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Heat storage in the Andaman Sea

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ABSTRACT. Heat storage in the Andaman Sea in upper 20 m, where a strong halocline seems to inhibit vertical heat transport has been evaluated and discussed in relation to the other parameters of heat budget. Estimation of annual evaporation gives rise to 137 cm compared to the range of 110-150 cm evaluated earlier using empirical formulae.

1. Introduction

Heat storage in the upper layers of the ocean is recognised as one of the important parameters in the heat budget of the oceans and the overlying atmosphere. The thermal structure in the upper layers of the sea is a result of surface heat exchange, mixing and advection. Surface heat exchange is the balance between incoming global radiation, reflected radiation, effective back radiation, sensible heat transfer and evaporation. Mixing is very much limited to the upper homogeneous layer. By the process of advection, heat may be transported from one locality to another. However, in closed basins, the net effect of advection may be negligible. In recent years, with the accumulation of bathythermograph (BT) data, several investigators (Pattullo 1957, Fritz 1958, Bryan and Schroeder 1960 and Bathen 1971) have estimated the quantum of seasonal heat storage in the surface layers in certain regions of Pacific and Atlantic Oceans. However, due to lack of sufficient data till recently, no such studies have been made for the Indian Ocean, in general, and for the Bay of Bengal, in particular. The purpose of present paper is to present the mean thermal structure of the Andaman Sea and evaluate the seasonal components of heat storage in relation to surface heat exchange parameters and estimate the evaporation rates in that region.

2. Data and results of analysis

2.1. *Thermal structure and heat storage*

The BT data at about 1200 stations in the Andaman Sea (available in the data files of the Indian National Oceanorgaphical Data Centre of NIO) have been used for constructing the mean monthly profiles. Andaman Sea is a small semi-closed basin bordered by Burma, Thailand, Sumatra and Andaman-Nicobar ridge. The net advective heat transport over the region is considered negligible. Though the sampling is uneven in space and time (especially so during summer monsoon), for the purpose of present investigation the available BT data is taken to represent average conditions over the area. Most of the BT data was collected during the period of the International Indian Ocean Expedition (IIOE), 1960-1965. Fig. 1 shows the annual march of temperature in the upper 270 metres. It is seen that the surface temperature exceeds 28 deg. C during most of the year (February to November) with highest values exceeding 29 deg. C during April to June.

Fig. 2 presents the distribution of the annual temperature range in the upper 270 m. Its distribution with depth is peculiar and contrary to the normal decreasing pattern. The annual range of temperature at surface is about 2.7 deg. C and decreases to a minimum of 2.2 deg. C at 20 m whereafter it gradually increases to a maximum of 7.5 deg. C at about 75 m. Further down, showing a minimum and maximum, the range decreases to about 0.8 deg. C at 270 m. In open oceanic conditions one would expect that the annual temperature range decreases continuously with depth and ultimately vanishes at the depth where surface influences are no more felt. A plausible explanation is the development of strong

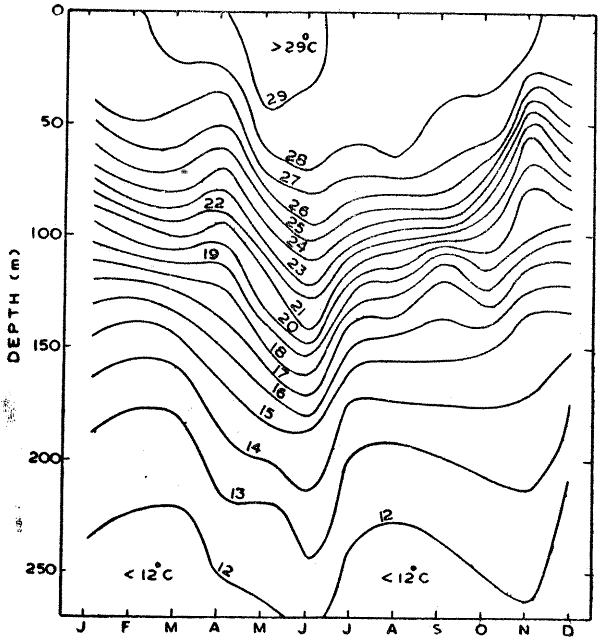

Fig. 1. Seasonal march of temperature in the upper layers of the Andaman Sea

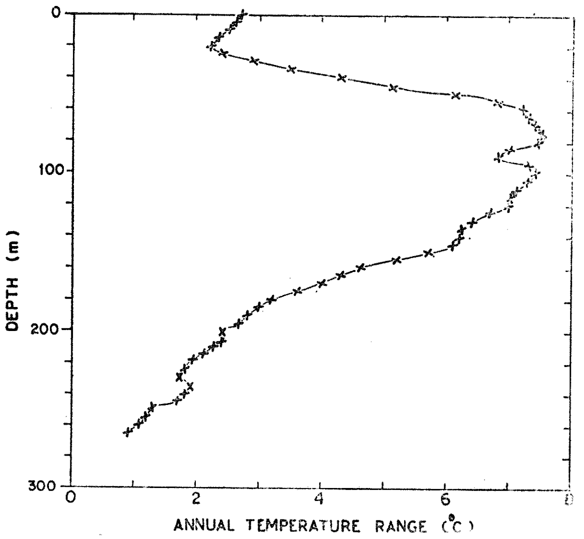

Fig. 2. Vertical distribution of average annual temperature range in the Andaman Sea

TABLE 1

Heat budget of the Andaman Sea

(units in kilo-cal cm^{-1} month^{-1})

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(1) S	1.1	—0.4	1.3	0.6	2.3	—1.2	—0.9	—0.3	—0.4	+0.2	—0.5	—1.7
(2) $R_s\downarrow$	11.7	14.5	15.5	14.5	10.5	9.2	7.4	6.6	9.1	10.3	10.4	9.8
(3) Q_i	11.0	13.7	14.6	13.6	9.9	8.7	7.0	6.2	8.5	9.6	9.8	9.2
(4) Q_b	3.6	3.4	3.4	3.2	2.8	2.3	2.5	1.6	2.3	2.7	3.0	3.2
(5) R	7.4	10.3	11.2	10.4	7.1	6.4	4.5	4.6	6.2	6.9	6.8	6.0
(6) $Q_e + Q_s$	6.3	10.7	9.9	9.8	4.8	7.6	5.4	4.9	6.6	6.7	7.3	7.7
(7) Q_e	5.7	9.7	9.0	8.9	4.4	6.9	4.9	4.5	6.0	6.1	6.6	7.0
(8) Q_s	0.6	1.0	0.9	0.9	0.4	0.7	0.5	0.4	0.6	0.6	0.7	0.7

pycnocline associated with large influxes of fresh water from the rivers *Irrawady* and *Salween.* Associated with these discharges, a strong halocline forms at a depth of 20 m (Ramesh Babu and Sastry 1976). Panakala Rao (1977) has studied stability of water column in the north Indian Ocean and his studies for the Andaman Sea region indicates that the water column near the surface is strongly stratified. He further points out that because of this stratification, vertical transfer of properties by eddy diffusion processes is very much reduced. Thus, it is felt that in the region the seasonal heating effects are confined to upper 20 m only. The large annual temperature range at about 100 m is possible due to vertical movements of the thermocline (La Fond and La Fond 1968 and Colborn 1975).

The amount of heat stored in a month in the upper 20 m of the water column was obtained by vertically integrating each monthly temperature profile at 5 m intervals from surface to 20 m using the equation :

$$H = \rho c_p \int_0^{20} T\,dz$$

where ρ is the density, c_p specific heat at constant pressure, T temperature and z depth. In the above

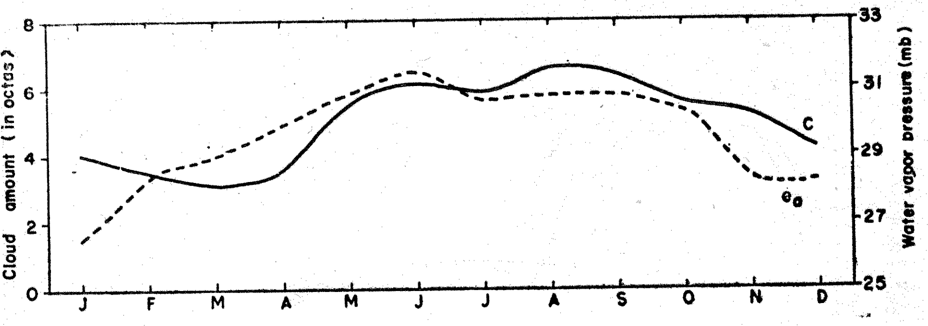

Fig. 3. Seasonal march of cloudiness (C) and water vapour pressure (e_a) of the air over the Andaman Sea (average for the period 1963-1964)

equation, ρc_p is considered constant and is assigned a value of 0.977 cal cm^{-3} °C^{-1} (Bathen 1971). The monthly variations in the heat storage are then evaluated by taking differences of heat content of successive months and are shown in line 1 of Table 1. Generally, the rate of heat storage is zero during late May and late December. It is positive (gained by the sea) during the period from March to May. With the onset of the summer monsoon, it becomes negative (lost by the sea) and the rate of heat lost decreases with the summer monsoon season. After a small amount of heat gained in October, the rate of heat change again becomes negative and increases from November to December. The average rate of heat stored during the hot weather season (March-May) is about 1.4 kilo-cal cm^{-2} month^{-1} whereas it is lost from the sea at an average rates of 0.7 and 0.4 kilo-cal cm^{-2} month^{-1} during summer and winter monsoons respectively. The effect of strong summer monsoonal winds is seen in the relatively higher rates of heat lost during this period. However, on an average, the amount of heat stored in the upper 20 m during the period from December to May is found to be 2.3 kilo-cal cm^{-2} month^{-1}. In the foregoing section, the other heat budget components are discussed in relation to the heat storage terms.

2.2. *Radiation balance*

The net incoming radiation Q_i absorbed at the sea surface is the difference between the downward flux of the global solar radiation $R_s\downarrow$ and the reflected radiation ($R_s\downarrow\alpha$ where α is the albedo of the sea surface). Measurements of the global radiation made during the period 1965—67 at Port Blair (11°14′ N, 92° 43′E) have been considered to represent the incoming radiation over the Andaman Sea. Average monthly values of global radiation are listed in line 2 (Table 1). The annual average of $R_s\downarrow$ for the above period is about 130 kilo-cal cm^{-2} while the climatic mean is about 150 kilo-cal cm^{-2} for the Andaman Sea (Mani *et al.* 1967). The albedo of the sea surface is taken as 6 per cent following Colo'n (1960) even though it is known to have diurnal and annual variations and is also dependent of sea state. The values of Q_i [$=R_s\downarrow(1-\alpha)$] are given in line 3 (Table 1).

The effective back radiation Q_b has been computed following Wyrtki's (1966) equation. The required surface meteorological data were extracted from the atlas published by Ramage *et al.* (1972). The mean values of Q_b are presented in line 4 (Table 1) and line 5 (Table 1) gives the values of radiation balance R $(=Q_i-Q_b)$. Incoming radiation absorbed at the sea surface shows maxima during March and November and minima during August and December. The annual variation of Q_i largely depends on the cloudiness as seen from Fig. 3. The winter minimum is due to progress of the sun. The effective back radiation varies over a relatively small range comparable to that of Q_i. Maximum and minimum values of Q_b are 3.6 and 1.6 kilo-cal cm^{-2} month^{-1} observed during January and August respectively. These maxima and minima are constant with the cloudiness and vapour pressure of air (Fig. 3). It may be remarked here that the annual range of Q_b in the Andaman Sea is slightly higher compared to that arrived at by Colo'n (1960) for the Caribbean Sea which is located at similar latitudes.

The annual variation of radiation balance R again shows a double maxima during March and October-November (Fig. 4). The difference between the radiation balance R and heat storage S is given in column 6 and this is the amount of heat energy available for sensible heat transfer (Q_s) and evaporation (Q_e) assuming advection processes in the area of study are considered

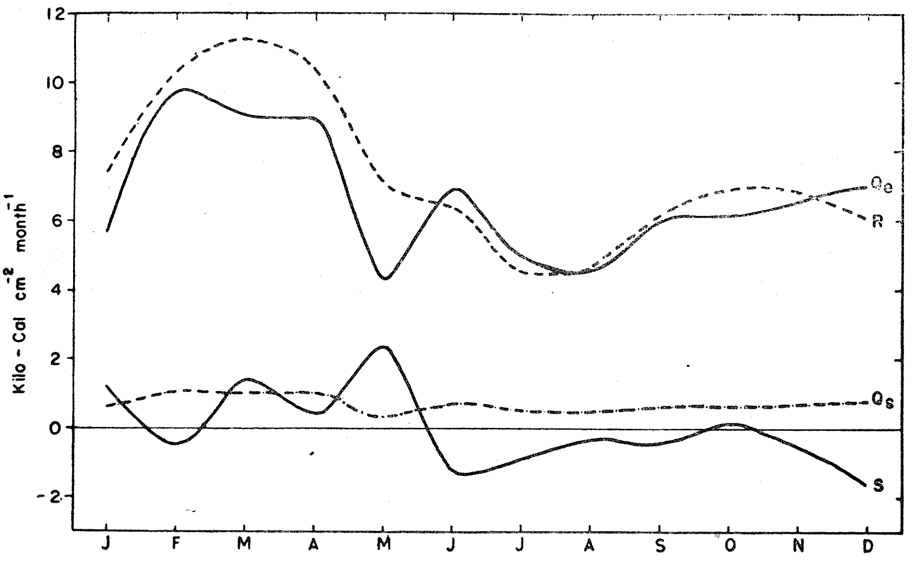

Fig. 4. Seasonal march of heat budget components

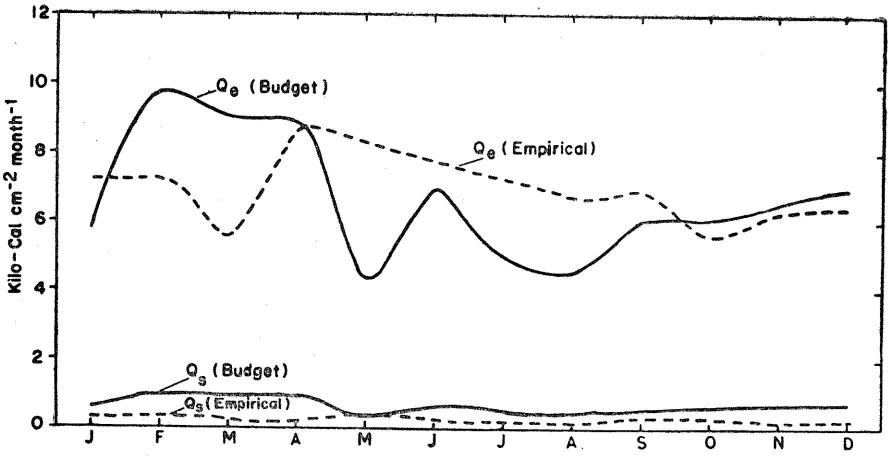

Fig. 5. Comparison of Q_e and Q_s with those obtained by empirical formulae

negligible as mentioned earlier. Assuming the Bowen's ratio as 10 per cent, the values of Q_e and Q_s have been estimated and are given in lines 7 and 8 (Table 1). Q_e varies from 9.7 kilo-cal cm^{-2} month^{-1} in February to 4.4 kilo-cal cm^{-2} month^{-1} in May with corresponding monthly evaporation rates of 16.7 and 7.6 cm. Thus evaporation during late winter and early spring is considerably higher. Slightly higher values are also seen during June. Annual evaporation based on this methodology works out to be 137 cm. Sensible heat flux (Q_s) varies over a small range with higher values of the order 1.0 kilo-cal cm^{-2} month^{-1} occurring during late winter and early spring.

3. Discussion

Fig. 5 shows a comparison of the estimates of Q_e and Q_s computed as above and those evaluated by Ramage *et al.* (1972) using empirical formulae. The Bowen's ratio in the above cited work is low varying from 2.4 to 5.2 per cent. A survey of literature shows different values of Bowen's ratio. For example, Venkateswaran (1956) gives an average value of 5 per cent for the Andaman Sea. Saha and Suryanarayana (1972) have presented charts of mean monthly fluxes of sensible and latent heats for the period 1965-'67 which gives values of 8 and 15 per cent for the months of July and August respectively. In yet another survey, Saha's (1970) work gives rise to values of 9 and 11 per cent for January and July during 1964 while Ramanatham *et al.* (1968) have reported very low values (about 2 per cent) over the Bay of Bengal. It is felt that the Bowen's ratio is not a constant and it is possible that it varies depending upon the actual environmental conditions. The changes obtained by choosing any of these values of Bowen's ratio are not very sensitive especially so in Q_s.

Q_e follows closely the radiation balance R (Fig. 4) and gives a certain amount of confidence in its evaluation with the present methodology. The estimate of annual evaporation (137 cm) obtained here by the budget method is comparable to the estimates made earlier by several workers using empirical formulae. Venkateswaran (1956) estimates 110 cm while Ramanatham *et al.* (1968) estimate annual evaporation at 150 cm. From the atlas of Ramage *et al.* (1972), the average annual average evaporation (during the period 1963-64) is found to be about 145 cm for the Andaman Sea. However, monthly values of evaporation by the budget and empirical methods are observed to be different. Fig. 5 shows that during late winter and early spring, evaporation rates worked out considerably higher while during monsoon they are lower compared to empirical estimates. It may be remarked that more realistic estimates of Q_e and Q_s could be obtained by (1) evaluating advection of heat transport, (2) considering the seasonal variations in the depth of halocline, (3) choosing proper values for Bowen's ratio and (4) sampling depth-temperature structure, uniform both in space and time.

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