Interannual Variations of Aerosol Optical Depth over Coastal India: Relation to Synoptic Meteorology

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ABSTRACT

Interannual variations in spectral aerosol optical depths (AOD) were examined using the data obtained from a chain of ground-based multiwavelength solar radiometers from various locations of the Indian peninsula during the dry winter season (January–March) of 1996–2001. All of the stations revealed significant interannual variations, even though the spatial pattern of the variations differed over the years. These interannual variations were found to be significantly influenced by the extent of the southward excursion of the intertropical convergence zone (ITCZ). The years in which the southward excursion of the ITCZ was less (i.e., the years when the wintertime ITCZ was closer to the equator) showed higher AODs than the years in which the ITCZ moved far southward. The spatial variation was found to be influenced by large-scale vertical descent of an air mass over peninsular India, the Arabian Sea, the Indian Ocean, and the Bay of Bengal.

1. Introduction

Regional distribution of aerosols, their interannual variabilities, and the spectral optical depths are essential inputs to regional and global aerosol models to assess regional radiative forcing and climatic impacts. Analysis of the spectral aerosol optical depth (AOD) data over peninsular India based on ground-based measurements (Moorthy et al. 2001) and over the Arabian Sea and tropical Indian Ocean using National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) data (Rajeev et al. 2000; Li and Ramanathan 2002; Nair et al. 2003) during the recently culminated Indian Ocean Experiment (INDOEX) have shown significant interannual variations in spectral AODs during the northern winter (dry) season (January–March). These changes were found to be more pronounced at shorter (visible) wavelengths. Based on the INDOEX data, Satheesh and Ramanathan (2000) and Ramanathan et al. (2001) reported abnormally high AODs over the northern tropical Indian Ocean in 1999 (about 2–3 times the values seen in 1998). Based on multiyear and multistation data, Moorthy et al. (2001) showed that the increase in the AODs in 1999 was much smaller over peninsular India and was not spatially uniform over the coastal Indian regions. They also reported that such increases existed earlier in 1997 and attributed it partly to the reduced southward excursion of the intertropical convergence zone (ITCZ) in those years. Based on multiyear AVHRR-deduced AODs at 630 nm and synoptic winds [National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR)], Nair et al. (2003) attributed the high AOD values observed in 1999 over the tropical Indian Ocean region to the prevailing changes in the upper-atmospheric dynamics and also to the northward shift in the ridgeline over central India.

In this paper, we examine the interannual variation of wintertime spectral AODs at various locations over peninsular India during 1996–2001. The reasons for choosing this period are that (i) during this period the prevailing atmospheric circulation in the lower tropo-

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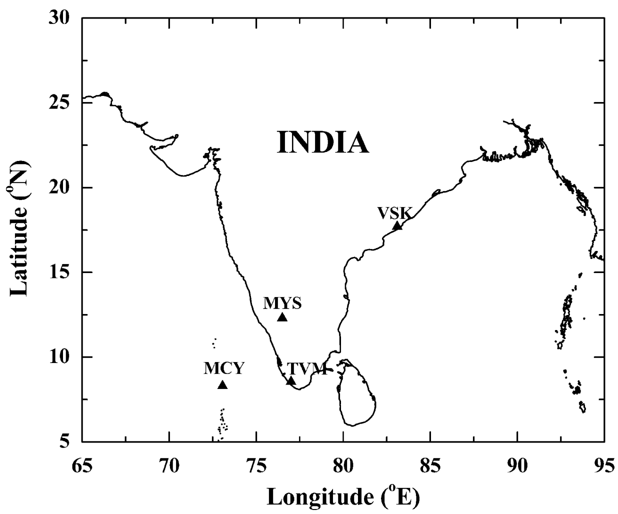

FIG. 1. Distribution of the MWR network stations. The stations are represented by triangles and are identified with their short names.

sphere is northerly/northeasterly, which is directed from the central Indian landmass toward the oceanic regions, (ii) the ITCZ lies in the Southern Hemisphere, and (iii) the precipitation is negligible. The purpose was to examine the nature of the interannual variations in the AODs over coastal Indian regions using an extended database, to investigate whether these variations were spatially homogeneous over the peninsula, and to delineate their possible associations with the synoptic circulations and the north–south excursion of the ITCZ.

2. Experimental data

The spectral AOD data used for this study are obtained from the multiwavelength solar radiometer (MWR) network stations of the Indian Space Research Organisation's Geosphere Biosphere Program (ISRO-GBP; Moorthy et al. 1999a, 2001). These stations are Trivandrum (TVM; 8.55°N, 76.9°E), Visakhapatnam (VSK; 17.7°N, 83.3°E), Mysore (MYS; 12.3°N, 76.5°E), and Minicoy (MCY; 8.3°N, 73.04°E), distributed over peninsular India (Fig. 1). Of these stations, Trivandrum is a rural, coastal location lying on the west coast (Arabian Sea) of India, whereas Visakhapatnam is a coastal, industrialized, urban location lying on the east coast (Bay of Bengal); Mysore is an inland, continental, semi-urban location with no major industrial activities, and Minicoy is an island site lying in the Arabian Sea (about 400 km west of Trivandrum), representing a maritime environment devoid of any industrial activities. The MWRs used at all of these locations were nearly identical and were operated regularly on clear-sky conditions [i.e., on periods during which the sky was cloud free (visible to naked eye, including visible cirrus) or on partly cloudy days when no visible clouds were present for an angular diameter of at least 10° around the sun]. The data were collected and analyzed following the Langley plot technique using a common protocol (Moorthy et al. 1999a). Effects of invisible and patchy clouds were removed by screening the data using a Student statistic at 0.995 confidence coefficient. A dataset was typically of at least 3 h in duration and had a relative airmass variation by a factor of at least 2. The consistency of the zero-airmass intercept was used to check the stability, and, during the period under study, this value was generally within 3%. This, along with the other uncertainties in the estimation of AOD [arising mainly out of the finite field of view of the instrument (2°), the uncertainties in the molecular scattering and absorption estimates, etc.], puts the uncertainty in the range of 0.02–0.04 at different wavelengths, with the higher values at the shorter wavelengths (<500 nm) and at 935 nm, and during high AODs (>0.5). More details are given in earlier papers (Moorthy et al. 1997, 1999a, 2001; Satheesh and Moorthy 1997). Spectral AODs ($\tau_{p\lambda}$) were estimated regularly on all clear/partly clear days (during periods of unobscured solar visibility) at 10 wavelengths (380, 400, 450, 500, 600, 650, 750, 850, 935, and 1025 nm), and the AODs for the months of January, February, and March of 1996–2001 formed the database for this study. Besides being the period in which the prevailing synoptic winds are northeasterlies and precipitation is insignificant, this was also the period of intense INDOEX observations during 1996–99. Trivandrum, Visakhapatnam, and Mysore had a substantially longer database, extending for more than 10 yr, than id Minicoy, which had only 39 months of data spanning from January 1995 to March 1998. Table 1 gives the details of the database used.

For the purpose of examining the interannual variations of AOD, the entire data for the period of January–March of each year is considered as one ensemble. The daily mean AOD values are grouped into this ensemble, separately for each station and for each year, and are averaged to obtain a single AOD spectrum for each station and for each year. This kind of grouping and averaging smoothes out the short-term and mesoscale fluctuations in the AOD, which are more local in nature, and retains the variations at synoptic scales.

The mean AOD of the seasonal ensemble $(\tau_{p\lambda})_s$ and its standard deviation σ_s and standard error ε_s for each station and for each year from 1996 to 2001 are estimated as

TABLE 1. Details of the database used in this study.

Station	Aerosol environment	Total database availability	Period of this study (Jan–Mar)
Trivandrum (8.55°N, 76.9°E)	Northern tropical, coastal, semiurban	Nov 1985–present	1996–2001
Visakhapatnam (17.7°N, 83.3°E)	Northern tropical, coastal, urban, industrial	Dec 1987–present	1996–2001
Mysore (12.3°N, 76.5°E)	Northern tropical, continental, semiurban	Oct 1988–Dec 1999	1996–99
Minicoy (8.3°N, 73.04°E)	Northern tropical island, maritime, natural	Jan 1995–Mar 1998	1996–98

$$(\tau_{p\lambda})_s = \left(\frac{1}{N_s}\right)\sum_{i=1}^{N_s}(\tau_{p\lambda i})_s, \quad (1)$$

$$\sigma_s = \frac{1}{(N_s - 1)}\left\{\sum_{i=1}^{N_s}[(\tau_{p\lambda i})_s - (\tau_{p\lambda})_s]^2\right\}^{1/2}, \quad \text{and} \quad (2)$$

$$\varepsilon_s = \left(\frac{\sigma_s}{\sqrt{N_s}}\right), \quad (3)$$

where the subscript s denotes the seasonal mean and N_s stands for the number of days of data in each seasonal ensemble (for each year and for each station).

Because the AODs at TVM, VSK, and MYS were available regularly for about a decade prior to 1996, it was possible to estimate the climatological mean AOD for the season considered. This was done by using the available AOD data from each station (Table 1) prior to 1996 for the period of January–March and obtaining the climatological mean $[(\tau_{p\lambda})_{\rm cl}]$, standard deviation, and standard error from Eqs. (1)–(3). In estimating the climatological mean AOD, the data pertaining to the volcanically perturbed period (from June 1991 to November 1993) caused by the eruption of Mount Pinatubo in June of 1991 have been excluded from the analysis, based on the temporal duration of the perturbation (Moorthy et al. 1996). Because Minicoy did not have the long-term data, the climatological mean was not estimated. Using these statistics, an estimate of interannual changes in the winter-mean AOD was made by computing the deviation δ_λ of the seasonal mean AOD of each year [Eq. (1)] from the corresponding (seasonal) climatological mean. Thus,

$$\delta_\lambda = (\tau_{p\lambda})_s - (\tau_{p\lambda})_{\rm cl}. \quad (4)$$

Positive values of δ_λ in a particular year imply that the seasonal mean AODs for that year are higher than the climatological mean, whereas negative δ_λ indicates that the seasonal mean AODs are lower than the climatological mean values. The significance level of this deviation is represented by the standard error ε_δ of δ_λ estimated following the principle of propagation of errors (Ku 1966; Fisher 1925, 177–212) as

$$\varepsilon_\delta = \sqrt{\frac{\sigma_s^2}{N_s} + \frac{\sigma_{\rm cl}^2}{N_{\rm cl}}}, \quad (5)$$

where $\sigma_{\rm cl}$ is the standard deviation and $N_{\rm cl}$ is the number of days of data in the climatological ensemble. The values of $\delta_\lambda > \varepsilon_\delta$ are statistically significant.

3. Results

a. Trivandrum

The left side of Fig. 2 shows the seasonal mean AOD spectra for Trivandrum (remote coastal location at the southwest tip of the Indian peninsula) for 1996–2001, in the frames from bottom to top. In each frame, the climatological-mean AOD spectrum (labeled as CLM) is also shown for comparison. The vertical bars over the points represent the standard deviation of the mean [estimated using Eq. (2)]. In the right panel of Fig. 2, the year-to-year variations in δ_λ are shown in grayscale. It can be seen from these figures that during 1997, 1998, 1999, and 2001 the seasonal-mean AODs are higher than the climatological means, particularly at the shorter wavelengths ($\lambda \leq 650$ nm); whereas in 1996 and 2000 the seasonal mean AODs are either comparable or somewhat lower than the climatological mean values at all of the wavelengths. The positive deviations in 1997 and 1998 are conspicuous only at the shorter wavelengths, whereas they are significant at almost all of the wavelengths in 1999 and 2001. In terms of absolute magnitudes at the midvisible wavelength (500 nm), high positive deviations in AODs are seen in 1997, 1999, and 2001.

b. Visakhapatnam

In contrast to the above, the interannual variations of the AODs and δ_λ for the east coast station VSK are shown in Fig. 3 in left and right panels, respectively (following the same conventions as for Fig. 2). (During 1998, the data at VSK were available only for the month of January.) It is seen that, in contrast to the pattern at TVM, at VSK the AOD spectra do not differ remarkably from the climatological mean, except in

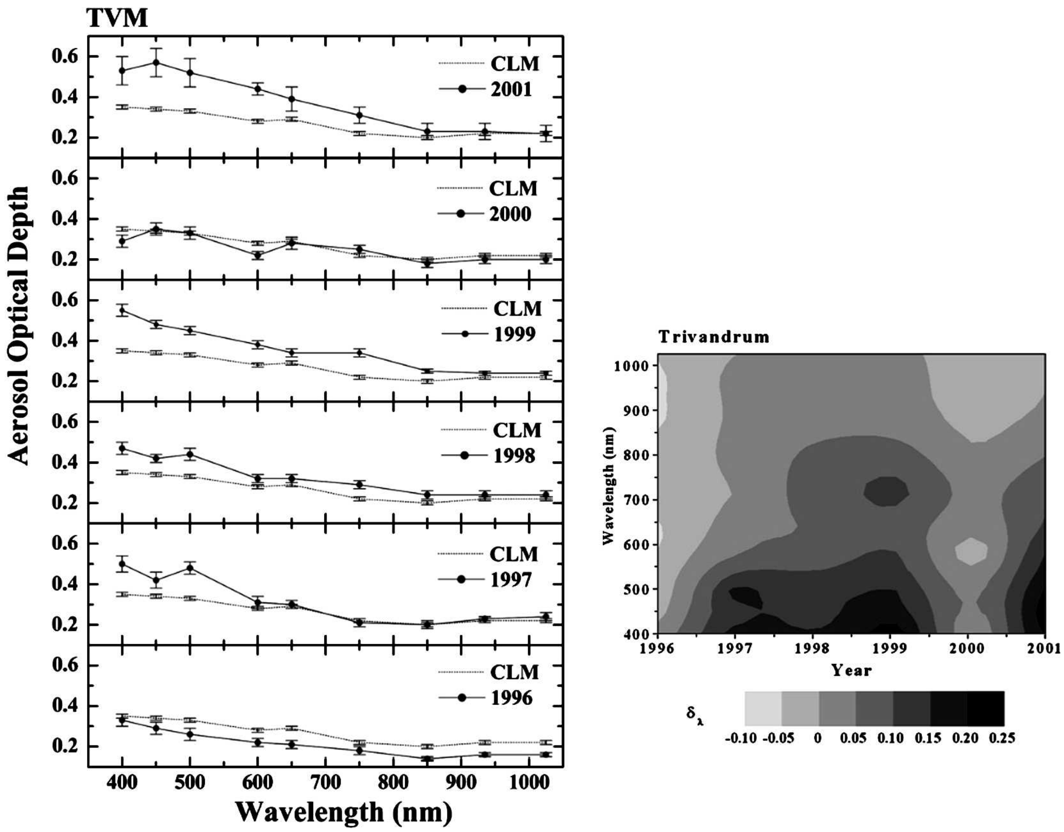

FIG. 2. (left) The spectral variation of the yearly seasonal (Jan–Mar) mean AODs (continuous line) for Trivandrum for 1996–2001 is shown. In each panel, the CLM AOD spectra are also shown (dotted line). (right) The interannual variation of δ_λ for the period 1996–2001.

2001 and weakly in 1997. During the other years (1996, 1998, 1999, and 2000), the deviations are mostly within the error bars. It is interesting that even in 1999, when remarkably high AODs were reported at several locations in the west coast and northern Indian Ocean (Satheesh and Ramanathan 2000; Moorthy et al. 2001; Nair et al. 2003), the seasonal-mean AODs at VSK are slightly higher than the climatological-mean AODs only at the two shortest wavelengths while at the other wavelengths they are comparable. In other words, the deviations δ_λ in 1999 were insignificant, indicating that the interannual variations did not occur the same way over peninsular India.

c. Mysore

Examining these features for the continental station Mysore (lying in western India) in Fig. 4, following the earlier conventions, it is seen that at shorter wavelengths ($\lambda \leq 650$ nm) the seasonal mean AODs are higher than the climatological means (δ_λ is positive) during all four years while they are comparable at longer wavelengths ($\lambda > 650$ nm). This is in contrast to the features seen at TVM and VSK. Nevertheless, in terms of absolute magnitudes, the deviations (positive) are significantly higher during 1997 and 1999 than during 1996 and 1998 (right panel of Fig. 4), similar to the case observed at TVM. It is interesting that the high AODs in 1999 are seen at the western inland station MYS also while they were not seen at VSK, lying on the east coast.

d. Minicoy

For Minicoy, the climatological AODs were not computed, because of the short database. However, the mean AOD spectra for the 3 yr (1996–98) shown in Fig. 5 clearly indicates that during 1997 the AODs were consistently higher at all of the wavelengths in comparison with 1998 and were consistently higher for wavelengths below 750 nm for 1996. This pattern is more in line with those observed at TVM and MYS.

It is interesting that CIMEL Electronique Company sunphotometer measurements at Kashidhoo Climate Observatory (KCO) in the Maldives (lying downwind of Trivandrum and Minicoy) also revealed significantly

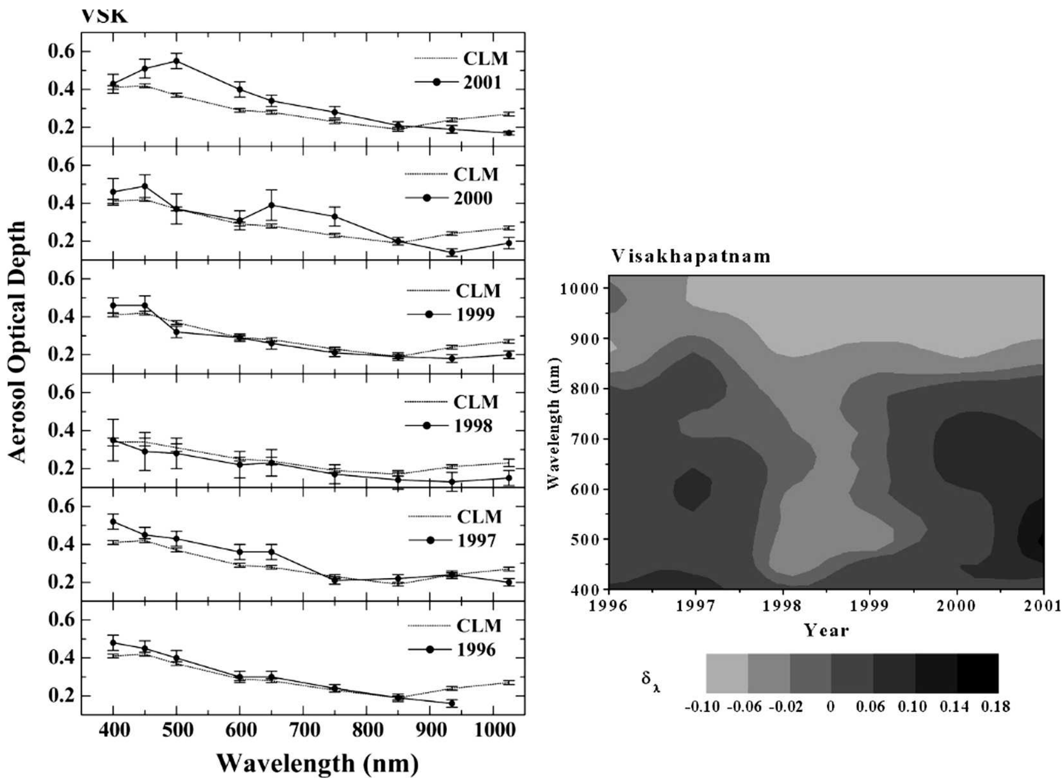

FIG. 3. Same as Fig. 2, but for the east coast station Visakhapatnam for 1996–2001.

high AODs in 1999 when compared with 1998 (Satheesh and Ramanathan 2000) that which resembled the features seen at the western stations TVM, MYS, and MCY.

e. Ångström exponents

Ångström exponent α deduced from the AOD spectra by using the equation $\tau_p = \beta\lambda^{-\alpha}$ is useful to infer particle characteristics, and its curvature in the optical depth space (α'; first derivative of α with respect to $\ln\lambda$) is useful to infer the dominance of accumulation and coarse aerosols (e.g., Eck et al. 1999; O'Neill et al. 2001). At locations where the aerosols are dominated by accumulation aerosols such as those from biomass burning or urban pollution, α showed large curvature in optical depth space with high values for α'. To examine this aspect, we have computed the Ångström exponents for two spectral regimes—α_V for the visible regime (wavelength range 400–750 nm) and α_N for the near-infrared regime (750–1025 nm)—by evolving least squares fit between the wavelengths and the corresponding AODs in a log–log scale separately for each spectral regime. The results are summarized in Table 2. Despite the significant variations from year to year and station to station, it is seen that, in general, α_V ranges between ~0.8 and ~1.3, with comparatively higher values at the eastern location VSK. This result is attributed to the increased urban and industrial activities at VSK in comparison with the other three locations. However, no systematic association is seen between α_V and AOD at any of the stations, unlike the cases discussed by Eck et al. (1999) for locations at which biomass smoke/urban pollution/desert dust contributed substantially to the AOD variations. Note that in their study the prominent source of accumulation aerosols (biomass smoke/urban pollution) resulted in a several-fold increase in AOD, which otherwise was very low (~0.05). In our case, even the lowest AODs were very high ($\geq$0.25) at all locations, even during the years in which the deviation was insignificant. It is seen from Eck et al. (1999) that the association between AOD and α almost leveled off for AODs > 0.25. Furthermore, α_N varied randomly, being frequently low and with negative values of α. This result could be due to the varying contributions of coarse-mode aerosols produced locally (e.g., sea salt at the coastal and island stations and dust at Mysore), the abundance of which might vary randomly with year and location. We have also examined the derivative α' (Eck et al. 1999) of α_V, and that also did not show any remarkable dependence of AOD, unlike the cases dis-

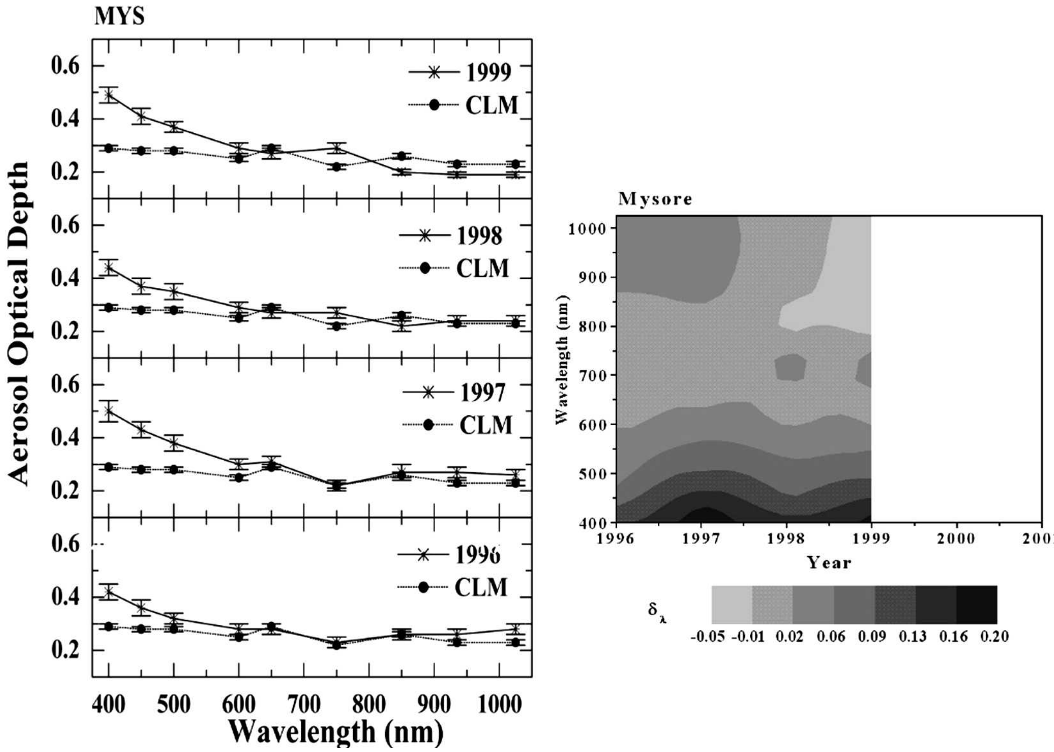

FIG. 4. Same as Fig. 2, but for the western continental station Mysore for 1996–99.

cussed by Eck et al. (1999) in which both α and α' increased remarkably with AOD at 500 nm [when the AOD increased from the background-dominated condition (~0.05) to the biomass-dominated condition (≥0.25)]. However, this increase almost leveled off at AOD = ~0.25. They also have shown that when the coarse-mode aerosols were also significant (as in the case with desert dust) the pattern deviated considerably, with α' becoming low and negative like those seen frequently in our study for stations like TVM, MCY, and MYS. Nevertheless, higher values of α' (in the range of 1.6–2.7) were seen at VSK, which had significant urban and industrial activity. Our observations suggest several possibilities such as 1) absence of a single-source dominance at any of the locations (except perhaps at VSK); 2) significant role of long-range transport of aerosol from the West and East Asian regions (Jha and Krishnamurti 1999; Moorthy and Saha 2000), which would be bringing in coarse mineral dust and aged accumulation aerosols, respectively, in addition to those from the Indian mainland; and 3) the substantial amount of sea-spray aerosols. From analytical considerations, O'Neill et al. (2001) also have shown that such a departure in the behavior of α and α' could arise from changes in aerosol types associated with differing synoptic air masses and source trajectories. These appear to be important at our locations.

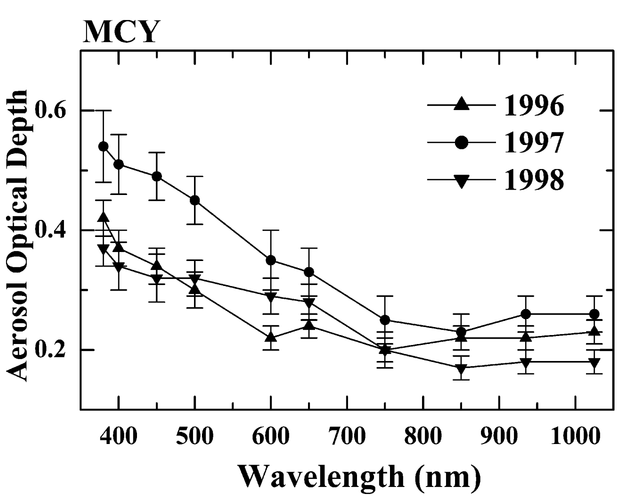

FIG. 5. Spectral variation of AOD for the island station Minicoy for 1996–98.

4. Discussion

Examination of the spectral AODs during 1996–2001 at various locations over peninsular India showed that the winter mean AODs exhibited considerable interannual variations and that these variations are spectrally

TABLE 2. Variations of the Ångström wavelength exponent over the period at different locations over different spectral regimes [α_V corresponds to the exponent evaluated for the visible regime (400–750 nm), α_N corresponds to that for the near-infrared regime (750–1025 nm), and the AOD is at 500 nm].

	TVM			VSK			MYS			MCY		
Year	AOD	α_V	α_N	AOD	α_V	α_N	AOD	α_V	α_N	AOD	α_V	α_N
CLM	0.33	0.94	−0.07	0.37	0.99	−0.62	0.28	0.33	−0.05	—	—	—
1996	0.26	1.33	0.26	0.4	1.13	1.80	0.32	0.88	−0.58	0.34	1.07	−0.24
1997	0.48	0.82	−0.50	0.43	1.22	0.03	0.38	1.21	−0.52	0.49	1.08	−0.66
1998	0.44	0.81	0.58	0.28	1.04	0.48	0.35	0.81	0.30	0.32	0.71	−0.31
1999	0.45	0.45	1.09	0.32	1.28	0.22	0.37	0.93	1.33	—	—	—
2000	0.33	0.90	0.61	0.37	0.59	2.05	—	—	—	—	—	—
2001	0.52	0.94	1.04	0.55	0.85	1.57	—	—	—	—	—	—

distinct and are not spatially homogeneous over peninsular India. The interannual variations are more conspicuous at the shorter (visible) wavelengths ($\lambda \leq 650$ nm), where the small submicron aerosols in the accumulation regime contribute significantly to the AOD. These particles are generally believed to result from secondary production mechanisms (e.g., gas-to-particle conversion) and to grow by subsequent microphysical processes (Andreae 1995) and hence are more associated with anthropogenic activities (Ramanathan et al. 2001) and would have a more regional perspective. Moreover, these fine particles have a larger residence time in the atmosphere during the winter season because of the lack of wet removal mechanisms over this region, and hence they are amenable for long-range transport. On the other hand, the coarse particles, which influence the longer wavelengths, are short-lived and hence would produce effects that are more local in nature. The highest AOD deviation occurred during 1999 in west coast locations (TVM and MYS); in 1997 it occurred at the east coast station (VSK). Further, the results also revealed that high AODs occurred not only in 1999 (as was reported during several independent measurements during INDOEX), but that similar highs were also observed in 1997 and 2001 at all of the stations and in 1998 at TVM and MYS. Though some kind of a similarity existed among the west coast stations, the pattern was different at the east coast station.

Observations of significantly high submicron aerosol concentrations and AODs in 1999 over coastal India, the Arabian Sea, and the northern Indian Ocean have been extensively reported by several scientists during INDOEX (Moorthy and Saha 2000; Satheesh and Ramanathan 2000; Moorthy et al. 2001; Kamra et al. 2001; Parameswaran et al. 2001; Jayaraman et al. 2001; Ramanathan et al. 2001; Nair et al. 2003), based on surface, in situ, and satellite measurements. Using AVHRR satellite data, Li and Ramanathan (2002) also reported an interannual variation in the AODs over the Arabian Sea and Bay of Bengal for the same period (northern winter), with high values occurring during 1997 and 1999, as compared with 1996 and 1998 (similar to the pattern seen at TVM, MYS, and MCY in the current study). Based on the AVHRR satellite-derived AODs over the Arabian Sea, Bay of Bengal, and northern Indian Ocean for the period of 1996–99, Nair et al. (2003) have reported very high values of wintertime AODs during 1999 and low values during 1996 and 1998. Integrating the satellite data over the entire oceanic region north of the equator for the period of January–March 1995–2001, Ramanathan et al. (2002) have reported an interannual variation in the AODs, with high values during 1999 in comparison with the other years. Further, they have estimated the AOD for a 1000 km × 1000 km region centered at the Maldives for the period of 1995–2000 and found high AODs during 1997 and 1999 in comparison with the other years. Based on the spectral AOD measurements over India during INDOEX, Moorthy et al. (2001) have reported high AODs (at short wavelengths) during 1997 and 1999 and low AODs during 1996 and 1998. They attributed the variation to the large-scale dynamics in the lower troposphere. Based on the ground-based sunphotometer measurements, Satheesh and Ramanathan (2000) have reported a significant increase in AOD, over the Maldives, by a factor of 2.5 from 1998 to 1999. Higher aerosol mass concentrations were reported by Parameswaran et al. (2001) during the winter of 1999 (when compared with 1998) over the Arabian Sea and northern India Ocean. Based on the in situ measurements during INDOEX, Shenoy et al. (2002) have reported a fivefold increase in the concentration of dimethylsulfide (precursor of non–sea salt sulfate) over the Arabian Sea and northern Indian Ocean from 1998 to 1999. However, most of these observations were limited to the INDOEX period (1997–99) and were based on a short database. Nevertheless, the magnitude of the reported variations was different at different locations.

Our studies show that such variations do occur during winter over this region and that the variations are spatially heterogeneous and do not occur the same way across peninsular India. The period under study (i.e., January–March) is the dry winter season over India, and the RH values generally are ≤60% at the surface and in the lower troposphere. An examination of the RH at the surface and at 850-hPa levels (respectively using measurements made over the land and from NCEP–NCAR data) showed that the mean RH for these months is between 30–% and 60% near the surface during daytime, with the higher values at the coastal regions, and is in the range of 40%–60% at the 925-hPa level, with interannual variations that are less than 10%. Such small changes in RH at the low RH levels would not cause the observed significant interannual variations in AOD. As such, we have examined the changes in AOD with the upper-air dynamics prevailing over this region.

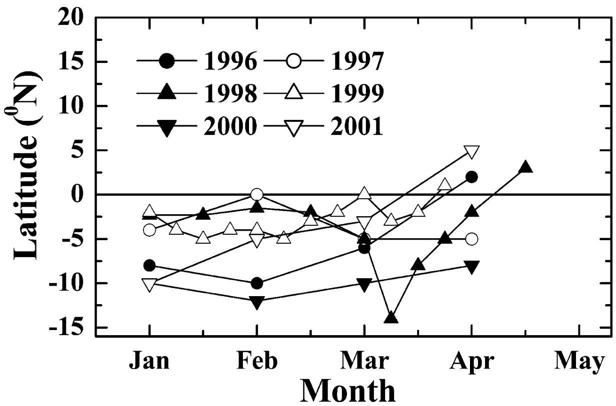

FIG. 6. Temporal variations in the mean position of the ITCZ for 1996–2001.

a. ITCZ

It is well known that the ITCZ is one of the most prominent and dynamic components of the tropical atmosphere. It constitutes the upward branch of the Hadley circulation and lies in the equatorial trough, where surface trade winds laden with heat and moisture from surface evaporation and sensible heating converge to form a zone of increased mean convection, cloudiness, and precipitation (Asnani 1993). The latent heat released in the convective cloud systems of the ITCZ is a critical component of the atmospheric energy balance. The fluxes of heat, momentum, moisture, and radiation between the atmosphere and the surface differ dramatically between the ITCZ region and the regions to the north and south of it. Thus, the position, structure, and migration of the ITCZ play an important role in determining the characteristics of ocean–atmosphere and land–atmosphere interactions on a local scale, the circulation of the tropical oceans, and a number of features of the earth's climate on a global scale. Even though the ITCZ persists almost continuously around the globe throughout the year, the annual excursion of the ITCZ is large over the Asian region (Asnani 1993). The location of the ITCZ is not always well defined, and its strength and position in a given month can change from year to year. Because the north–south excursion of the ITCZ and its variabilities are larger over the Asian region and also because of its important role in the spatial redistribution of continental trace species, including aerosols and trace gases, the interannual variation of AODs in this study are examined with respect to it. This is further accentuated by some of the findings during INDOEX, which have clearly indicated how the aerosol properties and abundances change sharply across the ITCZ (Rhoads et al. 1997; Moorthy et al. 1999b, 2001).

With the above considerations, we examined the interannual variations in the mean position of the ITCZ during the period of January–March for 1996–2001 over the longitudinal sector between 60° and 90°E. These positions were estimated from the horizontal wind vector (UV wind) maps produced by the National Centre for Medium Range Weather Forecasting (NCMRWF; Madan et al. 1999), wind vector and outgoing longwave radiation (OLR) maps derived from NCEP–NCAR reanalysis data (Kalnay et al. 1996), and meteorological reanalysis atlases of Jha and Krishnamurti (1998, 1999). The position of the ITCZ (latitude) was identified when at least two of the above yielded a common value. The position of the ITCZ was identified from the wind vector maps as the region of convergence with very low (minimum) wind speed on either side of which the winds were higher and in opposite directions. In the case of OLR maps, the ITCZ was identified as the region over which the OLR was the lowest (associated with maximum cloudiness). Because daily maps of all these parameters were not available for all of the months and years, the ITCZ positions were estimated from weekly-average maps and, in some cases, from monthly-average maps. Because the ITCZ is not a sharp line, but occurs as a band spread over a latitude range, the midpoint of the band was taken to mark the position of the ITCZ.

Temporal variations of the mean position of the ITCZ thus deduced are shown in Fig. 6. It can be noted from Fig. 6 that in 1996 and 2000, when the AODs at all of the stations are comparable to or below the climatological mean value, the ITCZ migrated farthest to the south of the equator (~10°S or farther) during most of the season (January–March). In contrast, in 1997, 1998,

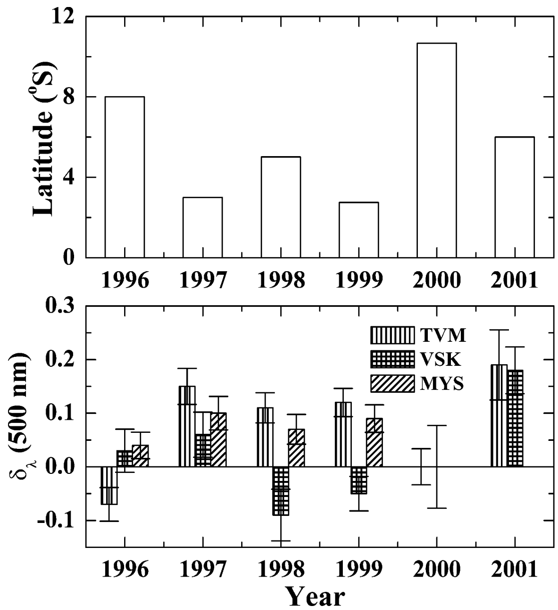

FIG. 7. (bottom) The interannual variations of δ_λ at 500 nm at Trivandrum, Visakhapatnam, and Mysore for 1996–2001, and (top) the corresponding interannual variations in the mean position of the ITCZ.

1999, and 2001 the southward excursion of the ITCZ was much shorter (generally up to ~5°S). In 1998, it was close to the equator (<5°S) during January and February before receding to as far as 15°S in March. During 1997, 1999, and 2001, the ITCZ was consistently located near 5°S and sometimes even north of it. This is now examined along with the deviation δ_λ in the AOD for each year in Fig. 7, where the bottom panel shows the interannual variation of δ_λ at a representative wavelength (500 nm) for TVM, VSK, and MYS and the top panel shows the average ITCZ location (obtained by taking the average of all of the mean positions shown in Fig. 6) for each year. This figure clearly shows that, in the years in which the average AODs are generally higher than the climatological values, the average position of the ITCZ was far less southward of the equator. Thus, there is a clear indication that the AODs over peninsular India during northern winter are strongly influenced by the extent of the southward excursion of the ITCZ, with the AODs increasing by as much as 0.2 at 500 nm over the climatological mean values, when the ITCZ, in general, remains between the equator and 5°S.

It is known that, during the northern winter season, the prevailing (synoptic) northeasterly winds are conducive for advection of continental aerosols to oceanic regions downwind. This aerosol-laden air meets the pristine oceanic air from the south at the ITCZ, resulting in convergence and updrafts. It has been established during INDOEX that the ITCZ acts like a virtual barrier, shielding the regions to its south from the aerosols and pollutants from the north (Moorthy et al. 1999b, 2001; Ramanathan et al. 2001). As a result, the aerosols from the northern continents are confined to a much shorter spatial span during the years in which the ITCZ is located nearer to the equator than in the years in which the ITCZ has migrated farther southward. The resulting stagnation or confinement would lead to the accumulation or piling up of aerosols, particularly in the accumulation range, because of their relatively longer residence time. This effect is augmented further by the nearly total absence of precipitation in this season over the potential source regions (continents lying upwind). [The residence time of aerosols in the Northern Hemisphere over the Indian Ocean region during INDOEX was found to be in the range of 7–10 days (Rasch et al. 2001; Ramanathan et al. 2001).] The combined effects of this confinement and the absence of removal mechanisms is likely to be felt more at stations lying relatively closer to the ITCZ (e.g., TVM, MCY, or KCO) than stations located far northward (e.g., VSK). Because VSK lies very far away from the ITCZ (in comparison with the other three locations), it may not have much dependence on the change in the extent of the southward excursion of the ITCZ. Because TVM, MYS, and MCY are far less industrialized and urbanized and lie relatively closer to the ITCZ (when compared with VSK), they respond more to the synoptic influence of the ITCZ, and the deviations at these locations follow an almost similar pattern.

b. Vertical winds

Over and above the horizontal confinement by ITCZ, vertical winds could also influence the aerosol loading and cause spatial heterogeneity. Strong and deep convections over the dry continental landmass upwind would favor increased vertical transport of aerosols over the source regions, which are then carried downwind by the prevailing winds and deposited at locations where there is a downdraft or descent of air mass, thereby providing an additional source of aerosols in locations far away from source regions. The mean vertical winds at 850 hPa over the latitude range from 25°N to 10°S and longitude range from 60°E to 90°E, deduced from the NCEP–NCAR reanalysis data (Kalnay et al. 1996), are shown in Fig. 8 for representative months of 1996–2001. The extreme right frame in each panel gives the net differences between February 1997 and 1996 (top), January 1999 and 1998 (middle), and January 2001 and 2000 (bottom). The vertical velocities are given in pascals per second, and positive values represent a descending air mass. (For the alti-

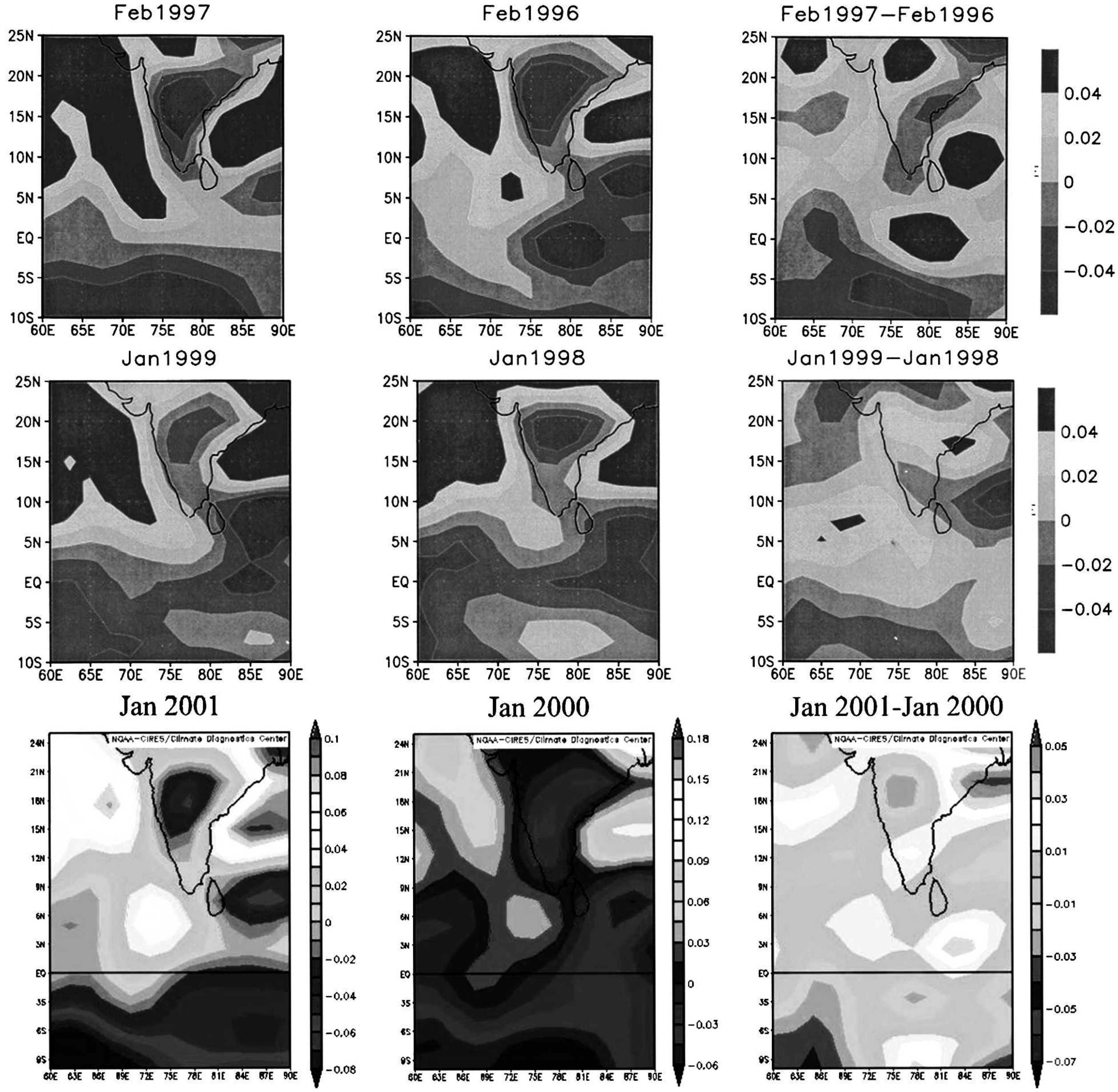

FIG. 8. Monthly mean vertical winds velocities (Pa s^{-1}) for the representative months of 1996–2001 (derived from NCEP–NCAR reanalysis data).

tude region considered, 1 Pa $s^{-1} \approx 0.1$ m s^{-1}.) Thus, the right frames show the net descent/ascent of air mass in February 1997, January 1999, and January 2001, as compared with the previous years. Significantly large descents are seen for 1997, 1999, and 2001, particularly over the west coast of India and north of the equator (Arabian Sea and northern Indian Ocean). Such stronger vertical descents of air mass are favorable for accumulation of aerosols, and the longer residence time of aerosols in this season results in an increase in their concentration. The impact of this effect would be potentially stronger for submicron aerosols, for the reasons discussed earlier, thereby causing an increase in the AODs at shorter wavelengths. In 1999, though the descent was stronger over the Arabian Sea, it was comparatively weaker over Bay of Bengal regions closer to VSK. This fact would also be partly responsible (in addition to the factors discussed earlier) for the AODs not increasing significantly at VSK in 1999 as compared with the western peninsular regions.

Now we will examine our findings in the light of earlier observations in this region during the northern winter season. Based on the measurements of spectral AODs and sky radiances with the Aerosol Robotic Network (AERONET) sun–sky radiometer in Kashidhoo during 1998–2000, Eck et al. (2001) have reported large interannual variations in the columnar optical properties of aerosols. They have found that the monthly mean AODs in February–April 1999 were 2 times those observed in 1998, with the AODs in 2000 being intermediate in magnitude. They attributed the interannual variations to the differences in the large-scale vertical and horizontal dispersion arising from differences in subsidence strength. These observations are very much consistent with the findings reported in this study. Measurements of near-surface aerosol mass concentration using a quartz crystal microbalance (QCM) impactor at Trivandrum revealed high concentrations of submicron aerosols in the winter months of 1999 as compared with 2000 (Pillai and Moorthy 2001; Pillai et al. 2002).

Based on the *NOAA-14* AVHRR satellite-derived AOD at 630 nm, Podgorny et al. (2003) and Parameswaran et al. (2004) have studied the impact of the 1997 El Niño–related Indonesian forest fires on the aerosol distribution over the tropical Indian Ocean [The Indonesian forest fires started in late July of 1997, lasted for about 5 months, and were later doused by the monsoon rainfall in December of 1997 (Pearce 1998).] These studies showed substantially large AODs over the equatorial Indian Ocean during September–November 1997 associated with the forest fires. Further, studies by Parameswaran et al. (2004) have also revealed that the mean AOD were slightly higher during February–April 1998, and associated them with a secondary increase in the fire counts. This would be partly responsible for the high AODs seen in 1998, despite the farther-southward migration of the ITCZ that year.

From five years of in situ QCM measurements of aerosol mass concentration and size distribution taken from the research vessel *Sagar Kanya* during INDOEX and satellite validation cruises, Ramachandran and Jayaraman (2002) have reported interannual variations in the near-surface aerosol mass concentration over the Arabian Sea and tropical Indian Ocean. Their measurements also indicated an increasing trend in the aerosol mass concentration, which they attributed to the combined effect of variations in the local meteorological conditions, increase in the anthropogenic activities, and production and transport of aerosols. From lidar measurements at the Maldives, Muller et al. (2001) have shown occurrences of strong elevated aerosol layers in the winter of 1999 and attributed them to advection. Based on the satellite data, Nair et al. (2003) have reported very high AODs over the Arabian Sea, Bay of Bengal, and northern Indian Ocean during 1999. They suggested the high AODs during 1999 were caused by the enhancement of the urban airmass flux over the Indian subcontinent, the northward shift of the extended anticyclone circulation over the Indian subcontinent ("central Indian ridge"), and the low southward excursion of the ITCZ.

5. Conclusions

The variation of wintertime mean AOD at various locations of peninsular India showed significant interannual variations, particularly at the shorter wavelengths, with highest AOD occurring during 1997, 1999, and 2001 as compared with 1996 and 2000.

The interannual variations showed inhomogeneity in the spatial distribution of AOD over the peninsula. The AOD variations at all of the west coast locations (TVM, MCY, and MYS) were more or less similar, whereas the east coast and more northerly station, VSK, behaved differently.

The interannual variations in AOD were found to be significantly influenced by the extent of the southward excursion of the ITCZ. The years during which the ITCZ was located closer to the equator (the southward excursion of the ITCZ being less) showed comparatively higher AODs at shorter wavelengths in comparison with other years in which the ITCZ migrated farther southward during winter.

Vertical winds derived from the NCEP–NCAR reanalysis data showed stronger descents, indicating subsidence and conditions conducive for confinement of longer-lived (accumulation size) aerosols in 1997, 1999, and 2001. This descent also showed heterogeneity in its horizontal extent in different years. The interannual variations in AOD were found to be stronger at locations for which the descents were stronger.

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REFERENCES

Andreae, M. O., 1995: Climate effects of changing atmospheric aerosol levels. *Future Climates of the World: A Modelling Perspective,* A. Henderson-Sellers, Ed., Vol. 16, *World Survey of Climatology,* Elsevier, 341–392.

Asnani, G. C., 1993: *Tropical Meteorology*. Vol. 1. Indian Institute of Tropical Meteorology, 602 pp.

Eck, T. F., B. N. Holben, J. S. Reid, O. Dubovik, A. Smirnov, N. T. O'Neill, I. Slutsker, and S. Kinne, 1999: Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols. *J. Geophys. Res.,* **104,** 31 333–31 349.

——, ——, O. Dubovik, A. Smirnov, I. Slutsker, J. M. Lobert, and V. Ramanathan, 2001: Column-integrated aerosol optical properties over the Maldives during the northeast monsoon for 1998–2000. *J. Geophys. Res.,* **106,** 28 555–28 566.

Fisher, R. A., 1925: *Statistical Methods for Research Workers*. Oliver and Boyd, 239 pp.

Jayaraman, A., S. K. Satheesh, A. P. Mitra, and V. Ramanathan, 2001: Latitudinal gradients in aerosol properties across the inter-tropical convergence zone: Results from the joint INDO–US study onboard *Sagar Kanya*. *Curr. Sci.,* **80,** 128–137.

Jha, B., and T. N. Krishnamurti, 1998: Real-time meteorological atlas during pre-INDOEX field phase. Florida State University Rep. 98-08, 104 pp.

——, and ——, 1999: Real-time meteorological atlas during the INDOEX-1999. Florida State University Rep. 99-09, 115 pp.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kamra, A. K., P. Murugavel, S. D. Pawar, and V. Gopalakrishnan, 2001: The background aerosol concentration derived from the atmospheric electric conductivity measurements made over the Indian Ocean during the INDOEX. *J. Geophys. Res.,* **106,** 28 643–28 652.

Ku, H. H., 1966: Notes on the use of propagation of error formulas. *J. Res. Natl. Bur. Stand.,* **70C,** 263–273.

Li, F., and V. Ramanathan, 2002: Winter to summer monsoon variation of aerosol optical depth over the tropical Indian Ocean. *J. Geophys. Res.,* **107,** 4284, doi:10.1029/2001JD000949.

Madan, O. P., and Coauthors, 1999: *Wind Analysis and Trajectories.* Vol. 2, *Meteorological Analysis during INDOEX Intensive Field Phase-1999*, INDOEX India Programme, 97 pp.

Moorthy, K. K., and A. Saha, 2000: Aerosol study during INDOEX: Observation of enhanced aerosol activity over the mid Arabian Sea during the northern winter. *J. Atmos. Sol. Terr. Phys.,* **62,** 65–72.

——, P. R. Nair, B. V. K. Murthy, and S. K. Satheesh, 1996: Time evolution of the optical effects and aerosol characteristics of Mt. Pinatubo origin from ground based observations. *J. Atmos. Terr. Phys.,* **58,** 1101–1116.

——, S. K. Satheesh, and B. V. K. Murthy, 1997: Investigations of marine aerosols over the tropical Indian Ocean. *J. Geophys. Res.,* **102,** 18 827–18 842.

——, K. Niranjan, B. Narasimhamurthy, V. V. Agashe, and B. V. K. Murthy, 1999a: Aerosol climatology over India, 1. Indian Space Research Organisation ISRO GBP MWR Scientific Rep. SR 03 99, 30 pp.

——, A. Saha, K. Niranjan, and P. S. Pillai, 1999b: Optical properties of atmospheric aerosols over the Arabian Sea and Indian Ocean: North–South contrast over the ITCZ. *Curr. Sci.,* **76,** 956–960.

——, ——, B. S. N. Prasad, K. Niranjan, D. Jhurry, and P. S. Pillai, 2001: Aerosol optical depths over peninsular India and adjoining oceans during the INDOEX campaigns: Spatial, temporal and spectral characteristics. *J. Geophys. Res.,* **106,** 28 539–28 554.

Muller, D., K. Franke, F. Wagner, D. Althausen, A. Ansmann, and J. Heintzenberg, 2001: Vertical profiling of optical and physical particle properties over the tropical Indian Ocean with six wavelength lidar, 1, Seasonal cycle. *J. Geophys. Res.,* **106,** 28 567–28 575.

Nair, S. K., K. Rajeev, and K. Parameswaran, 2003: Wintertime regional aerosol distribution and the influence of continental transport over the Indian Ocean. *J. Atmos. Sol. Terr. Phys.,* **65,** 149–165.

O'Neill, N. T., T. F. Eck, B. N. Holben, A. Simrnov, and O. Dubovik, 2001: Bimodal size distribution influences on the variation of Angstrom derivatives in spectral and optical depth space. *J. Geophys. Res.,* **106,** 9787–9806.

Parameswaran, K., P. R. Nair, R. Rajan, and D. B. Subrahamanyam, 2001: Spatial distribution of aerosol concentrations over the Arabian Sea and the Indian Ocean during IFP of INDOEX. *Curr. Sci.,* **80,** 161–170.

——, S. K. Nair, and K. Rajeev, 2004: Impact of Indonesian forest fires during the 1997 El Niño on the aerosol distribution over the Indian Ocean. *Adv. Space Res.,* **33,** 1098–1103.

Pearce, F., 1998: Playing with fire (preventing forest fires in Indonesia). *N. Sci.,* **157,** 36–40.

Pillai, P. S., and K. K. Moorthy, 2001: Aerosol mass size distribution at a tropical coastal environment: Response to mesoscale and synoptic processes. *Atmos. Environ.,* **35,** 4099–4112.

——, S. S. Babu, and K. K. Moorthy, 2002: A study of PM, PM10 and PM2.5 concentration at a tropical coastal station. *Atmos. Res.,* **61,** 149–167.

Podgorny, I. A., F. Li, and V. Ramanathan, 2003: Large aerosol radiative forcing due to the 1997 Indonesian forest fire. *Geophys. Res. Lett.,* **30,** 1028, doi:10.1029/2002GL015979.

Rajeev, K., V. Ramanathan, and J. Meywerk, 2000: Regional aerosol distribution and its long range transport over the Indian Ocean. *J. Geophys. Res.,* **105,** 2029–2043.

Ramachandran, S., and A. Jayaraman, 2002: Premonsoon aerosol mass loadings and size distributions over the Arabian Sea and the tropical Indian Ocean. *J. Geophys. Res.,* **107,** 4738, doi:10.1029/2002JD002386.

Ramanathan, V., and Coauthors, 2001: Indian Ocean Experiment: An integrated analysis of the climate forcing and effects of the great Indo-Asian haze. *J. Geophys. Res.,* **106,** 28 371–28 398.

——, P. J. Crutzen, A. P. Mitra, and D. Sikka, 2002: The Indian Ocean Experiment and the Asian Brown Cloud. *Curr. Sci.,* **83,** 947–955.

Rasch, P. J., W. D. Collins, and B. E. Eaton, 2001: Understanding the Indian Ocean Experiment (INDOEX) aerosol distribution with an aerosol assimilation. *J. Geophys. Res.,* **106,** 7337–7355.

Rhoads, K. P., P. Kelly, R. R. Dickerson, T. P. Carsey, M. Farmer, D. L. Savoie, and J. M. Prospero, 1997: Composition of the troposphere over the Indian Ocean during the monsoon transition. *J. Geophys. Res.,* **102,** 18 981–18 995.

Satheesh, S. K., and K. K. Moorthy, 1997: Aerosol characteristics over coastal regions of the Arabian Sea. *Tellus,* **49B,** 417–428.

——, and V. Ramanathan, 2000: Large differences in tropical aerosol forcing at the top of the atmosphere and Earth's surface. *Nature,* **405,** 60–63.

Shenoy, D. M., S. Joseph, M. Dileep Kumar, and M. D. George, 2002: Control and interannual variability of dimethyl sulfide in the Indian Ocean. *J. Geophys. Res.,* **107,** 8008, doi:10.1029/2001JD000371.