

# Spatial distribution of meteorological parameters around 900 hPa level over the Arabian Sea and Indian Ocean regions during the IFP-99 of the INDOEX programme as revealed from the constant altitude balloon experiments conducted from Goa

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During the IFP-99 of the INDOEX programme, an Indo-French joint scientific team conducted 17 constant altitude balloon flights from Goa mainly to study the various features of the continental air mass flow from the Indian subcontinent towards the ITCZ induced by the NE winter circulation and thereby to derive the transportation of the continental aerosols and trace gases to the Indian Ocean regions. Out of the 17 flights, 15 were successful. Data obtained from the Constant Altitude Balloon Experiment are analysed to study the features of the wind fields and thermodynamic parameters of the marine boundary layer at ~900 hPa level over the oceanic regions adjoining west-coast of Peninsular India. From the balloon co-ordinates, the instantaneous vector wind as well as its zonal and meridional components are esti-

ated. Also estimated are the ambient air temperature and relative humidity at 30 min interval. These data are examined for the spatial features.

Mean wind showed presence of three broad flow channels, from India, Africa and West Asia, that are important in influencing the Arabian Sea environment and provide potential pathways for transport of continental pollutants. Variations associated with the MJO oscillations are present in the zonal wind, close to the equator. On several occasions wind showed occurrence of eddies with anticyclonic circulation having temporal scales of one to five days. Temperature and humidity structure showed large dry areas over the Arabian Sea associated with the flow channels. Rather humid regions occur over coastal India and near the ITCZ.

One of the main experiments of the IFP-99 of the INDOEX programme was the super-pressure constant altitude balloon flights from Goa (15.46°N, 73.83°E), aimed to investigate the trajectories of air mass originating from the Indian subcontinent and their advance across the ocean, towards the ITCZ.

These airmasses carry aerosols and trace gases from the continent to the oceanic environments, which are normally devoid of these and produce perturbations in the radiative forcing over the ocean<sup>1</sup>. The French constant level balloon experiments were designed for drifting the balloons in the lower layers and to monitor accurately the thermodynamic features of the boundary layer motions on a large horizontal scale 3D positions<sup>2-4</sup>. Goa station was proved feasible to con-

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duct such experiments as was demonstrated from the balloon flights carried out during the FFP-98 of the INDOEX programme<sup>5</sup>. During the IFP-99, 17 flights were conducted. The experiment was conducted jointly by the Indian Space Research Organization and the Laboratory for Dynamic Meteorology (LMD) of CNRS, France, which also designed the payload. The super-pressure balloons flown during the campaign serve as meteorological platforms capable of monitoring accurately the motion and other thermodynamic features (temperature, humidity) of the boundary layer on a large horizontal scale. The spatial distribution of meteorological parameters during the IFP is presented here.

## Balloon systems

The balloons are made of mylar with 10 micron thickness and are transparent with a quasi-spherical envelope of 2.5 m diameter. The constant level is maintained by keeping the balloon under over pressure with properly weighted ballast. Since the volume remains generally constant, the trajectories follow quasi-isopycnic surfaces. The balloon

contains 16 spindles with 2 caps at the poles. The scientific payload with thermodynamic sensors and equipments are assembled inside the balloon at the bottom pole to protect them from the adverse environmental conditions when the balloons descent in the lower regions. A schematic diagram of the payload system is shown in Figure 1. Figure 2 depicts a fully assembled balloon ready for flight. The sensors and equipment are kept in a hard paper box of 10 x 10 x 100 cm. Other descriptions of the balloon systems are given below.

Gas used for inflation	Helium
Ceiling altitude	~ 900 hPa
Differential pressure at ceiling level	100±5hPa
Wt of the gas required	1350±20g
Wt of the balloon	~3 kg
Wt of the payload	~3 kg
Operational life	Several days to a week
Electric power	Lithium batteries

The internal sensors assembled inside the payload bay include: (i) One pressure sensor and one differential pressure sensor working on piezoelectric principle (accuracy ± 1 hPa); (ii) One thermistor mounted on the pressure sensor to measure thermal corrections.

Two thermistors and one hygrometer sensors are mounted in a light arms of 30 cm long at 120° of one another along the balloon equator. Accuracy of temperatures and humidity are 0.5°C and 2.5% respectively. The payload equipments consists of (a) GPS receiver to measure 3D positions (accuracy ± 100 m); (b), Argos transmitter (401.65 MHz) with transmitting power of 2 Watt and (c) microprocessors for data acquisition. During the

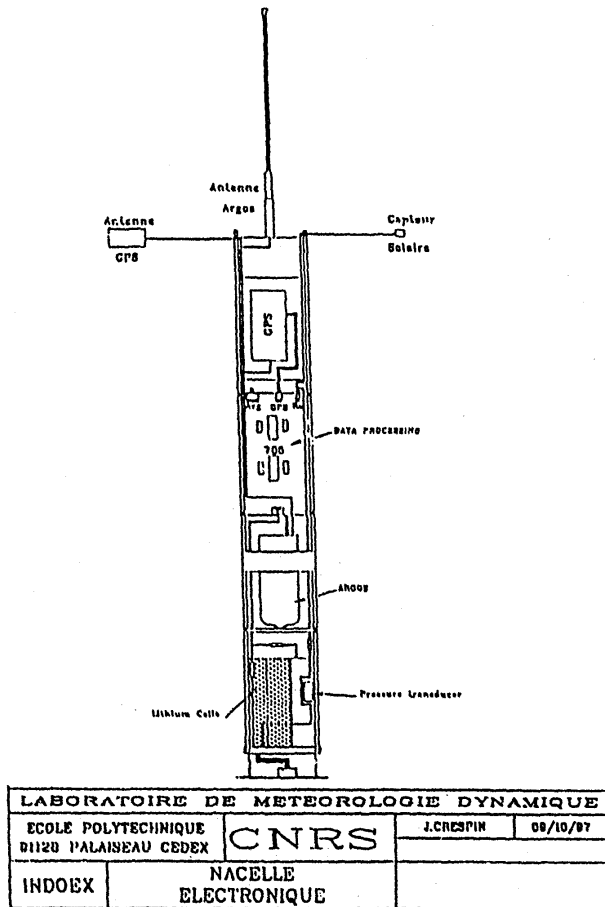


Figure 1. Schematic diagram of the payload system.



Figure 2. A fully assembled balloon ready for release.

Table 1. Balloon flight details

Launch details					Data lost			Data availability (Julian day)	
No	Date	Time	Nominal flight level (hPa)	Lifetime (days)	Date	Julian day	Location	Temperature (°C)	RH (%)
1	16 Jan.	0418	805	20	04 Feb.	35	4.4°N, 88.8°W	16-35	18-29
2	19 Jan.	0404	880	6	24 Jan.	24	2.2°S, 64.2°W	19-24	19-24
3	21 Jan.	0409	955	1					
4	22 Jan.	0404	940	5	26 Jan.	26	3.2°S, 77.7°W	22-25	22-24
5	26 Jan.	0410	960	5	31 Jan.	31	2.5°S, 73.2°W	26-31	-
6	27 Jan.	0410	920	10	05 Feb.	36	0.2°S, 89.2°W	27-34	27-33
7	07 Feb.	0410	910	8	16 Feb.	45	6.2°S, 64.2°W	38-44	38-44
8	07 Feb.	0530	890	4	10 Feb.	41	22.1°N, 75.3°E	38-40	38-40
9	12 Feb.	0430	910	9	20 Feb.	51	1.0°S, 59.5°W	43-50	43-50
10	13 Feb.	0404	940	10	21 Feb.	52	3.8°S, 71.4°W	44-47	43-46
11	15 Feb.	0410	920	9	23 Feb.	54	0.1°N, 71.8°W	46-54	45-54
12	19 Feb.	0400	960	4	22 Feb.	53	0.4°N, 65.6°W	50-52	-
13	20 Feb.	0405	930	4	23 Feb.	54	6.7°N, 61.7°W	51-54	51-54
14	21 Feb.	0402	940	10	02 Mar.	61	5.3°S, 38.0°W	52-57	51-56
15	23 Feb.	0400	940	6	28 Feb.	59	2.9°N, 59.5°W	54-59	54-59
16	25 Feb.	0405	930	7	04 Mar.	63	1.8°N, 48.3°W	56-63	-
17	28 Feb.	0415	930	11	10 Mar.	69	9.5°N, 49.1°W	59-68	59-68

flight, the position of the balloon and the thermodynamic data as measured by the sensors are sampled at 30 min intervals and transmitted at 401.65 MHz to Argos System on board NOAA satellites. The data are downloaded at the processing centre. The balloons fly at constant density levels and can provide a fairly good coverage of the vast area acting as pseudo-Lagrangian tracers of air parcels and as meteorological platforms in the marine boundary layer.

### The balloon campaign

The launch time was fixed at around 04.30 h before the peak of the land breeze so as to get the maximum benefit of drifting the balloon towards the sea in the desired path. Forecast trajectories obtained from three centers, viz. LMD, Paris based on ECMWF data; NCMWRF, New Delhi, and Florida State University, along with the routine radiosonde data from Goa Meteorological Observatory were systematically analysed for scheduling the balloon flights. The desired wind directions at the initial phase at the flying levels (~ 900 hPa) were Northerly to east-south Easterly. Balloons were released with the clearance from the ATC of Goa airport. The first balloon was launched on 16 January 1999 and the last on 28 February 1999. Totally 17 flights were conducted. Flight details are given in Table 1. The trajectories of all the flights are given in Figure 3. Flight no. 3 was short-lived probably due to leakage of gas. Flight no. 8 crossed the land area entangled in the local circulation. The average life of the balloons was around 7.5 days. The nominal flight pressure level was around 925 hPa except for the first flight which floated at higher level around 825 hPa. Hence totally data from 14 flights are obtained.



Figure 3. Trajectories of the 17 balloon flights.

### Data and method of analysis

Balloon positions were precisely obtained in all the flights from the GPS system but vertical positions were not accurate. Altitude informations were thus missed. But the height information was available from the pressure sensors after making corrections for offsets based on the ECMWF analysis when the balloons were drifting over the sea surface. Temperature data are generally good. The agreement between T1 and T2 was quite good with standard deviation of about 0.5 K. The hygrometric sensor was not shielded for isolation and hence the preliminary relative humidity data were corrected from the apparent relative humidity at the instrumental temperature. The meteorological data are corrected with the calibration coefficients of the relevant sensors. From the position coordinates of the balloon (provided at every 30 min by the GPS) the mean vector wind and its zonal and meridional

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components are estimated. The ambient temperature was estimated as the mean values given by the two temperature sensors and relative humidity (%) was obtained from the humidity sensor. The availability of the temperature and humidity data deduced from each flight are summarized in Table 1. These are used *TO* examine the basic nature of the air mass.

### Results and discussions

#### *Flight characteristics*

Out of the 17 balloon flights, flight no. 3 and flight no. 8 were considered failure because flight no. 3 was short-lived and flight no. 8 drifted over to Indian landmass. These are excluded from the present analysis. The trajectories of all other balloons are given in Figure 3 as a composite. It can be noticed that all the flights show the typical winter monsoon circulation prevailing over India and the Arabian Sea during the study period. In the first flight the balloon moved towards the southern coast of Africa and then crossed the equator and moved towards the south of Sri Lanka. In this flight, which was at a much higher altitude, the balloon took a loop around the African coast, near equator. In subsequent flights (e.g. nos 4, 5, 6 and 7) the movement of the balloons was due south. In the remaining flights (e.g. nos 13, 14, 15, 16 and 17) the movement of the balloons was gradually shifted towards west. These shifts in the mean trajectories are indicative of an oscillation in the zonal wind. This aspect was examined in detail by analysing the behaviour of  $u$  and  $v$  components of the wind as described in a subsequent section. The balloons were also subjected to noticeable diurnal oscillation within the tropical boundary layer. In almost all flights, the balloons underwent large vertical fluctuations in the levels towards end of the flight.

#### *Structure of mean wind: Different flow channels*

The spatial distribution of vector wind over the flight regions, combining all the flights, is shown in Figure 4. The wind vectors in the regions not traversed by the balloons are obtained through cubic interpolation. The most important observation is the presence of three organized flow patterns; (i) a flow from Indian subcontinent towards south, (ii) a flow from the West Asian region towards south, and (iii) a flow from African region towards north-east direction. These flow patterns show that the marine environment over the Arabian Sea and Indian Ocean north of the equator is influenced by combined effects of these air masses. Each of these air masses provides potential pathways for the transport of aerosols and trace gases of continental origin to the oceanic region. As these continental regions have distinct geographic features, different types and extent of anthropogenic, industrial and urban activities, the effluents also will have distinct physical and

chemical properties. All these get mixed (and perhaps accumulated) over the central Arabian Sea region and may result in complex optical effects. Similar observations of different air trajectories reaching over the Arabian Sea region (with their number varying within time scale of several days) have also been reported by Jha and Krishnamurti<sup>6,7</sup>. It may be recalled that based on spectral optical depths measurements using a multiwavelength solar radiometer on-board cruise #133 of INDOEX FFP, Moorthy *et al*<sup>8</sup> have reported enhanced levels of aerosol optical depths at 500 nm at Central Arabian Sea region (than over those seen near coastal Indian region). They also reported 5 to 10 times enhancement in the concentration of submicron aerosol concentration in these regions, associated with this increase in optical depth and attributed it to possible transport of aerosols from West Asian region. Using a highly resolved longitudinal scan of the north Arabian sea, immediately followed by a latitudinal scan of the Indian coastal region, Moorthy and Sana<sup>9</sup> have not only confirmed the above features but also reported that the mid-ocean enhancements are higher than the enhancements near the Indian coast. Similar enhancement in aerosol mass concentration (bulk sampling) and surface  $O_3$  concentration were also reported by other investigators too<sup>10,11</sup>, who attributed it to the air trajectories. The present observation of multiple flow patterns at 900 hPa level provides a direct experimental evidence to the occurrence of these pathways and their influence on the Arabian Sea environment.

#### *Long period oscillation in zonal wind*

Time variation of wind vector for different latitudinal regions derived from all flights is given in Figure 5. In Figure 5, the X-axis shows Julian day number and Y-axis the latitude. A careful examination shows a systematic change in the pattern of the wind in the zonal plane. This aspect was examined in detail by separating the wind into its zonal ( $u$ ) and meridional

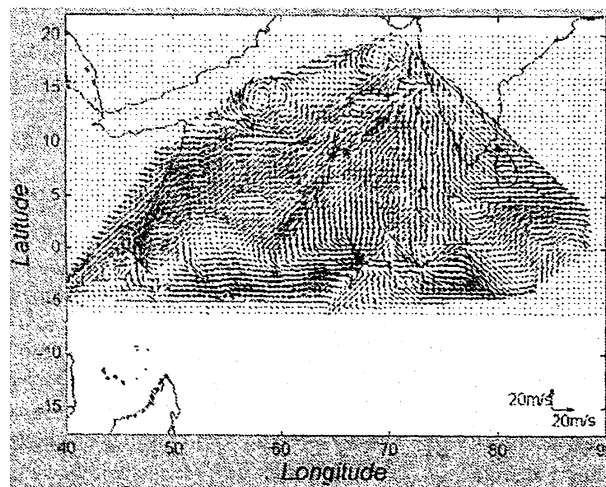


Figure 4. Spatial distribution of wind vectors of all the flights.

(v) components. The amplitude of the zonal wind component varied from + 13.0 m/s to - 14.6 m/s and that of meridional component varied from +12.0 m/s to 13.0 m/s. Figure 6 shows the time variation of these components (solid line representing the *u* component and dashed line the *v* component) for latitudes 4°, 5°, 6° and 7°N, where the ordinate shows the wind amplitude in m/s. Several periodicities are seen in both the components. Nevertheless, there is prominent one having a 30 to 40 day period in the *u* component. This period was observed right from the equator up to 12°N latitude; its amplitude being highest close to the equator decreasing towards higher latitudes. This periodicity was quite insignificant in the *v* component as evidenced by the dashed line in the figure. The oscillation in the zonal component is attributed the Madden Julian (MJ) Oscillation observed in the tropical region. It is the result of an eastward movement of large-scale circulation cells originating in the equatorial (zonal) plane<sup>12</sup>. Presence of similar oscillation in the zonal wind during monsoon season over tropical Indian Ocean has been reported earlier<sup>13</sup>. The zonal component of surface layer wind over continental India in the monsoon trough boundary layer region (at Lucknow) also shows this type of oscillations during the Indian monsoon season<sup>14</sup>. A number of studies relating to inter-seasonal variability of summer monsoon and Madden Julian oscillation are reported<sup>15-18</sup>. These oscillations in the zonal wind would also influence the continental impact felt over the Arabian Sea as it alters the relative dominance of different flow trajectories reaching the ocean (like the organized flow channels see in Figure 4). These flows, originating from distinct continental environments, carry region-specific aerosols and trace species along with them. Thus a change in their relative dominance over any given region over the sea will produce a corresponding temporal signature in its concentration and the general spatial pattern, with more concentration seen along the more favourable tracks. These oscillations being stronger close to the equator, such varia-

tions would become more apparent at latitudes close to equator. A more planned cruise experiment with finer latitudinal and longitudinal resolution over the Arabian Sea region (0 to 17°N and 55 to 75°E) will throw more light on these.

*Eddy motions*

Several balloons revealed occurrence of eddies of varying sizes over the ocean. A list of eddies, observed in different flights is given in Table 2 along with their approximate location and size. These are localized weak equatorial eddies often found near the equator<sup>3</sup>. These eddies show somewhat erratic behaviour. One big eddy (size of about 400 X 400 km) was observed in flight nos 1 and 17. A number of smaller eddies were also observed. The big eddy took 4-5 days to complete one loop whereas small eddies took less than a day to complete a loop.

*Geostrophic drag coefficient*

The part of the balloon trajectories where the flight level was rather constant (i.e. within 10hPa) was used to study the dynamics of the tropical boundary layer on large horizontal scale. Assuming the horizontal and vertical temperature gradients are negligible, for high wind conditions the geostrophic drag coefficient can be computed<sup>19</sup>. Winds along the flight trajectories where the flight level is rather steady and is around 900 hPa and above are used for this. The estimated geostrophic drag coefficient values are of the order of ~0.002.

*Spatial distribution of RH and temperature*

In order to examine the spatial variation of thermodynamic parameters, we combined the entire data (from 14 balloons)

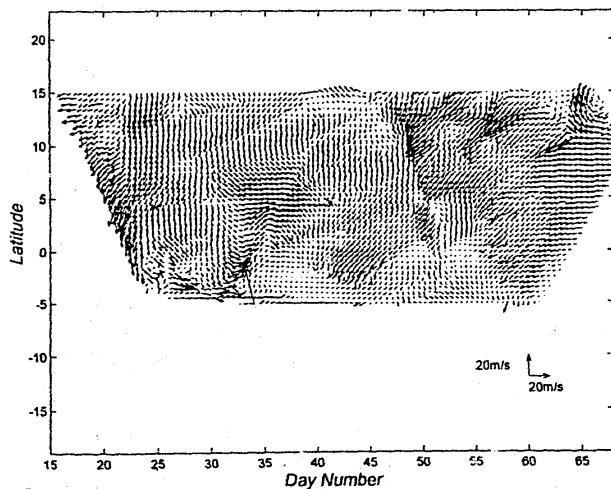


Figure 5. Spatial variation of mean wind with time

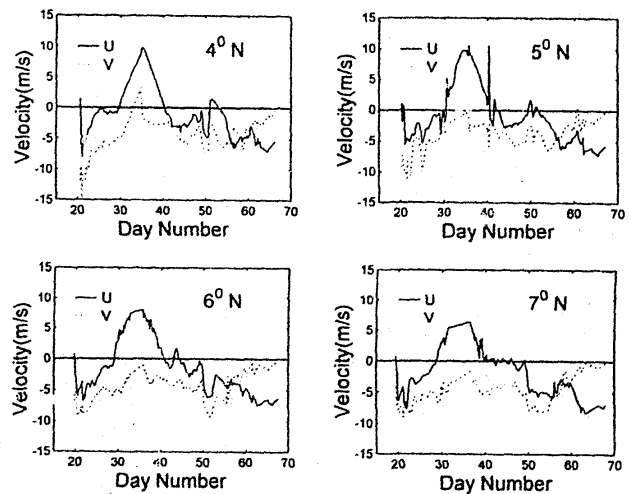


Figure 6. Time variation of *u* and *v* components of the wind showing MJ oscillations.

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to form a spatial array of the derived parameters and the average pattern over the study area covered by these balloons was examined at two distinct time windows; one in the day time and the other in the night time. In this case the data from flight number 1 also were not included because its floating altitude was considerably and consistently higher than that of all other balloons. The time windows have been judiciously selected because the ambient air temperature (T) and relative humidity (RH) will show diurnal variation and hence will have local time dependence. The balloons will be at different longitudes (different local time zones) on different days of

Table 2.

Flight no.	No. of eddies	Size	Duration and locations
1	5	1.400 x 400 km	5.5 days (0°-5°S, 44°-48°E)
	1 big and 4 small	2.60 x 150 km	
		3.20 x 40 km	
		4.10 x 5 km	
		5.10:: 2 km	
10	1 small	25 x 10 km	12-16°N; 56-60.5°E (3 to 5 clay)
11	J small	180 x 125 km	
15	1 small	200 x 90 km	
17	1 big	370 x 400 km	
	2 small	100 x 175 km	
		40 x 10 km	

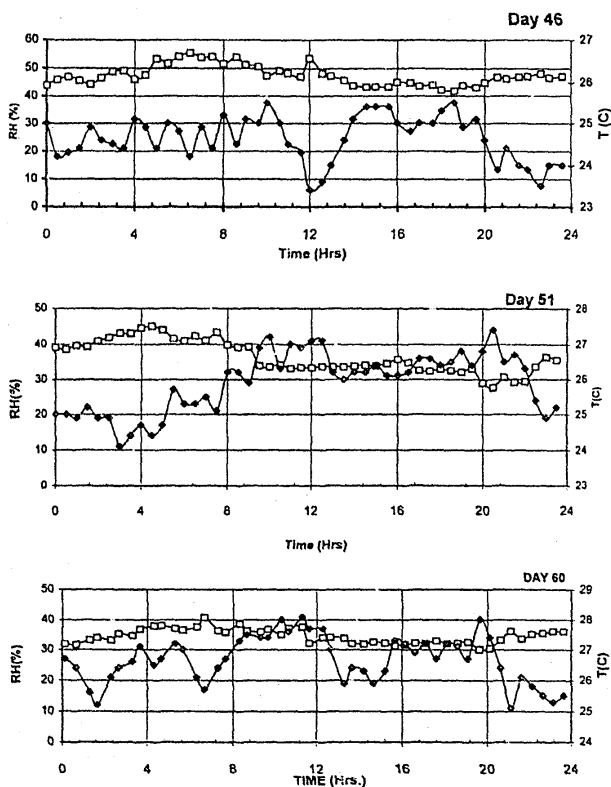


Figure 7. Typical diurnal variation of RH and T.

their life and the spatial data array, even at the same time (UT) of a day, will contain data obtained from different balloons that are floating at different longitudinal sectors. With a view to minimizing any deleterious effect of this on the inferred spatial pattern, we have selected the time windows to be centered around periods when the meteorological parameters (T and RH) show minimum temporal variation during their diurnal cycle.

Figure 7 shows the diurnal variation of RH and T on three different days as a typical example. In the figure, the line with dotted squares depicts the diurnal variation of RH while that with open squares that of temperature. The abscissa is time in UT. It is seen that even though the diurnal variation is significant microscopically, the variations are very small during the period 0800 to 1000 UT and 1730 to 2100 UT. Thus the mean value of RH and T obtained over a time window of  $\pm 1$  h width centered at 0900 UT and 1900 UT are considered fairly accurate enough to depict the spatial variation of RH and T during day and night respectively with minimum effects of the longitudinal difference of the positions of the different balloons. It is noticed that the maximum difference in the longitudes of different balloons in any day is  $< 20^\circ$  so that their local time can at most be off by  $\sim 80$  min. Thus

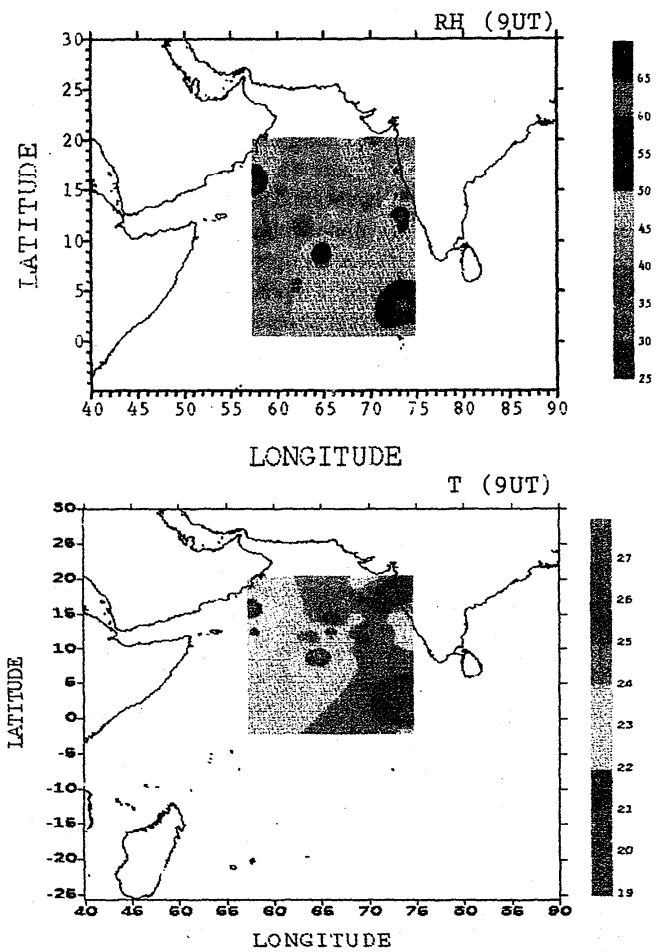


Figure 8. Spatial variation of RH (top) and T (bottom) at 900 hPa for 9 UT.

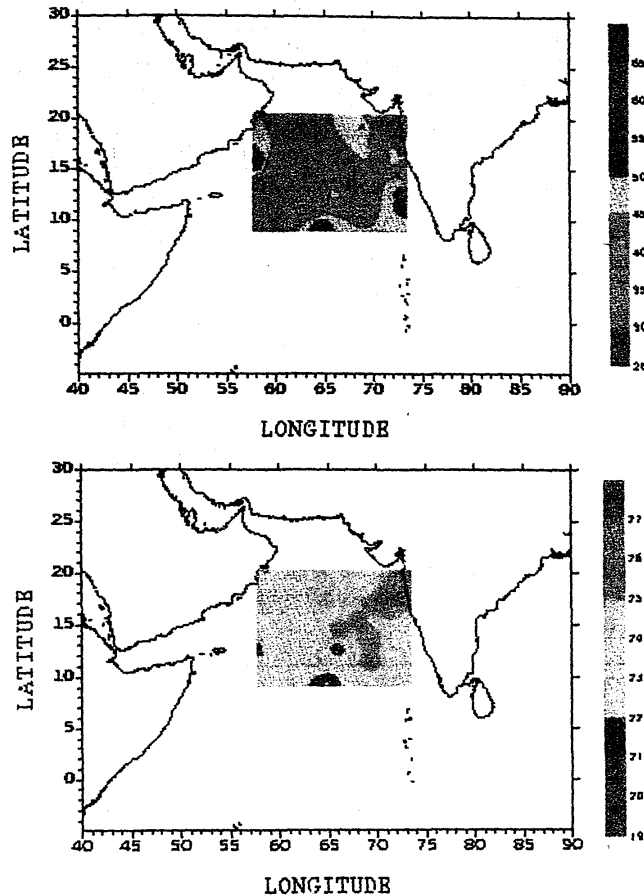


Figure 9. Same as Figure 8 but for 19 UT.

selecting a wide (~ 120 min) window centered at 0900 UT and 1900 UT will yield a fairly steady mean value.

The mean pattern of the spatial distribution of RH (%) and ambient T (°C) at ~ 900 hPa level for the 0900 UT time segment is shown in Figure 8 as contour levels in the latitude-longitude domain with RH at the top and T at the bottom. In evolving this pattern we have used only those values of RH & T obtained with in  $0900 \pm 1$  h UT and lying in the altitude range  $900 \pm 30$  hPa and the total altitude variation in the data in absolute terms being less than 100 m. Values, not satisfying any of the above conditions are rejected. Values between measurements are obtained by interpolation using a second order polynomial. Three relatively dry (RH < 45%) corridors are clearly discernible in Figure 8 (top panel), one extending from Indian coast, a second one apparently directed from the West Asian (Gulf) region and the third from the African region. These are clearly associated with the three organized flow channels seen in Figure 4. Viewed in the light of the above, the bottom panel of Figure 8 suggests that the channel from the Indian coast is the warmest while that from the African region is the coldest. The west Asian channel appears to lie in between. It is also seen that the low values of RH are not necessarily associated with cooler environment. All these show that the meteorological environment over the Central Arabian Sea is influenced significantly by all the

adjoining continents. Outside the dry corridors, RH increases both towards the Southern coast of India and down towards the equator. This is due to the increased convection as we approach the ITCZ, which was located centered ~ 4°S during the IFP period. This increased convection also gives rise to higher temperatures seen in the bottom panel.

The spatial distribution of RH and T during night (at 1900 UT), shown in Figure 9, also reveals essentially similar features except that the RH values are slightly higher everywhere. Relatively dry regions are seen associated with the three flow channels, and these meet over the Arabian Sea. It is quite interesting to note that it is over this region that Moorthy and Sana<sup>9</sup> also reported occurrence of enhanced optical depths, which they attribute to different air mass trajectories. They also show that the spatial variation columnar water vapour content deduced using a multiwavelength radiometer on board the IFP-99 cruise of the *Sagar Kanya*, also depicts high values centered around ( $\pm 5^\circ$  latitude) ITCZ and also over Indian Peninsula, with a rather dry environment over central and north Arabian Sea.

**Conclusions**

The constant altitude balloon experiment provided a unique and excellent opportunity to study the regional meteorology of the Arabian Sea and equatorial Indian Ocean, due West of India. The main findings of the study are:

1. There is an oscillation in the zonal wind with period in the range 30 to 40 days; which is insignificant in the meridional wind. This oscillation, associated with the MJ oscillation is stronger closer to the equator.
2. Vector wind pattern obtained from the balloon flights showed presence of three main organized flow patterns over the Arabian Sea; (i) from Indian coast, (ii) from the West Asian coast, and (iii) from the African coast. These flow patterns are generally consistent with air trajectory analysis results and are potential pathways for transporting aerosols and trace gases from the respective continents over to the ocean.
3. Thermodynamic parameters show existence of dry corridors associated with the above flow channels. The channels from Indian and the West Asian coasts are warmer than the African channel. This region signifies the influence of continental flow channels. A rather humid and warm environment was encountered along the West Coast of India and around the ITCZ.

The data obtained from the present experiment are unique for the Arabian Sea region with lot of potential to investigate the dynamics of the marine boundary layer. Further studies in this regard are underway.

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ACKNOWLEDGEMENTS. The Balloon Campaign could be successfully conducted only due to the whole hearted support received from Goa University; National Institute of Oceanography, Goa; IMD Office at Goa, and NCMRWF, New Delhi. Special thanks are due to Prof. B. S. Sonde, Vice-Chancellor, Goa University and Dr E. Desa, Director, NIO, Goa for establishing the launch facility at Goa. We also thank the INDOEX programme, sponsored by DOD, CSIR, DOE, DST and DOS as the nodal agency, under which the balloon experiments were successfully carried out. One of the authors K.S.A. thanks Shri. K. Narayana, Director, SHAR Centre and Shri. V. J. Thomas, Dy General Manager, TERLS for deputing him to the INDOEX Balloon Programme.