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Alongshore wind stress and heat flux divergence off Visakhapatnam, east coast of India

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Annual variation of heat flux divergence (Qv) was computed for the coastal waters of Visakhapatnam. The mean values of net heat exchange (Qn) and heat flux divergence (Qv) were found to be 114 and 115 $W.m^{-2}$ respectively on annual scale. The net heat storage in the water column is almost negligible. The winds and currents in the study area are favourable for upwelling during premonsoon and SW monsoon seasons. This resulted in large divergence of heat from the region.

The processes occurring at the interface between ocean and atmosphere are highly complicated in the coastal and nearshore waters. Since Indian Ocean plays an important role in global circulation, it is worthwhile to examine the variability of different meteorological and heat budget parameters on a monthly time scale. The available atlases[1-3] provide detailed information on climatological distributions of meteorological and heat flux parameters over the Indian Ocean. Some of the earlier studies[4-9] reported different aspects of the coastal waters of the central sector of the east coast of India, but detailed information on the heat flux divergence in the Visakhapatnam coastal waters is deficient. Keeping this in view, monthly mean variation of heat flux divergence in the shelf waters of Visakhapatnam has been studied for the period 1979-1982.

Materials and Methods

Monthly mean vertical temperature profiles have been obtained for the study area (Fig. 1) utilising more than 195 temperature profiles collected during 1979-82. A mechanical bathythermograph was used for these observations. These monthly mean profiles have been used to compute the heat content (H) and the rate of change in heat content (Qt) in the layer (0-40m). The marine surface meteorological data for the above period was used to compute the net heat exchange (Qn) across the air-sea interface. The details of data and their analysis have been described earlier[7].

The net heat exchange (Qn) was computed using the methods presented earlier[10] excepting the transfer coefficients, Ce and Ch, which are evaluated by Kondo's[11] method. The change in heat content (Qt) is computed by following Etter *et al.*[12]. The mean heat flux divergence (Qv) was obtained as:

$$Qv = Qn - Qt.$$

Results and Discussion

The mean monthly variation of different surface meteorological parameters and net heat exchange(Qn) shows that total cloud amount is < 4 octas during non-monsoon months while it reached a maximum during the southwest monsoon (Fig. 2A). Similarly, stronger winds (Fig. 2B) were observed during southwest monsoon (June-September). Air (Ta) and sea surface temperatures(Tw) are very close and the trend is the same throughout the period. Large range is noticed in dew point temperature between winter and the summer monsoon. A large range in dew point temperature is > 7°C while Ta and Tw exhibit low amplitudes on an annual scale

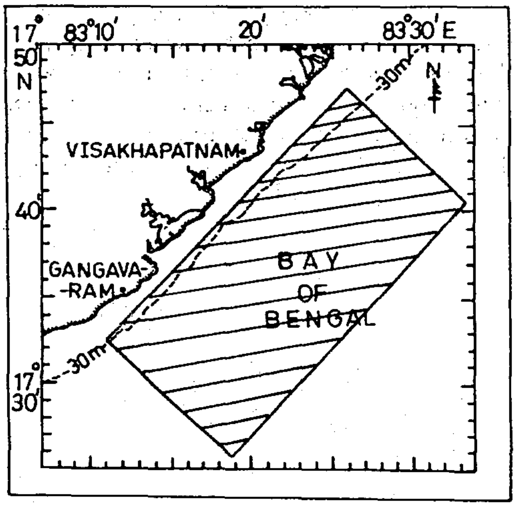

Fig. 1—Location map (study area is shaded)

(Fig. 2C). The sea-air temperature difference (Tw-Ta) was found to be − 1.7°C during May and 1.9°C in July (Fig. 2D) respectively. The vapour pressure gradient was low during the premonsoon and southwest monsoon, while it is higher in other seasons (Fig. 2E).

Variation of net heat exchange (Qn) was positive throughout the year except in November (Fig. 2F). It is almost stable during June-October. Qn gradually increased from January and reaches a maximum in May (220 W.m^{-2}). There is a sudden fall in Qn from May-June and October-November and the variation in Qn is close to zero during November and December.

The water column (0-40m) was isothermal during winter months. The surface water was cool due to northeasterly winds resulting in the convective circulation and vertical mixing in the layer and ultimately the temperature structure becomes isothermal. The mean SST (Fig. 3A) during SW monsoon season was 29°C and at 40m depth the temperature was about 27°C. The computed temperature value reported for southwest monsoon season, off Visakhapatnam[13] was 26 to 26.5°C. Earlier studies[7,8] also reported around 29°C during southwest monsoon season. The warmer temperatures could be due to the poor monsoon in 1979 and drought in 1982 which fall under the present study period (1979-82). The heat content (H) in the water column varied between 4.2 and 4.4 × 10^{9} J.m^{-2} during January to May and the maximum heat content occurred during June and October. There is a good correlation between the heat content and the sea surface temperature (Fig. 3A,B). A regression equation between SST and H is as follows:

$$H(\times 10^{9}\,J.m^{-2}) = 0.1128\,Tw + 1.265 \qquad ...(1)$$

The value of H estimated from BT data[9] (at a location 17° 59′N, 83° 53.9′ E) is compared with the computed value from Eq. (1). They are found to be 4.2 and 4.23 × 10^{9} J.m^{-2} respectively. It could be mentioned here that the above equation is valid for the coastal waters of Visakhapatnam under well mixed conditions.

Mean monthly variation of the rate of change in heat content (Qt) fluctuates between positive and negative values (Fig. 3C). Maximum Qt was observed

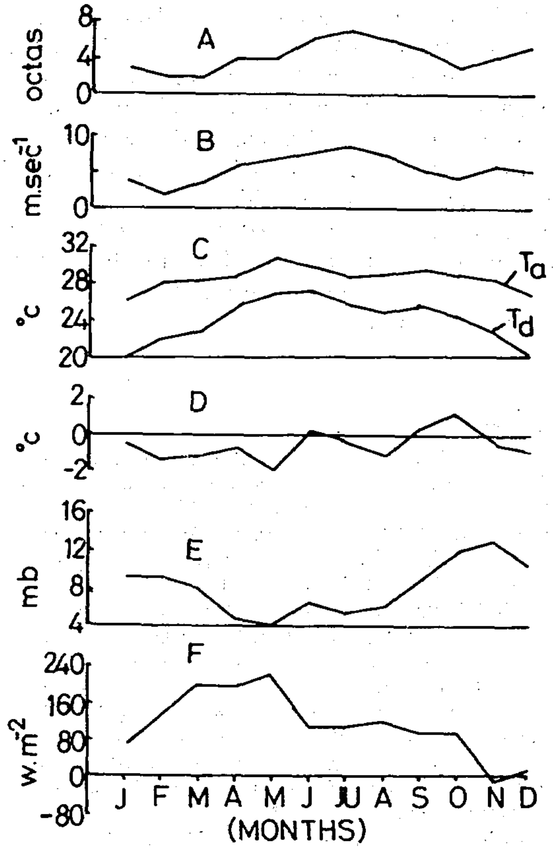

Fig. 2—Monthly variation of A) cloud amount (N); B) wind speed(U); C) dry bulb (Ta) and dew point temperatures (Td); D) sea-air temperature difference (Tw-Ta); E) vapour pressure gradient (e_s-e_a) and F) net heat exchange (Qn)

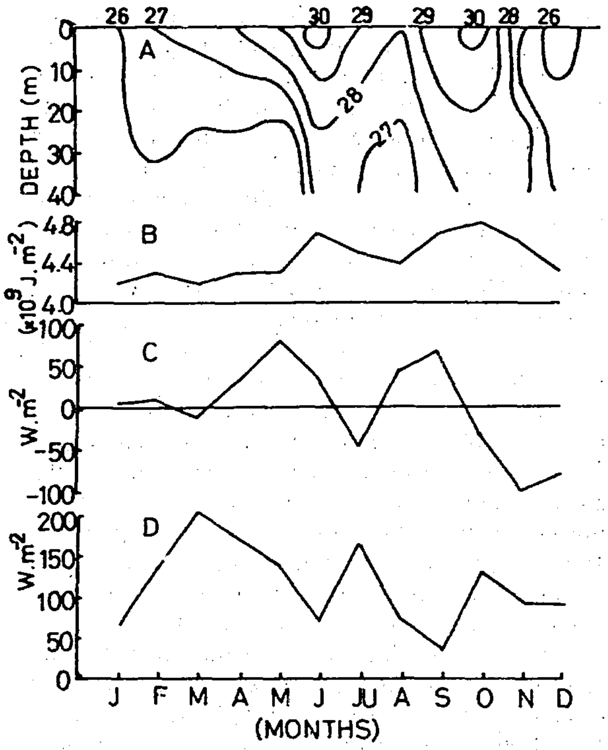

Fig. 3—Mean monthly variation of A) thermal structure, B) heat content(H), C) rate of change in heat content (Qt) and D) net heat flux divergence (Qv)

during May on the positive side and in November on negative side. It is almost negligible during January-March, and also on the annual scale. The variation of heat flux divergence (Qv) was positive throughout the year (Fig. 3D). In other words, net divergence takes place from the study region throughout the year. Qv was maximum (220 $W.m^{-2}$) in March with a secondary maximum (150 $W.m^{-2}$) in July.

The coastal waters off Visakhapatnam are generally influenced by southwest winds during April-September and by northeast winds during October to March. The variation of the heat flux divergence in these waters followed closely the variation of alongshore wind stress. This suggests that a good correlation exists between the alongshore wind stress (τ_y) (Fig. 4) and heat flux divergence (Qv). The regression equations and the correlation coefficients for the two periods are given below:

$$Qv = 6328.8\,\tau_y - 18.13 \qquad \text{...(2)}$$

(γ = 0.9; April-Sept.)

$$Qv = 4592.97\,\tau_y + 139.57 \qquad \text{...(3)}$$

(γ = 0.9; Oct.-March)

(τ_y is in $N.m^{-2}$ and Qv is in $W.m^{-2}$)

From the earlier data on currents[14,15] it could be mentioned here that the flow is generally north-northeasterly during Feb.-May[16] and the magnitude of the surface current ranges between 30 to 50 $cm.sec^{-1}$. The southwesterly winds during monsoon season cause N-NE currents and result in upwelling off Visakhapatnam[17] during July-August. Johns *et al.*[13] reported that, upwelling off Visakhapatnam to be expected due to the wind stress forcing, is suppressed by the fresh water discharge from the Hugli and Mahanadi rivers. However, south of Visakhapatnam, the upwelling process due to wind forcing can not be suppressed as the influence of fresh water discharge diminishes. Suryanarayana[18] also reported that the wind induced upwelling was dominant in the region south of Visakhapatnam. During postmonsoon, the flow was confined to the SW sector and favours sinking during October. The upwelling and sinking processes were simulated by Johns *et al.*[19] by a three-dimensional model and found to be in agreement with the observations. Thus, it may be inferred that inspite of the reversal of wind and coastal currents in the study region from southwest to northeast monsoon seasons, heat advection takes place throughout the year. Eventhough the correlation between alongshore wind stress and heat flux divergence is good, one should not ignore the role of fresh water discharge during southwest monsoon season.

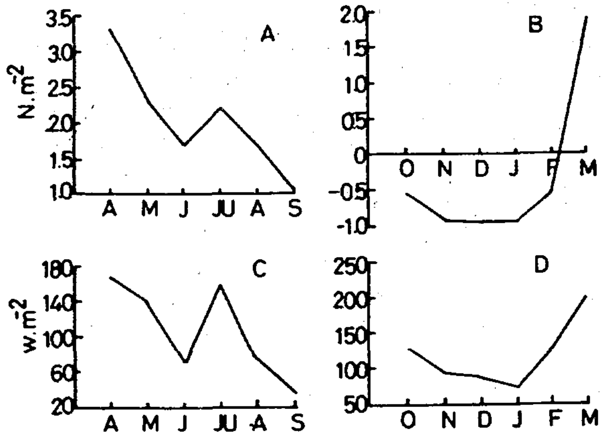

Fig. 4—Alongshore wind stress ($10^2 . \tau_y$) (A and B) and heat flux divergence (Qv) (C and D) during the periods, April-Sept. and Oct.-March

The present values of net heat exchange (Qn) are comparable with those reported earlier[3]. The net heat exchange (Qn) and heat flux divergence (Qv) were 114 and 115 $W.m^{-2}$ respectively on annual scale. In other words, the net heat gain at the surface is almost lost through advection and other interior physical processes. The present study showed that the heat flux divergence takes place throughout the year from the study area, due to the reversal of wind and coastal currents in association with the SW and NE monsoons. A good correlation was noticed between the alongshore wind stress and heat flux divergence. However, data for longer duration would help to confirm these results.

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