Comments on "On the Estimation of Overwater Bowen Ratio from Sea–Air Temperature Difference"*

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The Bowen ratio is an important parameter in the study of air–sea interaction, particularly in the study of moisture convergence. It is the ratio of sensible to latent heat exchange. Recently, Hsu (1998) reported an interesting relationship between the sea–air temperature difference ($T_s - T_a$) and the overwater Bowen ratio (B), based on thermodynamic considerations. He used the data collected at four stations in the Gulf of Mexico during the period 1993–97 and proposed a generic relationship of the form

$$B = a(T_s - T_a)^b \quad (1)$$

where the values of a and b are estimated from the field experiments. For open sea conditions, the value of a varied from 0.077 to 0.078, b from 0.67 to 0.71, and the correlation coefficient (r) from 0.85 to 0.89. Very similar results were found in a nearshore region (for Grand Isle, Louisiana). The equation with the highest correlation coefficient ($r = 0.85$) is given by Hsu (1998) as

$$B = 0.077(T_s - T_a)^{0.69}. \quad (2)$$

Normally, values of B are large for cold air outbreak conditions. Chou and Yeh (1986) observed B to vary between 0.61 and 0.78 over midlatitude coastal water during cold air outbreak events. During Air-Mass Transportation Experiment (14–28 February 1974), the value of B was about 0.8 over the Yellow Sea. Hsu also reported Bowen ratios that were substantially higher during a cold-air outbreak that resulted in enhanced sensible heat flux over latent heat flux under these conditions. The linear regression given by Hsu (1998) is

$$B = 0.097(T_s - T_a)^{0.81}. \quad (3)$$

Hsu (1999) further studied the relationship using the measurements made in the East China Sea, off San Diego, and in the equatorial Atlantic Ocean and proposed the following equation,

$$B = 0.146(T_s - T_a)^{0.49}, \quad (4)$$

which, in his opinion, is useful for tropical ocean and cold air outbreak conditions as well. However, Eq. (4) yielded higher rms (± 0.049) with our data (Table 1). He suggested that more data is needed to verify Eq. (1) for open sea conditions. He also expressed the need for the measurements over other oceanic areas to substantiate his results.

The main purpose of this study is to test the generic relationship proposed by Hsu (1998, 1999) over the northern Bay of Bengal (Indian Ocean), where the values of ($T_s - T_a$) do not normally exceed 2°C, and the Bowen ratio varies in the range from 0.02 to 0.2 (Sarma and Rao 1992; Sarma et al. 1997).

The long-term time series measurements on the surface meteorological parameters, collected on board ORV *Sagar Kanya* during the Monsoon Trough Boundary Layer Experiment during the summer monsoon period of 1990 were used to examine the relationships between ($T_s - T_a$) and B over the northern Bay of Bengal. The data were obtained at 20°N, 89°E from 18 August–1 September (Phase I) and from 8–19 September (Phase II), in the monsoon trough region. Air–sea heat fluxes and the overwater Bowen ratio were computed and reported earlier (Sarma et al. 1997).

Table 1 shows the daily mean values of latent (Q_e) and sensible (Q_h) heat fluxes, sea–air temperature difference ($T_s - T_a$), and overwater Bowen ratio (B) during 18 August–19 September 1990 with a data gap from 2 to 7 September. Figure 1 shows the scatter diagram plotted for the parameters ($T_s - T_a$) and B. We have noticed a very high correlation of 0.93 between ($T_s - T_a$) and B with 27 values. The power law curve fitting yielded values of a and b as 0.094 and 0.80 respectively. Thus the relationship between ($T_s - T_a$) and B emerges as

$$B = 0.094(T_s - T_a)^{0.80}. \quad (5)$$

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TABLE 1. Daily mean values of latent heat flux (Q_e), sensible heat flux (Q_h), the difference between the sea surface temperature (T_s) and air temperature (T_a), and the overwater Bowen ratio (B) at 20°N, 89°E in the monsoon trough region during MONTBLEX-90.

Date	Q_e	Q_h	$T_s - T_a$	B
18 Aug 1990	76.81	10.70	1.84	0.139
19 Aug 1990	66.69	5.15	0.50	0.077
20 Aug 1990	130.59	16.50	1.41	0.126
21 Aug 1990	123.66	9.31	0.86	0.075
22 Aug 1990	76.71	3.23	0.42	0.042
23 Aug 1990	62.46	2.91	0.42	0.047
24 Aug 1990	55.42	5.09	0.73	0.092
25 Aug 1990	36.03	1.93	0.31	0.054
26 Aug 1990	43.29	5.33	1.12	0.123
27 Aug 1990	68.81	2.90	0.44	0.042
28 Aug 1990	79.54	4.53	0.54	0.057
29 Aug 1990	88.76	1.91	0.25	0.021
30 Aug 1990	72.04	3.23	0.45	0.045
31 Aug 1990	48.70	2.69	0.58	0.055
1 Sep 1990	38.56	1.56	0.43	0.040
8 Sep 1990	54.30	2.48	0.40	0.046
9 Sep 1990	41.17	1.69	0.29	0.041
10 Sep 1990	39.73	3.82	0.66	0.096
11 Sep 1990	63.45	4.40	0.86	0.069
12 Sep 1990	51.59	8.94	1.75	0.173
13 Sep 1990	83.86	4.74	0.65	0.056
14 Sep 1990	77.51	4.63	0.62	0.060
15 Sep 1990	80.78	2.10	0.26	0.026
16 Sep 1990	57.80	2.46	0.29	0.043
17 Sep 1990	38.16	1.63	0.34	0.043
18 Sep 1990	70.14	7.59	1.34	0.108
19 Sep 1990	64.81	8.12	1.73	0.125

It is interesting to see that Eq. (5), with its coefficients a and b is nearly the same as Eq. (3) proposed by Hsu (1998) for cold air outbreak conditions. It may be noted that our values of C_e and C_h (bulk transfer coefficients for latent and sensible heat fluxes, also known as Dalton and Stanton numbers respectively) are different from those of Hsu.

We have estimated rms errors from Eqs. (2), (3), (4), and (5) using the dataset given in Table 1 and presented in Table 2. Equation (4), proposed by Hsu (1999) which represents cold air outbreak conditions, gives a higher rms error when compared with his other equations. Equation (3) of Hsu (1998) and our proposed present equation (5) yield a smaller rms error. The reasons for this striking similarity in B for the Bay of Bengal and the Gulf of Mexico cold air outbreak condition, though unclear at the moment, are attributed to the presence of a monsoon trough, a set of cyclonic vortices, characterized by intense downdraft, affecting the air temperature (Sarma et al. 1997).

TABLE 2. Rms errors with different equations.

Equations	Rms error
(2)	±0.021
(3)	±0.013
(4)	±0.049
(5)	±0.013

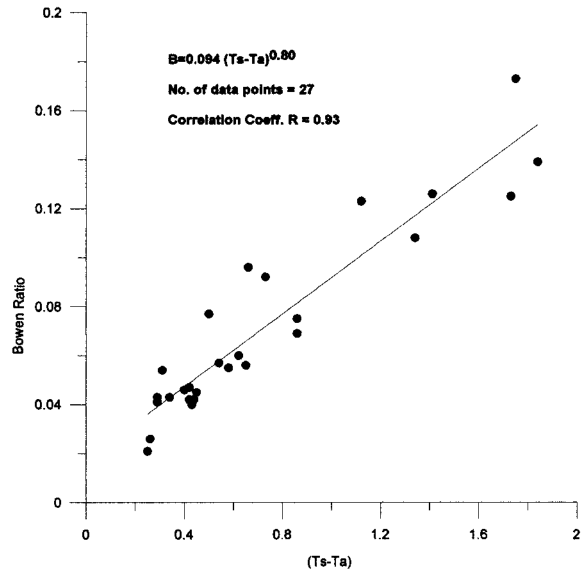

FIG. 1. Scatter diagram between ($T_s - T_a$) and overwater Bowen ratio (B) for the northern Bay of Bengal during the southwest monsoon of 1990.

It has been observed that ($T_s - T_a$) in the northern Indian Ocean generally remains small (Sarma and Rao 1992; Sarma et al. 1997). Hence, we recommend our Eq. (5) for operational use in the northern Indian Ocean in general and the Bay of Bengal in particular. However, this relationship (Eq. 5) needs to be tested for different conditions, with long-term time series data.

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