Monthly Variations of Net Heat Flux at the Air-Sea Interface in Coastal Waters Near Jeddah, Red Sea

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ABSTRACT *Based on 16 years of oceanographic and meteorological data the monthly variations of the net heat flux at the air-sea interface in coastal waters near Jeddah show that the sea gains an average of about 14 ± 2* $W\,m^{-2}$ *from April to October and loses about 79 ± 4* $W\,m^{-2}$ *from November to March. The loss of heat during the winter months is not compensated by the gain during the summer months and therefore leads to an annual average deficit of 25 ± 3* $W\,m^{-2}$*. The gain during summer may not favour the formation of a strong seasonal thermocline.*

RÉSUMÉ *Basées sur les données océanographiques et météorologiques de 16 années, dans les eaux côtières près de Jeddah, les variations du flux de chaleur net à l'interface air-mer indiquent que la mer gagne une moyenne de près de 14 ± 2* $W\,m^{-2}$ *d'avril à octobre et perd près de 79 ± 4* $W\,m^{-2}$ *de novembre à mars. La perte de chaleur des mois d'hiver n'est pas compensée par les gains de l'été, ce qui entraîne un déficit annuel de 25 ± 3* $W\,m^{-2}$ *. Les gains estivaux ne peuvent pas favoriser la formation d'une forte thermocline saisonnière.*

1 Introduction

The surface heat fluxes for the Red Sea region have often been calculated before (Hastenrath and Lamb, 1979; Hastenrath, 1980; Bunker et al., 1982; Ahmad and Sultan, 1987). The computations discussed here use a mixture of old and new bulk coefficients. They are a direct result of the recent revival of interest in finding definite values of the sea surface fluxes in regions where they are known to be strong. This revival is a response to the initiatives of the World Climate Research Programme (WCRP), established with a view to improving climate prediction.

Various methods of determining the heat fluxes are summarized by Pond (1975) and Kraus (1972). We use the Bulk Aerodynamic method to calculate the sensible and evaporative heat fluxes. In this method a bulk transfer coefficient c_s is defined so that the flux F_s is:

$$F_s = \rho_a \, c_s \, \bar{w} \, \overline{\Delta}_s$$

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where $\bar{w}$ is the mean wind speed, $\overline{\Delta}_s = \bar{s}_a - \bar{s}_w$ is the mean difference of the property s between air and water, and ρ_a is the density of air. Usually transfer coefficients are related to a standard height or converted to a value for that height, whereas $\bar{s}_w$ is defined as the value of the property at the surface and is usually obtained by sampling the water at some distance of the order of a metre below the surface. The complicated transfer processes are lumped together in the transfer coefficient c_s.

While recognizing that there may be as many problems with the available formulas for estimating long-wave radiation as with those for other terms in the heat budget, we have used the formulas given by Budyko (1974) (Eqs (2)–(10) and (2)–(13)) to estimate the net upward long-wave radiation, Q_b:

$$Q_b = \delta \, \sigma \, T_0^4 \, (0.254 - 0.0066 \, e_a) \, (1 - c \, n^2)$$

where e_a is the vapour pressure expressed in mm of Hg, T_0 is the absolute sea surface temperature; n is fractional cloud amount, c is a tabulated function of latitude that runs from 0.50 at the equator to 0.82 at 75°N; δ is the emissivity of the sea surface relative to that of a black body; and σ is the Stefan-Boltzmann constant.

2 The Red Sea

The Red Sea is situated in an arid zone where no river flow occurs and evaporation greatly exceeds precipitation. Based on previous work, Morcos (1970) concluded that the average annual evaporation in the Red Sea is 210 cm (168 $\mathrm{W\,m^{-2}}$). More recent estimates of evaporation are: 135 $\mathrm{W\,m^{-2}}$ (Bunker, 1976); 109 $\mathrm{W\,m^{-2}}$ (Hastenrath and Lamb, 1979); 183 $\mathrm{W\,m^{-2}}$ (Bunker and Goldsmith, 1979); 165 $\mathrm{W\,m^{-2}}$ (Ahmad and Sultan, 1987). These estimates are considerably higher than the annual evaporation amounts from corresponding latitudes of the other oceans, which range from 120 to 130 cm $\mathrm{a^{-1}}$ (96–104 $\mathrm{W\,m^{-2}}$) (Morcos, 1970).

Neuman (1952) gave a small negative value of the sensible heat flux for the Red Sea. Other estimates are: 5 $\mathrm{W\,m^{-2}}$ (Bunker, 1976); 3 $\mathrm{W\,m^{-2}}$ (Bunker et al., 1982); -3 $\mathrm{W\,m^{-2}}$ (Ahmad and Sultan, 1987).

The net long-wave radiation term amounts to 75 $\mathrm{W\,m^{-2}}$ (Hastenrath and Lamb, 1979); 48 $\mathrm{W\,m^{-2}}$ (Bunker, 1976); 76 $\mathrm{W\,m^{-2}}$ (Bunker and Goldsmith, 1979); 57 and $\mathrm{W\,m^{-2}}$ (Ahmad and Sultan, 1987).

Various estimates of solar radiation have been made for the Red Sea area. Hastenrath and Lamb (1979) charted the net flux of short-wave radiation. Their annual average for the Red Sea is 230 $\mathrm{W\,m^{-2}}$. The solar radiation at Port Sudan between 1964 and 1968 (Meteorological Office, 1981) had a mean annual value of 225 $\mathrm{W\,m^{-2}}$ (Bunker et al., 1982). Bunker and Goldsmith (1979) give an estimate of 263 $\mathrm{W\,m^{-2}}$, which was favoured by Bunker et al. (1982) for their calculation of the heat balance of the Mediterranean and Red seas. From the solar radiation recorded at inland stations along the eastern side of the Red Sea, Ahmad and Sultan (1987) estimated an average of 220 $\mathrm{W\,m^{-2}}$ for the Red Sea.

3 Data Analysis

The investigation of the air-sea interaction processes demands meteorological information in addition to the sea surface temperature. Monthly averages of the temperature at 1 m below the surface near Jeddah are given at three locations (Fig. 1).

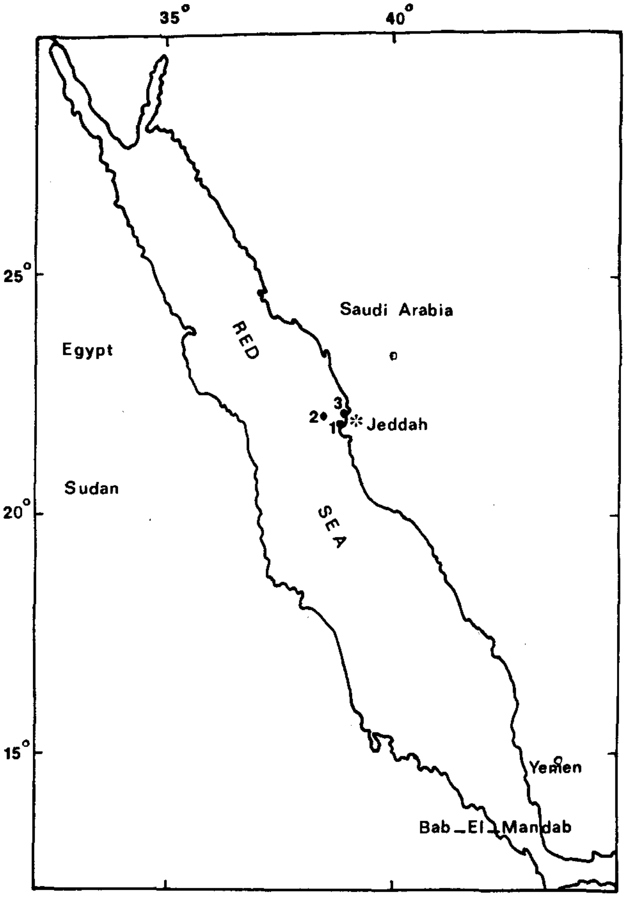

Fig. 1 Map showing the surface temperature data locations:

1. Data from saline water conversion corporation
2. Data from Robinson (1973)
3. Data collected by Marine Physics Department, King Abdulaziz University at the mouth of Sharm Obhur

(1) The temperature data at the first location are collected on a 6-hourly basis by the Saline Water Conversion Corporation (SWCC). Monthly averages of these data from 1978–1985 are shown in Table 1.

(2) Monthly averages of the temperature based on BT data (1944–1969) and hydrocast data (1923–1966) near Jeddah are also given in Table 1. These data were compiled by Robinson (1973).

(3) Monthly averages of the sporadic data for a site near the mouth of Sharm Obhur collected by the Department of Marine Physics, King Abdulaziz University, Saudi Arabia. These averages are based on the hydrocast data for 1981–1986. Monthly averages of the meteorological variables at Jeddah (21°40′N, 39°09′E) for the period 1970–85 are shown in Table 2. The measurement sites for oceanographic and

TABLE 1. Monthly averages of the sea surface temperature (°C) near Jeddah (21°30′N, 39°12′E)

	Data Sources		
Month	SWCC 1978–1985	M.K. Robinson*	Marine Physics Department 1981–1986
January	27.03	26.5	26.0
February	26.53	26.0	24.8
March	27.45	26.3	25.9
April	28.53	26.9	28.3
May	29.74	28.5	28.3
June	30.19	29.5	—
July	30.54	30.5	—
August	31.16	31.2	29.3
September	30.51	31.0	31.4
October	31.22	30.2	30.6
November	30.18	30.0	29.4
December	28.34	28.0	28.3

*Average of BT 1944–1969 data and hydrocast 1923–1966 data.

TABLE 2. Mean of monthly averages and standard deviations of year-to-year variability of the meteorological variables near Jeddah (21°40′N, 39°19′E) for the 16-year period 1970–85

Month	Air Temperature (°C)	Relative Humidity (%)	Wind Speed ($m\ s^{-1}$)	Cloud Cover (tenths)
Jan.	23.2 ± 0.2	61 ± 2	3.5 ± 0.2	2
Feb.	23.5 ± 0.5	60 ± 1	3.3 ± 0.2	1
Mar.	25.2 ± 0.1	58 ± 1	3.9 ± 0.2	1
Apr.	27.5 ± 0.4	56 ± 4	3.3 ± 0.2	1
May	29.8 ± 0.2	56 ± 1	3.8 ± 0.3	1
June	30.6 ± 0.3	58 ± 2	3.9 ± 0.2	0
July	32.0 ± 0.1	54 ± 2	3.5 ± 0.1	0
Aug.	31.9 ± 0.2	58 ± 1	3.5 ± 0.1	1
Sept.	30.9 ± 0.2	67 ± 1	3.4 ± 0.2	2
Oct.	29.0 ± 0.3	67 ± 1	2.6 ± 0.1	0
Nov.	26.9 ± 0.1	62 ± 1	3.0 ± 0.1	2
Dec.	24.5 ± 0.2	59 ± 2	3.4 ± 0.2	1

meteorological data may be considered representative of the coastal areas of the central Red Sea. Based on the monthly sea surface temperatures of Robinson (1973) and meteorological data for 1970–85, the various components of the heat budget are calculated and are given in Table 3. The monthly variations of these components are also shown in Fig. 2.

4 Evaporative and sensible heat fluxes

The evaporative and sensible heat fluxes (Q_e and Q_h) will depend on the choice of the transfer coefficient c_s. In constructing the *Atlas of the Heat Balance of the Earth*

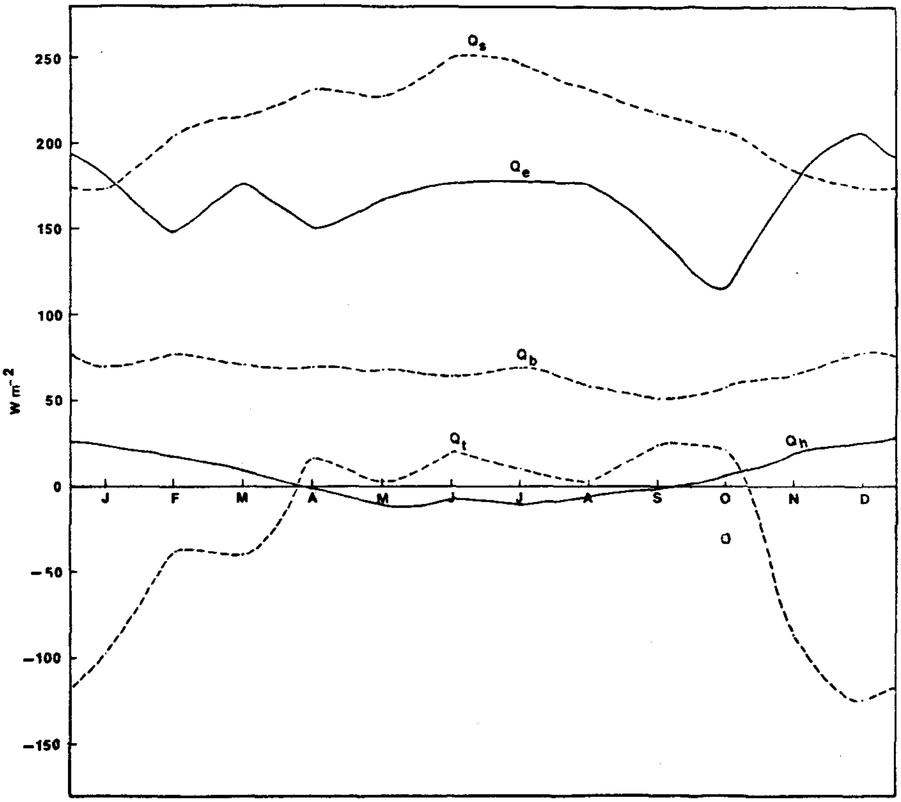

Fig. 2 Temporal variations of the heat balance terms computed on the basis of 1970–85 meteorological data.

(Budyko, 1963) a constant value of $\rho_a c_s = 2.5 \times 10^{-6}$ g cm^{-3} was used for calculating evaporation from the oceans (126 cm a^{-1}), giving $c_s = 2.1 \times 10^{-3}$. This value is favoured by Bunker et al. (1982) and by Ahmad and Sultan (1987) for their calculations of the heat balance of the Red Sea. In a review by Robinson (1966), the results of seven papers on such a topic by various authors give a mean value of $\rho_a c_s = (1.8 \pm 0.3)\ 10^{-6}$ g cm^{-3}. It is evident that the mean evaporation from the global ocean calculated using such a value of $\rho_a c_s$ would be 28% lower than the value obtained from Budyko's atlas. Considering the data related to the oceanic heat balance only in Robinson's review (1966), a value of $(2.4 \pm 0.4)\ 10^{-6}$ g cm^{-3} for $\rho_a c_s$ results. This value differs little from that used for constructing the maps of evaporation from the oceans (Budyko, 1963). The transfer coefficient c_s becomes $(2.0 \pm 0.3)\ 10^{-3}$. In the present calculations the lower limit $c_s = 1.7 \times 10^{-3}$ is used for calculating evaporation and sensible heat flux. With the numerical values the bulk aerodynamic equations for Q_e and Q_h are given below.

$$Q_e = 3.08\,(e_0 - e_a)W \qquad \mathrm{W\,m^{-2}}$$

where e_0, e_a are the saturated vapour pressure at the sea surface temperature and the

TABLE 3. Mean of monthly estimates and standard deviations of year-to-year variability of the short-wave radiation Q_s, sensible heat flux Q_h, evaporative heat flux Q_e, net long-wave radiation Q_b, and net flux of heat Q_t for the coastal waters near Jeddah, based on 16 years (1970–85) of meteorological data (Units: $\mathrm{W\,m^{-2}}$). The last column gives the monthly evaporation (cm).

Month	Q_s	Q_h	Q_e	Q_b	Q_t	Evaporation
Jan.	173 ± 3	23 ± 3	180 ± 13	69 ± 1	−99 ± 5	19
Feb.	204 ± 2	17 ± 4	148 ± 12	77 ± 2	−38 ± 3	14
Mar.	216 ± 3	9 ± 2	177 ± 10	70 ± 1	−40 ± 2	19
Apr.	231 ± 4	−4 ± 3	150 ± 7	69 ± 1	16 ± 3	16
May	226 ± 4	−10 ± 4	166 ± 6	67 ± 1	3 ± 1	18
June	250 ± 2	−9 ± 1	177 ± 6	63 ± 1	19 ± 3	18
July	246 ± 3	−11 ± 2	178 ± 7	69 ± 1	10 ± 2	19
Aug.	233 ± 4	−5 ± 2	177 ± 5	58 ± 2	3 ± 1	19
Sept.	219 ± 2	−1 ± 2	145 ± 4	51 ± 1	24 ± 3	15
Oct.	209 ± 5	6 ± 1	124 ± 7	58 ± 2	21 ± 4	13
Nov.	182 ± 3	19 ± 4	181 ± 10	64 ± 1	−85 ± 5	19
Dec.	175 ± 4	24 ± 3	206 ± 0	78 ± 1	−133 ± 7	22
Annual Average	214 ± 3	5 ± 3	168 ± 8	66 ± 1	−25 ± 3	211

vapour pressure at the air temperature, both expressed in millibars. W is measured in $\mathrm{m\,s^{-1}}$.

$$Q_h = 2.02\,(T_0 - T_a)W \qquad \mathrm{W\,m^{-2}}$$

where T_0 and T_a are the sea surface and air temperatures in °C. The values computed for these terms from the 1970–1985 meteorological data are given in Table 3.

5 Radiative fluxes

The net long-wave radiation Q_b is calculated by Budyko's (1974) formula which with numerical values becomes:

$$Q_b = 5.7 \times 10^{-8}\,(0.254 - 0.005\,e_a)\,(1 - 0.59\,n^2)$$

where e_a is expressed in millibars. Computed values of this quantity are given in Table 3.

The monthly averages of the solar radiation Q_s recorded near Jeddah for the period 1980–1985 were made available by the Meteorological and Environmental Protection Agency (MEPA) and are given in Table 3.

The net flux at the air-sea interface Q_t is obtained from the heat balance equation, neglecting the exchange of heat by advective and diffusive processes.

6 Results and discussion

The monthly variations of the net heat flux at the air-sea interface in coastal waters near Jeddah (Table 3) show that the sea gains heat from April to October and loses heat from November to March. The average loss of about 79 ± 4 $\mathrm{W\,m^{-2}}$ is not compensated by the gain of 14 ± 2 $\mathrm{W\,m^{-2}}$ during the summer months. This leads to an annual average deficit of 25 ± 3 $\mathrm{W\,m^{-2}}$.

The heat flux deficit is in agreement with general features of the Red Sea. The low salinity and high temperature water from the Gulf of Aden enters the Red Sea at the surface and while moving north its salinity increases and temperature decreases owing to the high rate of evaporation. The gain of about 14 ± 2 $\mathrm{W\,m^{-2}}$ during summer suggests that a weak seasonal thermocline may develop in the area whereas the loss of 79 ± 4 $\mathrm{W\,m^{-2}}$ from November to March is high enough to erode a thermocline.

The sensible heat flux is positive from October to March and negative for the remainder of the year. The annual average sensible and evaporative heat fluxes, net long-wave radiation and recorded solar radiation are 5 ± 3; 168 ± 8; 66 ± 1 and 214 $\mathrm{W\,m^{-2}}$, respectively. The evaporation is lowest in February and October (14–13 cm) and highest in December (22 cm). The annual evaporation is 211 cm, which is in fair agreement with the average value given by Morcos (1970). The monthly rainfall data for Jeddah (1961–1980) do not seem to have any relation to the monthly variation of evaporation.

Bunker et al. (1982), using the method of Bunker (1976), with monthly mean meteorological variables and a constant exchange coefficient $c_s = 1.4 \times 10^{-3}$, estimated an annual heat gain of 47 $\mathrm{W\,m^{-2}}$ for the Red Sea; also the heat advection by water exchange through the straits of Bab-el-Mandab would require a loss. They speculated that either the solar radiation is overestimated or the evaporation is underestimated. The solar radiation measured at Port Sudan (20°N, 41°E) has a mean annual value of 225 $\mathrm{W\,m^{-2}}$ compared with a calculated value of 264 $\mathrm{W\,m^{-2}}$, thus reducing the gain by 39 $\mathrm{W\,m^{-2}}$. Bunker and Goldsmith (1979) used an exchange coefficient 2.1×10^{-3} thus increasing the estimated evaporation from 135 to 183 $\mathrm{W\,m^{-2}}$. With measured values of solar radiation of 225 $\mathrm{W\,m^{-2}}$ at Port Sudan the deficit is 37 $\mathrm{W\,m^{-2}}$ compared with the oceanographic deficit of 7 $\mathrm{W\,m^{-2}}$ used by Bunker et al. (1982). Our results give a deficit of 25 ± 3 $\mathrm{W\,m^{-2}}$, but our calculations are for the Jeddah area and may only be representative of the central Red Sea.

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