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Variability of the oceanic boundary layer characteristics in the northern Bay of Bengal during MONTBLEX-90

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Abstract. Variability of the ocean surface boundary layer characteristics on daily time-scale is studied utilizing the 3-hourly hydrographic data collected at a stationary location (20°N, 89°E) in the Bay of Bengal during August (18th – 31st) and September (9th – 19th), 1990 under MONTBLEX-90 field programme. The daily variations of temperature, salinity, σ_0, mixed layer thickness, stability, heat content and rate of change of heat content in the upper 100 m are discussed in relation to prevailing weather (depressions) and hydrographic conditions (influx of fresh water, presence of eddies). The mixed layer thickness is examined through temperature- and σ_0-based criteria considering also the surface salinity in the latter. The T-based mixed layer thickness is always higher than that of σ_0-based thickness. The rate of change of heat content is also computed up to the depth of 20°C and 14°C isotherms which takes into account the vertical motion and hence divergence. With the development of a low into a deep depression close to the study area, intense upwelling of subsurface cold waters is noticed from 100 m to the bottom of the surface mixed layer (20 m) from 18th to 20th August. The upwelling is weakened by 21st August when the depression moved away from the study location. This variation of upwelling is supported by the variation of surface mixed layer thickness, static stability at 30 m depth, heat content in the upper 100 m and the heat content up to the depth of 20°C isotherm from 18th to 21st August. The rate of change of heat content in the upper 100 m and up to the depths of 20°C and 14°C isotherms leads to net heat storage during August and to net heat depletion during September. This together with the net surface heat gain lead to an import (197 Wm^{-2}) and export (233 Wm^{-2}) of heat during August and September respectively through horizontal advective processes. These advective processes are attributed to the presence and movement of a warm core eddy through the study location.

Keywords. Ocean boundary layer; Bay of Bengal; heat budget; heat content; warm core eddy; southwest monsoon; MONTBLEX-90.

1. Introduction

Upper oceanic boundary layer studies are important for understanding the momentum and heat energy exchanges between the ocean and overlying atmosphere. These exchange processes are further influenced by the prevailing weather disturbances. This is particularly true during southwest monsoon in the northern Bay of Bengal where many monsoon lows/depressions are formed/developed under the influence of the 'monsoon trough' which in general, lies along an axis passing through northwestern India up to the head of the Bay of Bengal. In order to understand the variability of the atmospheric as well as marine boundary layer in detail in relation to the monsoon trough (during the period of southwest monsoon of 1990 on the land and in the northern Bay of Bengal), an extensive observation program acronymed MONTBLEX (MONsoon Trough Boundary Layer EXperiment) was organized by the Department of Science and Technology (DST) in association with various national laboratories, institutions and universities. The important synoptic weather features like the shift in the location of the monsoon trough, cyclonic disturbances and the activity of the monsoon during the MONTBLEX-90 period have been documented by Gupta (1990). Rao and Murty (1992) studied the temporal variability of air temperature and water vapour content in the lower troposphere (up to 600 mb) over the northern Bay of Bengal at a stationary location utilizing the upper air data collected during MONTBLEX-90. Similarly, Sarma *et al* (1992) analyzed the surface meteorological data collected during the same experiment and showed that the sea surface gained heat during the observation period (18th – 31st August and 9th – 19th September, 1990) in spite of many cyclonic weather disturbances that prevailed in the study area. Murty *et al* (1993) studied the variability of upper (100 m) layer heat content and showed that the upper ocean lost 110 Wm^{-2} of heat during 18th – 20th August, 1990 and 1000 Wm^{-2} during 12th – 13th September, 1990 under the influence of depression/low during these periods. In addition, the presence of meso-scale eddies in the Bay of Bengal (Swallow 1983; Cutler and Swallow 1984; Rao *et al* 1987; Babu *et al* 1991) would also contribute to the variability in the heat and salt contents of the upper ocean. In this paper, we examine the temporal variability of the oceanic boundary layer characteristics in the northern Bay of Bengal during MONTBLEX-90 in relation to the prevailing weather and hydrographic conditions.

2. Data and methodology

The water temperature and salinity data collected using CTD probe (make: Sea Bird model SBE-11, USA) at 3-hourly intervals in the northern Bay of Bengal at a stationary location (20°N, 89°E; figure 1) onboard ORV *Sagarkanya* during the southwest monsoon period (18th – 31st August and 9th – 19th September) of 1990 under MONTBLEX-90 programme have been utilized. The accuracies of the CTD temperature and salinity sensors are ± 0·005°C and ± 0·002 PSU (Practical Salinity Unit) respectively. The data quality control procedures are detailed in Anon (1990). The daily averages of temperature,

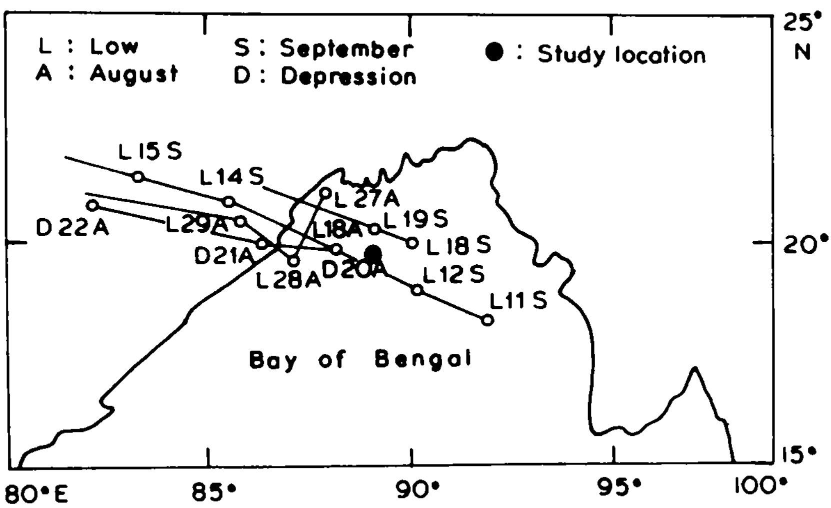

Figure 1. Area of study with trajectories of depressions.

salinity and σ_θ are obtained for the upper 100 m depth during August and September. The thickness of the surface mixed layer is obtained through two criteria. In the first criterion (temperature based) the thickness of the mixed layer is chosen as the depth where the water temperature is less by 1°C from the sea surface temperature following Murty *et al* (1992). Since the study area comes under the influence of a huge influx of fresh water and precipitation during the southwest monsoon, considerable variations in the salinity field occur which in turn affect the upper layer stratification thereby the mixed layer thickness. Hence, an alternative criterion based on σ_θ variation is adopted (Suga and Hanawa 1990) for determining the thickness of the surface mixed layer. This is the depth where the density is the surface density plus a chosen value. The chosen value is the increment in density obtained when the surface temperature is reduced by 1°C with salinity held constant.

The water stability (E) in terms of the Brunt-Vaisala frequency is computed from the changes in the daily averages of *in situ* density over a 10 m thick slab using the following equation (Pollack 1954):

$$E = g/\bar{\rho}[\mathrm{d}\rho/\mathrm{d}z - g\bar{\rho}/C^2],$$

where g is the acceleration due to gravity (9·8 ms^{-2}), ρ is the sea water density (kgm^{-3}), $\bar{\rho}$ is the mean density in the water column of dz, z is the depth (m) and C is the sound velocity (ms^{-1}) in sea water (Chen and Millero 1977).

The heat content of the upper water column is computed up to the fixed depth (100 m) and up to the depths of 20°C and 14°C isotherms using the following equation:

$$HC = \bar{\rho}C_p \int_o^D \Delta T \mathrm{d}z,$$

where C_p is specific heat of sea water at constant pressure, ΔT is mean temperature of the layer of thickness dz and D is the depth of the water column considered. The heat content above the chosen isotherm which takes into account the vertical motion and hence divergence in the water column (Emery 1975) is useful for the upper layer heat budget and correlates well with the net heat flux at the sea surface.

From the daily mean values of HC, the rate of change of heat content is estimated as:

$$HS = \mathrm{d}HC/\mathrm{d}t = (HC_{(i+1)} - HC_i)/(24 \times 3600),$$

where the subscript 'i' represents the day.

3. Results and discussion

3.1 *Salient weather features*

The weather during 18th – 25th August is dominated by monsoon depressions and low pressure systems over the north/northwestern Bay (Gupta 1990). A low was formed on 18th August about 150 km to the west of the study location and developed there into a deep depression by the 20th and crossed the coast near Paradeep on the morning of 21st (figure 1). The monsoon trough shifted to the foot of the Himalayas during 24th – 26th August and shifted southward during 27th – 30th August. During 10th – 11th September temporary northward shift of the monsoon trough was noticed and during 12th – 13th September a low passed over the study area (figure 1).

3.2 *Surface meteorological conditions*

The influence of the above weather conditions is clearly reflected in the daily variation of the surface wind field during August and September (figures 2a and 2b). With the development of deep depression the wind speed increased from 2 m/s on 18th August to 8 m/s on 20th August (figure 2a). The direction of wind was southwesterly initially, but under the influence of the deep depression exhibited a variation from southwesterly to southeasterly and southerly. With the northward shift of the monsoon trough the wind speed showed a gradual decrease from 21st to 26th August. A second maximum in wind speed with southerly direction was noticed on 29th August when the monsoon trough extended southward. During September also the higher speeds were associated with southerly winds (figure 2b) under the influence of a passing low.

The daily march of latent heat flux (Q_E) and the net heat flux (Q_N) at the sea surface during August (figure 3a) exhibited variations in accordance with the above weather conditions. Large latent heat flux (140 Wm^{-2}) and lower (60 Wm^{-2}) net heat gain (positive heat flux) occurred at the time of deep depression. It is also seen that the heat gain is decreased by about 80 Wm^{-2} from 18th to 20th August due to enhancement of latent heat flux by similar magnitude during the same period. As the monsoon trough moved northward the latent heat flux decreased and hence the net heat gain increased. Similarly with the southward shift of the monsoon trough the latent heat flux picked up and the net heat gain exhibited a decrease from 27th to 31st August. During September also, the latent heat flux and the net heat flux exhibited variations due to the prevailing weather conditions.

3.3 *Temperature*

The daily variation of temperature at selected depth levels (surface, 10, 30, 50, 75, 100 m) in the upper 100 m is shown in figures 4a and 4b for August and September respectively. The SST showed a gradual decrease of about 0·3°C from 29·1°C to 28·8°C under the influence of the low and deep depression from 18th to 21st August (figure 4a). The influence of this weather disturbance is felt up to a depth as deep as 100 m as seen from relatively lower temperatures up to 100 m depth from 18th to 22nd August. These lower temperatures are due to intense upwelling of cold waters in the upper 100 m water column. Gopalakrishna *et al* (1993) also reported storm-induced upwelling from about 80 m depth at a distance of around 110 km from the storm-centre. The slightly higher temperature differences between the surface and 30 m on 18th and 19th August are clearly due to the upwelling reaching the sea surface. After the disappearance of the depression from the study area, the SST slowly increased to 29·1°C by 25th August coinciding with the northward shift of the monsoon trough and consequent increase in net surface heat flux. With the increase of net heat gain and the reduction in the turbulent mixing due to winds, the temperature difference (between surface and 30 m) becomes minimum and leads to a thick isothermal layer occupying the top 30 m between 22nd and 31st August. Below this layer, the temperature increased rather rapidly from 22nd to 28th August at all the depth levels.

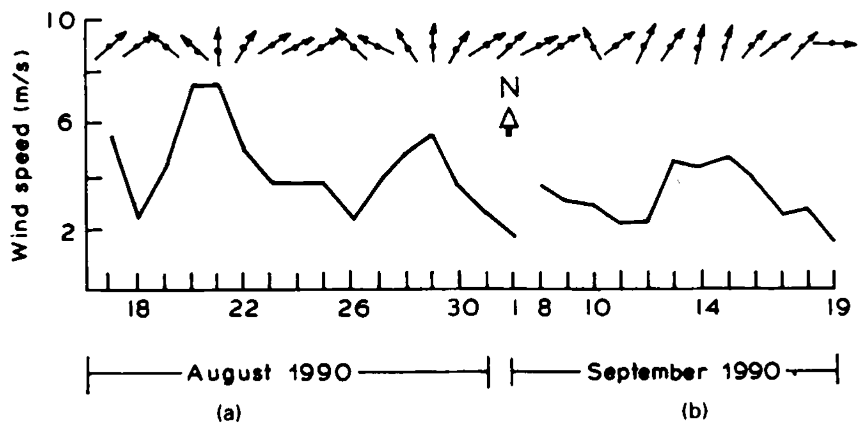

Figure 2. Variation of surface wind field during MONTBLEX-90 for August and September.

In September, the thick surface isothermal layer continued till the end of the observation period (figure 4b). Below this layer the temperature showed a gradual decrease from 11th to 17th at 50 m and 75 m depths. The temperature difference between surface and 50 m is low from 9th to 12th September and gradually increased to a higher value on 18th September. At 100 m the temperature varied between 21°C and 22°C.

While the decrease of SST is 0·2°C under the influence of a deep depression that developed close to the study area, the decrease of SST is 0·1°C when a low passed over the study area (12th – 13th September).

3.4 *Salinity*

In August, the daily variation of salinity shows a thin (10 m) isohaline layer in the top 10 m water column with its salinity increasing gradually from 31·9 PSU on 18th to 33·2 PSU on 26th August and then decreasing to 32·2 PSU by 31st August (figure 5a). The low salinity on 18th is due to the influence of fresh water influx from the northern Bay against the prevailing southwesterlies. The increase of salinity of the isohaline layer from 18th to 26th August could be due to mixing between the less saline fresh water and the relatively saline waters moving northward from the south of the study location (Murty *et al* 1992) under the influence of strong southeasterly/southerly winds associated with the depression and persistence of mixing after the cessation of strong winds. Large salinity differences are noticed from surface to 30 m depth on 18th only due to overlying low-salinity waters. At and below 30 m, salinity is slightly high (compared to the salinity on the next few days) from 18th to 21st supporting the upward movement of subsurface saline waters during the intense upwelling process as mentioned above. At 100 m salinity is uniform at 34·9 PSU. The minimum salinity difference between surface and 30 m depth from 23rd to 29th August suggests the thickening of the surface isohaline layer which is characterized by relatively high salinity.

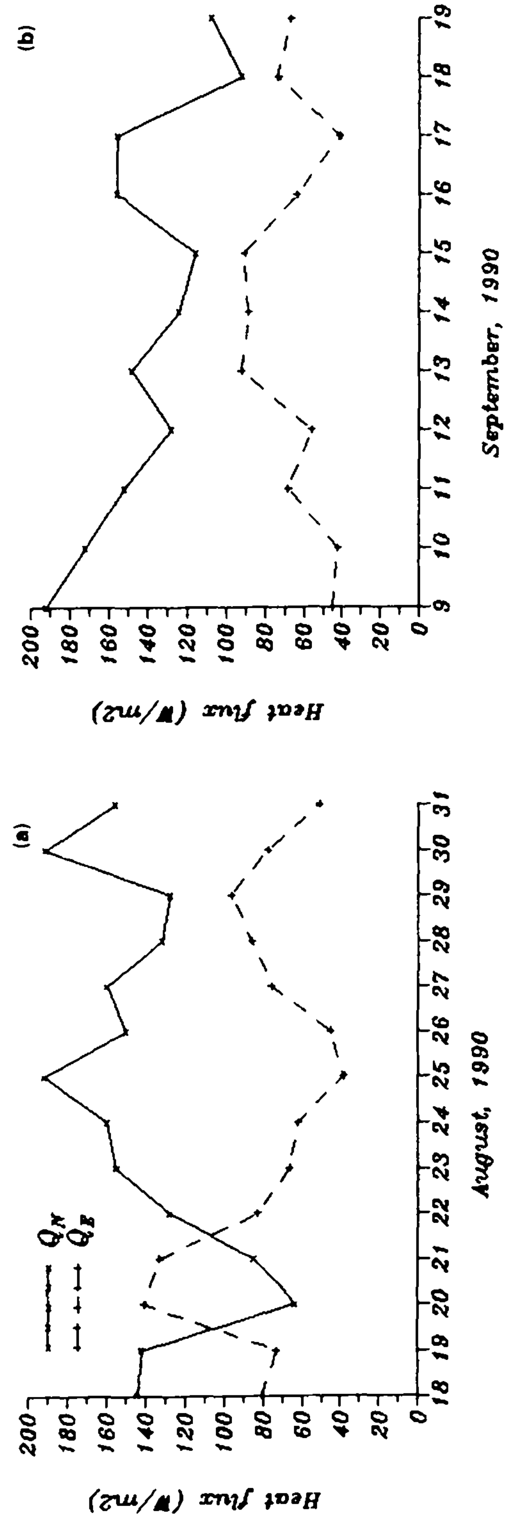

Figure 3. Variation of net surface heat gain (Q_N) and latent heat flux (Q_E) during MONTBLEX-90 for August and September.

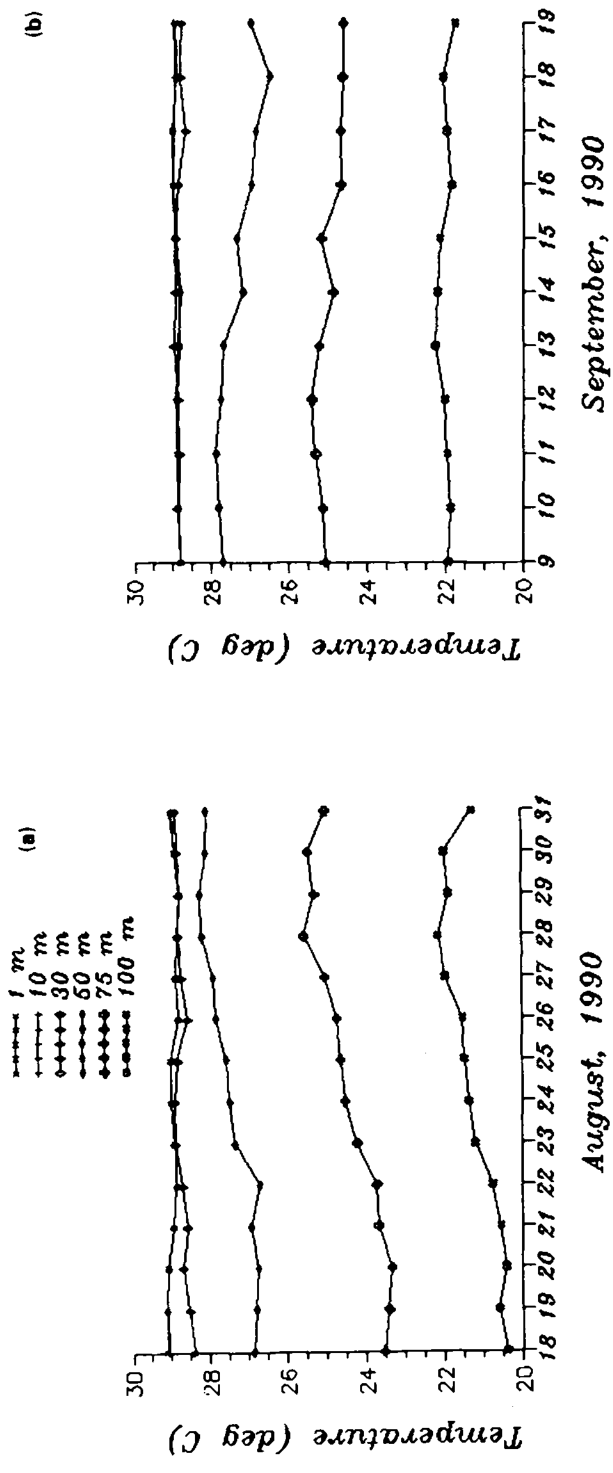

Figure 4. Temperature distribution in the upper 100 m during MONTBLEX-90 for August and September.

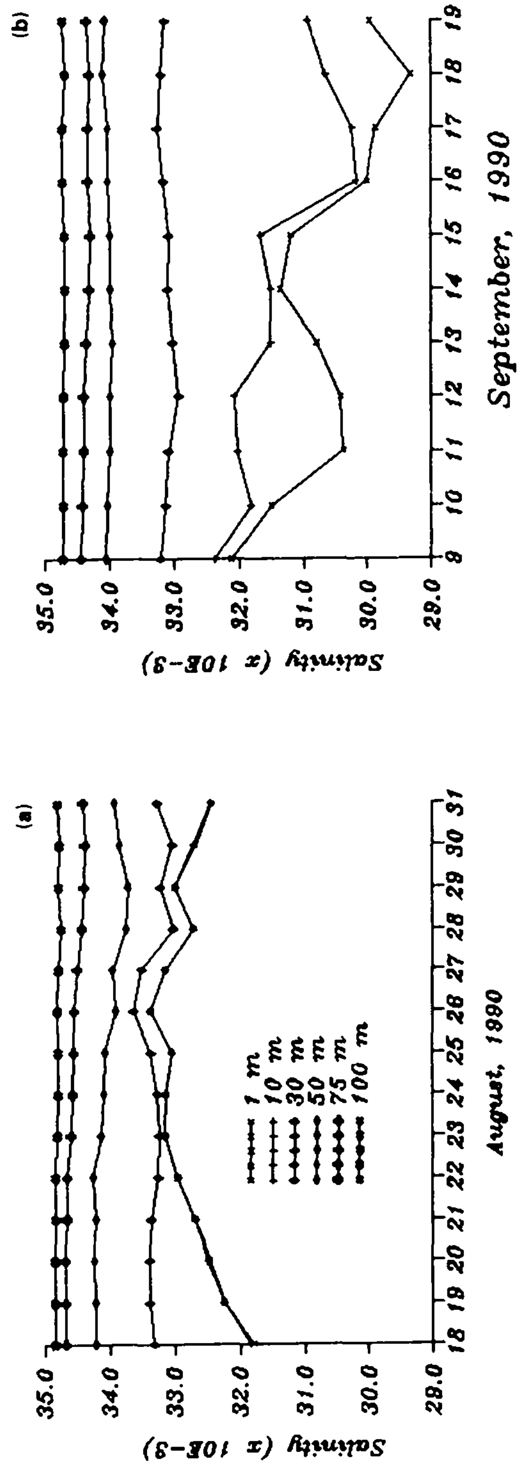

Figure 5. Salinity distribution in the upper 100 m during MONTBLEX-90 for August and September.

During September, a decrease of salinity in the top 10 m is clearly seen from 9th to 18th September coinciding with the period of the passing of a low and the relatively higher speeds of southwesterly/southerly winds (figure 5b). The salinity distribution at the surface and 10m indicates greater influx of fresh water towards the study location when compared to that in the top 10 m during August. The occurrence of slightly saline waters in the top 10 m from 13th to 15th September indicates the northward movement of southern saline waters and their mixing with the fresh waters of the north Bay.

The fresh waters at the study location are in general noticed at the times of lower winds both during August and September, though the southwesterly winds persisted. It can be noted that in general the thin isohaline layer is embedded within the thick (30 m) surface isothermal layer. At and below 30 m depth, the daily variations of salinity are small.

3.5 *Density anomaly* (σ_θ)

In the upper 30 m, the density variations are very closely related to the salinity variations both in August and September (figures 6a and 6b). Below 30 m, the dominant influence of temperature on the density distribution is noticed as salinity variations become small. The occurrence of denser waters at subsurface depths from 18th to 22nd August could largely be due to the intense upwelling processes under the influence of the development of a deep depression close to the study area. The decrease in density at 50 m, 75 m and 100 m depths from 22nd to 29th August indicates the presence of warm waters at these depths.

3.6 *Mixed layer thickness* (*MLT*)

The MLT obtained through the σ_θ-based criterion is lower than that obtained by the T-based criterion. The large differences between the two MLTs become more clear from the scatter plots (figures 7a and 7b) of the mixed layer thicknesses computed following the two criteria. During August, two types of clusters can be seen in the scatter plot (figure 7a); one cluster shows near linear relation when the fresh water influx is insignificant while the second cluster exhibits large scatter indicating the effect of stratification on σ_θ-based MLT. During September, the influx of fresh water has dramatically worsened the relation between the MLTs with σ_θ-based MLT remaining much lower than the T-based MLT. This underlines the importance of stratification in the northern Bay of Bengal in the mixed layer dynamics; any effort to model the mixed layer should invariably include salinity.

The daily variation of MLT during August and September is shown in figures 8a and 8b respectively. In August, both the criteria showed lower MLTs on 18th and increased very little by 20th August. The σ_θ-based MLT increased steeply to about 32 m from 21st to 24th August when wind speed exhibited a decrease. The variation of σ_θ-based MLT is in accordance with the wind speed between 27th and 31st August. The σ_θ-based MLT can be considered as the layer of dominant turbulent mixing due to winds at the surface as it coincided nearly with the thickness of the surface isothermal layer. In that case, the lower MLTs from 18th to 20th August indicate the dominance of the upwelling process over the turbulent mixing, though winds are strong during this period under the influence of the developing deep depression. The T-based MLT exhibited a gradual

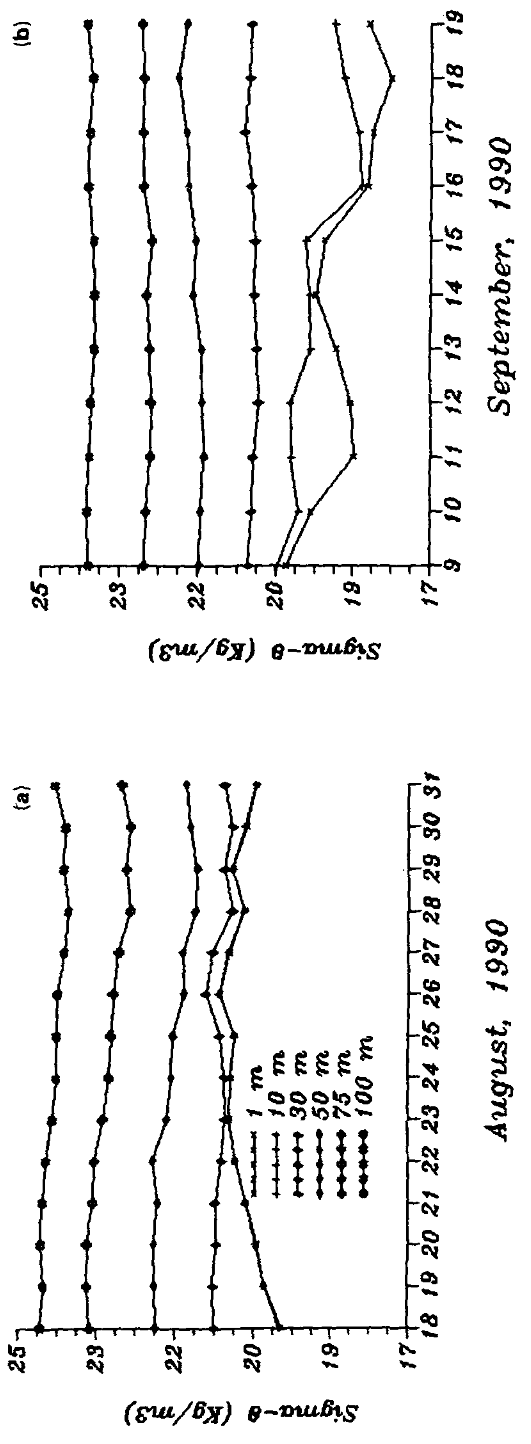

Figure 6. σ_θ distribution in the upper 100 m during MONTBLEX-90 for August and September.

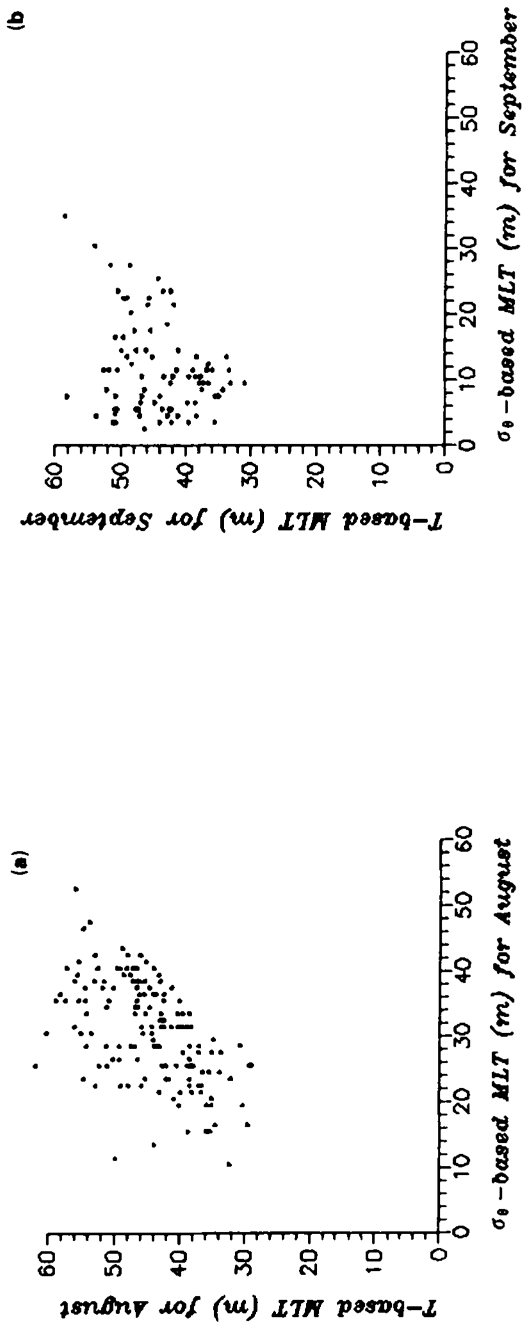

Figure 7. Scatter plot of T-based and σ_θ-based mixed layer thickness for August and September.

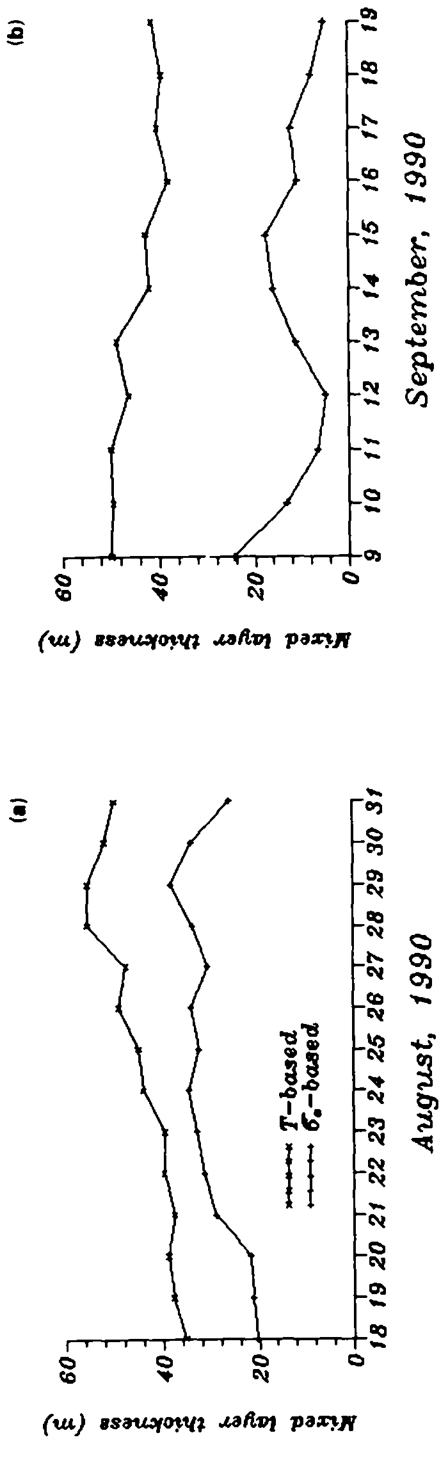

Figure 8. Variation of T-based and σ_θ-based mixed layer thickness during MONTBLEX-90 for August and September

increase from 21st to 29th August and the differences in both the MLTs increased beyond 24th August. The increase of T-based MLT indicates warming below the σ_θ-based mixed layer.

During September, the σ_θ-based MLT variation is in accordance with the wind speeds at the surface. The higher the wind speeds the higher the σ_θ-based MLT. Also, on the days of fresh water influx the MLT is low. The σ_θ-based MLT decreased from 24 m on 9th September (figure 8b) to 6 m on 11th September in association with low salinity waters at the surface. The increase of MLT during 12th – 14th September is due to vertical mixing under the influence of higher winds of the passing low. One can notice large differences between σ_θ-based and T-based MLTs though the latter exhibits a gradual decrease. This decrease in T-based MLT indicates the cooling below the σ_θ-based mixed layer as SST was stable throughout the period from 9th to 19th September.

3.7 *Stability*

The stability of the water column over a 10 m slab at various depth levels is shown in figures 9a and 9b for August and September respectively. In August, very low stability is noticed at 10 m depth as this depth lies within the surface mixed layer (figure 9a) in which vertical gradients of density are low. The stability is considerably high ($9{\cdot}5 \times 10^{-4}\,s^{-2}$) on 18th at 30 m depth (25 – 35 m slab) just below the σ_θ-based MLT and is associated with intense upwelling of colder waters giving rise to higher vertical density gradients. This higher stability at 30 m restricts the upwelling effect reaching the sea surface. The rapid decrease of stability at 30 m depth after 18th August is followed by an increase of stability at 50 m depth indicating the deepening of the mixed layer thickness. This suggests that the turbulent mixing is strong and influences a deeper water column. At 75 m and 100 m depths the stability is relatively lower than that at 50 m depth. This shows that the vertical density gradients are lower at these depths compared to those at 50 m. These weak density gradients must be due to warming at subsurface depths suggesting the active role of horizontal advective processes.

During September, the stability at 10 m and 30 m depths exhibited opposite variation (figure 9b) and their daily variation is closely related to the daily variation of mixed layer thickness. The high variability in stability at 10 m is a result from the large density gradients generated by freshwater influx. The stability at 50 m, 75 m and 100 m depths varied within a narrow range and the stability at 100 m lies in between that at 50 m and 75 m depths. The gradual increase of stability at 100 m from 13th to 19th September suggests the increase in vertical density gradients which in turn shows that the horizontal advective processes are dominant.

3.8 *Upper layer heat content*

Figures 10a and 10 b represent the daily variation of upper layer heat content during August and September respectively. In August, the upper layer heat content is low ($109 \times 10^8\,Jm^{-2}$) from 18th to 22nd and exhibits a decrease by about $0{\cdot}2 \times 10^8\,Jm^{-2}$ from 18th to 20th under the influence of the development of the deep depression. The corresponding heat loss would be about $110\,Wm^{-2}$ in 48 hours. It appears that this heat loss has been utilized for the enhancement of latent heat flux by nearly up to the same magnitude at the air-sea interface during 18th to 20th August (figure 3a),

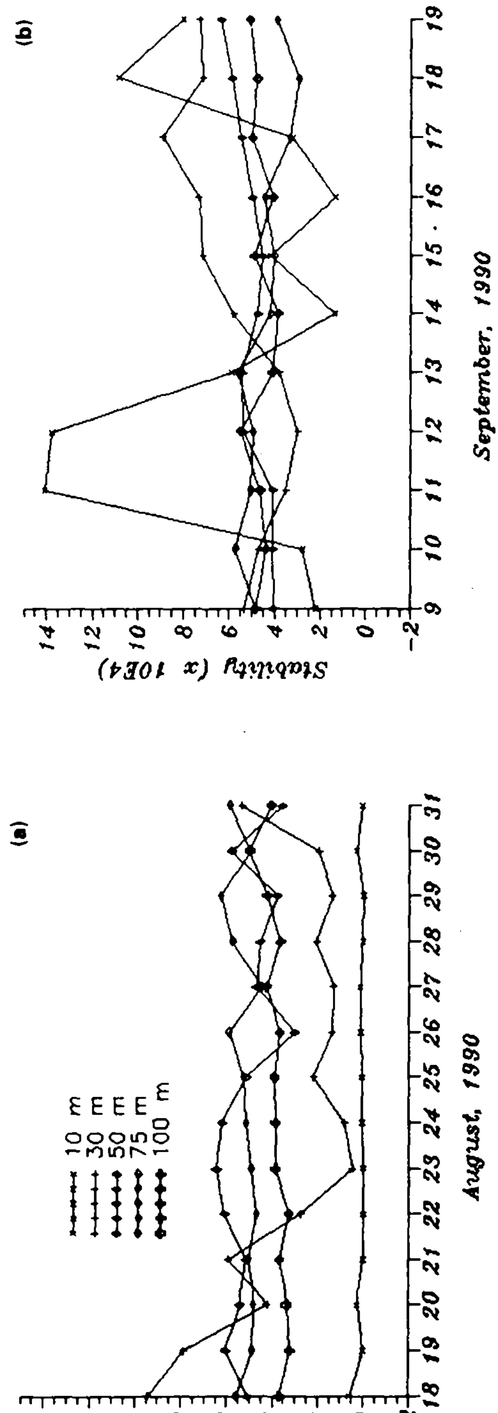

Figure 9. Stability distribution in the upper 100 m during MONTBLEX-90 for August and September.

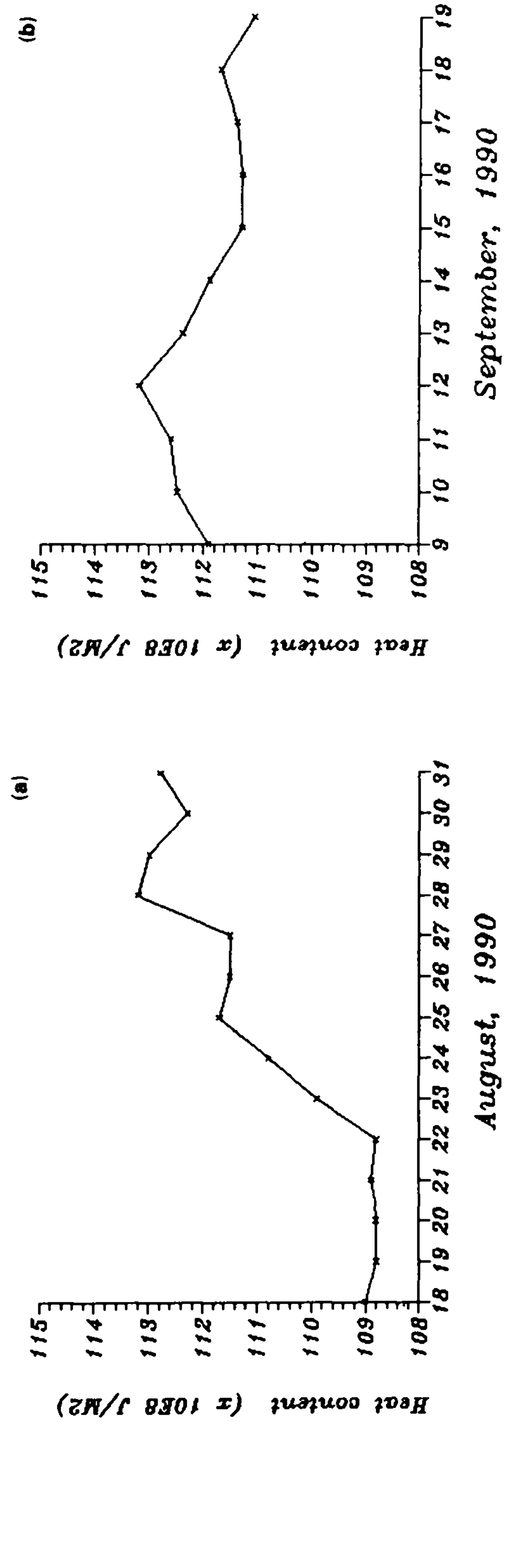

Figure 10. Variation of heat content in the upper 100 m during MONTBLEX-90 for August and September.

suggesting that the air-sea interaction is active with a positive feed-back from sea to air in the study area during this period. The heat content is invariant for the next two days, i.e. from 20th to 22nd August, and increased rapidly from 23rd to 25th August and gradually thereafter.

During September, the heat content in the upper layer increases from $111{\cdot}8 \times 10^8 \mathrm{Jm}^{-2}$ on 9th to $113{\cdot}5 \times 10^8 \mathrm{Jm}^{-2}$ on 12th September (figure 10b). It has decreased rapidly by 13th September when a low passed over the study location. However, the decrease of heat content is continued for the next two days, i.e. from 13th to 15th September, and exhibited an increase beyond 15th September.

When the variation of the upper layer heat content during August and September is examined in relation to the net heat flux at the sea surface during August and September, it is noticed that the increase (decrease) in the heat content is not entirely due to the increase (decrease) of net surface heat gain. It is also seen that the decrease of heat content at the time of depression and low is continued up to the next two days both during August and September. Further, at the time of decrease in the net heat gain the upper layer heat content is increased.

3.9 *Rate change of upper layer heat content*

The daily variations of rate of change of upper layer heat content during August and September are shown in figures 11a and 11b respectively. The surface layer loses (negative values) heat energy initially from 18th to 19th August and gains (positive) heat energy from 20th to 21st August due to the development of deep depression. This shows that the intense upwelling on 18th is weakened by 21st. Heat gain is dominant from 22nd to 28th August.

During September, heat gain in the upper layer is noticed initially and heat loss dominates from 12th to 15th. This is followed by weak heat gain and subsequently heat loss.

The mean values of the net heat flux (Q_N) at the sea surface, the rate of change of heat content up to a fixed depth of 100 m (Q_T), up to the depth of 20°C isotherm (Q_{T20}) and up to the depth of 14°C isotherm (Q_{T14}) for August and September are presented in table 1. During August the 20°C isotherm varied between 103 m and 117 m with the mean temperature of the column up to this isotherm varying from 25·55°C to 26·19°C. During September the 20°C isotherm varied between 107 m and 122 m with the mean temperature of the column varying from 25·66°C to 25·93°C. From the table, it is noticed that the sea surface gains heat energy to the tune of 141 Wm^{-2} both during August and September. The rate of change of heat content up to 100 m depth, however, indicates that the water column experiences a heat gain of 338 Wm^{-2} during August and heat loss of 93 Wm^{-2} during September. The rate of change of heat content computed up to the depth of 20°C isotherm (Q_{T20}) also shows a heat gain of about 950 Wm^{-2} during August and a heat loss of 170 Wm^{-2} during September. Extending the computations up to the depth of 14°C isotherm (Q_{T14}) also resulted in a heat gain during August and heat loss during September respectively.

The above mean values reveal that the water column considered receives excess heat energy over the net heat input at the surface during August and gives away more heat energy during September, though there is a net heat input at the surface. This suggests that there is import of heat towards the study location and export of heat from the study

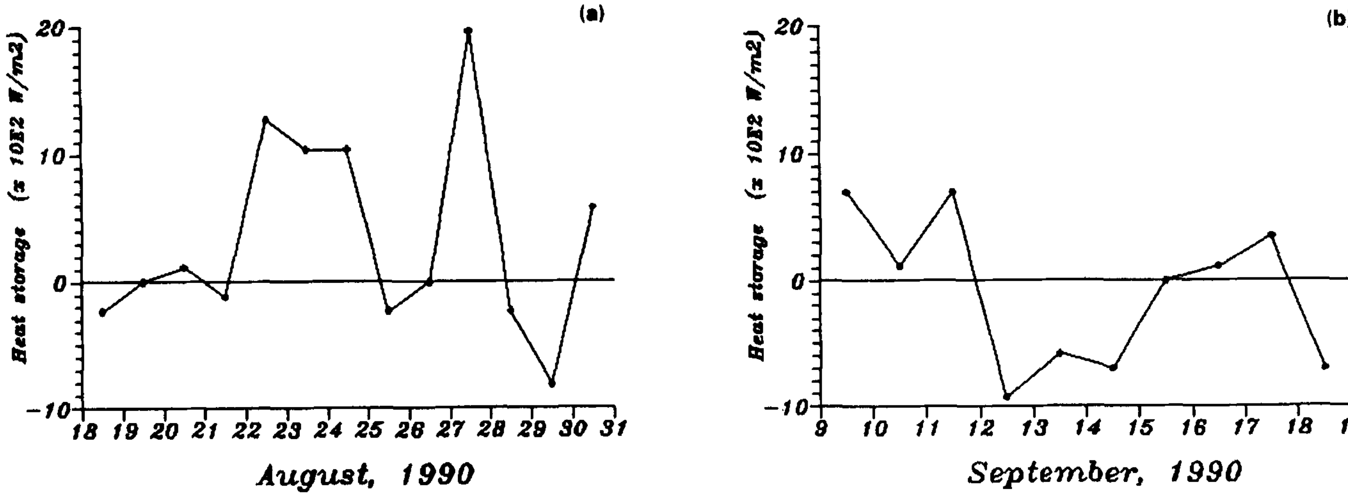

Figure 11. Variation of heat storage in the upper 100 m during MONTBLEX-90 for August and September. Positive (negative) indicates heat gain (loss).

Table 1. Upper ocean heat budget in the northern Bay of Bengal during southwest monsoon of 1990 (Q_N – net surface heat gain at the sea surface; Q_T – net heat storage in the upper 100 m; Q_A – heat import (+ ve)/export (− ve) due to lateral advective processes in the upper 100 m; Q_{T20} – net heat storage up to the depth of 20°C isotherm; and Q_{T14} – net heat storage up to the depth of 14°C isotherm). Units.: Wm^{-2}

Heat budget parameters	August	September
Q_N	141	140
Q_T	338	−92
Q_A	197	−233
Q_{T20}	950	−169
Q_{T14}	1039	−427

location due to lateral advective processes. On an annual scale the net heat input at the surface may be balanced by lateral heat export leaving out no local heat storage in the water column (Hastenrath and Lamb 1979a). However, on the seasonal or on shorter time scales it can be realised that the net heat gain at the sea surface (Q_N) will be utilized for the local heat storage (Q_T) and lateral heat export or import (Q_A) within the ocean (Hastenrath and Lamb 1979a), thus $Q_N = Q_T + Q_A$. From the mean values of Q_N and Q_T it can be estimated that the heat import during August amounts to 197 Wm^{-2} and heat export of 233 Wm^{-2} during September due to lateral advective processes (table 1) in the upper 100 m water column. Similarly, the Q_{T20} and Q_{T14} also indicate heat import during August and heat export during September, however with larger magnitudes compared to those in the upper 100 m water column. This shows that the trend of heat import during August and heat export during September are not altered even if the heat content computations were carried out up to a fixed depth level (100 m) or up to the depth of an isotherm, though the latter case takes into account the vertical movement of the isotherm and hence the vertical motion and the divergence in the water column above an isotherm. This suggests that the estimated heat import and export are mainly due to the lateral advective processes.

The above estimated heat import and export could be substantiated from the abrupt increase of mean temperature of the upper 100 m by about 0·8°C from 22nd August to 13th September and a decrease by about 0·2°C thereafter (figures 12a and 12b). The depths of the 26°C isotherm and 34·0 PSU isohaline have also shown a gradual deepening from 22nd August to 13th September and a gradual shoaling thereafter (figures 12c and 12d). A critical examination of the vertical movement of isotherms and isohalines in the upper 200 m water column during August and September reveals a similar trend of variation as that of the 26°C isotherm and 34·0 PSU isohaline. From these figures one can safely assume that the mean depths of occurrence of the isotherms and isohalines remained more or less unchanged from 31st August to 8th September though no data were available during this period. This observed deepening of isotherms and isohalines from 22nd August to 13th September indicates the advection of warm and less saline waters into the study area during this period which also gets its

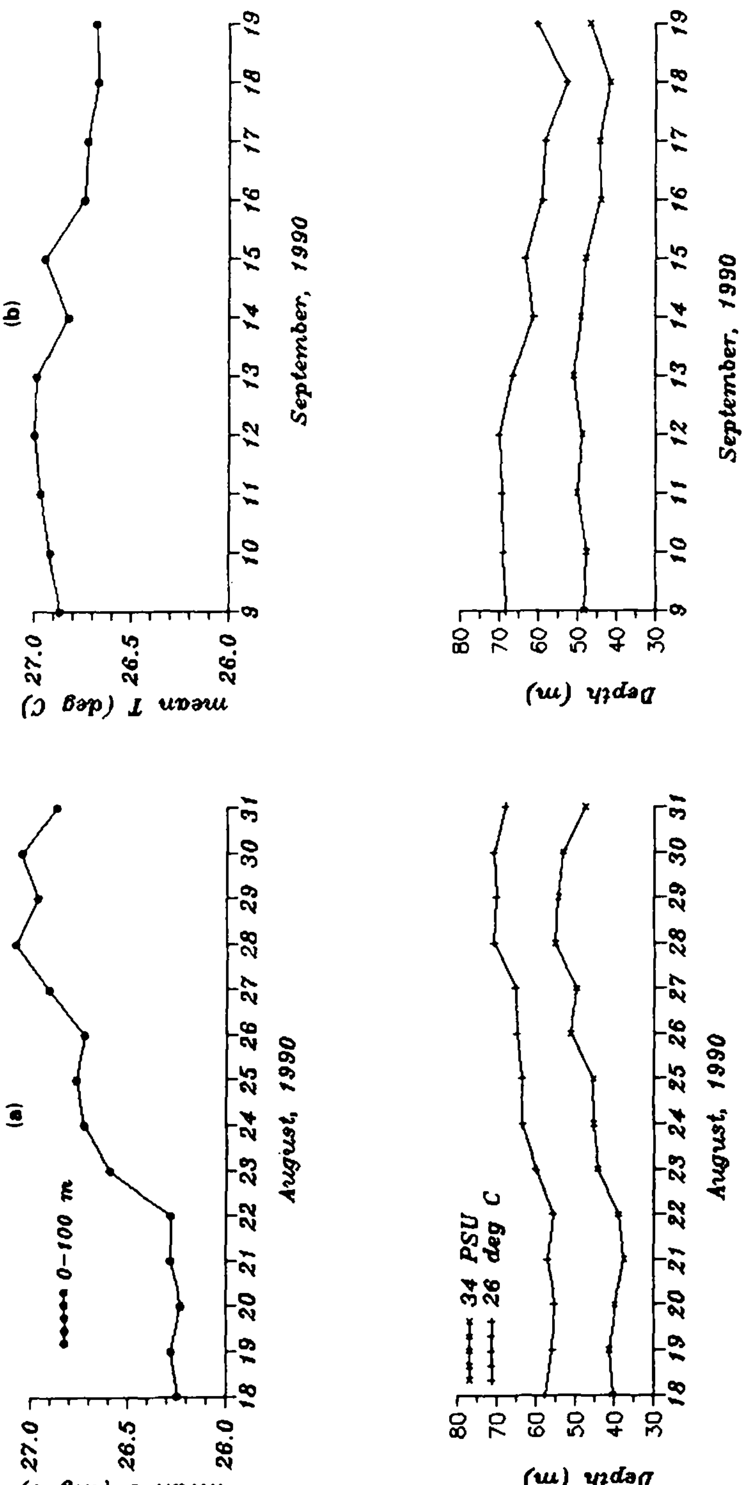

Figure 12. Variation of mean layer temperature and depths of 26°C isotherm and 34 PSU isohaline during MONTBLEX-90 for August and September.

support from the estimated heat import during August. The climatological wind stress curl (Hastenrath and Lamb 1979b; Babu 1987; Singh 1993) is positive which is conducive to divergence and hence to upwelling of cold waters. This rules out warm water sinking at the surface during this period. Hence, it can be inferred that the observed warming of the upper layers is due to the movement/advection of a warm core eddy (anticyclonic rotation) during 22nd August – 13th September towards the study location. The occurrence of peak values of depths of isotherms and isohalines on 28th August indicates that the core of the eddy was present at the study location on that day. Similarly, the decrease in the mean temperature in the upper 100 m, and the shoaling of the 26°C isotherm and 34·0 PSU isohaline beyond 13th September together with the estimated heat import during September can be attributed to the movement of the warm core eddy away from the study location. Earlier studies of Rao *et al* (1987) based on current meter measurements in the shelf region also infer the presence and movement of warm, less saline anticyclonic eddy in the northwestern Bay of Bengal during the southwest monsoon. However, more field observations are required to substantiate and adequately describe this oceanic feature in the northern Bay of Bengal during the southwest monsoon.

4. Summary and conclusions

The analysis of the data at a stationary location in the northern Bay of Bengal during the southwest monsoon of 1990 revealed two prominent events by which the oceanic upper layer characteristics are affected. Firstly, the intense subsurface upwelling of colder waters from a depth of 100 m is noticed during the development of deep depression at a distance of about 150 km from the study area from 18th to 20th August. The effect of depression-induced upwelling, however, has reached up to the base of the surface homogeneous layer. Because of this, the observed changes in SST are not large during the development period of deep depression. It is also highlighted that active air-sea interaction with positive feed-back from the sea to air prevailed during the development of deep depression wherein the heat loss from the surface layer is utilized to enhance the latent heat flux. Secondly, the advection of a warm core eddy, characterized by relatively less saline waters at its centre, towards the study area is inferred from the gradual increase of mean temperature of the upper layer, mixed layer thickness, and depths of the 26·0°C isotherm and 34·0 PSU isohaline from 22nd August to 13th September with the eddy centre at the study location on 28th August. The net heat loss from the upper layer during September without significant changes in the surface heat fluxes (when compared to August values) is then due to the movement of the eddy away from the study location on 13th September, which might also be aided by the passing low during 12th – 13th September. The lateral advective processes affecting the ocean boundary layer characteristics of the study area by bringing in heat during August and removing it during September are then clearly due to the presence and movement of the warm core eddy (through the study area) during the southwest monsoon – an important feature that has emerged from the MONTBLEX-90 programme in the northern Bay of Bengal. In order to adequately describe this oceanic feature and understand its role on the oceanic boundary layer characteristics more field observations in the northern Bay of Bengal during the southwest monsoon are suggested.

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