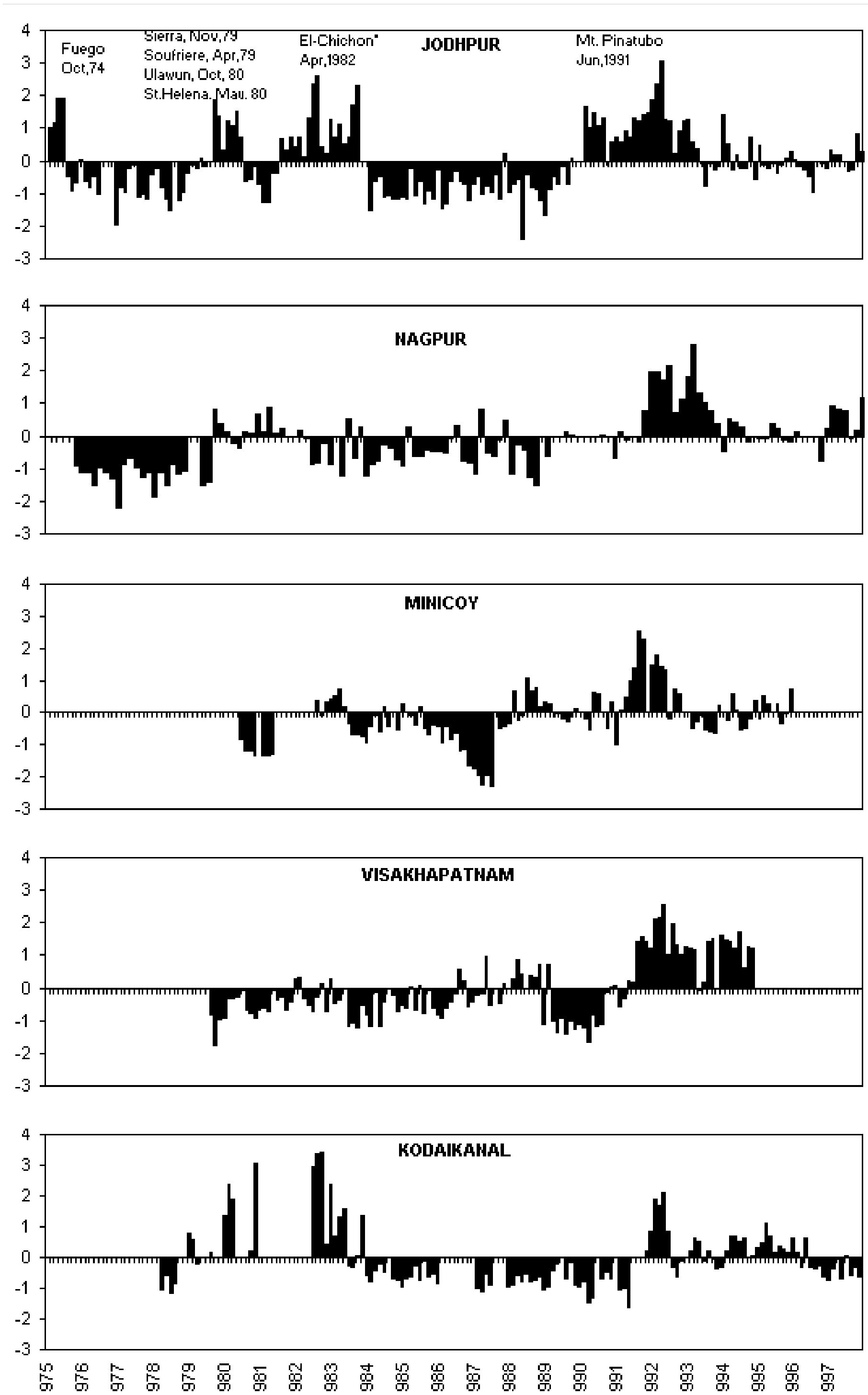

Fig. 5. Standardised monthly turbidity anomaly (Oct-May)

lying near the subtropics can experience further poleward mixing (Trepte and Hitchman, 1992). Stratospheric Aerosol and Gas Experiment-II observations indicate that the primary transport of Mt. Pinatubo aerosol from low latitude to southern latitude occurred above 20 km (McCormick and Veiga, 1992).

The volcanic material remained equatorward several months after the eruptions because of the absence of planetary wave induced mixing within the summer easterly flow. The increase of turbidity in case of El-Chichon was smaller as compared to that after the Mt. Pinatubo eruption, although the zonal wind data reveal that during both the eruptions, QBO easterlies were present over the equator at 30 hPa, the reason being the later eruption injected much more sulfurous materials into the stratosphere as compared to the El-Chichon eruption.

Perturbations in the background turbidity over Indian stations are apparent in the periods following major volcanic activities such as El-Chichon in 1982 and Mt. Pinatubo in 1991. Since tropospheric aerosols and molecular scattering usually dominate the turbidity values, it is expected that several smaller volcanic eruptions are not evident in the record. The effect of El-Chichon and Mt. Pinatubo eruptions can be examined by normalizing each turbidity value to form a standardized monthly turbidity anomaly (Fig. 5) (only few graphs representing continental, coastal and island stations are given here). In order to find out the extent and persistence of the effect of Mt. Pinatubo eruption, monthly mean values of turbidity for the years 1991, 1992, 1993 have been compared with the average values for the period 1986-90, the relatively volcanically quiescent period before the Mt. Pinatubo eruption. It is found that the turbidity increase attributed to the aerosol injected into the stratosphere after the volcanic eruption of Mt. Pinatubo was observed after a lag of about one month from the episode. The increase in atmospheric turbidity values following the volcanic eruptions was discernible for 1.5 - 2 years after the eruption.

4. Conclusions

The observed atmospheric turbidity values at all the stations show systematic seasonal as well as long-term variation apart from random fluctuations. However, the nature of variation is station dependent and seasonal variation appears to be the strongest feature for all the stations. This is because of regional sources and meteorology. Most of the turbidity values lie within the turbidity range of 0.10 - 0.35 for all the continental stations, and for islands and coastal stations the range is 0.10-0.25, while hill stations Kodaikanal and Srinagar found to have lower values in the range 0.05 - 0.15. TSPM values are significantly correlated with turbidity in all the months except in rainy season. During rainy months TSPM values decrease sharply as compared to turbidity values, the reason being the dust load in the atmosphere is reduced considerably by rainout and washout but the increased moisture content contributes to a rise in the turbidity values. Annual mean values of the turbidity coefficients computed for the two consecutive decades, 1976-85 and 1986-95, show a general increase of turbidity during the later decade at all stations except Kodaikanal. The increasing trend in turbidity at wavelength 500 nm indicates that it is caused more by fine size range aerosol which are the product of primary and secondary production processes associated with anthropogenic sources of pollution. The comparative percentage frequency of occurrence of turbidity coefficient (B) at different stations for the periods 1986-90 and 1991-95 indicate that Allahabad and Visakapatnam have undergone drastic changes in their distributions. Jodhpur, Nagpur and Minicoy have shown an increasing bias towards higher values of B, although broadly retaining the shapes of the distribution curves.

All of the GAW stations show anomalously high values of atmospheric turbidity in 1982-83 and 1991-92 following the eruptions of El-Chichon, Mexico, in April, 1982 and Mt. Pinatubo, Philippines, in June, 1991. The increase in atmospheric turbidity values following these eruptions was discernible for 1.5-2 years after the eruption.

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