

Thermal response of upper layers of Bay of Bengal to forcing of a severe cyclonic storm: A case study

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Upper ocean response to forcing of a severe cyclonic storm during May 1990 in the western Bay of Bengal was studied using the XBT data sets collected (4 d after passage of storm) under Indian TOGA programme. A maximum lowering in the sea surface temperature (SST) by 2.7°C relative to prestorm conditions and an increase in SST by 1°C during the poststorm regime of about 2 weeks were noticed close to the storm centre on the right side of the storm track. Presence of upwelling of cold water from deeper depths relative to prestorm conditions and its persistence during poststorm regime in the vicinity of the storm centre were revealed. Deep homogeneous surface layer of thickness about 55 m was developed at a distance of 110 km from the storm centre under the influence of strong winds.

Genesis and intensification of weather disturbances occur over warm seas in the tropics. The ocean thermal energy, released in the form of sensible and latent heat fluxes, gets transferred into kinetic energy within the cyclone¹. As a result, strong winds develop and produce intense mixing and divergent flows in the upper layers of the ocean. This results in redistribution of waters through entrainment and upwelling from depths below resulting in cooling of surface layer^{2,3}. Several studies⁴⁻⁹, show appreciable drop in SST as a response of the upper ocean to the forcing of weather disturbance. Surface cooling to the extent of 6°C is also documented⁴. Certain abnormalities observed in the actual response of the ocean to a moving disturbance have also been summarized and discussed¹⁰⁻¹².

Most of the above mentioned studies were conducted for the Atlantic and Pacific oceans. Case studies have not been reported for the north Indian Ocean especially for the Bay of Bengal which experiences rich cyclonic weather. The present study details a case study of the response of the upper layers of the western Bay of Bengal to the forcing of a severe cyclonic storm during May 1990 based on a survey made under Indian TOGA (Tropical Ocean Global Atmosphere) XBT programme.

A well marked low was formed in the southwest Bay of Bengal on 4 May 1990 which rapidly

intensified into a deep depression, cyclonic storm and subsequently into a severe cyclonic storm with a core of hurricane winds. It traversed initially northwestward and subsequently northward parallel to the coast and finally crossed the Andhra coast in the evening of 9 May near Masulipatnam causing an extensive devastation. The trajectory of the cyclone is depicted in Fig. 1 together with the dates and stages of intensification of the cyclone.

Materials and Methods

Vertical temperature measurements made (T7 XBTs of M/s. Sippican Inc, USA, depth range 0-760 m, temperature accuracy $\pm 0.2^\circ\text{C}$ and depth accuracy $\pm 2\%$) along Madras-Port Blair-Madras shipping route (Fig. 1) during 12-23 May 1990 were used. All XBT traces were digitized at 5 m depth interval. Surface meteorological data including SST were also collected at 50 km interval along the shipping route. Thermal structure in the upper 300 m along Madras-Port Blair section was prepared and presented. Climatological mean thermal structure for May along the section also was prepared based on temperature data of Levitus¹³. This was used as the background thermal structure to estimate changes in the upper ocean temperature caused by the passage of the storm.

Heat content of the upper layers was computed using the formula¹⁴:

$$H = \rho C_p \int_0^z \bar{T} \cdot dz$$

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where H is the heat content (cal.cm^{-2}) of water column; ρ mean density of water column (1.025 gm.cm^{-3}); C_p specific heat of seawater at constant pressure ($0.965 \text{ cal. g}^{-1} \text{ deg C}^{-1}$); \bar{T} mean temperature of the layer; and dz is layer thickness (m).

Results and Discussion

It would have been most ideal to compare thermal sections representing pre and poststorm conditions based on actual measurements to access the response of upper layers of the ocean to the storm forcing. However, in the absence of pre-storm temperature data, it is presumed, in this study, that the climatological thermal regime for May broadly represents prestorm conditions. An examination of temperature data (available at IN-ODC and NIO) from the western Bay, the climatological^{13,15} and blended weekly SST maps for May show the presence of warm ($> 30^\circ\text{C}$) surface waters off Madras in the western Bay. Figure 2 shows climatological (A) and observed (B) thermal structure and temperature anomaly field (C) along Madras-Port Blair section. Climatological SST (Fig. 2A) shows a gradual increase towards western Bay (from 29.5°C in the east to 30.2°C in the west) while the observed SST (Fig. 2B) shows a decrease (from 29.5°C in the east to 27.5°C in the west) towards the western Bay. The temperature difference between climatology and May 1990 is attributed to the passage of severe cyclonic storm. The dashed line in Figs. 2A and B shows the thickness of the surface homogeneous layer and it is clear that after the passage of the storm the homogeneous layer thickness increased from 30 to 55 m on the right of the storm track ($82^\circ 42'E$). Deepening of this homogeneous layer is due to strong vertical mixing⁹ in upper layers caused by strong wind forcing. On 8 May, Indian *MV Viswamohini* passing this region reported 70 m.sec^{-1} wind speed and

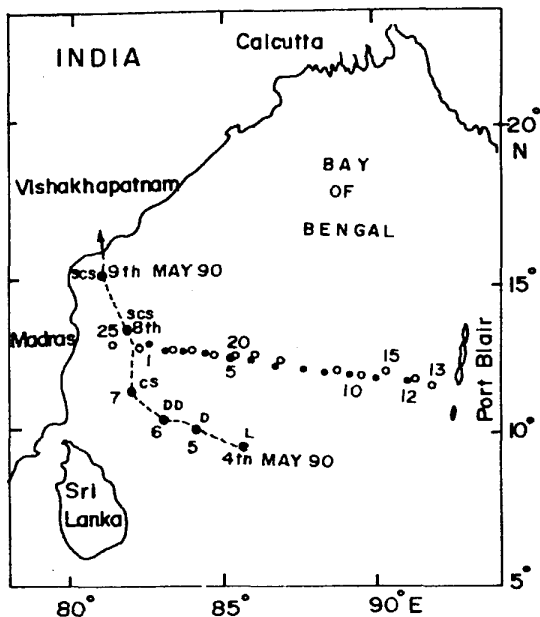


Fig. 1 – XBT stations occupied along the shipping route Madras-Port Blair (sts 1-12) during 12-15 May 1990 and Port Blair-Madras (sts 13-25) during 20-23 May 1990. [The cyclone trajectory (---) is also depicted]

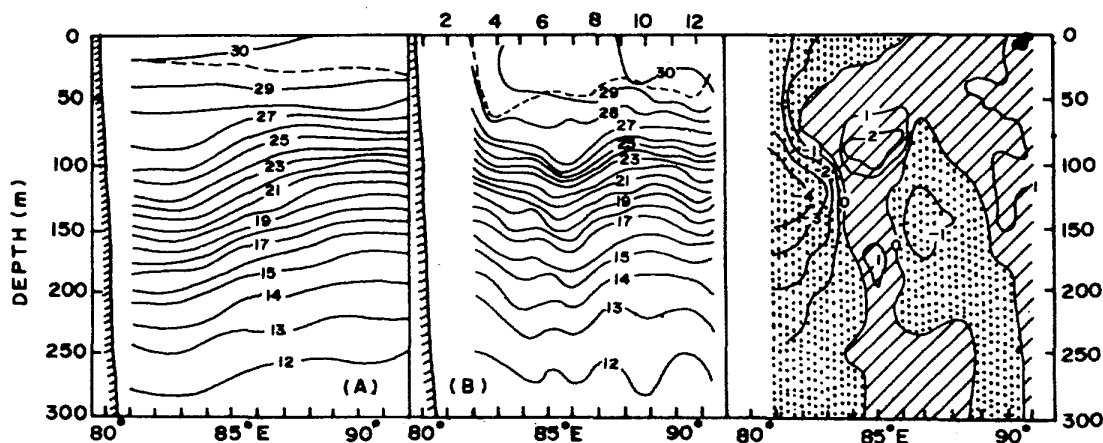


Fig. 2 – Vertical sections of (A) mean climatological, (B) observed thermal structure and (C) temperature anomaly ($\Delta T = T_{\text{May 1990}} - T_{\text{climatological}}$) along Madras – Port Blair route (The thickness of the surface homogeneous layer is denoted by dashed line in A and B. Cooling and warming areas in C are stippled and hatched respectively)

912 hpa pressure at a distance of about 100 km away from the observational station¹⁶. This deepening of surface homogenous layer is consistent with the earlier studies^{8,9,17}.

The most striking feature in Fig. 2B, when compared with Fig. 2A, is upsloping of isotherms caused by strong upwelling in the neighbourhood of the storm. The upswing of the isotherms beneath the centre of the storm is seen extending up to a depth of 280 m indicating the vertical extent of the storm influence. The effect of storm induced upwelling even to greater depths was documented⁹ earlier. The thickness of near surface homogeneous layer is decreased towards the centre of the storm. There were no XBT measurements towards left side of the storm track except SST measurements to visualize the complete picture of upwelling effect. The 30°C isotherm which is present at 20 m depth in the climatological thermal structure (Fig. 2A) is absent up to 88°E under the influence of the storm (Fig. 2B) and the isotherms 29° and 28°C are uplifted towards the surface from 45 and 65 m depths respectively.

In order to quantify the actual cooling that occurred in the water column due to the passage of the storm, temperature anomaly $\Delta T = (T_{May\ 91} - T_{Climatological})$ is presented as a vertical section in Fig. 2C. The cooling regime (stippled area) is predominant near the storm track and represents the effect of storm induced processes. SST anomaly is more negative ($> 2.7^\circ\text{C}$) close to the storm centre and decreased towards east. At subsurface depths (50-200 m) temperature anomaly is more negative and reached values above 4.5°C close to the storm centre. Warming regimes (hatched areas) with anomaly values in excess of 2°C in the depth interval of 50-150 m are noticed away from the storm centre. Warm anomaly pockets are attributed to slow compensating sinking waters away from the centre of the storm. The overall configuration of warming and cooling patterns in Fig. 2C is in broad agreement with previous studies^{17,18}.

The above findings can be viewed clearly from the comparison of observed vertical temperature profiles (1) obtained 4 d after the passage of the storm at 3 locations (82°52'E; 83°E and 84°30'E) away from the storm centre with the climatological background temperature profiles and (2) at nearly the same locations (Fig. 3). The first set of temperature profiles (1 and 2), close to the storm centre, indicates lowering of SST by 2.7°C , development of surface homogeneous layer and thermocline shoaling at subsurface depths (set A) under the influence of storm. Vertical temperature

profiles (set C) taken at 84°30'E indicate insignificant lowering of SST (0.5°C) followed by warming at subsurface depths (50-120 m). Profiles (set B) taken at 83°40'E indicate intermediate stages from set A to set C. One can visualize heat loss from the surface layer (close to the storm centre) which can be accounted for the net heat loss across sea-air interface through sensible heat and latent heat fluxes and upwelling of cold waters from deeper depths. Price⁵ suggested that the ocean response to a hurricane increases with decreasing hurricane translation speed and with increasing intensity. In the present case, since the storm has moved rather slowly with an average speed of $3.85\text{ m}\cdot\text{sec}^{-1}$, its influence is also clearly seen at intermediate depths in the form of thermocline shoaling suggesting strong upwelling. This is substantiated by the uplift of 20°C isotherm by about 50 m towards the storm centre. The warming, at subsurface depths at distances away from storm centre, probably suggests sinking process and wave effects produced by the storm.

It would be interesting to look into SST pattern during poststorm regime to identify the retreat characteristics of the temperature field in the study area. Figure 4 shows the observed SST 4 d (A) and 14 d (B) after the passage of the storm during poststorm regime along Madras-Port Blair section. Also presented in the figure is the climatological (background) SST¹³ (C) along the section. Within the poststorm regime, SST increased over 1°C close to the storm centre in 10 d period. This suggests that more than 2 weeks' period is required for the revival of SST to prestorm conditions in the case of severe cyclonic storm⁸. Similar observations have been made for the Atlantic and Pacific oceans^{3,9}.

Since there was no continuous XBT data in the upper 300 at some stations along Port Blair-Madras section, vertical temperature profiles obtained at 3 locations (83°E, 84°E and 84°30'E) 14 d after, are compared (Fig. 5) with those obtained 4 d

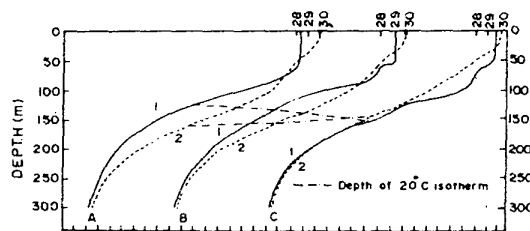


Fig. 3 - Comparison of observed (4 d after the passage of the storm) and climatological temperature profiles at three locations (A-82°52'E; B-83°40'E and C-84°30'E) away from the storm centre

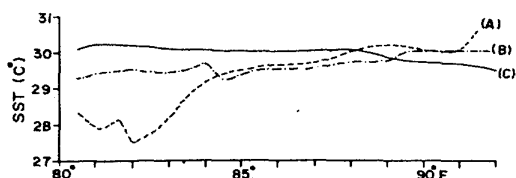


Fig. 4—Observed sea surface temperature 4 d (A), 14 d (B) after passage of the storm and climatological SST (C) along Madras-Port Blair section.

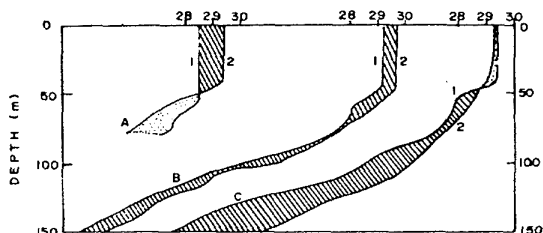


Fig. 5—Inter comparison of poststorm vertical temperature profiles (1: 4 d after and 2: 14 d after passage of the storm) at three locations (A—83°E; B—84°E and C—84°30'E) away from the storm centre. Cooling and warming areas are shown with stippled and hatched areas respectively

after passage of the storm to understand changes in surface as well as interior processes. This comparison reveals an increase of surface layer temperature including SST by 1°C up to 50 m depth in the vicinity of the storm centre (set A) in the 10 d period. Below 50 m, temperature decreased within the 10 d period (for profile 2, data are available only up to 80 m). In the vicinity of the storm centre while the surface layer gains heat during 10 d period through air-sea interaction processes, subsurface layer loses heat indicating the persistence of upwelling at subsurface depths even 14 d after passage of the storm.

As one moves away from the storm centre, the temperature profile at 84°E (set B) and 84°30'E (set C) reveals a progressive decrease towards east in SST and surface layer temperature in the 10 d period. However, below the surface layer one would see increase in temperature in sets B and C compared to set A. Similar feature is also noticed in set C of Fig. 3. This is also substantiated from the heat content computed for the profiles 1 and 2 in sets A, B and C of Fig. 5. Close to the storm centre (set A) the heat contents show

a gain of 4 kcal.cm⁻² in the upper 50 m and a heat loss of 3 kcal.cm⁻² between 50 and 80 m leading to a total heat gain of 1 kcal.cm⁻² in the upper 80 m water column in the 10 d period. Similarly, for sets B and C the heat gain in the upper 80 m water column is 3.5 kcal.cm⁻² and 0.4 kcal.cm⁻² respectively. Considerable increase in the heat gain from set A to set B indicates the warming conditions during the poststorm regime. The minimum SST differences east of 84°30'E (Fig. 4) and the lesser heat gain at the same location (set C, Fig. 5) are suggestive of lateral extent of storm influence, which is about 250 km right of storm centre.

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