JKAU: Mar. Sci., **Vol. 20**, pp: 21-29 (2009 A.D. / 1430 A.H.)

Estimation of the Net Surface Heat Flux in the Arabian Gulf Based on the Equilibrium Temperature

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Abstract. The concept of equilibrium temperature provides a direct and easy method to estimate the net heat flux at the air-sea interface compared to the conventional methods where the net surface heat flux is determined based on the balance of incoming solar radiation, net back radiation flux, sensible heat exchange, and the evaporative heat flux. In the northern part of Arabian Gulf the sea surface temperature is higher than the equilibrium temperature indicating a net loss of heat, whereas in the southern part the sea surface temperature is lower than the equilibrium temperature resulting in the net gain of heat at the air-sea interface. The net surface heat flux at the air-sea interface for the Arabian Gulf as a whole is 8 W/m^2. This gain of heat in the Arabian Gulf will be dispersed in the water column and then out through the Strait of Hormuz.

Keywords: Arabian Gulf, net surface heat flux, equilibrium temperature, thermal exchange coefficient.

Introduction

Changes in heat stored in the upper layers of the sea surface can be described by the imbalance between the incident solar radiation flux, the longwave radiation flux emitted from the sea surface, the sensible heat and the latent heat fluxes from the sea surface to the atmosphere. The determination of the heat exchange through the boundary layer at an air-sea interface is very important to examine several scientific applications such as; weather forecasting, investigation of atmospheric and oceanic circulation, investigation of the dynamics of climate, and investigation of thermal modifications in the lower atmosphere and the upper ocean (Simpson and Paulson, 1979).

Several methods known to oceanographers and commonly used to determine the heat flux include; the profile method, the eddy correlation method, and the dissipation method. Those methods are summarized by Kraus (1972), Pond (1975), and Dobson *et al.*, (1980). The bulk aerodynamic formulations are a conventional method to estimate momentum flux, latent heat flux, and sensible heat flux over a large area between the ocean and atmosphere. Knowing the weather information at a certain height, say 10 m, and sea surface temperature along with the bulk transfer coefficients, which are experimentally determined, it can serve as a foundation for most ocean and weather models. The accuracy of the Bulk formulae will highly depend on the determination of the transfer coefficients for any particular situation. Unfortunately each of these coefficients reveals a strong dependence on sea state, wind speed, stability, and measurement height (Taylor, 1984). However, because of the simplicity of the bulk aerodynamic method, most researchers adopt it for estimating the flux. Nevertheless, encompassed within the bulk aerodynamic method are more than 20 different semi-empirical relationship schemes. In addition, the same input data can yield estimated fluxes differing by as much as 100% (Blanc, 1983).

This study uses the equilibrium temperature method to estimate the net heat flux at the sea surface in the Arabian Gulf (hereinafter referred to as the Gulf) (Fig. 1). The Gulf has undergone several investigations of estimating the heat flux; the earliest work was made by Privett (1959) in which he estimated the evaporation rate as 144 cm/y. In the late 1970s a heat budget study of the Indian Ocean was made by Hastenrath and Lamb (1979), they have charted the Gulf basin based on long term data observations from 1911 to 1970. Meshal and Hassan (1986) computed the evaporation rate over the Gulf as 202 cm/y. Ahmad and Sultan (1991) have estimated the net annual average heat flux of $-21 W/m^2$. Based on long-term moored time series observations at the Strait of Hormuz; Johns *et al.*, (2003) estimated the water exchange through the strait. A calculation of freshwater and associated heat fluxes gives estimate of net flux as -7 ± 4 W/m^2 over the surface area of the Gulf.

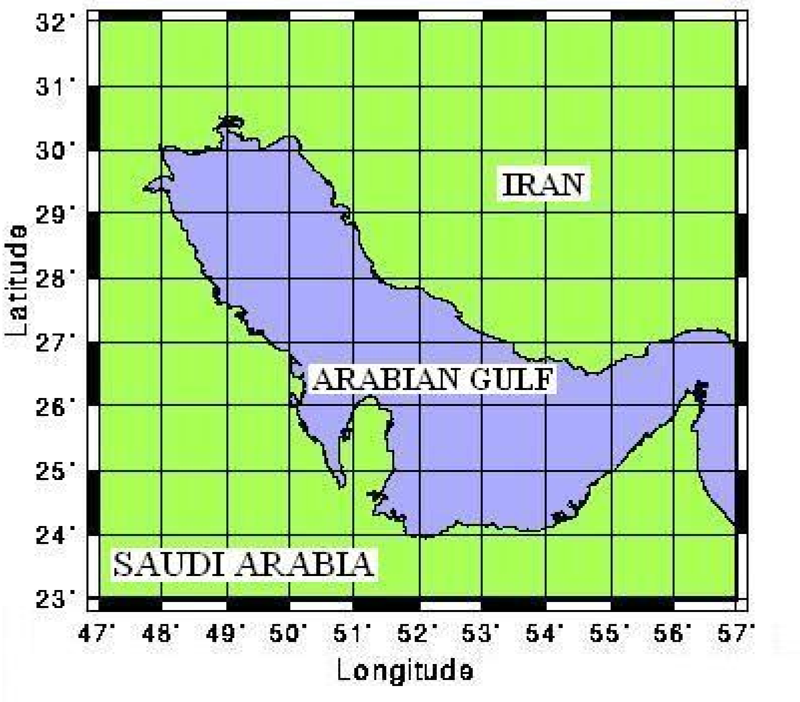

Fig. 1. Map of the study area (23° N/32° N - 47° E/57° E) with one degree resolution.

The Equilibrium Temperature Method

The equilibrium temperature concept was introduced by Edinger *et al.* (1968); the equilibrium temperature (T_e) is a hypothetical water surface temperature; *i.e.* when the sea surface temperature at equilibrium temperature, the net heat flux exchange between the sea surface water and the air would be theoretically zero. This method depends on several heat flux exchange processes including back radiation, sensible, and evaporative fluxes at the sea surface and the overlying air. The sea surface temperature (T_s) rate responds to these processes based on the thermal exchange coefficient [γ] (W/m^2 ºC). This coefficient describes the rate at which sea surface temperature responds to these heat flux exchange processes. If the net rate of heat flux per unit area at the sea surface can be present as [γ ($T_s - T_e$)], then a simple equation can be introduced as (Edinger *et al.*, 1968):

$$Q_T = [\gamma (T_e - T_s)]$$

Brady *et al.* (1969) have shown the relationship between the thermal exchange coefficient and the equilibrium temperature to a good approximation as:

$$T_e = T_{dp} + \frac{Qs}{\gamma}$$

where T_{dp} is the dew point temperature and Q_S is the incoming solar radiation per unit area. Since the Gulf is being surrounded by a hot arid area, lack of precipitation, then it is subjected to higher evaporation rate. In the Gulf region, both Q_S and T_{dp} are having greater values during summer season compared to the winter season, however T_{dp} has strong contribution to the seasonal variations of T_e (Ahmed and Sultan, 1994). The thermal exchange coefficient [γ] is given by Edinger *et al.*, (1974) as a function of wind speed and sea surface temperature (T_s):

$$\gamma = 4.5 + 0.05\ T_s + (\eta + 0.47)\ S(w)$$

Various formulas are summarized for the wind speed S(w) by Edinger *et al.*, (1974), $S(w) = 3.3w$; where wind speed w is given by m. sec^{-1} and η given as:

$$\eta = 0.35 + 0.015\ T_n + 0.0012\ (T_n)^2$$

$$T_n = 0.5\ (T_s + T_{dp})$$

Data Analysis and Methodology

The mean monthly meteorological and sea surface temperature primary variables for the period of 1996-2006 (11-years) were obtained from the Comprehensive Ocean-Atmosphere Data Set (COADS). Primary variables considered in this study include the air temperature T_a, sea surface temperature T_s, surface wind speed w, relative humidity R_H, and total cloudiness. The data used in this study are based on year-month summaries trimmed of the individual marine weather reports in 1^o latitude by 1^o longitude grid. Year-month summaries come in different formats; the data in this study are based on the enhanced statistics format, so as to accommodate more extreme climate events, and using a broad collection of marine and weather observations from ships, buoys, *etc.* The study area (Fig. 1) 24^o N/30^o N - 48^o E/56^o E with one degree resolution has a total number of 18 grid points over water. The $1^o \times 1^o$

year-month data records for every single variable have been constructed by averaging each month for the whole 11-years. Some of the marine-weather observations at some grid points (Table 1) are not taken in this study due to data limitation.

Table 1. The individual missing marine-weather observations at several grid points in the study area.

Latitude	Longitude		
30° N	48° E	49° E	50° E
27° N	53° E	–	–
26° N	50° E	51° E	–
24° N	52° E	53° E	54° E

Based on total cloud cover data at each grid point, the solar radiation incident under cloudy conditions Q_s was derived by Reed (1977); the formula has included the solar radiation incident under clear sky Q_{sc} derived by Seckel (1970) [given by Reed, 1977].

$$Q_{sc} = (A_o + A_1 \cos\phi + B_1 \sin\phi + A_2 \cos 2\phi + B_2 \sin\phi)$$

where ϕ is $(2\pi/365)(t - 21)$, t is the Julian day and the A's and B's are latitude-dependent coefficients, which are suggested by (Reed, 1977).

$$Q_s = Q_{sc}\,(1 - \mu C + 0.0019\beta)\,(1 - A)$$

μ is a constant taken as 0.62, C is the fractional cloud cover, β is the noon solar altitude in degrees, and A is the albedo. The computed results of Q_s are given in Table 2.

Table 2. Computed values of Qs (W/m^2) for the period of 1996-2006 (11-years) ensemble in the Gulf.

Latitude	Longitude							
	49° E	**50° E**	**51° E**	**52° E**	**53° E**	**54° E**	**55° E**	**56° E**
29° N	252	248	–	–	–	–	–	–
28° N	246	250	249	–	–	–	–	–
27° N	–	250	253	252	–	–	–	–
26° N	–	–	252	252	254	252	251	251
25° N	–	–	–	250	260	260	257	–

From the annual-monthly average of each meteorological variable and sea surface temperature for the 11-years; the dew point temperature T_{dp} and the thermal exchange coefficient γ were obtained and the equilibrium temperature T_e for each degree resolution were computed as given in Table 3.

Table 3. Computed values of T_e (°C) for the period of 1996-2006 (11-years) ensemble in the Gulf.

Latitude	Longitude							
	49° E	50° E	51° E	52° E	53° E	54° E	55° E	56° E
29° N	19.1	19.6	–	–	–	–	–	–
28° N	19.5	21.3	21.4	–	–	–	–	–
27° N	–	21.3	21.6	22.0	–	–	–	–
26° N	–	–	21.4	21.7	22.4	22.4	22.7	22.6
25° N	–	–	–	21.9	22.2	22.2	21.8	–

Results and Discussion

The heat flux exchange at the sea-air interface can be estimated in term of the thermal exchange coefficient γ and the equilibrium temperature T_e; based on meteorological variables and sea surface temperature. This study has used the thermal exchange coefficient and the equilibrium temperature as a reference based on one degree resolution, for the period of 1996-2006 (11-years), to estimate the net heat flux Q_T at the Gulf surface water. This attempt has not been done in this body of water according to the literature review, however number of studies have been conducted to estimate the net heat flux based on the bulk aerodynamic method.

The net heat flux exchange at the sea-air is very important dynamic feature in determining the heat of the water basin. The computed values of the net heat flux over the Gulf basin (Table 4) show a heat loss in the northern side (49° E-51° E); which indicates the sea surface temperature is higher than the equilibrium temperature. At the southern side, the sea surface temperature is less than the equilibrium temperature, the Gulf gain heat at the air-water interface (52° E-56° E). The average net heat flux Q_T for the total grid points over the gulf basin was computed and showed that there is a surface heat gain of about 8 W/m^2. Using the same data and the same technique; the annual average of net heat flux Q_T for 1° latitude by 1° longitude boxes has been computed over the gulf basin and the average heat flux exchange at the sea-air interface for the eleven years data showed a surface heat gain within the same range. These data are given in Table 5.

Table 4. Computed values of net heat flux Q_t (W/m^2) for the period of 1996-2006 (11-years) ensemble in the Gulf.

Latitude	Longitude							
	49° E	50° E	51° E	52° E	53° E	54° E	55° E	56° E
29° N	−3	−25	–	–	–	–	–	–
28° N	−13	−20	−58	–	–	–	–	–
27° N	–	1	−37	11	–	–	–	–
26° N	–	–	−13	0	29	32	50	37
25° N	–	–	–	22	46	45	36	–

Table 5. Annual means of Qs (W/m^2), sea surface temperature T_s, wind speed w, relative humidity RH, dew point temperature T_{dp}, thermal exchange coefficient γ, the equilibrium temperature T_e, and net heat flux Q_t (W/m^2) for the period of 1996-2006 (11-years) in the Gulf.

Year	Q_s (W/m^2)	T_s (°C)	Wind (m/s)	RH %	T_{dp} (°C)	γ (W.m^2. °C)	T_e (°C)	Q_t (W/m^2)
1996	252	27.2	4.6	71.6	21.6	34.5	28.9	59
1997	251	26.6	5.8	73.2	21.0	40.9	27.1	20
1998	254	27.8	5.6	71.2	22.0	41.5	28.1	12
1999	264	28.0	6.0	70.7	21.4	43.9	27.5	−22
2000	264	27.3	6.0	70.9	20.8	42.7	27	−13
2001	259	28.0	5.9	70.9	21.8	43.8	27.7	−13
2002	243	27.6	5.8	73.4	21.5	42.6	27.2	−17
2003	247	27.5	5.6	71.8	21.6	40.8	27.7	8
2004	242	26.7	6.4	74.0	21.4	45.6	26.7	0
2005	249	27.2	5.3	74.6	22.0	39.4	28.3	43
2006	247	27.4	5.6	69.0	21.5	40.8	27.6	8
Avg.	**252**	**27.4**	**5.7**	**71.9**	**21.5**	**41.5**	**27.6**	**7.8**

Several studies have been taken in the Gulf basin using the conventional Bulk formulae, which highly depend on conduction and sensible heat process, radiative and evaporative heat fluxes, and the determination of the transfer coefficients for any particular situation. However, in this paper; the net rate of total heat flux at the air-sea interface was evaluated in terms of the thermal exchange coefficient and the equilibrium temperature based on one degree resolution from the available data. The method used in this research showed a simple way to estimate the net heat flux exchange at the water surface in the gulf basin.

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التقدير الإجمالي للدفق الحراري السطحي للخليج العربي بناءً على حرارة الاتزان

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المستخلص. فكرة درجة الاتزان الحراري تقـــدم طريقـــة مبســـطة ومباشرة لتقدير إجمالي الدفق الحراري السطحي لماء البحر وذلـــك عند الطبقة الملامسة للهواء مقارنة بالطرق التقليدية التي تســـتخدم تقديرات الإشعاع الشمسي، والإشـــعاع المرتـــد، وتبـــادل حـــرارة التوصيل، ودفق حرارة التبخير. درجة حرارة سطح البحـــر فـــي الجزء الشمالي من الخليج العربي أعلى من درجة حرارة الاتـــزان، وهذا مؤشر على نقصان إجمالي الدفق الحراري السطحي، بينما في الجزء الجنوبي من الخليج، كانت درجة حرارة سطح البحر أقل من درجة حرارة الاتزان، مما يسبب في زيادة إجمالي الدفق الحراري عند السطح. المحصلة النهائية عند حساب إجمالي الدفق الحـــراري للخليج العربي كاملاً كانت ٨ وات/م^{٢}. هذه الزيادة فـــي الحـــرارة المكتسبة عند سطح الخليج العربي يتم فقدانها في عمود الماء ثم إلى خارج الخليج عن طريق مضيق هرمز.

الكلمات المفتاحية: خليج عربي، إجمالي دفق حـــراري ســـطحي، حرارة الاتزان، معامل التبادل الحراري.