JKAU: Mar. Sci., **Vol. 16,** pp: 133-140 (2005 A.D. / 1425 A.H.)

Advective Heat Transport to the Red Sea at the Strait of Bab-el-Mandab

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Abstract. The semi-enclosed nature of the Red Sea can be used as a test volume in an attempt to assess the accuracy of climatological air-sea interface fluxes, if the advective heat transport at Bab-el-Mandab is accurately known. However, there are few estimates of the advective heat to the Red Sea and even they differ significantly. A review of these estimates is made. It is shown that based on an evaporation rate of $2m.a^{-1}$, and the monthly mean volume transports and average temperatures for the two/three layers near the sill, as shown from the previous studies, the annual average advective heat transport to the Red Sea is about $17W.m^{-2}$.

Introduction

The Red Sea is a semi-enclosed basin (Fig. 1). The only significant opening is the Strait of Bab-el-Mandab connecting the South of the Red Sea to the Gulf of Aden. The climate is arid and consequently the annual evaporation rate is about 2 $m.a^{-1}$ (Morcos, 1970 and Ahmad & Sultan, 1987 & 1989). In response to this surface buoyancy loss there is a near-surface influx of water from the Gulf of Aden which undergoes density increase in the Red Sea. It sinks and eventually leaves the sea through the narrow and shallow Strait of Bab-el-Mandab. The buoyancy driven circulation is affected by the seasonal change of wind pattern in the southern part of the Red Sea.

In particular, the reversal of the monsoon modifies the exchange through the Strait of Bab-el-Mandab. During winter it enhances the surface inflow of the two-layer exchange system. During summer, wind is thought to be the main rea-

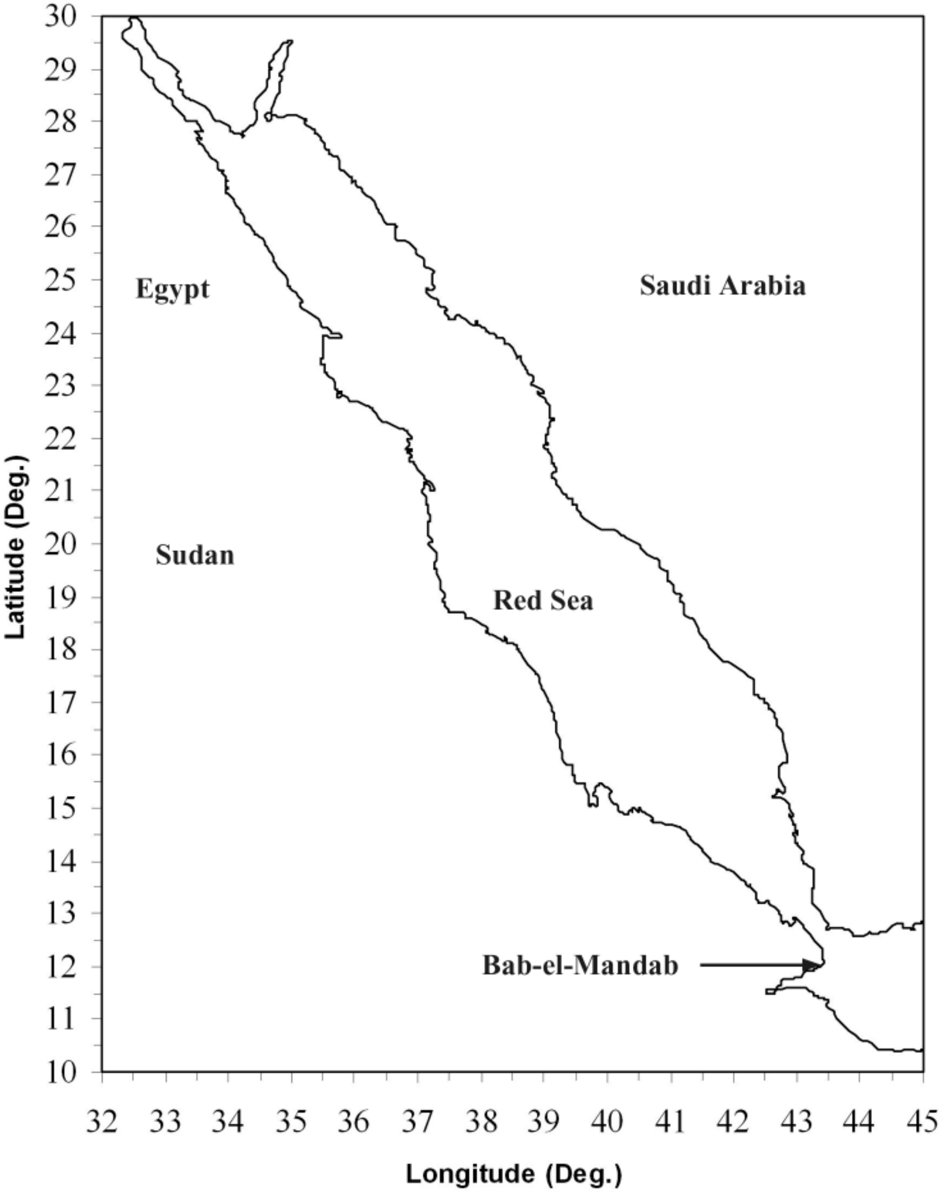

Fig. 1. Red Sea map.

son for the development of the observed three-layer exchange system at the Strait, with near surface outflow, intermediate inflow of Gulf of Aden water, and bottom outflow of Red Sea water (Patzert, 1974; Maillard & Soliman, 1986 and Smeed, 1997).

The dynamical processes associated with the buoyancy forcing of the Red Sea have been the subject of several studies (Cember, 1988; Eshel *et al*., 1994; Woelk & Quadfasel, 1996, Maxworthy, 1997 and Tragou & Garrett, 1997), but the accurate modeling of the buoyancy driven circulation requires adequate knowledge of the air-sea interface fluxes. Unfortunately the results from the various heat budget studies vary so greatly that they tend to be rather speculative exercises. However, the semi-enclosed nature of the Red Sea can provide a check on these fluxes if the advective heat transport at Bab-el-Mandab is accurately known.

The Oceanic Heat Flux

The only heat transfer by ocean currents is at Bab-el-Mandab. Conditions are complicated because of the reversal of wind direction associated with monsoon. Siedler (1968) measured a surface inflow to the sea of about $0.6 \times 10^6 m^3.sec^{-1}$ in November 1964, confirming Vercelli's (1927) observation of March 1924. Patzert (1974) shows that these flows are typical of the winter season, being replaced by a shallow surface outflow reaching about $0.2 \times 10^6 m^3.sec^{-1}$ in August. The surface currents are largely compensated by subsurface flows in the opposite direction. Patzert (1974) calculated a heat transfer to the sea of 3×10^{12}W which averaged over the area of the Red Sea ($0.45 \times 10^6 km^2$) corresponds to about $7 W.m^{-2}$. Ahmad and Sultan (1989) give an annual average advective heat flow of 19 $W.m^{-2}$ at Bab-el-Mandab based on average seasonal temperature difference between the upper and lower layers and the variation of in- and outflows. More recently Tragou *et al.* (1999) estimated the monthly variations of heat transport into the Red Sea. They give an annual average of 8 ± 2 $W.m^{-2}$ into the sea based on monthly mean volume transports and temperatures. They considered a constant value of E_{net} = 0.02 SV as the monthly estimates of heat transport are rather insensitive to seasonal changes in evaporation. Here E_{net} = E-P where E is the evaporation and P the precipitation both in $m.s^{-1}$. These authors also pointed out that the maximum seasonal mean sea level change, according to Patzert's analysis can be as high as 0.30 m leading to an equivalent volume transport of 0.009 SV, which will not make any significant contribution to the advective heat transport as the increased inflow at Bab-el-Mandab during the period of higher sea level will almost balance out by the increased outflow when the sea level decreases. Ahmad and Sultan (1993) also report higher mean sea level in January and lower in August with a range of about 50 cm.

Advective Heat Transport

Tragou *et al*. (1999) estimated the annual mean heat transport $\overline{F}_T$ from the formula:

$$\overline{F}_T = \frac{1}{A}\,\rho\,c_p\left(-\overline{F_1T_1} + \overline{F_2T_2} - \overline{F_3T_3} - \overline{AE_{net}T_s}\right)$$

where:

F_1: is surface outflow and is present during summer only, the intermediate (summer only) or surface inflow.

F_2: The surface inflow.

F_3: The bottom outflow.

A: The surface area of the Red Sea (0.45×10^6 km^2).

ρ: The mean water density 1025 kg.m^{-3}.

c_p: The specific heat of water 3986 J.C^{o-1}kg^{-1}.

T_s: The sea surface temperature.

T_1, T_2, T_3: Are the temperatures of the respective layers.

According to the authors the term $AE_{net}T_s$ represents a measure of the heat transport due to the volume of water that leaves the basin through the sea surface. Their monthly mean volume transport and temperatures of the respective layers based on the comprehensive review of the previous studies (Vercelli, 1927; Siedler, 1968; Patzert, 1974; Maillard & Soliman, 1986; Souvermezoglou *et al*., 1989 and Levitus *et al*., 1994) are reproduced in Table 1.

In the heat budget studies, the air-sea interface fluxes balance along with the advective in/outflow. If we apply the heat balance equation to the world ocean as a whole, the advective term is zero as all the advective flows are internal and must add to zero. On an annual basis, in a semi-enclosed area like the Red Sea, the balance of air-sea interface fluxes become equal to the net advective heat transport. The advective heat transport at Bab-el-Mandab will be given by:

$$\overline{F}_T = \frac{1}{A}\,\rho\,c_p\left(-\overline{F_1T_1} + \overline{F_2T_2} - \overline{F_3T_3}\right)$$

The term $AE_{net}Ts$ which represents the heat transport due to the volume of water that leaves the surface due to the evaporation may not be included in the equation. The process of evaporation takes away the heat and changes in water temperature and salinity. The advective heat and salt transfer are based on the in-outflow volumes and their respective temperature and salinity.

Based on the monthly volume transports and temperatures (Table 1) and with their E_{net} = 0.02SV, the advective heat transfer to the Red Sea is calculated and is given in the 2nd column of Table 2. The annual average is about $13W.m^{-2}$.

Table 1. Monthly mean volume transports for the near surface layer F_1 present during summer only, the intermediate (summer only) or surface inflow F_2 and the bottom outflow F_3 along with their average temperatures (After Tragou *et al.*, 1999).

Month	F_1 (SV)	F_2 (SV)	F_3 (SV)	T_1 (C°)	T_2 (C°)	T_3 (C°)
1	–	0.57	0.55	–	25.0	22.5
2	–	0.40	0.38	–	24.9	22.7
3	–	0.57	0.55	–	25.2	22.5
4	–	0.42	0.40	–	26.0	22.5
5	–	0.38	0.36	–	26.3	22.5
6	0.06	0.31	0.23	29.5	25.1	22.3
7	0.20	0.25	0.03	30.7	24.9	22.5
8	0.21	0.33	0.10	30.9	24.2	22.4
9	0.09	0.20	0.09	31.2	22.9	22.0
10	–	0.52	0.50	–	26.7	22.0
11	–	0.57	0.55	–	26.6	20.6
12	–	0.51	0.49	–	25.9	22.1

Table 2. Computed values of advective heat flux F_T into the Red Sea considering E_{net} = 0.02SV (column 2) and E_{net} = 0.03SV (column 3 and 4).

Month	F_T $W.m^{-2}$	F_T $W.m^{-2}$	F_T $W.m^{-2}$
1	17	19	19
2	12	14	14
3	18	20	20
4	17	20	20
5	17	20	19
6	8	10	11
7	5	–3	–3
8	–7	8	–4
9	–2	0	1
10	26	29	28
11	35	37	37
12	22	24	24
Annual Average	13	17	16

Tragou *et al.* (1999) consider an evaporation of 1.60 ± 0.35 $m.a^{-1}$ which is lower than the previous estimates of about 2 $m.a^{-1}$ (Morcos, 1970; Bunker *et al*., 1982 and Ahmad & Sultan, 1987 & 1989). Considering an evaporation rate of about 2$m.a^{-1}$, gives E_{net} of 0.03 SV. By keeping the outflow (F_1 and F_3 in Table 1) as constant and adjusting the monthly inflows as inflow = outflow + 0.03 SV, the computed values of advective heat flux are given in the 3rd column of Table 2. The annual average is 17 $W.m^{-2}$. Similarly by keeping the inflow (F_2 in Table 1) as constant and adjusting the monthly outflows as outflow = inflow – 0.03 SV the computed values of advective heat flux are given in the 4th column of Table 2. Here the annual average is 16$W.m^{-2}$.

Discussion

It is seen that the advective heat transport at Bab-el-Mandab is sensitive to the amount of evaporation. However, with the accepted rate of 2$m.a^{-1}$, the net advective heat is 17$W.m^{-2}$. Even with a lower value of 1.6$m.a^{-1}$ for evaporation (Tragou *et al*., 1999) the advective heat transport is 13$W.m^{-2}$.

Patzert (1974) estimated a net heat transport of about 7$W.m^{-2}$ into the Red Sea from temperature and current measurements at Bab-el-Mandab. The calculations are based on a two layer flow with reversal in summer and the suppression of the lower outflowing layer. Consequently, the advective heat flow out of the Red sea in summer is higher and is about 40% of the advective heat inflow in winter months. This makes the net advective heat into the Red Sea lower on an annual basis.

Ahmad and Sultan's (1989) estimate is 19$W.m^{-2}$ through the Strait. Tragou *et al.* (1999) report a value of 8 ± 2$W.m^{-2}$. However, using their data and their evaporation rate of 1.60$m.a^{-1}$ the advective heat transport is about 13$W.m^{-2}$ instead of 8$W.m^{-2}$. With presently accepted value of 2$m.a^{-1}$ for the evaporation in the Red Sea the advective heat transport is 17$W.m^{-2}$ in close agreement with Ahmad and Sultan (1989). Exchange between the Red Sea and the Mediterranean through the Suez Canal is negligible, so advective heat exchange at Bab-el-Mandab provides a strong constraint on the Red Sea surface heat fluxes.

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الانتقال الحراري إلى البحر الأحمر عن طريق مضيق باب المندب

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المستخلص. إن طبيعة البحر الأحمر كبحر شبه مغلق تمكننا من معرفة مدى دقة معدلات الدفق عند الحد الفاصل بين سطح البحر والهواء، وذلك عن طريق معرفة الدفق الحراري عند منطقة باب المندب. توجد عدة دراسات للدفق الحراري في البحر الأحمر، ولكن يوجد تفاوت كبير فيما بينها. ولقد وجد أن المتوسط السنوي للدفق الحراري إلى البحر الأحمر ١٧وات/ م^{٢} تقريبًا، وذلك اعتمادًا على المسح الأدبي سابقًا، والذي أخذ في الاعتبار أن معدل البخر السنوي ٢م، والمتوسط الشهري لحجم انتقال المياه، والمتوسط الشهري لدرجة الحرارة، وذلك في حالة وجود طبقتين أو ثلاث طبقات فوق عتبة باب المندب.