

Summer Monsoonal Heat Balance for Upper Central Equatorial Indian Ocean

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Using the data obtained at 3 h interval during summer monsoon days (25-31 July 1977), the time history of the surface heat balance parameters of the central equatorial Indian Ocean (2°N to 2°S; 76° to 80°E) is examined on a shorter time scale. A general increase in the heat content of the upper 200 m water column at an average rate of about 900 W.m⁻² is mainly attributed to the oceanic interior (advection) processes. A simple heat budget model is adopted to compute the advection rates whose orders are found comparable with those of observed currents near the study area.

In the central equatorial Indian Ocean there is an atmospheric equatorial trough—a quasi permanent synoptic feature during summer monsoon—which strengthens when the monsoon over India is weak¹. It is a region of low cross equatorial water vapour flux together with low evaporative and high sensible heat fluxes in contrast to the other parts of the Indian Ocean²⁻³. This area is recognised as one of the important active zones for the generation of cloud masses which propagate towards north at intra-seasonal time scale with 30-50 d oscillation period during monsoon season⁴. Knox⁵ and McPhaden⁶⁻⁷ have examined the dynamical and thermodynamical aspects of this oceanic area at monthly time scales. However, no particular attention has been paid to study in this region, the variability of heat budget on shorter time scales (< 30 d) even though short period harmonics are known to dominate the power spectra of zonal and meridional wind components⁸.

Using time-series data collected during July 1977 for 7 d as a part of Indo-Soviet MONSOON-77 programme, short term variability in the heat budget of the upper central equatorial Indian Ocean is critically examined. Also, advection rates in upper 200 m water column are estimated adopting a simple heat budget model for the region of study.

Materials and Methods

The heat content H (J.m⁻²) of the upper water column (0-200 m) is computed from equation

$$H = \rho C_p \int_0^z T dz$$

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where ρC_p is a constant⁹.

The net energy exchange R (W.m⁻²) across the sea surface is estimated as

$$R = R_N - (Q_e + Q_s)$$

where R_N ($Q_I - \alpha Q_I - Q_b$) is the radiation balance between absorbed incoming radiation after reflection at the surface (α is albedo) and net longwave radiation (Q_b); Q_e , Q_s are the evaporative and sensible heat fluxes respectively. Q_I and α have been obtained directly from actinometric observations made on board the research vessels whereas Q_b (W.m⁻²) is obtained from the following empirical formula¹⁰.

$$Q_b = 0.9894 (143.7 - 0.9 TW - 0.46 RH) (1 - 0.0765N)$$

where TW is the sea surface temperature; RH is relative humidity (%) and N is the cloud amount (octas). The fluxes Q_e and Q_s (W.m⁻²) are estimated from the following bulk aerodynamic formulae.

$$Q_e = 2.5404 (e_s - e_a) V_a$$

$$Q_s = 1.6756 (T_s - T_a) V_a$$

where V_a is the wind speed (m. sec⁻¹); e_s is saturated vapour pressure of air (mb) at sea surface; e_a is the vapour pressure of air (mb) at anemometer height; T_s and T_a are sea surface and air temperature (°C) respectively. In the above equations, the constants have been obtained after considering drag coefficient as 1.4×10^{-3} ; specific heat of air at constant pressure as 1.0048×10^3 J.kg⁻¹ K⁻¹; density of air as 1.28 kg.m⁻³ and latent heat of vapourisation as 24.49×10^5 J.kg⁻¹.

Estimations of both H and R have been made using 3 h interval data of bathythermograph, actinometric and surface meteorological observations ob-

tained on board 4 ships (OKEAN, SHIRSHOV, PRIBOY and SHOKALASKY) which maintained a stationary polygon formation by positioning at respective locations—st1 (northern), 2°N and 78°E; st 2 (eastern), 0° and 80°E; st 3 (southern), 2°S and

78°E and st 4 (western), 0° and 76°E—in the central equatorial Indian Ocean during 25-31 July 1977.

Results

Thermal structure of upper ocean—Fig. 1 shows

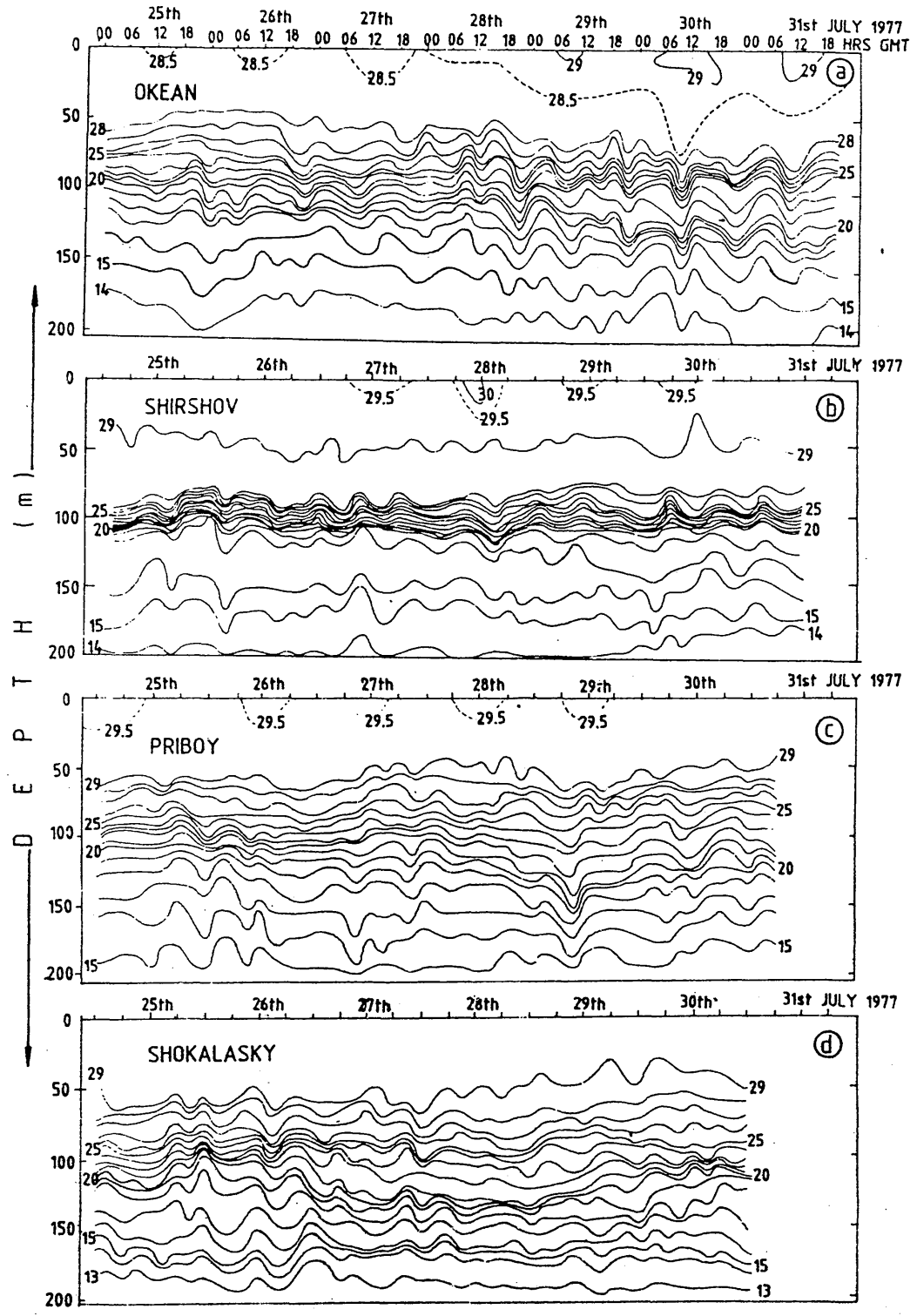


Fig. 1—Temperature (°C) distribution in upper 200 m water column for 25-31 July 1977 at (a) st 1 (b) st 2 (c) st 3 and (d) st 4 in the central equatorial Indian Ocean

time evolution of vertical thermal structure observed in the upper 200 m layer at 4 stations. Relatively cold waters are present in the surface layer at st 1, while at sts 2 and 3 warm surface waters are encountered. Amongst the 4 stations, st. 2 exhibits a distinct thermal structure as seen from the presence of a deeper thermocline with very sharp gradients between 75 and 125 m depths. Near 200 m depth, relatively cold waters ($< 13^{\circ}\text{C}$) at st 4 and warm waters ($> 14^{\circ}\text{C}$) at st 3 are present. The temperature in the surface layer at st 1 steadily increases with time as seen from deepening of 28.5°C isotherm (Fig. 1a) while at st 3 there is a decreasing trend in the surface layer temperature (Fig. 1c).

The temporal variation in the heat content H of the upper (0-200 m) water column (not presented here) based on original 3 h data shows in general an increasing trend superimposed with high frequency oscillations of semi-diurnal period. In order to filter out the short period fluctuations from the original data, the heat budget parameters are averaged separately for each day and their daily variations are examined.

Daily variations—Fig. 2 shows the variation of different parameters of thermal structure and surface meteorological fields which are smoothed. Sea surface temperature (SST) is comparatively less variant at st 4 while an increase of about 0.5°C at sts 1 and 2 and a decrease of the same order at st 3 are seen (Fig. 2A). Thermocline is distinctly deep (≈ 85 m) at st 2 in contrast to its uniform shallow nature at other

stations (Fig. 2B). The H in 0-200 m water column in general increases during first 4 d of the study and thereafter it slightly lowers together with a decrease in the spatial gradients (Fig. 2C). On an average, H is low at st 1 and high at st 3. It is interesting to see that the weak winds around 29 July, associate with low surface pressure over the polygon area (Figs. 2D and 2G).

R_N (area average) is steady around 150 W.m^{-2} during 26-29 July while at the beginning and ending of the observational period, it is greatly reduced to around 50 W.m^{-2} (Fig. 3A). It is in general higher at st 1 and lower at st 4. The association of high and low R_N values with respective low and high cloud regimes (Figs. 3A and 2F) brings out clearly the effect of clouds on net absorbed radiation at the sea surface. The combined flux $Q_e + Q_s$ is also seen steady around 100 W.m^{-2} during 26-29 July (Fig. 3B) like that of R_N giving rise to a net heat gain R at about 60 W.m^{-2} whereas the sea has lost heat to the atmosphere at about the same rate during the rest of time (Fig. 3C). This results in a zero net heat energy transfer across the sea surface for the entire observational period (Table 1).

Discussion

The spatial variations in the thermal structure across the equator (warm waters in the south and cold waters in the north) infer the presence of westerly geostrophic current in south and easterly geostro-

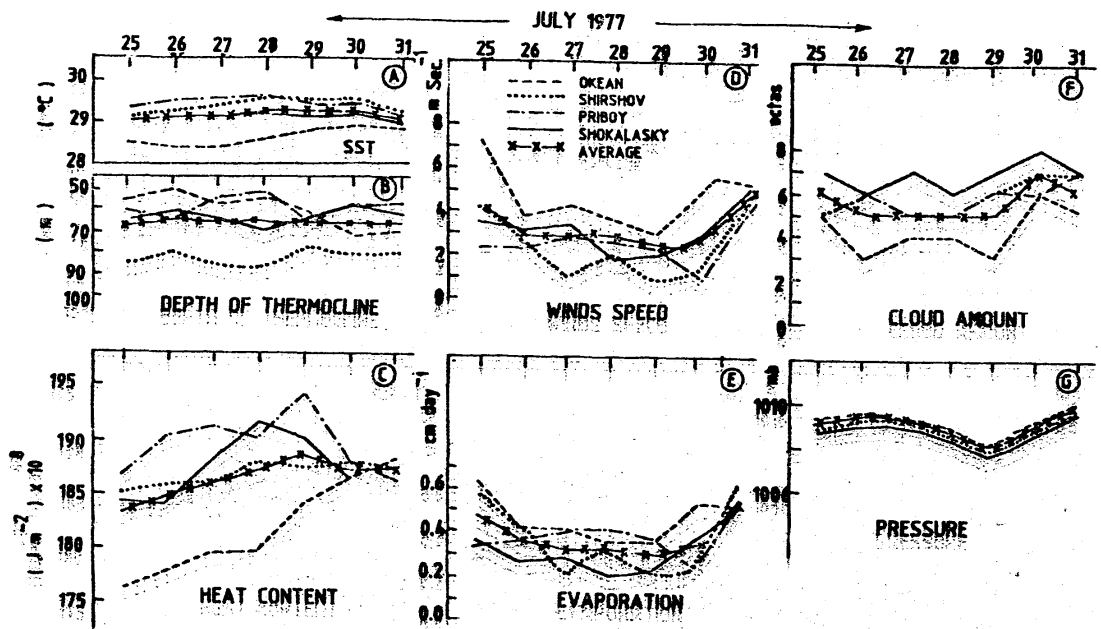


Fig. 2—Daily averages for 25-31 July 1977 at different locations [(A) SST ($^{\circ}\text{C}$); (B) depth of thermocline (m); (C) heat content (J.m^{-2}); (D) wind speed (m. sec $^{-1}$); (E) evaporation rate (cm. d $^{-1}$); (F) cloud amount (octas) and (G) surface pressure (mb).

phic current in north of the equator giving rise to a shear zone in between these opposite zonal currents. This current shear causes a northward heat transport across the equator resulting in an increase in the

heat content of water column at north (st 1) as reflected from the gradual descent of 28.5°C isotherm (Fig. 1A). The northward heat transport across the equator is considered as an anomaly occurring on the time scales of few days during monsoon since the seasonal heat transport estimates¹¹⁻¹³ indicate a net southward transport across the equator.

On an average, the ratio $\Delta H_i / \Delta H_o$ of the heat content change due to ocean interior processes to that actually observed is 98%. On the occasions such as of net heat loss across the ocean surface during 25-26 July and of net heat loss in the water body during 29-30 July (Table 1), the ratio $\Delta H_i / \Delta H_o$ is even more than 100% meaning that part of the heat imported into (exported from) the area by ocean interior processes has been supplied to (from) the atmosphere. Earlier McPhaden⁷ has also clearly demonstrated that the heat content changes in the upper 200 m are due to oceanic interior processes in association with time varying geostrophic currents rather than by surface fluxes.

A model is considered for further evaluating the role of advection in the heat budget of the upper ocean. The general heat budget equation is

$$\frac{\partial H}{\partial t} = A_h \left[\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} \right] - \left[u \frac{\partial H}{\partial x} + v \frac{\partial H}{\partial y} \right] + K \quad \dots (1)$$

where A_h ($\text{cm}^2 \cdot \text{s}^{-1}$) is the horizontal eddy diffusion coefficient; u and v ($\text{cm} \cdot \text{s}^{-1}$) are the velocity compo

nents along x and Y axes. The orders of $\frac{\partial^2 H}{\partial x^2}$ and $\frac{\partial^2 H}{\partial y^2}$ are found to be 10^{-12} and 10^{-11} respectively in

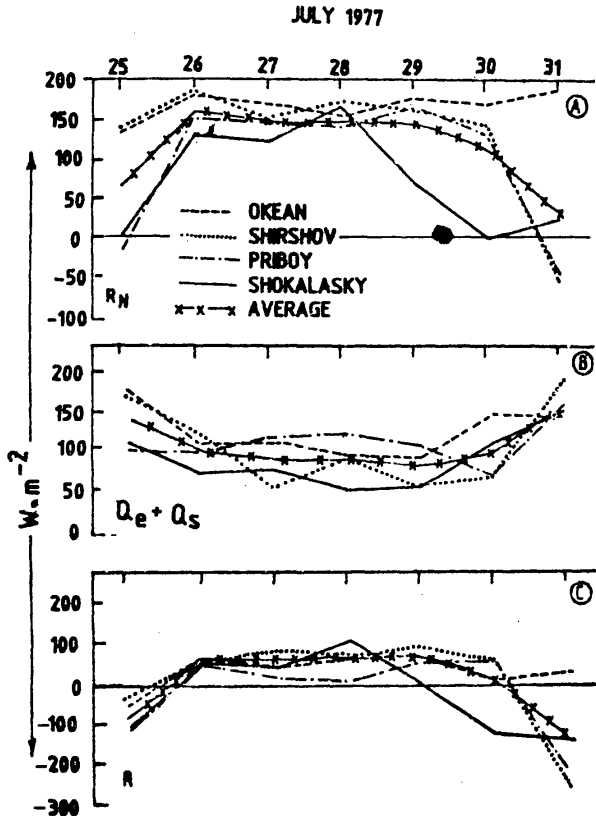


Fig. 3—(A) Net radiation; (B) combined latent and sensible heat flux and (C) net heat flux across the sea surface ($\text{W} \cdot \text{m}^{-2}$) for the period 25-31 July 1977.

Table 1—Daily Averages of Various Heat Budget Components and Changes in Heat Storage

Heat budget	Date (July 1977)							Mean
	25	26	27	28	29	30	31	
R_N ($\text{W} \cdot \text{m}^{-2}$)	61	160	146	162	143	110	23	115
$Q_s + Q_e$ ($\text{W} \cdot \text{m}^{-2}$)	145	106	96	96	86	106	168	115
R ($\text{W} \cdot \text{m}^{-2}$)	-84	53	50	65	57	4	-145	0
H ($\text{J} \cdot \text{m}^{-2} \times 10^8$)	183.2	185.0	186.6	188.0	189.5	187.8	...	186.9
Heat storage change ($\text{Watt} \cdot \text{m}^{-2}$)	Date (July 1977)							
	25-26	26-27	27-28	28-29	29-30			
ΔH_o	1675	1675	1340	1549	-1717			
ΔH_R	-16	52	58	61	31			
ΔH_i	1691	1623	1282	1488	-1748			
$\Delta H_i / \Delta H_o$ (%)	101.6	96.9	95.7	96.1	101.8			

ΔH_o = observed; ΔH_R = contribution from R ; ΔH_i = contribution through ocean interior processes.

the equatorial oceanic regions in contrast to those in the boundary frontal areas and hence the contributions of these terms in Eq. 1 are considered negligible

in comparison with 10^{-2} order of $\frac{\partial H}{\partial t}$ when a

constant order of 10^{-6} is assigned for A_h^9 . Then Eq. 1 is reduced to

$$\frac{\partial H}{\partial t} = - \left[u \frac{\partial H}{\partial x} + v \frac{\partial H}{\partial y} \right] + R \quad \dots (2)$$

Eq. 2 can be solved after replacing x and y components by total field as following:

$$\frac{\partial H}{\partial t} = C \frac{\partial H}{\partial n} + R$$

$$\text{where } \frac{\partial H}{\partial n} = \left[\left(\frac{\partial H}{\partial x} \right)^2 + \left(\frac{\partial H}{\partial y} \right)^2 \right]^{1/2}$$

$$\text{and } C = \left[u^2 + v^2 \right]^{1/2}$$

It is interesting to note that the orders of derived currents are comparable with currents observed at nearby Gan Island by Knox⁵ (Table 2). This gives some confidence about the assumptions made in the formulation of the heat balance model and further shows that advection processes seem to play a major part in the heat content variability. The computed currents are relatively steady during most of the observational period (25-31 July, 1977) while the flow suddenly reverses and strengthens at the end of the period. The vectoral mean flow for the observational period is around 20 cm.sec⁻¹ with a predominant northerly anomalous component. It is difficult to ascertain the sudden reversal in the computed flow field since high frequencies with the order of few days periods are not possible to discern from the data of Knox⁵. However, the present study suggests the presence of possible anomalies in transequatorial seasonal heat transport on shorter time scales in the Indian Ocean during summer monsoon. The resultant anomalous convergence of heat energy near the

Table 2—Computed Currents from the Heat Balance Model and Observed Currents Near the Study Area⁵

Computed	Date (July 1977)				
	25-26	26-27	27-28	28-29	29-30
Speed (cm.sec ⁻¹)	71	65	56	70	157
Direction (deg.)	353	360	14	17	185
Observed	Date (July 1973)				
	5	12	19	26	
Speed (cm.sec ⁻¹)	43	48	55	70	
Direction (deg.)	270	202	290	255	

equator would then affect the dynamics of equatorial atmosphere through boundary processes.

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