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Diurnal variability of heat fluxes over the coastal waters off Visakhapatnam during post-monsoon and winter seasons

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Diurnal variability of heat fluxes in the coastal waters of Visakhapatnam has been studied during post-monsoon (Oct, 2006) and winter (Jan-Feb, 2007) seasons utilizing the surface meteorological data and radiation measurements on-board CRV Sagar Sukti and mechanized boats. Estimated values of short and long wave radiation are well comparable with the measured values. Latent (Q_{LH}) and sensible (Q_{SH}) heat fluxes are computed from bulk aerodynamic method. Total enthalpy (i.e. Q_{LH}+Q_{SH}) was 50-200W/m^2 and 10-200W/m^2 (on diurnal scale), during post monsoon and winter seasons respectively. The net heat exchange (Q_N) was 137W/m^2 and 92W/m^2 under the above seasons. Daily mean values of Bowen Ratio (B) in the study region varied between 0.02 and 0.14,. A simple relationship [$(B=0.057(Ts-Ta)^{0.89}$; N = 20; r = 0.82; significant at > 99% level)] between Bowen's ratio (B) and sea-air temperature difference has been proposed for unstable conditions. High correlation (r = 0.87) is found between the values of Q_{LH} estimated and obtained from the above relationship.

[**Keywords**: Heat flux, Ocean, Radiation, Enthalpy, Wind]

Introduction

Air-sea fluxes over the ocean surface play an important role in regional and global climate. Several studies reported the air-sea fluxes over the Indian Ocean. Some studies reported the diurnal variation of heat fluxes using the data sets collected under MONTBLEX[1] and BOBMEX[2]. Most of the studies dealt with the variations of the fluxes over the deep ocean. Sadhuram *et al.*[3] reported the diurnal variation of the fluxes at few selected locations of east coast of India during April-1990. The variability of the net heat exchange in the coastal waters off Visakhapatnam under different seasons was reported earlier[4]. In a recent study[5], the enthalpy (i.e. latent + sensible heat fluxes) is found to play an important role in the intensification of the severe cyclone "Nargis" (May 2008) which devastated Myanmar. It is reported that the enthalpy was 900W/m^2 which is nearly 300% higher than the climatological value (~ 300W/m^2). In this study, the variability of latent, sensible heat, enthalpy and net heat exchange during post monsoon (Oct, 2006) and winter seasons (Jan-Feb, 2007) has been examined. A simple equation to compute Bowen ratio (B) using only sea-air temperature difference (Ts-Ta) is proposed for unstable conditions, which has not been reported earlier.

Material and Methods

The time series measurements of radiation and surface meteorological parameters were made for various phases. The data collected (for a few days) onboard CRV Sagar Sukti (NIO research vessel) and mechanized boats during Oct. 2006, Jan.-Feb. 2007, have been used to compute the effective back radiation, latent and sensible heat fluxes, Bowen ratio and wind stress. The study area is shown in Fig .1 and the details of data collection are shown in Table 1.

The data collected during phase I represents post monsoon, while in phases II-V represent winter season. Surface meteorological data were collected at hourly interval. The Short wave radiation (incoming and outgoing) was measured by Albedo Meter (Make: Kipp & Zonen; Spectral response: 0.305 to 2.8 µm; Accuracy ~10 w/m^2; averaging time - 5 min.) and the Long wave radiation (incoming and outgoing) was measured by Net Pyrgeometer (Make: Kipp & Zonen; Spectral response: 5 to 10 µm; Accuracy ± 10%; averaging time-5 min.). Radiation measurements were done only onboard CRV Sagar Sukti (Jan & Feb 2007). Sea Surface Temperature (SST) was measured by a Bucket Thermometer. Dry bulb and Wet bulb Temperatures were measured by a Psychrometer and the Wind Speed was measured by a portable air-meter.

The heat budget components: Q_{LH} (latent heat flux), Q_{SH} (sensible heat flux), $Q_{LH}+Q_{SH}$ (enthalpy), Q_N (Net heat flux) were calculated from the observed data. Almost clear sky conditions are observed during the above phases. The daily mean values of incoming short wave radiation are computed using the formula suggested by Seckel and Beaudry[6] under clear sky conditions and an albedo of 0.06 suggested Payne[7] in these latitudes.

$$Q_{sw} = A_o + A_1 \cos\phi + B_1 \sin\phi + A_2 \cos 2\phi + B_2 \sin 2\phi \quad (1)$$

Latitude 20°S to 40°N	Latitude 40°N to 60°N
$A_o = -15.82 + 326.87 \cos L$	$A_o = 342061 - 1.97L - 0.018L^2$
$A_1 = 9.63 + 192.44 \cos (L+90)$	$A_1 = 52.08 - 5.86L + 0.043L^2$
$B_1 = -3.27 + 108.70 \sin L$	$B_1 = -4.80 + 2.46L - 0.017L^2$
$A_2 = -0.64 + 7.80 \sin 2(L-45)$	$A_2 = 1.08 - 0.47L + 0.011L^2$
$B_2 = -0.50 + 14.42 \cos 2(L-5)$	$B_2 = -38.79 + 2.43L - 0.034L^2$

Q_{SW} is the clear-sky mean daily insolation (W/m^2)

$\phi = (t-21)(360/365)$

t is the time of year (days)

L is latitude.

The Net long wave radiation for clear sky is obtained from Anderson's[8] formula.

$$Q_{NLW} = \epsilon\,\sigma\,[T_s^{\,4} - T_a^{\,4}(0.74 + 0.0049 e_a)] \quad (2)$$

Є is the emissitivty of the sea surface (0.97)

σ is the Stefan Boltzman constant (5.67×10^{-8} W/m^2/k^4)

Ta is the air temperature in °K

Ts is the Sea surface temperature (SST) in °K

The bulk aerodynamic formulae were used to determine wind stress (τ), latent (Q_{LH}) and sensible (Q_{SH}) heat fluxes in this study. For this study, the bulk transfer coefficients suggested by De Cosmo *et al.*[9] are used in this computation.

$$\tau = \rho_a C_D U^2 \quad (3)$$

$$Q_{SH} = \rho_a C_p C_H (T_s - T_a) U \quad (4)$$

$$Q_{LH} = \rho_a L C_E (e_s - e_a) U \quad (5)$$

where ρ_a is the density of air (kg/m^3), C_p is the specific heat of air at constant pressure, C_H is the Stanton number (non-dimensional bulk aerodynamic coefficient for heat

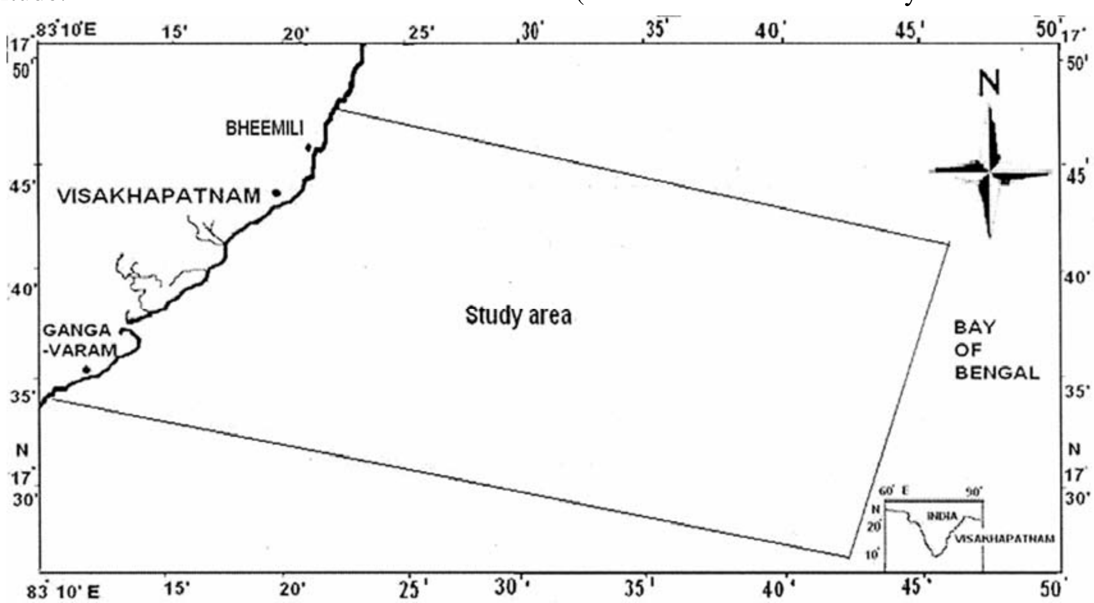

Fig. 1—Study area

Table 1—Dates of data collection in the coastal waters of Visakhapatnam

	Period	Details of data collection	Vessel
Phase – I	19-20 Oct. 2006	Bucket SST, Dry bulb and Wet bulb Temperatures, Wind Speed.	Boat
Phase – II	14-17 Jan. 2007	Short wave radiation, Long wave radiation, Bucket SST, Dry bulb and Wet bulb Temperatures, Wind Speed.	CRV Sagar Sukti
Phase – III	21-26 Jan. 2007	Short wave radiation, Long wave radiation, Bucket SST, Dry bulb and Wet bulb Temperatures, Wind Speed.	CRV Sagar Sukti
Phase – IV	31st Jan. to 5th Feb. 007	Short wave radiation, Long wave radiation, Bucket SST, Dry bulb and Wet bulb Temperatures, Wind Speed.	CRV Sagar Sukti
Phase – V	23-25 Feb. 2007	Bucket SST, Dry bulb and Wet bulb Temperatures, Wind Speed.	Boat

transfer), C_E is the bulk transfer coefficient of Latent heat flux (1.3×10^{-3}), L is the Latent heat of vaporization (2.5×10^6J/Kg/°C), e_s and e_a are saturation vapor pressure and atmospheric vapor pressure at the standard level respectively, C_D is the drag coefficient, Ta is the air temperature (°C), Ts is the sea surface temperature (°C), U is the wind speed (m/sec).

To determine the air-sea fluxes we have used exchange coefficients for heat and momentum (i.e., C_D, C_H and C_E) that have a simple polynomial dependence on wind speed and linear dependence on the air-sea temperature difference[10]. A quadratic or higher order dependence on wind speed is necessary because a drag coefficient with a linear dependence on wind speed has been shown to be inadequate[11]. Bowen ratio (B) ($=Q_{SH}/Q_{LH}$) has been estimated and developed a formula to compute 'B' using (Ts – Ta), following Hsu[12,13] for unstable conditions.

Results and Discussions

Diurnal variability of wind stress and heat fluxes

The diurnal variability of wind speed (U), sea surface temperature (SST), wind stress(τ) and the heat budget parameters named as Short wave radiation (Q_{SW}), Net long wave radiation (Q_{NLW}), Sensible heat flux (Q_{SH}), latent heat flux (Q_{LH}), enthalpy ($Q_{LH}+Q_{SH}$) Net heat flux (Q_N) have been presented in the Figures 2 to 7.

Table 2 shows the mean surface meteorological parameters, vapour pressure gradient (e_s - e_a) and air-sea temperature difference (Ts-Ta). Dry bulb temperature (Ta) was maximum (29.7 °C) in Oct.2006 and a secondary maximum was observed in Feb.2007. Sea surface temperature during phase I appear to be maximum and is close to the value reported earlier[4]. The wind speed (U) varied between 1.5 – 3.5 m/sec. The average values of the all parameters during these periods are in good agreement with mean monthly values reported earlier[4].

During phase I, the wind speed is found to be maximum in the morning of 20th October having an intensity of 5 m/sec and minimum (0.3 m/sec) is observed at the mid night (Fig. 2a). The Sea Surface Temperature (SST) reaches maximum value of 31°C and it is fairly constant during the entire diurnal cycle with a variation of ≈0.8°C (Fig. 2b). The net long wave radiation (Q_{NLW}) gradually decreased by after noon (1400 hrs) on 19th October and reaches to its minimum value of 25 W/m^2 and there after it gradually increased. A sudden rise in net long wave radiation is observed from 0700 hrs on 20th Oct. (Fig. 2c). The wind stress (τ) and enthalpy ($Q_{SH}+Q_{LH}$) are shown in Fig. 2d. A good correlation exists between the wind stress and enthalpy. The maximum enthalpy observed (≈225 W/m^2) at 0700 hrs on 20th October, which may be due to the maximum wind speed prevailing at that time. The wind stress reaches the maximum value of ≈0.045 N/m^2 at 0700 hrs on 20th October.

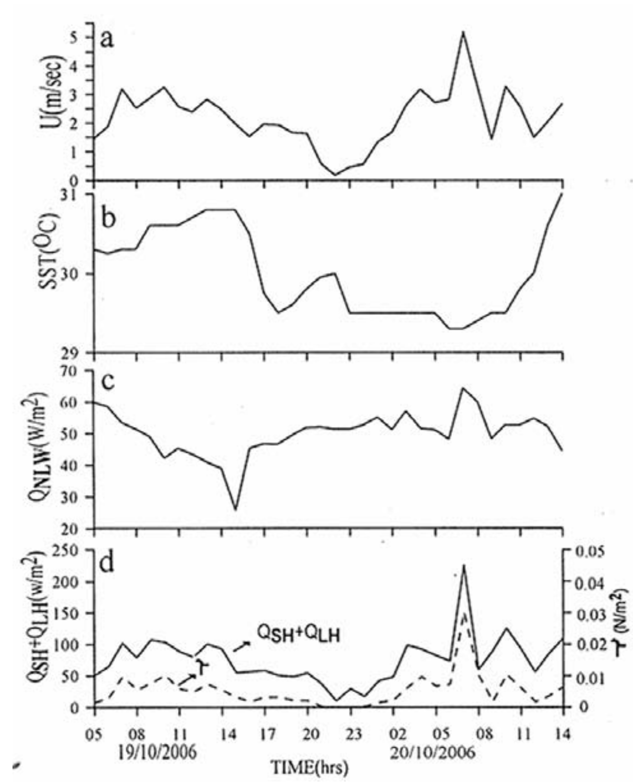

Fig. 2—Diurnal variability of (a) wind speed (m/sec); (b) sea surface temperature (°C); (c) Net long wave radiation (Q_{NLW}, W/m^2); (d) enthalpy ($Q_{SH}+Q_{LH}$, W/m^2) & wind stress (τ, N/m^2) during Phase – I (19th-20th Oct. 2006), (Post-monsoon Season)

Table 2—Mean meteorological parameters during different periods

Phase	period	Ta (°C)	Tw (°C)	Ts (°C)	U (m/sec)	e_s-e_a (mb)	Ts-Ta (°C)	τ (N/m^2)
I	19-20 Oct.2006	29.7	26.0	29.9	2.2	11.20	0.2	0.004
II	14-17 Jan.2007	25.3	22.4	26.7	2.6	09.70	1.4	0.007
III	21-26 Jan.2007	25.9	23.2	27.1	2.8	09.13	1.2	0.009
IV	30-05 Feb.2007	25.7	22.6	26.8	3.1	09.80	1.1	0.013
V	23-25 Feb.2007	27.0	22.3	27.4	1.6	12.73	0.4	0.002

Ta=Dry bulb temperature; Tw=Wet bulb temperature; Ts=Sea surface temperature; U=Wind speed, e_s-e_a=Vapour pressure gradient; Ts-Ta=sea-air temperature difference; τ = Wind stress.

During phase II, the maximum intensity of wind speed is observed (6m/sec) from 1000 to 1500 hrs on 16th January and minimum value is observed (≈0.2 m/sec) from 0000 to 0900 hrs on 15th January (Fig.3a). The sea surface temperature reached the primary maximum of 28.5°C and secondary maximum (28°C) is observed on 15th January (Fig. 3b) which is less than that observed in phase I. Generally the maximum values of sea surface temperatures are observed during day time due to the solar heating. We notice that wind speeds also affect the sea surface temperature through mixing which is quite obvious (Figs. 3a & b). The value of short wave radiation reached maximum (≈770W/m^2) during noon time. The maximum values of net long wave radiation are observed during the night times (Fig. 3c). In this phase, a similar trend is also observed in the enthalpy and wind stress (Fig.3d). They are found to be highly fluctuating on a diurnal scale with higher values at 1800 hrs on 14th and 15th January and at 1100 hrs and 0200 hrs on the remaining days. It is mainly due to the increase in wind speeds on these days and a general lag in the heat loss is observed.

During phase III, the wind speeds are higher than the previous two phases (Fig. 2a, 3a and 4a) reaching 9 m/sec. On 25th January, winds are very much high (8.7 m/sec) around 2000 hrs and decreases on the following day (Fig. 4a). Wind speed reached zero at 0600 to 1000 hrs on 23rd Jan. The SST shows maximum values around 1200 hrs in all the days and minimum values in the early hours of the day (Fig. 4b). In this phase the short wave radiation shows the maximum value of 827 W/m^2 around 1200 hrs on 26th January. Q_{NLW} is minimum around 0700 hrs on 24th Jan. which may be due to the decrease in SST (Fig. 4c). Maximum enthalpy (>250 W/m^2) and windstress (>0.1 N/m^2) was observed during phase III (Fig. 4d). Wind is observed to be higher in these days, as the maximum intensity of wind speed is 8 m/sec on 4th and 5th Jnauary (Fig. 5a). Maximum SST (28°C) is recorded at 1200 hrs on 2nd Feb. and minimum (25.8°C) at 0200 hrs on the same day (Fig. 5b). Q_{NLW} mostly varied between 10 to 250W/m^2 (Fig. 5c). The strong winds resulting in hgh enthalpy and wind stress (Fig. 5d).

Winds are moderate at 1900 hrs on 23rd Feb. and then decreases to a minimum 0300 hrs on 24th February. The wind speeds are showing a gradual increase with maximum on 4th and 5th February and minimum on 15th, 26th January and 2nd February (Fig. 6a). During phase V, the SST is showing similar trends as in phase IV (Fig. 6b). The net long wave radiation observed to be maximum at 1900 hrs on 23rd February (Fig. 6c). The enthalpy and wind stress follow the same trend observed in the wind spped.

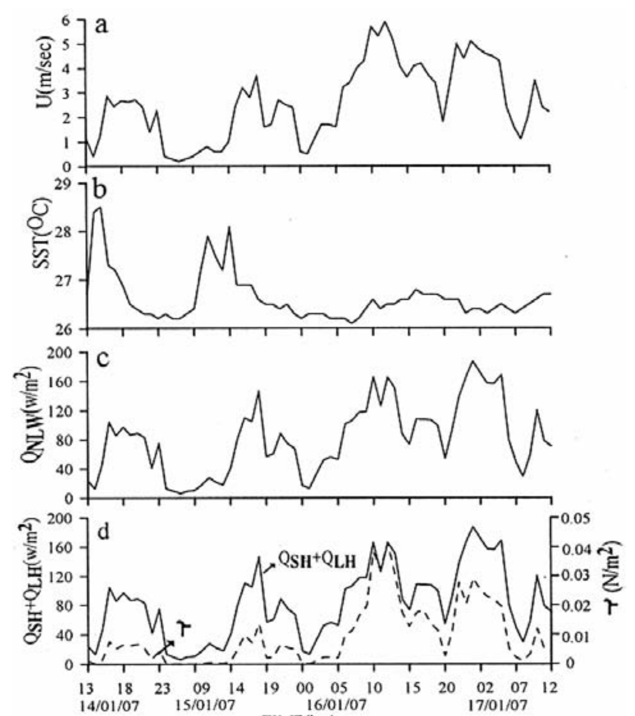

Fig. 3—Same as Fig.2 but during Phase-II (14/01/07 to 17/01/2007) (Winter Season)

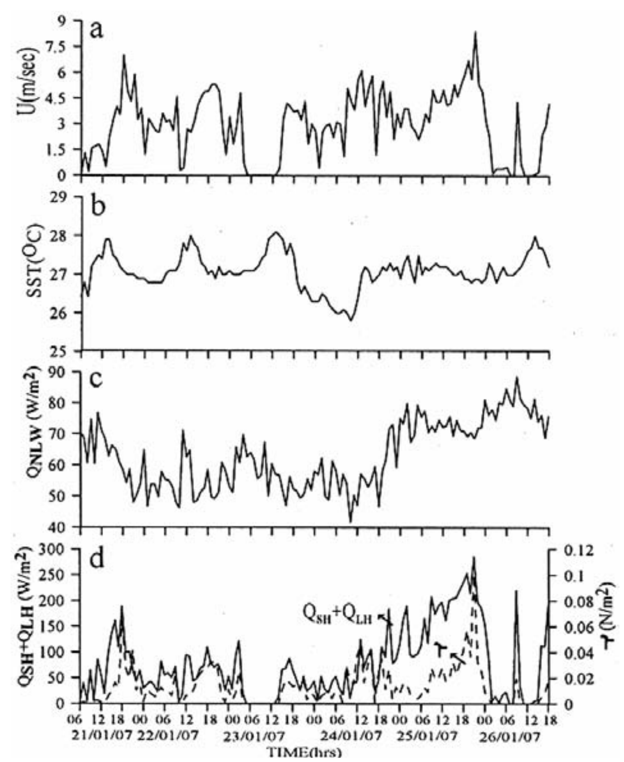

Fig. 4—Same as Fig.3 but during Phase-III (21/01/07 to 26/01/2007), (Winter Season)

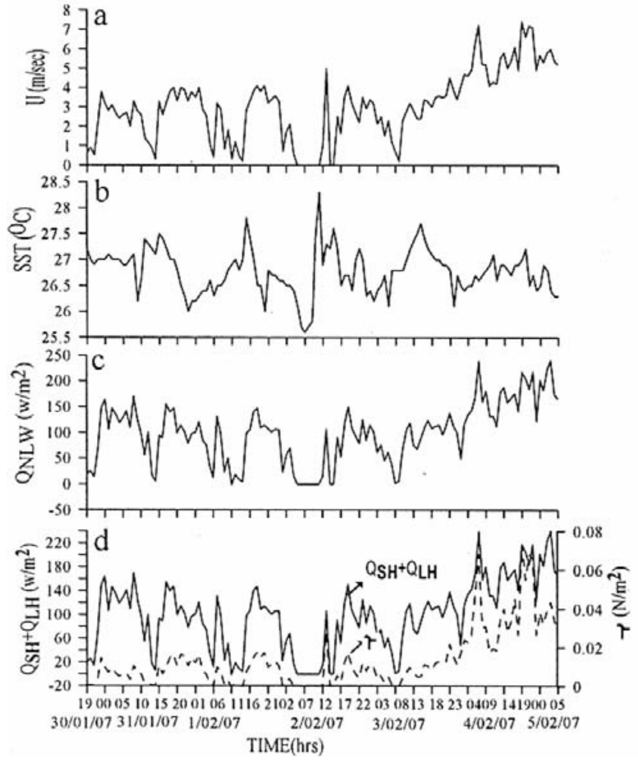

Fig. 5—Same as Fig.4 but during Phase-IV (30/01/07 to 05/02/2007) (Winter Season)

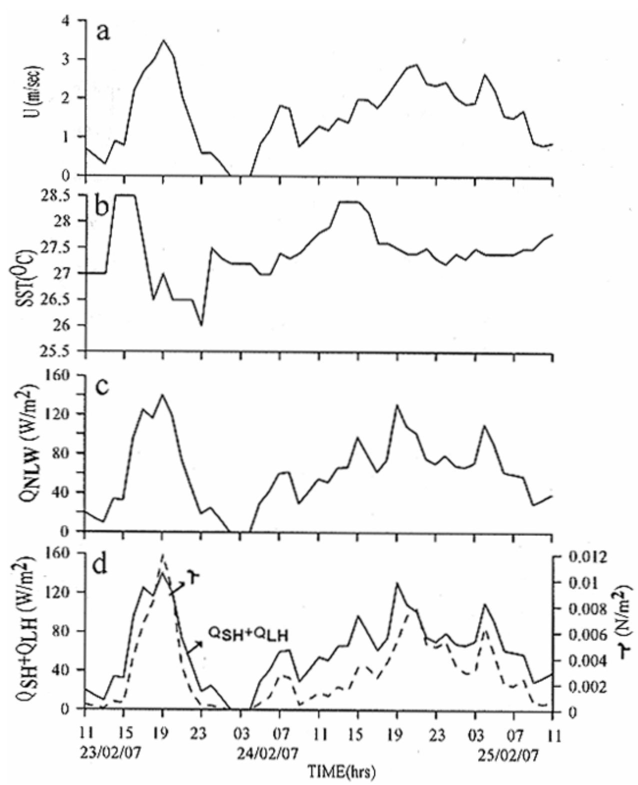

Fig. 6—Same as Fig.5 but during Phase- V (23/02/07 to 25/02/2007) (Winter Season)

Which is quite obvious. The enthalpy is more at 1900 hrs on 23rd Feb. due to the maximum wind sppeds at that time (Fig. 6d

Seasonal variability of net heat exchange

Tables 3 & 4 show the mean heat budget parameters during post monsoon and winter seasons. The net insolation (Q_{SW}) varied between 230–265 W/m^2 while the net long wave radiation (Q_{NLW}) ranged between 50–68 W/m^2. The latent heat flux (Q_{LH}) varied between 60–99 W/m^2. The total enthalpy varied from 62–104 W/m^2 in the study area. The net heat exchange (Q_N) varied between 69–138 W/m^2 (Table. 3). Average values of Q_{SH}, Q_{LH}, enthalpy and Q_N during post monsoon and winter seasons are well comparable with those reported by Sadhuram *et al.*[4] (Table 4).

Daily mean values of wind speed, wind stress, net heat exchange from the sea (Q_N) along with the enthalpy for all cruises has been presented in Fig. 7 a & b. It is observed that both these parameters are inversely related to each other. The Q_N has primary maximum (149 W/m^2) on 19th October with a secondary maximum (140 W/m^2) on 24th February. Negative value (~-19 W/m^2) was observed on 25th January and on 5th February. On cool winter days the heat loss from the sea is more and hence one can expect more heat loss in the months of January and February (Fig. 7b). It is also noticed that net heat flux decreased drastically to negative values on 25th January and 5th February (Fig. 7b). This was due to the enhanced heat loss because of the strong winds noticed on those days.

Relationship between Bowen Ratio (B) and sea– air temperature difference (Ts - Ta)

Hsu[12] proposed a relationship $B = a\,(Ts - Ta)^b$ for unstable conditions, where ‘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. Similar results were proposed for nearshore region. Hsu[13] reported another equation, $B = 0.146\,(Ts\text{-}Ta)^{0.49}$ which is useful for tropical ocean and cold air out break conditions. Sadhuram *et al.*[14] tested this relationship for North Indian Ocean and proposed a new equation, $B = 0.094\,(Ts\text{-}Ta)^{0.80}$.

Here, we have tested the relationship over the coastal waters, which has not been studied earlier. The values of B varied from 0.017 to 0.136 while

Table 3—Mean heat budget parameters under different phases (I –V)

Phase	Qsw (W/m^2)	Q_{NLW} (W/m^2)	Q_{LH} (W/m^2)	Q_{SH} (W/m^2)	$Q_{SH}+Q_{LH}$ (W/m^2)	Q_N (W/m^2)
I	262	50.5	73.3	0.6	073.9	137.5
II	223	67.4	76.0	5.6	081.6	073.6
III	230	63.6	70.4	5.4	075.8	090.2
IV	239	65.4	99.0	5.3	104.3	069.5
V	265	66.1	60.8	0.9	061.7	137.2

Qsw = Insolation at sea surface; Q_{NLW} = Net Long wave radiation; Q_{LH} = Latent heat flux; Q_{SH} = Sensible heat flux; $Q_{SH}+Q_{LH}$ =enthalpy; Q_N = Net heat exchange

Table 4—Mean heat budget parameters during post monsoon (Phase I) and winter seasons (Phase II - V)

Season	Q_{LH} (W/m^2)		Q_{SH} (W/m^2)		$Q_{SH}+Q_{LH}$ (W/m^2)		Q_N (W/m^2)	
	a	b	a	b	a	b	a	b
Post monsoon	73	82	0.6	0.6	73.6	82.6	137	135
Winter season	77	71	4.0	3.0	81.0	74.0	0.92	106

a – Present study, b – Sadhuram et al (1995)

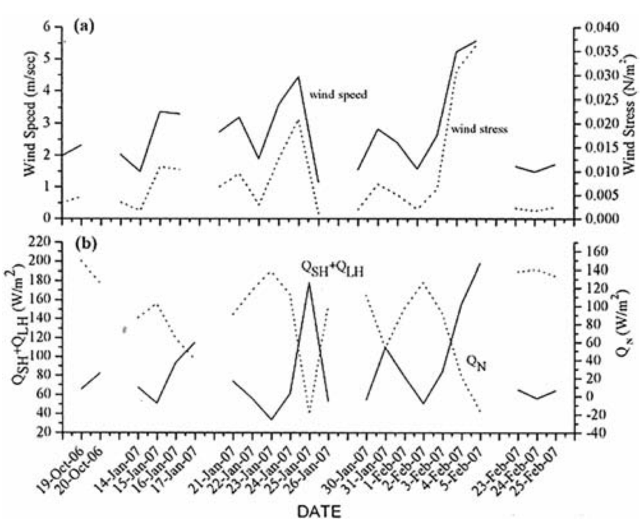

Fig. 7—Daily mean variability of: (a) wind speed (m/sec) and wind stress (τ, N/m^2); (b) Net heat flux (Q_N, W/m^2) and enthalpy ($Q_{SH}+Q_{LH}$, W/m^2)

(Ts-Ta) varied from 0.3 to 2.2°C Table 5. The correlation between B and (Ts - Ta) is found to be very high ($r = 0.82$; $N = 20$; significant at > 99% level) (Fig.8). The corresponding equation is shown below.

$$B = 0.057\,(Ts - Ta)^{0.89} \qquad (6)$$

High correlation ($r = 0.87$; $N=20$; Significant >99% level) is found between the values of Q_{LH} estimated from Eq. 5 and obtained from the above relationship (Eq. 6) (Fig.9). This has to be tested with more data sets. However, it is useful to compute Q_{LH} in the absence of dew point temperature which is normally not available from buoys.

Table 5—Daily mean values of latent heat flux (Q_{LH}), sensible heat flux (Q_{SH}), the difference between the sea surface temperature (Ts) and air temperature (Ta), and the Bowen ratio (B)

Date	Q_{LH}	Q_{SH}	Ts-Ta	B
20-Oct-06	80.966	1.415	0.3	0.017
14-Jan-07	64.408	3.387	1.2	0.052
15-Jan-07	47.836	2.959	1.3	0.062
16-Jan-07	86.128	7.034	1.4	0.082
17-Jan-07	105.723	9.033	1.6	0.085
21-Jan-07	70.718	3.230	0.8	0.046
22-Jan-07	51.479	4.552	0.9	0.088
23-Jan-07	30.492	3.128	0.9	0.102
24-Jan-07	54.908	5.992	1.1	0.109
25-Jan-07	166.218	12.070	1.7	0.072
26-Jan-07	48.828	3.773	1.8	0.077
30-Jan-07	48.015	6.530	1.9	0.136
31-Jan-07	99.176	10.529	2.2	0.106
1-Feb-07	75.882	2.852	0.5	0.037
2-Feb-07	49.312	1.181	0.5	0.024
3-Feb-07	80.560	3.471	0.8	0.043
4-Feb-07	148.167	7.071	0.7	0.048
5-Feb-07	191.970	5.733	0.6	0.030
24-Feb-07	54.188	1.657	1.0	0.031
25-Feb-07	60.462	3.616	1.2	0.060

In this study the variability of heat fluxes (diurnal/daily/seasonal) in the coastal waters off Visak hapatnam has been examined utilizing the data collected onboard CRV Sagar Sukti and mechanized boats, under post monsoon (Oct, 2006) and winter (Jan-Feb, 2007) seasons. Total enthalpy ($Q_{LH}+Q_{SH}$) was found to be 50-200W/m^2 during post monsoon; 10-200W/m^2 during winter season, on diurnal scale. Net heat exchange (Q_N) varied between 137W/m^2

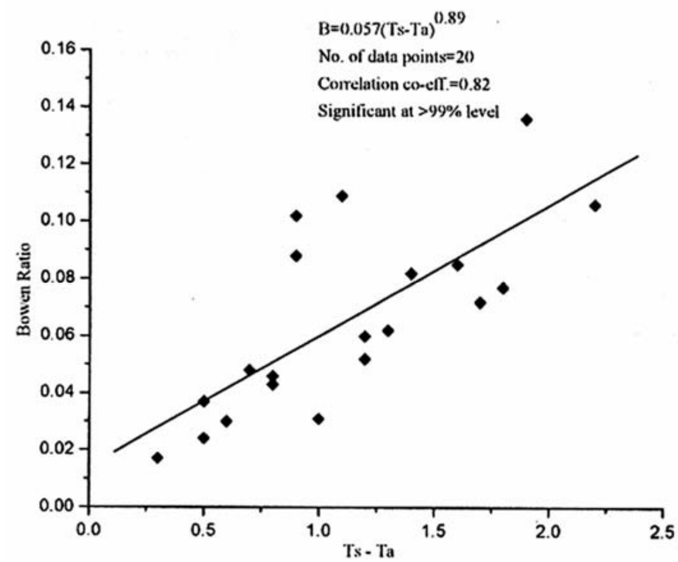

Fig. 8—Scatter plot between Bowen ratio (B) and sea-air temperature difference (Ts-Ta) under unstable conditions

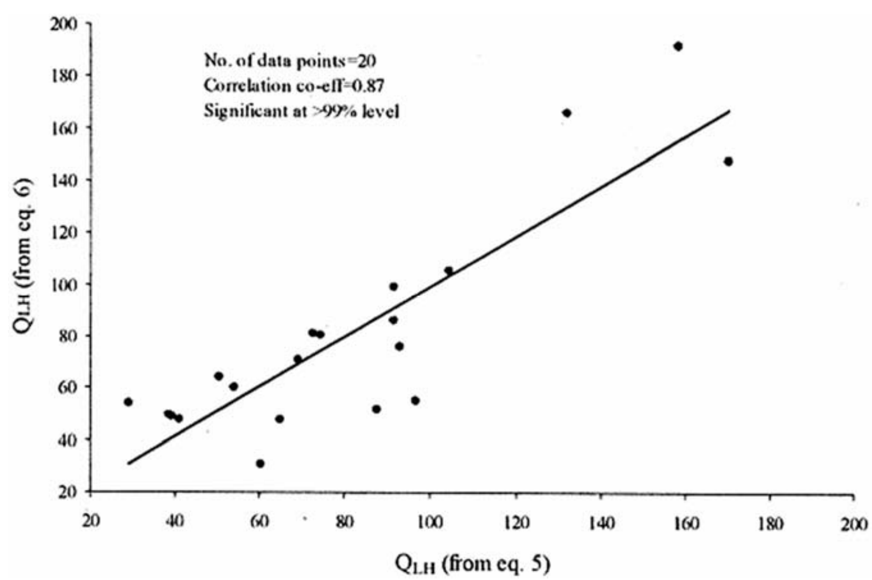

Fig. 9—Scatter plot between the computed (from eq. 5) and estimated values of Q_{LH} from the present method (eq. 6)

and 92W/m^2 from post monsoon to winter season. A simple relationship between Bowen ratio (B) and sea-air temperature difference (Ts-Ta) has been developed for unstable conditions which is useful to estimates Q_{LH} in the absence of dew point temperature.

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References

1 Sarma Y V B, Seetaramayya P, Murthy V S N, and Rao D P, Influence of the monsoon trough on air–sea interaction in the head of the Bay of Bengal during the southwest monsoon of 1990 (MONsoon Trough Boundary Layer EXperiment-90). *Bound.-Layer Meteor*, 82, (1997) 517–526.

2 Bhat G S, Ameenulla S, Venkataramana M & Sengupta K, Atmospheric boundary layer characteristics during the BOBMEX-Pilot experiment. *Proc. Indian Acad. Sci.* (*Earth Planet. Sci.*), 109, (2000) 229–237.

3 Sadhuram Y, Prabhakara Rao B, Rao D P, Subba Rao V & Rao T V N, Diurnal variability of heat fluxes and heat content at a few locations off central east coast of India during April 1989. *Mausam*, 43, 2, (1992) 147-150.

4 Sadhuram Y, Prabhakara Rao B, Rao D P & Subba Rao V, Spatial and temporal variability of the heat budget parameters

and currents in the coastal waters of Visakhapatnam, east coast of India. *Indian J. of Mar. Sci.*, (1995) 82-86.

5 Lin I I, Chen C H, Pun I F, Liu W T & Wu C C, Warm ocean anomaly, sir-sea fluxes and the rapid intensification of tropical cyclone Nargis (2008). *Geophys. Res. Lett.,* 36 (2009), LO3817.doi:10.1029/2008GLO35815.

6 Seckel G R & Beaudry F H, The radiation from the Sun and sky over the North Pacific Ocean. (Abstract); *Trans. Amer. Geophy. Union*, 54, (1973) 1114.

7 Payne R E, Albedo of the Surface.*J.Atmos. Sci.,* 29 (1972) 959-970.

8 Anderson E R, Energy budget studies, water-loss Investigations: Lake Hefner studies*, U.S. Geol. Surv. CIRC*., 229, (1952) 71-88.

9 DeCosmo J, Katsaros K B, Smith S D, Anderson R J, Oost W A, Bumke K & Chadwick H M, Air-sea exchange of water vapor and sensible heat: The Humidity Exchange Over the Sea (HEXOS) results. *J. Geophys. Res.*, 101, (1996)12,001-12, 016.

10 Kara A B, Rochford P A & Hurlburt H E, Mixed layer depth variability and barrier layer formation over the North Pacific Ocean, *J. Geophys. Res.,* 105, (2000) 16783–16801.

11 Blake R A, The dependence of wind stress on wave height and wind speed. *J. Geophys. Res.,* 96, (1991) 20531-20545.

12 Hsu S A, A relationship between the Bowen ratio and sea-air temperature difference under unstable conditions at sea, *J. Phys. Oceanogr*., 28, (1998) 2222-2226.

13 Hsu S A, On the estimation of over water Bowen ratio from sea-air temperature difference, *J. Phys. Oceanogr*, 29, (1999) 1372–1373.

14 Sadhuram Y, Ramana Murthy T V, Sarma Y V B & Murthy V S N, Comments on “On the Estimation of over water Bowen Ratio from sea-air Temperature difference”. *J. Phys. Oceanogr*., 31, (2001) 1933-1934.