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Thermohaline and current structure off Cochin during December 1986

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Time series measurements of surface meteorological elements, vertical temperature and salinity profiles and subsurface currents at selected depths, made at a station off Cochin (depth 65 m), were utilised to describe short-term variability of these parameters during 4-8 December 1986. The vertical temperature profiles were nearly isothermal but showed diurnal perturbations of about 0.5°C in the upper layers. The salinity structure showed influx of Bay of Bengal/Equatorial Indian Ocean waters carried by the prevailing northerly current. The currents at all depths were northerly against the local wind direction, with speeds over 40 cm.sec^{-1} at 10 and 20 m depths during the first 2 d. The currents exhibited semidiurnal periodicity indicating predominance of semi-diurnal tide. The vertical current shear was maximum between 10 and 20 m depths which also decreased with the weakening of the flow from 6 to 8 December.

The unique wind and current system during summer causes significant upwelling off the southwest coast of India while sinking is noticed during winter despite northerly winds[1,2]. On a seasonal cycle, the variability in the upper oceanic characteristics off the southwest coast of India is quite large both in temperature (22°C-31°C)[2,3] and in salinity[4] ($30\text{-}36 \times 10^{-3}$) fields. However, corresponding information on surface and subsurface currents is meagre due to lack of direct measurements. The present knowledge of current structure in the northern Indian Ocean is limited to the surface layer on a monthly mean basis in the form of atlases, which are prepared from ship drift data[5,6]. Other sources include dynamic topography charts[7,8], drifting buoys[9] and few direct current measurements at selected locations[10-17]. Though several attempts have been made to study the spatial and seasonal variability of hydrographic conditions off the west coast of India and particularly off Cochin[1,18], the corresponding information on the intra-seasonal or short-term variability is not available. In the present study it is attempted to describe and document the short-term variability of temperature, current and salinity fields at a station off Cochin during early December.

Data

RV Gaveshani was anchored off Cochin (09°57'N, 75° 45'E; station depth, 65 m) from 4 (1100 hrs) to 8 (1200 hrs) December 1986. The standard surface marine meteorological elements, viz. atmospheric pressure, total cloudiness, wind speed and direction dry and wet bulb temperature and sea surface temperature (SST) were collected at hourly intervals. A MICOM BT (T S K —Japan; accuracy ±0.05°C) was used for hourly observations of subsurface temperature. Subsurface salinity was determined from the hydrocast made at 1200 hrs every day. Four Aanderaa current meters (Model RCM-4) were moored at 10, 20, 30 and 50 m depths for measuring speed and direction of currents at 10 min interval.

Results and Discussion

The intra-diurnal and synoptic scale variability of ocean thermal structure is mostly influenced by the prevailing atmospheric conditions through forced (wind stress) and free (buoyancy effects) mixing. To assess the role of surface heat energy exchange processes at the air-sea interface on the subsurface thermal structure, cumulative heat flux (ΣQ), SST, heat content of the upper 50m water column (HC_{50}) and the depth-time section of the temperature are studied (Fig. 1). The details of the heat budget computations are given in Joseph *et al*[19]. Heat content down to 50 m (the deepest point where the temperature data are available) is computed using the expression

$$HC_{50} = \rho C_p \int_0^z T_z \, dz$$

where ρ is the mean density of the water column, C_p the specific heat at constant pressure and T_z the mean

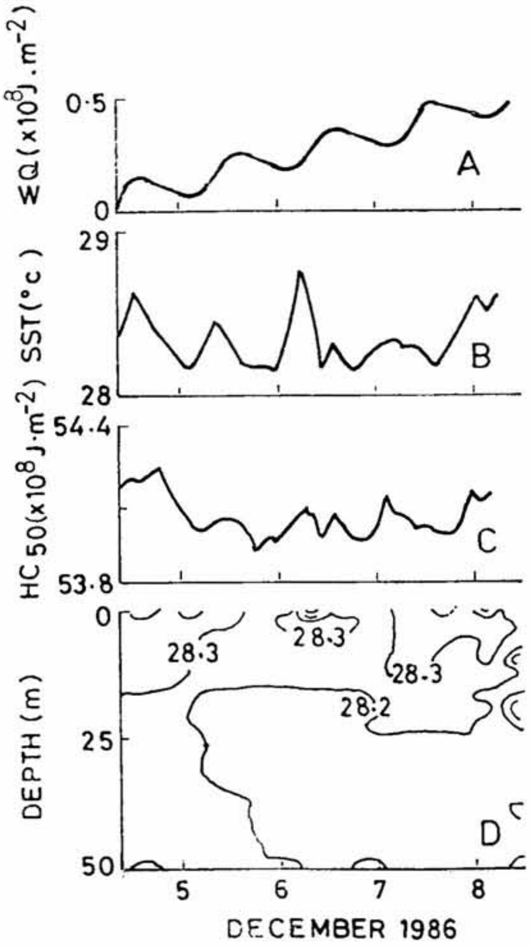

Fig. 1—(A) Cumulative heat flux (ΣQ), (B) time series of heat content of the water column down to 50 m (HC_{50}), (C) time series of sea surface temperature (SST) and (D) depth-time section of temperature

temperature of the water column of the depth slab dz. In this study dz is taken as 10 m. Isotherms in the depth-time section of temperature is contoured at 0.1°C interval.

ΣQ (Fig. 1A) showed heat accumulation of 0.5×10^8 $J.m^{-2}$ during the 4 d observational period. This accumulated heat can increase the temperature of the 50 m water column by 0.25°C. However, such an overall increase was not observed either in SST (Fig. 1B) or in HC_{50} (Fig. 1C). But the diurnal heating/cooling cycle was clearly reflected in SST and HC_{50}. Most of the observational dates were characterised by higher winds (> 5 m. sec^{-1}) and cloudy sky (4 octa) except on 7 December. The near zero winds (1.5 m.sec^{-1}) and clear sky (1 octa) on 6 December caused the trapping of radiation in the upper thin layer and resulted in the maximum diurnal amplitude of SST. However, HC_{50} did not exhibit the corresponding variability due to the occurrence of the middle level cooling in the thermal structure (Fig. 1D). Fig. 1D also revealed that cooling started at middle layers (depth 15-20 m) on 5 December which extended up to 50 m depth. The heating/cooling cycle limited to the top thin layers (10 m) caused small scale thermal inversions which are clearly evident from Fig. 2. In general, the thermal structure was nearly isothermal as expected from the climatological studies[1,4].

The mean salinity profile (Fig. 3) showed waters $< 34 \times 10^{-3}$ which is much lower than the salinity of typial Arabian seawater[8]. Darbyshire[4] and Pankajakshan *et al.*[20] reported advection of low saline Bay of Bengal/Equatorial Indian Ocean waters into the eastern Arabian Sea during winter. This results in a reduction of salinity by about 2×10^{-3} in the upper 30 to 60 m column off the southwest coast of India during this period, compared to the southwest

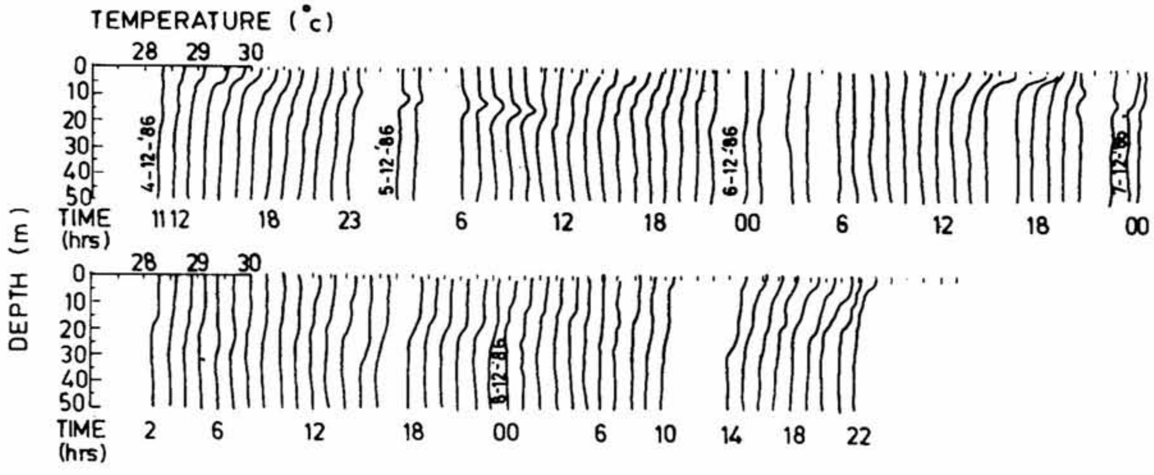

Fig. 2—Time series of hourly vertical temperature profiles

monsoon conditions. In the present data set, low saline waters were observed down to 60 m, whereas Murty and Madhusoodanan[21] noticed the thickness of this water column only down to 30 m during January 1985. This could be related to the year to year variations in current pattern, as well as to the characteristics of waters transported. The reason for a mild subsurface salinity maxima (34×10^{-3}) around 15 m depth is not clear.

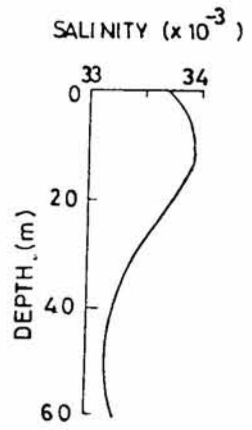

Fig. 3—Mean vertical salinity profile

The time series of current vectors recorded at 10 min. intervals (10, 20, 30 and 50 m) are presented in Fig. 4. In general, the currents were stronger (about 40 cm. sec^{-1} on 5 and 6 December) at 10 and 20 m compared to the currents at 30 and 50 m. Though the flow was oscillatory at all depths, it was more prominent at 20 m. The current direction was consistently northwards during this period, which is in marked contrast with the observations of Premchand[13]. He noticed highly variable currents off Cochin (20 m) during January-February 1982. The increased bottom friction and proximity of land might have contributed to more oscillatory currents at shallower depths[13]. A drastic decrease in the current speed was observed at all depths after 1200 hrs on 6 December 1986. This implies the rapid changes in the local circulation pattern in the study area. The subsurface cooling noted in the thermal structure (Fig. 1d) has to be viewed as the manifestations of these variations in the flow field.

The vector averaged surface wind and subsurface currents at 10, 20, 30 and 50 m are given in Table 1. The prevailing wind was northerly (mean direction: 15° and speed 3.6 m.sec^{-1}) and subsurface currents were north-northeasterly with maximum speed ($\bar{u}$ = 9 cm.sec^{-1} and $\bar{v}$ = 19.6 cm.sec^{-1}) and variability (σu = 9.2 cm.sec^{-1} and σv = 12.3 cm.sec^{-1}) in the surface layers (upper 10 m). The mean monthly surface current charts[5,6] show a southerly flow off Cochin from March to September and northerly flow

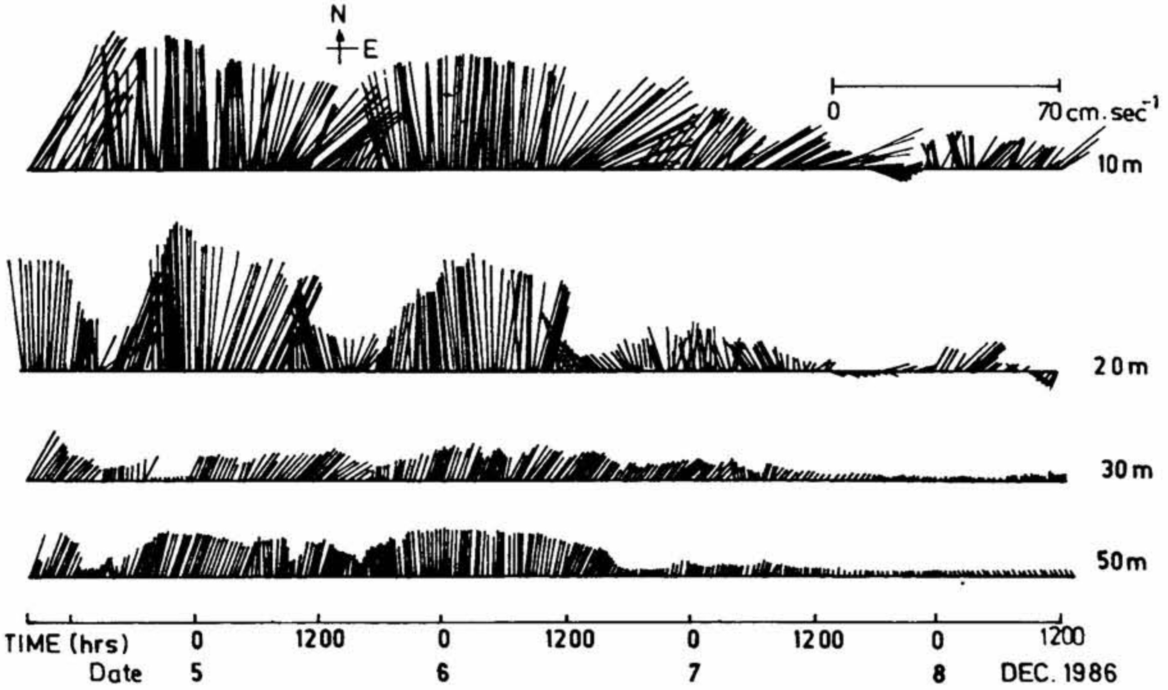

Fig. 4—Time series of current vectors

Table 1—Vector averaged surface wind and subsurface currents

	$\bar{u}$	σ_u	$\bar{v}$	σ_v
Surface wind (m. sec^{-1})	1.80	0.80	3.05	1.20
Subsurface currents (cm. sec^{-1}):				
Depth (m)				
10	8.981	9.248	19.605	12.333
20	1.971	5.243	15.317	12.660
30	3.975	2.710	4.878	3.140
50	1.514	1.832	6.601	4.928

from November to January. The observed currents in the present study were northerly against the weak northerly winds, which is in agreement with the previous results[5,7]. The northerly flow during this period is mainly due to baroclinic effects, i.e. a density gradient current.

The current field in the ocean contains different periodic oscillations with clockwise and anticlockwise components. For vector time series observations, the rotary spectral method is more appropriate in determining the periodicities as well as energy rather than the scalar Fourier series for u and v components[22].

The rotary spectra are based on velocity field decomposition.

$$V = u + iv$$

where, u and v denote the east and north components. Negative and positive frequencies are referred to as clockwise and anticlockwise components respectively. The current record of 100 h, with 10 min sampling interval, was divided into 2 segments, each consisting of 256 points. These segments were subjected to spectral analysis after passing through a Hann window and the results were averaged over the same frequencies. At all depths, diurnal and semidiurnal periods dominated both in the clockwise (continuous line) and anticlockwise (dashed line) spectra (Fig. 5). On the whole, the spectral energy is more in the clockwise band (~2 times), indicating the predominance of clockwise oscillations especially in the lower frequencies (below that of semidiurnal tides).

The dynamic instability within the water column resulting from the vertical current gradient was described in terms of vertical current shear. The current shear between the depths 10 and 20 m, 20 and 30 m and 30 and 50 m was computed following Halpern[23] and presented in Fig. 6. In general, the

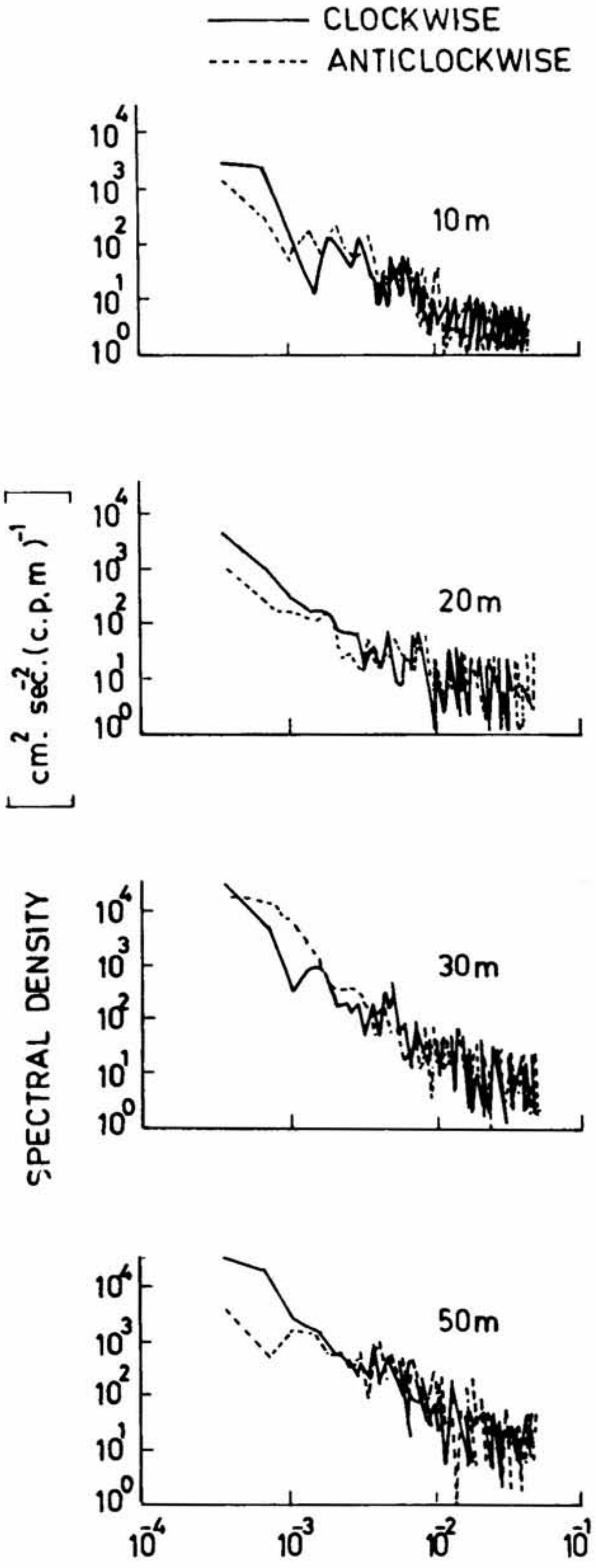

Fig. 5—Rotary spectra of subsurface currents (10, 20, 30 and 50 m)

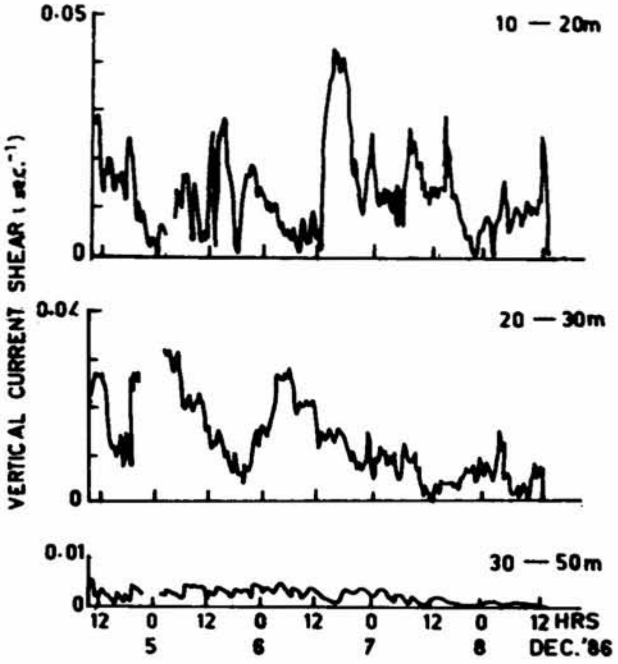

Fig. 6—Time series of vertical shear

shear was large between 10 and 20 and 20 and 30 m depths compared to that between 30 and 50 m depths. Further, the current shear also showed semidiurnal oscillations. The decreasing trend of shear with time between all depth slabs can be attributed to the general weakening of currents, especially from 6 December. This coincides with the subsurface cooling in the thermal structure. Below 30m depth the shear was negligibly small, indicating weak vertical gradient of currents and hence weak mixing.

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