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Short term responses in ocean thermal characteristics during winter to atmospheric forcing and advection off Bombay, west coast of India

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The observed variability of meteorological forcing parameters and ocean thermal characteristics was examined in relation to MLD(mixed layer depth) and heat content based on time series data collected off Bombay during winter at 2 sites(deep and shallow) and vertical temperature sections. Both surface meteorological forcing and thermal variability were predominantly of semidiurnal and intra-semidiurnal periods. Delay for MLD shoaling and deepening in response to heating and wind stirring was more at deep site. Increased thermal variability and inversions between 80 and 150m characterised the deep site on the slope while well mixed warmer waters were present at shallow site on the shelf Differential heat advection of cold and warm waters above and below 80m at deep site and progressive mild cooling of shelf waters at shallow site were supported by probable warm and cold core eddy interaction and tidal flows.

Water characteristics in shallow and deep oceanic areas adjacent to the continental slope off west coast of India are greatly influenced by baroclinic adjustments related to the prevailing geostrophic flows during different seasons[1], interacted by coastal processes of mesoscale eddies and rotary currents. During winter regime, an anticyclonic vorticity exists in the Arabian Sea prior to the beginning of a reversal in the flow pattern by February/March[2,3]. Geographic features of the protruding Gujarat coastline engulfing the Bay of Cambay and the wide continental shelf south of it present topographic features conducive for the generation of mesoscale eddies[4], interacting also with the tidal streams superimposed on a coastal mean northerly/northwesterly flow. The influence of eddy like features and tidal flows on the thermal structure off the west coast of India and off Bombay has been earlier reported[5].

This paper presents the short term temporal and spatial variability of thermal structure and mixed layer depth (MLD) responses to the atmospheric forcing parameters of wind and heat fluxes along with the accompanying changes in heat content in the subsurface levels.

Materials and Methods

Mechanical bathythermograph (accuracy : ± 0.2°C and ± 5m) and TSK Micom bathythermograph (accuracy : ± 0.05°C and ± 3m) observations were made during 17-27 January 1986 (Fig. 1) on board *R V Gaveshani* (cruise 162). Time series positions were (i) deep, TS (D) at 18°50'N, 69°45'E and 1600m depth (site 1) and (ii) shallow, TS(S) at 18°50'N, 71°35'E and 80m depth (site 2). Spatial variation of the thermal structure was examined in vertical sections along 19°08'N and 18°50'N, covering the continental shelf and slope off Bombay. The standard surface marine meteorological observations of dry bulb, wet bulb and sea sur-

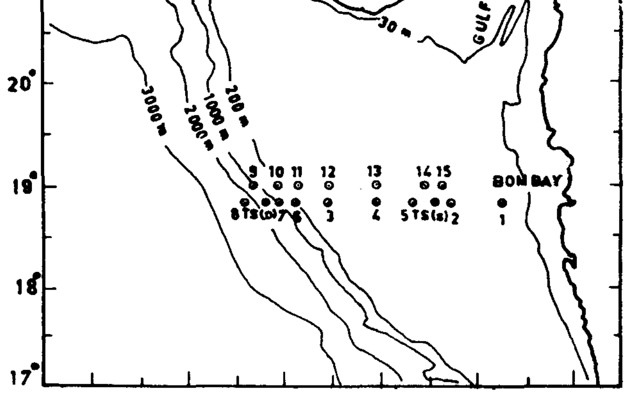

Fig. 1—Area map showing observation positions during 17-27 January 1986 off Bombay

face temperatures, pressure and wind were also made at all stations. Time series hourly/near hourly observations were made for nearly 72 h at site 1 during 19-22 January 1986 and at site 2 during 24-27 January 1986. Spatial observations were made in between the 2 time series observations. In the analysis of data, mechanical bathythermograph traces were utilised wherever Micom bathythermograph data gaps were observed. Bathythermograph data were quality controlled with reference to surface bucket temperature and reversing thermometer readings.

Heat budget components were computed using standard equations[6-9]. All downward fluxes were considered to be positive and upward fluxes negative. MLD was analysed as the shallowest depth where the temperature was less by 0.5°C from the sea surface temperature (SST). The heat content between any 2 depths in the water column was obtained using the relationship

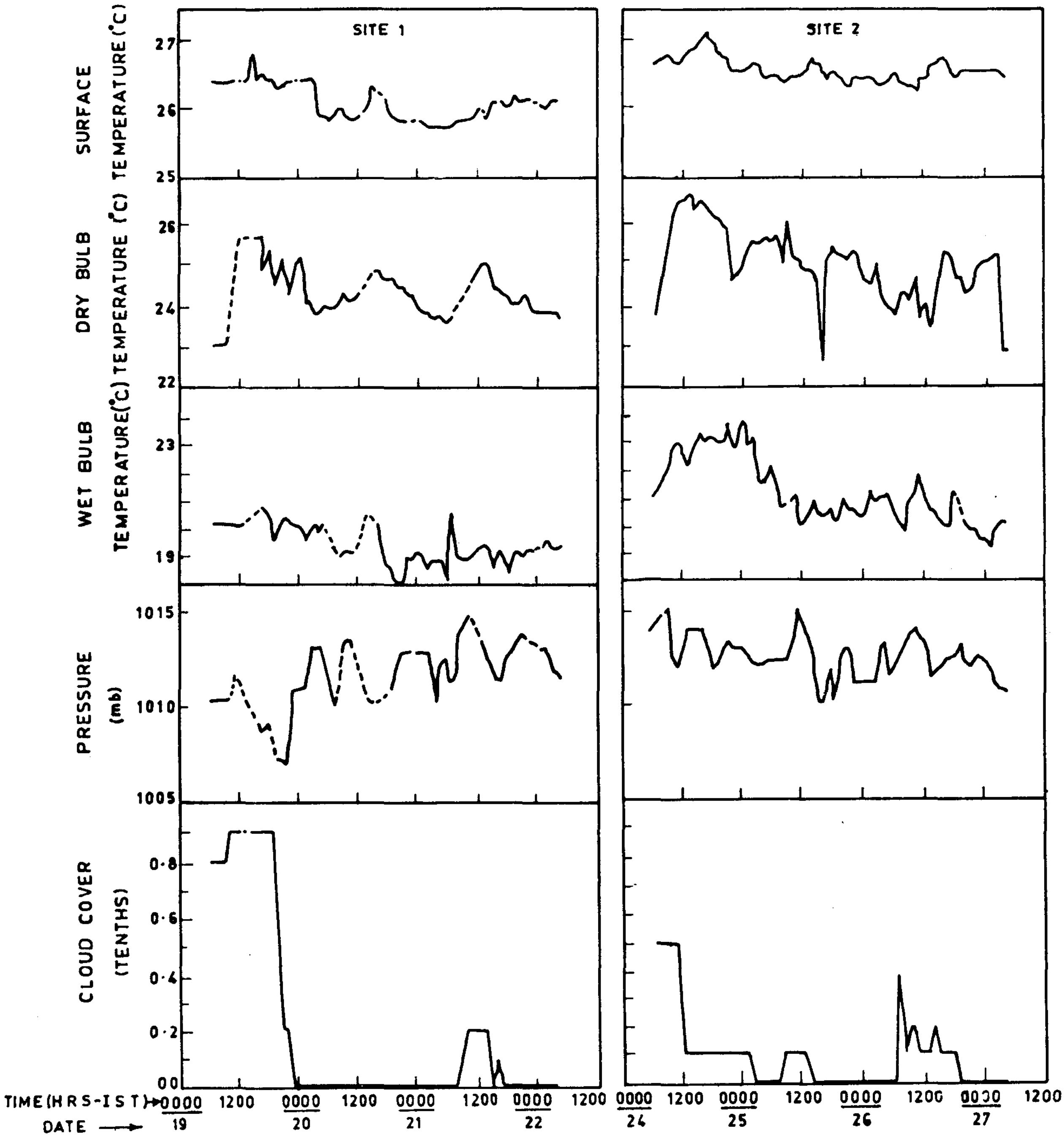

Fig. 2—Hourly march of standard surface meteorological parameters at sites 1 and 2

$$H = C_p \rho \int_{z_1}^{z_2} T dz$$

where H is the heat content, C_p is the specific heat of seawater at constant pressure, ρ is the mean density of the water column, T is the temperature of the seawater at any depth z and dz is the depth interval.

Results and Discussion

Synoptic variability of surface meteorological factors—At site 1 (Fig. 2), variability in SST (25.8°-26.8°C) showed diurnal amplitudes between 0.3 and 0.4°C, showing a progressive decrease of the magnitudes with time due to the probable cold water advection during 19-22 January 1986. The dry bulb and wet bulb temperatures also exhibited prominent diurnal and intradiurnal period oscillations with unstable and neutral air stability. Peaks in wet bulb temperature around noon on 19,20 and 21 January 1986 coincided with the wind speed minima (Fig. 3) resulting in the possible build-up of humidity. A weak low pressure disturbance on 19 January 1986 coincided with low wind speeds and increased cloudiness.

At site 2 (Fig. 2), SST (26.5°-27.2°C) was warmer and progressively decreased in time with diminishing amplitudes of diurnal variability (0.7° to 0.2°C)

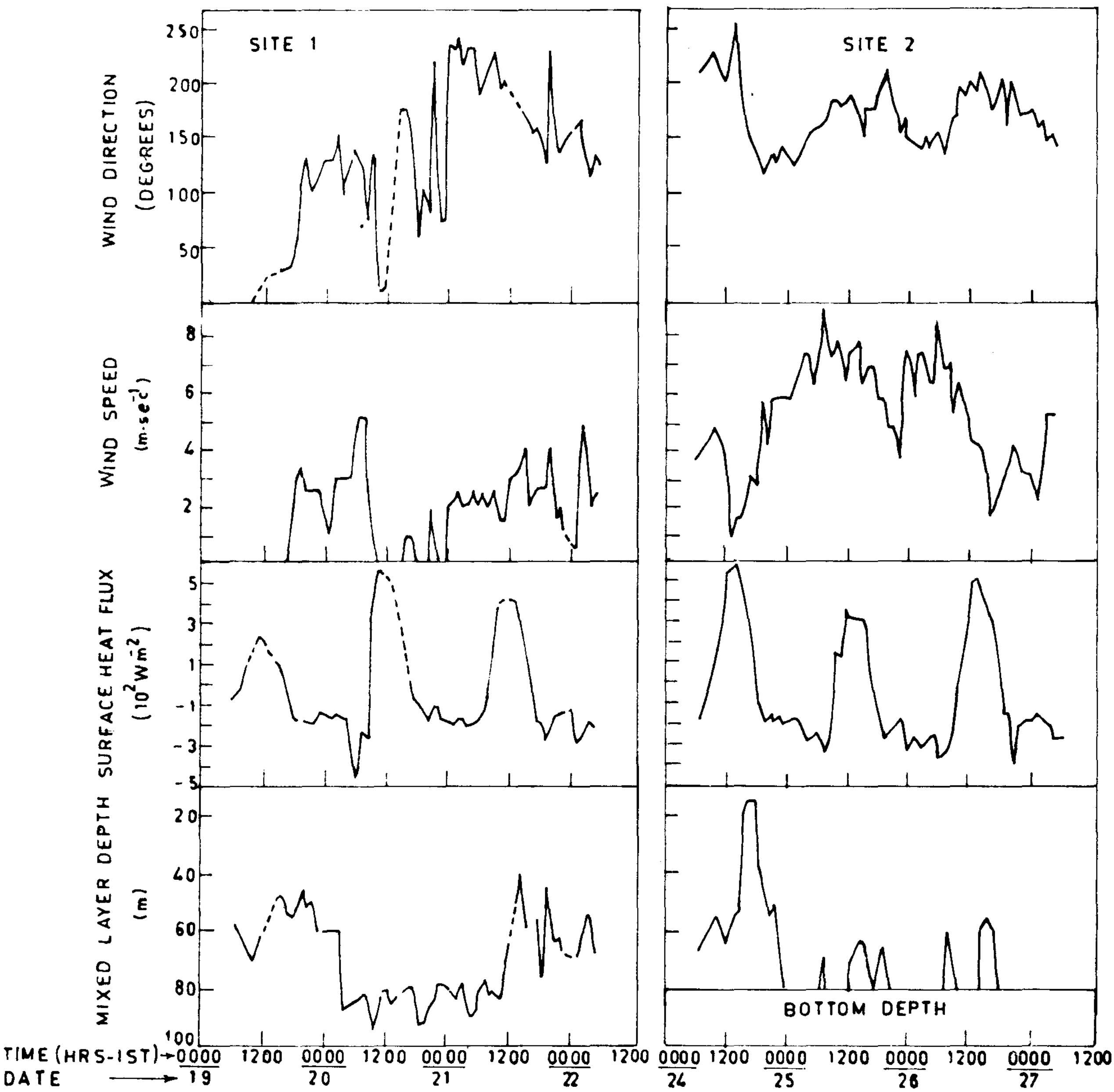

Fig. 3—Hourly march of surface wind, net heat flux and mixed layer depth at sites 1 and 2

during 24-27 January 1986. A similar decrease of dry bulb and wet bulb temperatures with progressive reduction in diurnal amplitudes was noticed while conditions of instability and neutrality prevailed. Increase in wet bulb temperature on 24 January 1986 and decrease on 25, 26 and 27 January 1986 were related to the minimum and maximum respectively of the wind speeds, together with building - up or depleting of moisture content. The pressure oscillations indicated the predominance of semidiurnal and intra-semidiurnal periods while clear skies prevailed, except for the first day.

Diurnal averages of SST at both sites indicated a progressive decrease of magnitudes in time till the end of the observations. The climatological values[10,11] of SST for the west coast area in the same latitude zones indicated a progressive fall in SST through January with a response delay of 1 month to the maximum cooling in December. The same was apparent in the observed SST variability at both the sites, eventhough a similar response to cooling was not noticed from the short period data set while advective influences were indicated.

MLD responses to wind forcing and heating—Low wind forcing (0-5 $m.sec^{-1}$) from the northerly, northeasterly and northwesterly directions at site 1, (Fig. 3) had mild increase on 20, 21 and 22 January 1986. Diurnal maxima of positive (210 to 560 Wm^{-2}) and negative (-300 to -450 Wm^{-2}) surface heat flux were related to short wave maxima around noon and night time increases of heat loss. The time variation in MLD (40-90 m) indicated a delay of 3 - 6 h in shoaling response to day time heating at calm or weak wind conditions as on 19 January 1986 and a delay of 8-12 h in deepening response to persistently increasing winds and convection as on 20 January 1986.

At site 2 (Fig. 3) northeasterly/northwesterly wind forcing exhibited variability (0-9 $m.sec^{-1}$) while changes in direction from easterly to westerly components occurred in harmony with the changing pressure gradients during land and sea breezes over the diurnal cycle. The variation of maxima of net heating (350-600 Wm^{-2}), and net cooling (-390 to -400 Wm^{-2}) reflected the dominance of short wave flux. MLD shoaling (up to 15 m) was conspicuous on 24 January 1986 at noon in the presence of weak winds. MLD deepening was resulted afterwards up to the bottom (80 m) from persistent increase in wind speeds with short spells of MLD shoaling above bottom (by 10 - 20 m) during noon heating. MLD shoaling in response to day time heating was delayed by 3-4 h, while MLD deepening in response to cooling was delayed by 6 h at the shallow site.

Thermal profiles—From the composite plots of thermal profiles (Fig. 4), during January 1986 increased thermal spread especially at the bottom of MLD and thermocline was apparent at site 1. Presence of warmer and isothermal waters, resulting from increased mixing up to the bottom with relatively narrow spread of temperatures, was unique at site 2. Thermal profile variation at site 1 (Fig. 5A) also reflected MLD variability, perturbed mainly by diurnal and semi-diurnal period oscillations. Increased presence of inversions between 80-150 m or below also indicated the probable influence of warm advection between these levels. In contrast, higher degree of mixing of shelf waters up to the bottom was indicated by the isothermal profiles at the shallow site (Fig. 5B).

Time variability of thermal structure—The time variation in isotherm depths (Fig. 6) provides a different view of the progressive changes in thermal structure at sites 1 and 2. At site 1 (Fig. 6A) cooling of surface layers up to 80 m was apparent by the surfacing of 26°C isotherm alongwith the warming of the layers below, as evident by the convergence of isotherms between 22 and 25°C after 20 January 1986. The isotherm variability at the shallow site (Fig. 6B) was minimal with weak stratification (gradients < 0.5°C), purturbed mainly by semi-diurnal/ intrasemidiurnal oscillations.

At site 1, the difference in temperatutres between surface and 80 m decreased after 20 January 1986 with a mild increase thereafter, while the difference in temperature between 80-150 m showed a general increase during the same period. Minimum temperature differences between different levels up to 70 m and their progressive mild decrease after 25 January 1986 were observed at site 2.

Variability of heat content—The features discussed above are also manifested in the computed heat content variations for the 2 sites (Fig. 7). The observed mean surface and subsurface variations of

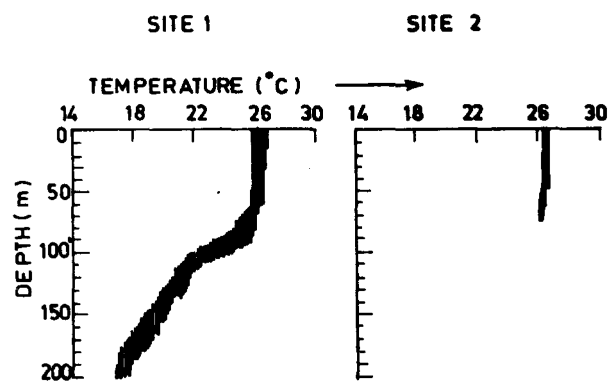

Fig. 4—Composite plots of temperature versus depth for sites 1 and 2

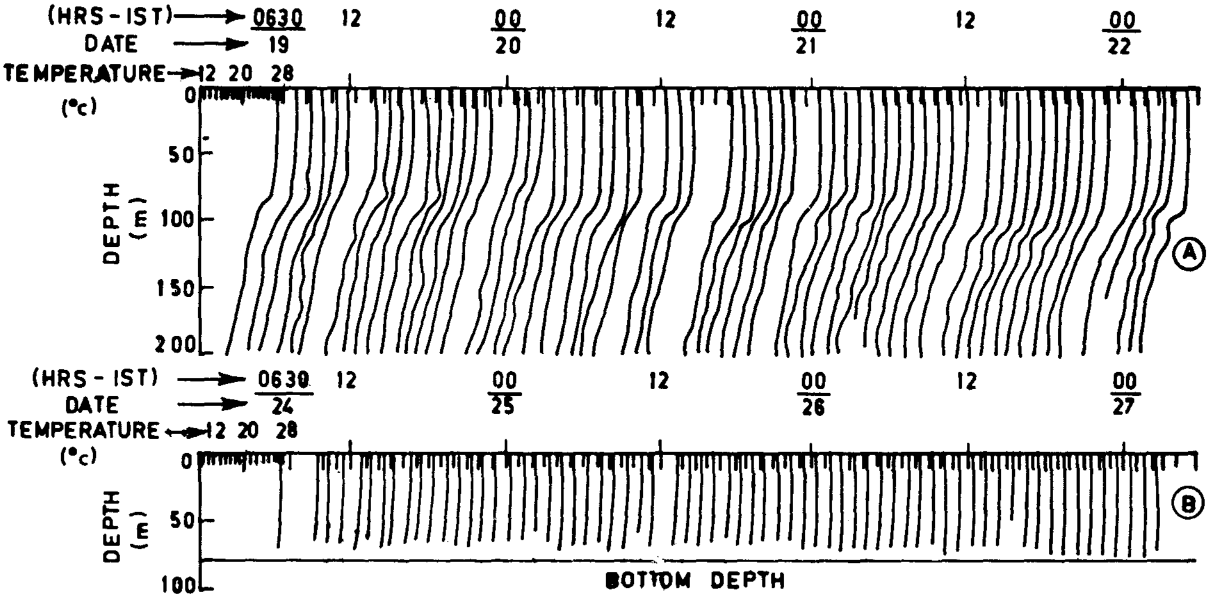

Fig. 5—Time variation of observed temperature profiles at (A) site 1 and (B) site 2

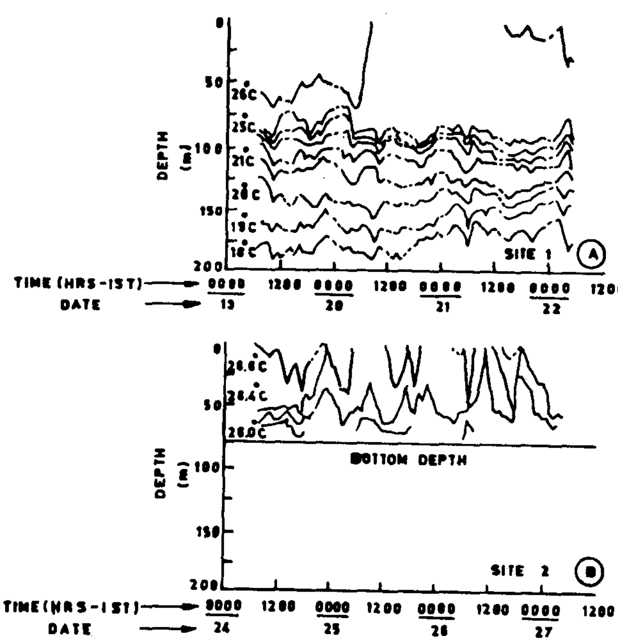

Fig. 6—Time variation of isotherm depths at (A) site 1 and (B) site 2

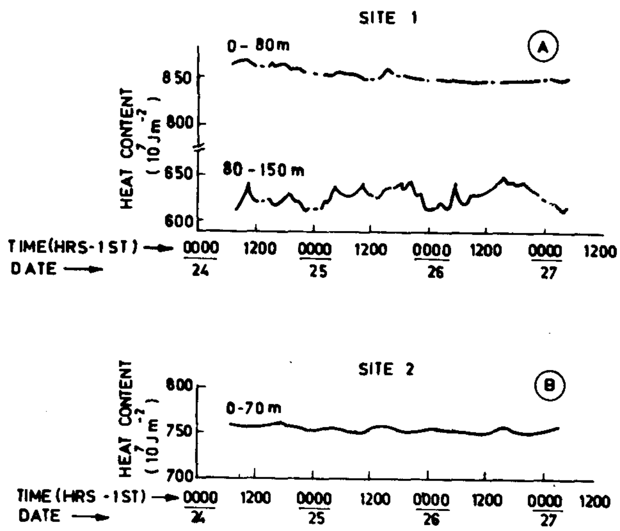

Fig. 7—Time variation of heat content (A) between 0-80m and 80-150m at site 1 and (B) between 0-70m at site 2

heat content at both sites over the diurnal/intradiurnal oscillations were not resulted directly from the surface fluxes (Fig. 3), but were from lateral advective fluxes. The differential heat advection between 0 and 150m was also reflected in the isotherm and profile variations, especially at the deep site by the presence of temperature inversions between 80 and 150m.

Spatial variability of temperature and advective influences—Spatial sections of temperature along 18°50'N and 19°08'N (Fig. 8) provide inferences on mean flow across the latitudes in addition to the spatial variability, by means of the slopes of isotherms, as temperature plays dominant role in deciding density currents[12]. Northerly mean flow with the continental shelf was indicated along with the wavy patterns at the edge suggesting the presence of mesoscale eddies, domes corresponding to anticlockwise vortices and troughs corresponding to clockwise vortices. Differences in vertical advection by warm water sinking (anticyclonic) at st 6 and cold water upwelling (cyclonic) at site 1 (Fig. 8A), adjacent to each other and their lateral interaction, being restricted by the steep bottom gradients of the slope below 80m might have resulted in the thermal inver-

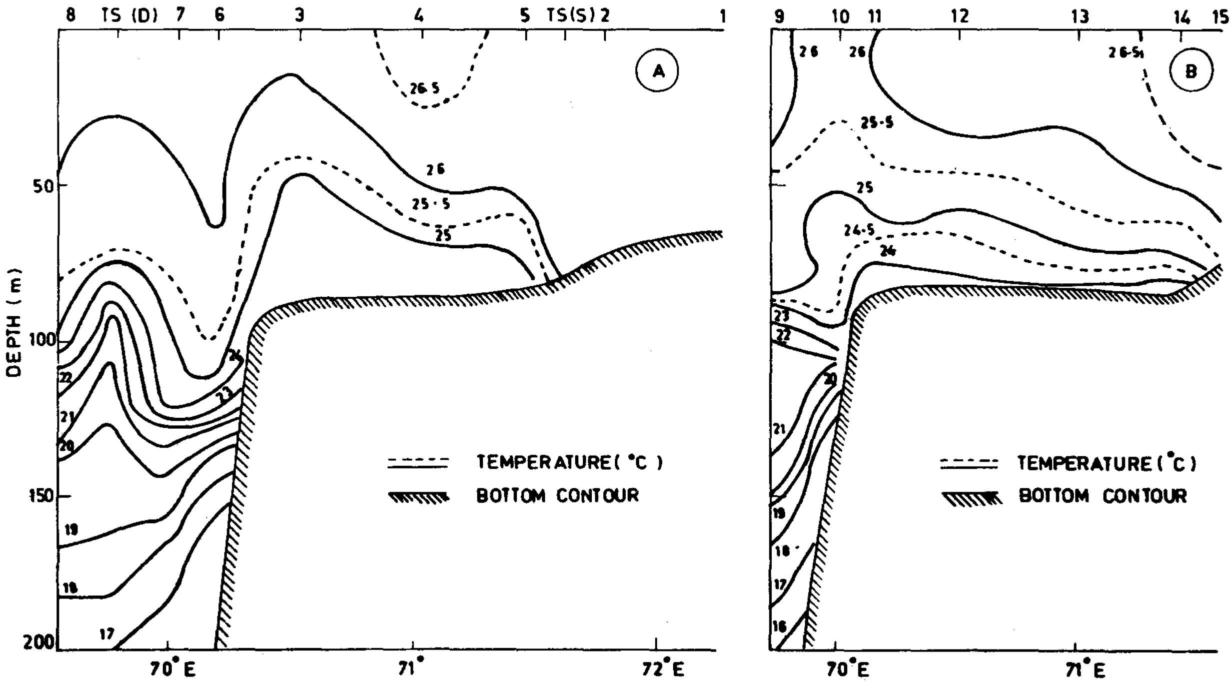

Fig. 8—Spatial sections of temperature along 18° 50'N (A) and 19°08'N (B)

sions observed below this level (Fig. 5A) at the site 1. The presence of cold core eddy at the outer slope, prominent above 80m, might be the source for cold advection above 80m at the same site. The presence of cold core eddies (anticlockwise) at st. 3 (Fig. 8A) and at st. 10 (Fig. 8B) on the outer shelf and their shoreward translation possibly produced the reduction in heat content by cold advection at site 2. The nature of cold and warm water perturbations observed at the continental shelf and margin appears similar to that reported in the Gulf of Mexico[13,14] and off Australian coast[15]. The contribution from the rotary tidal flows to the differential thermal advection at different levels also cannot be ruled out.

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