Mausam, (1997), **48**, 1, 33-40

551.593.54 : 551.581

Climatic impact on atmospheric turbidity at some Indian stations

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(Received 25 January 1996)

सार — आविलता पर जलवायु के प्रभाव का मूल्यांकन करने के लिए प्रधान अवयव विश्लेषण का प्रयोग करते हुए विभिन्न जलवायु क्षेत्रों में चार भारतीय बेपमॉन स्टेशनों के आंकड़ों का विश्लेषण किया गया है । उप-मौसमी, मौसमी और वार्षिक चक्र तैयार करने में इन स्टेशनों के आंकड़ों के स्पेक्ट्रमी विश्लेषण से सहायता मिली है । यह पाया गया है कि वायुमंडलीय आविलता सतह अभिवाह, आंधी में धूल के उड़ने अथवा वर्षा में बाढ़ के माध्यम से जलवायु संबंधी कारकों द्वारा प्रभावी रूप से नियंत्रित है और यह मूलरूप से एक छोटी क्षोभमंडलीय परिघटना है । वार्षिक चक्र और दीर्घ अवधि विभिन्नताओं को प्रत्युत्पन्न करने में प्रधान अवयव विश्लेषण समाश्रयण निदर्श का कार्य निष्पादन संतोषजनक पाया गया है ।

ABSTRACT. Data from four Indian BAPMoN stations in different climatic regions were analysed using principal component analysis (PCA) for the evaluation of climatic impact upon turbidity. Spectral analysis (FFT) of the data for these stations has helped to bring out the sub-seasonal, seasonal and annual cycles. It is found that the atmospheric turbidity is predominantly controlled by climatic factors through surface fluxes, transport of dust or rain washout and is mainly a lower tropospheric phenomenon. The performance of the PCA regression model is found satisfactorily in reproducing the annual cycle and long period variations.

Key words — Aerosol, Climate change, Principal component analysis, Spectral analysis, Atmospheric turbidity.

1. Introduction

The atmospheric aerosol is largely crustal or marine in origin over background areas. Thus dependence of atmospheric turbidity, which is a measure of the columnar aerosol load, upon meteorological parameters is important for the assessment of local and regional impacts of climate change. On the other hand, the likely impact of the aerosol on climate is itself an important problem of the region. Patterson and Grams (1981) made some preliminary calculations with aircraft sampled size distribution data collected during MONEX-1979 shows that the radiation divergence of the middle troposphere over north Arabian Sea region could be partly due to the aerosol. It may be realised that this mechanism could be a strong candidate among the causes of inversions that hang low over the north Arabian Sea and have the possibility of interacting significantly with monsoon dynamics (Srivastava *et al.* 1992).

Khemani *et al.* (1982) have observed a bimodal distribution of aerosols with one mode in the size range of 0.4 - 0.5 μm and the other mode at less than 0.3 μm, which is a characteristic of the background aerosol. The larger size fraction is likely to be a result of coagulative growth of hygroscopic particles under humid conditions and would not contribute substantially to atmospheric turbidity. In the present analysis of the relationship of meteorological parameter with turbidity, it is found that the variations in upper air, humidity affects the turbidity. Although atmospheric optical depth due to aerosol is an important parameter for the Indian region. No major study has yet been made to understand its relationship with the climate of the region. The object of this paper is to examine these aspects.

It may be stated here that as a condition for acceptance of a climate regression model of turbidity, the annual cycle and the important features should be explained satisfactorily. In this regard proper averaging of variables is important. Beginning from daily values which has the limitation of low correlation overall, due to a finite residence time of aerosols, the meteorological parameters could alter in the opposite sense.

2. Method of analysis

2.1. *Measurement of turbidity coefficient*

Sunphotometeric observations are made at the stations Jodhpur, Mohanbari, Vishakhapatnam and Minicoy under the Background Air Pollution Monitoring Network (BAPMoN) programme. The measurements are made at 500 nm wavelength using Volz sunphotometer. The error analysis for Indian BAPMoN data has been presented by Srivastava *et al.* (1992). It suffices to mention here that turbidity coefficient (log 10) variations greater than 0.015 at mean sea level should be considered significant.

2.2. *Spectral analysis*

The spectral analysis has been done with daily average turbidity coefficient data on a seasonal basis by using the FFT technique. The data is made stationary by removing curvilinear trend with the help of a third degree polynomial. A few gaps were there in the data since observations are suspended during clouded conditions. The monsoon season has been entirely left out because of frequent rains. Data gaps upto 3 days have been filled up using the Newton-Gregory interpolation technique. Gaps more than this have been interpolated by inverting the frequency domain transform of the data set. Care has been taken to preserve data continuity with a 3-day band on either side of the gap and by conserving the standard deviation. It may be noted that the number of such data gaps are extremely few (1 or 2 in each season). The Fourier inverse technique employed for interpolation has been found to be more suitable than all types of polynomial fitting techniques, because it conserves the spectral quality of the data.

2.3. *Principal component analysis*

The principal component analysis provides a simple means of transforming a data-set matrix X_{ij} having i variables and j observations of the ith variable into a score matrix S_{ij} defined as follows :

$$S_{ij} = L_{ii} X_{ij} \tag{1}$$

where, i = 1, ..., M and j = 1, ... , N

where, L_{ii} is the transformation matrix, known as the load matrix.

The transformation is such that all the i vectors constituting the S_{ij} matrix are orthogonal to each other. This property is not expected necessarily out of the matrix X_{ij}. The first vector explains the maximum variance in the data set. The second vector explains a further possible maximum out of the remaining variance and so on. All the vectors are orthogonal to each other. Thus, they are called 'principal components'. Each of them represents a process or phenomenon that act independently of each other. This particular property makes it more suitable for multiple regression analysis.

The principal components are obtained by diagonalising the correlation or co-variance matrix of the data matrix X_{ij}. In our case we have normalised our data matrix. This takes care of making the ranges of values of various meteorological elements like lapse rate, wind, pressure and other parameters comparable to each other.

2.4. *Regression model of turbidity*

The score matrix replaces the monthly average data matrix for the purpose of linear multiple regression with observed turbidity of the type,

$$T_j = A + \sum_{i=1}^{9} a_{ij} S_{ij} \tag{2}$$

where, A is called the regression constant and is interpreted as the intrinsic average turbidity of the location to which the climate modulations are algebrically added.

The model generated turbidity series and the observed series (both monthly) are subjected to spectral analysis for checking whether the significant modes are preserved by the model or not.

2.5. *Choice of parameters*

A set of sixteen meteorological elements were screened for their ability to explain turbidity for the four Indian BAPMoN stations in distinct climatic regions. Nine of them as listed below in the foot note

TABLE 1

Principal components of turbidity

Station	PC	Variation Expl. (%)	Principal component loadings								
			1	2	3	4	5	6	7	8	9
JDP	I	42	–.79	.85	.76	–.01	.05	–.80	–.45	.73	.69
	II	33	–.51	–.13	–.10	.94	.95	.18	.79	.49	–.13
MHB	I	45	–.77	.72	.69	–.43	.71	–.83	–.45	.71	.63
	II	27	.52	–.60	.40	–.69	–.51	.34	–.57	.44	.53
VSK	I	46	–.77	.79	.77	.64	.01	.56	.72	.71	.77
	II	23	–.42	–.08	.06	.09	.90	–.70	–.56	.09	.45
MNC	I	46	–.53	-.60	.70	.62	.84	–.65	–.12	–.78	.92
	II	18	–.35	.40	.29	–.53	–.12	–.58	–.75	.11	–.11

1. Surface pressure, 2. Surface maximum temperature, 3. Surface wind, 4. Surface relative humidity, 5. Relative humidity at 850 hPa, 6. Morning lapse rate (Surface to 850 hPa), 7. Evening lapse rate (Surface to 850 hPa), 8. Meridional wind at 850 hPa., 9. Zonal wind at 850 hPa.

Note — Meridional wind southerly is positive and northerly is negative, zonal wind westerly is positive and easterly is negative.

of Table 1 were retained. These variables represent the state of atmosphere that determines the amount of dust it can hold in suspension. Table 1 gives the loading factors for the first two eigen vectors only and shows that for different stations different variables combine with the different weightages in determining each of these vectors.

We have divided the data in three periods as follows :

(a) Pre-Monsoon : February - May

(b) Monsoon : June - September

(c) Post-Monsoon : October - January

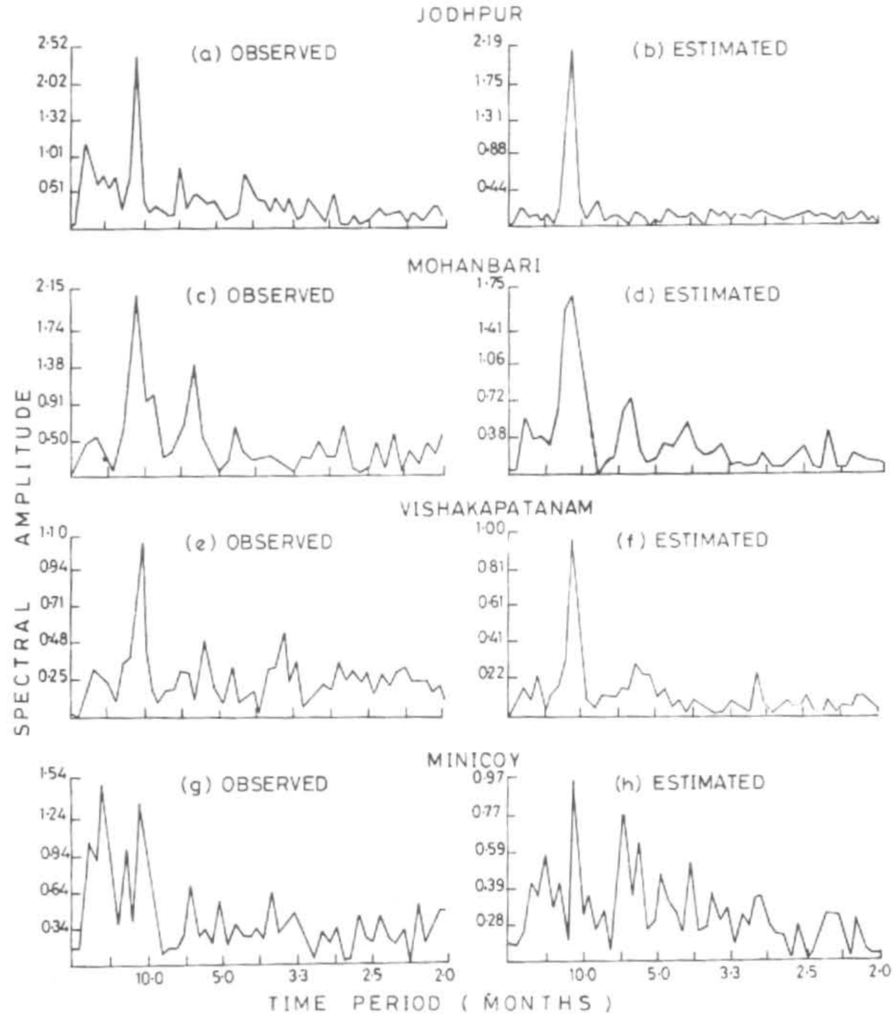
3. Result and discussion

3.1. *Power spectrum of turbidity time series*

The power spectrum of observed atmospheric turbidity and model generated turbidity are shown in Figs. 1 (a-h). It may be seen that for three stations Jodhpur, Mohanbari and Vishakhapatnam the most important annual mode is reproduced in the model result. However for Minicoy station the meteorological model generates an extra six monthly mode which is not present in the power spectrum of observed values. It is quite obvious that the combination of meterological factors which produce high turbidity occurs twice a year. This is possibly related to the passing of sun overhead during pre-monsoon and its return during post-monsoon season. The high values of turbidity, occurring after the monsoon season, are due to local causes and an additional transport of dust across the ocean. This source is not found during the wind regime preceding monsoon. Hence although the PCA model expects high turbidity during both the seasons, in actual practice only maxima exists during the post-monsoon.

The relative contributions of different frequency modes based on FFT analysis at some of the stations for which continuous data is available (daily mean data) are shown in Figs. 2 (a-d).

It can be seen from Figs. 2(a&b) that at Jodhpur the 3-4 days cycle is more predominant during pre-monsoon as compared to that of post-monsoon period. This can be associated with frequent dust raising wind prior to monsoon period. However, the power spectrum of post-monsoon is less noisy compared to pre-monsoon. In contrast to Jodhpur, Minicoy shows that power spectrum of the data during pre-monsoon



Figs. 1(a-h). Power spectra of monthly average atmospheric turbidity and model generated turbidity

is less noisy compared to the post-monsoon as can be seen from Figs. 2 (c & d) also 3-4 days cycle is less pronounced in the pre-monsoon period.

3.2. *Regression model for climatic control of turbidity*

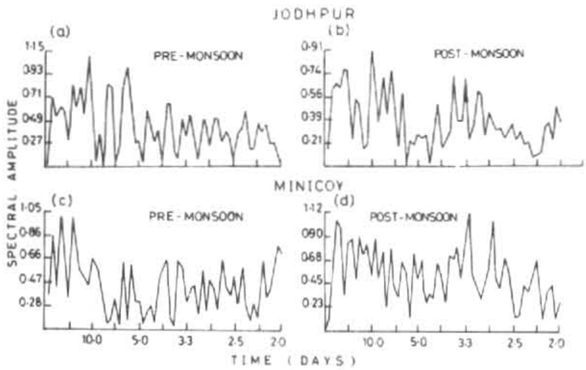
As a first guess regression analysis for the daily values of atmospheric turbidity were carried out. It was found that these values explain a low percentage of variance. The regression constants which represent non-climatic control do not give a realistic value of atmospheric turbidity. Since the regressions were not physically explainable. These two short-comings could be improved by using the PCA technique for monthly average data. In the regression model, turbidity has been described as a linear function of all the nine PC's. The independent variables in this analysis are the original data matrix transformed to orthogonal space. This matrix is called the score matrix. The constants and coefficients of the regression are given in Table 2. The output results are presented graphically in Figs. 3 (a-d). The quality of the fit was tested by splitting the data set into three groups; two lying out side the distance of standard deviation from the mean and one lying within the standard deviation limit.

It may be seen from Table 2 that lower values are over estimated and higher values are underestimated, which shows that the some of the variables interact nonlinearly. Hence a linear model fails to predict the extreme values. The distribution of turbidity occurrence is skewed towards higher side in case of Mohanbari, Minicoy and Vishakhapatnam whereas, it is reverse for Jodhpur.

TABLE 2

Regression coefficients in turbidity model

Station	Regression constant	Regression coefficients								
		1	2	3	4	5	6	7	8	9
JDP	.113	–.007	.002	–.008	.025	.016	.002	.042	.048	.037
MHB	.202	–.005	–.015	–.000	.022	.007	.104	–.018	–.035	–.210
VSK	.134	–.003	–.003	.005	.004	.017	–.019	–.020	–.000	–.021
MNC	.151	–.004	–.004	.004	–.007	.009	–.008	.010	–.009	–.013



Figs. 2(a-d). Power spectra of atmospheric turbidity from daily data

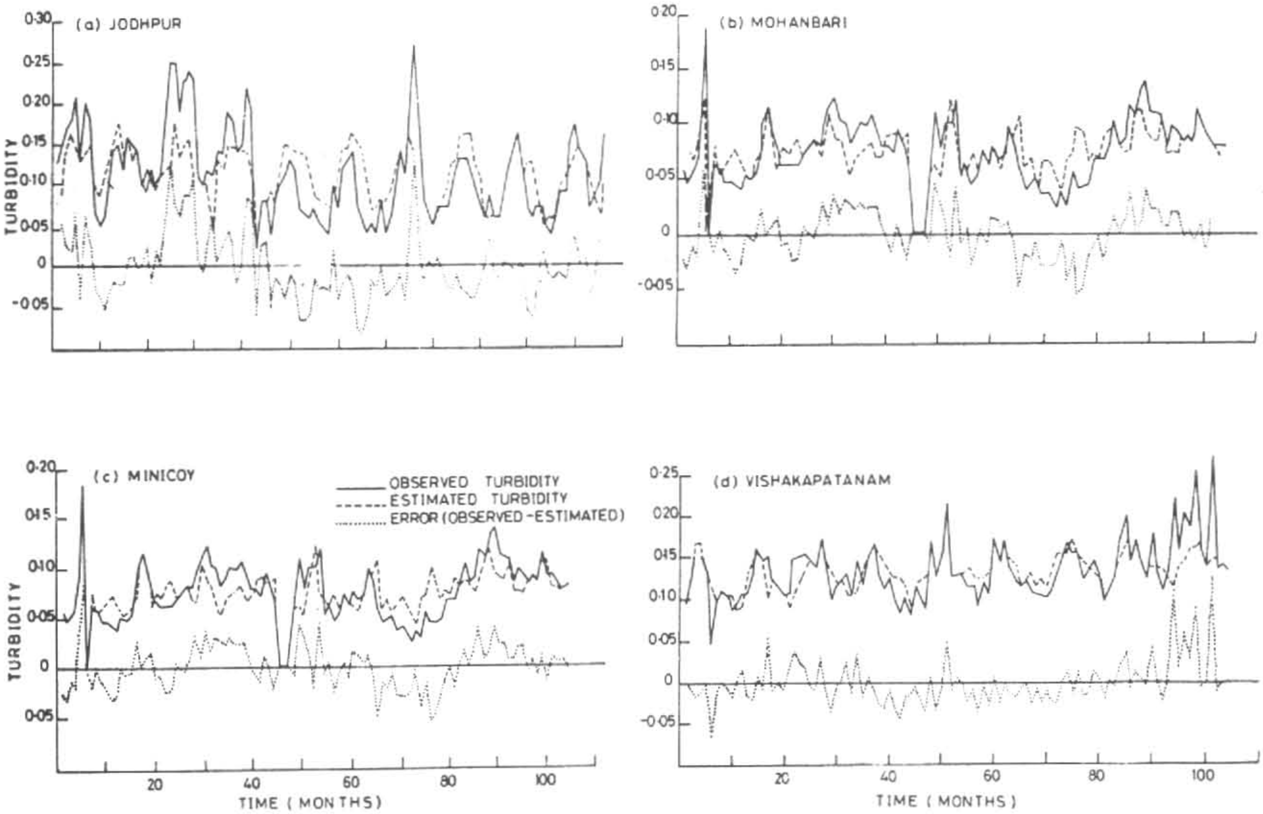
The regression constants which are the non-climatic control of turbidity obtained from the model are different for different stations. It is clear from these constants that river basin with thick alluvial deposits (Mohanbari, constant = 0.202) seem to have higher turbidity than desert region (Jodhpur, constant = 0.113). The Island in the Arabian Sea (Minicoy, constant = 0.157) is more turbid compared to coastal station (Vishakhapatnam, constant = 0.138).

3.3. *Principal component analysis of turbidity*

The results based on the computation of principal component analysis are given in Table 1 for the period (1980-89) for which the data has been analysed. It may noticed that at all stations the first two PCs explain a sizable portion of the total variance of the meteorological variables numbered 1-9 which are significant at 5% level. Hence the physical significance of only first two PCs are being discussed. The signs of the loading are adjusted for each PC in accordance with the sign of the corresponding coefficient in the regression with turbidity.

(a) *Jodhpur*

The first two PC's explain 75% variance. The first PC gives the highest correlation coefficient (0.52) with turbidity. The surface wind, surface maximum temperature and both negative lapse rate are positively correlated with turbidity. This can be explained by the facts that during the summer, the station frequently experiences dust storms due to which particulate matter goes up into the atmosphere to a considerable depth (Bryson *et al.* 1963). Thus surface maximum temperature alongwith surface wind and high negative morning lapse rate are quite favourable parameters for convective and dust raising activities, thereby injecting large quantities of particulate matter into the atmosphere causing increase in turbidity. Southerly and westerly winds are also positively correlated with the turbidity which show that during monsoon period these winds only enhance the dust raising, as these winds do not carry substantial amount of moisture reflected by relative humidity at 850 hPa level. Hence, first PC is a typical feature of pre-monsoon and monsoon period. The second PC indicates that high evening lapse rate is positively correlated with turbidity. It reflects that inversion becomes strong during night giving rise to formation of haze and fog. It also reflects that surface pressure is negatively correlated while relative humidity at surface and 850 hPa level alongwith the southeasterly winds are positively correlated with turbidity. These characteristics are associated with the western disturbances. It is a well known fact that the station frequently experiences western disturbances during winter season. Thus the second PC is a typical feature of winter season.



Figs. 3(a-d). Time series of monthly average turbidity

(b) *Mohanbari*

The first two PC's explain about 74% of variance with highest correlation coefficient (0.56) between second eigen vector and turbidity. The effect of surface maximum temperature, surface wind and lapse rate (particularly morning) appear with positive loads representing the local source of dry convective dust raised during February to April. The surface relative humidity acts in opposite sense indicating inhibition of locally raised dust during moist conditions. However, the relative humidity at 850 hPa level is also positively correlated. This could be due to hygroscopic aerosols behaving like scatterers after growing to sufficiently large size (> 0.5 μm) in humid upper air conditions.

The meridional and zonal winds at 850 hPa level indicate strong transport of marine air over the Assam valley during the Southwest monsoon period. Hence first PC is a typical feature of pre-monsoon and monsoon periods. The second PC shows that relative humidity at surface and 850 hPa level alongwith southwesterly winds at 850 hPa level are positively correlated with turbidity. It also shows that in the morning the lower atmosphere is stable while in evening it is unstable. It may be mentioned that during winter the main wind flow pattern is northwesterly over the entire northern Indian region. But this northwesterly wind flow turns to southwesterly over the Assam valley which carries moisture from north Bay of Bengal. Thus second PC is a typical feature of winter and high values of turbidity occur as a result of aerosols trapped under the winter inversion at low levels.

(c) *Vishakhapatnam*

The first two PC's explain about 69% of variance with highest correlation coefficient (0.40) between first PC and turbidity. First PC indicates that surface maximum temperature, surface wind, surface relative humidity, relative humidity at 850 hPa level alongwith morning and evening positive lapse rate are positively correlated with turbidity. However, northeasterly winds at 850 hPa level are negatively correlated. This can be explained by the fact that during summer, there is a consequent occurrence of sea breeze and formation of the stable layers in the lower atmosphere (Kumar 1984). During this period mixing heights are less than 400 m. At 850 hPa level an anticyclone forms during this season with its centre lying northeast of the station over the sea. During its easternmost location, the winds at the station change from the usual northwesterly to northeasterly. During the northeasterly flow the usual sea breeze inversion vanishes and the turbidity goes up. Thus first PC is a typical feature of summer season. The second PC shows that westerly winds, relative humidity at 850 hPa level alongwith both morning and evening lapse rates are negatively correlated. This is attributed to westerly wind at 850 hPa level which carries substantial amount of moisture during monsoon, also cyclonic activities disturb the weather which favour vertical mixing. This causes pumping of moisture into upper levels. Filippov and Mirumyuanti (1983) have reported that a strong effect of relative humidity on the optical state of matter. Ben Mohammed and Frangi (1983) have reported higher turbidity in humid season. Thus second PC is a feature of monsoon season.

(d) *Minicoy*

First two PC's explain about 64% of variance, with highest correlation coefficient (0.33) between first PC and turbidity. First PC indicates that turbidity is positively correlated with all the climatic factors except surface pressure and surface maximum temperature. This can be explained by considering that northerly and westerly winds at 850 hPa level are possibly associated with the transport of dust. The BAPMoN data reveals that turbidity begins to build up from late winter and proceeds till the advent of southwest monsoon winds (Srivastava *et al.* 1992). Patterson and Grams (1981) had reported the characteristics of a thick haze layer over north Arabian Sea. It has been found that the entire Arabian Sea is invaded by this dust originating over African and Saudi Arabian deserts. The turbidity is low only during the northeast trade wind regime before monsoon season. With the reversal of winds to westerly regime, it begins to build up. The relative humidity at surface and 850 hPa level are positively correlated whereas, surface maximum temperature is negatively correlated with turbidity. This could be associated by the fact that during monsoon season substantial amount of moisture is advected, thereby increasing the turbidity. Hence the first PC reflects the feature of monsoon and post-monsoon seasons. The second PC shows that surface maximum temperature, surface wind speed and the negative of both lapse rates and southeasterly winds are positively correlated with turbidity whereas relative humidity at surface and at 850 hPa level are negatively correlated. During the winter winds flow pattern at 850 hPa level is northeasterly. At these latitudes low level inversions do not form during the winter months. But in disturbed weather conditions a low pressure area forms in south-east Arabian Sea during this season and the winds change from northeasterly to southeasterly at 850 hPa. These winds carry substantial amount of moisture and are likely to enhance turbidity. Thus second PC reflects winter condition.

4. Conclusions

(*i*) When the weather variables are converted to corresponding principal components, they serve to identify the climatic features responsible for turbidity variations in a better way.

(*ii*) The meteorological regression model for atmospheric turbidity fails to explain a significant variance of the data primarily because of the fact that dust once raised by certain mechanism fails to settle down as fast as the mechanisms change.

(*iii*) The monthly average of turbidity is very well explained by monthly averaged climate variables. The seasonal cycles are well reproduced. The performance of the model is decidedly better in the mean ± standard deviation range.

(*iv*) The principal components are identified with seasonal patterns. At all stations, the summer maxima of turbidity is explained with the first principal component. However, for Minicoy it appears that the first principal component reflects the post-monsoon condition. However, late winter and early pre-monsoon turbidity is due to the 2nd principal component at Minicoy which is identified with dust transport.

(*v*) In the Indian region the transport of dust is generally from west to east, but locally raised dust is the most dominant cause of turbidity variations.

(*vi*) In the peninsular stations and in vegetated regions the growth of hygroscopic aerosols is around 0.5 μm size due to moisture is another important source.

Acknowledgements

We are grateful to our several colleagues for the excellent support given in painstaking collection of air pollution data over the past several years.

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