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A note on the heat balance of the Mediterranean and Red Seas

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ABSTRACT

The Mediterranean and Red Seas are used as test volumes in an attempt to assess the accuracy of estimates of climatological air-sea fluxes calculated using meteorological observations from merchant ships.

Although the radiative flux estimates are subject to error, especially those of net longwave radiation, it is difficult to obtain an acceptable heat balance if the evaporative fluxes are calculated using values for the exchange coefficient now widely accepted by specialists in near-surface turbulent transport. Larger coefficients seem to be needed: they may be a compensation for ships' avoidance of high winds and for systematic errors of observation.

1. Introduction

Meteorological observations made from merchant ships have for many years been used for climatological studies of the transfer of heat, water and momentum at the sea surface (Jacobs, 1951; Privett, 1960; Budyko, 1963). Recent workers (Bunker and Worthington, 1976; Bunker, 1976; Hastenrath and Lamb, 1978, 1979) and others have refined the earlier estimates using the increased number of observations and improved knowledge of the transfer processes involved.

Some differences between the results of different authors arise from their use of different empirical expressions to calculate the various fluxes from the ships' observations and others can arise from their use of different data sets. Relatively small systematic differences in surface fluxes can have a large effect on estimates of climatologically interesting quantities, such as the divergence of the meridional heat flux carried by ocean currents.

There are few regions where the advective oceanic heat flow is known well enough to provide a useful comparison with surface flux estimates: this note attempts such a comparison for the Mediterranean and Red Seas, with particular reference to the methods used by Bunker and Goldsmith (1979) and Goldsmith and Bunker (1979).

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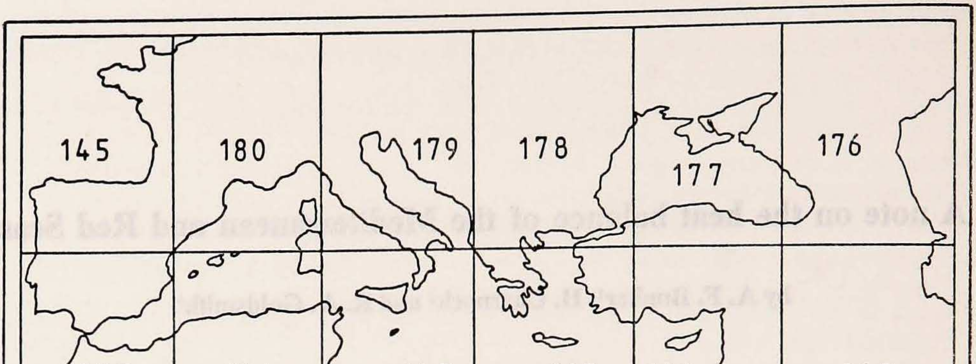

Figure 1. Location chart for Marsden squares covering the Mediterranean and Red Seas.

2. The Mediterranean Sea

a. The oceanic heat flux. The only effective transfer by ocean currents is at the Strait of Gibraltar. Here direct measurements have been made for some short periods (Lacombe *et al.*, 1964; Boyum, 1967). Their values for the outflow range from about 0.5×10^6 to 1.5×10^6 m^3 sec^{-1}. The temperature difference between outflow and inflow is also variable but taking 2°C to 3°C as typical leads to a heat loss by the Mediterranean as a whole of between 5 and 20×10^{12}W. Averaging over the 2.5×10^{12} m^2 area of the sea gives a mean loss of about 5 W m^{-2}.

This is an approximate figure but since it is small relative to the mean flux of solar radiation it provides a strong constraint on the overall energy budget of the Mediterranean. Even 10 W m^{-2} is a desirable target for the accuracy of climatological flux estimates.

b. Surface fluxes. The Mediterranean (Fig. 1) is covered by Marsden Squares

Table 1. Mean annual values of radiative and turbulent fluxes for Marsden Squares covering the Mediterranean and Red Seas. Figures in columns headed Bo have been estimated by methods described by Budyko, those headed Br by methods described by Bunker (see text).

		Solar radiation	Infra-red radiation		Evaporative heat loss		Sensible heat loss	
Marsden Square	Area 10^{11} m^2	Bo W m^{-2}	Bo W m^{-2}	Br W m^{-2}	Bo W m^{-2}	Br W m^{-2}	Bo W m^{2-}	Br W m^{-2}
109	0.97	203	51	57	88	67	0	3
141	2.75	220	54	81	139	107	12	14
142	6.20	215	54	72	147	113	11	13
143	7.36	207	51	65	128	99	10	12
144	2.95	199	50	58	112	87	7	9
178	0.32	173	49	70	137	110	29	32
179	2.23	173	51	68	119	92	14	15
180	2.43	173	51	66	134	108	16	18
68	1.57	258	41	68	163	113	−2	0
69	0.86	264	43	76	175	137	11	9
105	2.25	265	54	80	199	150	4	7

109, 141, 142, 143, 144, 178, 179, 180, surface fluxes for which are available from the ASHFLA component of the Climatology and Air/Sea Interaction collection at the Woods Hole Oceanographic Institution (Goldsmith and Bunker, 1979). Table 1 summarizes the main values which have been taken from annual summaries of fluxes averaged over whole Marsden Squares. The use of fluxes averaged over smaller areas might change our estimates but seems unlikely to affect our conclusions.

Columns 3, 4, 7, 9 of Table 1 are based on the methods used by Bunker (1976). He used a series of ships' observations for the years 1941–72, designated TDF-11, provided on magnetic tape by the U.S. National Climate Center. To calculate the solar and net longwave radiation fluxes he used methods described by Budyko (1963) modified only slightly by adopting the albedo values of Payne (1972). For the evaporative and the sensible heat fluxes he used the well-known bulk equations which, in the usual nomenclature, are

$$LE = LC_E\, \rho (q_s - q_{10}) U_{10} \tag{1}$$

$$S = C_H\, \rho\, c_p\, (T_S - T_{10}) U_{10} \tag{2}$$

Bunker used individual observations and after a thorough study of the published research on near-surface turbulent transport he specified C_E, which he took equal to C_H, as a function of wind speed and of stability. The values he adopted

Table 2. Values of the exchange coefficient for water vapor used by Bunker (1976) in the bulk formula for evaporative heat flux (Eq. 1). The values tabulated are of $10^3 C_E$.

Wind speed (m s^{-1})	Air minus sea temperature class (K)						
	>5.0	4.9 to 1.0	0.9 to 0.2	0.1 to −0.2	−0.3 to −1.0	−1.1 to −4.9	<−5.0
0.01- 3.0	0.07	0.30	0.72	1.32	1.65	2.05	2.52
3.01- 6.0	0.22	0.67	1.12	1.34	1.45	1.68	2.01
6.01- 9.0	0.69	1.17	1.36	1.44	1.46	1.58	1.79
9.01-12.0	1.06	1.36	1.48	1.53	1.58	1.65	1.79
12.01-15.0	1.39	1.58	1.61	1.64	1.68	1.74	1.84
15.01-20.0	1.59	1.68	1.75	1.80	1.82	1.86	1.94
20.01-25.0	1.74	1.79	1.83	1.86	1.88	1.86	1.93
25.01-30.0	1.81	1.84	1.85	1.86	1.87	1.88	1.90
>30.0	1.86	1.86	1.86	1.86	1.86	1.86	1.86

are shown in Table 2. His results so far as the heat balance of the Mediterranean is concerned can be summarized as follows:

Solar radiation		Net longwave radiation		Evaporative heat transfer		Sensible heat transfer		Residual	
W m^{-2}		W m^{-2}		W m^{-2}		W m^{-2}		W m^{-2}	
202	−	52	−	101	−	13	=	36	(3)

The resulting surplus was in poor agreement with the oceanographic observations, which indicate a deficit of about 5 W m^{-2}. Bunker and Goldsmith (1979) concluded that the radiation fluxes were the most likely source of error. In particular it seemed likely that error would be introduced into the net longwave flux estimates by the use of a formula which involved only surface observations, so Bunker developed a method by using the Elsasser radiation diagram with climatological values of upper air humidity to construct seasonal charts of the surface net longwave flux for (a) complete cover of low cloud, (b) complete cover of medium and high cloud, (c) clear sky.

Examples of such charts for the North and South Atlantic are to be found in Bunker and Goldsmith (1979): similar charts have been constructed for the Indian Ocean (including the Mediterranean and Red Seas). Together with seasonal charts of low and of medium plus high cloud amount they can be used to estimate the average values of the net longwave flux from each Marsden Square.

The results which apply to the Mediterranean appear in column 5 of Table 1 and the revised values for the heat balance become:

Solar radiation		Net longwave radiation		Evaporative heat transfer		Sensible heat transfer		Residual	
$W\ m^{-2}$		$W\ m^{-2}$		$W\ m^{-2}$		$W\ m^{-2}$		$W\ m^{-2}$	
202	−	68	−	101	−	13	=	20	(4)

It will be seen that although the revised value for the net longwave radiation is significantly greater than the earlier estimate, the resulting surplus remains in relatively poor agreement with the deficit estimated from oceanographic observations.

The value for solar radiation is consistent with calculations made using the Smithsonian formula and the cloud factor recommended by Reed (1977). It has been independently estimated by Bethoux (1979) as 195 $W\ m^{-2}$. In an earlier work (Bethoux, 1977) he shows that the formulas of Berliand (1960) and of Matsuike *et al.* (1970), together with climatological values of cloudiness, give results in good agreement with those observed at several coastal and island stations in the Mediterranean. He also shows that his value is in good agreement with that of Colacino and Dell'Osso (1974) who used a formula due to Lumb (1964) together with climatological values for the amounts of cloud of the various types. Taking into account the possible effect of increased aerosol and of orographic cloud at land stations it seems unlikely that Bunker overestimated the solar radiation by more than about 5 $W\ m^{-2}$.

There do not appear to be any published measurements of the net longwave flux in the Mediterranean region which would provide a check on the estimated flux but Bethoux (1977) has used an expression due to Laevastu (1960) to calculate values for July and December. He also shows charts of the net longwave flux for May and December which have been calculated by Colacino and Dell'Osso (1974) using a formula proposed by Anderson (1952). The annual values estimated by Bethoux and by Colacino and Dell'Osso are virtually identical with each other and with Bunker's revised value of 68 $W\ m^{-2}$.

There remains considerable uncertainty, particularly concerning the net longwave flux, but if the independent estimates by other authors are taken to imply that the values for the radiation fluxes of (4) are approximately correct then the remaining error must be sought in the estimates for the turbulent fluxes, in particular in that of the evaporative flux which much exceeds the flux of sensible heat.

In this connection it is interesting to note that as well as using the individual ships' observations, Bunker and Goldsmith (1979) also calculated the turbulence fluxes using the method of Budyko (1963): he used Eqs. (1) and (2) with monthly mean values of the meteorological variables and a constant exchange coefficient $C_E\ (=C_H) = 2.1 \times 10^{-3}$. The resulting values appear in columns 6 and 8 of Table 1 and the Mediterranean heat budget becomes:

Solar radiation W m^{-2}		Net longwave radiation W m^{-2}		Evaporative heat transfer W m^{-2}		Sensible heat transfer W m^{-2}		Residual W m^{-2}	
202	−	68	−	130	−	11	=	−7	(5)

The increased evaporative flux of 130 W m^{-2} is to be compared with the value of 123 W m^{-2} which Bunker (1971) got using Budyko's method, with the same coefficient, on data from the US Naval Weather Service Command (1970). It leads to an indicated deficit for the Mediterranean which is consistent with the oceanographic observations.

3. The Red Sea

a. The oceanic heat flux. The only transfer by ocean currents is at Bab-el-Mandeb. Conditions are even more complicated than those at the Strait of Gibraltar because of the reversal of wind direction associated with the monsoon. Siedler (1968) measured a surface inflow to the sea of about 0.6×10^6 m^3sec^{-1} in November 1964, confirming Vercelli's (1925) observation of March 1924. Patzert (1974) shows that these flows are typical of the winter season, being replaced by a shallower surface outflow reaching about 0.2×10^6 m^3sec^{-1} in August. These surface currents are largely compensated by subsurface flows in the opposite direction.

The temperature differences between the upper and lower flows are also variable from about 2°C in winter to 10–15°C in summer. The resulting mean annual heat transfer is small: Patzert (1974) calculated it as a transfer to the Red Sea of about 3×10^{12} W which averaged over the area of the sea corresponds to about 7 W m^{-2}. Again this is an approximate figure, small enough relative to other terms in the surface heat balance to provide a strong constraint on the overall heat budget of the Red Sea.

b. Surface fluxes. The Red Sea (Fig. 1) is covered by Marsden Squares 68, 69 and 105. Table 1 gives the relevant results from Goldsmith and Bunker (1979) which have been treated in the same way as those for the Mediterranean reported in Section 2.

The heat budget of the Red Sea calculated by the method of Bunker (1976), (columns 3, 4, 7, 9 of Table 1) becomes:

Solar radiation W m^{-2}		Net longwave radiation W m^{-2}		Evaporative heat transfer W m^{-2}		Sensible heat transfer W m^{-2}		Residual W m^{-2}	
263	−	48	−	135	−	5	=	75	(6)

As for the corresponding Mediterranean estimates, the resulting surplus is in poor agreement with the small deficit implied by the oceanographic observations.

Bunker's own method for estimating the net longwave flux produces a considerably increased figure: the revised values (columns 3, 5, 7, 9 of Table 1) become:

Solar radiation W m^{-2}		Net longwave radiation W m^{-2}		Evaporative heat transfer W m^{-2}		Sensible heat transfer W m^{-2}		Residual W m^{-2}	
263	−	76	−	135	−	5	=	47	(7)

The indicated surplus is, however, still in poor agreement with the heat transfer estimated from the flows at Bab-el-Mandeb.

The accuracy of the radiative flux estimates is difficult to assess. The solar radiation has been estimated using the method described by Budyko (1963) but originally due to Berliand (1960); the use of the formula due to Matsuike *et al.* (1970) would give a value in good agreement, as would the use of the Smithsonian formula and the cloud factor recommended by Reed (1977). For the Mediterranean values calculated by these methods have been found to agree with each other and with the observations from coastal and island stations but the only Red Sea observations, from Port Sudan (20N, 41E) between 1964 and 1968 (Meteorological Office, 1981), give a mean annual value for the solar radiation which would correspond to a net flux at the sea surface (albedo 6%) of 225 W m^{-2} compared with the calculated value of 264 W m^{-2}. Observations from stations close to but outside the Red Sea include Tel Aviv (30N, 35E), where observations from 1964 to 1972 would give 213 W m^{-2}, compared with a calculated 218 W m^{-2}, Tahir (30N, 31E), where observations from 1964 to 1972 would give 225 W m^{-2} compared with a calculated 228 W m^{-2} and Aden (13N, 45E) where observations from 1958 to 1964 (Meteorological Office, 1981) would give 246 W m^{-2} compared with a calculated value of 265 W m^{-2}.

None of the formulas take account of the increased opacity over the Red Sea which is due to sand and dust. This would be expected to be greater at land stations than over the sea: the appropriate values for the net flux of solar radiation over the sea might then be lower than those calculated but by a smaller fraction than indicated by the observations at Port Sudan or at Aden, perhaps by 10 to 20 W m^{-2}.

Hastenrath and Lamb (1979) give charts of the net flux of short wave radiation which include the Red Sea, calculated using the theoretical framework of Bernhardt and Phillips (1958). Their annual average for the Red Sea appears to be about 230 W m^{-2}; they attribute the difference from values calculated using Budyko's (1963) method to their use of a stronger cloud reduction factor (see Reed, 1977).

The accuracy of the net longwave estimates is even more difficult to assess, in the absence of published observations. Hastenrath and Lamb (1979) use an expression attributed to Budyko (1958): by averaging the values in Figures 18 and 19 in the atlas of Hastenrath and Lamb, one can calculate the annual radiation surplus of the Red Sea as approximately 155 W m^{-2}. If their net solar radiation is taken as 230 W m^{-2} the net longwave loss becomes 75 W m^{-2}, in remarkably close agreement with that calculated by Bunker. Neither method takes account of the possible effect of increased quantities of sand and dust in the atmosphere over the Red Sea. This would lead to a decrease in the net longwave flux which would to some extent offset the effect of the corresponding attenuation in the flux of solar radiation.

The Red Sea radiative fluxes are by no means well established but (7) shows that unless the solar radiation has been considerably overestimated and/or the net longwave radiation considerably underestimated then, as for the Mediterranean Sea, the evaporative flux has been underestimated. The same statement can be made about the estimates of Hastenrath and Lamb (1979). The basis of their calculation of radiative fluxes has been referred to above: for the turbulent fluxes they used Eqs. (1) and (2) with monthly mean values for the meteorological variables and a constant exchange coefficient C_E $(=C_H) = 1.4 \times 10^{-3}$, a value which they adopted as typical of the relevant entries of Table 2. Their heat budget for the Red Sea, taken as the average of the values graphed for the Southern and the Northern Red Sea in Figures 18 and 19 of their atlas, is as follows:

Net radiation surplus (solar-longwave)		Evaporative heat transfer		Sensible heat transfer		Residual	
W m^{-2}		W m^{-2}		W m^{-2}		W m^{-2}	
156	–	109	–	0	=	47	(8)

The indicated surplus is in poor agreement with the small deficit found from the oceanographic observations. The radiation surplus seems more likely to have been under- rather than over-estimated: it again appears that the evaporative flux is under-estimated.

Some indication of the magnitude of the implied under-estimation can be obtained from the calculations of the turbulent fluxes by Bunker and Goldsmith (1979) using Budyko's method (Eqs. (1) and (2) with monthly mean values of the meteorological variables and $C_E = C_H = 2.1 \times 10^{-3}$). The resulting values appear in columns 6 and 8 of Table 1: the Red Sea heat budget becomes:

Solar radiation		Net longwave radiation		Evaporative heat transfer		Sensible heat transfer		Residual	
W m^{-2}		W m^{-2}		W m^{-2}		W m^{-2}		W m^{-2}	
263	–	76	–	183	–	3	=	1	(9)

This indicates a near-balance between the radiation surplus and the turbulent heat flux as compared with the small deficit calculated from oceanographic observations by Patzert (1974). An allowance for dust in the atmosphere over the Red Sea would make the residual negative, as observed.

4. Discussion

Reed (1977) has commented that the estimates of insolation from the various empirical formulas vary so greatly that heat budget studies tend to be rather speculative exercises: Simpson and Paulson (1979) have discussed the considerable errors which can be made by using empirical formulas to estimate the net longwave radiation.

Nevertheless, we feel that the long-term mean radiative heat transfer to the semi-enclosed Mediterranean and Red Seas has been estimated well enough to make it seem likely that the method developed by Bunker (1976) under-estimates the evaporative heat flux from them. This is a matter of some interest because Bunker developed the values of C_E given in Table 2, which is the basis of his method, after a thorough study of the literature on the turbulent transfer of water vapor and heat over free water surfaces. Most specialists in that field would agree that Bunker's method, used with individual observations of high quality, is such as to give a good approximation to the corresponding surface fluxes of water vapor and of sensible heat.

The extent to which Bunker's method may under-estimate the evaporative heat flux can be assessed by noting that corresponding estimates made by Goldsmith and Bunker (1979) using the method of Budyko (1963) are such as approximately to balance the heat budgets of the Mediterranean and Red Seas. It is difficult to make a direct comparison of the Bunker and the Budyko formulas. Bunker's exchange coefficient (Table 2) varies with wind speed and stability and is applied to individual ship's observations of the meteorological variables while Budyko uses a constant exchange coefficient on monthly mean values.

By comparing (4) with (5) and (7) with (9) it is clear that a uniform increase in Bunker's coefficients, by a factor of 1.29 for the Mediterranean and of 1.36 for the Red Sea, would produce the same flux estimates as the use of Budyko's method. From Table 2 it will be seen that a common value for C_E using Bunker's method is $C_E = 1.4 \times 10^{-3}$, so that values of C_E centered on 1.8×10^{-3} and 1.9×10^{-3}, used with individual observations, would lead to estimates of the evaporative flux consistent with the heat budgets of the Mediterranean and Red Seas. The same values are obtained by using Budyko's method with $C_E = 2.1 \times 10^{-3}$, implying that the use of monthly mean values for the meteorological variables of Eq. (1) under-estimates the evaporative flux by about 10%.[4] This agrees

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[4] The figures in columns 8 and 9 of Table 1 show that the use of monthly means has a much greater effect on the estimates of the sensible heat flux than on the evaporative heat flux, presumably because of the differing distribution of the air-sea temperature difference and the air-sea humidity difference.

with the view of Bunker (1971) but is not supported by the analysis of Ocean Weather Ship observations by Esbensen and Reynolds (1981).

Various micrometeorological studies have established Eq. (1) using measurements of the highest accuracy practicable made by instruments arranged to interfere as little as possible with the airflow. Some results are reviewed by Friehe and Schmitt (1976) who show that the value $C_E = 1.3 \times 10^{-3}$ is appropriate in near-neutral conditions at the standard height of 10 m. Our consideration of the heat balance of the Mediterranean and Red Seas has indicated that the effective exchange coefficient for use with individual merchant ship's observations from those areas may be as high as $C_E = 1.8$ or 1.9×10^{-3}. Can such an increase be a compensation for systematic differences between the ships' observations and those made in research projects? Ships' avoidance of high winds may also contribute, though this seems unlikely to produce major bias in the Red Sea.

All ships distort the air flow and modify the wind, temperature and humidity distribution and Bunker (1976) examined the few relevant observations and concluded that an increase in C_E by 10% would compensate for this, applying this 10% increase in compiling the values given in Table 2. It seems unlikely, however, that flow distortion could account for an increase in the effective C_E from 1.3×10^{-3} to 1.8 or 1.9×10^{-3}: one is driven to suspect that there are systematic errors in the observations themselves or that the sampling is strongly biased by ships' avoidance of strong winds. This is difficult to confirm, however, for no calibration of ships' meteorological observations appears to have been published. Bunker (1976) showed that long term average observations from North Atlantic Ocean Weather Ships are in good agreement with those from merchant vessels in their vicinity and this encouraged him to estimate the probable error in his evaporative heat flux estimates as less than 10% for a population of more than 500 observations.

On the other hand, Privett (1960) pointed out a sizable discrepancy between two sets of ships' observations. He used a heat budget method to estimate the evaporative heat flux and then deduced the effective value of C_E for use in Eq. (1) with monthly mean values for the meteorological variables. Applying precisely the same procedures to mean values of meteorological observations for the same areas of the ocean he found $C_E = 2.3 \times 10^{-3}$ for observations from ships reporting to the U.S. Weather Bureau and $C_E = 1.8 \times 10^{-3}$ for observations from ships reporting to the British Meteorological Office. A similar situation at O.W.S. Alpha is reported by Robinson (1966).

The comparison between the estimates of evaporative heat flux in (8) and (9) similarly gives cause for concern. Both were calculated from Eq. (1) using monthly mean values of the meteorological variables and a constant value for C_E. Goldsmith and Bunker (1979) used Budyko's value of $C_E = 2.1 \times 10^{-3}$ to get 183 W m^{-2}, Hastenrath and Lamb (1979) use $C_E = 1.4 \times 10^{-3}$ to get 109 W m^{-2}. The ratio of the estimates (1.68) differs significantly from the ratio of the coefficients (1.5). Arithmetic errors apart, the explanation for the difference must be sought in the observations used or in some more subtle effect of space/time averaging. Hastenrath and Lamb used ships' observations from 1911 to 1970, a data set considerably overlapping that of Bunker and Goldsmith who used ships' observations from 1941 to 1972.

Such differences between data sets imply some systematic error in the observations: our attempts to establish the heat budgets indicate that so far as the Mediterranean and Red Seas are concerned this may be such as to make Bunker's method under-estimate the evaporative heat flux.

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