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On the association between aerosol optical depths and surface meteorological conditions in a tropical coastal environment

PRABHA R. NAIR and K. KRISHNA MOORTHY
Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram

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सार — स्थल आधारित पैसिव मल्टी वेवलेंथ सौर रेडियोमीटर के प्रयोग द्वारा उष्णकटिबंधीय तटीय केन्द्र थुम्बा, त्रिवेन्द्रम (8.55° उ०, 77° पू०) में नवम्बर 1985 से मई 1991 तक की अवधि के दौरान कोल्यूमनर एरोसोल स्पेक्ट्रल ऑप्टीकल डेप्थ डाटा आकलित किए गए। यह आकलन प्रकाशीय सघनता में मौसमी परिवर्तनों का संबंध और उनका प्रबल मौसम वैज्ञानिक स्थितियों से संबंध का अध्ययन करने के लिए किया गया है। एक नियमित मौसमी परिवर्तन के संबंध में प्रेक्षण लिए गए, जिसमें ग्रीष्म/पूर्व मानसून ऋतु में प्रकाशीय सघनता अधिकतम हो जाती है और शीत ऋतु में न्यूनतम हो जाती है। सतह पवन गति (तटीय) और वर्षा तथा ऐरोसोल स्पेक्ट्रल ओप्टीकल डेप्थ के मध्य महत्वपूर्ण संबंधों का पता चला है। निष्कर्षों के संबंध में असहमति पर विचार-विमर्श किया गया है।

ABSTRACT. Columnar aerosol spectral optical depth data, estimated using a ground based passive multi-wavelength solar radiometer at the tropical coastal station of Thumba, Thiruvananthapuram (Trivandrum) (8.55°N, 77°E) during the period November 1985 to May 1991, are examined to study the association of the seasonal variations in the optical depths and their association with the prevailing meteorological conditions. A systematic seasonal variation has been observed, with the optical depths maximising in the summer/pre-monsoon season and reaching a minimum in the winter season. Significant association has been observed between the seasonal variations of aerosol spectral optical depths with those of the (on-shore) surface wind speed and the rainfall. The implications of the findings are discussed.

Key words — Atmospheric aerosols, Rainfall, Wind, Convective activity, Boundary layer, Optical depth, Anthropogenic, Wavelength.

1. Introduction

Atmospheric aerosol optical depth is a measure of the extinction produced by the atmospheric aerosols, present in the vertical column, to the (solar) radiation passing through it. This is a parameter of importance in atmospheric radiation budgeting and in atmospheric corrections to the satellite imageries (Kaufman *et al.* 1990, Halthore *et al.* 1992), as well as in the studies on physical properties of aerosols (King *et al.* 1978) and their association with meteorological parameters like wind, rainfall and relative humidity (Peterson *et al.* 1981, Suzuki and Tsunogai 1988, Moorthy *et al.* 1991). Ground-based solar spectral extinction measurements using multi-wavelength radiometers provide estimates of τ_p as a function of wavelength (Shaw *et al.* 1973, Moorthy *et al.* 1989). The estimation of $\tau_{p\lambda}$ (at multiple wavelengths) facilitates deduction of the size distribution function by numerical inversion techniques (Quenzel 1970, King *et al.* 1978, Moorthy *et al.* 1991) and columnar loading.

As the physical properties of atmospheric aerosols (such as, size distribution, shape, refractive index and water activity) depict large variabilities spatially and temporally (due to the variety of production, sustenance and loss mechanisms) the aerosol spectral optical depths also depict spatial and temporal changes. At any location, the characteristics of aerosols are determined by a combination of all the above processes (which could be both natural and anthropogenic) relevant to the location. Due to the comparatively short residence times and increased susceptibility to natural and anthropogenic perturbations, aerosols in the boundary layer and lower troposphere exhibit more variability in their characteristics. Thus, in a natural environment, where the atmosphere is rather free from any strong anthropogenic perturbations, the aerosol characteristics would undergo changes associated with changes in the atmospheric processes, such as, winds (Peterson *et al.* 1981, Hoppel *et al.* 1990), precipitation (Junge 1963, Flossmann *et al.* 1985), convective activity (Pueschel *et al.* 1972) and atmospheric parameters, such as, relative humidity and integrated water vapour content (Mohamed and Frangi 1983, Garrison 1992). In a coastal location, winds and their direction as to whether they are on-shore or off-shore, also would be important (Peterson *et al.* 1981, Suzuki and Tsunogai 1988, Moorthy *et al.* 1991). All these would have their

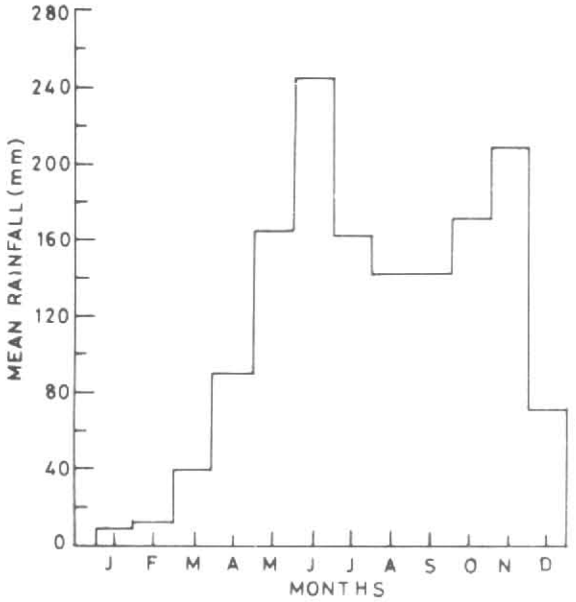


Fig. 1. Month-to-month variation of monthly total rainfall over Thumba (average for last 20 years)

signatures on the aerosol optical depths and their temporal variations.

In this paper, we present the results of a study on the (systematic long-term) seasonal variations of aerosol spectral optical depths and their association with the seasonal changes in the surface winds and rainfall at the tropical coastal station, Thumba, Thiruvananthapuram (8.55°N, 77°E) situated at the southwest coast of India. The station is far removed from major industrial activities and represents a natural coastal aerosol environment [Moorthy *et al.* 1993(a)].

2. Data

The data, used for this study, comprise of columnar aerosol optical depths ($\tau_{p\lambda}$) at nine narrow wavelength bands centred at 400, 450, 500, 590, 700, 750, 800, 935, 1025 nm, obtained using a ground based multi-wavelength solar radiometer (MWR), for 228 clear days spread over the period November 1985 to May 1991. The details of the instrumentation and estimation of $\tau_{p\lambda}$ (from the total optical depth deduced by the Langley technique) using climatological models of neutral atmosphere, ozone etc. are described elsewhere [Moorthy *et al.* 1989, 1991, 1993 (a & b)] and hence are not repeated here. The stability of the MWR system over the years has been ensured by monitoring the Langley (zero-airmass) intercept, the variation of which about the mean has been less than 2% at any wavelength.

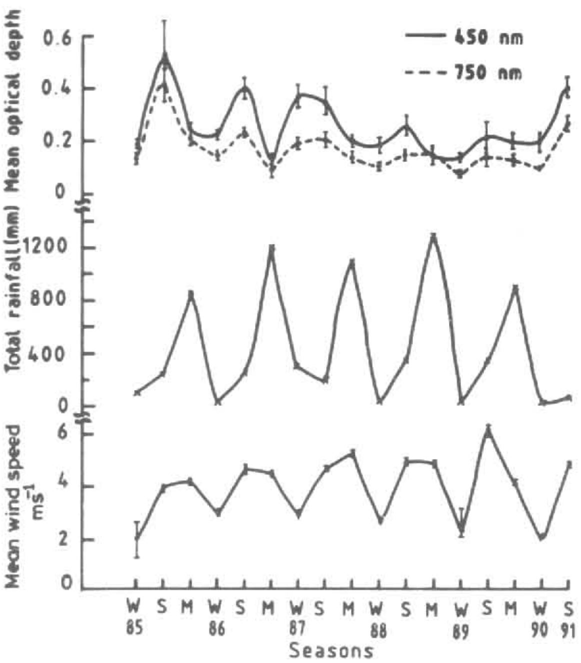


Fig. 2. Top panel: Seasonal variations of mean aerosol optical depth at two representative wavelengths 450 nm and 750 nm

Middle panel: Variation of seasonal total rainfall.

Bottom panel: Variation of seasonal mean westerly wind speed.

The vertical bars correspond to standard error.

Data on the prevailing meteorological parameters are obtained from the adjacent station. These comprised of the surface wind (speed and direction) data obtained at ~3 m above the ground and the daily total rainfall in mm, both for the period November 1985 to May 1991. From the wind data, the westerly wind speed has been computed. For the coastal geometry of this station, westerly wind corresponds to an on-shore wind (from sea to land) and is taken as positive following the meteorological convention. Besides these data, the monthly averaged values of daily mean and maximum surface temperature, recorded at the station have also been used.

3. Results and discussion

3.1. *Seasonal variations*

For examining seasonal variations of aerosol optical depths, the data for each year has been grouped into three distinctive seasons relevant for this tropical (coastal) location. Due to the proximity to the equator, sharp changes in climate are not experienced here. Most of the meteorological parameters do not undergo any significant changes during an year except the rainfall associated with the Asiatic monsoon (Rao 1976, Das 1986). Hence in dividing the year into different seasons, the monsoon is considered as the prominent seasonal feature. The month-to-month variation of monthly total rainfall (mm) for Thumba averaged over a twenty year period is shown in Fig. 1.

It can readily be seen from Fig. 1 that more than 75% of the annual rainfall occurs during the period June to November and these six months together are considered as monsoon (M) season for the present study. The months December to February are considered as winter (W) season. This season is characterised by scanty rainfall (< 5% of the annual). The summer (S) season (March to May) is characterised by moderate rainfall (~ 18%) of the annual, higher land temperature (typical maximum day time temperature lying around 34-36°C) and dry surface conditions. The rainfall during this season occurs mostly in the afternoon hours, particularly in April-May months, as brief spells and is a meso-scale phenomenon associated with pre-monsoon summer rains.

Based on the above classifications, the individual day $\tau_{p\lambda}$ values (at each wavelength λ) obtained in the months of March to May of a year are classified under summer, those of June to November under monsoon and those of December alongwith January and February of the following year under winter seasons of the year and averaged to estimate the seasonal average optical depths ($\tau_{p\lambda}$) alongwith the standard deviation (σ_λ) and standard error (ε_λ). In the top panel of Fig. 2 are shown the seasonal variation of the aerosol optical depths from winter of 1985 (W85) to summer of 1991 (S 91) at two representative wavelengths; 450 nm and 750 nm. The variations at the other wavelengths being similar to the ones shown (Fig. 2) are not included in the figure. The vertical bars over the points represent the standard error ε_λ. The main features of the seasonal variations are the following:

(a) The aerosol optical depths, in any year, attain the peak values in summer season, (in 1989 and 1990, the peaks are not well developed at longer wavelengths) and minimum in winter season (except in 1987).

(b) The summer peak in optical depths show a decreasing trend from 1986 to 1990 followed by an increase in 1991. On the other hand, the monsoon and winter optical depths do not exhibit any such trend and remain more or less at a steady level.

In the middle and bottom panels of the Fig. 2 are shown the variations of seasonal total rainfall (R) and the seasonal average westerly wind speed (U) respectively, estimated from the surface meteorological data (described in the earlier section). It can be seen from the figure that strong westerly winds (speeds ranging from 4 to 6 ms^{-1}) prevail during summer and monsoon seasons while winter season is characterised by weak westerlies. The rainfall is extensive (~850-1300 mm) in the monsoon season, weak (200-400 mm) in summer and scanty (10-40 mm) in winter.

Comparison of the seasonal variations of aerosol optical depths with those of wind speed and rainfall yields the following points:

The seasonal mean wind speed has an annual minimum (~2 to 3ms^{-1}) in winter season, when $\tau_{p\lambda}$ also, in general, attains its annual minimum. In summer season, when $\tau_{p\lambda}$ reaches its annual peak, the rainfall is weak and the winds are strong. In the monsoon season, when both wind and rainfall are strong, $\tau_{p\lambda}$ generally is low, tending towards the winter minimum (exception to the general feature is the minimum occurring in M87). These observations are indicative of association between the seasonal variations of aerosol spectral optical depth with those of wind speed and rainfall.

3.2. *Correlation with wind speed and rainfall*

With a view to examine these associations quantitatively, we have estimated the correlation coefficients ρ_{12}, between seasonal mean aerosol optical depths ($\tau_{p\lambda}$) and the westerly wind speed (U) and ρ_{13}, between $\tau_{p\lambda}$ and seasonal total rainfall (R) for each wavelength for the entire data period (spread over seventeen seasons). In Fig. 3 we have plotted ρ_{12} and ρ_{13} for the different MWR wavelengths. The dashed line drawn parallel to the abscissa represents the 90% significance level of the coefficient (Fisher 1970). It may be noted that even though the coefficients, generally, are below the 90% significance level, the correlation is always positive with U and negative with R. This observation is significant in the sense that, it indicates a depletion in the average optical depths with increase in rainfall and an enhancement in optical depth with increase in wind speed.

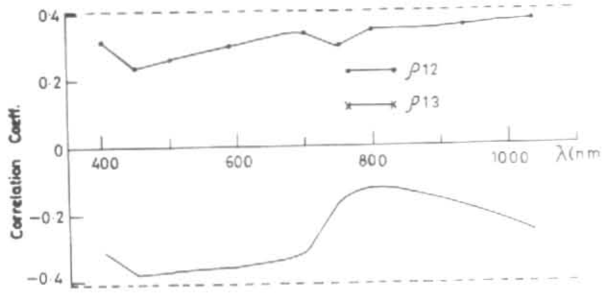


Fig. 3. The plot of the total correlation coefficients ρ_{12} and ρ_{13} against wavelength. The dashed lines parallel to the abscissa correspond to the 90% significance level of the coefficient

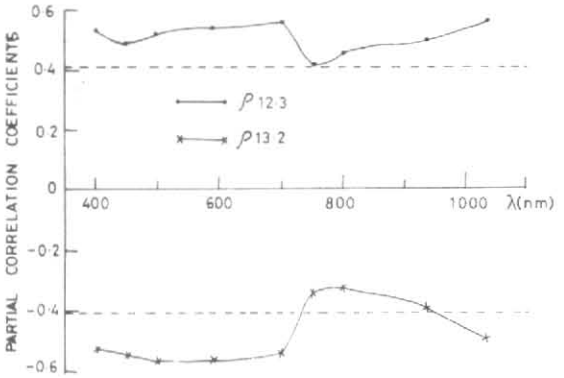


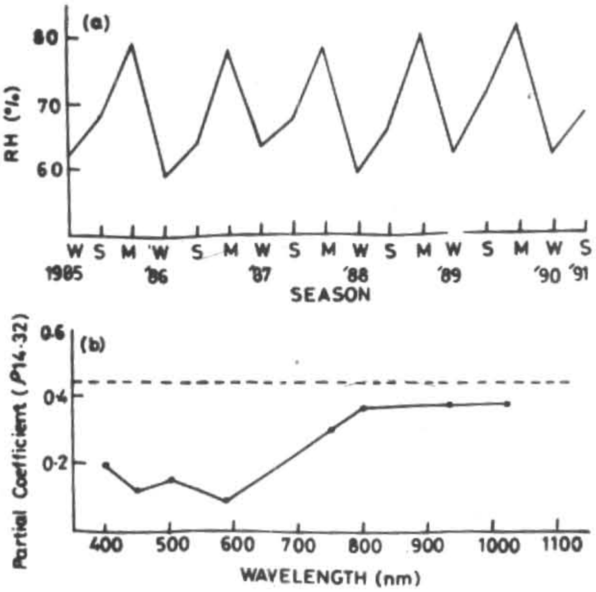
Fig. 4. Same as Fig. 3, but for the partial correlations $\rho_{12.3}$ and $\rho_{13.2}$

The aerosol optical depth over any location strongly depends on the columnar loading and the size distribution of aerosols (Kaufman and Fraser 1981, Patterson and Gillete 1977) which in turn are determined by the cumulative effects of various production, removal and transport mechanisms of aerosols. In the lower atmospheric region, the wind and rainfall characteristics, as well as the surface features and convective activity, all would influence the aerosol properties. Aerosol optical depths/ turbidities have been observed to be strongly influenced by the prevailing air-mass types (*e.g.*, Mani *et al.* 1969, Peterson *et al.* 1981). At coastal stations increased optical depths are observed associated with marine air-masses, compared to continental air-masses (*e.g.*, Hoppel *et al.* 1990).

Extensive studies of marine aerosols (Peterson *et al.* 1981, Hoppel *et al.* 1990) have shown presence of large aerosols ($r > 0.5$ µm) in the marine boundary layer, abundance and the size spectrum of these strongly depend on the wind speed and production mechanisms involved (Junge 1963, Lovett 1978, Monahan *et al.* 1983, Andreas 1990, Hoppel *et al.* 1990). Wind speeds exceeding 3 ms^{-1} are found to be conducive for formation of white caps over ocean surface and lead to production of aerosols by breaking of bubbles and bubble jet action (Lovett 1978, Monahan *et al.* 1983). During periods when the winds are strong and are of a favourable direction (on-shore) these marine aerosols are found to be carried over to the coastal and inland locations and produce characteristic signatures (Khemani *et al.* 1984, Suzuki and Tsunogai 1988, Moorthy *et al.* 1991). Being a coastal station, a significant marine aerosol input would thus occur at Thiruvananthapuram during the summer and monsoon seasons when the on-shore winds are strong. This input would be a minimum during winter season when the wind speed U also shows the annual minimum (Fig. 2).

The main removal mechanisms of aerosols are sedimentation, impaction scavenging and rainout/ washout effects of precipitation (Prospero *et al.* 1983, Jaenicke 1984). In the troposphere, where 90% of the aerosols exist, wet removal (due to rainout and washout) form the chief depletion mechanism of aerosols (Jaenicke 1984, Flossmann *et al.* 1985). The wet removal is found to be linearly correlated with the rainfall (Hicks 1977). Theoretical and modelling studies have shown that number concentration of aerosols is reduced by 48% to 94% through wet removal processes, the reduction being more for the large particles ($r > 0.1$ µm) (Flossmann *et al.* 1985). Reduction in atmospheric turbidity associated with rainfall has also been reported by others (Chacko and Desikan 1967, Mani *et al.* 1969, Joseph and Manes 1977). From *in situ* measurements of altitude profiles of aerosols at Thumba using rockets Jayaraman and Subbaraya (1993) have reported significant depletion in aerosol loading and change in particle characteristics associated with the monsoon.

The above considerations basically explain the nature of the observed association of aerosol spectral optical depths with westerly wind speed and rainfall, being positively associated with the former and negatively with the latter. However, the coefficients are not quite significant when the total



Figs. 5 (a & b). (a) Seasonal variation of mean surface RH (averaged for the MWR observation period) for Thumba, (b) The partial correlation coefficients $\rho_{14.23}$ between RH and $\tau_{p\lambda}$ after removing the association with wind and rainfall. The horizontal dashed line represents the 90% significance level of the correlation coefficients

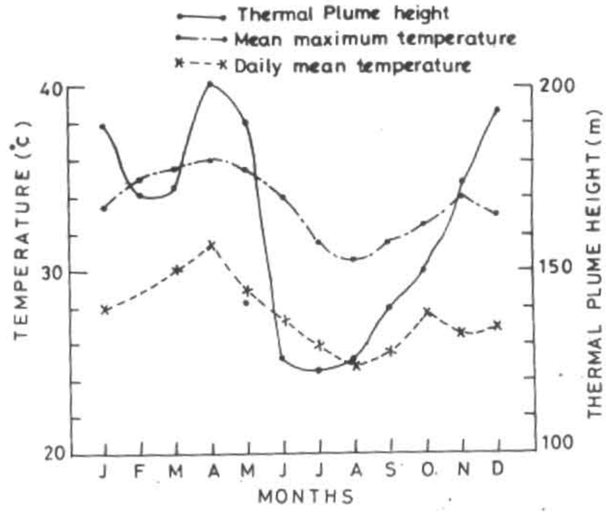


Fig. 6. Month-to-month variations of mean thermal plume height, mean daily-mean temperature and mean maximum temperature for Thumba

correlations are considered. Moreover, as can be seen from Fig. 2, the annual minimum $\tau_{p\lambda}$ occurs mostly in winter season, whereas the peak in rainfall occurs in monsoon season, in fact R is minimum in winter. During monsoon both rainfall and wind speed are high and in winter both are low, thereby indicating a good association between the two.

An estimate of the direct correlation between these two parameters (U and R), using the data for the seventeen seasons considered in this study, yields a coefficient $\rho_{23} = 0.44$ which is quite significant (> 90% level). In view of this significant positive correlation between U and R and the opposite nature of their association with $\tau_{p\lambda}$, (U having a positive correlation and R negative) it is essential to remove the effect of the other parameter on $\tau_{p\lambda}$ when its association with one parameter is being investigated. This is accomplished by estimating the partial correlation coefficients $\rho_{12.3}$ (between $\tau_{p\lambda}$ and U, eliminating the effect of R) and $\rho_{13.2}$ (between $\tau_{p\lambda}$ and R eliminating the efffect of U) following the standard statistical methods (Fisher 1970). These coefficients are plotted in Fig. 4 for the different wavelengths alongwith the 90% significance levels for the partial correlations. A dramatic increase in the correlation is evident from Fig. 4 with most of the coefficients lying above the 90% significance level for $\rho_{12.3}$ and $\rho_{13.2}$ (except $\rho_{13.2}$ at 750, 800 and 935 nm where they are slightly below 90% level). This clearly brings out the role of wind as a generation mechanism of aerosols (leading to enhancement in $\tau_{p\lambda}$) and rainfall as a removal mechanism (leading to depletion in $\tau_{p\lambda}$).

However, it should be noted that the aerosol optical depths obtained by using the MWR correspond to the integrated columnar atmosphere while the various processes discussed above are important only in certain atmospheric regions. The rainfall, associated with the monsoon, would cause wet removal in the entire troposphere (*e.g.*, Jayaraman and Subbaraya 1993) while the effects of winds for aerosol production would be more significant in the boundary layer and lower troposphere. The abundance and size spectrum of the wind generated aerosols would strongly depend on the wind speed (Lovett 1978) while the wet removal is significant to large and giant aerosols (Flossmann *et al.* 1985). This would lead to distinct spectral variations in aerosol optical depths which are reflected in partial correlations also.

In addition to the above discussed mechanisms, other processes, such as, mechanical processes of the action of wind on land surface, changes in the convective activity (in the terrestrial boundary layer), the changes in the ambient relative humidity (RH) and the rate of photochemical reactions leading to gas-to-particle conversion are also important in producing seasonal changes in aerosol optical depths (Pueschel *et al.* 1972, Meszaros 1981). Changes in the precipitable water vapour content in the atmosphere is known to cause associated changes in optical depths and turbidities (Mani *et al.* 1969, Mohamed and Frangi 1983, Garrison 1992). Seasonal variations of average surface RH for Thumba for the MWR observation period [shown in Fig. 5 (a)] reveals fairly high values of RH (> 60%) throughout the year, as would be expected for a coastal environment, with a sharp peak during monsoon season. However, as revealed in Fig. 5 (b), the correlations with $\tau_{p\lambda}$ are poor as indicated by the partial correlation coefficients between the two ($\rho_{14.23}$) after removing the association with wind and rainfall.

Height of the thermal plume echoes detected by ground based sodar is an index of the strength of the convective activity taking place in the boundary layer which is an effective means of causing vertical mixing of aerosols. Strong convection would be able to sustain more number of large and giant aerosols, well mixed, for longer duration of time. Studies of the annual variation of the thermal plume heights at Thiruvananthapuram (Kunhikrishnan *et al.* 1990) have shown higher values for the plume height during March to May with peak in April followed by a broad minimum during June to September months. In Fig. 6 we have plotted the variation of monthly mean values of (a) thermal plume height, (b) the daily mean temperature and (c) maximum temperature along with the standard errors, for Thumba. It can be seen that the strong convective activity would prevail during summer season when all the three parameters show high values while during monsoon season the convective activity is quite small. The high land temperature, weak rainfall and strong surface winds in summer are conducive for aerosol generation by the action of wind on dry land surface which are then readily mixed by the convective activity. There is a decrease in the mean surface temperature of about 5° to 7°C and of about 5.5°C in the maximum temperature from summer to monsoon season. The thermal plume height also decreases considerably, indicating the decrease of convective activity. The land is wet and not conducive for mechanical production, even though winds continue strong. These processes would result in the observed enhancement in $\tau_{p\lambda}$ during summer and depletion during monsoon season.

The winter season is characterised by a low in the rainfall and wind speed; the prevailing winds are off-shore (Rao 1976) except for the day time sea breeze in the coastal boundary layer. This sea breeze, though adds a westerly (on-shore) component to the prevailing winds (Narayanan 1967), the speeds are quite small (Fig. 2). The ground, left considerably wet by the monsoon that has preceded, is not conducive for mechanical aerosol generation. The photochemical processes leading to gas-to-particle conversion reactions also would be weak in winter (Meszaros 1981). Thus the seasonal production processes being weak and a substantial wet removal already taken place, the optical depths, generally, are representative of the background conditions. Viewed in this perspective, it is quite interesting to note that in all the six winter seasons considered in this study, the background aerosol optical depths remain at about the same value, irrespective of the peak values attained in the preceding or succeeding summer. As the location, Thumba, is quite free from any major industrial activity leading to exhausts favourable for aerosol generation and is not urbanized, this observation is significant that in this tropical coastal region over the years the background aerosol level appears to remain almost steady; superposed with systematic seasonal variations associated with the prevailing meteorological processes. However, the reasons for the gradual decreasing trend in the summer optical depths from 1986 to 1990 and the subsequent increase in 1991 are not understood at present.

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