of the profile, and resistivity of above 100 Ωm in the elevated area which is not contaminated. Thus, this technique provides useful and interesting information about the polluted zone.

The imaging over the contaminated areas, although providing interesting information, can only be interpreted qualitatively. As discussed above, the interpretations are ambiguous and can only be improved with other control information from boreholes or chemical sampling. None of the five images measured across the contaminated sites show any strong lateral change in resistivity and it must be admitted that similar information could be obtained with resistivity sounding. A few soundings over the area can indicate likely sites for low resistivity regolith and heavy contamination.

The imaging technique has proved to be a powerful one in groundwater contamination studies. Electrical images provide a more detailed view of the sub-surface structure than can be obtained using other geophysical techniques and therefore lead to a better understanding of the local hydrogeology.

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Response of the Bay of Bengal to Gopalpur and Paradip super cyclones during 15–31 October 1999

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Response of the Bay of Bengal to two tropical cyclones, i.e. Gopalpur and Paradip super cyclones, during 15–31 October 1999, is studied using a stationary mooring buoy for marine meteorological observations. The National Institute of Ocean Technology (NIOT, Chennai) has deployed this buoy at 13°N, 87°E, by fixing various meteorological instruments and sensors to acquire sea surface temperature (SST), air temperature (Ta), wind speed (Ws), wind direction (Wd) and ocean currents (Cs) using remote sensing technique through INSAT-1D satellite at an interval of 3 h. The results of the analysis of the above parameters have shown clearly a response (SST difference between before and after formation) of about 0.7°C for the Gopalpur cyclone and 0.9°C for the Paradip cyclone. Ta has shown rapid variations following the rapid movement of cloud decks across the buoy during the cyclone period. The observed changes in the wind speed and direction are in concurrence with analysed mean sea level pressure oscillations. Finally, this study recommends more buoy-based marine meteorological observations over this region and the neighbouring areas, where the tropical cyclones generally occur and subsequently hit the Coromandal coast.

DURING the post-monsoon season in October 1999, two severe cyclones had formed over the Bay of Bengal with their centres at 13.8°N, 92.8°E (03 UTC 15 October) and 12.5°N, 98°E (12 UTC 25 October) respectively, during the period from 15 to 19 October and 25 to 31 October. Both these tropical cyclones moved in a north-westerly direction and crossed the Coromandal coast of India at Gopalpur and Paradip in sequence. The important features to be noted about these two cyclones are as follows. (1) The incipient development of the above two cyclones took place over an area where tropical cyclones rarely originated in October; the actual location is 10–13°N, 85–90°E (ref. 1). (2) These systems moved very fast over the ocean and slowed down just prior to the landfall. (3) Following slowness, these systems further intensified into very severe cyclones, with a core of hurricane winds. However, the second cyclone had become a super cyclone just prior to the landfall and stagnated over the coastal region for about two days. (4) Both these systems brought great disaster to the people of Orissa.

During the month of October, cyclones generally originate over an area between 10–15°N and 85–90°E (refs 1–3). These systems generally move in a west-north-westerly direction and cross Tamil Nadu–Andhra coast, but some systems occasionally recurve northwards near 13°N, 86.5°E and move in a north or north-easterly direction and hit the Bangladesh coast subsequently[3]. It is well known that the meteorological observations over the Bay of Bengal during the season of tropical cyclones are sparse and paucity of data persists. The main reason for this, obviously, is due to the disastrous conditions that prevail in the cyclone field and none dare to venture into it. Nevertheless, there are a few occasions where some observations in the cyclone field have been reported elsewhere[4,5]. These observations generally confine to a small period and area of opportunity.

In the present study, an opportunity has arisen to examine a case study of a couple of tropical cyclones in the Bay of Bengal using meteorological observations of a buoy, DS-3 (13°N, 87°E) deployed by the National

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Institute of Ocean Technology (NIOT), Chennai. This study aims to examine the variability of sea surface temperature (SST), air temperature (Ta), wind speed (Ws), wind direction (Wd), the surface ocean currents (Cs), in relation to the genesis, maintenance and motion of the above two tropical cyclones. This study also emphasizes the importance and need for more buoy observations surrounding the areas where the tropical cyclones generally form/originate. This study will enable us to understand the plausible reasons for formation of tropical cyclones.

NIOT had installed the mooring buoy by fixing sensors working on remote sensing techniques, for obtaining the meteorological observations. In the present study, we have used the foregoing parameters. The observations have been obtained at an interval of 3 h, after averaging a ten-minute interval data for one-hour period; the wind field and air temperature were observed at a height of 3 m above the sea surface. Whereas the currents and the bulk water temperature (bulk SST) were measured at a depth of three metres below the sea surface[6]. The accuracy and resolution of the SST sensor were respectively ± 0.1°C and 0.01°C. This implies precision of sensor and it can be read up to second decimal. The sampling duration and frequency were 10 min and 1 Hz respectively; the accuracy and resolution of the wind, air temperature and current sensors are shown in Table 1. Figure 1 shows the tracks of both the Gopalpur cyclone (southern track) and the Paradip cyclone (northern track). Table 2 shows the daily mean sea level pressure (hPa) distribution, which was visually picked up from IDWR (Indian daily weather reports) charts, at the buoy and in the centre of the cyclone (innermost isobar). Table 2 reveals that the pressure at the buoy is always higher than the central pressure of the cyclones. The pressure at the buoy varied from 1002 to 1012 hPa, whereas the central pressure of the Gopalpur cyclone varied from 1000 to 1008 hPa, the low pressure being observed when the cyclone became a very severe cyclonic storm on 17

Table 1. Buoy sensor specifications (NIOT). Sample duration and frequency of observation

Sensor	Make	Range	Accuracy	Resolution	Sampling duration/frequency
Air temperature	Omge Eng	10–50°C	± 0.1°C	0.01°C	10 min, 1 Hz
Wind* (speed, direction)	Lambrecht	0–60 m s^{-1}, 0–360	± 1.5%FS, ± 3.6°	0.07 m s^{-1}, 0.1°	10 min, 1 Hz
Water temperature**	NE Sensortec	– 5–45°C	± 0.1°C	0.01°C	10 min, 1 Hz
Surface current** (speed, direction)	NE Sensortec	0–6 m s^{-1}, 0–360°	± 3%FS, ± 2°	0.005 m s^{-1}, 0.36°	10 min, 1 Hz
Wave (full spectrum)	Seatex	± 20 m, 0–360°	± 10 cm, 5°	1 cm, < 0.1	17 min, 2 Hz

*Sensor was at 3 m above the sea surface; **Sensor was at 3 m depth below the sea surface; Sampling interval: Once in every 3 h.

Table 2. Daily mean sea level pressure (hPa) distribution at the buoy and in the centre of the Gopalpur and the Paradip cyclones picked up from the Indian daily weather reports at 03 UTC

Date	Latitude	Longitude	Stn. pressure	C. pressure	System
Gopalpur cyclone					
14.10.99	12.0°N	83.5°E	1010	1008	Low
15.10.99	13.5°N	92.5°E	1008	1008	D
16.10.99	16.0°N	88.5°E	1005	1002	CS
17.10.99	18.0°N	85.5°E	1006	1000	VSCS
18.10.99	20.5°N	85.5°E	1008	1000	VSCS
19.10.99	23.0°N	86.5°E	1008	1002	DD
Interim period					
22.10.99	–	–	1010	–	–
23.10.99	–	–	1012	–	–
24.10.99	–	–	1011	–	–
Paradip cyclone					
25.10.99	12.8°N	98°E	1012	1010	D
26.10.99	14.5°N	94°E	1008	1002	CS
27.10.99	16.0°N	92°E	1006	998	SCS
28.10.99	18.0°N	89°E	1006	996	VSCS
29.10.99	18.5°N	88°E	1008	1000	VSCS
30.10.99	20.5°N	86°E	1009	1002	Sup. CS
31.10.99	20.5°N	87°E	1008	1000	D

D, depression; DD, deep depression; CS, cyclonic storm; SCS, severe cyclonic storm; VSCS, very severe cyclonic storm; Sup. CS, super cyclonic storm (> 120 knots); Stn., station (buoy).

and 18 October 1999. The central pressure of the Paradip cyclone varied from 998 to 1002 hPa. The low value (998 hPa) corresponds to 27 and 28 October 1999, when the system was evolving from a cyclone to a severe cyclonic storm. However, the central pressure of the super cyclone of 30 October 1999 was only 1002 hPa, which is slightly higher than the central pressure of the severe cyclonic storm on 29 October 1999. The range of pressure gradient between the buoy and centre of the cyclones varied from zero to 10 hPa; zero value corresponds to 15 October 1999, 10 hPa corresponds to 27 and 29 October 1999. Figure 2 *a–d*) shows a typical example of the mean sea level pressure distribution and illustrates the way in which these systems transformed quickly from a cyclonic storm (16 and 27 October 1999) to very severe cyclonic storms (17 and 28 October 1999) when they were approaching the coastline. Figure 2 also illustrates the nature of change of the isobaric pattern at the buoy (circle with cross) following the north-westward translation of these systems.

The Gopalpur cyclone first organized as an incipient depression on 15 October 1999, 03 UTC and lay at 13.8°N, 92.8°E. During the same period (03 UTC), an intense low pressure area had also formed at the Tamil Nadu coast to the west of the buoy (Figure 3). A trough line which is passing through the buoy joins the above two low-pressure areas. The depression moved west-north-westward and lay at 14.2°N, 90°E by 12 UTC. It had intensified into a cyclonic storm, moved further north-westward and lay at 16.4°N, 88.8°E by 03 UTC on 16 October 1999 (Figure 2 *a*). It further developed into a severe cyclonic storm with a core of hurricane winds, translated north-westward rapidly and lay at 17.8°N, 87°E, 12 UTC on 16 October 1999. Subsequently, it had slackened in its speed and slowly translated further north-westward, lay at 18°N, 85.6°E by 03 UTC on 17 October 1999. Analysed synoptic charts of the mean sea level pressure distribution at the time of intensification and slow motion corresponding to 03 UTC on 16 and 17

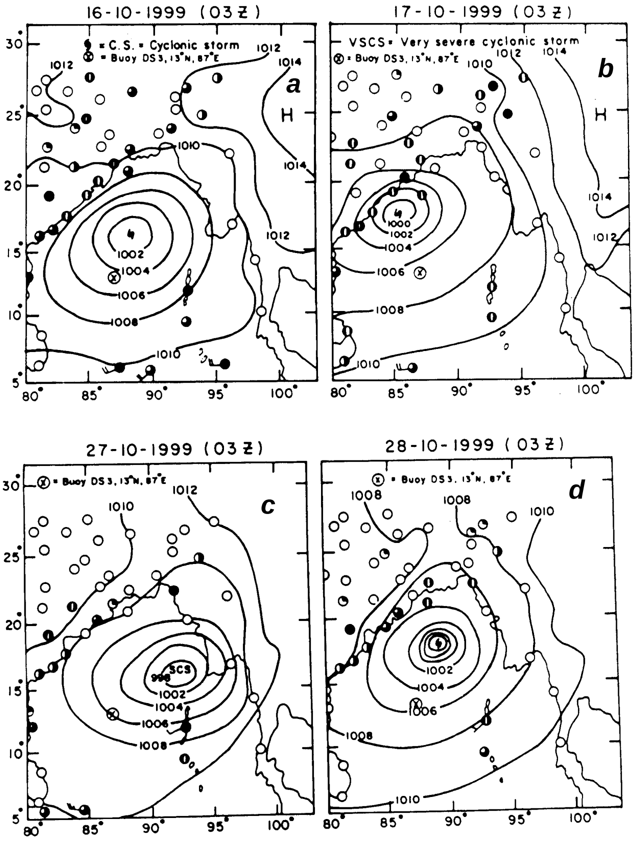

Figure 2. Charts of mean sea level pressure distribution on (***a***) 16 October 1999; (***b***) 17 October 1999; (***c***) 27 October 1999 and (***d***) 28 October 1999.

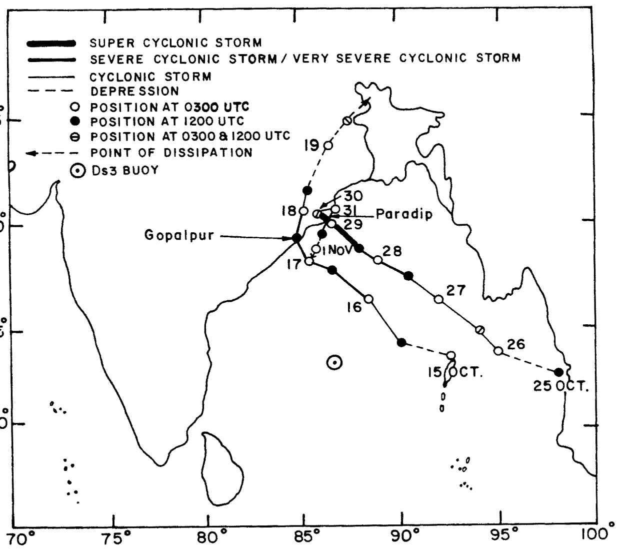

Figure 1. Tracks of severe and super cyclonic storms formed over the Bay of Bengal during 15–31 October 1999.

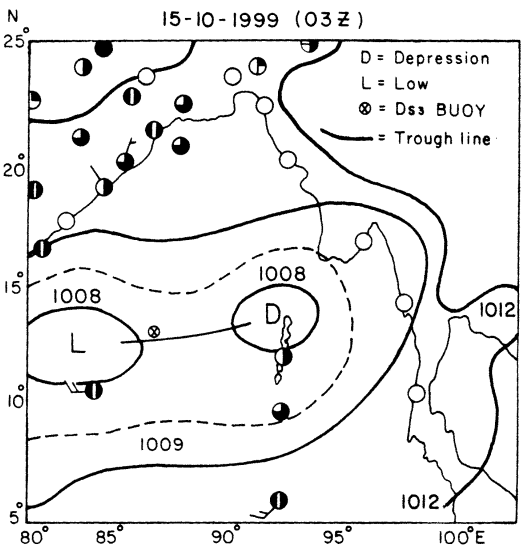

Figure 3. Chart of mean sea level pressure distribution on 15 October 1999.

October 1999 are respectively shown in Figure 2 *a* and *b*. The day-to-day fall in central pressure and the respective increasing number of innermost closed isobars show the intensity of the evolving system. The buoy position may be identified in Figure 3 at 13°N, 87°E (circle with cross). The impact of landfall was found to be close to Gopalpur, 19°N, 85°E at 12 UTC on 17 October 1999. It recurved northward and moved slowly with reducing intensity into a cyclonic storm on 18 October at 03 UTC and 12 UTC and became unimportant on 19 October 1999.

Similarly, the Paradip cyclone had originated as a depression at 12.8°N, 98°E at 12 UTC on 25 October 1999. It moved rapidly with the same intensity up to 14°N, 95°E and lays there until 03 UTC on 26 October 1999. By 12 UTC on the same day, it slowly translated northward and intensified into a cyclonic storm and lay at 14.8°N, 94°E. Having continued to translate north-westward rapidly, it had taken the positions respectively at 16.2°N, 92°E by 03 UTC and 17.5°N, 90.6°E by 12 UTC on 27 October 1999; at 18.1°N 89.1°E by 03 UTC and 18.9°N, 88.1°E by 12 UTC on 28 October 1999 (intensified into a severe cyclonic storm with a core of hurricane winds). Translating westward slowly between the latter two points, with the same intensity, it suddenly turned into a super cyclonic storm with wind speeds greater than 120 knots and crossed the coast near Paradip between 03 UTC and 12 UTC on 29 October 1999. It stagnated on the land between Paradip and Bhubaneshwar approximately at 20.8°N, 86.1°E, up to 30 October 1999 (03 and 12 UTC). Because of stagnation and intensification, this cyclone had caused heavy devastation over the region by killing several thousand people, cattle, fowl and damaging property worth crores of rupees. Figure 2 *c* and *d* show the analysed synoptic charts of the mean sea level pressure distribution at 03 UTC on 27 and 28 October 1999 respectively. The closed circular isobaric pattern shows the nature of intensity of the cyclone on these two days. Further, one can notice the buoy position (circle and cross) which lay on 1006 hPa on both the days with respect to the central pressures 998 hPa and 996 hPa respectively.

On 31 October 1999, the system weakened into a cyclonic storm and slowly moved eastward and lay near the coastline at 20.9°N, 86°E, by 03 UTC. It further recurved and moved slowly southward and lay at 19.6°N, 86.3°E, by 12 UTC on 31 October 1999, and at 18.9°N, 86°E by 03 UTC on 01 November 1999. Finally, it dissipated there in the sea near the coastline.

Figure 4 shows the three-hourly distribution of the buoy observations, SST, Ta, Ws, Wd, during the period from 03 UTC on 14 October 1999 to 21 UTC on 21 October 1999. The surface ocean currents were also analysed, but are not shown in the paper due to space constraints. The above observations show very typical variations in relation to the weather disturbance over the neighbourhood of the buoy in the Bay of Bengal (Figure 2). The initial observations just one day prior to the formation of the cyclone, i.e. at 03 UTC on 14 October 1999, showed a value of 29.5°C, 28.8°C, 4.5 m s^{-1}, 150°, true north in SST, Ta, Ws and Wd respectively. The corresponding current speed at this hour was 65 cm s^{-1}, with an eastward flow. The above parameters tend to fall between 03 UTC and 15 UTC, except SST during the period 03 to 06 UTC. The SST rose to 29.6°C during this period. At 15 UTC, the parameters read as follows: SST = 29.4°C, Ta = 28°C, Ws = 3.5 m s^{-1}, Wd = 130° true north and the current speed = 48 cm s^{-1} (120° true north). Thereafter typically, all the above parameters showed a raise, during night hours (15 UTC to 21 UTC), to their previous (03 UTC) values. 29.5°C, 28.8°C, 4.5 m s^{-1}, 60 cm s^{-1} in

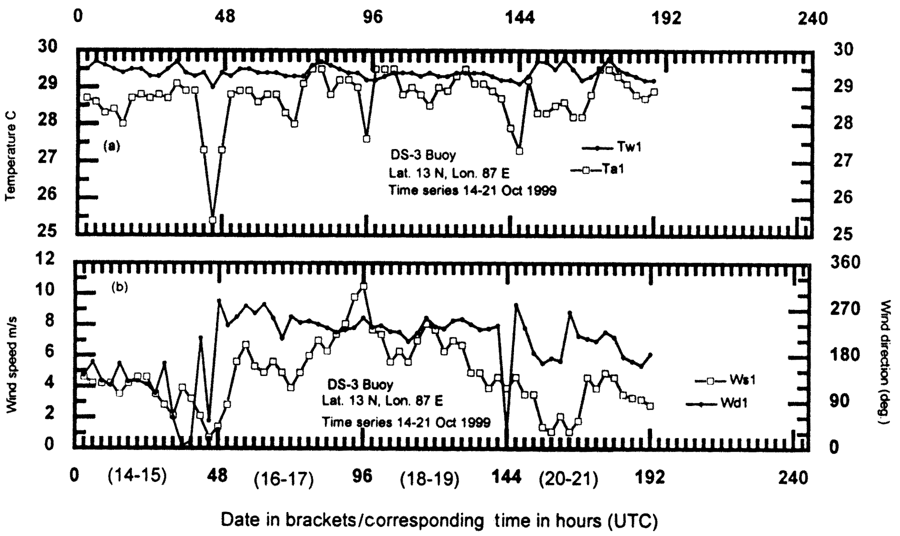

Figure 4. Time series distribution of (***a***) sea surface temperature (SST), air temperature (Ta) and (***b***) wind speed (Ws), wind direction (Wd) during the Gopalpur cyclone period 14–21 October 1999.

SST, Ta, Ws and current speed respectively. At this stage, the wind and the current directions were 120° and 90° true north respectively. During the incipient developing period (00 UTC to 03 UTC on 15 October 1999) of the depression (vide Figure 3), there was a sharp fall in SST, with the air temperature remaining the same. The reason for the sharp fluctuations between two observations, i.e. the rise and fall in SST by 0.1°C (within the accuracy of instrumental error), during 03 UTC to 15 UTC is not clearly known. However, one plausible reason for this type of fluctuation may be due to the horizontal transport of non uniformly mixing small-scale warm water eddies across the buoy. Further, at the time of formation (03 UTC, 15 October 1999) the SST showed a lowest value of 29.3°C, Ta was 28.8°C, the wind and current speeds and direction respectively were 3.2 m s^{-1} (120°) and 55 cm s^{-1} (90°). Following the west-north-westward movement of the system, by 09 UTC on 15 October 1999, all the parameters appeared to have reorganized; current speed increased to 80 cm s^{-1}, SST and Ta respectively increased to 29.7°C (0.4°C increase) and 29.1°C (0.3°C increase). But the wind speed had reduced to 2 m s^{-1} due to the existing trough line near the buoy (Figure 3). The above discussion indicates that the wind field and currents appear to have fluctuated rapidly following variations in the surface pressure field during the organizing phase of the cyclone. At this juncture, the wind field had come down to 2 m s^{-1}, the current speed increased to 80 m s^{-1}, at 09 UTC on 15 October 1999. It is generally believed that the wind field immediately above the ocean surface under homogenous condition, controls the surface currents. But during recent studies, Krauss and Businger[6] and Bye[7] have revealed that the surface currents can be generated by direct wind stress, as in the classical Ekman model and the Stokes drift, derived from the surface wave motions, under sudden and pronounced wind changes. However the changes that occur in the current speed are independent of wind speed as noted in this study. These values appear to be very typical of the time of observation, which may occur by warming due to solar heating in the field of the trough. In the trough line, the weather is typically cloud-free and paves a way to strong insolation. This insolation eventually warms the surface water layer and the neighbouring atmospheric air column rapidly and tends to increase the SST and Ta. By 12 UTC, when the system had come close to the buoy at 14.2°N, 90°E, SST, Ta and current speed decreased, while the wind speed increased from 2 to 4 m s^{-1}, implying rapid intensification of the system. The SST, Ta and Ws had further fallen rapidly to 29°C, 25.4°C and 0.5 m s^{-1} respectively, by 21 UTC on 15 October 1999 (Figures 1 and 4). When we compare Figures 2 *a* and 3, one may infer that two closed low-pressure systems were present on either side of the buoy at 03 UTC on 15 October and an intense pressure system was present at 03 UTC on 15 October 1999 to the north-east of the buoy. This implies that there was a rapid change in the surface pressure pattern in the area of study after 03 UTC, 15 October and 03 UTC, 16 October 1999. This type of reorganization in the pressure pattern during the above period (e.g. 15 UTC to 21 UTC, 15 October 1999) might have affected the changes in the meteorological fields, as we have seen above. However the currents seemed to increase continuously (71–81 cm s^{-1}) with a rapid change in the direction 90–110° true north. The observed rapid fall of SST (29°C) and air temperature (25.4°C) is expected to be due to the occurrence of rainfall and cold downdrafts associated with the convective cloud decks moving across the area into the cyclone centre. The SST and air temperature restored to their preformative stage values (29.4°C and 28.8°C), the Ws had rapidly increased to a value of 5.8 m s^{-1} with a sudden change in direction, clockwise from 30 to 270° and remained around 270° true north, the current speed 85 cm s^{-1} (and no change in the direction) by 03 UTC on 16 October 1999, when the system moved to the new position at 16.4°N and 88.8°E (Figure 2 *a*). In Figure 2 *a*, the buoy position is located (circle with cross) in the south-west sector of the cyclone and between the two parallel isobars 1004 and1006 hPa. This type of isobaric pattern envisages a wind direction of 270°, keeping the pressure gradient northward into the centre of the system due to 'Buys Ballot's law'. During the rest of the period from 03 UTC, 16 October to 21 UTC, 21 October 1999, the SST undulated between 29 and 29.8°C, and the air temperature between 27.3 and 29.5°C. The currents showed two peak values, 87 cm s^{-1} and 92 cm s^{-1} (current direction nearly same) respectively, corresponding to 12 UTC, 16 October and 21 UTC, 18 October 1999, with a minimum value of 65 cm s^{-1} at 18 UTC, 17 October 1999. The reason for this rapid change in the above parameters may be due to the rapid change in the development of the low pressure system from 15 to 17 October 1999, as revealed by the Figures 2 *a* and *b*. There was a rapid fall in the current speed between 21 UTC, 18 October (92 cm s^{-1}) and 21 UTC, 20 October 1999 (36 cm s^{-1}), with a sharp undulation between them. The peak current values coincided with the weak winds, which implies an opposite trend in both these parameters during this period. During the period of landfall from 03 UTC, 17 October to 03 UTC, 18 October 1999 by which period the cyclone became a very severe cyclone of intensity T-5, the wind speed showed a rapid increase from 6 to 11 m s^{-1}, with constant direction 240° (this phenomenon is consistent with the observed pressure pattern; Figure 2). The current speed reduced with a slight change in direction 90–110° true north, the SST reduced again from 29.7 to 29.2°C, and the air temperature from 29.5 to 27.6°C. All these changes in the above parameters may be attributed to the eventual changes in the low pressure system.

Figure 5 shows the distribution of SST, Ta, Ws and Wd during the period from 03 UTC, 22 October to 21 UTC, 31 October 1999 when the Paradip cyclone occurred (see

Figure 1). It is seen from Figure 5 that both the SST and Ta have shown large fluctuations during the first three days (22–24 October 1999) before formation of the second system, observed to be a transition period between the first and second system. The observed undulations/fluctuations in SST and Ta may be attributed to the fluctuations in weather (bad and fair) conditions, due to the sporadic movement of cloud decks across the study area from time to time. The clouds generally propagate in random and non-uniform modes; sometimes they shade the sun, sometimes they do not. Bradley *et al.*[8] also observed similar features in the Atlantic trade-wind belt. This type of random motion in the cloud decks might have caused the undulations in the SST and Ta.

At 18 UTC on 22 October 1999, SST, Ta and Ws showed low values of 29°C, 26.3°C and 2 m s^{-1} respectively. The reason may be due to both nocturnal cooling of sea surface response due to earlier severe cyclone and ongoing bad weather. Following this, Ta and Ws increased with a change in wind direction, rapidly in next three hours. These parameters may have undergone undulations due to rapid movements of cloud decks. Subsequently, the SST remained constant (29°C) during the next three hours. The surface currents had also responded very quickly, undergoing changes. Further, it is seen from Figure 5 *a*, that during the period 00 UTC, 23 October to 12 UTC, 25 October 1999 (when a depression had formed), the SST showed a systematic diurnal oscillation, keeping daytime sea surface warming and nocturnal cooling. During this period, the wind speed remained below 3 m s^{-1} with a variable wind direction and Ta also followed these undulations. This implies the existence of a high pressure area (1010–1012 hPa) near the buoy (Table 2). The observed SST was 29.9°C, Ta was 28.8°C and Ws was 3 m s^{-1}, 330° true north at the time of formation at 12 UTC, 25 October 1999. The corresponding current speed was 40 cm s^{-1}, 150° true north. The rapid increase in SST and Ta during this hour compared to those observed during the previous days seems to have occurred in the high-pressure area surrounding the buoy, where clouds are generally sparse and more radiation is received at the surface. Following the north-westward movement of the depression from 12 UTC, 25 October to 15 UTC, 29 October 1999, during which period the cyclone had undergone different stages of development (from a depression to severe cyclone, Figures 1, 2 *c* and *d*), the SST appeared to have fallen continuously from 29.9 to 29°C, with an observed response of 0.9°C. During this period, the air temperature showed rapid undulations with a minimum value of 26.8 and 27.5°C respectively at 12 UTC, 26 October and 03 UTC, 29 October 1999, and a high value of 29.8°C at 06 UTC, 27 October 1999. The corresponding wind speed showed a gradual increase from 3 to 8 m s^{-1} up to 12 UTC, 28 October 1999, with constant wind direction which remains more or less steady (325° true north). This feature seems to be consistent with the on-going pressure changes in this area (Figure 2 *c* and *d*). During a short period of time between 12 and 21 UTC, 28 October 1999, the wind speed suddenly raised to 10–11 m s^{-1}, during which period the cyclone had developed from a severe cyclone to super cyclone close to the Paradip coast immediately following the landfall. There was sudden decrease in wind speed up to 7 m s^{-1} by 03 UTC, 29 October 1999, following the landfall. These changes may be attributed to the changes in horizontal pressure gradients near the buoy (Figure 2 *c* and *d*). Subsequently the wind speed gradually raised to about 9–10 m s^{-1} and remained constant from 12 UTC, 30 October 1999 with a constant wind direction around 230°, following the recurvature of the system towards the south, near the coast (Figure 1).

In order to examine the energy (sensible and latent heat) exchange processes at the air–sea interface, some computations have been made using the SST, Ta and wind

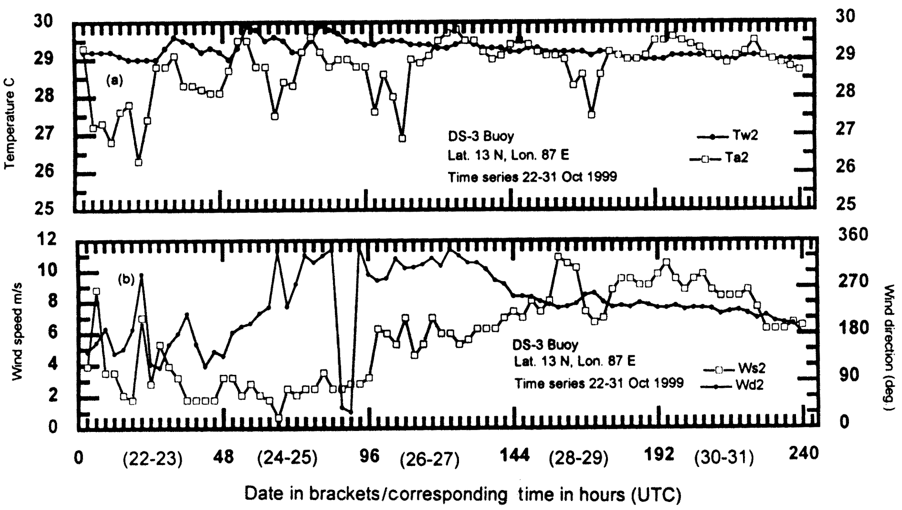

Figure 5. Same as Figure 4, but for the Paradip super cyclone period, 22–31 October 1999.

field with a bulk aerodynamic method suggested by Hsu. We have first calculated sensible heat flux using,

$$Q_H = rC_pC_T(T_{sea}–T_{air})U_{10}, \quad (1)$$

where *r* the density of air = $1.23*10^3$ kg m^{-3}, C_p specific heat capacity at constant pressure = 1005 J m^{-2} s^{-1} and C_T the sensible heat coefficient = $1.45*10^{-3}$.

Then we have computed Bowen's ratio,

$$B = 0.146(T_{sea}–T_{air})^{0.98}. \quad (2)$$

Knowing Q_H and *B*, the latent heat flux (Q_E) is calculated using the ratio,

$$Q_E = Q_H/B, \quad (3)$$

The *U* and *V* components and the momentum flux ($t = rC_dU_{10}$) have also been computed to understand the variability of the wind components and the transfer of momentum at the air–sea interface near the buoy during different stages of development of the above cyclones. In this study, we take $C_T = C_d$ assuming neutral conditions of the atmosphere. In the present case, since the humidity measurements are not made at the buoy, we followed the procedure suggested by Hsu[9] to calculate the Bowen's ratio for unstable conditions and then computed Q_E. The error obtained due to this method is only 10% from the direct computation of Q_E. Further, the wind speed (U_3) is observed at 3 m height from the sea level; however, we assumed, $U_{10} = U_3$, as the wind speed does not change with height in the surface layer due to well mixing in the cyclone field.

Figures 6 and 7 show the distribution of *U* and *V* components, DT (SST – Ta), Q_H, BR, *t*, and Q_E (for unstable conditions) during both the cyclones. From Figure 6 *a*, both the *U* (westerly-positive) and *V* (southerly-positive) components show opposite trends (U^-, V^+) initially, before formation of the depression. They tend to alter the sign at the time of formation with a lull. Following the formation, the *U*-component becomes positive and increases rapidly following the rapid development of the system into a severe cyclone (Figure 1). The corresponding *V*-component slackened for some time and followed the speed of *U*-component up to 21 UTC, 17 October 1999. There was again a sudden lull in both the components at 00 UTC on 18 and 20 October 1999 tends to become zero and

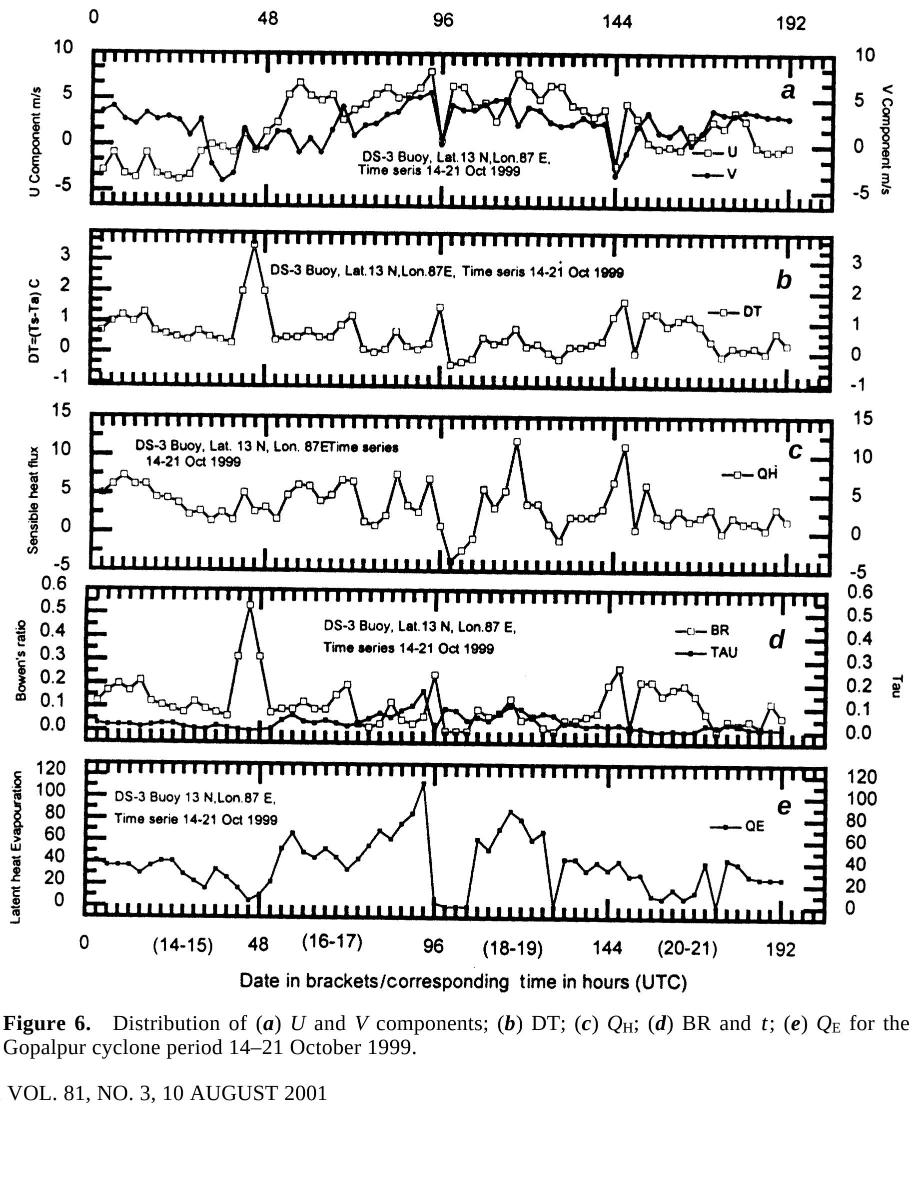

Figure 6. Distribution of (***a***) *U* and *V* components; (***b***) DT; (***c***) Q_H; (***d***) BR and *t*; (***e***) Q_E for the Gopalpur cyclone period 14–21 October 1999.

-4 m s^{-1} respectively. The above period corresponds to landfall of the cyclone. The highest values of U and V, 7.5 and 5 m s^{-1} respectively, observed at 21 UTC, 17 October 1999, coincided with the landfall of the cyclone with a core of hurricane winds (Figure 2 *b*). Figure 6 *b* shows the air–sea temperature difference, DT. The observed highest value was 3.2°C, which corresponds to lowest air temperature observed (Figure 5 *a*) at 21 UTC, 15 October 1999. Thereafter DT varied from –0.4 to 1.4°C during the period of progression of the cyclone. The Q_H varied from – 5 to + 10 W m^{-2}; the highest value corresponds to the strong U-component (due to a gusty wind), which in turn corresponds to dissipating stage of cyclone at 21 UTC, 18 October 1999. During the period of development from 03 UTC, 16 October to 21 UTC, 17 October 1999 (Figure 2 *a* and *b*), Q_E increased gradually to a value of 110 W m^{-2}. However, in general, Q_E varied around 40 W m^{-2}. The Bowen's ratio showed a highest value of 0.5, which corresponds to a high value of DT (3°C) on 15 October 1999. This value coincided with lowest air temperature, that occurred under bad weather condition as explained above. During the remaining period of observation, Bowen's ratio varied from 0 to 2.5. The t varied from 0.01 to 0.1 N m^2 (Figure 6 *d*).

Figure 7 *a*, shows the distributions of U and V components for the Paradip cyclone. In this case also, the above parameters show an opposite trend prior to cyclone formation, with a lull at the time of formation. Thereafter, they again exhibited the opposite trend in the distribution. During 26–28 October 1999 when the cyclone intensified from a depression to a very severe cyclone, absolute values of both the wind components increased very rapidly (6 m s^{-1}). DT appeared to vary between – 0.5 and 2.5°C. These changes in DT may be attributed to both diurnal variations of SST and the sporadic changes in Ta due to the convective activity in the cyclone-affected area. Q_H generally showed very low values (± 5 W m^{-2}) except during the initial period of formation on 22–23 October and at the time of intensification on 26 October 1999. Q_H showed high values of 20–30 W m^{-2} during these two periods. The increase in Bowen's ratio during this period was followed by an increase in DT, which varied from 0 to 0.4. t showed low values at the beginning, 22–25 October 1999 corresponding to the lowest wind speed

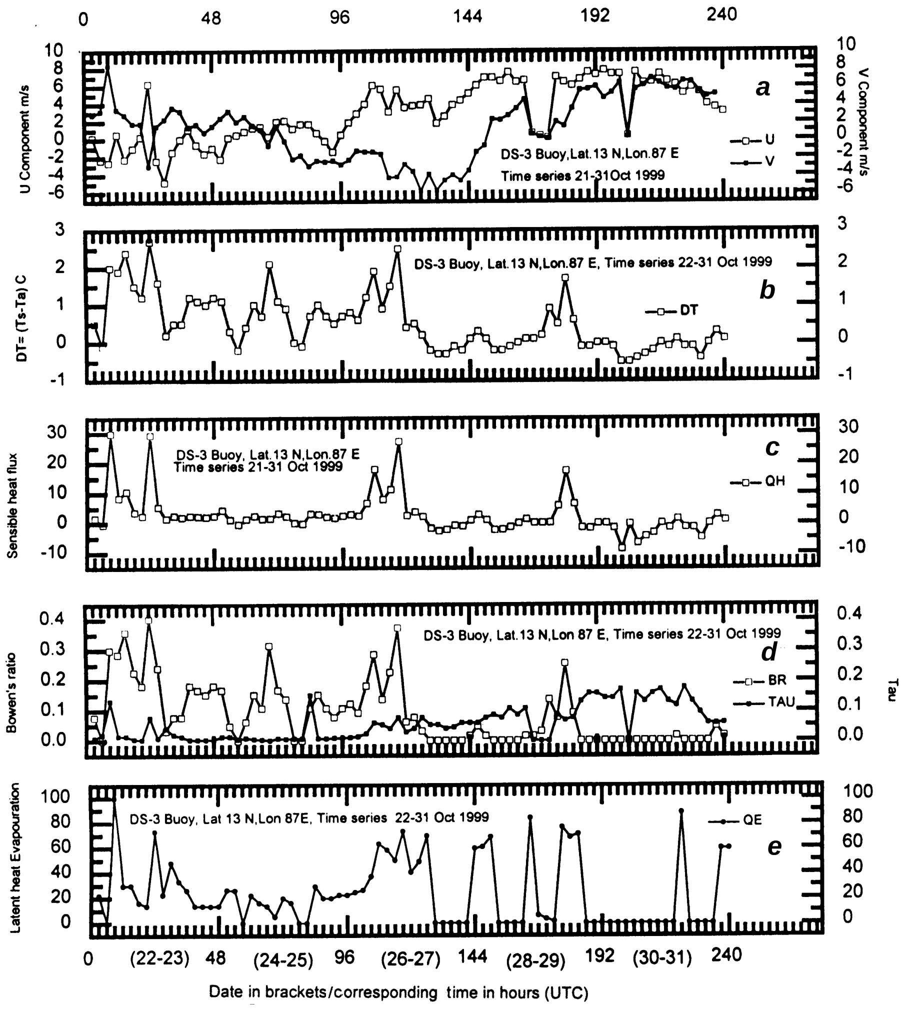

Figure 7. Same as Figure 6, but for the Paradip cyclone period 22–31 October 1999.

(< 4 m s^{-1}), It increased following an increase in wind speed, due to intensification of the cyclonic storm between 26 and 31 October 1999. High values (0.15 N m^{-2}) were observed between 30 and 31 October, during which period recurvature of the cyclone was noted (Figure 1 and Figures 1 and 7 *d*). Q_E varied from 20 to 100 W m^{-2}. The fluctuations in Q_E were independent of the development of the cyclone.

It is interesting to note from Figures 6 *a*, *d* and 5 *a*, *d* that the Bowen's ratio seems to have shown relatively high values during low wind speed conditions (< 4 m s^{-1}), which correspond to initial stage of formation, compared to the values obtained during the high wind speed conditions (> 4 m s^{-1}) during developing stages of both tropical cyclones. In contrast to this, the *t* showed very low values during the initial stages and relatively high values during developing stages of the cyclones. This implies that the turbulent transport of sensible heat due to buoyancy dominated over that of mechanical mixing[8,10]. It has been reported[10] that during light wind conditions, the two effects become important as turbulent transport due to buoyancy which dominates over that due to mechanical mixing, and the sea surface becomes quite smooth, so that molecular and viscous transport become important.

In the present study the SST was recorded at a depth of 3 m, which is also a level of current meter observations. In this case, the SST may be called as a bulk SST, which slightly differs from that of the surface water film temperature. During disturbed weather conditions due to cyclones and consequent transport of cloud clusters across the region, the sea surface film cools slightly from that of the bulk SST, but under clear sky and low wind conditions, the sea surface rapidly warms up due to intense solar radiations during daytime. Therefore the surface film temperature becomes higher than the bulk SST. Due to the disparity in the above observation there will be slight variation in the sensible heat flux[10]. According to the climatological atlas of the Indian ocean[11], the values of the SST, Ta, Ws, Wd, Q_H, Q_E, at the buoy are respectively, 28°C, 23°C (+5°C), 5 m s^{-1}, 45° true north, 0, 5 W m^{-2}. A close similarity was seen on comparison of the above climatological values with those observed in the present study with the exception of some anomalies during disturbed conditions. The observed mean SST was about 1°C higher than the climatological value.

A close examination of the response (cooling of the surface waters) of the ocean at the buoy to the above two north-westward translating tropical cyclones (Figures 1 and 2) has revealed that the response is about 0.7°C due to the first system and 0.9°C due the second system. The above values seem to be very low compared to those observed by Price[12] and Seetaramayya and Master[5]. Price observed a decrease of 2°C at a depth of 2 m from the surface as the hurricane Eloies passed over the EB-10 buoy in the Gulf of Mexico, whereas Seetaramayya and Master[5] observed a decrease of 1°C at the surface, immediately after passage of the onset vortex close to the observing ship (*ORV Gavashini*) in the eastern Arabian Sea during Monex 1979. The intensity of response, perhaps, depends on the proximity of the observing station from the centre of the cyclone. It is further observed in the present study that the ocean currents (at 3 m depth) seems to have shown an opposite trend to that of the wind speed following the cyclone intensification. However, a model simulation of a hurricane by Chang and Anthes[13] has shown that there is an increase in current speed with a corresponding increase in wind speed close to the hurricane centre. The plausible reason for the observed opposite trends in the currents and wind speeds over the Bay of Bengal is not yet known. Nevertheless, two classical reasons, Ekman model and Stokes drift, under sudden and pronounced wind conditions are a plausible explanation for the above changes in the current speed[6,7]. Finally, in the present study the INSAT-1D satellite-linked remote sensing oceanic DS-3 buoy has made an outstanding contribution to recording meteorological elements such as Ta, SST, Ws, Wd and Cs during the period (15–31 October 1999) of the Gopalpur and Paradip severe tropical cyclones in the Bay of Bengal, in the absence of any convectional observations. These remote observations have brought out clearly the response of the ocean to the ongoing weather changes due to both the above cyclones, as revealed by the surface pressure fields shown in Figures 2 *a*, *b* and 3 in the Bay of Bengal.

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