Seasonal heat content variations in the Northwestern Indian Ocean

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ABSTRACT

The changes of heat storage of the Somali Basin in the western Indian Ocean, as shown from 55 detailed temperature sections along the western sea lane (tanker XBT program 1975-1979), are only partly accounted for by the net heat gain at the sea surface. Vertical movement of the thermocline and horizontal advection appear to be the cause of major changes both between and during the monsoons. During the southwest monsoon the large amount of heat stored in the 0 to 400-m layer during northern spring (up to 31 × 10^8 Jm^-2) is redistributed with a heat loss of approximately 13 × 10^8 Jm^-2 in the upper 0 to 100-m layer and the gain of a similar amount in the 100 to 400-m layer, caused to a large extent by the dynamic response of these layers to the monsoon wind stress. In late autumn this heat is then advected from the region.


INTRODUCTION

Indian Ocean heat storage is greatly influenced by the forcing signal of the semiannual monsoons. Because of the extreme conditions of evaporation and wind stirring at the sea surface imposed by the monsoons in the Somali Basin region and the intense solar heating between monsoons during northern spring and autumn, the seasonal changes in net positive heat gain through the sea surface can be relatively large. Various investigators have pointed out, however, that the local heat exchange with the atmosphere can...
hardly account for the large amounts of heat stored seasonally in the upper ocean at low latitudes. Düing and Leetmaa (1980) suggest that Arabian Sea coastal upwelling is a major cause of heat storage variability. In the western equatorial Atlantic, Merle (1980) points out that the annual cycle of heat content appears to be the result of vertical movement of the thermocline associated with the dynamical response of the ocean to the seasonally varying winds. In fact, he shows that the rate of heat storage change can be up to ten times larger than the net input through the sea surface. Vertical movement of the thermocline as a means of changing heat content is shown to be important by Emery (1976) also. He correlated heat content in the upper layer (0 to 250 m) with the depth of the 14 °C isotherm of the northeastern Pacific Ocean. In the northwestern Indian Ocean, because of the strong currents associated with the eddy field circulation during the monsoons (Bruce, 1979), horizontal advection is also of significance. An example of the configuration and horizontal extent of the eddies in the Somali Basin is indicated in Figure 1.

Heat absorbed from the atmosphere by the ocean in tropical regions has to be exported meridionally out of the region to higher latitudes. In the case of the Arabian Sea and Somali Basin which extend to about 25°N, most of this heat must leave southward across the Equator.

In order to examine what is probably the region subjected to the greatest seasonal variability in the Arabian Sea, a series of 55 temperature sections of 63 XBT stations each (0-450-m depth) have been examined. Exxon tankers were used as ships of opportunity along the western sea lane en route from Cape Town to the Persian Gulf (Bruce, 1979) between October 1975 to December 1979. The sections along the sea-lane (Fig. 1) extend from 2°S to 22°N and station spacing is relatively close particularly in the Somali Basin region (approximately 15 to 20 nautical miles), thus the small-scale details of the boundaries with strong temperature gradients occurring during periods of maximum upwelling in the southwest monsoon are sampled. As will be seen, it becomes important when estimating the heat content in a region of strong currents and eddies, that closely spaced sampling be obtained.

The stations falling only along the 2 to 12°N portion of the sea-lane have been used in order to keep sampling within the Somali Basin and north of the Equator. The eddies which develop during the southwest monsoon within the Somali Basin, particularly the northern eddy (Bruce, 1979), seasonally have strong horizontal gradients and vertical displacements of the thermocline. From the XBT sections used here...
HEAT GAIN AT SEA SURFACE

The seasonal distribution of net heat gain at the sea surface with strong semiannual peaks is the result of gain from long-wave minus short-wave radiation and also minus evaporative and sensible heat loss. Of the latter two, evaporative loss is by far the larger, having maxima during each monsoon, thus reducing the net heat gain to approximately zero values at these times.

The net heat gain at the sea surface from different sources is given in Figure 3. There is relatively close agreement between the Bunker (1976) and Colborn (1975) curves at the semiannual maxima, whereas there is slightly closer agreement with the Bunker and Hastenrath, Lamb (1979) curves at the minimum values. There is considerable spacial variability in the heat gain values mapped in the Somali Basin (see Hastenrath, Lamb, 1979), particularly during the monsoon period, and thus these means for the basin would have a relatively high standard deviation at this time (estimated at approximately ±20% of the mean). The Bunker values (unpublished for the Indian Ocean) determined by the method discussed by Bunker (1976) have been used in this study and were felt to be the most accurate for depicting heat gain in this region. The net annual heat gain at the sea surface for the Somali Basin is positive amounting to: Bunker, 80 Wm⁻²; Colborn, 67 Wm⁻²; and Hastenrath and Lamb, 58 Wm⁻². This gain must then be exported from the region by various means.

HEAT CONTENT

The seasonal changes in the heat content of the upper layer (0 to 100-m) for the 1975-1979 observational period are shown in Figure 4. In this layer the largest of the positive semiannual signals commences at the end of each northeast monsoon during the time of the northern spring sea-surface heat gain (Fig. 3). After

Figure 3
Net heat gain at the sea surface in Somali Basin. Bunker distribution calculated according to Bunker (1976) within basin region approximately 2°N-12°N; H & L is Hastenrath and Lamb (1979), their Figure 16; Colborn (1975), his Figure 25.

Figure 4
Heat storage from XBTs in the 0-100 m layer between 2°N-12°N in the Somali Basin from October 1975 to December 1979 along tanker sea-lane (Fig. 1) with duration of northeast (NE) and southwest (SW) monsoons given. Vertical scale length is 10⁶ Jm⁻².
the southwest monsoon begins to develop, a large heat loss in this layer occurs, reaching minimum heat content toward the end of the southwest monsoon. Also at this time the surface heat gain approaches a minimum. The second of the semiannual signals occurs during the northern autumn surface heat-gain maximum and then decreases near the start of the northeast monsoon.

The monthly means of the heat content from the 1975-1979 sections for the 0 to 100-m, 100 to 200-m, and 200 to 400-m layers, each adjusted to its annual mean (Fig. 5), all indicate a large January-February increase. However, after the February-March period the layers below 100 m change relatively little until June when the southwest monsoon has commenced. At this time it appears that heat previously stored in the 0 to 100-m layer is then distributed downward. By the middle of the southwest monsoon (July) a loss of approximately $13 \times 10^8 \text{ Jm}^{-2}$ in the 0 to 100-m layer and a gain of approximately $13 \times 10^8 \text{ Jm}^{-2}$ in the 100 to 400-m layers occurs, suggesting a pronounced vertical transfer of heat downward to a large extent by the ocean's dynamic response to the monsoon. The strong sea surface (and mixed layer) warming during northern spring followed by the downward transfer of heat to depths of 200 m and below during the late southwest monsoon (July-September) is clearly illustrated in Figure 6.

HEAT CONTENT RATE

The rate of heat-storage change minus the sea-surface heat gain (Fig. 7) indicates the degree of convergence or advection of heat during the year. In the entire 0 to 400-m layer maximum convergence (heat import) occurs during January-March, with values reaching over 280 Wm$^{-2}$, to a large extent caused by heat import in the 100 to 200-m layer. Note that the 0 to 100-m layer during December-April has relatively little input from advection (amounting to slightly over 60 Wm$^{-2}$, probably negligible) indicating that in this layer the net surface heat gain (December-April) of approximately $10 \times 10^8 \text{ Jm}^{-2}$ from the atmosphere accounts for nearly all of its increase in heat content of approximately $11 \times 10^8 \text{ Jm}^{-2}$. The heat gain of the 0 to 400-m layer from December-April amounts to approximately $31 \times 10^8 \text{ Jm}^{-2}$ or about 3 times the heat furnished from the atmosphere.

During June-August the downward movement of heat from the 0 to 100-m layer to the deeper layers is shown, suggesting that a relatively small amount of heat is exported horizontally from the region, whereas the vertical movement of the thermocline becomes important at this time. The reverse appears to be the case during the October-December period when a large heat export by horizontal advection from the 0 to 400-m layer amounting to over 600 Wm$^{-2}$ occurs, which is comparable to the Gulf Stream heat export at the sea surface during January-February (Bunker, 1976). If the net heat gained at the sea surface for the September-December period amounting to approximately $13 \times 10^8 \text{ Jm}^{-2}$ is added to that lost in the 0 to 400-m layer, approximately $27 \times 10^8 \text{ Jm}^{-2}$, the total comes to approximately $40 \times 10^8 \text{ Jm}^{-2}$ which must be advected from this region. Relatively small losses, however, occur in the 0 to 100-m layer, as may be seen.

In part, heat might be advected away by subsurface southward flows such as those described by Quadfasel and Schott (1983). Strong zonal flow near the Equator also might remove heat as suggested by the semiannual maxima in surface dynamic height ($1^\circ \text{N}-1^\circ \text{S}$) along the tanker sea-lane where it crosses the Equator (Fig. 8). From the equatorial region heat would then be advected into the southern hemisphere. Moored current meter records on and near the Equator indicate a pronounced semiannual signal of eastward and westward flow which extends considerably deeper than the 400 m level discussed here (Luyten, Roemmich, 1982). The signal occurs as far east as Gan (approximately $73^\circ \text{E}$; Knox, McPhaden, 1980).

CONCLUSIONS

It would appear that the energy of the eddy field, particularly during the southwest monsoon, plays a significant role in the storage and in the vertical and horizontal transfer of heat in the western Indian Ocean, especially in the Somali Basin. Merle (1980) has found a somewhat similar situation in the western equatorial Atlantic.

In the case of the Somali Basin, there appear to be three stages in the heat transfer process. First, the large import of heat commences near the beginning of the northeast monsoon. The 100 to 400-m layer appears to receive heat by advection, whereas in the 0
Figure 6
Temperature, °C, of sea surface (upper) and at 200 m depth (lower) along XBT sections from 2°S-22°N (see Fig. 1) for period from October 1975 through December 1979.
to 100 m layer, heating correlates well with the strong net surface gain in northern spring. Next, as the southwest monsoon commences, much of the heat stored in the upper 100 m is moved vertically downward to deeper layers while cooler upwelled water, uplifted by the dynamic forcing of the wind, removes heat from the upper layer (Fig. 9). Lastly, in the third stage, post-southwest monsoon cooling commences in the deeper layers with relatively rapid advection of heat from the 100 to 400-m layer.

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