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Arabian Sea Cooling: A Preliminary Heat Budget

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ABSTRACT

To assess the importance of possible feedbacks between ocean and atmosphere in the Arabian Sea, we computed a preliminary heat budget for the upper ocean layer. The observed total heat loss during the Southwest Monsoon between April and August is essentially balanced by three phenomena: positive heat gain from the atmosphere, negative northward heat flux across the equator, and heat loss due to upwelling along the coasts of East Africa and Arabia. Upwelling constitutes the dominant factor and the question is discussed as to which processes replenish the cold upwelled water on a seasonal time scale.

The average annual heating rate above and beyond seasonal fluctuations is found to be 24 W m^{-2}. This net heat input must be compensated by ocean currents. The manner in which the ocean accomplishes this remains to be clarified.

1. Introduction

A number of recent studies have suggested that there is a relationship between sea surface temperature anomalies and anomalies in rainfall over India. The variability of sea surface temperature over the Arabian Sea (Fieux and Stommel, 1976) has been linked to records of rainfall over India by a correlation analysis of data from 1900 to 1960 (Shukla and Misra, 1977). Shukla (1975) has further shown that insertion of warm anomalies of Arabian Sea temperatures into the general circulation model of the Geophysical Fluid Dynamics Laboratory results in higher precipitation over India. However, the recent study by Raghaven *et al.* (1978) questions the validity of fixing in time an anomaly in the sea surface temperatures as was done in the Shukla computations. They find that the anomalies are, in fact, short-lived and episodes of strong and weak monsoons coincide with fluctuations of sea surface temperatures in the western Arabian Sea on time scales as short as one week. Nevertheless, correlations have been demonstrated between the intensity of the East African low-level jet and Indian rainfall (Findlater, 1969; Saha, 1974).

As a first step in assessing the importance of possible feedbacks between the ocean and the atmospheric circulation in this region, a preliminary heat budget for the upper layer in the Arabian Sea is computed. The region is characterized by pronounced summer cooling of the upper mixed layer as shown in Wyrtki (1971). Comparison of areas that are cooled (Fig. 1) with the fully developed atmospheric Somalí Jet in July (Fig. 2) reveals that areas of high wind speed approximately coincide with areas of strongest surface cooling. One might therefore be tempted to conclude that direct wind effects such as evaporative cooling and wind stirring are dominant factors in determining the upper layer ocean temperature and that oceanic effects such as horizontal advection and upwelling play a relatively minor role. It will be shown that the opposite is true. Upwelling constitutes the dominant factor in the summer cooling and the question then arises as to which processes replenish the cold upwelled water. Various mechanisms such as winter cooling in the northern Arabian Sea, southward flow at intermediate depths under the Somali Current, and the deep western boundary current are briefly discussed as mechanisms for exporting heat out of the Arabian Sea.

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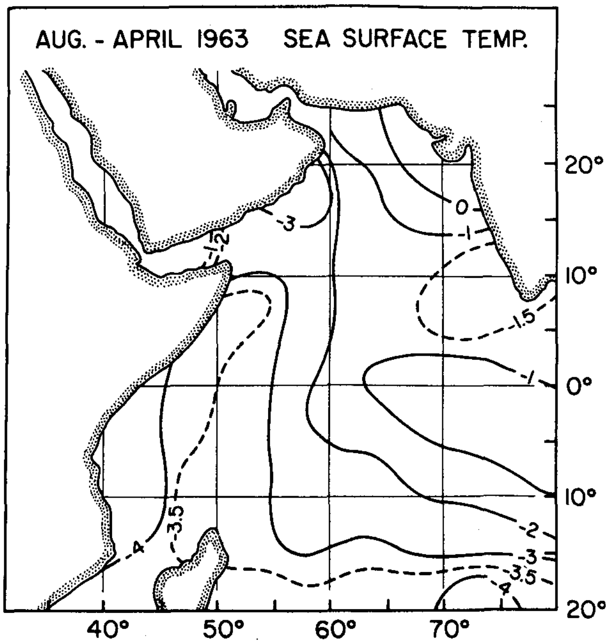

FIG. 1. Decrease in sea surface temperature (°C) in the Arabian Sea between April and August 1963 (from Ramage *et al.*, 1972).

2. Heat budget computation

In order to assess the relative importance of the various physical factors that cause the cooling of the Arabian Sea during the southwest monsoon, the heat budget is computed. The area that is considered is delineated by the equator to the south and by the longitude meridian of 75°E to the east. We assume that most of the net seasonal heat exchange does not penetrate into or below the main thermocline except due to upwelling. Hence the depth or level to which the computation is carried is deeper than the mixed layer and is chosen to be in the upper part of the permanent thermocline. The zero-order heat budget equation is given by

$$Q_\Sigma = Q_{\mathrm{h.ex}} + Q_{\mathrm{a.eq}} + Q_{\mathrm{upw}}, \tag{1}$$

where

Q_Σ total change in heat content in the above described box based on the observed temperature change between April and August

$Q_{\mathrm{h.ex}}$ net radiation gain minus heat loss through evaporation minus sensible heat loss

$Q_{\mathrm{a.eq}}$ heat advected across the equator

Q_{upw} heat change due to upwelling of water from below the depth of the main thermocline

Fluxes across 75°E are considered negligible because of the small oceanic opening and the small horizontal temperature differences across it.

Estimates of the individual terms in Eq. (1) are necessarily crude, and possess large error margins. The methodology for computing each of these terms is as follows:

1) Q_Σ: In computing the changes in the heat content in the upper ocean between April and August area-averaged temperature data from the monograph by Colburn (1975) were used. His data were primarily from the time period of the International Indian Ocean Expedition (1960–65). Hence the oceanographic and atmospheric data were taken at essentially the same time. Colburn subdivides our region of interest into eight subareas. Each of these was chosen so as to contain only observations that had similar vertical and temporal thermal characteristics. A difficulty in estimating changes in the heat content is that major seasonal, vertical displacements of the thermal structure occur as a dynamic response to changes in the wind forcing. Under the assumption that was mentioned earlier that most of the net seasonal heat exchange does not penetrate below or into the permanent thermocline, we are interested in estimating heat storage above this level. Fixed levels were chosen in each of Colburn's subareas that were deeper than the mixed layer but lay in the upper part of the permanent thermocline. Reasonable variations in these levels did not change our estimates of heat content by more than 25%. These levels are given in Table 1. Thus

$$Q_\Sigma = \frac{\bar{\rho} c_p}{\Delta t} \sum_{i=1}^{8} \Delta T_i A_i h_i,$$

where ΔT_i is the change in the average temperature; A_i and h_i are the area and reference depth chosen in each subarea (see Table 1); $c_p = 4.18$ J g^{-1} °C; $\Delta t = 4$ months; and $\bar{\rho}$ is the mean density.

2) $Q_{\mathrm{h.ex}} = \bar{H}_E A$, where $\bar{H}_E$ is the average net

TABLE 1. Depth level of subareas (following Colburn, 1975) which is deeper than mixed layer and above which temperature change from April to August was computed.

	Subarea A_i							
	1	2	3	4	6	11	17	20
Depth level h_i (m)	60	100	70	50	70	50	75	80
Average temperature change ΔT_i (°C)	−2.75	−1.25	−1.0	+0.5	−4.0	−2.0	−1.5	−1.5

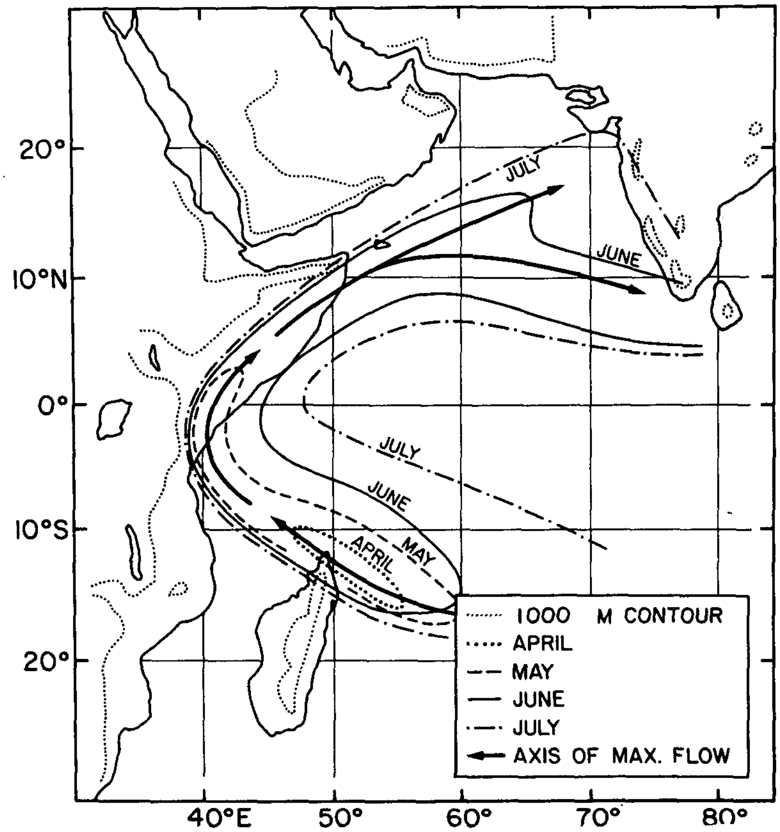

FIG. 2. Successive positions of the 20 kt isotach at 1000 m during the onset of the northern summer monsoon, April–July (from Findlater, 1971).

heat gain from April to August of 1963: It was determined from the atlas by Ramage *et al.* (1972). The average was over A, the area of the Arabian Sea as defined above.

3) $Q_{\text{a.eq}} = \rho M \Delta T c_p$, where ρM is the mass transport across the equator near the western boundary: The value chosen was $(10 \pm 3) \times 10^6$ metric tons s^{-1}. This was the transport as measured by Swallow and Bruce (1966) in this location during 1963. The average temperature difference ΔT between this (cool) northward flow and the compensating (warm) southward flow across the equator further to the east was estimated to be $2.5 \pm 0.5°C$. This value was obtained from the atlas by Wyrtki (1971).

4) $Q_{\text{upw}} = \tau L \Delta T c_p f^{-1}$: During the Southwest Monsoon the winds blow almost parallel to the coasts of Somalia and Arabia. The Ekman transport is directed to the right of the wind stress and hence there is a transport of the surface layers away from these coasts. This requires upwelling of colder subsurface water. The rate of upwelling along the coast is given by $\tau L f^{-1}$ where τ is the mean wind stress from May to August. We chose a value of 3.5 ± 1.0 dyn cm^{-2} (Bruce, 1979, private communication). The length L of the coastline off Somalia and Arabia where pronounced upwelling takes place is ~1600 km. The Coriolis parameter is evaluated at about 9°N. The mean difference between the upwelled water and the temperature in the interior of the basin was estimated to be $\Delta T = 3.5 \pm 1.0°C$ (Wyrtki, 1971). Since mass has to be conserved, the influx of upwelled water must be compensated for by an outflow somewhere. This can occur either by a depression of the thermocline in the Arabian Sea or an outflow across the lateral boundaries of our region. In either case ΔT represents the temperature difference between the outflowing (or sinking) water in the mixed layer and the upwelled water.

The resulting balance (W) thus becomes

$$\underbrace{-(2.7 \pm 1.3) \times 10^{14}}_{Q_\Sigma} = \underbrace{(2.3 \pm 0.8) \times 10^{14}}_{Q_{\text{h.ex}}} - \underbrace{(1.1 \pm 0.5) \times 10^{14}}_{Q_{\text{a.eq}}} - \underbrace{(3.8 \pm 1.9) \times 10^{14}}_{Q_{\text{upw}}}. \quad (2)$$

It is seen that the observed cooling Q_Σ in the upper layer of the Arabian Sea is balanced within the error bars of our estimates. Let us consider the individual terms on the right-hand side of Eq. (2) as well as certain implications and questions resulting from these estimates.

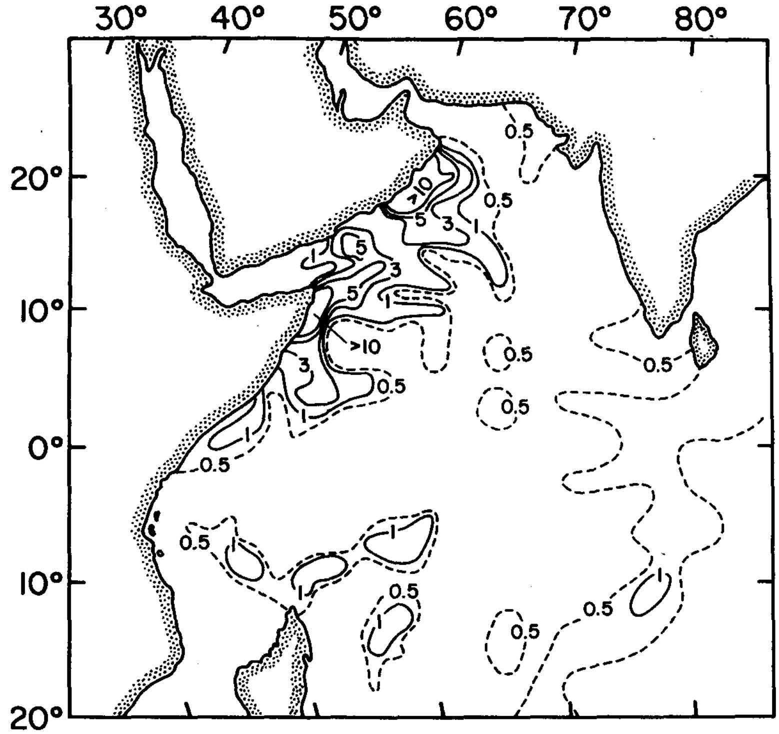

FIG. 3. Nitrate distribution as an upwelling indicator between May and October (from Wyrtki, 1971).

3. Discussion

One unexpected result is that $Q_{h.ex}$ is positive. It might have been expected that during the height of the Southwest Monsoon the evaporative heat loss would be greater than the heat gain due to incoming radiation (Colon, 1964). In fact, this is only true for small areas under the Somali Jet. For the whole area the radiation overbalances the evaporative cooling. This heat gain is more than cancelled by the large negative heat flux northward across the equator, $Q_{a.eq}$, and the intense upwelling, Q_{upw}, off Somalia and Arabia.

Our estimate of the heat transport across the equator depends on the volume transport in the top layer of the Somali Current. The value of $(10 \pm 3) \times 10^6$ tons s^{-1} that was used appears to be low when compared to larger transport measurements further downstream (Düing, 1978). Perhaps the near-equatorial section of Swallow and Bruce (1966) did not reach far enough to the east. Consequently, the heat transport across the equator by the Somali Current system might be larger than we estimate.

It is a bit surprising that cooling by upwelling, Q_{upw} is the largest term. The importance of this process in the summer cooling of the Arabian Sea has been stressed by Saha (1974). An illustration of the horizontal area affected by summer upwelling is provided by the nitrate distribution in summer (Fig. 3) (Wyrtki, 1971). One has to keep in mind (i) that nitrate can only reach the surface by upwelling (the upwelled water is subsequently advected into the interior of the Arabian Sea), and (ii) that the summer values in Fig. 3 cover the minimum area affected by upwelling since nitrate is immediately taken up by plankton when reaching the euphotic zone and not only when reaching the surface. The regions with large nitrate values correspond clearly with the regions of strong cooling (Fig. 1).

Two important questions arise out of these computations. First, how is the summer cooling, which appears to be primarily a result of the upwelling, balanced in the annual heat budget? Second, how is the large quantity of water that is upwelled replenished at depth? The accumulated, observed heat loss Q_Σ from May to August amounts to $2.8 \pm 2.0 \times 10^{21}$ J. The net heat gain $Q_{h.ex}$ from September to April in the same area amounts to approximately 4.6×10^{21} J. Thus the heating throughout the rest of the year more than balances the summer cooling within our error estimates. From September to April there is no evidence that upwelling or cross-equatorial heat flux in the surface layers by the Somali Current system is important.

There remains the question of what replenishes the volume of cold water that is reduced, by the upwelling. Several processes are probably important in this. Winter cooling of surface waters in the

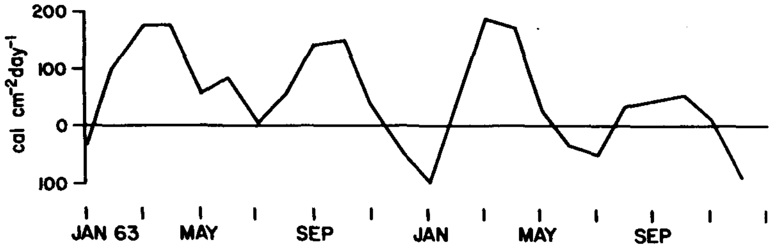

FIG. 4. Total net heat exchange of the Arabian Sea (1963–64). 1 cal cm^{-2} day^{-1} = 0.48 W m^{-2}.

northernmost corner of the Arabian Sea and subsequent sinking and spreading southward may be one possible source of cold water at intermediate depths. During the late winter over a period of 2.5 months, the mixed layer in an area of $\sim 1.2 \times 10^6$ km^2 which comprises the Gulf of Oman and the coastal region of Arabia cools to 25°C (Wyrtki, 1971); the corresponding heat loss amounts to -1.9×10^{14} W. This is half of what we expected the cooling due to upwelling to be. The cooled water mass sinks to 200 m depth and mixes with water from the Persian Gulf. The combined water spreads southward and eastward. As it spreads it sinks and becomes denser changing its density from $\sigma_t \approx 26.0$ to $\sigma_t \approx 27.2$. Along the coasts of Arabia and Somalia, where summer upwelling takes place, this water mass is found between 200 and 500 m and hence lies at a depth from which upwelling can take place.

Mass exchanges with the Red Sea and the Persian Gulf also contribute to the mass and heat budgets at intermediate depths in the Arabian Sea. However, the mass exchanges amount only to about 0.3×10^6 metric tons s^{-1} and hence are unimportant because of their small size and the small amount they contribute to the overall budgets.

The fact remains that only about half of the replenishment of the upwelled water can possibly be accounted for. The situation might be even worse than this as we learn more about the deep circulation in the Arabian Sea. Current measurements off Somalia in 1975 (Düing, 1977) as well as more recent measurements by Düing and Schott in the same area have revealed the presence of a mean southward flow along the Somali coast at intermediate depths. Since neither the vertical nor horizontal extent of this flow are known at present, its significance and impact on the heat and mass budgets of the Arabian Sea cannot be determined.

So far we have examined the heat budget on a seasonal time scale. Fig. 4 illustrates that on the yearly average the Arabian Sea is a region of positive heat input into the ocean. In 1963 the average input was 36.9 W m^{-2}; in 1964 it was 11.6 W m^{-2}. The two-year average is 24 W m^{-2}. For the whole Arabian Sea (as we defined earlier) with an area of 6.4×10^{12} m^2 this amounts to 1.5×10^{14} W. What balances this?

Clearly, processes internal to the Arabian Sea cannot balance this input. There must be a mean transport of heat southward across the equator. Upwelling along the Somali and Arabian coasts cannot accomplish it. Part of the upwelled water is possibly renewed by wintertime cooling of surface waters and its subsequent sinking in the Gulf of Oman. In essence, this process "stores" the winter cooling and balances it against part of the summer heating. The average heating rate of 24 W m^{-2} includes this storage and later release and is in excess of these amounts. To keep the Arabian Sea from heating up, heat has to be transported across the equator.

One way this could occur is to bring in cold water in the deep western boundary current and export warmer water at some shallower depth. Other possibilities exist. For example, such an exchange of warm and cold water could take place at intermediate depths either along the western boundary or in the interior. To demonstrate that such processes can in principle transport enough heat we suppose the exchange is strictly via the deep western boundary current. At this time no direct measurements exist to indicate that such a current flows across the equator. However, at 12°S, Warren (1977) found evidence for a deep northward flow of about 5×10^6 metric tons s^{-1}. If this continued across the equator then a temperature difference between it and an outgoing flow of 7°C would be sufficient to balance the net heat input of 24 W m^{-2}. During the Southwest Monsoon the heat transfer by the Somali Current is in the same direction. During the Northeast Monsoon, this current reverses. The role of seasonally reversing currents in the upper layer in the annual heat budget remains to be clarified.

4. Implications for large-scale air-sea interaction

This straightforward computation, with its large uncertainties has been instructive in a number of ways. If the results had indicated that the heating and cooling of the ocean was purely in response to variations in the local heat exchange with the atmosphere, then the ocean would probably have only minor feedback effects on the atmosphere. In fact, the opposite was suggested. The main contributor to the oceanic cooling appears to be upwelling. This process can occur on a time scale of days and hence major events in the ocean and the atmosphere have comparable time scales and the potential for strong interaction exists. For example, a strong monsoon could lead to extensive upwelling which, in turn, would stabilize the lower layers of the atmosphere. Hence, less water vapor would get into the atmosphere which might lead to less convection and a reduced atmospheric circulation. It will be interesting to look for such connections by comparing the time lags between the pulsations of the Somali Jet and the upwelling off Somalia and Arabia as are observed during FGGE.

On longer time scales the Somali Current becomes important. It represents the response of the central portion of the Arabian Sea to strong, coherent fluctuations of the monsoonal wind system (e.g., the onset of the monsoon). The time scale for this response is weeks. Hence, it introduces possible interaction with the atmospheric circulation on longer time scales.

In the mean or on very long time scales the mean oceanic circulation must also play an important role. Without a mean export of heat out of the Arabian Sea, it would heat up. The manner in which the ocean accomplishes this heat export remains to be clarified. Is there a deep western boundary current north of the equator? What is the extent and importance of the mid-depth flows that have recently been discovered? These and some of the questions about the response of the Somali Current to the onset of the Southwest Monsoon and the upwelling along Somalia will be addressed during a forthcoming international experiment that will take place during Special Observing Period II of FGGE off the Somali coast called Indian Ocean Experiment (INDEX).

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