Spatial variation of aerosol spectral optical depth and columnar water vapour content over the Arabian Sea and Indian Ocean during the IFP of INDOEX

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Extensive solar spectral extinction measurements are made over the Arabian Sea and Indian Ocean (between 60°E and 78°E longitude and 15°N and 20°S latitude) using a ten-channel multi wavelength solar radiometer (MWR) and a 4-channel EKO Sun photometer on-board the cruise #141 of ORV *Sagar Kanya* during the Intense Field Phase (IFP) of the Indian Ocean Experiment (INDOEX) from 20 January to 12 March 1999. From these measurements, the columnar aerosol optical depths and columnar content of water vapour are estimated; and their spatial variations examined.

The results show occurrence of fairly high values of aerosol optical depths along the West Coast of India. The optical depths decrease gradually as one moves down south, with an e^{-1} scaling distance of ~ 1200 to 1300 km. Extremely low (near zero) values are encountered in mid Indian Ocean due south of 10° latitude (i.e. on the south of the ITCZ) followed by a weak increase close to Mauritius. Presence of an extensive region of enhanced aerosol optical depths (which we call the West Asian High) is seen in the mid-Arabian Sea between 5° and 10°N westward of 65°E longitude which is stronger and wider than those seen along the coastal regions of India. This effect is seen at the longest wavelength (1025 nm) also. Variation of columnar water vapour content (W g cm^{-2}) shows highest values (> 3 g cm^{-2}) around the equator (~ 3°N to 5°S extending over the entire longitude region) possibly associated with the ITCZ. Moderately high values are encountered along the coastal regions of India and also close to Mauritius. Compared to these, the northwest Arabian Sea (between 5 to 15°N and 60° to 70°E) shows rather dry atmosphere with $W < 2$ g cm^{-2}, indicating prevalence of drier continental conditions. The implications of the findings are discussed.

DURING the period January to March of 1999 extensive and co-ordinated ground based, and ship-borne experiments were conducted to estimate aerosol spectral optical depth over coastal India and the oceanic environments over the Arabian Sea and Indian Ocean between 15°N and 20°S latitude and 60°E and 78°E longitude. These were carried out as part of the Intense Field Phase (IFP-99) of international programme INDOEX (Indian Ocean Experiment). The chief objective was to study the spatial distribution of aerosols along the Indian Coast and over remote area of the Arabian Sea and Indian Ocean, and the role of the Inter Tropical Convergence Zone (ITCZ) in the spatial distribution of these at locations far away from potential source regions[1].

Ground-based observations were carried out from Trivandrum (TVM, 8.55°N; 77°E), located at the western coast, near the southern tip of India; while the ship-borne measurements were made using instruments taken on board the ORV *Sagar Kanya* during its cruise #141, from 20 January to 12 March 1999. The data obtained from all these measurements are used to study the spatial distribution of aerosol optical depth and columnar water vapour. The results are presented and are discussed in the light of the earlier observations during the FFP-98 period[2].

Instrumentation, data and analysis

The investigations reported here are made using two instruments, designed to make spectral extinction measurements of directly transmitted solar flux, from which the aerosol optical depths can be estimated. These are a ten-channel multi wavelength solar radiometer (MWR) developed at the Space Physics Laboratory and described earlier[2,3], and a commercially available four-channel Sun Photometer (ESP), type MS-120 of EKO, Japan. The MWR makes measurements at discrete wavelengths 380, 400, 450, 500, 600, 650, 750, 850, 935 and 1025 nm having a full width at half maximum bandwidth in the range 6 to 10 mm. The ESP makes measurements at 368, 500, 675 and 778 nm, at a narrower bandwidth of 5 nm. Both these instruments together covered a wavelength range of 368 to 1025 nm; with one common wavelength at 500 nm. More details of these instruments are given

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elsewhere[2], and hence are not repeated. In addition to the above, one more MWR identical to the one on-board the ship was in regular operation at Trivandrum, as part of a long-term scientific program under ISRO-GBP. The data from this instrument for the period January to March 1999 also were used in the present study.

During the IFP of INDOEX, the *Sagar Kanya* sailed off Goa on 20 January 1999 and after making exhaustive survey of the oceanic regions returned on 12 March 1999. The cruise track is shown in Figure 1, with the daily position of the ship marked by a circle on it and identified by the date. The filled circles identify the dates on which either the MWR or the ESP was operated while the open circles represent days when no data could be collected due to adverse sky conditions. The most important feature of the IFP-99 cruise was a detailed longitudinal section at ~ 15°N from 58°E to 73°E closely followed by a latitudinal section parallel and very close to the Indian coast from 17°N to 10°N and back. This enabled a highly resolved spatial sampling of the Arabian Sea, within a short span of time of less than two weeks.

The raw data obtained from the MWRs and ESP are analysed following the conventional Langley technique of evolving an empirical least-squares fit to the Lambert–Beer law[4,5] to deduce the columnar total optical depth (t_l) of the atmosphere. Subtracting from t_l, the contributions due to molecular scattering and absorption by ozone and water vapour, the columnar aerosol optical depth t_{pl} are estimated at each of the wavelength l. The details of this standard method are available in the literature[4] and its application to the MWR data and the errors involved are described elsewhere[2,6] and thus not repeated. The optical depths t_l obtained at 935 nm, which lies close to the *r s t* band of water vapour, are used along with those at 850 and 1025 nm to estimate the columnar content (*W*) of water vapour following an iterative procedure making use of an empirical transmission function. The details of this are given in an earlier paper[7]. Thus we have t_{pl} at 10 wavelengths, and *W* from each set of MWR observations and t_{pl} at 4 wavelengths from each set of ESP observations. Generally the MWR/ESP measurements made on a single day is considered as single data set if these are made within a span of less than 100 km and a single set of t_{pl} values (and *W*) are deduced from this data. However, on occasions when these measurements are made at two distinct locations separately by > 100 km from each other (on a single day) or the measurements span over distances exceeding 100 km, such data are considered as two distinct sets and t_{pl} are deduced separately from each set of observations taking care that they span over a period of at least 2 h. Generally this occurred when the observations were made from morning till evening and the ship had sailed almost throughout. In all, 57 sets of t_{pl} estimates are made along the track. These together with the regular data obtained from the MWR at Trivandrum formed the basic data set for our study. Here it may be noted that on some days only one of the instruments (either MWR/ESP) could be operated on the cruise due to logistic constraints and as such maximum data were available at the common wavelength of 500 nm.

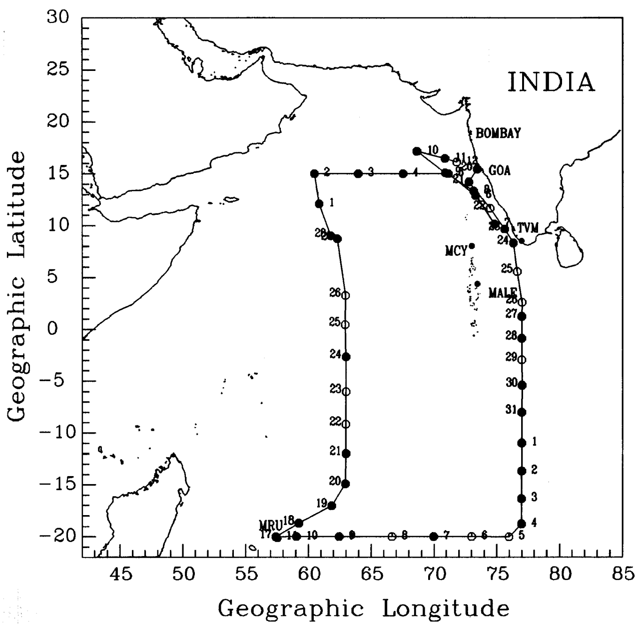

Figure 1. Schematic representation of the cruise track of the ORV *Sagar Kanya* during the IFP-99 (points joined by continuous line) of INDOEX along with ground stations. The points correspond to the ship's daily position at 0600 GMT. The filled circles are used to indicate the availability of MWR/ESP data on the day, while open circles indicate absence of data, due to cloudy sky conditions. Details are given in the text.

Results

Before presenting the results, the consistency, reliability and inter-usability of the t_{pl} data obtained using the MWR and ESP have been examined by making an inter-comparison of the t_{pl} estimates made by these instruments from simultaneous measurements made at the same location at the common wavelength of 500 nm. Such inter-comparisons were made at Trivandrum in January 1998 (prior to the FFP-98) and in April 1998 (after the FFP-98) and also during the two cruises. The results are shown in Figure 2 where the dashed line represents the ideal case when both the instruments would yield the same t_p. It can be noticed that the experimental points are well mixed and fall fairly well about this line generally within the expected errors (~ 0.01 to 0.015) and with a correlation of $r^2 = 0.88$, which is highly significant. Thus the data from both the instruments remained statistically stable and consistent during the study period. With this background we examine the results in detail.

Spatial variation of aerosol optical depth

For studying the spatial variation of aerosol optical depth, the data at 500 nm were examined, as highest number of measurements are available at this wavelength. Besides, this wavelength is more sensitive to scattering or extinction by submicron aerosols, which have longer atmospheric residence times. The spatial variation of t_{pl} at 500 nm is shown in Figure 3 as contours with the colour scheme representing different levels of t_p as shown by the vertical bar beside it. In evolving this spatial pattern, we have also used the t_p values obtained at Trivandrum during the IFP period and also those obtained at Goa, a few days prior to the cruise. The following features are clearly discernible from the figure.

(i) There are two regions of enhanced optical depths (at 500 nm) along the west coast of India; one down south of Goa centred at ~ 10°N and the other (weaker) down south of Trivandrum at ~ 6°N.

(ii) The optical depths generally decrease outward, towards open ocean. Following the contour levels, differentiated by the colour scheme, it can be seen that t_p decreases with an e^{-1} scaling distance of ~ 1200 to 1300 km. This value of the north–south gradient is in general conformity with the earlier estimates of spatial gradients under calm wind conditions during the pre-INDOEX data by Satheesh *et al.*[8].

(iii) In the South Indian Ocean beyond 5°S (the ITCZ was located at ~ 4°S during the IFP period), i.e. over the oceanic regions due south of the ITCZ, extremely low values of t_p are concentrated, including locations around Mauritius. In the return leg on a couple of occasions higher values of t_p occurred in this region, but that is considered as isolated events associated with the strong (>10 m s^{-1}) wind speeds.

(iv) However, the most outstanding feature in Figure 3 is the observation of a stronger and extended region of high optical depth located between 5–10°N; 58–63°E longitude, more than about 1000 km west off Indian coast. This 'high' optical depth region, which we call as the 'West Asian High' just because of its proximity to the continental regions of West Asia, is well separated from the 'Indian Highs', occurring along west-coast of India, by well defined areas of low aerosol optical depth. This observation has been particularly possible because of the longitudinal section at ~ 15°N in the cruise track, closely followed by the latitudinal section parallel and close to the Indian coast.

As the MWR provided t_p values at longer wavelengths also, it is possible to examine the spatial variation at the near IR wavelength. Figure 4 shows the spatial variation of t_p at 1025 nm (which is free from any gases absorption including water vapour). The legends and data are similar to Figure 3.

Examining the figure, it is seen that the features remain more or less similar at 1025 nm also; except that the coastal highs become broader and the 'West Asian High' a bit weaker (compared to the relative patterns at 500 nm). Also a weak high is observed in the southern hemisphere (~ 20°S, 75°E). Even though enhanced coarse particle concentration is likely to occur close to the coast due to continental proximity and wave breaking, the occurrence of the 'West Asian High' and also a weaker mid ocean southern hemisphere high at ~ 20°S, 70°E need further explanation as these regions are far removed from continents.

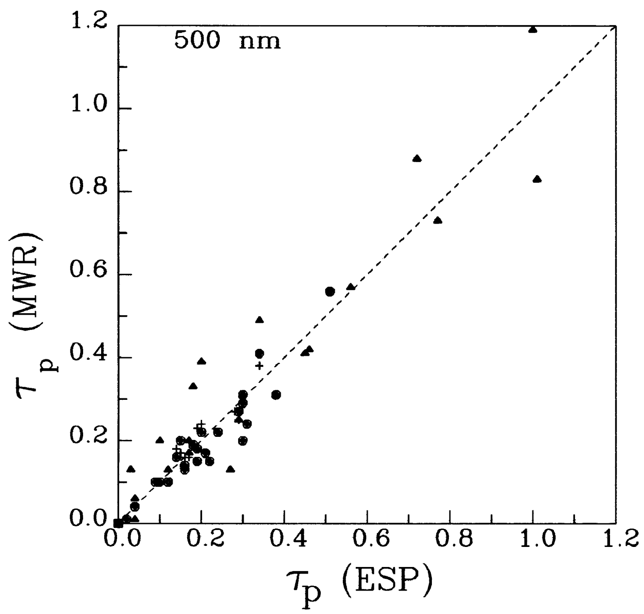

Figure 2. Intercomparison of t_p at 500 nm estimated using MWR and ESP data. The dashed line represents the ideal case when both estimates are the same. Typical errors in the estimate range from 0.01 to 0.015, but the error bars are not shown to avoid over crowding.

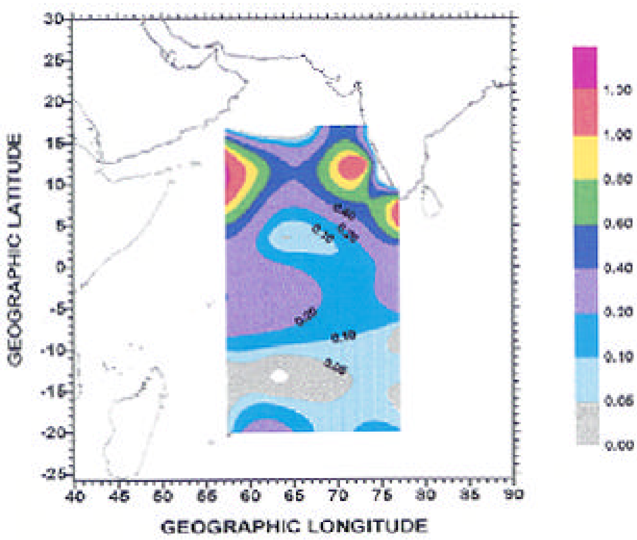

Figure 3. Spatial variation of t_p at 500 nm during the IFP-99 cruise. Each colour corresponds to a given range of t_p as identified by the vertical bar by the side. The ground station t_p data from Trivandrum during the cruise and from Goa prior to the cruise are also incorporated.

Discussion

Our results on the spatial variation of aerosol optical depths have shown broadly two regions of high activity; the ‘Indian High’ close to the West Coast of India and the ‘West Asian High’ clearly separated from the Indian High. In this context, it is to be recalled that based on the analysis of the data of the FFP of the INDOEX, in 1998, Moorthy *et al.*[2,9] have reported the occurrence of the secondary high in the Central Arabian Sea and attributed it to the significant enhancement in the concentration of small, accumulation mode ($r < 0.5$ µm) aerosols. Based on the meteorological re-analysis atlas for the FFP[10], they also suggested the possible cause of this secondary high to the transport of fine aerosols from West Asian landmass. Similar observations of this secondary high were made based on deck level bulk sampling of aerosols during the FFP by Parameswaran *et al.*[11].

Transport of continental aerosols to long distances over oceanic environment by prevailing winds is not new; and has been extensively studied[12,13]; both across the Atlantic and over Indian Ocean. In most cases winds from ‘potential source regions’ carry aerosols to remote locations. In fact the longitudinal section at 15°N of IFP-99 cruise track was specifically planned to enable more extended and exhaustive study over this region. This has fructified into the findings in Figures 3 and 4. However, the interesting angle of our observations is that during the IFP period the mean winds (at surface and at 900 hPa level) were mostly northerly to north-easterly over the West Coast and peninsular India[14]. Moreover, the IFP period has been one of the anomalous periods for coastal Indian region (Trivandrum for example) with extended hazy sky conditions prevailing in February and March of 1999 and this is rather unusual for this region. In fact, at Trivandrum, where the MWR has been in regular operation for more than a decade, such hazy conditions have rarely occurred during this season. This has also been confirmed by several other workers from other parts of the country. Nevertheless, the ‘Indian Highs’ are less conspicuous than the ‘West Asian High’. This suggests additional factors which might include, local production/enhanced source activity over West Asian region; different nature (composition) of the aerosols at the Indian and West Asian High regions, changes in the atmospheric water vapour content and spatial changes in the general circulation pattern providing different pathways for transport, which would be responsible for the observed features.

In this context we first examine the surface wind speeds during the cruise period. Figure 5 shows the spatial distribution of mean wind (averaged 6 hourly) in speed and direction along the cruise track. It can be seen that generally the winds have been weak to moderate with speed ≤ 7 m s^{-1} except in the region southward of 15°S where wind speed reached as high as 14 m s^{-1} at ~ 75°E. It has been well established from earlier observations that increase in wind speed over ocean causes an exponential increase in the optical depth particularly when the winds are purely marine[3,15]. It has also been established that the effect of wind speed is felt more at the longer wavelengths and at the coarse particle regime ($r > 1.0$ µm)[3,15,16]. Examining in this perspective, the weak high seen in t_p at 1025 nm at ~ 20°S, 75°E in Figure 4 can be attributed to the strong south easterly oceanic winds experienced there (Figure 5). In contrast to this, the region of West Asian High encounters only moderate to weak winds, but the wind direction changes from westerly to north easterly between 5°S and 5°N. So the effect of wind does not

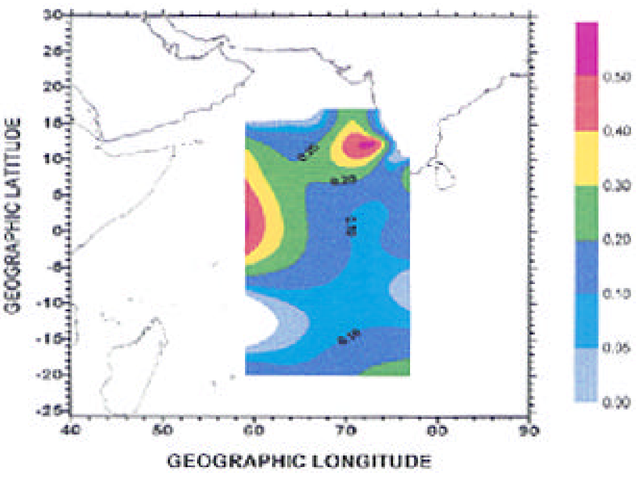

Figure 4. Same as Figure 3 but at 1025 nm wavelength.

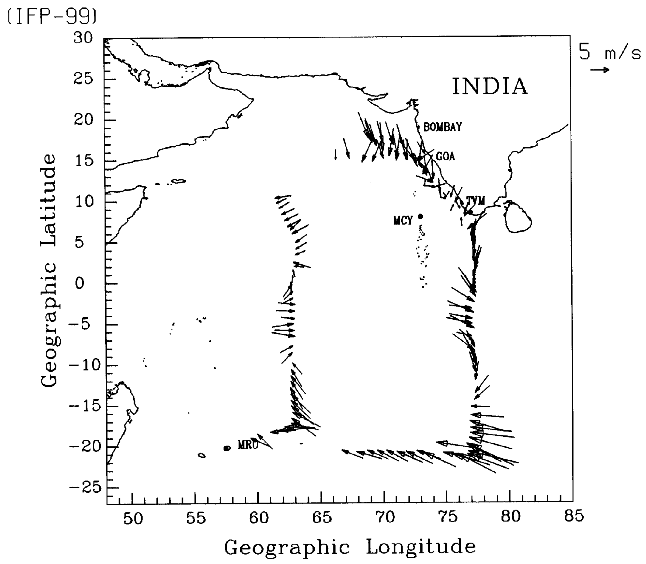

Figure 5. Spatial variation of the mean surface wind, obtained from the ship met data. The length of arrow is directly proportional to wind speed and the direction of the arrow indicates the direction from where the wind is blowing. The length of the arrow for wind speed of 5 m s^{-1} is shown on the top right corner of the figure. Tip of the arrow is at the ship’s locations.

appear to be a potential cause for the West Asian High. In the coastal Indian region, the winds are low downward Goa, and variable due to land–sea–breeze activity. This variable wind would at least partly lead to enhancement of aerosols due to recycling by the land–sea–breeze cells. Between 10 and 15°N, the winds are stronger and are northwesterly with probable continental aerosol components.

Secondly we examine the possible effect due to changes in water vapour content (W). The effect of change in W on t_p has been extensively studied[7] and an increase in W causes a nonlinear increase in t_p at all wavelengths (covered by the MWR) and this becomes appreciable for $W > 3$ g cm^{-2}. As we have the estimates of W, made simultaneously with those of t_p using the MWR, we have plotted the spatial variation of W in Figure 6. From the figure it is clearly seen that high (> 3 g cm^{-2}) values of W occur around the equator (most possibly in the region of the ITCZ) and over coastal India (regions lying inside the yellow, red and pink contours). Comparing Figure 6 with Figures 3 and 4, we see that even though the high concentration of water vapour may be partly contributing to the Indian High close to Trivandrum, the West-Asian High occurs in a rather drier environment with $W \leq 2$ g cm^{-2}. This fact is also supported by the Constant Altitude Balloon Experiment (CABE) data. Thus we can exclude wind speed and humidity from the potential sources for the 'West Asian High'.

It is well known that the oil fields of the west Asian countries are regions of intense anthropogenic and urban activities. Besides oil wells, a number of large oil refineries and oil-based industries also exist in these regions. It is possible that the effluent from all these would contain sulphur compounds and soot. The soot component is very important because of its absorptive nature. These countries also have extensive arid regions and the transport of fine mineral dust by winds will be more effective during the study period owing to the prevailing dry conditions and the favourable wind directions. Global scale meteorological re-analysis by Jha and Krishnamurti[10,17] showed that the lower tropospheric flow patterns over these regions (of West Asian High) are rather complicated with trajectories coming from India and from West Asia. Analysis of mean wind at ~ 900 hPa level during the IFP period, from the 17 constant altitude balloon flights from Goa[14] have shown three potential flow channels over the mid Arabian Sea; one from the Indian peninsula, the second from the Afro-Egyptian sector and the third from the African sector. Appu *et al.*[14] have also shown a 30–40 day oscillation in the zonal component of the wind showing that the relative strength of these flow channels at a given location over the ocean is variable in time. All these three flow channels, originating from distinct geographical regions, act as potential pathways for transport of aerosols, particularly the sub-micron aerosols which have longer atmospheric residence time. These aerosols would have distinct composition depending on the potential source mechanisms in these regions. Moreover, during the IFP there is an anticyclonic circulation prevailing with its centre located roughly above these regions (wind field analysis from NCMRWF, New Delhi). This would favour subsidence of aerosols picked up by the West Asian trajectories (both mineral and anthropogenic), as well as part of those carried from the Indian landmass getting recycled. All these aerosols are basically of fine nature (influencing the shorter wavelengths) and hence would have longer atmospheric residence times. This can be a potential contributor to the West Asian High. Similarly the mean fields[12] also show that wind trajectories originating from South East Asian regions reach the oceanic regions down the peninsular region of India, and these might also be contributing to the high seen down India.

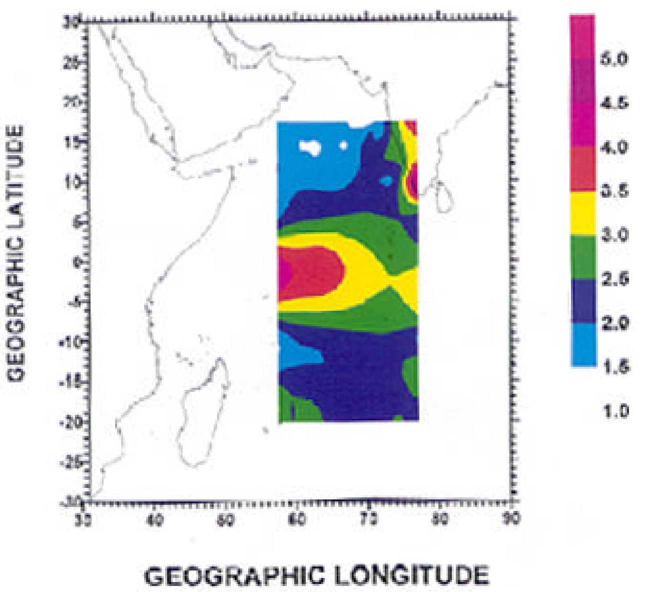

Figure 6. Spatial variation of columnar water vapour content. Note the enhanced regions around the equator (associated with the ITCZ) and over coastal India and the dry region over Central Arabian Sea.

Our observational results on the aerosol features over the Arabian Sea need to be further quantified by conducting more planned observations. For example, the West Asian high, though clearly indicated, is not fully evolved and it is not clear whether it is detached from the Arabian landmass or connected to it. Similarly, the composition of aerosols in the Indian high and West Asian high needs to be understood. This is vital not only from understanding and characterizing the source potentials, but also from estimating the radiative effects. All these can be resolved by conducting at least one more planned cruise during the same months extending up to the coastal regions of West Asia and having a few latitudinal and longitudinal sections between India and West Asia. A similar study in the Bay of Bengal will help to resolve the effects of the East Asian air trajectories on the south peninsular region of India.

Conclusions

The main conclusions of our study are the following:

(i) There exist a strong and extended region of high aerosol activity in the mid-Arabian Sea (which we call the West Asian High) detached from the 'Indian Highs' seen along coastal region of the Indian peninsula.

(ii) The West Asian High does not appear to be associated with either strong winds over the sea surface or high water vapour content. Rather it appears to be resulting from the combined effects of transport of aerosols from the West Asian regions, the Indian peninsula and the African region. The relative strength of these trajectories would determine the strength and position of this high. Besides, aerosol composition also would be important (particularly the amount of soot and other absorbing aerosols).

(iii) Central Indian Ocean and the south of ITCZ have very low optical depths.

(iv) Columnar water vapour shows high values close to the ITCZ and relatively dry environment over the Arabian Sea.

1. Ramanathan, V. *et al.*, Indian Ocean Experiment (INDOEX), A multiagency proposal for a field experiment in the Indian ocean, C^4 Publication #162, Scripps Institution of Oceanography, UCSD, La Jolla, CA 92093-0221, USA, 1996, p. 83.
2. Moorthy, K. K., Saha, A., Niranjan, K. and Pillai, P. S., *Curr. Sci.*, 1999, **76**, 956–960.
3. Moorthy, K. K., Satheesh, S. K. and Murthy, B. V. K., *J. Geophys. Res.*, 1997, **102**, 18,827–18,842.
4. Shaw, G. E., Reagan, J. A. and Herman, B. M., *J. Appl. Meteorol.*, 1973, **12**, 374–380.
5. Shaw, G. E., *Pure Appl. Geophys.*, 1976, **114**, 1–14.
6. Satheesh, S. K. and Moorthy, K. K., *Tellus*, 1977, **B49**, 417–428.
7. Nair, P. R. and Moorthy, K. K., *J. Atmos. Solar Terr. Phys.*, 1998, **60**, 563–572.
8. Satheesh, S. K., Moorthy, K. K. and Murthy, B. V. K., *J. Geophys. Res.*, 1998, **103**, 26183–26192.
9. Moorthy, K. K., Pillai, P. S., Saha, A. and Niranjan, K., *Curr. Sci.*, 1999, **76**, 961–967.
10. Jha, B. and Krishnamurti, T. N., Real-time meteorological reanalysis atlas during pre-Indoex field phase-98, Scientific Report, FSU report # 98-08, Tallahassee, FL 32306-4520, USA, 1998.
11. Parameswaran, K., Nair, P. R., Rajan, R. and Ramana M. V., *Curr. Sci.*, 1999, **76**, 947–955.
12. Prospero, J. M., Glaccom, R. A. and Nees, R. T., *Nature*, 1981, **289**, 570–572.
13. Piketh, S. J., Annegarn, H. J. and Tyson, P. D., *J. Geophys. Res.*, 1999, **104**, 1597–1607.
14. Appu, K. S. *et al.*, *Curr. Sci.* (*Suppl.*), 2001, **80** (this issue).
15. Lovett, R. F., *Tellus*, 1978, **30**, 358–364.
16. Moorthy, K. K., Satheesh, S. K. and Murthy, B. V. K., *J. Atmos. Terr. Phys.*, **60**, 1998, 981–992.
17. Jha, B. and Krishnamurti, T. N., Real-time meteorological atlas during the INDOEX-1999, Scientific Report, FSU Report #99-09, Tallahassee, FL 32306-4520, USA, 1999.