

## Studies on Thermal Fields in the Bay of Bengal

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**Abstract:** As an Indian component of the International Tropical Ocean Global Atmosphere (TOGA) program, the National Institute of Oceanography, Goa, has initiated a long term observational program during 1990 with financial support from the Department of Science & Technology. The main objective of the program is routine monitoring of the upper ocean thermal structure along selected shipping lanes in the seas around India on annual and interannual time scales. Utilizing the near bi-monthly XBT data along Chennai-Andamans section collected using ships of opportunity during 1991-96, spatio temporal variability of upper layer thermal fields is examined on annual and interannual time scales. The observed variability is supported with two independent data sets: (a) Renold's weekly SSTs, and (b) TOPEX altimeter sea-level anomalies. During the observational period a few events were captured to examine thermal response of the upper ocean to varying storm forcing. Special CTD cruises were conducted to supplement the XBT data and identified the presence of Arabian Sea origin high salinity waters at sub-surface depths in the central Bay of Bengal during south-west monsoon season.

Further, an improved temperature climatology for the Bay of Bengal is developed by compiling all the available temperature profiles, which outnumbered (doubled) the temperature data used in the best known Levitus and Boyer (1994) temperature climatology. Distribution maps of Levitus and Boyer climatology revealed several artifacts when compared with new climatology. In addition, with the help of new temperature climatology, detected long baroclinic Rossby waves.

### INTRODUCTION

Bay of Bengal, the eastern arm of the North Indian Ocean, is a unique basin with very special possibly unique characteristics such as: (a) Pole-ward transportation of heat and mass are restricted as its northern boundary is a land-mass at about 21°N, (b) Seasonal reversal of winds and circulation (Hastenrath and Lamb, 1979 and Potemra et al., 1991), (c) Fresh water discharge from adjacent rivers into the Bay causing the near-surface circulation more of a thermohaline nature (Shetye et al., 1993); (d) It is directly connected to the eastern equatorial Indian Ocean at its southern boundary making it more influenced to the equatorial processes such as Kelvin waves (Yu et al., 1991 and McCreary et al., 1996), and (e) The Bay is more cyclogenetic with the formation of tropical cyclones during pre- and post-monsoon seasons (Joseph, 1994 and Ganesan et al., (1994) and monsoon depressions at the head Bay during southwest monsoon season (Sanil

Kumar et al., 1994) causing short term variability in the wind field and thus modify the surface circulation.

Compared with other oceans, the Bay is the least explored, studied and understood. Observations in the Bay of Bengal started gaining momentum only after commissioning of the research vessels R.V. GAVESHANI, O.R.V. SAGAR KANYA, and F.R.V. SAGAR SAMPADA. In addition, through collaborative programs, such as MONSOON-77, MONEX-79 (Indo-Soviet collaborative summer monsoon experiments), Indian Ocean Experiment (INDOEX) and First GARP Global Experiment (FGGE), synoptic data were generated at few selected locations in the Bay, which have improved the data coverage. Month-wise distribution of all the available historic temperature data at surface in the Bay of Bengal is presented in Fig.1. Even then the data coverage is mostly confined to the western boundary of the basin (off the east coast of India) than in the interior. The situation is much worse

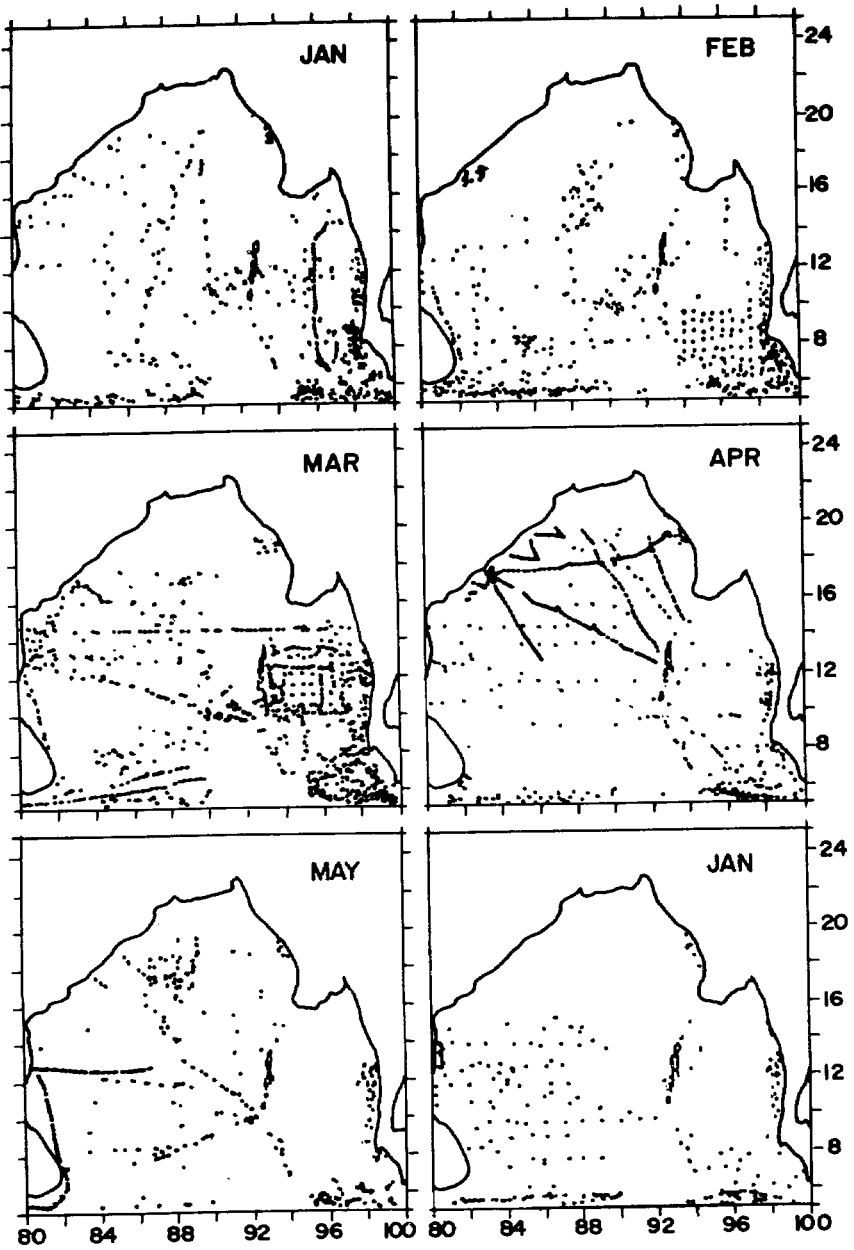
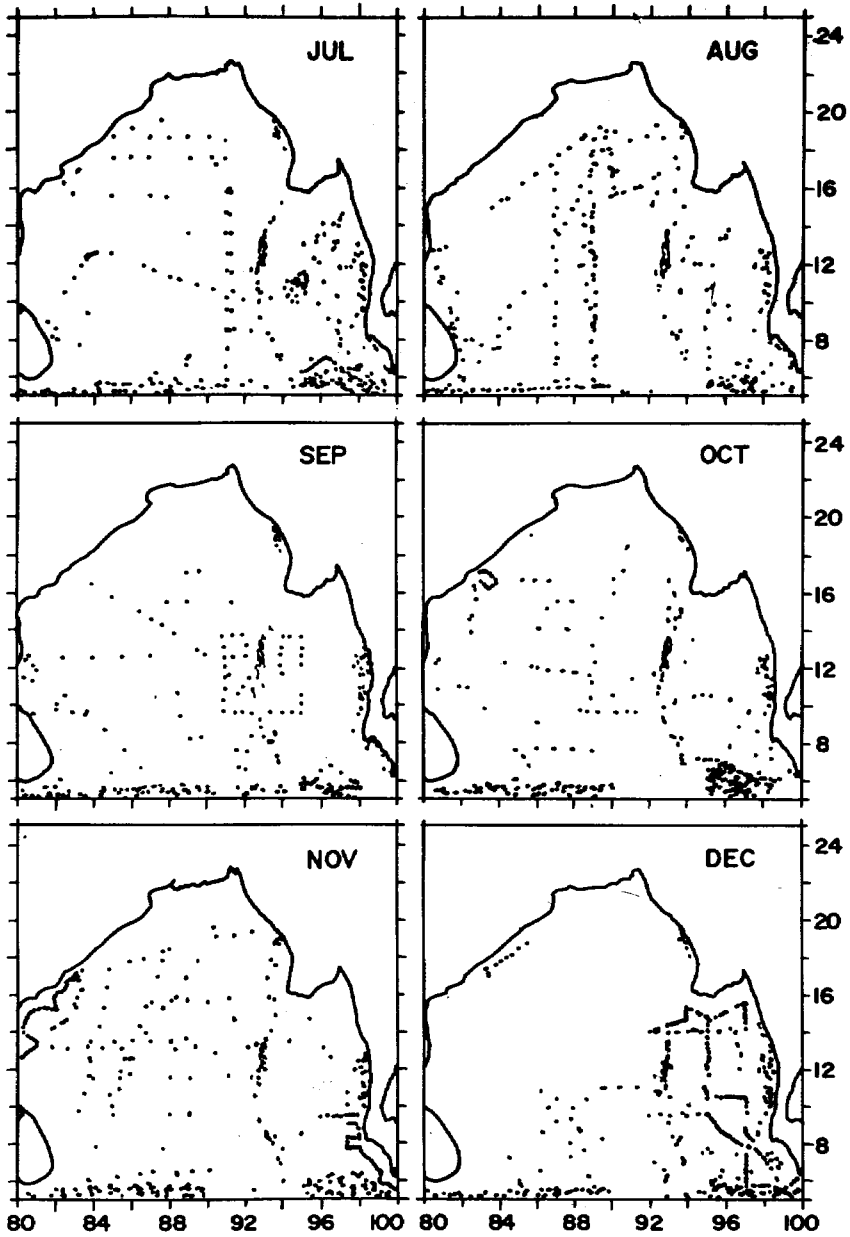


Fig.1. Historical data distribution of temperature at surface.

Fig.1 Continued.....



in the sub-surface depths. The entire northeastern region of the Bay is virtually devoid of any data. Further, all the available data for the Indian Ocean region are synthesized in a few atlases and Levitus and Boyer (1994) temperature climatology, henceforth referred as LB94 for the world oceans is the best known among all.

Utilizing the coastal data, circulation and hydrography off the east coast of India is fairly well documented (Gopalakrishna and Sastry, 1985; Somayajulu et al., 1987, Murty et al., 1992; Shetye et al., 1991, 1993 and 1996). However, knowledge on the open ocean circulation is rather limited. Hitherto, there are only two studies (Murty et al., 1992 and Suryanarayana et al., 1988) available describing the open ocean circulation on a basin scale compared with number of studies on coastal circulation. Even these studies explained only broad scale features, scales larger than Rossby radius of deformation. Mean monthly climatologies of mixed layer depth, sea surface temperature and surface currents for the north Indian Ocean are prepared by Rao et al., (1991). Short time variability of upper layer thermal structure is also documented (Rao et al., 1981, 1983 and 1987). A few case studies on the response of the Bay of Bengal to the storm forcing are also available (Rao et al., 1983, 1987 and Gopala Krishna et al., 1995). Using a multi-layer reduced gravity model, Potemra et al., (1991) simulated most of the surface and sub-surface circulation patterns of the Bay. These features are mainly impelled by the remote forcing from the equator as suggested by Yu et al., (1991) and McCreary et al., (1993) confirmed this result with 2 ½ layer model.

Scientists have realized the importance of examining the inter-annual variability of global climate, of which El Nino event is the strongest. The World Climate Research Program (WCRP) has launched a decadal (1985-1994) international collaborative program known as Tropical Ocean Global Atmosphere (TOGA) primarily to monitor the subsurface thermal variability on various time scales to predict short term variability of the climate as the memory of climate system resides in the ocean. Under

the TOGA program, Expendable Bathy Thermographs (XBTs) are extensively used to collect upper ocean thermal data along shipping lanes around the globe. Operation of XBTs is advantageous over other temperature measuring equipment because these are inexpensive and easy to operate even on moving ships. This data is widely used in the initialization of climate forecasts and operational ElNino Southern Oscillation (ENSO) diagnostics and to examine large-scale circulation patterns. Detailed description of the currents in the Pacific were presented by Kessler and Taft (1987) and Picaut and Tournier (1991) based on the XBT data sets. In several cases, the XBT data sets were used to determine geostrophic currents by developing T/S relationship (Kessler and Taft, 1987 and Murty et al., 1999).

However, similar studies are not available for the Bay. It was not possible to examine year-to-year variability of thermal fields at any location in the Bay because no section or area in the Bay was ever surveyed continuously for longer (5 - 10 years) periods. All the previous studies are based on one-time observations only. After identifying this lacuna, the National Institute of Oceanography, Goa has initiated a long-term observational program along (a) Chennai-Andamans-Calcutta (b) Chennai-Singapore and (c) Mumbai-Mauritius shipping lanes as an Indian component of the International TOGA Program. Composite map indicating XBT data coverage along the above routes for the period 1990-1998 is depicted in Fig.2. Each solid dot represents XBT station. The Department of Science & Technology (DST) supported this program during 1990-1998 and is presently funded by the Department of Ocean Development (DOD). In the present article, major scientific achievements under the Bay of Bengal project are discussed in a general sense.

## **MAJOR SCIENTIFIC ACHIEVEMENTS DURING 1990-1998**

### **Field Experiments**

Under the Indian National TOGA XBT Program, The National Institute of Oceanography, Goa,

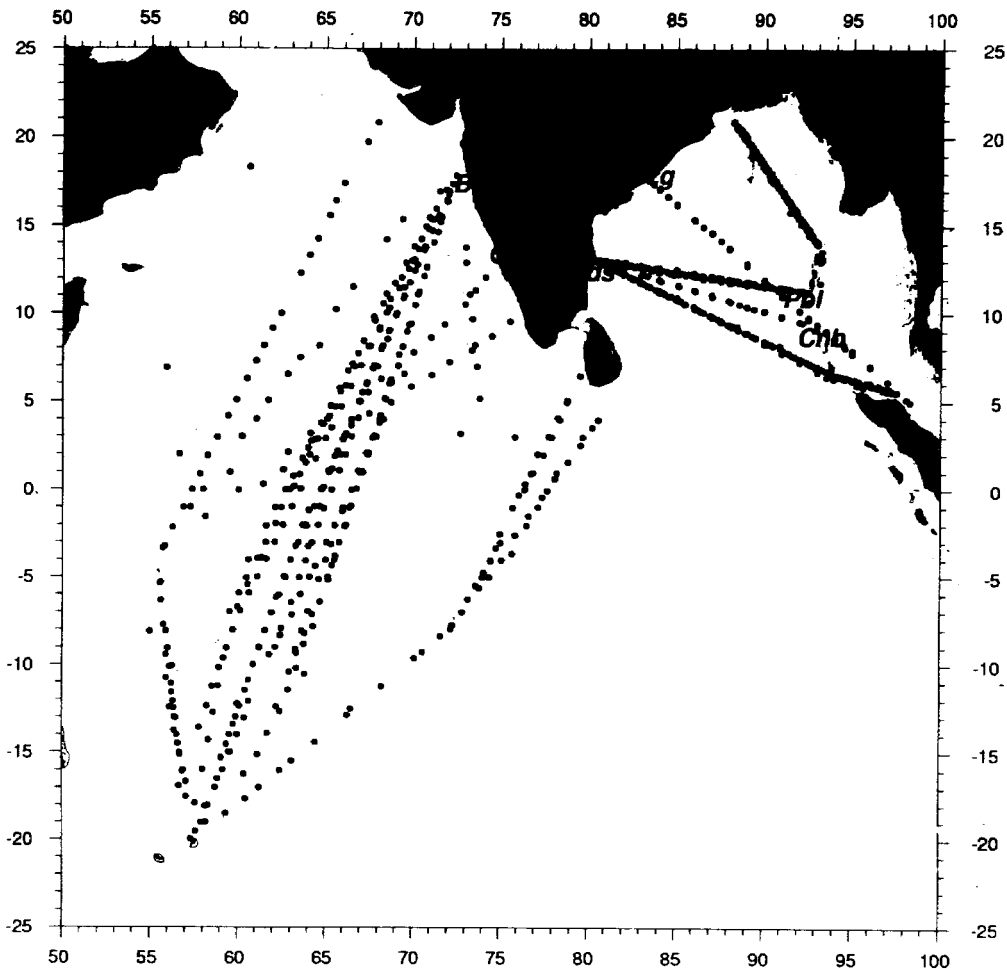


Fig 2. Composite map showing XBT data coverage in the seas around India under India XBT Program.

has designed and implemented systematic measurements on the upper ocean thermal fields along selected shipping routes in the seas around India to study the spatio-temporal evolution of near-surface thermal structure for an improved prediction of regional short-term climate fluctuations in the monsoon and storms. The sub-surface thermal data is obtained by deploying M/S. Sippican Inc, USA; make T 7 XBT probes (0-760 m depth range, 5 m depth

accuracy, 0.2°C temperature accuracy) and personal computer based Mark - 12 recording unit. The XBT data are collected at nearly 50 km spatial interval close to the coasts and at 100 km interval in the open ocean. Such a fine resolution temperature in the coastal region have been collected in order to resolve some of the known features, such as coastal upwelling, boundary currents, etc. Under this program, although bimonthly sampling was originally

planned, it could be implemented strictly due to non-availability of merchant ships. At each XBT station, standard surface marine meteorological parameters were also measured. In order to supplement and validate these XBT data, on a few occasions CTD surveys were also carried out in the Bay of Bengal.

After completion of every XBT field observation, data is processed by comparing individual temperature profiles with neighborhood profiles to ensure spatial consistency along each section and to identify the spurious data. These profiles were also compared with the historic data collected during the same month of previous years and with the temperature climatology of LB94. Duplicate profiles due to repeat launching of probes were eliminated. Further, the quality control procedures listed in Bailey et al., (1994) were also followed. The data was formatted following TOGA sub-surface data centre formats before supplying to the user community and data centres.

#### **Year to Year Variability (1996 & 1998)**

The utility of XBTs was convincingly demonstrated to explain the observed short-term climate anomalies associated with ENSO in the Pacific Ocean. A need exists to characterize similar variability for the Indian seas for an improved prediction of monsoon and cyclonic storms. However, most of the studies to date for the Bay of Bengal are based on one time measurements only, which explained gross features with scales larger than Rossby radius of deformation. Practically no studies exist to document and explain possible low frequency variability in the Bay of Bengal. The six year (1991-1996) near bi-monthly XBT data set offers an unique opportunity to examine this issue for the first time in some detail. The year-to-year variability is examined in terms of prevailing synoptic conditions. A careful examination has revealed that the amplitude of year-to-year variability is greater than the measurement accuracy of XBT system. The variability is also noticed in the oceanographic features, such as strength and location of occurrence of Indian

Monsoon Current in the central Bay, evolution of western boundary current, and coastal upwelling intensity off Chennai. Further, the influence of warm phase El Nino events of 1992-'93 and 1997-'98 in the Pacific is clearly identified in the subsurface thermal structure in the central Bay of Bengal. The observed year-to-year variability is further confirmed by comparing with two other independent data sets - Renold's weekly averaged SSTs (Renold and Smith, 1994) and TOPEX/POSIDON altimeter sea level anomalies (Gopalakrishna, 1998).

Along Chennai - Andamans section, August and October months are surveyed during all the six years. As an example, snap-shot thermal sections of August are presented in Fig.3 in order to describe the year to year variability. Under monsoon forcing, in general all thermal sections exhibited 2°C cooling and 50m deepening of surface isothermal layer from west to east except during 1994 & 1995, where the cooling in the western region is only 1°C indicating variability among the years. Similarly, year-to-year variability is also noticed in the coastal upwelling feature with presence of intense coastal upwelling during 1991, while it is moderate during 1993 and 1995. Earlier studies of Gopalakrishna and Sastry (1985), Shetye et al., (1991) and Murty et al., (1992) also reported such coastal upwelling during summer monsoon period in the Bay of Bengal. Interestingly a pocket of warm (>29°C) waters is noticed in the western region during most of the years, spreading up to 88°E during 1995 suggesting weaker monsoonal cooling. A dome-like structure between 86° and 88°E with stretching of isotherms in the depth range of 80-120m is another dominant feature noticed in 1991 and 1992 sections. Generally, stretching of isotherms in opposite directions indicate a shear zone or under current. In the present case it is caused due to the presence of Indian Monsoon Current (Gopalakrishna et al., 1995). Snap-shot thermal sections clearly exhibited year to year variability in several features. Although not presented here, similar variability is also noticed in other months.

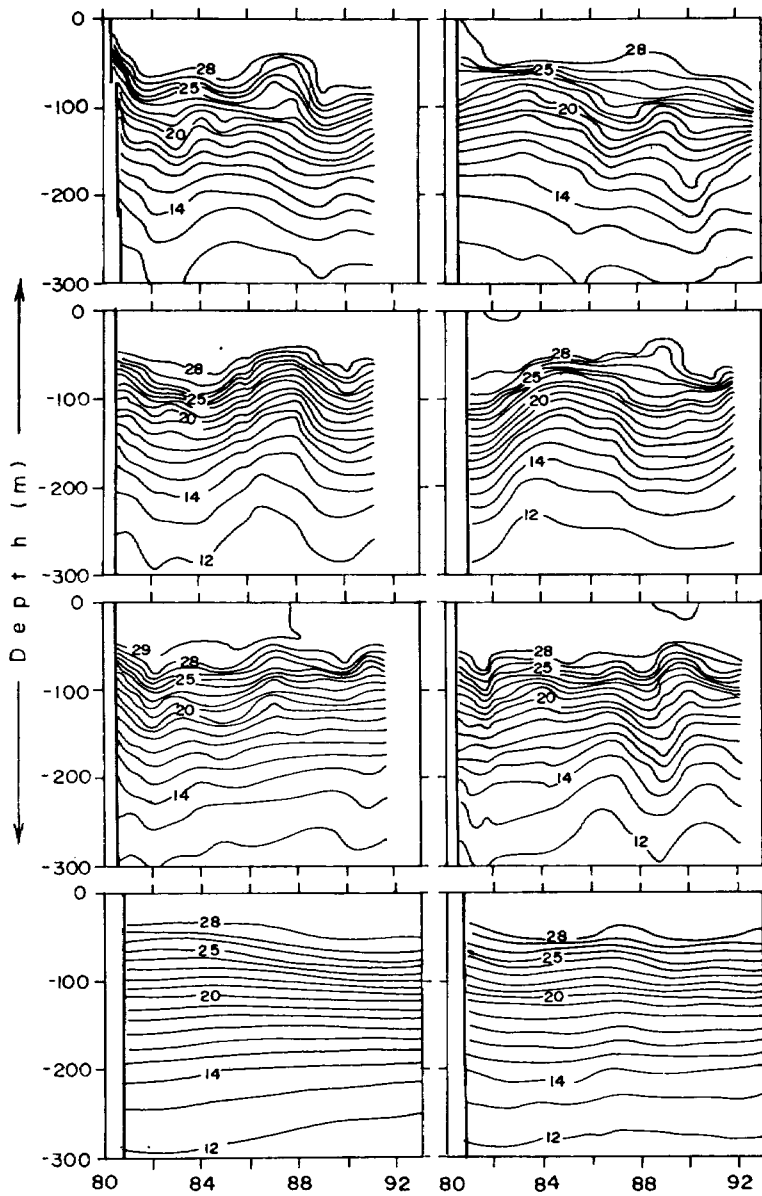


Fig. 3. Snapshots of thermal structure (<300m) along Chennai- Andamans XBT transect. LB94 and MC97 climatologies during August.

## Upper Ocean Response to Moving Storms

The Bay of Bengal is well known for the formation of intense meteorological disturbances during pre- and post- monsoon seasons because major portions of the Bay remain warmer throughout the year with surface waters warmer than 28°C (Gadgil et al., 1984). These systems usually propagate westward or northward and hit either the east coast of India or Bangladesh coast causing enormous damage. Cyclonic storms significantly modifies the upper few tens of meters and the changes brought about in the temperature profiles represent the oceanic thermal response to the storm forcing. There are several case studies describing storm influence on the upper ocean (Fedrov et al., 1979 and Price, 1981), but all pertains to Pacific or Atlantic Oceans. Although Bay of Bengal experiences severest storms, there are few studies describing ocean response to the storm forcing (Rao, 1987).

During the XBT surveys, the signatures of a few storm events of varying intensities were captured. In some cases, it was a fortuitous coincidence to have both pre- and post-storm temperature profiles. These data sets are utilized, to describe and explain the observed dramatic changes in the temperature field associated with storm forcing. The observed variability in the revival time scales in attaining pre-storm conditions are estimated. Two case studies (May 1990 and June 1996) are examined here to explain upper ocean response to the storm forcing. Fig.4 shows the trajectories of cyclonic storms together with XBT sections. Fig.5(A-C) is prepared to explain horizontal and vertical extent of storm influence. SST distribution of 3 days after storm passage (dashed line in Fig.5A, upper panel) show dramatic decrease (2.7°C) compared to the background SST (30.7°C, solid line). The reduction is greater towards right hand side of the storm center and reached closer to the background SSTs, when moved away from the storm center. Post-storm SST distribution (14 days after storm passage, dotted line in Fig.5A), although shows reduction compared to background temperature, an increase of >1°C

from the dashed line is visible, indicating that the revival time scales is of the order of two weeks. Further, SST distribution show larger differences only up to 86°E ( $\approx$  400 km away from storm center) compared with background temperature, indicating that the storm influence in horizontal direction is limited to about 400 km.

Vertical temperature profiles at different locations (close to the storm center, away towards right hand side and far away towards right hand side) obtained during post-storm period are compared with background profiles at the same location (bottom panel of Fig.5B) to examine storm influence in the vertical plane. Under the influence of storm forcing temperature profile closest to the storm center (first set of profiles), obtained 3 days after storm passage, clearly shows temperature reduction in the near-surface layer w.r.t the background profile and development of surface homogeneous layer and thermocline shoaling at sub-surface depths. This reduction is attributed to the direct heat losses from the surface layer. Deepening of the surface homogeneous layer (second set of profiles) inturn caused warming in the thermocline region. Price (1981) has suggested that the response of the upper ocean layers increases with slow moving high intensity storms. In the present case, the storm has moved rather slowly with an average speed of 3.5 m sec<sup>-1</sup> modifying the surface and sub-surface layers significantly. This is further substantiated by the shoaling of 20°C isotherm (Connected by a line) by about 45 m towards the storm center.

However, these features became less conspicuous, when moved away from the storm center (third set of profiles Fig.5C). Similarly, comparison of temperature profiles obtained 14 days after storm passage with background profiles clearly showed an increase in the near surface water temperature indicating two to three weeks as the revival time scales.

In order to view the progressive evolution of the vertical temperature profiles together, all the profiles obtained along Chennai - Andamans route during both pre (Fig.6 top panel, 6-9 June 1996) and post-storm (Fig.6, bottom panel, 18-20 June 1996) periods are presented. Near-



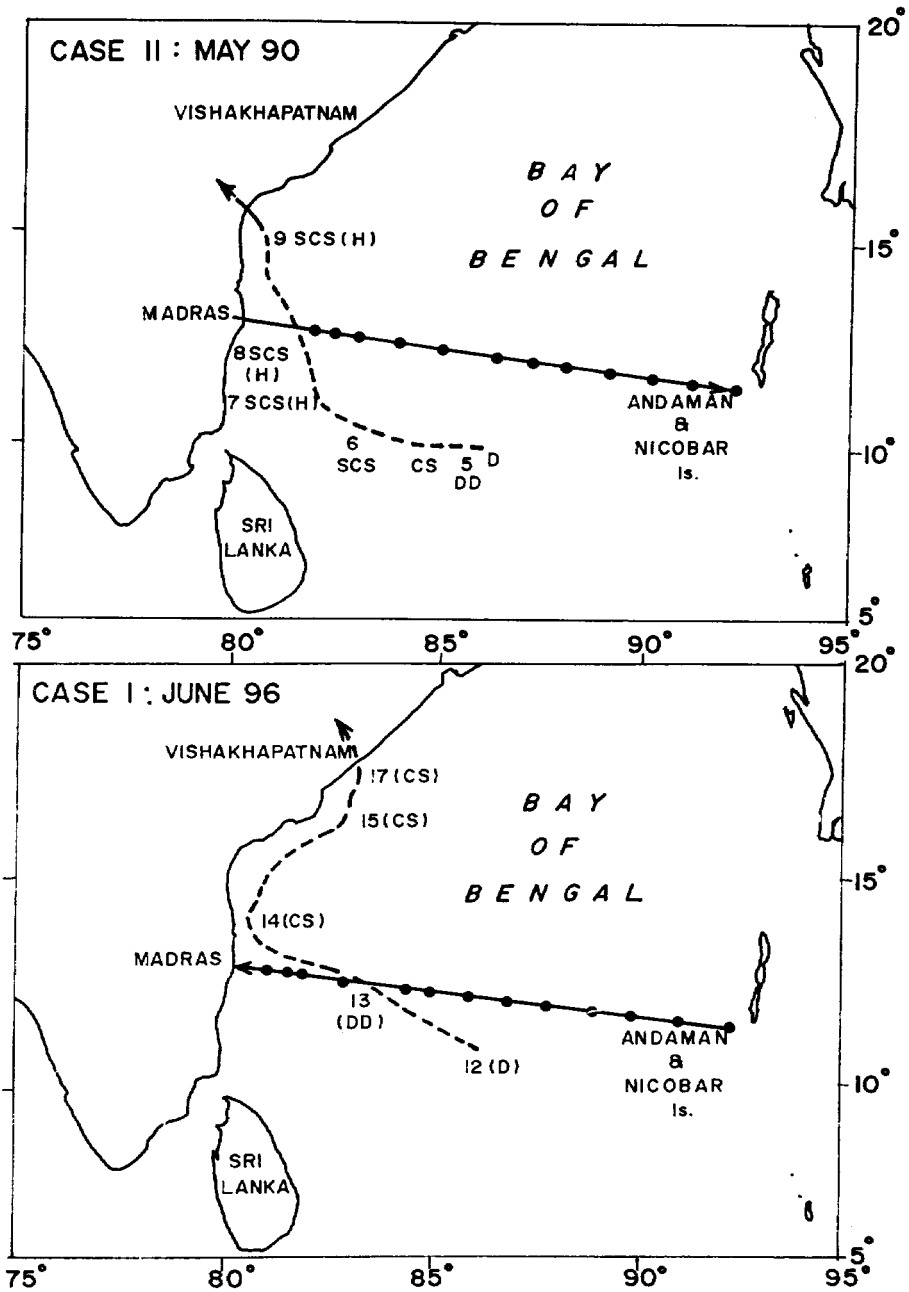


Fig.4. Dashed line represents trajectories of cyclonic storms in the Bay of Bengal with daily positions and its intensity during (a) 5-9 May 1990, upper panel and (b) 12-17 June 1996, lower panel. Solid line in upper panel represents XBT transect and in the lower panel represents CTD section along Chennai - Andamans.

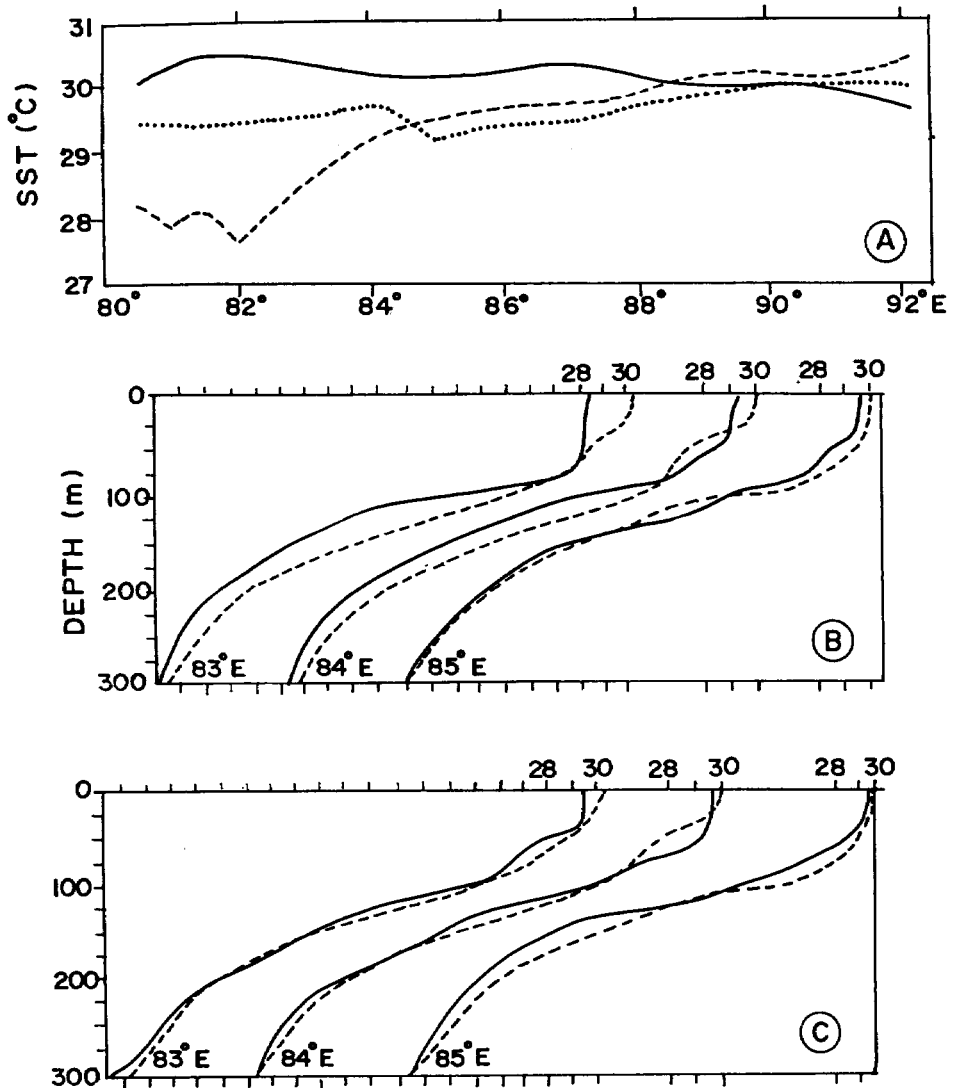


Fig.5. Panel (A) SST distribution along Chennai - Andamans XBT transect during 12-14 (dashed line), 21-23 May 1990 (dotted line) both representing post-storm and May of MC97 (solid line) representing pre-storm regime. Panel (B) Vertical temperature profiles at selected locations for the period 12-14 May (dashed line). Panel (C) Vertical temperature profiles at selected locations for the period 21-23 May (dashed line).

isothermal layer temperatures of more or less all the pre-storm profiles show warm waters with an average value of 30°C and with uniform layer thickness (40m). Depth of 20°C isotherm (dashed line) in general show slight westward down sloping tendency except near the very first two profiles, which show up-swing. However, under the storm influence, post-storm profiles show distinct cooling in its near-surface isothermal layer temperature with progressive deepening from 55m (first profile) to 90m at 84°E (fourth profile) which is situated towards right hand side of the storm trajectory. More interestingly, depth of 20°C isotherm clearly indicates upswing towards closer to the storm center confirming cold water entrainment in to the base of the near-surface isothermal layer. Further, limit of the horizontal extent of the storm influence may be visualized from the progressive shoaling up of near-isothermal layer thickness towards eastern end of the XBT section from fourth profile towards right hand side.

### **Entry of Arabian Sea Waters into the Central Bay of Bengal during Summer Monsoon Season**

Most of the snap-shot XBT thermal sections obtained during south west monsoon season along Chennai - Andamans exhibited a dome-like structure with vertical stretching of isotherms in the thermocline (90 – 125 m depth range). This is attributed to the presence of an undercurrent known as the Indian Monsoon Current. This current showed year-to-year variability (east-west shift) in its location and strength. A few special CTD surveys were organized along this shipping lane during July 1993 and August 1991 to confirm this feature. A similar dome-like feature is also seen in the vertical salinity sections of CTD in the same depth range. It is interesting to notice the presence of a high salinity cell (35.2 PSU) at 88°E during July '93 and a broad high salinity cell between 86° & 88°E during August '91. Doming of isotherms and isohalines is associated with positive wind stress curl over this region (Babu, 1987). Through water mass

analysis, these waters are identified as the Arabian Sea origin waters. Further, computed relative velocity distribution maps exhibited northward flows (30 cm Sec<sup>-1</sup>) in the region of Monsoon Current during monsoon season (Gopalakrishna et al., 1996). Recently, Gopalakrishna et al (1998) compiled all the available temperature, salinity and Oxygen data of south west monsoon season for the North Indian Ocean. Horizontal distribution maps are prepared and identified the most possible path for the passage of the Arabian Sea High Salinity Waters in to the central Bay of Bengal.

### **Development of New Temperature Climatology**

A good number of near-surface temperature climatologies are available for the Indian Ocean. Among these, although LB94 is considered as the best available for the world oceans, it has several limitations in respect of data density and interpolation procedures, resulting in smoother fields. With the acquisition of additional XBT data under Indian TOGA program, a need was felt to improve LB94 for the Bay of Bengal. A new temperature climatology (NC98) was developed by augmenting all the available temperature data utilized by LB94, and additional data acquired from various sources within India and from outside and the data collected under Indian TOGA program. All these data are subjected to standard quality control checks and finally about 13,000 profiles are utilized to develop NC98. The number of temperature profiles utilized in NC98 is nearly double to that of LB94. In addition, a superior objective mapping procedure was used to generate realistic temperature climatology for the Bay of Bengal. Comparison of temperature data distribution at surface and 500m depth in preparing LB94 (Fig.7) and NC98 (Fig.8) clearly indicate the improvement in NC98. XBT lines under the Indian Program are distinctly visible in NC98. Following are the salient features, when compared with the analyzed fields in NC98 and LB94.

Periodicity of SST distribution is annual in NC98 and semi annual in LB94. Artifacts such

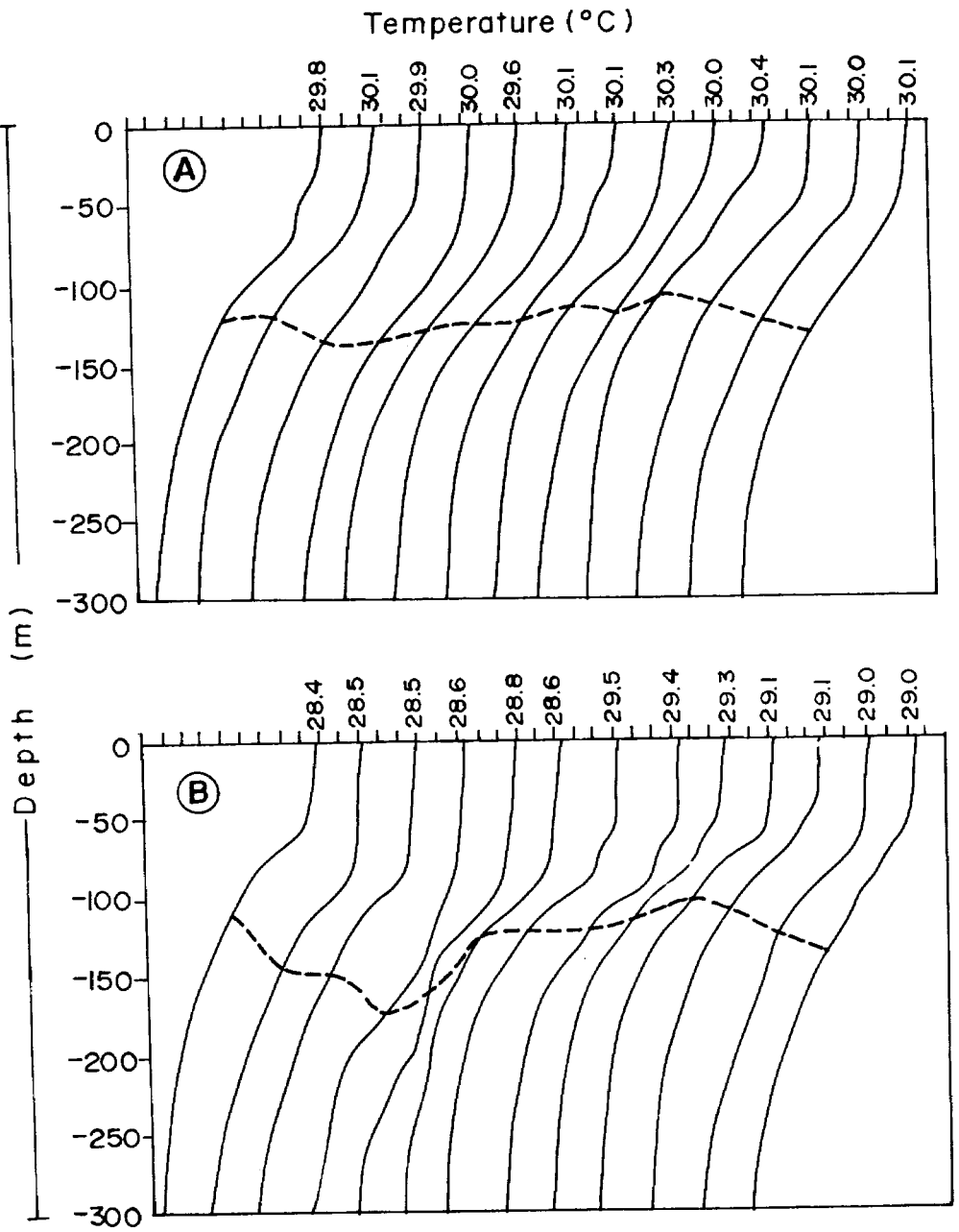


Fig.6. Upper panel: CTD temperature profiles obtained during 6-9 June 1996 (pre-storm regime) and lower panel: XBT profiles obtained during 22-24 June 1996 (post-storm regime).

as: (i) strong secondary warming along the east coast of India during September, (ii) Presence of warm waters during October and (iii) cold waters in the northern Bay are observed in LB94. These artifacts are mainly because of non-availability of data at these locations.

### **Rossby Waves in the Bay of Bengal**

Rossby waves are disturbances on a density interface of a layered ocean. They play a very important role in ocean circulation by allowing ocean to respond to an overlying wind field. There are number of mechanisms for generation of Rossby waves. Rossby waves play an important role during El Niño Southern Oscillations (ENSO) cycle. Numerical studies of Potemra et al., (1991) and Shankar et al., (1996) have shown that gross features of the Bay of Bengal circulation can be described by Kelvin waves and Rossby waves. Recent studies of Shankar et al., (1996) and McCreary et al., (1996) have shown that although the interior Ekman pumping is the primary driving force for East Indian Coastal Current (EICC), other forcing mechanisms must be considered to explain the dynamics of EICC.

Utilizing the New Temperature climatology (NC98), an attempt is made to capture Rossby wave signals in the Bay. Methodology followed is very similar to the one followed by Kessler (1990) and Meyers (1979). The 20° isotherm is selected for detecting long Rossby Waves in the Bay. Annual cycle of depth of 20°C isotherm (D20) variations from NC98 along different latitudes is presented in Fig.9, which shows clear westward propagating signals at all latitudes with varying periodicity. Annual Rossby waves are persistent north of 6°N. Semi-annual Rossby waves are dominant in the southern Bay south of 6°N and in the Andaman region at 12°N. In order to test the observed signals for their consistency with long Rossby waves theory, dispersion relation is used for long Rossby waves. This relation contains Kelvin wave speed of which no estimates are available for the Bay. Kelvin wave speeds are estimated in two different methods and got 185 Cm Sec<sup>-1</sup> for first mode baroclinic Kelvin wave speed assuming

the Bay as a two layer structure with lower at rest and upper layer is active. The second method is purely a statistical, and produced a value of 165 Cm Sec<sup>-1</sup>. Therefore, 185 Cm Sec<sup>-1</sup> seems to be more appropriate for the Bay because Rossby wave speeds, estimated from this value, are in good agreement with observed Rossby wave speeds.

### **SUMMARY, CONCLUSIONS AND SUGGESTIONS**

The Bay of Bengal continues to draw our attention due to its several very special, possibly unique features. Although there are several studies dealing with coastal circulation covering both monsoon seasons and also fresh water influence on the near-surface circulation, literature on open ocean circulation on the basin scale is very limited. In addition, recently a number hypotheses have been proposed on the driving mechanisms within the Bay, most of which emphasize the role played by the remote forcing (Rossby and Kelvin wave propagation) in setting up circulation. However, till date there is not a sufficient data base to check these hypotheses, or even to prove the existence of these waves. Further, available literature on the hydrography and circulation of the Bay of Bengal is based on individual cruises representing a season or given region. Till date, literature on variability studies on any time scale in the Bay of Bengal is practically non-existent. All this is mainly because, no area or a particular section in the Bay of Bengal is ever surveyed repeatedly on shorter time interval over longer periods.

As an Indian component of international Tropical Oceans and Global Atmosphere (TOGA) program, the National Institute of Oceanography, Goa, has designed a special sampling strategy using ships of opportunity and collected high quality near bi-monthly upper ocean thermal data along selected shipping lanes in the seas around India. The main objective of this program is to understand and document the evolution of upper ocean thermal structure on annual time scales and to examine its year-to-year variability. Utilizing the snap-

## Data Distribution for Levitus

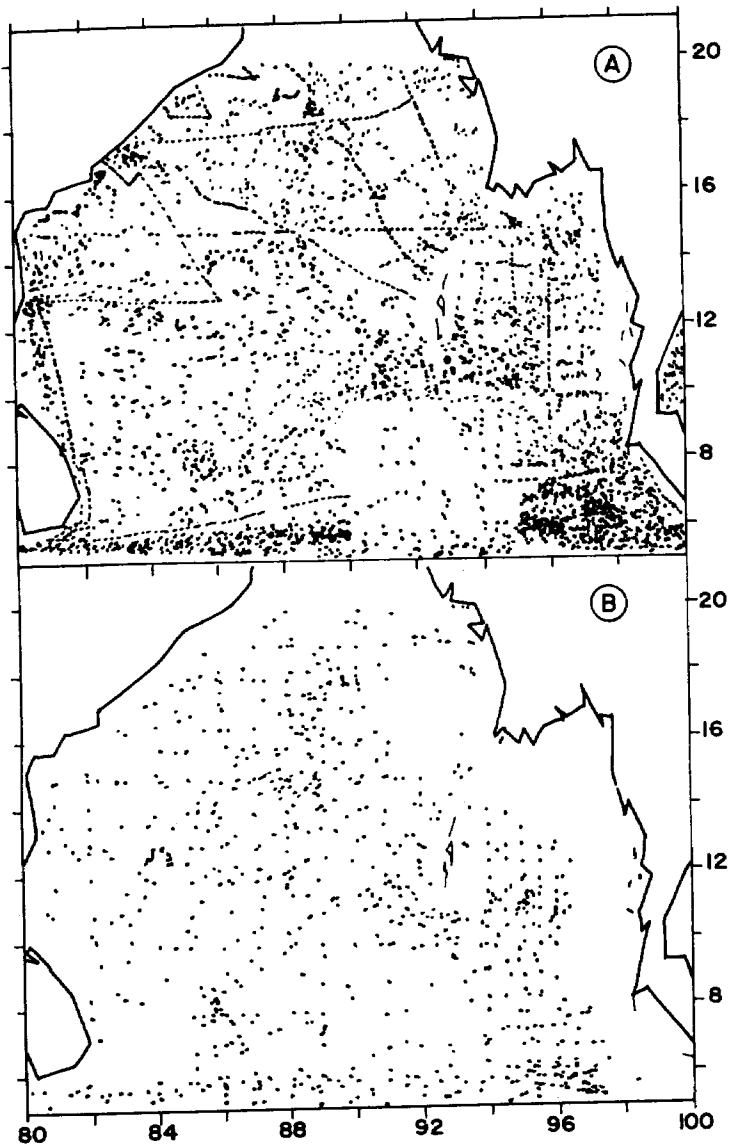


Fig.7. Top panel : Temperature distribution at sea surface in the Bay of Bengal from Levitus climatology.  
Bottom panel : Same as above but for 500 m. depth.

## Data Distribution for NC 98

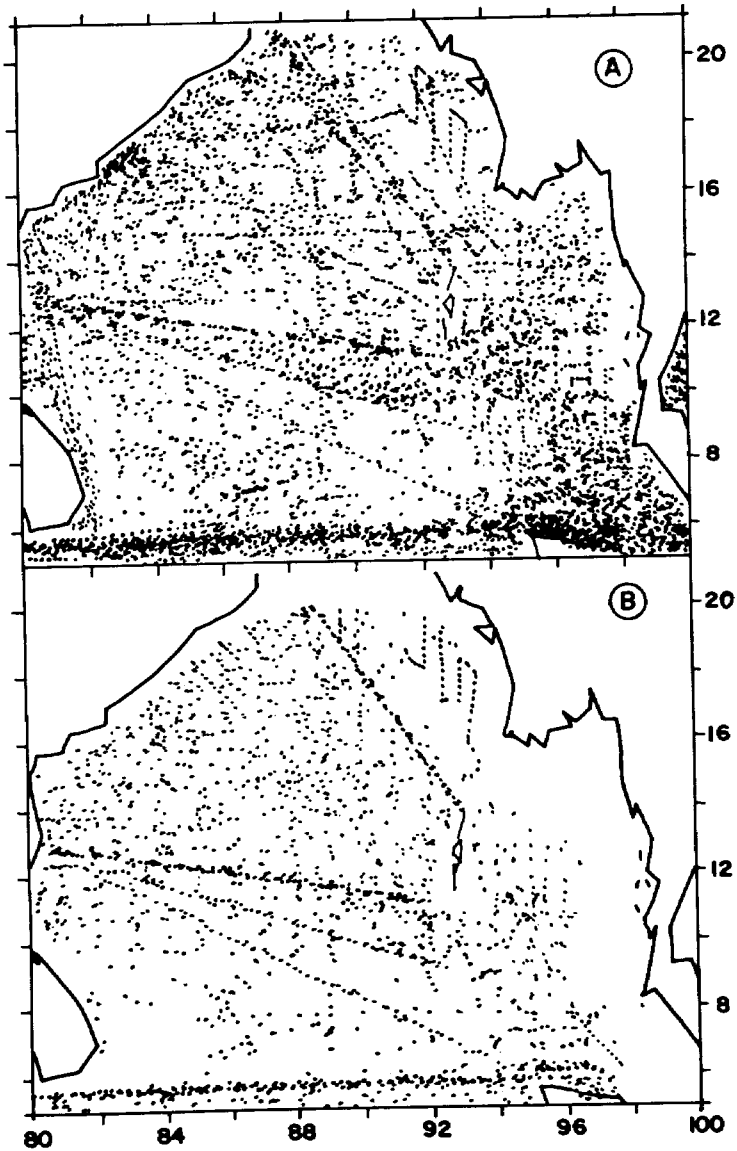


Fig.8. Top panel : Temperature distribution at sea surface in the Bay of Bengal from new climatology developed under TOGAXBT project XBT sections are distinctly seen in this diagram.  
Bottom panel : Same as above but for 500 m. depth.

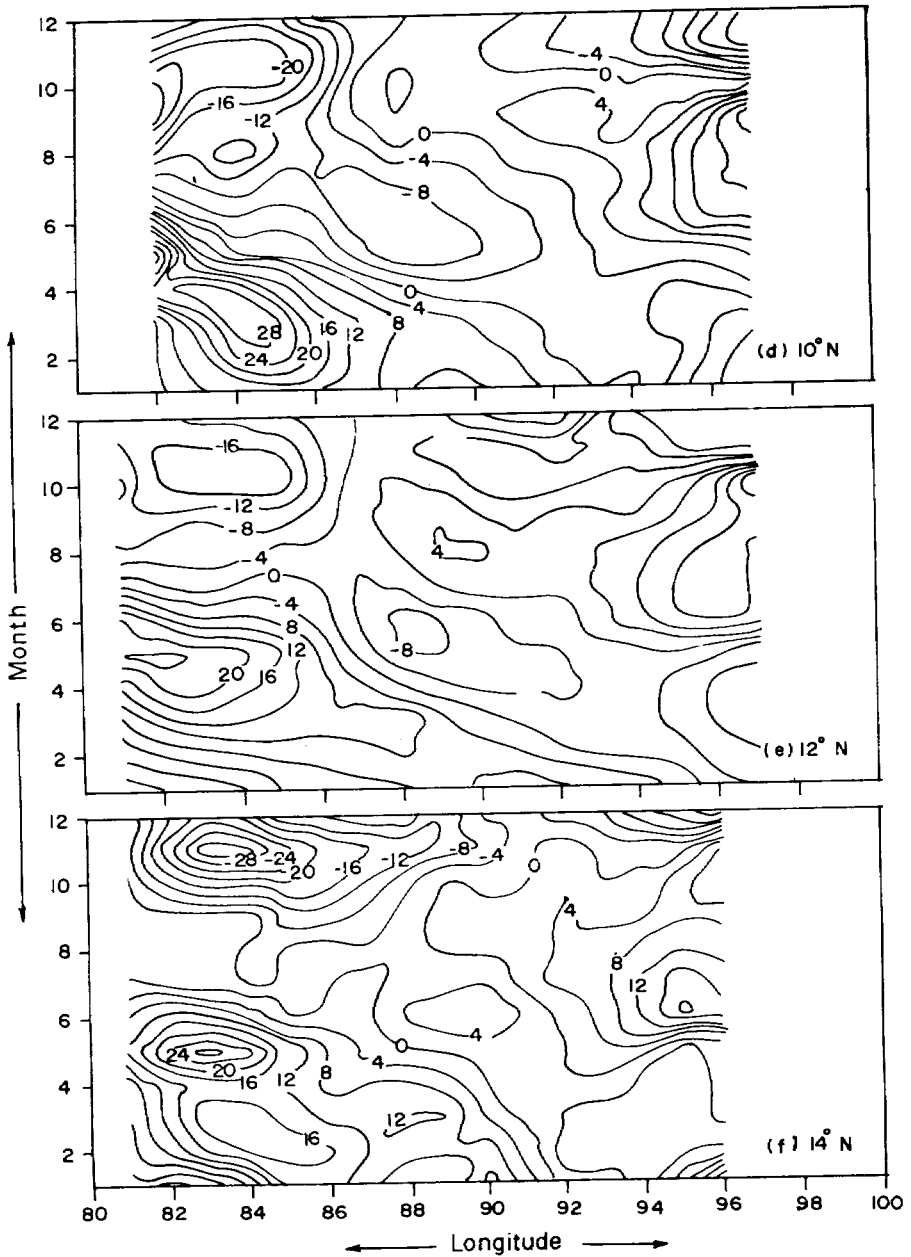


Fig.9. Annual cycle of depth of 20°C isotherm (D20) oscillations along 5°N, 6°N, 8°N, 10°N, 12°N, 14°N, 16°N, 18°N, 20°N. D20 oscillations clearly show westward propagating wave signal with dominance of annual periodicity over the whole Bay (north of 6°N) and semi-annual periodicity south of 6°N



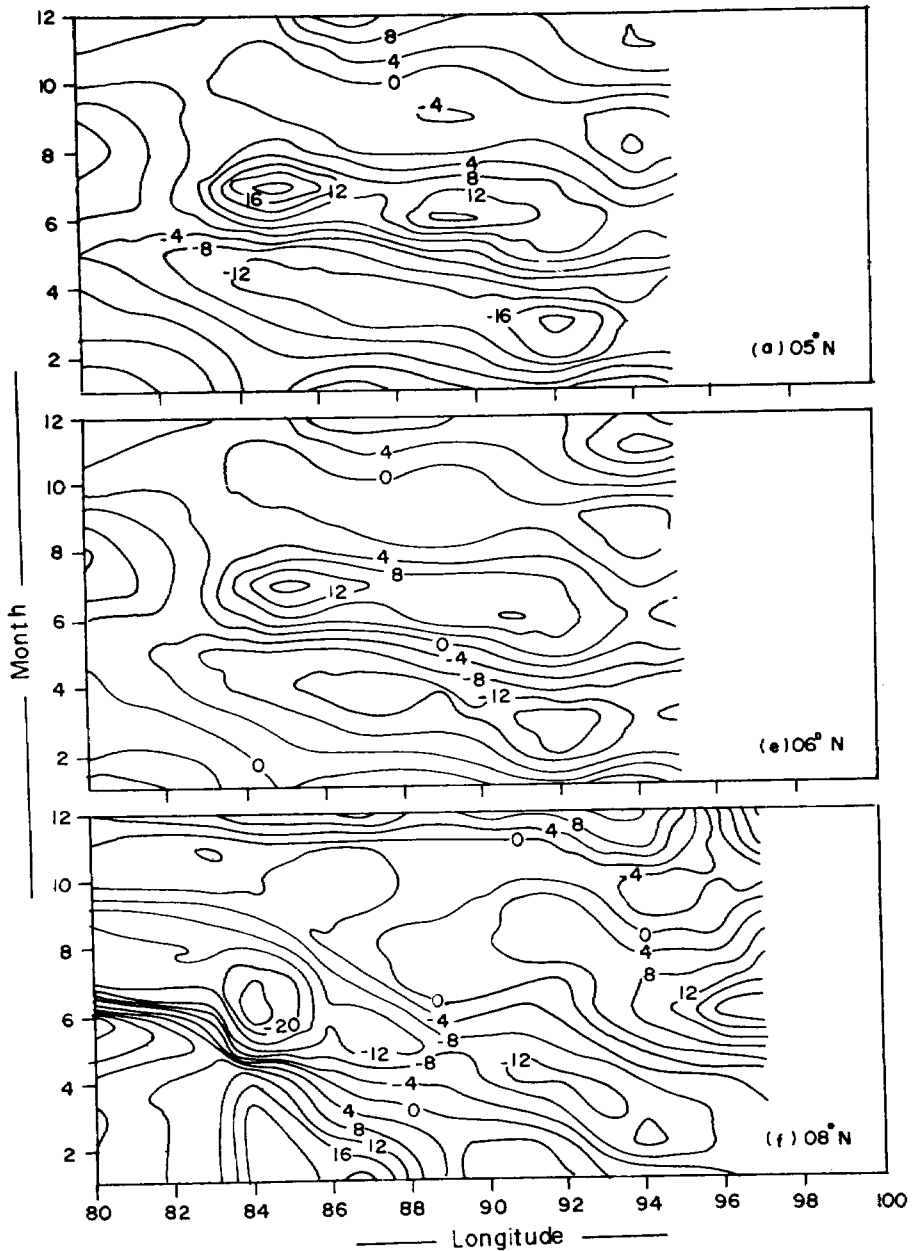


Fig.9. Continued.

shot thermal sections obtained along Chennai - Andamans section during 1991 – 1996, year-to-year variability is documented. These snapshot sections revealed significant year-to-year variability in features such as location and strength of the Indian Monsoon Current, intensity of coastal upwelling off Chennai coast and evolution of western boundary current. Further, thermal response of the upper ocean to the storm forcing is examined and revival time scales for the disturbed Bay to come back to its original state are documented

Considering the deficiency in the best known Levitus and Boyer (1994) temperature climatology for the Bay, a new climatology is made with nearly double the observations of LB94. This new temperature climatology is used to identify long Rossby waves in the Bay and the forcing mechanism for the generation of Rossby waves is examined. Westward propagating wave signals are observed in the Bay at all latitudes with dominant annual periodicity in most parts of the Bay.

Systematic XBT data collection for longer periods along fixed shipping routes must be continued to examine the inter annual variability of upper layer thermal fields. Modified temperature climatology need to be further improved by collecting voluminous data particularly in the eastern Bay. Similarly, salinity climatology also has to be developed. Long-term stationary position data sets are essential for complete understanding of Rossby wave characteristics in the Bay of Bengal.

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