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Seasonal variation of the flow in the strait of Bab al Mandab

Bal al Mandab
Red Sea
Exchange
Seasonal
Fluxes

Bab al-Mandab
Mer Rouge
Echange
Variabilité saisonnière
Flux

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ABSTRACT

There is a strong seasonal variation in the exchange flow through the strait of Bab al Mandab connecting the Red Sea to the Gulf of Aden (Thompson, 1939). In the winter a two-layer flow is observed in the strait. Dense intermediate water from the Red Sea flows into the Gulf of Aden and warmer fresher surface water flows into the Red Sea. In the summer season the direction of the surface flow is reversed and a third layer, of density between that of the surface layer and that of the intermediate Red Sea water, flows into the Red Sea. An analysis of this intrusion of cold water from the Gulf of Aden into the Red Sea is made using XBT data. The speed of propagation is. 0.06 m s^{-1}. Following the onset of the winter monsoon in September, downwelling in the Gulf of Aden cuts off the supply of cold water. In the following weeks convective mixing entrains the intrusion into the overlying mixed layer. During the summer there are net fluxes of heat and salt out of the Red Sea. These fluxes, as well as the net evaporation from the sea surface, play an important role in determining the winter time exchange and the properties of the outflow from the Red Sea. Application of two-layer hydraulic theory suggests that the winter time exchange is sub-maximal, *i.e.* the exchange fluxes are influenced by other processes within the Red Sea and the Gulf of Aden. It is suggested that the stratification in the Gulf of Aden has an important effect upon the exchange.

RÉSUMÉ

Variabilité saisonnière de la circulation dans le détroit de Bab al-Mandab.

Les échanges d'eaux entre la Mer Rouge et le Golfe d'Aden, par le détroit de Bab al-Mandab, sont marqués par une forte variabilité saisonnière. En hiver, une circulation à deux couches est observée : l'eau intermédiaire dense sort de la Mer Rouge tandis que l'eau entrante est plus chaude et moins salée. En été, la circulation superficielle s'inverse et une troisième couche apparaît : de densité comprise entre celles des deux couches précédentes, cette eau froide entre dans la Mer Rouge à la vitesse de 0,06 m s^{-1}. En septembre, à l'établissement de la mousson d'hiver, une plongée d'eau dans le Golfe d'Aden interrompt l'intrusion d'eau froide ; dans les semaines qui suivent, la couche froide se mélange par convection avec l'eau sus-jacente.

En été, des flux nets de chaleur et de sel sortent de la Mer Rouge où se produit une forte évaporation. Ces transferts ont un rôle déterminant dans l'échange hivernal et les propriétés des eaux sortant de la Mer Rouge. Le modèle à deux couches, appppliqué à l'échange hivernal, ne décrit pas toutes les observations ;

Les échanges sont donc certainement influencés par d'autres phénomènes dans la Mer Rouge et le Golfe d'Aden. La stratification du Golfe d'Aden a probablement un effet important sur les échanges.

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INTRODUCTION

Like the Mediterranean, the Red Sea is an almost completely enclosed basin. The only significant opening is the Strait of Bab al Mandab connecting the south of the Red Sea to the Gulf of Aden. The narrowest section of the strait, close to Perim Island, is only 18 km wide. The shallowest sill over which the deep water must pass is about 140 m deep and located close to Hanish Island, about 120 km from Perim Island.

The average rate of evaporation over the Red Sea has been estimated to be 2 m yr^{-1}. Integrated over an area of 453,000 m^2, this represents a net flux, E, of $\sim$ 0.03 Sv. This flux must be balanced by a net inflow through the strait. Because the inflow through the strait is greater than the outflow, then, in order for the total quantity of salt to be conserved, the salinity of the outflow must be greater than that of the inflow. Indeed the deep water in the Red Sea has a high salinity of about 40.5.

Conservation of volume and salt alone do not determine the exchange flux and the outflow salinity. Bryden and Stommel (1984) considered the very similar case of the Mediterranean. They showed that the application of the condition of hydraulic control in the strait of Gibraltar, as well as the conservation of volume and salinity, could be used to predict the exchange flux and the outflow salinity. Bryden and Kinder (1991) have examined the problem again in more detail.

Observations (Siedler, 1968) made in the winter suggest that the flow through Bab al Mandab is hydraulically controlled, but it is likely that the exchange is sub-maximal. This would imply that the exchange is not limited by the strait alone, but that other processes in the Red Sea and the Gulf of Aden are important. Phillips (1966) presented a model of the annually averaged circulation of the Red Sea in which the exchange is limited not by the processes in the strait but by the mixing and dissipation within the Red Sea. Tragou and Garrett (1995) have examined Phillips model again. They found that the model requires a very viscous flow for the model to match the observed conditions. Tragou and Garrett (1995) noted that the model does not take account of the seasonal variation in the surface buoyancy flux.

In contrast to the Mediterranean, there is also a strong seasonal variation in the exchange flow through Bab al Mandab (Thompson, 1939). In the winter a two-layer flow is observed in the strait. Dense water from the Red Sea flows into the Gulf of Aden and warmer fresher surface water flows into the Red Sea. In the summer season the direction of the surface flow is reversed and a third layer, of density between that of the surface layer and that of the intermediate Red Sea water, flows into the Red Sea.

The winter and summer exchange flows are illustrated in Figure 1. We refer to the three water types as Gulf of Aden intermediate water (GAIW), Red Sea outflow water (RSOW), and surface water (SW), their approximate properties, observed within the strait, are summarised in Table 1. These values have been estimated from the data presented by Siedler (1968), Patzert (1974), and Maillard and Soliman (1986). Note that these values are indicative only; the actual temperature and salinity vary in both space and time. The potential density, s_θ, and reduced gravity, g', are also shown for each layer. The reduced gravity is defined as $g' = g\frac{\Delta\sigma_\theta}{\sigma_\theta}$, where g is the acceleration due to gravity, and $\Delta\sigma_\theta$ is the change in density between the layer and the underlying layer.

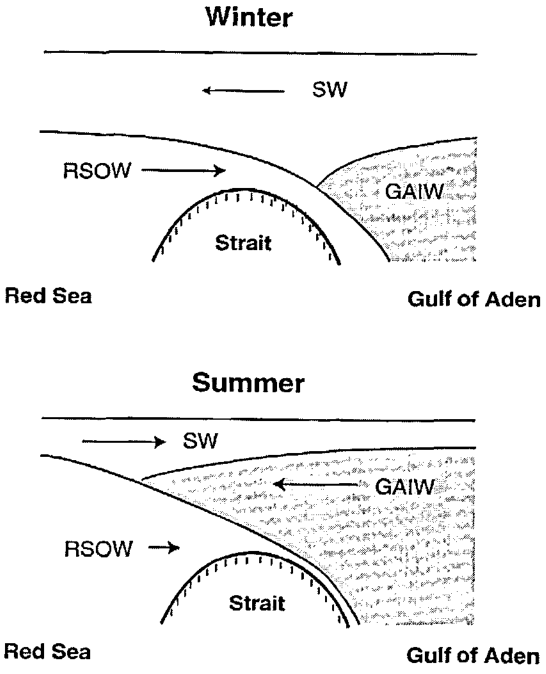

Figure 1

Sketch of the two circulation patterns in the strait of Bab al Mandab. (a) Winter, (b) Summer.

Table 1

Approximate values of the properties of the three layers. The reduced gravity, g', is calculated using the difference in density between the layer and the underlying layer.

Layer	Temp (°C)	Salinity (psu)	σ_θ kg m^{-3}	g' m s^{-2}
Surface - summer	32	37	22.5	0.033
Surface - winter	26	37	24.5	0.014
Intermediate	18	36	26.0	0.018
Deep	22.5	40	27.9	–

The sub-surface layer (GAIW) that flows into the Red Sea in summer is several degrees colder than the RSOW, and fresher than the surface layer. GAIW has been observed in the Red Sea as far north as 18° N (Jones and Browning, 1971).

A large part of the circulation in the Red Sea occurs in the upper 200 m, The deep water in the Red Sea is formed mostly by deep convection in the northern Red Sea. This water is slightly saltier and warmer than the mid depth (100-200 m) water which forms the majority of the RSOW. It is thought that the outflow of Red Sea water is much reduced during the summer (Maillard and Soliman, 1986).

It has long been recognised (Thompson, 1939) that the change in circulation of the strait is associated with the monsoon winds. Throughout the year the wind, constrained by orography, blows predominantly along the axes of the Red Sea and the Gulf of Aden. In the winter season (November to May) the wind blows westward in the Gulf of Aden and north-westwards in the southern Red Sea. The directions of these winds are reversed and the speeds are reduced in the summer season (June to October). Although it is sometimes suggested that the reversal of the surface flow is due to the effect of the local wind stress, Patzert (1974) correctly showed that it is the wind induced upwelling in the Gulf of Aden that is primarily responsible for the change.

In this paper historical data is analysed to examine the seasonal variation in the flow through the strait of Bab al Mandab. The importance of the seasonal variability on the annually averaged exchange fluxes and on the circulation within the Red Sea is discussed with the aid of a simple model.

Analysis of historical XBT data

The NODC data base has been used to examine the seasonal variability of the oceanography of Bab al Mandab and the southern Red Sea. The data were collected between 1967 and 1989. Unfortunately there are almost no CTD observations from this area in the NODC data base, so XBT data only are presented. Therefore, in the following discussion, it is necessary to infer approximate values of salinity from the correlation between temperature and salinity observed in previous studies and summarised in Table 1. A few outlying profiles have been removed, but the NODC data have not been processed in any other way.

To aid the analysis of the data a set of co-ordinates were defined as follows

$$x = (x' - y'/\sqrt{2}) \qquad (1)$$

$$y = (x' + y')/\sqrt{2} \qquad (2)$$

$$x' = 111.2 \times \cos(12.5) \times (\text{longitude} - 43.25) \qquad (3)$$

$$y' = 111.2 \times (\text{latitude} - 12.5) \qquad (4)$$

So that the origin is at the narrowest section of the strait and the x axis is aligned approximately with the axis of the strait. The data were separated into a number of along strait divisions (*see* Tab. 2 and Fig. 2). Data from the Gulf of Aden (GA), the strait (S), the region just to the north of the strait (E), and in the central Red Sea (C) are shown in Figures 3*a-d*. In each figure all the observations of temperature are shown as a function of depth in summer and in winter. The summer data were recorded between days of year 225 and 270, and the winter data between days of year 45 and 90. A number of features are evident from these figures.

Table 2

The along stream divisions into which the XBT data were separated.

Division	x Range (km)
GA	- 50, 0
S	0, 150
E	200, 400
C	900, 1100

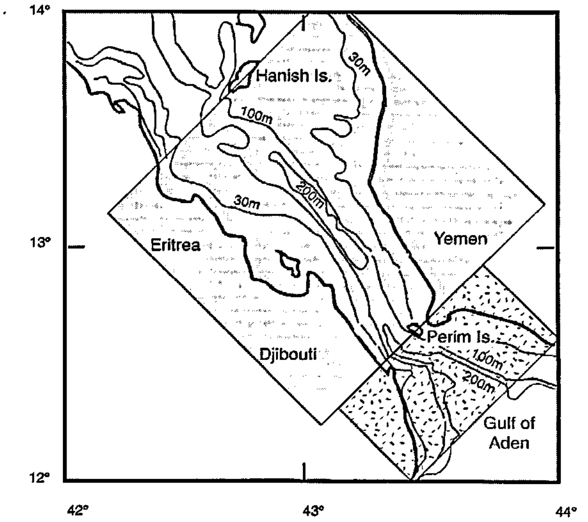

Figure 2

The southern Red Sea and the strait of Bab al Mandab. The stippled and shaded areas indicate two of the divisions, GA and S, used in the analysis of the XBT data.

Winter

To the south of the strait, in the Gulf of Aden, the surface mixed layer (26-28 °C) is about 100 m deep. Immediately below the surface layer cold (15-17 °C) GAIW is found in the Gulf of Aden. But deeper still (below 200 m) RSOW (21.7 °C) is evident. The depth and temperature of the mixed layer in the strait is similar to that in the Gulf of Aden, but there is no evidence of GAIW there or in the Red Sea. Both in the strait and the Red Sea RSOW lies immediately below the surface layer.

Summer

The surface layer in the Gulf of Aden is much shallower, so that below about 20 m the water is cooler, and denser

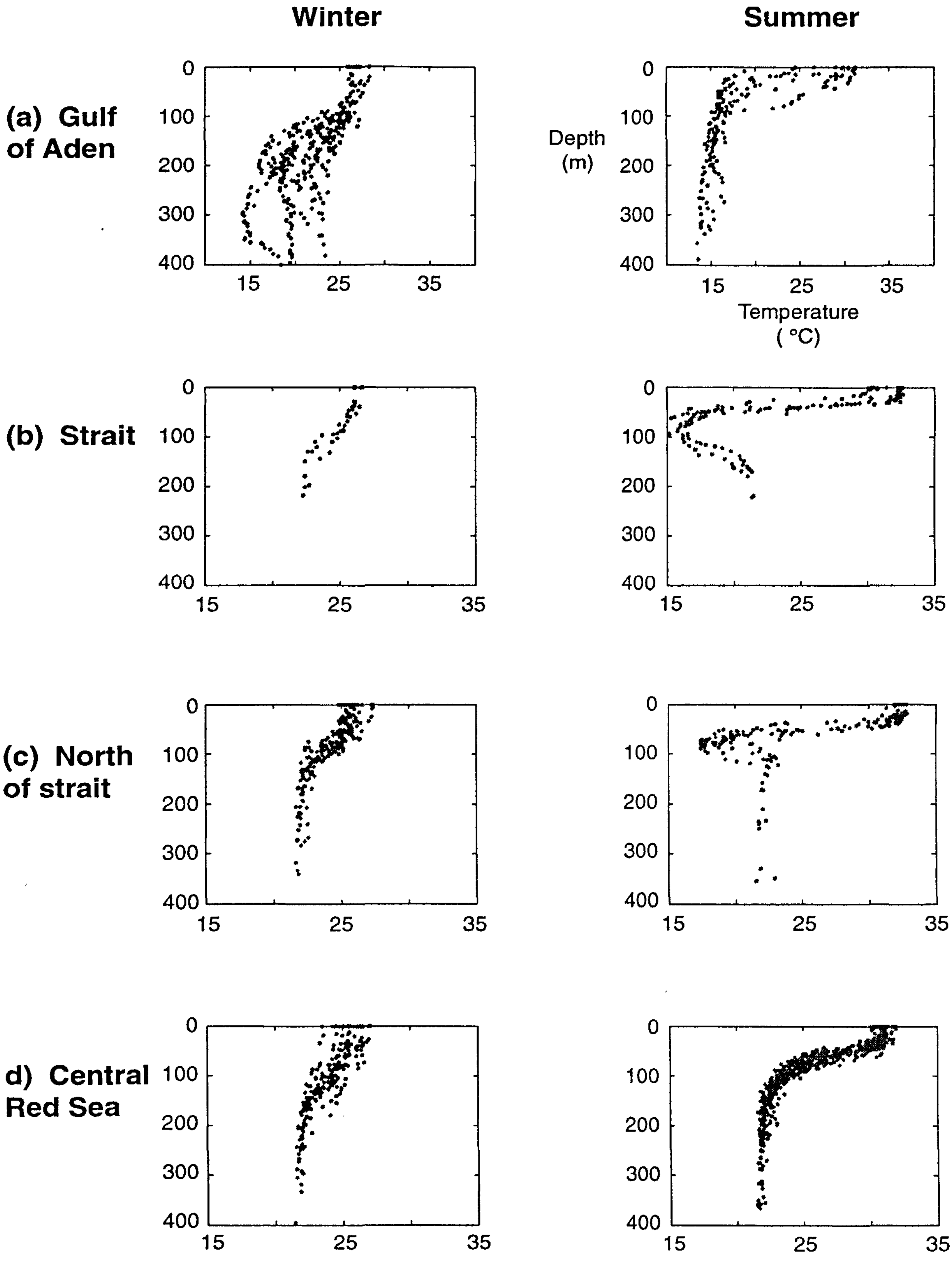

Figure 3

Vertical profiles of temperature in winter (days 45-90), and summer (days 225-270). (a) division GA, (b) division S. (c) division E, and (d) division C.

than in the winter. This is the result of upwelling induced by the summer monsoon. In the central Red Sea the mixed layer is shallower, but the water above 100 m is warmer, and less dense than in the winter. Thus, as described by Patzert (1974) there is a change in the hydrostatic pressure gradients that causes GAIW to flow into the Red Sea. The intrusion of GAIW is seen in the strait and further into the Red Sea (Figs. 3*b*, *c*), but not in the central Red Sea (Fig. 3*d*). RSOW water is evident below the intrusion in the strait, but is not evident in the upper 400 m of water in the Gulf of Aden.

The intrusion of GAIW into the Red Sea

The extent of the intrusion of intermediate water into the Red Sea is illustrated in Figure 4*a* in which all observations of temperatures in the ranges <16 °C, 16-18 °C, and 18-20 °C are plotted as a function of the time of year and distance (x) into the Red Sea. For reference all observations in the NODC data base are also plotted in Figure 4*b*. The intrusion is first apparent in the strait in June and propagates at an average speed of 5.5 km day^{-1} extending almost 800 km into the Red Sea by mid October. The temperature of the intrusion decreases as it advances indicating mixing with the overlying and underlying water. There are relatively few observations in November, but it appears that by the end of October the intrusion is no longer there, or is very much warmer. The rapid disappearance suggests that the cold water layer in Red Sea is mixed into the surface layer.

Figure 4 also indicates that during the winter season the cold water layer in the Gulf of Aden extends to within a few kilometres of the strait at Perim. As discussed further in the "Exchange" fluxes section, it is likely that the depth of this layer influences the exchange throughout the year.

The dynamics of the intrusion of GAIW into the red Sea

The data in Figure 4 were collected over many years and so suggest that the time of the initial entry into the strait, the speed of the of propagation within the Red Sea, and the time of the disappearance of the cold layer vary little from year to year, though some exceptions are evident.

As discussed above, GAIW is able to penetrate into the Red Sea after the onset of the summer monsoon because of the intense upwelling in the Gulf of Aden which changes the hydrostatic pressure gradients in the strait. In this section the processes involved in the propagation of the intrusion and its fate at the end of the summer are discussed.

Propagation of the intrusion into the Red Sea

The data in Figure 4 indicate that the intrusion propagates into the Red Sea with a speed of about 0.06 m s^{-1}. The current meter observations of Maillard and Soliman (1986) suggest that the mean speed of the intrusion the narrowest section of the strait, close to Perim Island, was about 0.25 m s^{-1}. The decrease in speed is presumably due to the lateral spreading of the intrusion as enters the Red Sea. From Maillard and Solimans estimate of the flux of GAIW, 0.36 Sv, and assuming a layer thickness h = 40 m, the average width of the intrusion is 150 km. This is of the order of the width of the deep channel that runs along the axis of the Red Sea.

Mixing with the overlying water will also affect the propagation of the intrusion. The gradients of temperature and salinity are such that double diffusive mixing can occur.

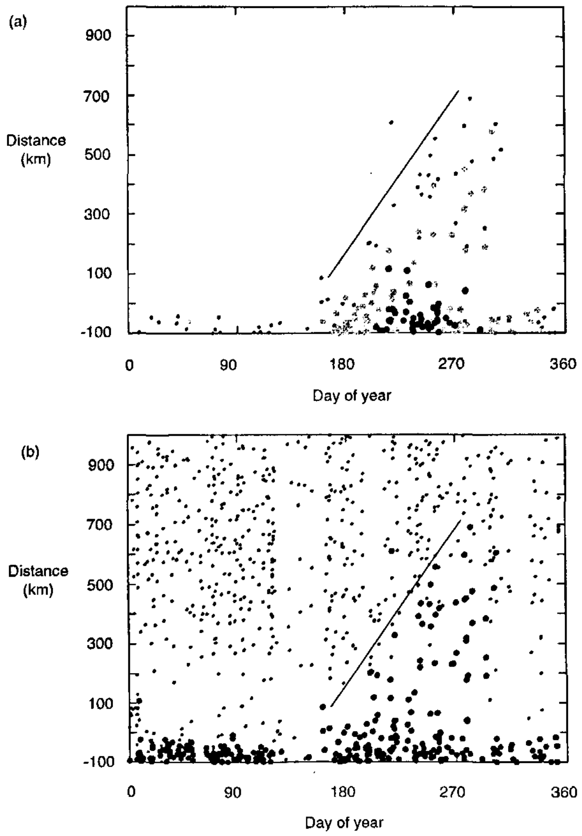

Figure 4

Day of year vs. distance (x) plot for all observations in the NODC data base. (a) Observations in the upper 120 m of temperatures less than 16° C (large black circle), 16-18° C (large grey circle) and 18-20° C (small black circle). (b) Observations of temperatures less than 20° C in the upper 400 m are indicated by the larger circles all other observations are represetned by smaller circles. The line indicates propagation at a rate of 5.5 km/day.

Salt fingering is possible above the intrusion and diffusive convection is possible below the intrusion. Both of these processes increase diapycnal mixing. The data in Figure 4 show that the value of the temperature minimum increases with distance into the Red Sea. This is due both to mixing and to the variation of temperature of the intruding water that enters the Red Sea. Unfortunately the data presented here are not sufficient to quantify the role of mixing.

Application of the thermal wind balance indicates that the thickness of the intrusion will vary by about 20 m across an intrusion of width 150 km. There is, however, insufficient data in the NODC database to confirm this. In the summer the depth of the mixed layer in the Gulf of Aden is very shallow. Figures 3*a* and 5*a* suggest that it is in places less than 10 m deep. The thickness of the intrusion also tends to zero within in the Red Sea. If two layer hydraulics could be applied to this situation, the vanishing layer depths would indicate that the flow is supercritical either side of the strait and that the exchange is maximal. However, the presence of the lower layer makes the situation harder to interpret.

The fate of the intrusion

Although some observations have shown small temperature inversions as late in the year as December (Robinson, 1974). Figure 4 indicates a relatively sudden end to the intrusion in late October. This suggests that the intrusion is mixed into the surface layer. This hypothesis is supported by observations of temperature in the upper 10 m (Fig. 5). In September the maximum surface temperatures are found within 400 km of the strait, but in November there is a sea surface temperature maximum about 800 km into the Red Sea (the most northerly extent of the intrusion). This is contrary to the conclusion of Bethoux (1987) who suggested that the intermediate layer flows back into the Gulf of Aden.

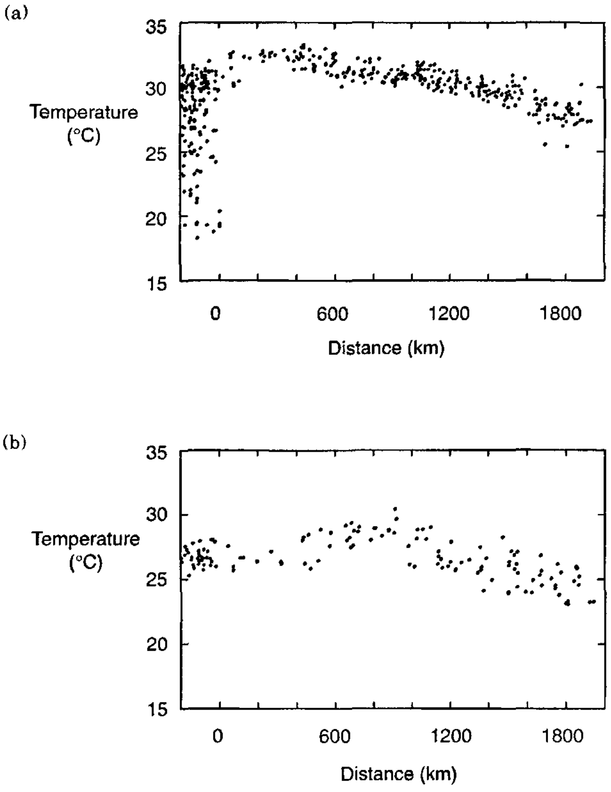

Figure 5

Temperature vs. distance (x) for all observations made between depths of 0 m and 10 m. (a) Between day 225 and 270 and (b) between day 315 and 360.

The wind speed does increase in the winter but the winds cannot provide enough energy to account for the deepening of the surface layer. Convective mixing is responsible.

Stratification is determined by horizontal fluxes as well as vertical fluxes of buoyancy. The buoyancy transport through the strait is approximately $g' Q_2 = 1.3 \times 10^4$ m^4 s^{-3}. At its maximum extent the intrusion has an area $A \sim 120$ km × 800 km. If the divergence of this transport were distributed uniformly over the area it would represent a vertical buoyancy flux of 1.4×10^{-7} m^2 s^{-2}, equivalent to a surface heat flux of almost 200 W m^{-2}.

It is probable that the divergence is concentrated at the head of the advancing intrusion so that the effective buoyancy flux will be less. However, the increase in temperature of the intrusion with distance into the Red Sea evident in Figures 4 and 6 suggests that it is a reasonable approximation to assume that the divergence of the horizontal flux is uniform over the area of the intrusion.

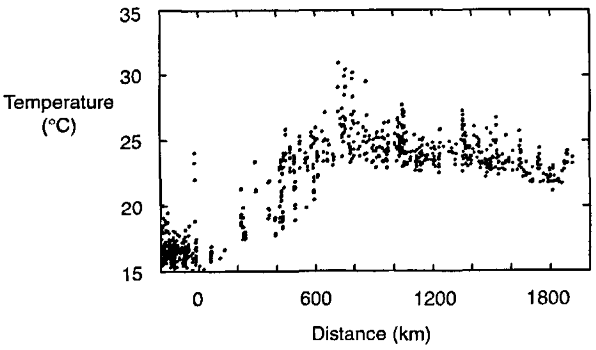

Figure 6

Temperature vs. distance (x) for all observations made between day 225 and 270 between depths of 70 m and 100 m. Note that the minimum temperature is higher further into the Red Sea.

It seems likely, then, that the flux of GAIW into the Red Sea must cease before the convective mixing due to the air-sea buoyancy flux can entrain the intrusion into the mixed layer. Examination of temperature data just outside the strait in the Gulf of Aden (Fig. 7*a*) and that in the southern Red Sea (Fig. 7*b*) suggests that downwelling associated with the end of the summer monsoon cuts off the flux of GAIW into the Red Sea a few weeks before the intrusion is mixed away.

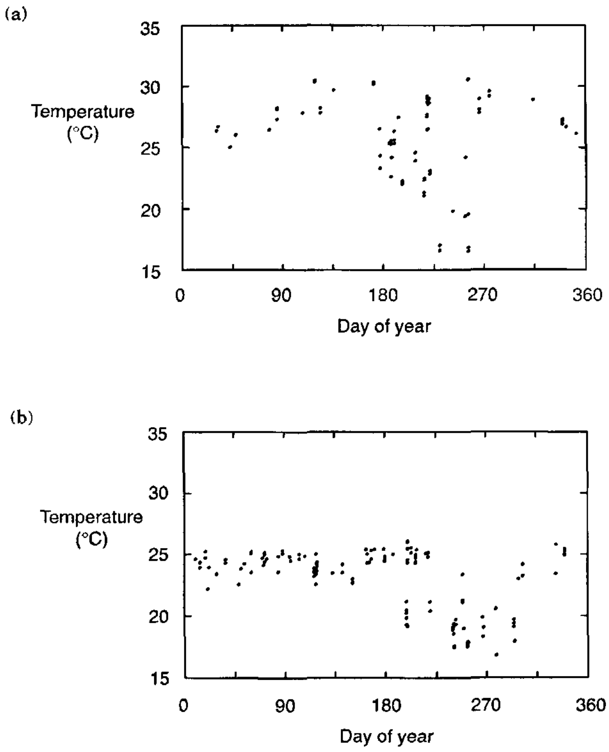

Figure 7

Temperature vs. day of the year for all observations made (a) between depths of 20 m and 30 m in division GA, and (b) between depths of 70 m and 80 m in division E.

Exchange fluxes

Maillard and Soliman, (1986) estimated that, at the height of the summer season, the flux of GAIW into the Red Sea was 0.36 Sv. Although the current meters from which the flux was estimated were only in the intermediate layer they estimated that only 10 % of the return flow was in the deep layer. Thus during the summer there is a net flow of heat and salt out of the Red Sea. Models of the circulation in the Red Sea have often assumed that the circulation is driven by the annual mean surface buoyancy flux alone (Phillips, 1966; Tragou and Garett, 1995). In this section we examine the impact of the summertime exchange upon the fluxes through the strait during the rest of the year, and in particular the properties of the RSOW.

A model

By assuming steady two-layer flow and applying conservation of. volume, conservation of salt, and the condition of hydraulic control in the strait of Gibraltar, Bryden and Kinder (1991) estimated the inflow and outflow volume fluxes, and the salinity of the outflow as a function of the geometry of the strait, the rate of evaporation and the salinity of the inflow. A similar model of the Red Sea is presented below. However, in this model account is taken of the seasonal variation of the flow in the strait and the effects of temperature differences between the inflow and outflow.

It is assumed that there are two seasons, summer and winter, and that during each season the fluxes of the inflow and outflow, and other variables remain constant. Summer occurs during a proportion γ of the year. Observation suggest that γ is approximately 0.25.

In what follows the superscripts S and W refer to summer and winter values respectively. Volume fluxes are denoted by Q, temperatures by T and salinities by S. Subscripts "+" and refer "–" to inflow and outflow respectively. The temperature of the sea surface, from which water evaporates, is denoted by T_S.

Assuming that the total salt and heat contents are unchanged at the end of a single annual cycle, and that the volume of the Red Sea remains constant throughout the year; the conservation equations imply that

$$(1-\gamma)\,(Q_{+}^{W}\,S_{+}^{W} - Q_{-}^{W}\,S_{-}^{W}) = -B^{S} \tag{5}$$

$$(1-\gamma)\,(Q_{+}^{W}\,T_{+}^{W} - Q_{-}^{W}\,T_{-}^{W} - E^{W}\,T_{S}^{W} + F^{W}) = -H^{S} \tag{6}$$

and

$$Q_{+}^{W} - Q_{-}^{W} = E^{W} \tag{7}$$

Where F^{W} is the average flux of heat across the sea surface during the winter season,

$$B^{S} = \gamma\,(Q_{+}^{S}\,S_{+}^{S} - Q_{-}^{S}\,S_{-}^{S}) \tag{8}$$

is the net flux of salt into the Red Sea during the summer, and

$$H^{S} = \gamma\,(Q_{+}^{S}\,T_{+}^{S} - Q_{-}^{S}\,T_{-}^{S} - E^{S}\,T_{S}^{S} + F^{S}) \tag{9}$$

is the corresponding flux of heat.

If the flow is hydraulically controlled in the strait in winter, then the exchange flux is given by

$$Q_{X}^{W} = \frac{1}{2}\,(Q_{+}^{W} + Q_{-}^{W}) = c\,(g'^{W}\,D)^{1/2}\,DW. \tag{10}$$

Where

$$g'^{W} = \left(\frac{g}{\rho_0}\right)(\alpha\,(T_{-}^{W} - T_{+}^{W}) + \beta\,(S_{-}^{W} - S_{+}^{W})), \tag{11}$$

D is the depth of the sill, and W is the width of the strait at the narrowest section. The parameter c depends upon a number of factors such as the geometry of the strait, and the value of the barotropic flux. In particular c is dependent upon whether or not the flow is maximal. For flow with no barotropic flux through a strait of rectangular cross-section the maximum possible value of c is between 0.21 and 0.25 (Farmer and Armi, 1986). The exact value is dependent upon the geometry of the strait (Dalziel, 1991). If the exchange is sub-maximal then the value of c is determined by conditions exterior of the strait.

The inflow temperature and salinity are set by the conditions in the Gulf of Aden but the outflow values are determined by the processes within the Red Sea. Assuming that the surface temperature is equal to the inflow temperature then equations (5) and (6) can be written as

$$(T_{+}^{W} - T_{-}^{W}) = \frac{(-(1-\gamma)^{-1}\,H^{S} - F^{W})}{Q_{-}^{W}} \tag{12}$$

and

$$(S_{+}^{W} - S_{-}^{W}) = \frac{(-(1-\gamma)^{-1}\,B^{S} - E^{W}\,S_{+}^{W})}{Q_{-}^{W}} \tag{13}$$

Equations (10), and (11) then imply

$$Q_{X}^{W} = Q_{-}^{W} + \frac{1}{2}\,E^{W} = \left(\frac{K}{Q^{W}}\right)^{1/2}. \tag{14}$$

Where

$$K = (cDW)^{2}\,D\left(\frac{g}{\rho_0}\right) \times \frac{[\beta\,((1-\gamma)E^{W}\,S_{+}^{W} + B^{S}) + \alpha\,(H_{0}^{S} + F)]}{(1-\gamma),}, \tag{15}$$

$H_{0}^{S} = H^{S} - \gamma\,F^{S}$, and $F = \gamma\,F^{S} + (1-\gamma)\,F^{W}$ is the net annual heat flux into the Red Sea. Assuming that E^{W} is small compared to Q_{-}^{W} implies that

$$Q_{-}^{W} = (K)^{1/3} - \frac{1}{3}\,E^{W}. \tag{16}$$

Properties of the winter outflow

Equation (15) indicates that there are four terms which contribute to the exchange flux. In the case of the Mediterranean where the seasonal variation in fluxes is smaller and the net annual heat flux is small the first term is dominant and is the only one included in Bryden and Kinder's model.

In principle the outflow temperature and salinity can be calculated using equations (12) and (13) if each of the terms in (15) is known. However, it is thought that there is a small outflow of deep water in the summer and so the values of T_{-}^{W} and S_{-}^{W} have a small effect upon H_0^S and B^S. Furthermore, the net annual air sea flux of heat is not well known, and the best estimates are in fact obtained from the oceanographic fluxes through the strait. However, it is still useful to consider each of the terms in the equation (15).

The first term, $(1-\gamma)\beta E^W S_1^W$ is due to the net evaporation during the winter. The rate of evaporation in winter, approximately 0.03 Sv, is only slightly greater than in the summer. Thus $(1-\gamma)\beta E^W S_1^W \sim 6.2 \times 10^5$ kg s^{-1}.

The second and third terms arise from the net fluxes of salt and heat out of the Red Sea during the summer season. Maillard and Soliman (1986) estimated that the average flux of GAIW into the Red Sea was 0.3 Sv, and that 10% or less of this was returned in the bottom layer. In equations (8) and (9) it is assumed that there is no flux in the lower layer, in this case $\beta B^S \sim 1.5 \times 10^5$ kg s^{-1} and $\alpha H_0^S. \sim 3.2 \times 10^5$ kg s^{-1}. If we assume that 10% of the outflow occurs in the lower layer then these terms are reduced to 1.4×10^5 kg s^{-1} and 2.9×10^5 kg s^{-1} respectively. The sum of these terms is 70% of the term due to the evaporation.The final term in (15) is that due to the net annual heat flux across the sea surface. Bunker *et al.* (1982) calculated the heat flux from meteorological data, however, they concluded that uncertainties in the calculation of the fluxes of latent heat and radiation were such that the estimate was less reliable than that available from oceanographic measurements in the Bab al Mandab strait. Assuming a winter time inflow of 0.4 Sv through the strait, the implied net annual heat flux is almost zero. Note, however, that a net annual flux of just 1 W m^{-2} into the Red Sea would give $\alpha F \sim -0.6 \times 10^5$ kg s^{-1}.

Control by the strait

The temperature and salinity of the inflow and outflow are in fact better known than the terms on the right hand side of equations (12 and 13). Estimates of the exchange fluxes have also been made in winter, *e.g.* Siedler (1968), and in summer, *e.g.* Maillard and Soliman (1986), but there are still large uncertainties in these values. Constraining the solution of (12-15) to agree with the observations can be used to estimate the unknown parameters, in particular the value of c.

If the channel were rectangular, the effects of rotation, mixing, wind stress and dissipation were negligible, the sill and narrows coincident, and stratification was simply two homogeneous layers then hydraulic theory indicates that the maximum possible value of c is 0.25 (Dalziel, 1991). Using the results of Boreman and Garrett (1989), Bryden and Kinder (1991) suggested a suitable value for the Strait of Gibraltar, whose channel is approximately triangular in section, was 0.07.

The interface in between the upper and lower layers in the Red Sea during the winter is at a depth of about 90 m (*see* Fig. 3 *b*), a little below half of the sill depth (140 m). Two-layer hydraulic theory (Dalziel, 1991) would imply that the exchange is therefore sub-maximal. However, the flow is also influenced by the intermediate layer in the Gulf of Aden and convective mixing in the surface layer. As noted above the intermediate layer in the Gulf of Aden extends right up to the strait. It seems likely that the height of this interface not only determines the onset of the summer regime but also influences the wintertime exchange.

Setting $c = 0.07$ the outflow volume flux, temperature and salinity are predicted to be 0.52 Sv, 23.5 °C and 39.6. This volume flux is greater than Siedlers (1968) estimate of 0.42 Sv. Decreasing c to 0.05 gives $Q_{-}^{W} = 0.41$ Sv $T_{-}^{W} = 22.9°$ C and $S_{-}^{W} = 40.3$, very close to the observed values. Such good agreement is probably fortuitous given the approximations and uncertainties described above. However, it does support the hypothesis that the exchange flow through the strait is sub-maximal. Note that the direction of the wind stress in the strait during winter is such as to increase the exchange flow. Thus other processes must be responsible for the sub-maximal exchange.

The above estimates were made using the summer fluxes derived from Maillard and Solimans observations assuming that 10% of the outflow occurs in the deep layer, and assuming $E^W \sim 0.03$ Sv and F (the net annual heat flux) is zero. A net annual heat flux of 1 W m^{-2} increases T_{-}^{W} by 0.3 °C but does not change Q_{-}^{W} or S_{-}^{W} significantly. Increasing E^W by 10% increases S_{-}^{W} by 0.2 but only slightly increases T_{-}^{W} and Q_{-}^{W}.

By setting $\gamma = 0$ and leaving all other parameters unchanged the case of an annually averaged two layer exchange can be examined. In this scenario it is found that the salinity of the outflow is reduced only slightly but that the temperature is increased by several degrees to that of the inflow (because there is no net annual air sea flux) and the outflow volume flux is 0.34 Sv.

CONCLUSIONS

Analysis of XBT data from the NODC database summarised in Figure 4 shows, commencing in late June, the intrusion of cold water from the Gulf of Aden into the Red Sea. The speed of propagation is 0.06 m s^{-1}. The temperature of the intrusion increases as it propagates indicating mixing with the surrounding water.

By the end of September the intrusion extends 800 km from the strait of Bab al Mandab. Following the onset of the winter monsoon in September, downwelling in the Gulf of Aden cuts off the supply of cold water. In the following weeks convective mixing entrains the intrusion into the overlying mixed layer.

The intrusion results in net fluxes of heat and salt out of the Red Sea during the summer season. These fluxes, as well as the net evaporation from the sea surface, play an important role in determining the winter time exchange and the properties of the outflow from the Red Sea.

Application of two-layer hydraulic theory suggests that the winter time exchange is sub-maximal, *i.e.* the exchange fluxes are influenced by other processes within the Red

Sea and the Gulf of Aden. It is suggested that the height of interface between the surface layer and the colder subsurface water in the Gulf of Aden plays an important role in determining the exchange flux. To examine this hypothesis further a three-layer hydraulic model of flow through straits is being developed.

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