Aerosol loading in coastal and marine environments in the Indian Ocean region during winter season

K. Parameswaran, Prabha R. Nair, Rekha Rajan and M. Venkata Ramana*
Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram 695 022, India

The mass loading of aerosols in the coastal and marine environments is studied using a high volume sampler (HVS) and a low pressure impactor (LPI) during the first field phase of the Indian Ocean Experiment (INDOEX). These studies show that aerosol loading at Thiruvananthapuram is in the range 20–130 μg/m³, depending on the wind direction. During the sea breeze period, the concentration is low, and during the land breeze period, it is rather high. The mean size distribution obtained using the LPI, in general, shows a trimodal distribution. The measurements conducted on the cruise show that the mass loading over the ocean, near to the Thiruvananthapuram coast, is ~ 25–40 μg/m³ which is comparable to that observed on the coast during the day. At Male a significant reduction in aerosol loading is observed when the prevailing flow pattern from north changed to south. This indicates an increased concentration of aerosols in the northern hemispheric air. A sharp decrease in aerosol loading is observed at the Inter-Tropical Convergence Zone (ITCZ), ~ 15°S during the southward voyage of the ship. South of ITCZ, aerosol loading is less than that in the north. A significant reduction in aerosol concentration is observed during the return voyage in the latitude region 12°S to the equator. An enhancement in aerosol loading is observed in the central Arabian Sea (lat. 10–15°N), which is higher than near the Indian coast. The cruise data also showed a significant positive correlation between the columnar aerosol optical depth (at 0.5 μm wavelength) and the surface mass loading.

THE INDOEX intensive scientific campaign was planned for January 1999, with the first field phase (FFP) of this experiment conducted in February–March 1998. The scientific cruise started on 18 February 1998 and ended on 30 March 1998. In this cruise, a number of aerosol, radiation and boundary layer experiments were performed. In connection with this programme, intense aerosol charactseristics were measured over the continent from January to May 1998. Two types of aerosol samplers were operated on the surface as well as on the cruise to study the mass loading and size distribution of aerosol particles. As already mentioned, a single stage high volume sampler (HANDI-VOL G2000) monitored the mass loading of total suspended particles (TSP). The sampling rate of this equipment is ~ 20 cubic feet per minute. The aerosol sample is collected on a quartz fibre collection substrate. The blank substrate is preheated and desiccated before hand to eliminate the effect of condensed water vapour. The tare weight is taken using a microbalance. After sample collection, the substrate is again desiccated before weighing. From the mass of the substrate before and after the sample collection, the mass of particles collected for a fixed time period is obtained. Thus, along with a known flow rate, the mass concentration is estimated.

Also during the cruise period, a 14-stage Andersen low pressure impactor (LPI) is operated on the surface to study size distribution of aerosol particles. The LPI provided information on 12 size bins in the rânge 0.08–25 μm of aerodynamic diameter. To determine the aerosol size distribution, the aerodynamic diameters are converted to appropriate Stock's diameters (which are close to the geometrical diameter of the particle) taking into account the particle density, which depends on the atmospheric relative humidity. The dry density is assumed to be 2.5 g/cm³. Using an appropriate model[1] for the variation of density with relative humidity, the density corresponding to the prevailed atmospheric humidity condition was estimated. The details of the sample collection and method analysis are presented elsewhere[2,3]. The LPI is operated regularly at Thiruvananthapuram to study the mass-distribution of near surface aerosols. Data obtained during winter of 1998 are used for the present study.

Aerosol measurements at the Thiruvananthapuram coast

During this campaign period the HVS and LPI were operated at Thiruvananthapuram to study the mass loading of total suspended particles (TSP) and their size distribution. Observations taken on different days show that the TSP concentration is in the range 24 to 44 μg/m³, when the prevailing surface wind is onshore. During night when

*For correspondence. (e-mail: spl_vssc@vssc.org)

land breeze sets in, the TSP concentration (m) increases significantly and is in the range 50 to 107 μg/m³. Hourly values of m for a 24-h period measured on 8 January 1998 are presented in Figure 1. During the period from 1100 IST to 1900 IST, a sea breeze prevailed. For rest of the periods, the wind was directed from the land. A sharp increase in m was seen during the wind transition phase. Around 2000 IST, m increases up to ~ 120 μg/m³. The night-time concentrations are larger than the day-time concentrations. The size distribution of near surface aerosols measured using the LPI is shown in Figure 2. Figure 2 *a* shows the mass distribution and Figure 2 *b*, the number-size distribution. Both present a trimodal type distribution with mode radii around 0.05, 0.6 and 4.4 μm of particle radius. Except for this fine structure, the gross form of the size distribution can be approximated to a power law with size index[4] (the number of particles in the radius range r and $r + dr$ is proportional to $r^{-\nu}$, ν being the size index) ~ 4.0 ± 0.07. The size distribution obtained using LPI is representative of the average distribution covering a time period of ~ 40 h which includes both day-time and night-time conditions. The average mass concentration of aerosol particles obtained from LPI measurements in January 1998 was 113 μg/m³. During the FFP of INDOEX, the HVS was installed on board the ship, and the LPI was operated on land at the Thiruvananthapuram coast. The LPI was operated during the starting phase of the cruise from 18 February 1998 to 23 February 1998 when the ship was sailing along the Indian coast. The mass distribution and number size distribution obtained in this measurement are presented in Figures 2 *c* and *d*. The shape of the size distribution is almost similar to that in Figures 2 *a* and *b* except that the mode radii shifted towards the larger size regime. The modes are observed around 0.2, 0.9 and 6.2 μm of particle radius. Aerosol mass loading obtained in this measurement is 133 μg/m³.

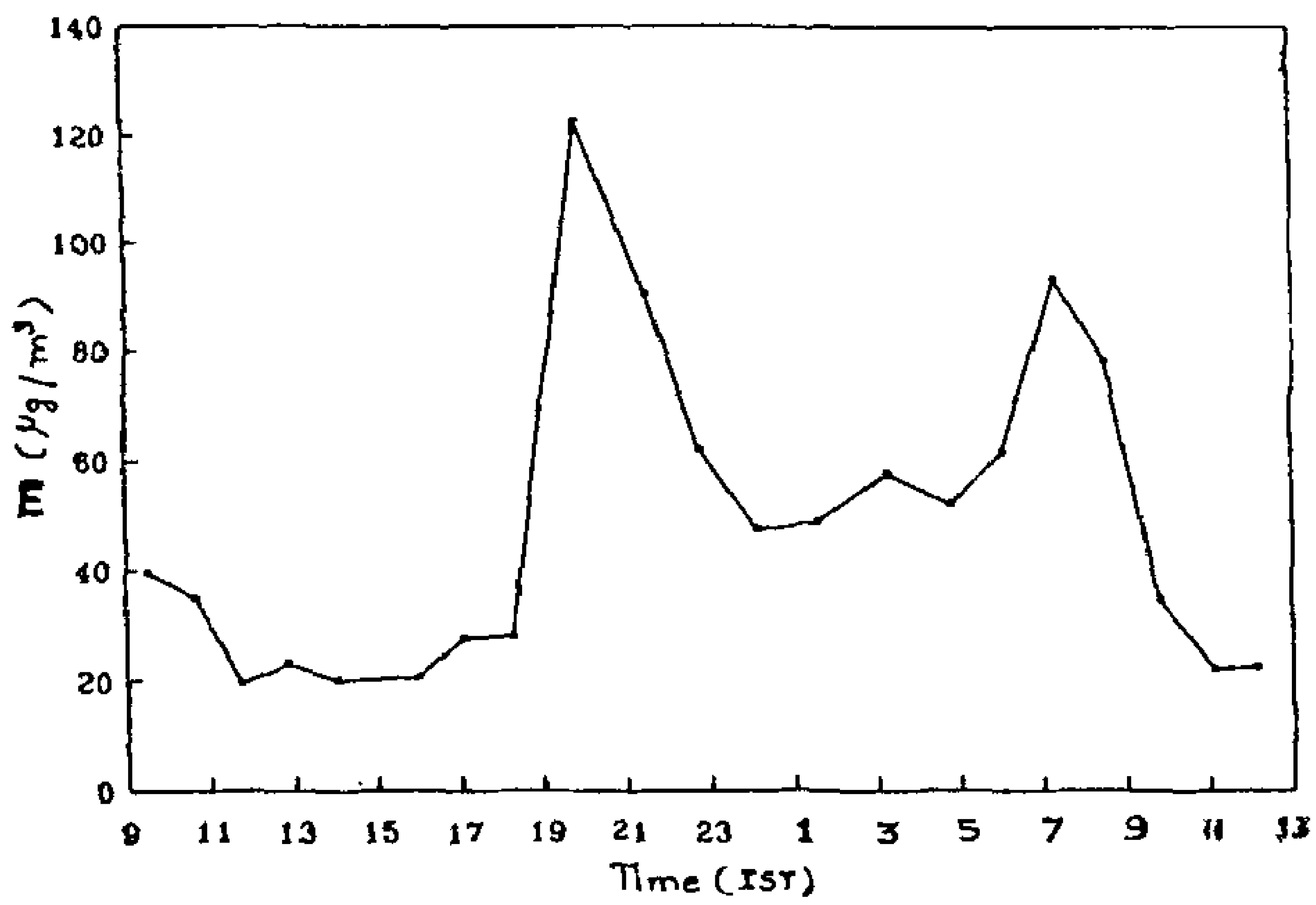


Figure 1. Diurnal variation of aerosol mass concentration observed at Thiruvananthapuram on 8 January 1998.

The size index of the number-size distribution shown in Figure 2 *d* is 4.03 ± 0.05, which is comparable to that obtained for January 1988.

Aerosol measurements on cruise

In connection with FFP 98, the scientific cruise #133 of *ORV Sagar Kanya* started from Goa on 18 February 1998. The HVS was one of the aerosol measuring instruments on this cruise. The sampler was located on the ship deck (~ 10 m above the sea level) towards the front end of the ship, since its position is selected such that it always samples the marine air from the front end of the ship uncontaminated by ship exhaust. In this voyage, the cruise covered a latitude region of 15°N to 20°S and a longitude region of 57°E to 76°E (refer to Figure 1 of Introductory Note). The HVS was operated almost every day (during the day-time), except during the port call at Male and Mauritius. The estimated mass concentration of aerosols from these measurements is presented in Table 1.

Figure 3 *a* shows a plot of aerosol mass concentrations along the cruise track. The length of the vertical bar is a measure of the mass concentration, and the associated dot indicates the mean position of the ship. Figure 3 *b* shows the variation of m with latitude, solid squares representing the data obtained during the southward voyage (up leg) and open circles during the return trip (down leg). From Figure 3 and Table 1, we see that the average concentration of aerosols near the Indian coast, during the up leg is ~ 29 μg/m³. This is comparable to the observed day-time mass concentration at the Thiruvananthapuram coast,

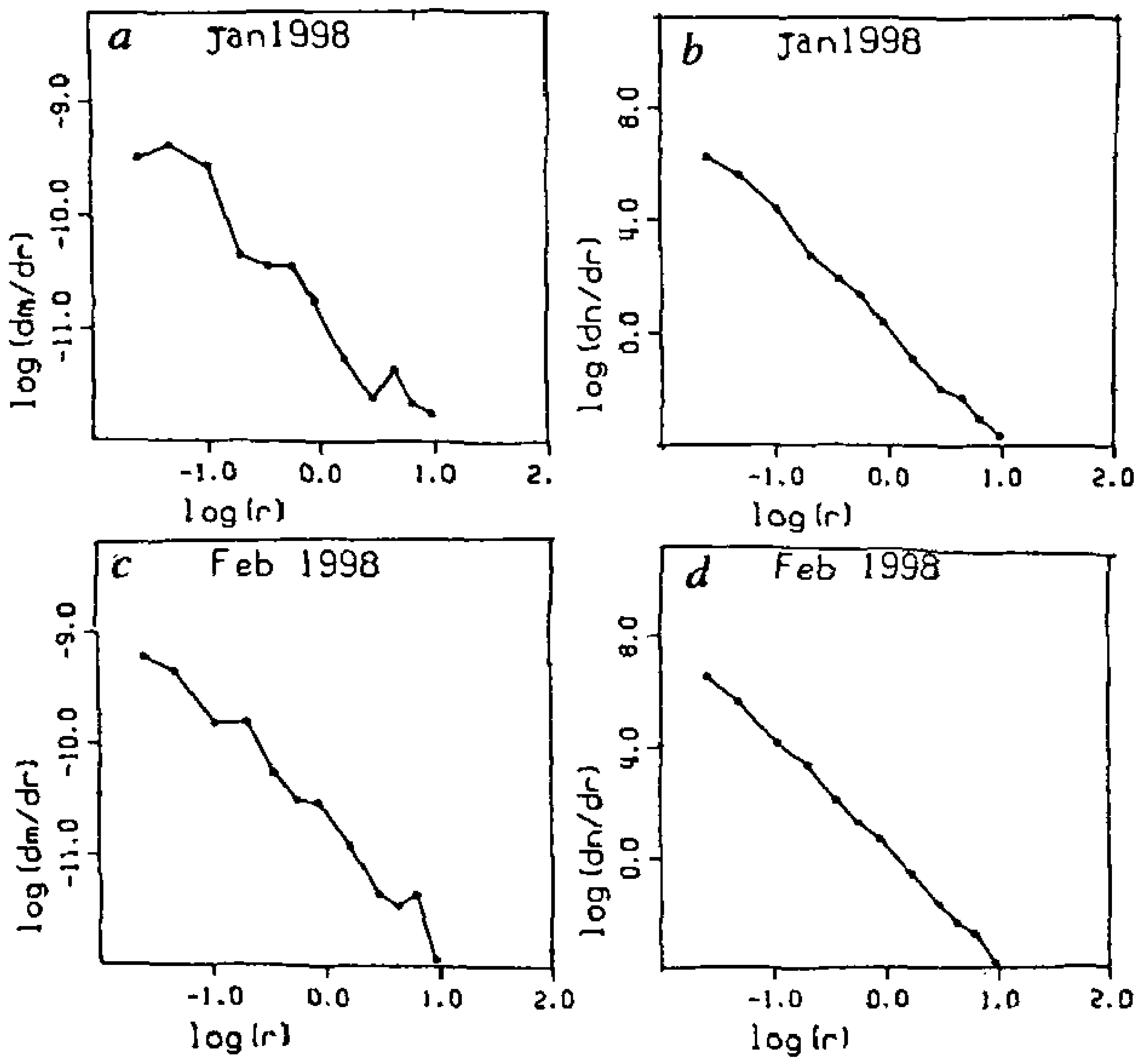


Figure 2. Mass distribution and number-size distribution for January and February 1998 at Thiruvananthapuram obtained using a LPI.

during the sea breeze period. South of Male, *m* remains more or less steady till the ship reaches close to ~ 10°S. It then sharply decreases (8 μg/m^3) around 13°S on 9 March 1998. On 11 March 1998 when the ship was positioned at 17.6°S, the mass concentration increased to 17 μg/m^3. Again in the return voyage when the observation started on 17 March 1998, *m* is ~ 15 μg/m^3. This decreased to 7 μg/m^3 on the next day when the ship was around 14°S. From this latitude till the ship crossed the equator, the aerosol mass concentration was significantly low (2–5 μg/m^3). This is lower than that observed during the up leg in the same latitude region. North of equator, the aerosol concentration increases with increase in latitude. The maximum in *m* is observed around 10 to 15°N (long. 69°E). This is significantly higher than that observed near the continent during the up leg (20–24 February 1998). For further interpretation of this data, it is required to know the details of the prevailing atmospheric dynamics such as flow pattern, location of ITCZ, wind speed, etc., during the cruise period.

Association between surface streamlines and aerosol concentration

Jha and Krishnamoorthi[5] have computed the surface streamlines and air trajectories on different days during the cruise period. These flow patterns are used to interpret the observed variations in *m*. The flow pattern during the starting phase of the cruise when the ship was sailing near the Indian coast is shown in Figure 4 along with mass loading on these days. As the flow pattern near the Indian coast is almost similar for the period 20–24 January 1998, a typical plot for 22 January 1998 is presented in this figure. The numerals in Figure 4 *b* represent the mass concentration (μg/m^3) at different mean positions of the ship.

Table 1. Aerosol mass concentrations measured at different locations during FFP 98 of INDOEX

Date	Latitude*	Longitude (°E)	Mass concentration (μg/m^3)	Position of ITCZ (°S)†	Remarks as noted from ship
Feb. 1998					
20	10.8	71.7	25.9		
21	9.2	73.6	20.7		
22	8.3	76.0	25.8		Thiruvananthapuram
22	8.4	76.0	23.7		Thiruvananthapuram
23	8.0	74.0	38.4		Minicoy
23	8.0	74.0	46.2		Minicoy
24	4.6	73.6	20.5		Male
March 1998					
1	4.5	73.5	18.6	5	Male
2	1.0	74.0	27.4	10	
3	–1.6	72.6	31.0	10	
4	–3.2	71.3	33.8	13	
5	–6.0	6.2	26.4	15	
6	–8.2	67.5	31.1	12	
7	–9.5	66.2	21.0	10	
8	–11.1	64.9	19.3	12	
9	–12.9	63.4	8.4	–	ITCZ
10	–	–	–	–	Rain§
11	–17.6	59.9	16.8	–	–
12	–	–	–	–	Mauritius
17	–15.9	61.1	14.5	5§	
18	–13.3	62.4	6.9	5§	
19	–10.9	63.6	1.6	5	ITCZ
20	–8.2	64.9	4.7	4	ITCZ
21	–5.7	66.2	4.8	10§	
22	–3.2	67.4	8.7	8§	
23	–0.6	68.0	4.8	9§	
24	2.8	69.1	14.1	10§	
25	5.5	69.0	18.7	1§	
26	8.8	69.0	30.3		
27	11.6	68.3	51.0		
27	12.6	68.3	43.5		
28	14.4	68.7	49.6		
28	14.5	69.5	53.4		

*Negative sign indicates south of equator.
†As provided by IMD (Brij Bhushan, personal communication).
§Indicates week ITCZ.

The anti-clockwise flow pattern originating from the southern hemisphere extends up to 10°S. The flow pattern south of 10°S latitude, in general, is southerly. In the northern hemisphere the surface winds are north-easterly. Air from the adjoining continent flows south up to ~ 10°S over the oceanic environment. In this period the Inter Tropical Convergence Cell (ITCC) in the Indian sector is located around this latitude. The hatches represent the area of precipitation in the convergence zone. The location of ITCZ as provided by the India Meteorological Department (IMD) on different days is given in Table1. From Figure 4 we can see that no significant precipitation occurred on the cruise track on these days. The aerosol-laden air from the continent continuously intercepts the cruise track, with aerosol mass concentrations of different days ranging from 20 to 40 μg/m^3. A small increase in m is observed near the Minicoy coast.

Figure 5 shows the streamlines[5] and aerosol loading along the cruise track from 24 February 1998 to 2 March 1998 which includes the halt period at Male also. When the ship was near Male, two observations taken on 24 February 1998 and 1 March 1998 showed significant deviations: the value of m observed on 24 February 1998 was 28 μg/m^3 and that on 1 March 1998 was 19 μg/m^3. Surface streamlines in Figure 5 show that the air usually encountered in the Male region originates from the northern parts. However, on 1 March 1998, the flow pattern changes drastically. On this day Male received streamlines originating from the southern hemisphere. This is associated with a significant decrease in m, indicating a decreased concentration of aerosols in the southern hemispheric air compared to that in the northern hemisphere. On 2 March 1998, when the flow restores its original pattern, the mass concentration increases to 28 μg/m^3, which is comparable to that observed near the Indian coast.

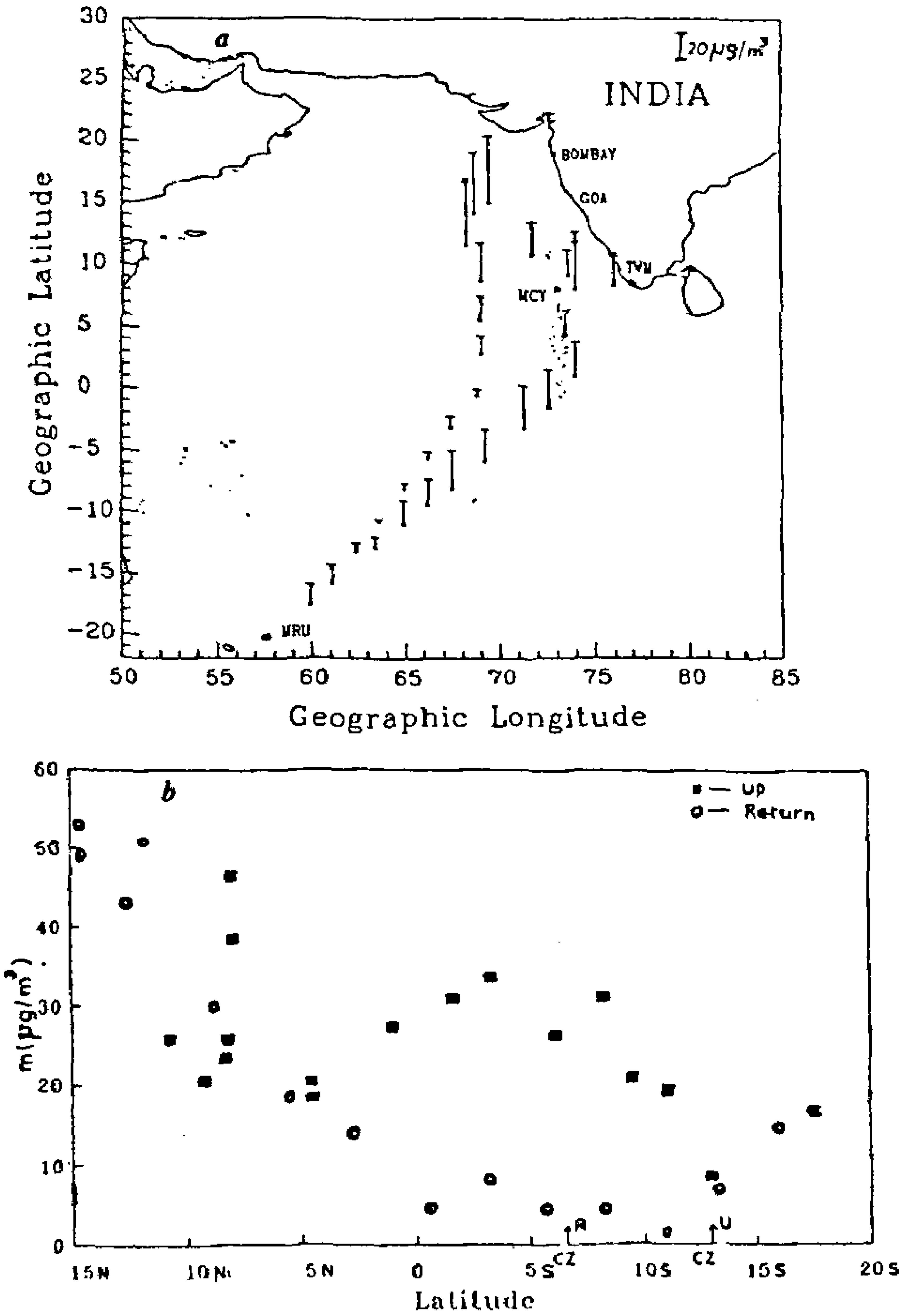


Figure 3. *a*, An illustrative plot of aerosol mass concentration measured along the cruise track. *b*, A plot of aerosol mass concentration with latitude for the up leg and down leg of the cruise.

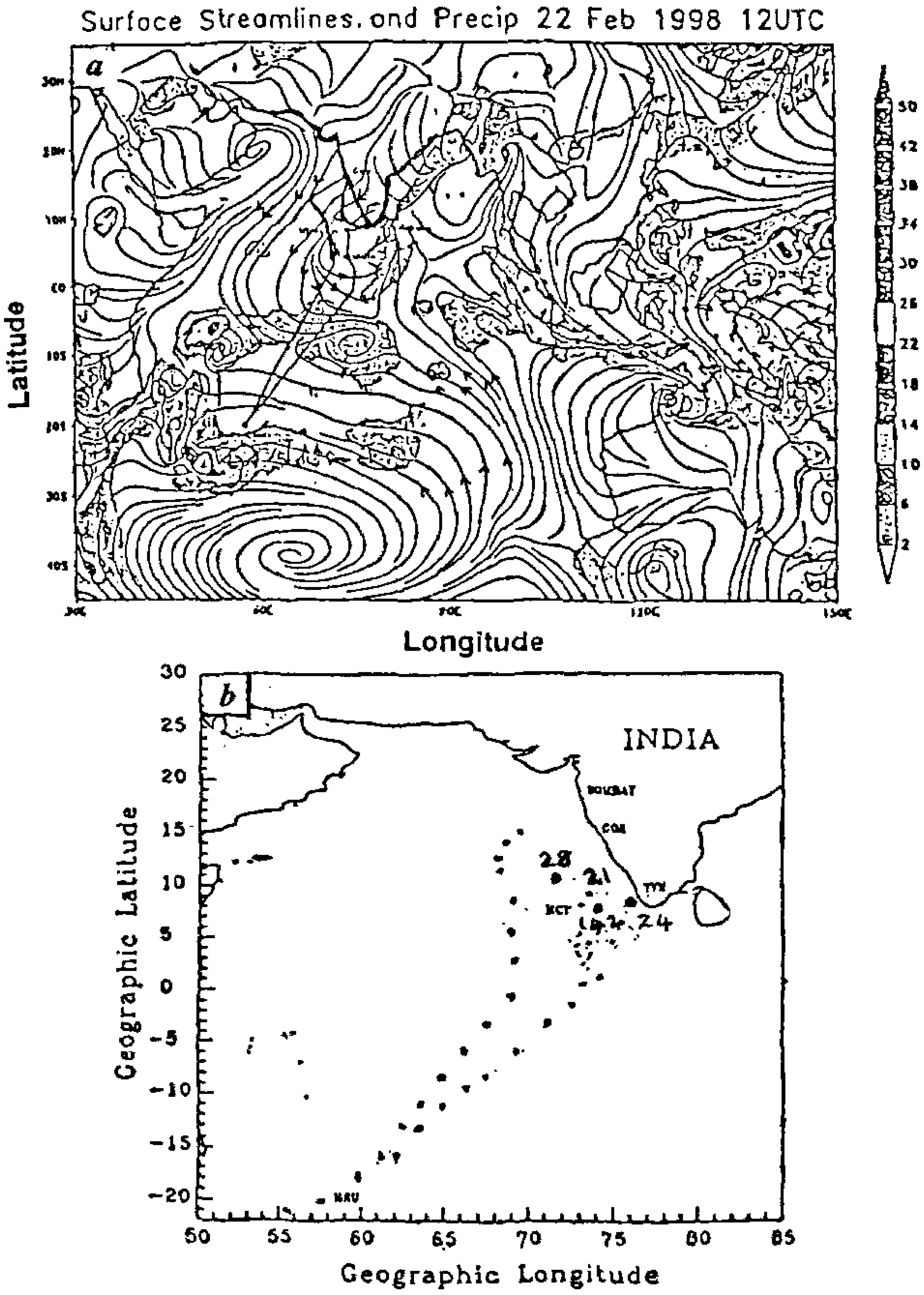
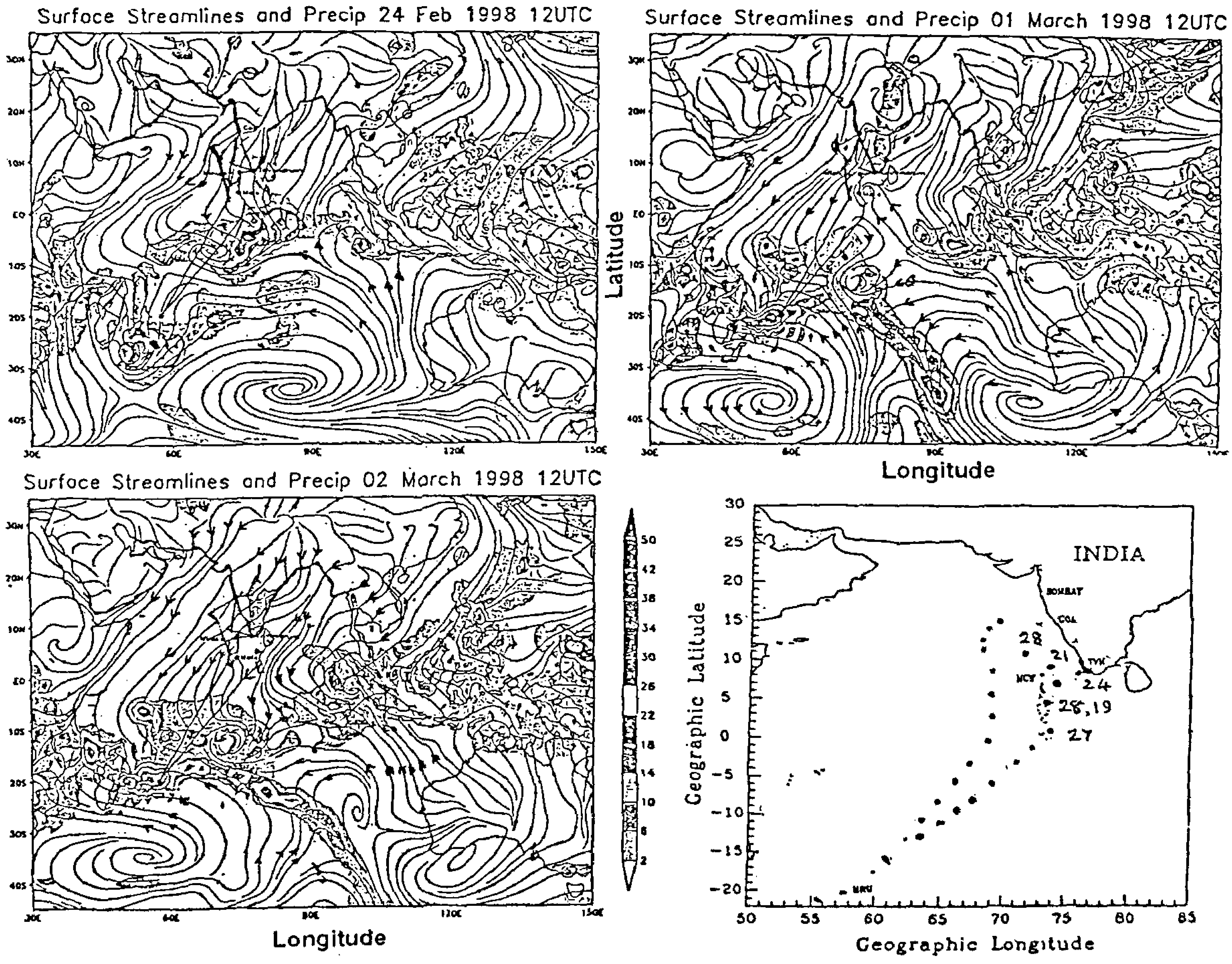


Figure 4. A typical surface streamline pattern during the start of the cruise along with mass concentration measured near the Indian coast.

Figure 6 shows the surface streamlines from 4 to 7 ırch 1998 along with the measured mass concentrations ıen the ship was sailing south of equator. During this riod, the air from north-easterly parts of the Indian ntinent after flowing over the Bay of Bengal reaches the ıise track. The aerosol loading shows an almost uniform ttern (around 30 μg/m^3). The convergence zone (ITCZ) still south of the ship position, however, on 7 March 98 as the ship approaches ITCZ, the mass concentration creases. Figure 7 shows the surface streamlines and ıss concentrations as the ship crossed the ITCZ. During ; period up to 9 March 1998, no significant precipita- ın occurred near the cruise track, though the sky was rtially cloudy associated with strong winds. On 9 March '98 the ship is well within ITCZ (i.e. ~ 12°S) and the ɜasured mass concentration (~ 8 μg/m^3) was signifi- ntly lower than that on the previous day. On 9 March '98 when the ship sailed through ITCZ, a heavy shower drenched the equipment, resulting in the loss of collected sample. The next observation on 11 March 1998, when the ship is south of ITCZ and approaching Port Louis, shows a value of $m \sim 17$ μg/m^3, which is significantly lower than that observed in the north of ITCZ on 2 to 7 March 1998. An observation on 17 March 1998 during the return trip showed a mass concentration of 15 μg/m^3, which is comparable with that observed on 11 March 1998. By this time the ITCZ moved north and weakened (Table 1).

Figure 8 shows the surface streamlines and mass concentration from 19 to 23 March 1998. When the cruise started from Mauritius, ITCZ was located around 5°S. During the course of the voyage it moved towards south up to 10°S (on 24 March 1998) and returned to 1°S (on 25 March 1998). This region encountered a strong convective system during this period. The surface streamlines influenced by this convective system and the associated



ıgure 5. Surface streamlines on 24 February 1998, 1 and 2 March 1998 at 12 UTC, along with mass concentration measured near the Indian ɔast and Male coast. The change in streamline pattern from 24 February 1998 to 1 March 1998 and the corresponding change in m at Male can be ɛen.

movements of ITCZ are seen in this figure. Divergent streamlines are observed on the cruise path, as the streamlines from north and south intercept on the cruise track in this region. This is associated with a sharp decrease in aerosol loading (2–8 µg/m^3). It may be noted that these values of m are significantly lower than the values concentrated during the up leg (20–30 µg/m^3), almost in the same geographic region. For a direct comparison the values of m encountered in this latitude region during the up leg are also shown in Figure 8 along with those in the down leg (enclosed in a quadrilateral frame). The movement of ITCZ from 5°S to 10°S and back might have resulted a significant scavenging of aerosols by way of the associated updraft, to distribute them globally through higher altitudes in stratosphere.

North of the equator the aerosol loading steadily increases with the latitude. Figure 9 shows the surface streamlines and mass loading towards the end of the cruise. The cruise track receives air from the north westerly part of central India, Pakistan and Gulf regions. Dry land mass (or desert) dominates these regions. The air originating from this region is rich in mineral dust, and these arid aerosols can travel long distances along the oceanic environment. For example, based on satellite imagery Ott *et al.*[6] have shown similar transport of dust outbreaks from the coast of Africa to the Caribbean crossing the North Atlantic Ocean. However, as the main transport occurs at higher altitudes[7,8], the effect will be less pronounced in the marine boundary layer. The present observation shows that even this small perturbation is observable in deck-level mass loading. The aerosol optical depth obtained using a multi-wavelength solar radiometer aboard the present cruise also showed a similar effect in this region[9]. In addition to arid aerosols, the submicron particles of anthropogenic origin also can contaminate this region (12° to 15°N). The observed mass

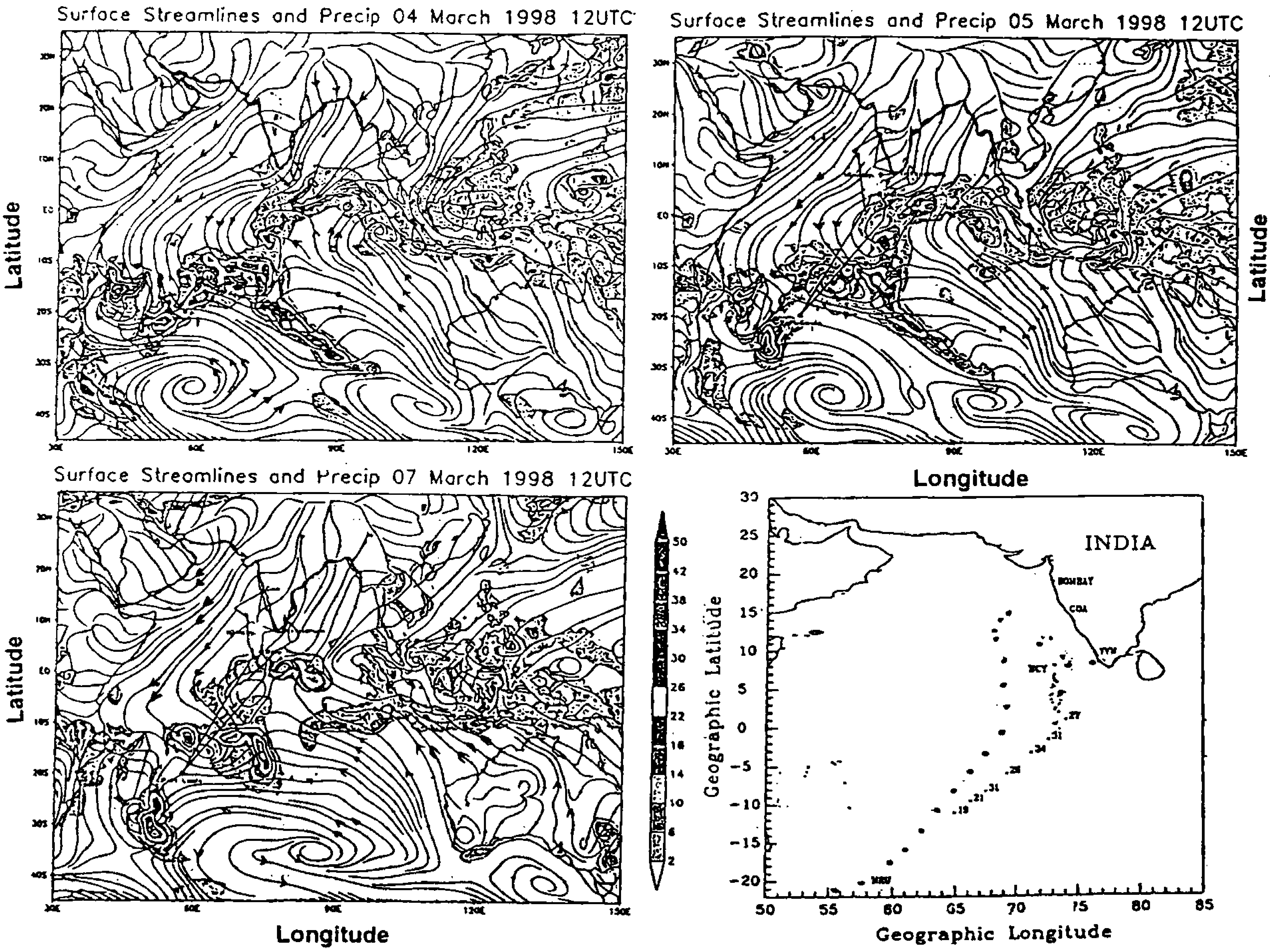


Figure 6. Surface streamlines (4–7 March 1998) and aerosol mass concentration in the far oceanic regions of Indian Ocean.

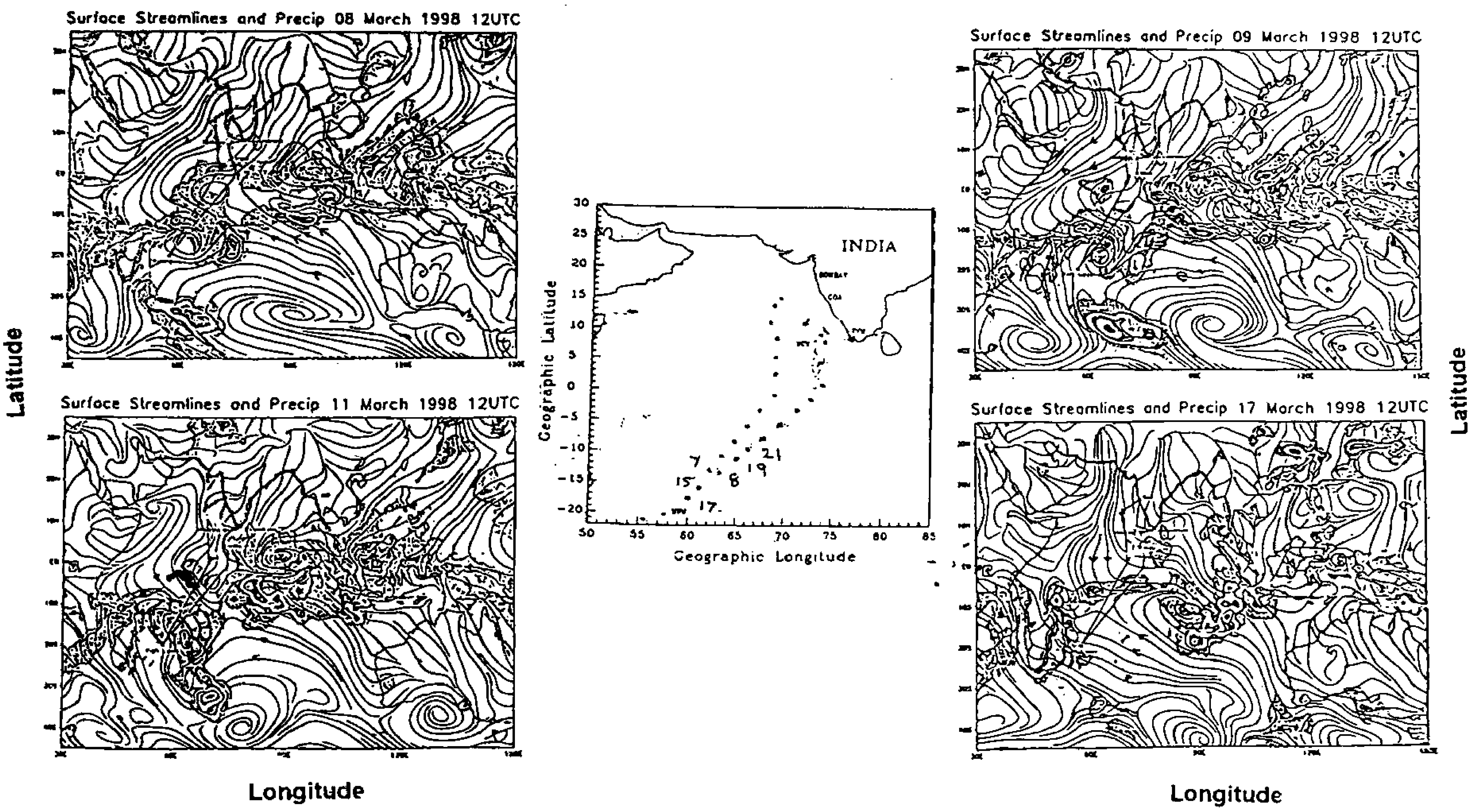


Figure 7. Surface streamlines and aerosol mass concentration in the ITCZ region and south up to Mauritius.

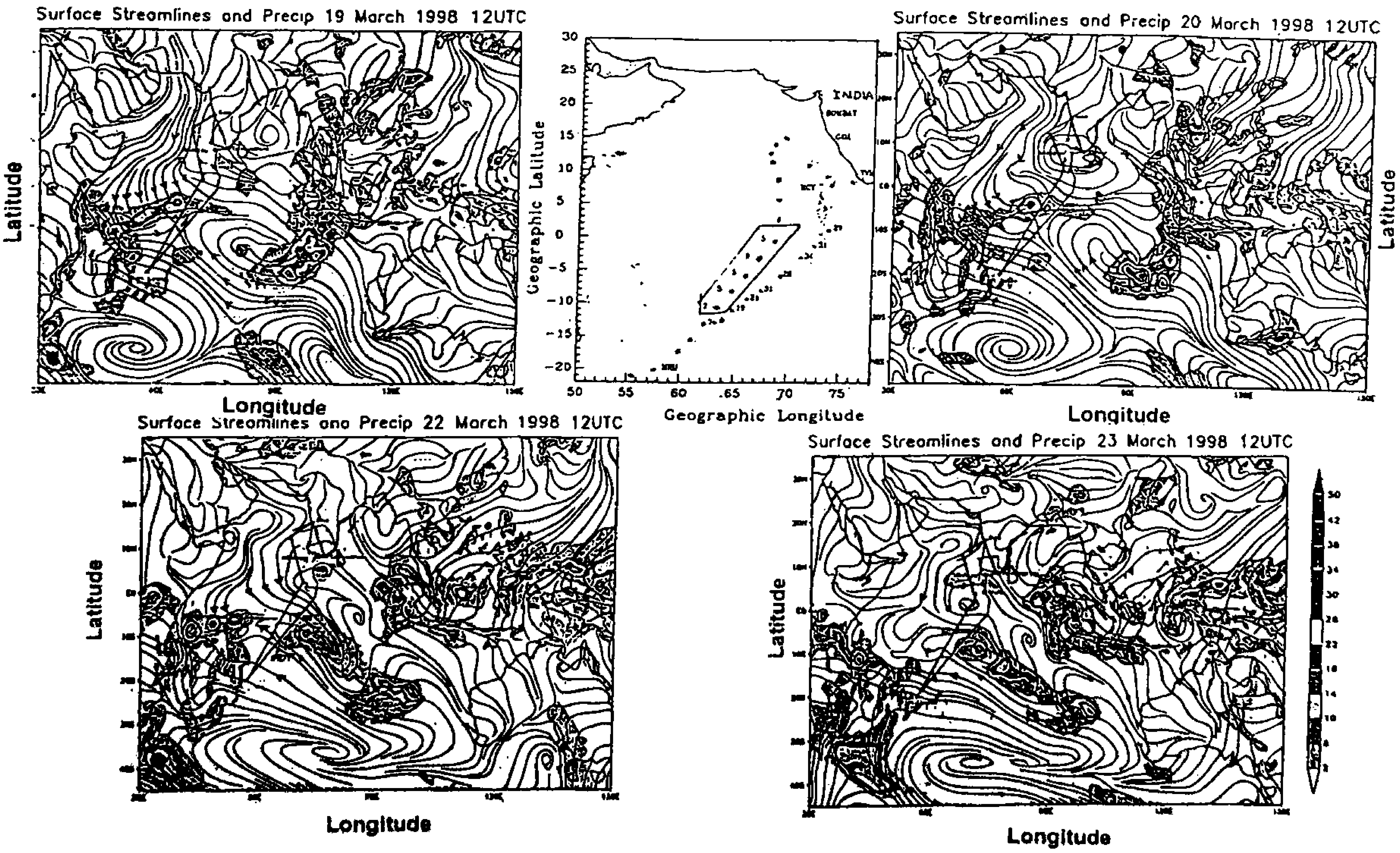


Figure 8. Surface streamlines and aerosol mass concentration in the far Indian Ocean region during the return voyage, associated with an oscillating ITCZ.

concentration is significantly higher than that near the Thiruvananthapuram coast during the starting phase of the cruise (Figure 4).

Comparison of columnar optical depth and mass loading

In addition to the HVS, a 10-channel solar radiometer helped study the spectral aerosol optical depths in the oceanic environment. The details of these studies are presented in by Krishna Moorthy *et al.*[9]. These results along with the earlier measurements[10] indicated an increased dominance of submicron particles near the coast. The aerosol optical depth in the shorter wavelengths showed a decrease with increasing distance from the coast. It is useful in this context to examine the association of the deck-level aerosol mass loading with aerosol optical depth. Figure 10 shows a mass plot of the aerosol optical depth (τ_a) at 0.5 μm wavelength (in which the contribution from submicron particles is quite significant) versus the deck-level mass loading at that location for different days for the cruise period. The mass plot shows a significant positive correlation (0.74), which is significant above 99% level of significance. The columnar optical depth can be estimated to be proportional to the mass loading ($\tau_a = bm$), the constant of proportionality being 0.005 $m^3/\mu g$, when m is expressed in $\mu g/m^3$. All along the cruise track the columnar aerosol optical depth is almost proportional to the deck-level mass loading (except for the deviations indicated by the scatter of points in Figure 10). This shows that the overall features and the association of deck-level mass loading with surface streamlines and dynamics are applicable for the aerosols in the entire column of the atmosphere. This is expected because significant contribution of τ_a comes from the first few kilometres of the atmosphere, and the surface mass loading is related to the integrated content in this region (as the active dispersion mechanism is the vertical convective diffusion).

Results and discussion

In connection with FFP 98 of the INDOEX programme a high volume sampler and a LPI have been operated on the

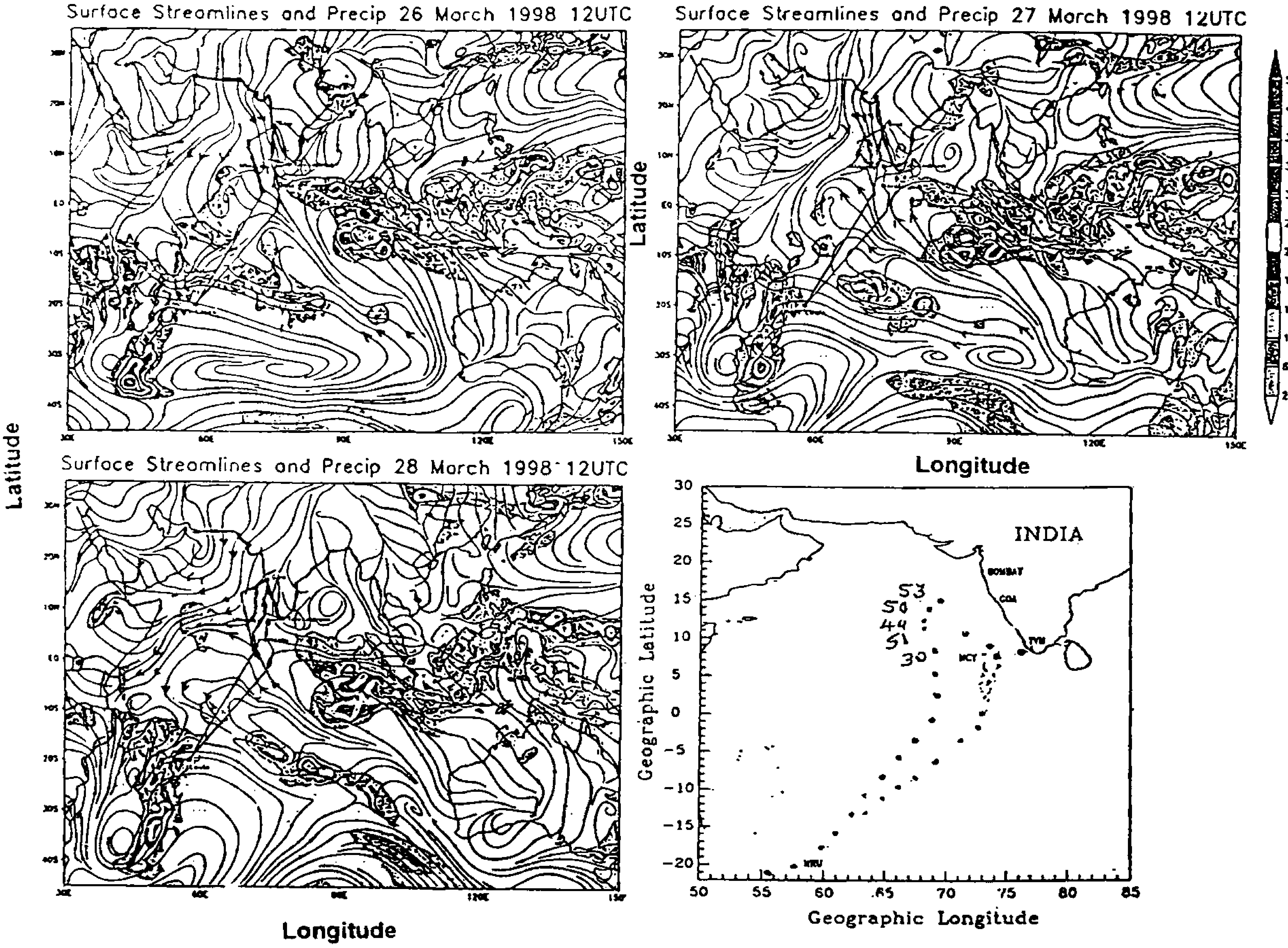


Figure 9. Surface streamlines and aerosol mass concentration in the middle Arabian Sea towards the end of the cruise.

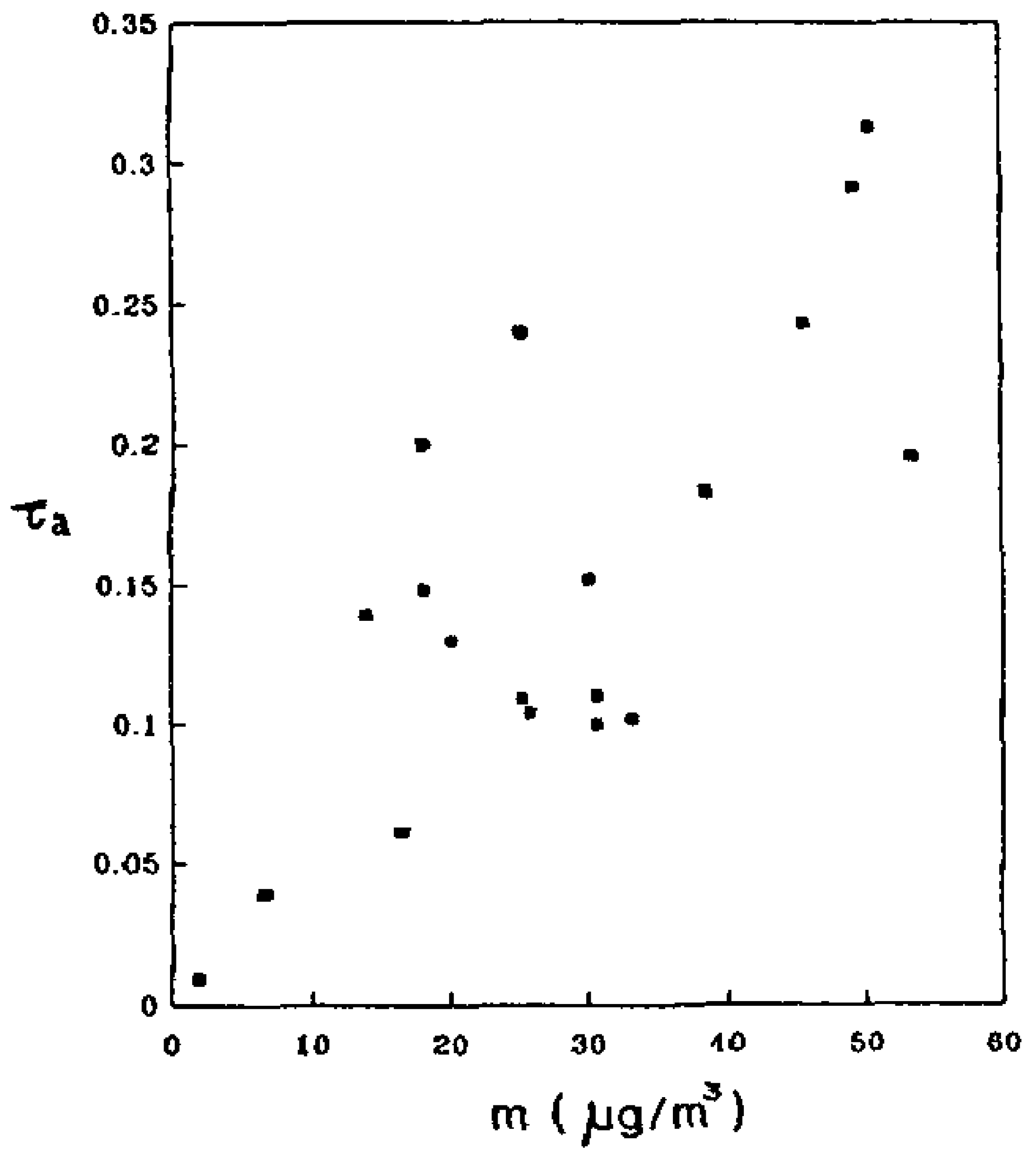


Figure 10. A mass plot of aerosol optical depth (at 0.5 µm) versus mass concentration measured during the cruise period.

surface at the coastal station Thiruvananthapuram as well as on the cruise. These measurements were conducted during the winter (January–February 1998) when the prevailing wind over the continent is north-easterly. Surface measurements showed that the mass concentration varies in the range 20–130 $\mu g/m^3$ depending on the wind direction. Average concentration which is ~ 35 $\mu g/m^3$ during the sea-breeze period increases by a factor of 2 to 3 during the land breeze period. Long-term averages including both day-time and night-time conditions, (obtained using the LPI) indicated a value of m in the range 110–130 $\mu g/m^3$.

Over the ocean, near the coast aerosol loading is ~ 25–40 $\mu g/m^3$. This is in agreement with the observed day-time concentrations at Thiruvananthapuram during the sea breeze period. Increased night-time concentrations observed over the coast can be confined to regions very close to the shore. The observations at Male from two different days having different wind directions have shown that the mass loading in 28 $\mu g/m^3$ when the prevailing surface wind is directed from the Indian coast (N–E). This decreases to 19 $\mu g/m^3$ when the wind direction changes to S–E. This indicates an increased concentration of aerosols in the northern hemispheric air compared to that in the southern hemispheric air. A decrease in aerosol concentration was observed near the ITCZ. A sharp decrease in m was observed within ITCZ. This can be mostly attributed to the increased vertical convection at the ITCC. The aerosol concentration south of ITCZ was less than that in the north. During the return voyage, the aerosol loading was significantly low in the latitude region 12°S to equator. This is attributed to the sweeping of a convective system and associated oscillation in ITCZ. North of equator the mass concentration steadily increases with increase in latitude. An increased concentration of aerosols observed in the central Arabian Sea (12–15°N) can be attributed to advection of arid aerosols from north. A significant positive correlation was observed between m and τ_a, indicating that these features are valid to a greater extent for the aerosol loading in the entire column of the atmosphere.

Ten-day back trajectories of air reaching the cruise track at different pressure levels in the far oceanic regions of the Indian Ocean, provided by Jha and Krishnamoorthi[5], show that near the surface (990 mb) the continental air from north advects up to ~ 12°S along the cruise track. South of this the southern hemispheric air from south and south-east (open sea) intercepts the cruise track. At higher altitudes (~ 850 mb) the air from east also intercepts the cruise track at both sides of the ITCZ. As a significant contribution of aerosol optical depth comes from lower altitudes, the spatial pattern seen in m and τ_a north of ITCZ is mainly contributed by air from north and north-east continents. During the down leg, south of Male, up to ITCZ (~ 5°S) advection of continental air from north and north-east is significant. South of ITCZ, the air reaching the cruise track mostly originates from open sea in the south-eastern parts. The aerosol loading in the southern hemispheric air (~ 15 $\mu g/m^3$) is ~ 50% less than that in the northern hemispheric air (~ 30 $\mu g/m^3$) advecting towards ITCZ. This extra amount of aerosols in the marine environment north of ITCZ would have been contributed by continental emissions.

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