ENERGY EXCHANGE BETWEEN THE SEA AND THE ATMOSPHERE AT DOHA HARBOUR (QATAR) IN THE ARABIAN GULF

F.M. EID, A.A.H. EL-GINDY, and M. OMNEYA

Oceanography Department, Faculty of Science, Alexandria University, Alexandria, Egypt.

تبادل الطاقة بين سطح البحر والهواء عند ميناء الدوحة (قطر)

في الخليج العربي

فهمي محمد عيد   و   أحمد عبد الحميد الجندي

أمنية محمود

قسم علوم البحار – كلية العلوم – جامعة الإسكندرية

يهدف هذا البحث إلى استخدام بيانات للأرصاد الجوية وعلوم البحار مرصودة في الفترة من ١٩٧٩ – ١٩٨٨ وذلك لحساب الميزانية الحرارية في ميناء الدوحة. وتعود أهمية هذه الدراسة إلى تأثير الميزانية الحرارية على الطقس الجوي وتغيرات درجة حرارة المياه مما يؤثر على البيئه البحريه.

وقد أتضح من هذه الدراسه مايلي :

أتسمت التغيرات السنوية للأشعاع الشمسي المتص بمدى كبير (١١٩ – ٣٧٤) وات/متر٢ كما وجد أن القيمة المتوسطة له ٢٤٨ وات/متر٢.

تقع قيم الحرارة المفقودة بواسطة الأشعاع المرتد من سطح البحر بين ٧٦.٦٤ وات/متر٢ وقيمته المتوسطه حوالي ٦٦ وات /متر٢.

يتم فقد الطاقة عن طريق البخر بمعدل يتراوح بين ١٠١, ٣٠١ وات/متر٢. وتبلغ قيمته المتوسطة ١٨١ وات/متر٢ .

بلغ معدل الفقد نتيجة للتوصيل الحراري بين سطح البحر والهواء قيمته العظمى (١١ وات/متر٢) خلال شهر ديسمبر بينما وجد أكبر معدل للاكتساب (٣٠ وات/متر٢) في شهر يونيو.

أظهرت الميزانية الحرارية وجود أكبر معدل فقد (٩١ وات/متر٢) في شهر ديسمبر وأكبر معدل اكتساب (٨٦ وات/متر٢) في شهر يوليو.

هناك اكتساب للحرارة على مدى العام. وربما يرجع ذلك إلى الأهمال الانتقال بالتيارات البحرية.

ABSTRACT

Meteorological and oceanographic data from 1979 to 1988 have been analyzed and utilized to calculate the heat budget terms of the water at Doha Harbour. The monthly mean of solar radiation has the largest annual amplitude, with a minimum (119 W/m^2) and maximum (374 W/m^2) occurring in December and June, respectively. The annual mean of the net absorbed solar radiation is 248 W/m^2. Heat loss by effective back radiation varied between 64 and 76 W/m^2, with an annual mean of 66 W/m^2. Heat loss due to evaporation oscillated between 101 and 301 W/m^2 with an annual mean of 181 W/m^2. Heat loss (or gain) by conduction of sensible heat is very small. The maximum heat loss by conduction (11 W/m^2) is found during December, whereas the maximum heat gain (30 W/m^2) occurred during June. The annual cycle of total heat transfer across the air-sea boundary is quite marked with maximum loss (about 91 W/m^2) during December and maximum gain (about 86 W/m^2) during July. There was a gain of heat at the air-sea boundary during the period from 1979 to 1988. This gain might be balanced by the advection term which is not considered due to lack of current data.

INTRODUCTION

The determination of the energy exchange between bodies of water and air is one of the principal concerns of oceanographic and limnological studies. Oceanographic studies of the energy budget are utilized for problems in seasonal temperature distributions, transport of energy by currents and the determination of water evaporation for quantitative calculations of elements in the hydrologic cycle [1]. The study of the distribution of sea temperature in any locality is an important subject, and is relevant to the physical and the biological regime. The sea temperature depends on energy exchange processes occurring at the air-sea interface and advective processes occurring below the sea surface. Solar radiation, effective back radiation, evaporation and conduction of sensible heat, at the air-sea interface, are the important terms in the annual balance of the heat budget. The advective processes are directly concerned with transport of water and are brought about by external forces such as winds, tides, and density differences of water masses. The sea water temperature change depends on the net transfer of heat into or out of the water in the area.

A general discussion of the heat budget of the sea is given in "The Oceans" [1]. Since then, there have been numerous studies [2-8]. No detailed studies were done on the energy exchange process in the Arabian Gulf but different trials were done to estimate the evaporation rate. The evaporation level in the open water of the Arabian Gulf is calculated using climatic data [9]. The average evaporation was 144 cm/year. The maximum rate was in December, and the minimum in May. The evaporation from the coastal water of the central part of the Arabian Gulf using the monthly average values of meteorological elements at three meteorological stations (Doha, Manama and Bahrain) was calculated [10]. The monthly mean evaporation was maximum in June (29.3 cm) and minimum in February (8.1 cm), with a total evaporation 202.6 cm. The pitch and open tank observations were fitted to new equations between evaporation levels, the saturation deficit and the wind speed reduced to sea level in three regions in the Arabian Gulf (Doha and Sharga airport and along Oman coasts) were fitted [11]. The mean annual evaporation from Doha and Sharga was 154 cm/year, and if Oman data are included it becomes 140 cm/year.

In this paper an attempt is made to estimate the rates of energy exchange at the air-sea interface at Doha Harbour.

DATA AND METHOD OF ANALYSIS

The present study is based mainly on data from Doha Harbour (25° 15'N, 51° 34'E, Fig. 1). The monthly means of sea surface temperature, air temperature, atmospheric pressure, clouds and scalar wind speeds were taken throughout the period from 1979 to 1988 [12, 13].

The heat budget of a column of water in the sea depends principally on:

Qns – net short-wave solar radiation (short-wave radiation of the sun and sky minus its reflected radiation from the sea,

Qb – effective back radiation (long-wave radiation from sea surface minus that from the atmosphere),

Qe – evaporation (and condensation),

Qc – conduction of sensible heat between the atmosphere and sea,

Qv – net amount of heat brought in or out by transport of water (advection),

Qt – the amount of heat used locally for changing the temperature of sea water (heat storage).

The heat budget in any time interval (Δt) can be expressed as [1].

$$Qns - Qb - Qe - Qc + Qv - Qt = 0$$

This equation assumes that transformation of kinetic energy to heat, heating due to radioactivity, chemical and biological activity, and transfer of heat through the sea floor, can be neglected.

In the present study the above equation is simplified as follows:

$$Qnt = Qns - Qb - Qe - Qc$$

where Qnt is the net (total) heat transfer across the air-sea boundary.

The net short-wave solar radiation (Qns) and net long-wave radiation (Qb) are computed as follows [2, 5].

$$Qns = Qos \, (1 - aC - bC) \, (1 - \alpha)$$

$$Qb = \varepsilon \, \sigma \, T_w^4 \, (0.39 - 0.056 \, \sqrt{q_a}) \, (1 - 0.53C^2) + 4 \varepsilon \sigma T_w^3 \, (T_w - T_a)$$

where:

a = b = 0.38 [4]

α = Albedo = 0.06

C = Fraction of cloud cover in tenths

ε = Emissivity = 1

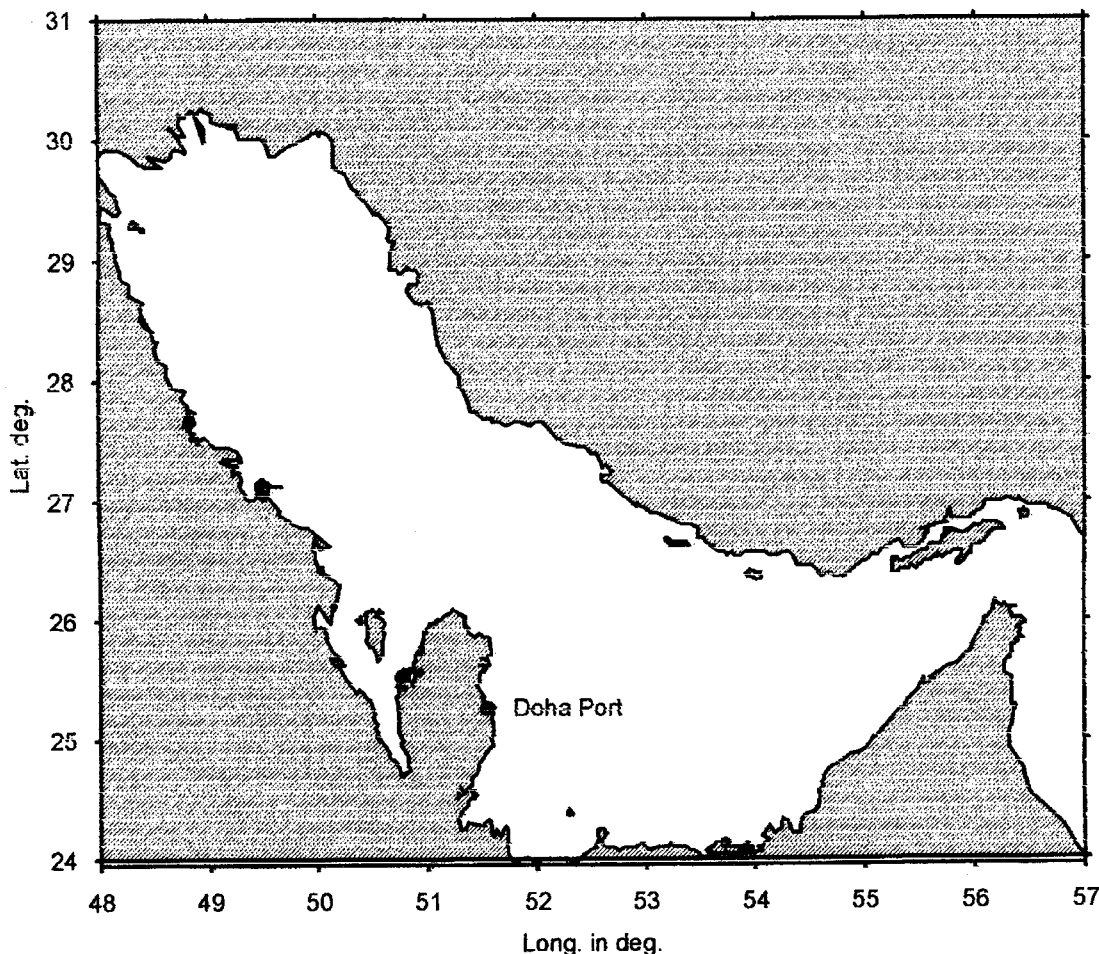σ = Stefan Boltzmann's constant

Fig. 1: The position of Doha Airport and the Port where data were collected.

q_a = Specific humidity (gm/kgm) at T_a

T_w = Sea surface temperature (°C)

T_a = Air temperature (°C)

Qos = Total incoming solar radiation by clear sky, and calculated using formula [14]:

$$Qos = 0.014\ A_n\ t_d\ \text{(gm al cm}^{-2}\ \text{day}^{-1})$$

The above formula is valid up to about 75° of the noon altitude of the sun. Above this altitude, the formula becomes:

$$Qos = 1.06\ t_d\ \quad \text{(gm al cm}^{-2}\ \text{day}^{-1})$$

A_n = The noon altitude of the sun (degrees)

t_d = The length of the day from sunrise to sunset (minutes)

A_n and t_d are calculated using the Page equation [15].

The net short-wave solar radiation depends also on the reflectivity of water (r) which is calculated by the following equation presented by Lombardo [16]:

$$r = a\ \alpha^b$$

α = altitude of the sun expressed in degrees,
a and b are constants depending on cloudiness [16].

The latent heat flux (Qe) and sensible heat flux (Qc) were computed by using the bulk aerodynamic formulas following [5] as:

$$Qe = \rho_a\ C_e L\ (q_w\text{-}q_a)\ W$$

$$Qc = \rho_a\ C_h\ C_D\ (T_w\text{-}T_a)\ W$$

where:

ρ_a = Air density (gm/cm^3),

C_e = Latent heat coefficient,

C_h = Sensible heat flux coefficient,

C_D = Specific heat of air at constant pressure
(0.2403 cal/gm at 10°C),

qw = Specific humidity at the sea surface temperature,

W - Scalar wind speed (m/sec),

L = Latent heat of vaporization = 596 - 0.52 T_w calories gm^{-1}.

The latent heat coefficient (C_e) is obtained by two different ways: i- according to Smith [17]; ii- as a constant (=1.84x10^{-3}). This constant is chosen so that the heat gain to the surface by solar radiation is balanced with that loss by back radiation, evaporation and conduction.

The net convection of sensible heat to and from the atmosphere (Qc) may be also calculated using the following equation:

$$Qc = R\ Qe$$

where R is the Bowen ratio.

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The rate of evaporation (E) in Doha Harbour is estimated by several formulas as following:

a- Using the bulk aerodynamic formula:

$$E = \rho_a \, C_e \, (q_w - q_a) \, W$$

The symbols are as mentioned above.

b- El-Gindy formula [11]:

$$E = 1.014 \, (W_z \, Cl)^{0.53} \, (Q_0 - Q_z)^{0.66} \times 0.6$$

W_z = Monthly mean wind speed in m/sec, at height z from sea surface.

Q_0 = The density of saturated water vapour at the sea surface temperature (gm/m^3),

Q_z = The density of water vapour at height z (gm/m^3),

Cl = A factor reducing the wind speed at height z, where wind was measured, to its value at 5 cm above mean sea level.

c- Anderson formula: [2]

Anderson [2] modified Sverdrup formula [18] to:

$$E = 4.70 \, (e_w - e_a) \, W_a/L$$

e_w = Vapour pressure (mb) of saturated air at sea surface,

e_a = Observed vapour pressure (mb) of air at height (a) cm above the sea surface,

W_a = Wind speed (m/sec) at height of a cm above the sea surface.

RESULTS AND DISCUSSION

1) Net short-wave radiation (Qns):

The net short-wave solar radiation (Qns) depends on the amount of incoming solar radiation increases both with increasing altitude of the sun and the length of the day-time. The reflectivity of water depends on the altitude of the sun and the amount of cloud cover. At Doha Harbour the reflectivity of water varies between 0.03 (during June/July) and 0.07 (during December/January).

The annual variation of the incoming solar radiation with clear sky (Qos) and the net short-wave radiation (Qns) which is absorbed by sea surface is shown in Fig. (2a). There is a marked annual cycle in the heat gain by solar radiation, where the higher values occur during summer and the lower ones in winter. The incident energy under a cloudless sky has a minimum value of 178 W/m^2 in December and a maximum of 418 W/m^2 in June. The annual cycle of the absorbed energy is in phase with that of the total incident solar energy under a cloudless sky, reaching a minimum (119 W/m^2) in December and a maximum (374 W/m^2) in June. It is evident that cloud cover has a major influence on how much solar radiation reaches the sea. The annual range of the incident energy under a cloudless sky reached to 240 W/m^2, whereas that amplitude of the net absorbed radiation is 255 W/m^2. The annual mean incident energy under a cloudless sky reached to 310 W/m^2, whereas that mean net short-wave solar radiation is about 248 W/m^2.
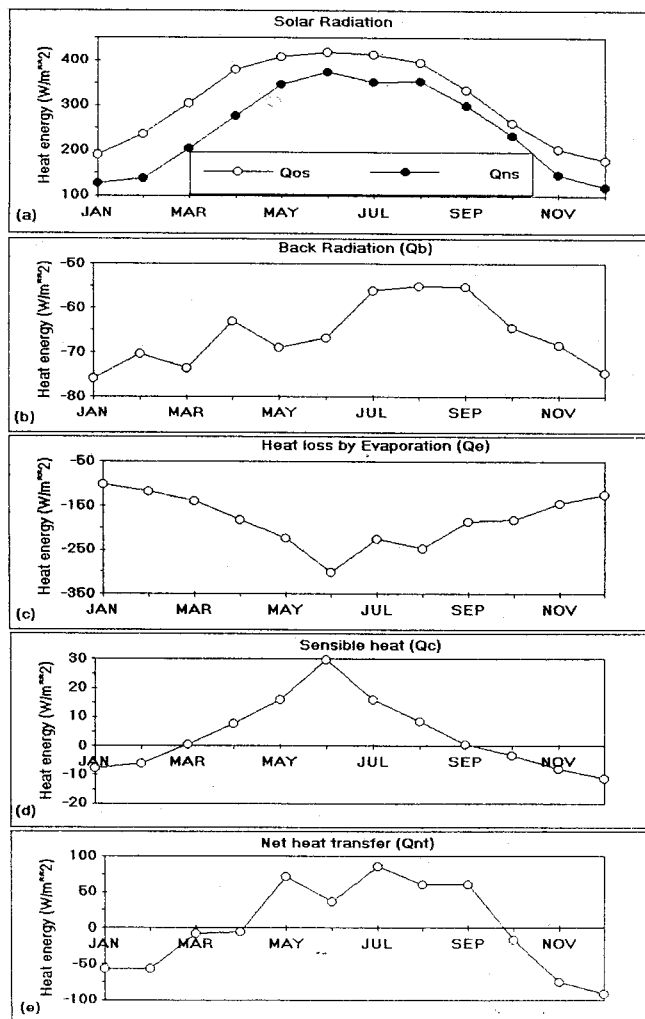

Fig. 2: The monthly mean variations of heat budget terms at Doha Harbour throughout the period from 1979 to 1988.

2) The effective back radiation (Qb):

The back radiation term (Qb) in the heat budget takes account of the net amount of energy lost by the sea as long-wave radiation. The net rate of loss of Qb depends upon the absolute temperature of the sea surface itself and upon the water vapour content of the atmosphere immediately above the sea. The higher rates of Qb occur at low temperatures and low humidity and vice versa. Fig. (2b) shows the monthly variations of the effective back radiation at Doha Harbour during the period of investigation. It is seen that, the effective back radiation oscillates between 55 W/m^2 (during August) and 76 W/m^2 (during January) with an annual mean of 66 W/m^2. Also, it is seen that, the annual amplitude of this radiation is very small compared to that of solar radiation.

3) Heat loss by evaporation (Qe):

The amount of evaporation (E) which is calculated by three different formulas is shown in Table (1). For the bulk equation, column 2, the value of Ce was taken as a variable according to [17]; while in column 3, Ce was given the value 1.84×10^{-3} to achieve the heat balance. The general pattern of the evaporation rate at Doha Harbour which is calculated by three different equations is the same. The

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evaporation rate is low during winter and high during summer. The minimum value for the evaporation is found in January, while the maximum one is observed in June.

Also, it is seen that, the rate of evaporation which is calculated using the El-Gindy equation is slightly lower than that calculated by the other two equations, while the values calculated using the bulk equation gives the highest values.

The annual mean evaporation, which was calculated using the bulk equation, the El-Gindy equation and the Anderson equation are 0.41 - 0.64, 0.38 and 0.46 cm/day, respectively. These values give an annual evaporation at Doha Harbour of about 150 - 234, 140 and 168 cm/year, respectively. The values given by the last two equations, as well as the bulk equation taking Ce according to Smith [17], are in agreement with those estimated by other authors [9].

Fig. (2C) shows the monthly variations of the heat loss from the sea surface at Doha Harbour due to the evaporation with Ce constant. It is seen that, a high amount of heat loss from the sea surface by evaporation occurred during the hot months (May to October). This evidence may be due to the lower differences between the sea surface temperature and the air temperature and the lower values of the relative humidity during these months. The maximum amount of heat loss by evaporation (about 301 W/m²) is observed in June, while the minimum one (101 W/m²) is found in January. The annual amplitude of heat loss by evaporation is 200 W/m² and the annual mean is 181 W/m².

4) Conduction of sensible heat (Qc):

The transfer of sensible heat between the sea and atmosphere is dependent mainly on the vertical temperature gradient across the interface. The annual distribution of Qc is shown in Fig. (2d). The heat is lost from the sea surface during the cold months, and gained by the surface layer during the hot months. The highest sensible heat lost from the sea surface (about 11 W/m²) was found in December, while the highest gains in the sea surface (30 W/m²) occur in June. The annual amplitude of Qc is about 41 W/m², whereas the annual mean is about -3.6 W/m². It should be noted that, the amount of Qc is fairly small compared to the contribution of other terms in the heat budget equation.

Table 1

The calculated amounts of evaporation (E) in cm/day at Doha Harbour

Month	E (cm/day) (Bulk equation) *	E (cm/day) (Bulk equation) **	E (cm/day) (El-Gindy eqn.)	E (cm/day) (Anderson eqn.)
January	0.29	0.35	0.26	0.24
February	0.33	0.41	0.28	0.28
March	0.32	0.49	0.32	0.34
April	0.36	0.65	0.39	0.46
May	0.43	0.79	0.45	0.57
June	0.58	1.07	0.53	0.78
July	0.43	0.80	0.46	0.59
August	0.50	0.88	0.48	0.64
September	0.43	0.66	0.41	0.48
October	0.51	0.65	0.39	0.46
November	0.42	0.51	0.33	0.36
December	0.36	0.44	0.30	0.30
Annual mean	**0.41**	**0.64**	**0.38**	**0.46**

* Ce according to Smith, [17]; ** Ce = 1.84 x 10⁻³

5) Total heat transfer across the air-sea boundary (Qnt):

The total transfer of heat across the air-sea boundary is presented in Fig. (2e). The principal feature of the annual cycle is that the greatest loss, of the order of 91 W/m², occurs in the winter (December) and the greatest gain, 86 W/m², occurs in summer (July). The periods of no net transfer occur during the latter part of April and September. The annual mean of the total heat transfer across the air-sea boundary is 0.55 W/m². This means that there is a net heat gain to the sea surface. This amount of heat must be balanced by advection (Qv) and/or the increase in the heat storage of the water column (Qt).

Table (2) shows the total annual transfer of heat energy at air-sea boundary at Doha Harbour throughout the period from 1979 to 1988 with an evaporation coefficient Ce=1.84x10⁻³. It is clear that the mean yearly gain of heat across the air-sea boundary during this period was 3020 W/m², and the mean loss 3007 W/m², resulting in a net gain of 13.5 W/m² (0.4%). Gains occurred in most years except in 1984, 1985, 1986 and 1988. The greatest gain of 241 W/m² (8.3%) occurred in 1983, while the smallest gain of 26 W/m² (0.9%) occurred in 1980. The greatest loss of heat (185 W/m²) occurred in 1984, while the smallest loss (15 W/m²) occurred in 1988. These annual changes may be related with the annual changes of sea surface temperature [19].

By taking the latent coefficient (Ce) according to Smith

[17], the results of the total transfer of heat across the air-sea boundary differ from that mentioned above, as shown in Table (3). It is clear that gains occurred in all years. The mean yearly gain of heat across the air-sea boundary was 3019 W/m^2, and the mean loss 2218 W/m^2, resulting in a net gain of 801 W/m^2. Therefore, this heat gain must be lost from the water column by advection and by heat storage. The amount of heat transferred by advection within Doha Harbour is not calculated in the present study due to the lack of current measurement.

CONCLUSION

Meteorological and oceanographic data at Doha Harbour reported by the State of Qatar [12, 13] throughout the period from 1979 to 1988 have been analyzed and utilized in calculation of the heat budget terms. The results showed that:

The annual cycle of solar radiation is quite marked, the maximum input (374 W/m^2) occurred in summer and the minimum (119 W/m^2) in winter.

The annual cycle of heat loss from the sea to the at-mosphere by effective back radiation is relatively small and varied from a minimum (55 W/m^2) in summer to a maximum (76 W/m^2) in winter.

The annual cycle of heat loss by evaporation is quite marked, with a maximum (301 W/m^2) in summer and a minimum (101 W/m^2) in winter.

The annual cycle of conduction of sensible heat showed a loss from the sea surface during the cold months with a maximum value of about 11 W/m^2. There was a gain in the sea surface during the hot months, with a maximum transfer of about 30 W/m^2.

The annual cycle of total heat transfer across the air-sea boundary is quite marked with a maximum loss of 91 W/m^2 during December and a maximum gain of 86 W/m^2 during July. The periods of no net transfer occur in the latter part of April and September. The balanced heat budget was achieved over the entire year by using an evaporation factor 1.84×10^{-3}. The other evaporation equations gave a net heat gain. If this net gain is true, it should be compensated by the advection term which is not included in the present study.

Table 2

The total heat energy transfer at air-sea boundary (W/m^2) at Doha Harbour during the period from 1979 to 1988 with constant latent heat coefficient Ce.

Year	Gain (Qg)	Loss (Ql)	Mean (Qm)	Difference (Qg-Ql)	(Qg-Ql/Qm %
1979	3010.7	2968.9	2989.8	41.8	1.4
1980	3016.5	2990.6	3003.6	25.9	0.9
1981	3044.4	3000.9	3022.6	43.5	1.4
1982	3050.5	2925.6	2988.1	124.9	4.2
1983	3035.1	2794.3	2914.7	240.8	8.3
1984	3040.6	3226.0	3133.3	-185.4	-5.9
1985	3007.9	3146.1	3077.0	-138.2	-4.5
1986	3000.0	3065.4	3032.7	-65.4	-2.2
1987	2990.8	2929.0	2959.9	61.8	2.1
1988	3008.0	3023.0	3015.5	-14.9	-0.5
Mean	**3020.4**	**3007.0**	**3013.7**	**13.5**	**0.4**

Table 3

The total heat energy transfer at air-sea boundary (W/m^2) at Doha Harbour during the period from 1979 to 1988 with variable latent heat coefficient following Smith, 1989.

Year	Gain (Qg)	Loss (Ql)	Mean (Qm)	Difference (Qg-Ql)	(Qg-Ql/Qm %)
1979	3014.2	2215.0	2614.6	799.2	30.6
1980	3017.3	2262.7	2590.0	854.6	33.0
1981	3032.5	2165.6	2599.0	866.9	33.4
1982	3035.8	2134.1	2584.9	901.7	34.9
1983	3022.6	2162.8	2592.7	859.8	33.2
1984	3030.4	2300.5	2665.5	729.9	27.4
1985	3012.7	2347.3	2680.0	665.4	24.8
1986	3008.4	2271.2	2639.8	737.2	27.9
1987	3003.3	2175.9	2589.6	827.4	32.0
1988	3012.7	2248.6	2630.7	764.1	29.1
Mean	**3019.0**	**2218.4**	**2618.7**	**800.6**	**30.6**

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