Aerosol optical depth studies during INDOEX: Comparison of the spectral features over coastal India with the pristine southern hemispheric environment over Mauritius

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Aerosol spectral optical depths, estimated using a ground-based network of multi wavelength radiometers (MWR) along the west coast of India [Trivandrum (TVM; 8.5°N, 77°E), and Minicoy (MCY; 8.3°N, 73.04°E)] and the pristine southern hemispheric environment at Mauritius (MRU; 20.26°S, 57.54°E) during the period January to June 1998 along with those obtained over the Arabian Sea and Indian Ocean during the INDOEX FFP-98 cruise (SK133) of ORV *Sagar Kanya*, are used to study the inter-hemispheric features of aerosols.

Results indicate that there is a significant hemispherical difference for aerosol spectral optical depth (AOD) at shorter wavelengths ($l \leq 650$ nm), while at the longer wavelengths ($l > 650$ nm), AOD does not show any appreciable variation with location. The spectral variation of AOD at TVM and MCY (for March 1998) depicted a similar pattern with the AOD values between 0.5 and 0.6 at shorter wavelengths and between 0.2 and 0.4 at longer wavelengths. In contrast to this, the AOD at MRU are very low, lying in the range 0.1 to 0.2 in the shorter wavelengths, whereas at the longer wavelengths the AOD values are more or less comparable (in the range 0.2 to 0.4) with the northern hemispheric stations. The cruise data clearly showed that the transition occurs generally across the ITCZ. The increased AOD at shorter wavelengths in the northern hemisphere indicates higher concentration of sub-micron aerosols in these environments arising mainly due to anthropogenic activities, while the AOD at the longer wavelengths is attributed mainly to be of marine origin.

In the post-cruise period, the spectral optical depths showed a gradual increase from March to June at MRU, while at TVM, the pattern followed more or less the climatological mean. By May the AOD at shorter wavelengths decreased at TVM (due to increased rainfall) and by June, the AOD at TVM are very much comparable with those seen at MRU, indicating a dominating marine aerosol influence at both these locations. The implications are discussed.

NATURAL and anthropogenic aerosols have a direct impact on the earth's radiation balance. They are distributed quite non-uniformly over the earth and consequently the effects of aerosols also show distinct features which are regional in nature. Scattering by aerosols can substantially decrease the incoming flux of short-wave solar radiation. They may also absorb the long-wave radiation emitted by the earth[1]. An increase in the optical thickness represents a transition from a rather clean condition to a more polluted condition[2]. Furthermore, the variation of the optical depth with wavelength of the radiation is strongly dependent on the size spectrum of aerosols. As such changes in the spectral (or wavelength) dependence of aerosol optical depth in space or time indicate similar changes in the size distribution of aerosols. This has been the main thrust of the Indian Ocean Experiment (INDOEX)[3], which investigates the inter-hemispheric transport of aerosols and trace gases. The focus of this paper is the study of the spatial variation of the wavelength dependence of aerosol optical depth as one moves from the coastal Indian regions to the pristine southern hemispheric environment. Besides presenting for the first time the aerosol features from the southern hemispheric environment (Mauritius), it also examines the temporal changes in aerosol optical depth spectra in the two hemispheres and its association with the movement of the ITCZ (Inter Tropical Convergence Zone) and regional meteorological processes.

Instrument details, data base and analysis

Aerosol spectral optical depths (AOD) were estimated at ten narrow wavelength bands centered at 380, 400, 450, 500, 600, 650, 750, 850, 935 and 1025 nm (selected using interference filters having full width half maximum band width in the range of 6 to 10 nm) using a multi wavelength radiometer (MWR) having an overall field of view

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of 2°. The MWR makes spectral measurements of ground reaching solar flux as a function of solar zenith angles during clear sky periods and from the measurement aerosol spectral optical depths (i_{pl}) are estimated as described by Moorthy *et al.*[4]. During the First Field Phase of INDOEX, coordinated ground-based measurements of aerosol optical depth were made over a spatial network of three MWRs, two along the west coast of India, one at Trivandrum (TVM; 8.5°N, 77°E) and the other from Minicoy (MCY; 8.3°N, 73°E); a tiny island in the Arabian Sea, approximately 400 km west of TVM. The INDOEX FFP-98 observation programme from these stations started in January 1998 and continued till June. Besides these, another MWR, identical to the above, was installed at the University of Mauritius, Reduit, Mauritius (MRU; 20.26°S, 57.54°E) in March 1998 and operated regularly since then jointly with the University of Mauritius. This yielded for the first time direct observations of aerosol optical depth to India from a pristine southern hemispheric environment situated further to the south of the typical annual southern most position of the ITCZ. This also gave a unique opportunity to study the southern hemispheric aerosols and compare the properties with those of the northern hemispheric environment, which is generally considered to be more polluted. In addition to these ground stations, another identical MWR was taken on-board the FFP-98 cruise #133 of ORV *Sagar Kanya* during the period 18 February to 31 March 1998 (see ref. 4 for details). This cruise provided an extensive spatial sampling of aerosol optical depth over the oceanic region lying between India and Mauritius. This programme thus enabled to study the north–south contrast in aerosol characteristics and the way the transition takes place. The locations of the ground stations and the cruise track are shown in Figure 1. From each set of MWR measurements made at each of these sites the columnar spectral optical depths (t_l) were estimated making use of the Langley plot method[5]. Subtracting the contribution due to molecular (Rayleigh) scattering and absorption by O_3 and water vapour (at the relevant wavelengths) from t_l the aerosol optical depths (t_{pl}) were deduced as detailed by Moorthy *et al.*[4] . The database used for our study is given in Table 1.

As the MWR data availability is mainly restricted by the clear sky condition, it was difficult to obtain simultaneous data from all the stations. Hence for the purpose of comparison of spectral features, the i_{pl} data have been grouped into ensembles characterized by the spatial/ temporal features as given in Table 2. For each of these ensembles we have estimated the mean, standard deviation (s_l) and standard error (e_l). In doing so, the i_{pl} values falling outside $\pm 2s_l$ of the mean are rejected as outliers.

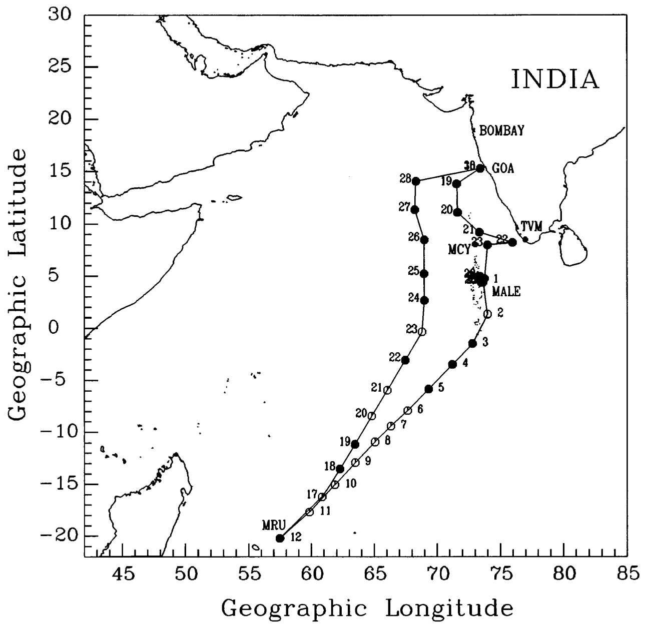

Figure 1. The network of MWR ground stations at TVM, MCY and MRU along with the cruise track of ORV *Sagar Kanya* during the FFP-98 of INDOEX. The solid circles show locations where MWR observations are made during the cruise.

Results

In the following, we examine the features of the aerosol spectral optical depth separately for pre-cruise, cruise and post-cruise periods, and present the results from spatial and temporal perspectives.

Pre-cruise period

For this, we have considered the data for January and first half of February 1998 (ensembles 1 and 2 in Table 2). The wavelength variation of t_{pl} for this period is shown in Figure 2, where the mean t_{pl} is plotted against l with January at the top and February at the bottom. It gives a mean picture of the prevalent condition along coastal India prior to the cruise. From Figure 2 it is clearly seen that the spectral variation pattern of t_{pl} are quite similar at TVM and MCY; with higher values at shorter wavelengths ($l < 650$ nm) and lower values at longer wavelengths

Table1. MWR database used in this study

Station	Period
Trivandrum	January to June 1998
Minicoy*	January to March1998
INDOEX-FFP cruise #133 of ORV *Sagar Kanya*	18 February to 31 March 1998
Mauritius	March to June 1998

*The MWR at Minicoy developed a technical snag by end of March 1998 and hence data are not available beyond that period.

(l > 650 nm). t_{pl} decreases, initially faster then slower, with increase in wavelength suggesting the presence of a substantial amount of sub-micron aerosols in the study area. Such a spatial variation is typical of a continental aerosol environment[6].

Cruise period – coastal water

The ship sailed off Goa on 18 February and reached Male on 24 February. On 1 March it left Male and sailed towards the open ocean. So during the second half of February, the ship sailed closer to the southwest coastal regions of India, Minicoy and Male. In Figure 3 we present the mean spectral variation of t_{pl} for this period obtained from the ship data and compare it with those obtained from the ground data. Figure 3 clearly shows that the spectral variations of t_{pl} are very much similar in all the three cases (notwithstanding minor differences). This indicates that the general nature of aerosol environment prevailing in these regions is quite similar. It appears as though all the three curves are obtained from a single large population and there is a significant continental influence on the aerosol characteristics in these areas.

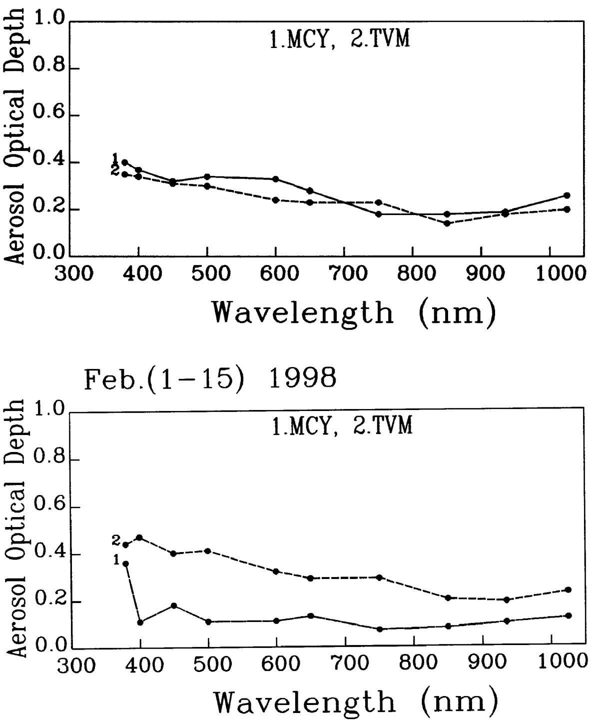

Figure 2. The wavelength variation of t_p for January 1998 (at the top) and first half of February (at the bottom). Details are given in the text.

Cruise period; open ocean

During the first half of March the ship sailed towards the open ocean and reached MRU on 12 March. From the AOD spectrum (Figure 4) it can be seen that the scenario has changed dramatically. The aerosol optical depth values estimated from data taken on-board ship are very low[4] compared to those obtained at TVM and MCY. The low values encountered on-board ship points to the rapid change in the aerosol environment due to the decrease in abundance of sub-micron aerosols due to absence of source contribution. At the longer wavelengths, however, the changes are quite small, suggesting that a substantial amount of the coarse particles contributing to the optical depth at these wavelengths are produced locally over the ocean.

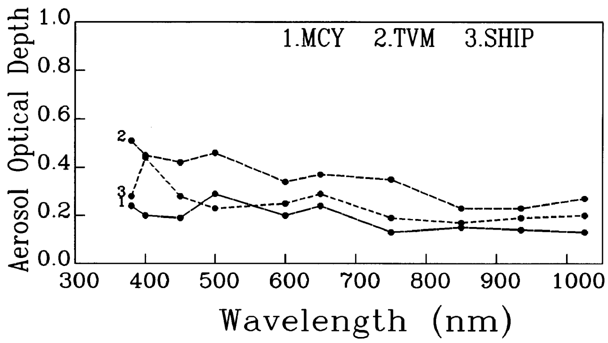

Figure 3. Aerosol optical depth spectra over coastal Arabian Sea in comparison with those of TVM and MCY.

Table 2. Space/time ensembles of aerosol optical depth data

Ensemble	Period	Mean location of the cruise	Characteristic features	Ground stations
1	1–31 January	Nil	Pre-cruise period	TVM and MCY
2	1–15 February	Nil	Pre-cruise period	TVM and MCY
3	16–28 February	At the West Coast of India (Goa to Male)	Cruise in coastal water	TVM and MCY
4	1–10 March	Onward-leg: Indian Ocean towards Mauritius	Indian Ocean (North of the ITCZ)	TVM, MCY and MRU
5	11–31 March	Ship at MRU on return leg	Crosses ITCZ	TVM, MCY and MRU
6	1–31 March		Cruise period	TVM, MCY and MRU
7	1–30 April	Nil	Post-cruise period	TVM and MRU
8	1–31 May	Nil	Post-cruise period	TVM and MRU
9	1–30 June	Nil	Post-cruise period	TVM and MRU

Ship in the pristine environment

The ship crossed the ITCZ during its onward journey during 6–9 March and reached Mauritius on 12 March 1998. The first ship-borne measurement of aerosol optical depth from the pristine southern hemispheric environment due south of the ITCZ was available on 13 March 1998 when the MWR on-board was operated at Port Louis (PLU), Mauritius. In the mean time the ground-based MWR station has become operational (on 8 March 1998) at the University of Mauritius, Reduit (RDT), Mauritius about 10–15 km away from PLU. Both these MWRs were operated simultaneously from their respective locations on 13 March 1998. Figure 5 shows the optical depth spectra in this case. It is quite interesting to note the extreme low values of t_{pl} at $l < 650$ nm in this case compared to all the previous cases, indicating a near absence of sub-micron aerosols on the south of the ITCZ. The ship left Port Louis on 17 March on its return leg, and was still in the pristine environment till 19 March, when it crossed the ITCZ from south to north. The aerosol optical depth spectra were much similar to those seen at Mauritius during this period as can be seen from Figure 6 where the t_{pl} values obtained from the ship are plotted together with those obtained at Mauritius. In contrast, the northern hemispheric stations continue to show high values for aerosol optical depth at the short wavelength regime.

Ship in central Arabian Sea; north of the ITCZ

Ship entered the central Arabian Sea crossing the ITCZ from the south, on its return leg. The MWR data from 22 March onwards till the ship returned to Goa on 31 March corresponds to the ‘rather polluted’ environment. Figure 7 shows the mean aerosol optical depth spectra for this case in comparison with those obtained at TVM, MCY and MRU. The Mauritius values continue to be lower as in Figures 5 and 6 but the ship values have now recovered to the pattern depicted in Figure 3, suggesting the return of the dominance of small particles. The t_p values at TVM and MCY continue to show their typical pattern with high τ_p at shorter wavelengths, as has been the case always. The AOD values seen at TVM and MCY also conform to the climatological pattern seen over years[7]. With a view to examining the (average) hemispherical differences in the spectral variation of t_p, we have plotted the monthly mean aerosol optical depth values for TVM, MCY and MRU for March 1998 in Figure 8. It clearly shows that the optical depth values are very much lower at the wavelengths

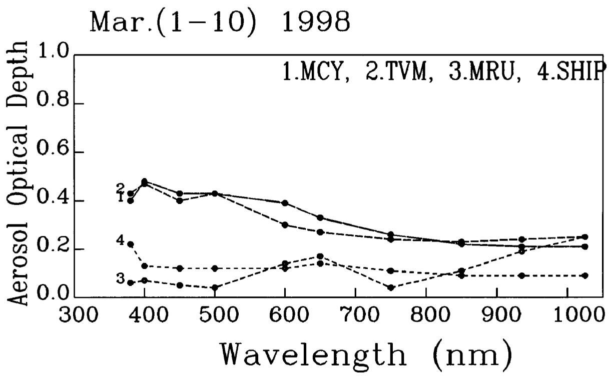

Figure 4. Same as Figure 3, but the ship is in the Indian Ocean.

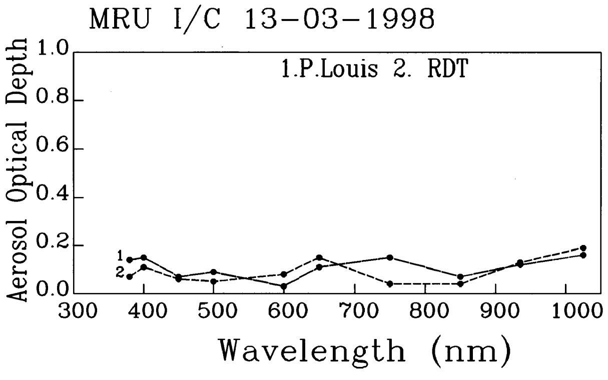

Figure 5. Intercomparison of t_p values onboard ship and at the University of Mauritius.

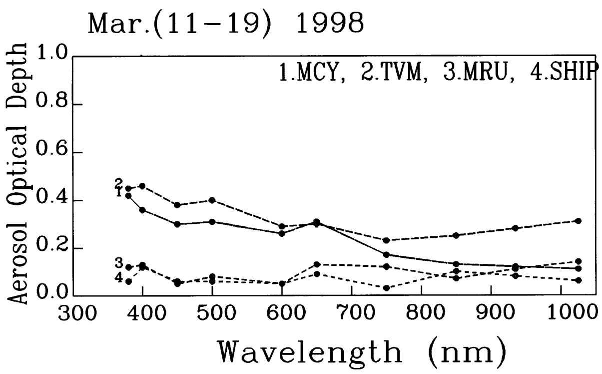

Figure 6. North-south contrast in the aerosol optical depth spectra with TVM and MCY in comparison with MRU and ship-borne measurements on the south of the ITCZ.

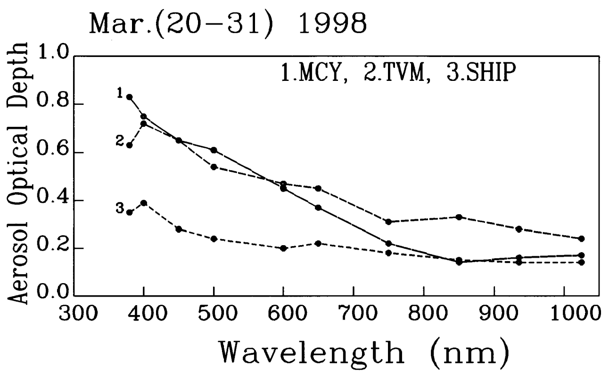

Figure 7. Aerosol optical depth spectra for TVM and MCY in comparison with that from the ship when the ship was in the central Arabian Sea. See the sharp increase in t_p at lower wavelengths.

shorter than 650 nm (the short wavelength regime) at MRU, compared to TVM and MCY (which are quite similar to each other). The optical depths at the longer wavelength, by and large, remain the same in all the three stations.

Post-cruise period

In the post-cruise period we had data from two of the network stations; TVM in the north and MRU in the south. The data available till June have been examined essentially to see (a) how the optical depth spectra at these two stations evolve with time, (b) what changes occur to the spatial features of $t_{pl} - l$ relationship as the ITCZ advances to the northern hemisphere, beyond TVM so that the two stations are now on the same side (southward) of the ITCZ and (c) how long the southern hemisphere station continues to be 'pristine'. Thus we compare the average monthly pattern of aerosol optical depth spectra of MRU with those of TVM in Figure 9 for April (top), May (middle) and June (bottom) of 1998. The comparison has to be limited to these two stations, as the MWR at MCY became non-functional from April. Figure 9 reveals several interesting features. At Trivandrum, the shape of aerosol optical depth spectrum in April remains similar to the previous months, though the values are higher than those seen in the January to March period. This is in general conformity with the climatological features for Trivandrum[8]. At Mauritius, the optical depth spectrum has become noisy and there is a significant build up in the optical depth values at the short wavelength regime ($l \le 650$ nm). This increase continues into May as seen from the middle panel of Figure 9. However, the values are still lower than those seen at Trivandrum; where of course there is sharp decrease in i_p (possibly due to the extensive rainfall experienced in May at TVM; 240 mm against the normal value of 186 mm received during May 1998). This decrease in May is unusual and contrary to the mean pattern for Trivandrum. By June, the optical depth spectra of TVM and MRU have become very much similar with comparable values. It is seen from the figure that the values are comparable due to the combined result of a decrease in TVM associated with the southwest monsoon (with its onset from June) and an increase at Mauritius. The t_p spectra at both stations are strikingly similar and show only weak wavelength dependence, typical of a marine environment.

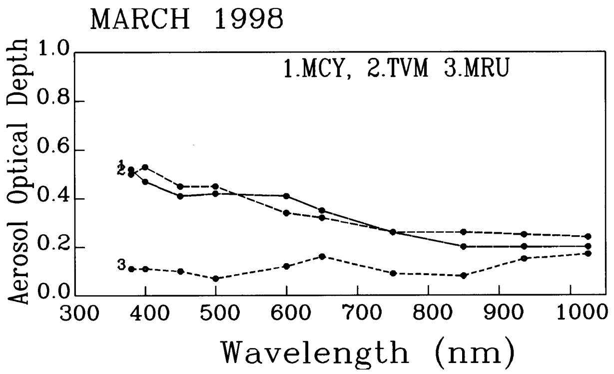

Figure 8. Aerosol optical depth spectra for March 1998, comparing TVM, MCY and MRU.

Discussions

Our study of the nature of atmospheric aerosols under the INDOEX has brought out several interesting features. Firstly, it has revealed a sharp contrast in the wavelength variation of t_{pl} at the short (wavelength) regime ($l \le 650$ nm) between the two hemispheres or more precisely between either side of the ITCZ. To be specific, t_{pl} is very much lower at locations due south of the ITCZ compared to the northern locations. In sharp contrast the AOD at the longer wavelengths ($l > 650$ nm) are nearly the same over the entire study region, except for minor differences. The Mie theory clearly shows that for a poly disperse aerosol system maximum contribution to t_{pl} at a given wavelength l comes from particles having sizes comparable to the wavelength[11]. Thus a large increase in the AOD at shorter wavelengths arises from large enhancement in the concentration of small, sub-micron (< 1 μm) aerosols in the atmosphere. The sudden decrease

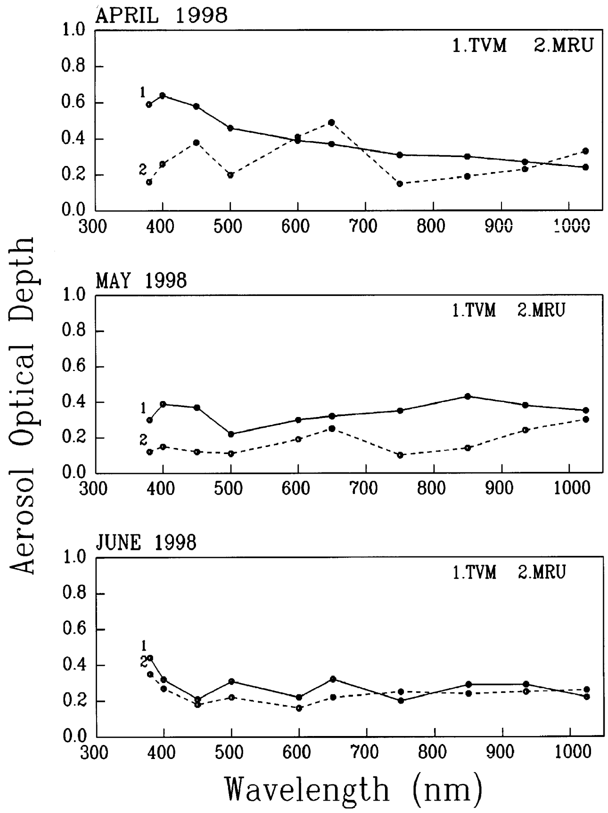

Figure 9. Aerosol optical depth spectra at MRU compared with TVM for April (top), May (middle) and June (bottom). See the gradual build up of t_p at $l \le 650$ nm at MRU.

in t_{pl} on the south of ITCZ and at Mauritius indicates sharp decrease in the concentration of these aerosols. In other words there is a substantial reduction in the abundance of sub-micron aerosols in the environment due south of the ITCZ compared to that in the northern regions. The features in Figures 4 and 5 show this. If we examine the typical synoptic scale wind fields during February to March (Figure 10), it is seen that in the study area north of the ITCZ, the airmass has a continental origin (has been over either the Indian/West Asian continent regions only a few days before). Unlike this, the airmass on the south of the ITCZ is basically oceanic in nature and is pristine. The former airmass would advect continental aerosols (from the region it traverses) and the smaller sub-micron ones would reach to far oceanic regions due to their longer atmospheric lifetime[9,12]. These sub-micron aerosols will be essentially resulting from secondary processes (i.e. gas to particle conversion process and subsequent coagulation and cloud cycling) and would comprise anthropogenic contributions and the non-sea salt marine contributions[9]. Thus the sharp decrease in t_{pl} to the south of the ITCZ is attributed to the highly reduced levels of sub-micron aerosols, due to reduced anthropogenic activities and also due to the apparent shielding by the ITCZ. In contrast to this, the larger aerosols would be mostly generated over the ocean by mechanical processes[13,14] and as such their contribution would not show large spatial variability. This explains the nearly similar values of t_{pl} observed at the long wavelength regime over the entire regions, north and south. The small changes would be due to changes in wind speeds. Thus during Indian winter, there exists a sharp contrast in the abundance of sub-micron aerosols, with highly depleted values reported from Mauritius.

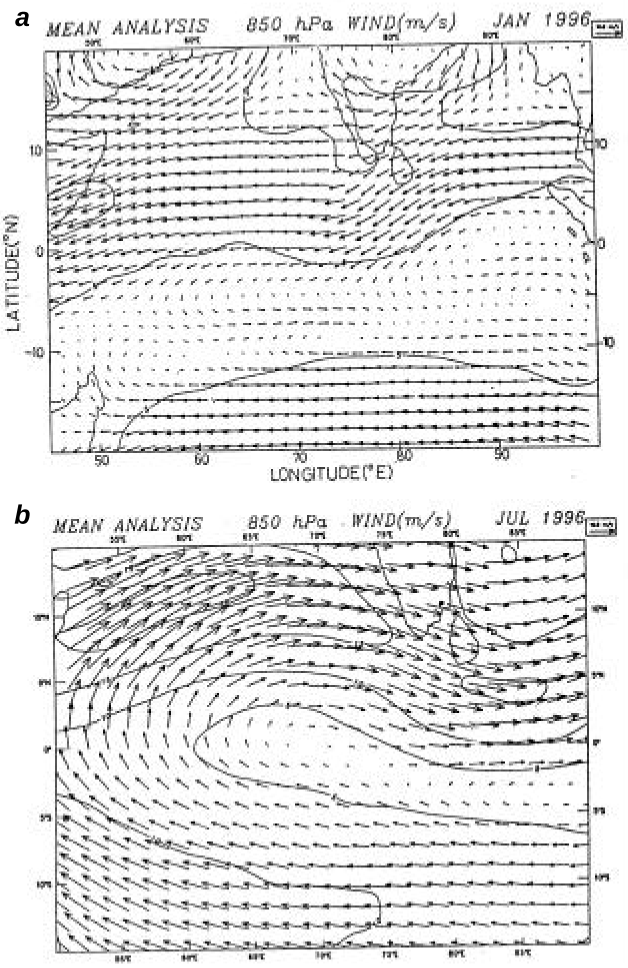

Figure 10. Typical synoptic wind field at 850 hPa level over the study area: (***a***) during January and (***b***) during July (source NCMRWF, New Delhi).

The second and more important aspect of our study is the gradual change in aerosol features, with change in the seasons, as revealed by Figures 8 and 9. The extremely 'clean and pristine' environment at Mauritius gradually changes to rather 'polluted' environment with a gradual increase in the aerosol optical depth, particularly in the short wavelength regime (Figure 9). In contrast, there is a decrease in optical depth at the 'polluted' northern hemispheric station (TVM). These features can be attributed partly to the contrast in rainfall (removal processes) at these two stations, partly to the change in synoptic circulations and the shift in the position of the ITCZ from south to north and partly to regional processes. The annual distribution of rainfall is almost out of phase at these two stations as can be seen from Figure 11 where monthly total rainfall is shown for TVM and MRU. As can be seen from this figure, during the period January to March, when rainfall is scanty (or almost nil) at Trivandrum, Mauritius experiences extensive and heavy rainfall. In fact the total rainfall during these months is more than 50% of the annual rainfall experienced at TVM. This period also is characterized by intense tropical cyclone activity at MRU[15]. This very heavy rainfall will lead to substantial wet-removal of aerosols. This will reflect more strongly at the short wavelength regime, as the sea spray aerosols from the ocean surrounding this tiny island will

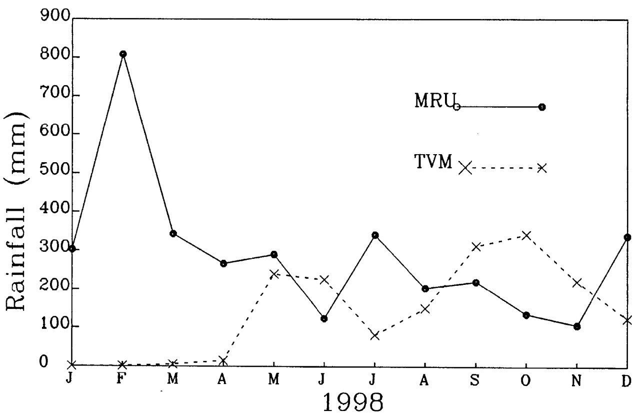

Figure 11. Annual distribution of monthly total rainfall for MRU (–) and TVM (--).

replenish the loss of coarse aerosols (at least partly). On the contrary, at Trivandrum the conditions are dry and winds are directed from the continent towards ocean. The ITCZ, located in the southern hemisphere, effectively shields these aerosols from reaching the environments further to its south, thereby maintaining the apparently clean environment over Mauritius.

During April to June, the rainfall at Mauritius decreases rapidly while at TVM there is a steady increase. Besides, by end of May/beginning of June, there is a large-scale biomass burning (of the sugarcane fields) at Mauritius before its harvest combined actions of these cause the sub-micron aerosol abundance to gradually build up, with consequent effects on t_p. The ITCZ also advances towards north and by June is considerably north of TVM, so that both TVM and MRU are on the same side of the ITCZ. The prevailing winds are oceanic in nature and are strong as in Figure 10 *b*. The extensive rainfall at TVM causes substantial wet removal of continental aerosols whereas the strong winds add substantial amount of coarse sea spray aerosols. This is a regular feature of TVM during summer and pre-monsoon season[15]. Thus both the stations show marine-like environment in June.

Summary

1. During Indian winter hemispherical differences are seen in the spectral variation of aerosol optical depth at the shorter wavelengths ($l \leq 650$ nm). In contrast to this, there was no appreciable variation of aerosol optical depths at longer wavelengths ($l > 650$ nm).
2. During Indian winter, there is significant loading of small particles along coastal India, Arabian Sea and Indian Ocean due north of the ITCZ. In the South of the ITCZ, the environment is quite clean and devoid of sub-micron aerosols due to the combined effects of the extensive rainfall (at Mauritius) and the apparent shielding by the ITCZ.
3. During Indian summer/monsoon season, there is a drastic decrease in aerosol optical depth in the north due to wet removal by the rains whereas the anthropogenic activity, agricultural practice along with reduced rainfall lead to increase in sub-micron aerosols at Mauritius. This, along with the northward movement of the ITCZ makes TVM and MRU show comparable optical depths.
4. More co-ordinated studies from these two stations using extended period of data will throw light on the hemispherical differences in the aerosol characteristics and the role of synoptic and regional processes in bringing out these changes.

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