Surface heat fluxes and their comparison with the oceanic heat flow in the Red Sea

Red Sea
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Mer Rouge
Chaleur
Flux superficiels

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ABSTRACT

Calculations for surface heat fluxes were made for the southern, central and northern regions of the Red Sea, based on monthly mean meteorological variables in the respective areas. The average annual values of sensible heat, evaporative and net long-wave radiation fluxes for the Red Sea as a whole are, respectively: $-3\,Wm^{-2}$, $169\,Wm^{-2}$ and $66\,Wm^{-2}$. The average of the recorded solar radiations at various stations along the eastern side of the three regions of the Red Sea is $210\,Wm^{-2}$. The advective oceanic heat flow of $19\,Wm^{-2}$ into the Red Sea at Bab-el-Mandab was calculated on the basis of the average seasonal temperature difference between the upper and lower layers and the variations of the in- and outflows. The deficit of $22\,Wm^{-2}$ at the air-sea interface is in fair agreement with the heat gain of $19\,Wm^{-2}$ through the straits of Bab-el-Mandab.

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RÉSUMÉ

Flux superficiels de chaleur dans la Mer Rouge comparés à l'apport en provenance de l'océan

Les flux superficiels de chaleur ont été calculés pour le sud, le centre et le nord de la Mer Rouge à partir des moyennes mensuelles de données météorologiques. Pour la Mer Rouge, les moyennes annuelles des flux de chaleur sensible, de chaleur latente d'évaporation et de rayonnement net thermique sont respectivement $-3\,Wm^{-2}$, $169\,Wm^{-2}$ et $66\,Wm^{-2}$. Le rayonnement solaire enregistré en différentes stations le long de la côte orientale des trois régions est en moyenne de $210\,Wm^{-2}$. L'apport de chaleur par advection à Bab-el-Mandeb est évalué à $19\,Wm^{-2}$ à partir de la moyenne saisonnière de la différence de température entre les couches superficielles et profondes et des variations des flux entrant et sortant. Le déficit de $22\,Wm^{-2}$ à l'interface air-mer est en bon accord avec le gain de chaleur de $19\,Wm^{-2}$ à travers le détroit de Bab-el-Mandeb.

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INTRODUCTION

There are few regions where the advective oceanic heat flow is sufficiently well known to provide comparison with surface heat flux estimates. Bunker *et al.* (1982) used the Mediterranean and Red Seas as test volumes to assess the accuracy of estimates of air-sea fluxes. The oceanic heat flux transfer for the Red Sea occurs at the straits of Bab-el-Mandab. Conditions are complicated because of the reversal of wind direction in the southern region associated with the monsoon. In winter, the exchange over the sill consists of a surface inflow to the Red Sea compensated by a subsurface outflow (Siedler, 1968; Grasshoff, 1969; Patzert, 1974). In summer, the reversal of the monsoon implies a reversal of the surface current in the southern Red Sea. A shallow surface layer 20 m deep flows to the south over the sill with a subsurface inflow and a deep outflow (Patzert, 1974; Sharaf el-Din, Mohamed, 1984).

The annual averages of in- and outflows are:

Bogdanova	1966	0.730×10^6	and	$0.692 \times 10^6\ m^3.s^{-1}$
Siedler	1968	0.59×10^6		0.43×10^6
Grasshoff	1969	0.29×10^6		0.26×10^6
Morcos	1970	0.358×10^6		0.33×10^6

The estimates of Siedler (1968) are based on the direct measurement of currents for about 2.5 days (2-5 December 1964) during winter only. Morcos (1970), Grasshoff (1969) and Bogdanova (1966) made calculations based on the principle of conservation of volume and salt. However Bogdanova (1966) used a relatively high value of evaporation (266 cm a^{-1}).

Morcos (1970) gave an annual average evaporation of 210 cm (167 Wm^{-2}). Bunker and Goldsmith (1979) revised the evaporation value to 183 Wm^{-2}. Hastenrath and Lamb (1979); Bunker (1976); and Bunker and Goldsmith (1979) respectively estimate net long-wave radiations as 75, 48, and 76 Wm^{-2}. Estimates of the short wave solar radiations include 230 Wm^{-2} (Hastenrath, Lamb, 1979) and 263 Wm^{-2} (Bunker, Goldsmith, 1979). Bunker (1976) and Bunker *et al.* (1982) estimated the sensible heat flux as 5 and 3 Wm^{-2} respectively. Ahmad and Sultan (1987) calculated the evaporative, sensible heat, net long-wave radiation and short-wave radiation fluxes as 165, −3, 57, and 220 Wm^{-2} respectively between the 21°N and 22°N latitudes of the Red Sea.

In the present study, estimates of the net surface heat fluxes for the southern, central and northern regions of the Red Sea are made and their average is compared with the oceanic heat flux at Bab-el-Mandab (Fig.). The southern region extends from Bal-el-Mandab to 18°N; the central region from 18°N to 23°N; and the northern region from 23°N to the Gulf of Suez. The oceanic heat flux calculation is based on the seasonal vertical temperature structure in the southern Red Sea and Gulf of Aden (Sharaf el-Din, Mohamed, 1984) and the exchange of water at Bab-el-Mandab (Poisson *et al.*, 1984). The heat balance terms are calculated on the basis of meteorological data (monthly means for the period 1970-1984; solar radiations 1975-1980 only) provided by the Meteorological and Environmental Protection Agency (MEPA) and monthly mean sea-surface temperature values are based on temperature data from 1855 to 1943 (Tunnel, unpublished; reported in Morcos, 1970). The values of these parameters for the three regions are given in Table 1.

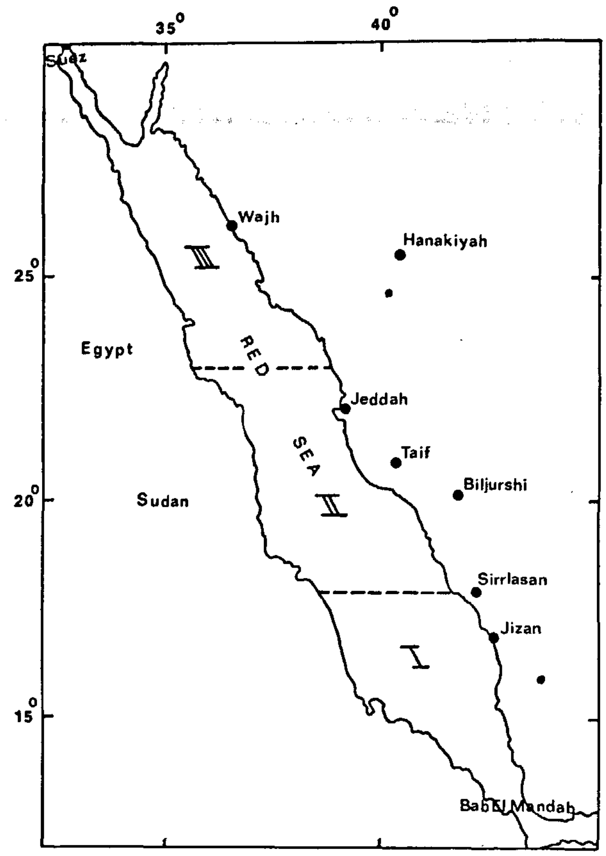

Figure
Map of the Red Sea, showing the three regions and the meteorological stations along the eastern side.

THE OCEANIC HEAT FLUX

The transport of heat by ocean currents at Bab-el-Mandab is calculated on a seasonal basis. The winter includes the months of December, January, February, and March. The summer months are June, July, August, and September. April and May are in spring and autumn covers October and November. Sharaf el-Din and Mohamed (1984) have studied the seasonal vertical temperature distribution in the southern Red Sea and the Gulf of Aden on the basis of fifty years of hydrographic data obtained from the National Oceanographic Data Centre, Washington DC and the Oceanographic Data Centre of France. The depth average temperatures of the inflowing and outflowing layers of water during the four seasons are: winter [25 and 23°C]; spring [27 and 23°C]; summer [27 and 22°C]; and autumn [26.5 and 23°C]. In calculating these temperatures for the summer months, an allowance has been made for a shallow surface layer, 20 m deep, flowing out at Bab-el-Mandab with an average temperature of about 29°C. The average inflows during the corresponding seasons are: 0.351×10^6, 0.351×10^6,

Table 1
Solar radiations, sea surface temperature and meteorological parameters for the: (1) *southern,* (2) *central and* (3) *northern regions of the Red Sea.*

Month	Solar radiations Wm^{-2} (1)	(2)	(3)	Sea surface temperature °C (1)	(2)	(3)	Air temperature °C (1)	(2)	(3)	Wind speed ms^{-1} (1)	(2)	(3)	Relative humidity % (1)	(2)	(3)	Cloudiness 10ths (1)	(2)	(3)
January	170	154	141	25.4	25.6	22.8	26.0	23.2	18.4	3.6	3.6	4.1	73	60	57	3	2	2
February	201	188	192	25.3	24.5	22.3	26.6	24.0	19.3	3.6	3.6	4.1	72	61	58	1	1	1
March	226	214	240	26.1	24.8	22.6	28.4	25.5	21.2	3.6	4.1	4.1	71	58	58	2	1	1
April	228	243	267	27.4	26.0	23.7	30.2	27.5	24.1	3.6	3.6	4.1	65	56	61	0	0	1
May	214	245	284	29.4	27.8	25.5	32.5	29.7	26.5	3.6	4.1	4.1	63	57	66	2	1	2
June	214	260	286	30.8	28.3	26.4	33.4	30.4	27.7	4.1	4.1	4.1	64	59	72	2	1	1
July	189	249	284	31.1	29.7	27.7	33.5	32.0	28.3	4.6	3.6	4.1	61	55	74	2	1	0
August	182	238	277	31.1	30.5	28.9	33.2	32.0	29.2	4.6	3.6	3.6	64	59	74	3	1	0
September	199	226	233	31.8	30.2	28.0	32.7	30.8	27.9	3.6	3.6	4.1	68	68	75	2	2	1
October	201	215	180	30.5	29.8	27.3	31.3	28.9	26.3	3.1	2.6	3.6	66	67	67	2	2	2
November	175	181	126	27.9	28.5	26.1	28.0	26.9	23.3	3.6	3.1	3.6	69	60	50	1	1	2
December	160	161	117	26.3	26.6	24.1	26.4	24.3	19.7	3.6	3.6	4.1	71	59	58	2	2	2

Table 2
The computed values of sensible heat flux (H_s), evaporative flux (H_e) net long wave radiations (H_b) and the net heat flux (H_t) at the air-sea interface for the: (1) *southern,* (2) *central, and* (3) *northern regions of the Red Sea* (*units* Wm^{-2}).

Month	H_s (1)	H_s (2)	H_s (3)	H_e (1)	H_e (2)	H_e (3)	H_b (1)	H_b (2)	H_b (3)	H_t (1)	H_t (2)	H_t (3)
January	−5	21	45	108	206	235	61	81	92	6	−154	−231
February	−12	4	31	98	161	206	62	77	89	53	54	−134
March	−21	−7	-	86	182	190	56	76	85	105	−37	−49
April	−25	−13	−4	118	169	159	58	74	76	77	13	36
May	−28	−19	−10	144	189	140	53	67	66	45	8	88
June	−27	−21	−13	179	184	106	48	63	58	14	34	135
July	−28	−20	−6	238	197	120	51	63	57	−72	9	113
August	−24	−13	−3	220	197	124	48	59	54	−62	−5	102
September	−8	−5	1	182	162	136	47	53	56	−22	16	40
October	−6	6	9	159	142	171	54	61	67	−6	6	−67
November	−1	12	25	159	187	222	62	72	81	−45	−90	−202
December	−1	20	45	134	218	249	63	79	90	−36	−156	−267
Annual	−16	−3	11	152	183	172	56	69	73	5	−34	−36

0.363×10^6, and $0.376 \times 10^6\,m^3/s$ respectively, with an annual average outflow of $0.330 \times 10^6\,m^3/s$ (Poisson *et al.*, 1984). The resulting seasonal advective heat transfer into the Red Sea is 11, 18, 24, and 23 Wm^{-2}, giving an annual average of about 19 Wm^{-2}. During winter, the exchange over the sill is a two-layer system; this changes to a three-layer system during summer. Patzert (1974) assumed that the bottom outflow during summer is an order of magnitude less than the subsurface inflow and surface outflow above it. Consequently, he calculated a negative heat flow to the sea for the summer months. Our data show, however, that surface outflow from the Red Sea during summer does not make the advective heat flow negative. Consequently the average annual heat inflow to the Red Sea is higher than Patzert's (1974) value of 7 Wm^{-2}.

Surface heat fluxes

The bulk aerodynamic method is used to valculate upward sensible and evaporative heat fluxes:

$$H_s = \rho_a c_p c (T_w - T_a) W,$$

and

$$H_e = \rho_a L c (q_o - q_a) W;$$

where ρ_a is the density of air, c_p is the specific heat of air at constant pressure, T_w and T_a are sea surface and air temperatures respectively, W is the wind speed, q_0 and q_a are saturated specific humidity at sea surface temperature and specific humidity in the air respectively, and c is the heat flux coefficient. The evaporative and sensible heat fluxes depend on the choice of the heat flux coefficient c. In constructing the "Atlas of the heat balance of the earth" (Budyko, 1963), a constant value of $c = 2.1 \times 10^{-3}$ was used for calculating evaporation from the world oceans (126 $cm \cdot a^{-1}$). Data pertaining to oceanic heat balance in Robinson's review (1966), give a value of $\rho_a c = (2.4 \pm 0.4) \times 10^6\,gm/cm^3$. This value differs little from that used by Budyko (1963). Bunker *et al.* (1982) and Ahmad and Sultan (1987) have favoured this value for calculating their heat fluxes of the Red Sea from monthly mean meteorological data. The net long wave radiation flux is given by Budyko (1974):

$$H_b = \varepsilon \sigma T_0^4 [a - b\, e_a^{1/2}][1 - cn^2],$$

where ε, is the coefficient of emissivity with a value of 0.985 (Kraus, 1972), σ is the Stefan Boltzman constant, T_0 is the absolute sea surface temperature, e_a is the vapour pressure in the air expressed in millimetres of mercury, n is the cloudiness in fractions of unity, and c is a factor which depends on latitude (Budyko, 1974). The values of this constant are 0.57, 0.59 and 0.61 for the southern, central and northern regions respectively; a and b are constants with values of 0.39 and 0.05.

The sensible and evaporative heat fluxes, net long-wave radiations and net heat flux at the air-sea interface were calculated for the southern, central and northern regions based on monthly mean meteorological data for the period (1970-1984) from Gizan (16.9°N, 42.6°E); Jeddah (21.5°N, 39.2°E); and Wajh (26.2°N, 36.5°E). These data are given in Table 2. The 15-year data at these stations show that the prevailing wind direction is west at Wajh and north northwest at Jeddah almost all the year round. At Gizan the wind direction is mainly west during summer and veers to southwest during winter. This shows that the dominant wind direction is from the ocean to the land. As these stations are close to the coast, the land data may be used to determine the fluxes.

The available recorded solar radiations from 1975-1980 (Ministry of Agriculture and Water) are:

Southern region: Sirrlasan (18.3°N, 42.6°E): 197 Wm^{-2}; Central region: Taif (21.4°N, 40.5°E): 214 Wm^{-2} and Biljurshi (20°N, 41.9°E): 216 Wm^{-2}; Northern region: Hanakiyah (25.4°N, 40.5°E): 219 Wm^{-2}.

Error analysis

The approach outlined in Beers (1957) and used by Weare *et al.* (1981) for their error estimation in surface heat fluxes in the tropical Pacific Ocean is applied to estimate the impact of uncertainty in the specification of the bulk formulas as well as the contribution of measurement errors.

The standard deviation of net heat gain or loss H_T is estimated by

$$S_{H_T} = (S_{H_S}^2 + S_{H_e}^2 + S_{H_b}^2)^{1/2}$$

where S is the standard deviation, and H_S, H_e and H_b are sensible heat flux, evaporation and net long-wave radiations respectively. The uncertainty in the estimation of incoming solar radiations is not included, as these are recorded and not estimated.

The standard deviation of the individual component can be determined using an equation

$$S=\left[\left(\frac{\partial v}{\partial x}\right)^2 S_x^2+\left(\frac{\partial V}{\partial y}\right)^2 S_y^2+\left(\frac{\partial V}{\partial z}\right)^2 S_z^2\right]^{1/2}$$

where v is the dependent variable and x, y, z are possible independent variables. The uncertainties in the sensible and evaporative heat fluxes for the three regions of the Red Sea were estimated from the annual averages ± standard deviations in sea surface and air temperature differences ($T_\omega - T_a$); wind speed w; heat flux coefficient c; and difference in saturation vapour pressure at the sea surface temperature and the actual vapour pressure at the air temperature ($e_0 - e_a$). These values for the three regions are:

	Region I	Region II	Region III
$(T_w - T_a)$ C°	-1.6 ± 0.3	-0.2 ± 0.5	1.1 ± 0.7
w m/sec	3.8 ± 0.1	3.6 ± 0.1	4.0 ± 0.1
c	$(1.8 \pm 0.3)\,10^{-3}$	$(1.8 \pm 0.3)\,10^{-3}$	$(1.8 \pm 0.3)\,10^{-3}$
$(e_0 - e_a)$ millibars	10.5 ± 0.5	14.4 ± 0.3	11.6 ± 0.6

The computed values of deviations in sensible heat flux for the three regions are ± 3; ± 4; $\pm 6\,Wm^{-2}$, giving an average of $\pm 4\,Wm^{-2}$. The uncertainties in evaporative heat flux are ± 7; ± 5; $\pm 8\,Wm^{-2}$ for the three regions respectively and the average for the Red Sea as a whole is $\pm 7\,Wm^{-2}$. The deviations in the net long-wave radiations were calculated from the deviation in sea surface temperature, vapour pressure and the amount of cloudiness. The average deviation for the Red Sea is $\pm 1\,Wm^{-2}$.

Therefore the average deviation in the net heat loss term for the Red Sea is about $\pm 8\,Wm^{-2}$, which will not affect the results significantly.

RESULTS AND DISCUSSION

In the southern region, the sensible heat flux is negative throughout the year. In the other two regions, this term is negative in summer but positive in winter. The annual average sensible heat flux is $-3\,Wm^{-2}$ for the Red Sea as a whole. In the southern region, evaporation is higher in summer and lower in winter; in the northern region it is the opposite. Evaporation is generally of the same order in summer and winter for the central region. The annual averages for the southern, central and northern regions are 152, 183, 172 Wm^{-2}, giving an annual average of 169 Wm^{-2} for the Red Sea as a whole. The net long-wave radiation term increases from the southern to the northern part of the Red Sea and the overall annual average is 66 Wm^{-2}. The recorded solar radiations at land stations on the eastern side of the Red Sea average about 210 Wm^{-2}, giving a deficit of about 22 Wm^{-2} at the air-sea interface for the sea as a whole. The deficit is in fair agreement with the heat gain of 19 Wm^{-2} through the straits of Bab-el-Mandab.

Hastenrath and Lamb (1979) calculated the fluxes for the Red Sea with monthly mean values for the meteorological variables and a constant exchange coefficient 1.4×10^{-3}, a value which they adopted as typical of the relevant values by Bunker (1976). Their evaporative flux is 109 Wm^{-2}. Bunker's (1976) exchange coefficient varies with wind speed and stability and is applied to individual ship's observations of high quality. The use of monthly mean values of meteorological variables with this exchange coefficient underestimates evaporation (Bunker *et al.*, 1982). Bunker and Goldsmith (1979), using Budyko's method with monthly mean values of the meteorological variable and $c = 2.1 \times 10^{-3}$, revised the value to 183 Wm^{-2}. This value was taken by Bunker *et al.* (1982) for their heat balance of the Mediterranean and Red Seas. The sensible and evaporative heat fluxes depend on the choice of the exchange coefficient c, and the method developed by Bunker (1976) underestimates these terms from the Red Sea. Although there is a considerable variation in the monthly values of the sensible and evaporative heat fluxes, the coefficient $c = 2.1 \times 10^{-3}$ gives a reasonable estimate when considering the annual averages.

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