SHORT-TERM VARIABILITY OF SURFACE HEAT BUDGET 
OF THE EAST CENTRAL ARABIAN SEA 
DURING NOVEMBER, 1992

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ABSTRACT

The analysis of surface meteorological data collected from the east central Arabian Sea during 10-28 November, 1992 revealed considerable variability in the meteorological parameters and heat budget components on both daily and diurnal time scales. The variation of sea surface temperature was well correlated with the variation of net surface heat gain on daily time scale. The overall net surface heat gain and evaporation rate were about 75 W m⁻² and 0.4 cm day⁻¹ respectively. On the diurnal scale, among all the parameters only the latent heat flux or evaporation showed variation with maxima during morning and late night hours and minimum around local noon. This diurnal variation of latent heat flux was resulted from the diurnal variation of wind stress.

Key-words: Air-sea interaction, surface heat budget, east central Arabian Sea.

INTRODUCTION

Studies on the air-sea interaction processes of the Arabian Sea on various time scales (diurnal, synoptic, seasonal, intra-seasonal, annual, inter-annual) are important for understanding the heat balance of the Arabian Sea which is subjected to the forcing of the semi-annually reversing wind systems (monsoons) with transitions of calm and variable winds in between. Rao and Rao (1985), Vinayachandran, Sadhuram and Ramesh Babu (1989), Zelen'ko and Resnyanskiij (1990) have studied the heat budget of the Arabian Sea for different seasons. Based on the climatological data Hastenrath and Lamb (1979) have presented the monthly variation of heat budget components for the Indian Ocean. Rao and Rao (1985) have presented the diurnal variability of the meteorological parameters and heat budget components off the west coast of India during onset phase of summer monsoon season. Rao, Sundararamam and Santa Devi (1981) and Harcesshukumar, Pradeep Kumar, Mathew and Joseph (1990) have studied the surface heat budget at selected locations in the Arabian Sea on shorter time scales. However, studies on shorter time scales particularly during early winter season under light wind conditions are not reported for the east central Arabian Sea. As a part of the on-going project 'Sea truth data collection for National
Ocean Remote Sensing Programme, we participated in a geophysical survey on board ORV Sagar Kanya (cruise no. 79) in the east central Arabian Sea during 10-28 November, 1992 and collected the surface marine meteorological data at regular intervals of three hours. The present study is aimed at understanding the short term variability (intra-diurnal) of the surface meteorological parameters and estimated heat budget components over the east central Arabian Sea under light wind conditions.

MATERIAL AND METHODS

While the ORV Sagar Kanya was on her way along the cruise track (Fig. 1) the surface meteorological data (total 135 observations) such as sea surface temperature (SST), air temperature (dry bulb and wet bulb), wind speed and direction, atmospheric pressure and visually observed cloud amount were collected regularly at three hourly intervals over the east central Arabian Sea during 10-28 November, 1992. The SST was measured with a bucket thermometer while the air temperature was obtained at 10 m height above the sea surface using a whirling psychrometer. The wind speed and direction were recorded at 10 m height with portable anemometer and wind vane system (make: Dynalab, India) and necessary corrections were applied to obtain the true wind field following the standard procedure (Anonymous, 1969).

![Cruise track of ORV Sagar Kanya (Cruise No. 79) and distribution of sea surface temperature.](image)

The heat budget components such as the net longwave radiation ($Q_B$), latent heat flux ($Q_E$), sensible heat flux ($Q_H$) and evaporation ($E$) were computed for
each set of meteorological observations following the standard bulk aerodynamic formulae (Stevenson, 1982)

The magnitude of wind stress ($\tau$) at the sea surface is computed from the following equation

$$|\tau| = \rho_a C_D U_10 |U_10|$$

where $|\tau|$ is wind stress in dyne cm$^{-2}$ and $C_D$ is non-dimensional drag coefficient.

The daily averaged incoming solar radiation ($Q_i$) reaching the sea surface is estimated at the latitude of noon-time latitude of the sun (the latitude at the position of the vessel at local noon of each day) using the empirical formulae of Seckel and Beaudry (1973) and later corrected for albedo (the reflection) at sea surface (Payne, 1972) and the effect of clouds (Reed, 1977).

Since the data were obtained from a continuously moving ship at three hourly intervals, inherent spatial variations are inevitable in the observations. It can be seen from the distribution of SST (Fig.1) that its spatial variation is limited to about 1°C over the study area with relatively low temperatures in the northern region. Assuming the spatial variations of the parameters within the distance (240 nm) covered by the vessel in a day are negligible, the daily and diurnal variations of the meteorological and computed heat budget parameters are examined. From the daily averages of the heat budget components, the net heat flux ($Q_N$) at the sea surface is estimated from the following equation:

$$Q_N = Q_i - (Q_B + Q_E + Q_H)$$

The positive values of $Q_B$, $Q_E$ and $Q_H$ indicate the heat loss to the sea while the positive values of $Q_N$ indicate heat gain to the sea.

RESULTS AND DISCUSSION

The observed wind speeds in the study area varied from 0.8 to 5 m sec$^{-1}$. Using the parametrization scheme of Kondo (1975), the neutral bulk transfer coefficients are computed for different wind speed ranges (0.3 - 2.2 m sec$^{-1}$; 2.2 - 5 m sec$^{-1}$). These transfer coefficients are then corrected to atmospheric stability as outlined in Stevenson (1982). For each set of observations, the diabatic bulk transfer coefficients ($C_D$, $C_E$ and $C_H$) are computed and used in the estimation of fluxes of heat and momentum. At wind speeds less than 2.0 m sec$^{-1}$ the magnitudes of these coefficients are high ($C_D = 2.76 \times 10^{-3}$, $C_E = 2.87 \times 10^{-3}$ and $C_H = 2.72 \times 10^{-3}$) and agree well with that of Kondo (1975) at these low winds. The lowest value of the diabatic transfer coefficients ($C_D = 1.42 \times 10^{-3}$, $C_E = 1.41 \times 10^{-3}$ and $C_H = 1.33 \times 10^{-3}$) is obtained for wind speed of 2.3 m sec$^{-1}$ under stable atmospheric conditions. These values are in agreement with that of Hicks (1972) for the wind speed range between 2 and 6 m sec$^{-1}$. The mean values of $C_D$, $C_E$ and $C_H$ are $1.97 \times 10^{-3}$, $1.97 \times 10^{-3}$ and $1.86 \times 10^{-3}$ respectively. The sea surface
temperature minus air temperature difference ($T_s - T_a$) and the wet bulb depression ($\Delta T = \text{dry bulb minus wet bulb temperature}$) are presented as indicators of the atmospheric stability and the moisture conditions of the overlying air. The positive (negative) values of ($T_s - T_a$) indicate unstable (stable) conditions. Higher values of wet bulb depression indicate higher dryness (lower humidity) of the surface airmass. The cloud amount (in tenths) in the study area is in general low and varied between 1 and 4.

Fig. 2. Daily variation of noon-time latitude during 11-28 November, 1992.

Fig. 2 represents the daily variation of latitude at the local noon (noon-time latitude) during the observation period. The daily averages of the surface meteorological parameters and the heat budget components would correspond to the respective noon-time latitudes. These noon-time latitudes happened to be the extreme latitude of observation in each day from 11th to 21st (except 18th) November. From 22nd to 28th November, the observations were made along the nearly west-east transects of the cruise track within the longitudes 68.7°E - 70.7°E. This suggests that the observations can be grouped into latitudinal belt (12.5°N - 17°N) and longitudinal belt (68.7°E - 70.7°E). Since the daily change of noon-time latitude from 11th to 21st November is considerably high, the above latitudinal belt is further divided into southern zone (12.5°N - 15°N) and northern zone (15°N - 17°N) within which the change in noon-time latitude between the days is relatively less. In each of the three zones, the temporal variability of the meteorological parameters and heat budget components is discussed on daily and diurnal time scales.
Fig. 3. Daily variation of the meteorological parameters and heat budget components for (A) northern zone, (B) southern zone and (C) eastern zone.

Daily variation

Northern zone (15° - 17°N) (Fig. 3A): In this zone, the wind speeds varied between 2 and 3 m sec⁻¹. The wind stress exhibited variation 0.15 to 0.2 dyne
cm$^2$. While the SST showed a gradual decrease, the $\Delta T$ exhibited an increase. The surface air mass is highly unstable on all days except on 21st. The sensible heat flux is almost insignificant while the net longwave radiation is nearly uniform (50 W m$^{-2}$). The variation of latent heat flux follows that of $\Delta T$ and showed a gradual increase from 11th (55 W m$^{-2}$) to 21st (150 W m$^{-2}$). Correspondingly, the rate of evaporation is extremely low on 11th (0.2 cm day$^{-1}$) and high on 21st (0.6 cm day$^{-1}$). The incoming solar radiation ($Q_i$) at the sea surface varied between 200 and 240 W m$^{-2}$. The variation in the total heat loss ($Q_l$) due to latent heat flux, sensible heat flux and net longwave radiation has mainly resulted from $Q_E$ and showed a gradual increase. This has effected the net surface heat flux ($Q_N$) which is positive during all the days indicating that the ocean surface gained heat energy. However, the magnitude of net heat gain decreased from 100 W m$^{-2}$ on 11th to 10 W m$^{-2}$ on 21st. The overall net heat gain in this zone is about 66 W m$^{-2}$.

**Southern zone (12.5°-15°N) (Fig. 3B):** Here also, the pattern of the daily variation of the meteorological and heat budget parameters is similar to that of in the northern latitudinal zone. However, the magnitude of variation in each parameter except solar radiation, is comparatively smaller in the southern zone. The solar radiation at the sea surface shows a variation between 250 and 210 W m$^{-2}$. Due to the gradual increase of total heat loss ($Q_l$), the net heat flux exhibited a decrease which varied between 72 and 136 W m$^{-2}$. The mean net heat gain is about 98 W m$^{-2}$.

**Eastern Zone (68.7° - 70.7°E) (Fig. 3C):** In this zone, the wind speed, SST, ($T_s-T_a$), $\Delta T$, latent heat flux, evaporation and net surface heat flux exhibited daily variations. The evaporation is maximum on 23rd and is minimum on 25th November. The sensible heat flux is positive and low (5 W m$^{-2}$). Net longwave radiation is about 55 W m$^{-2}$. Latent heat flux varied between 80 and 140 W m$^{-2}$. The net heat gain is low (20 W m$^{-2}$) on 22-23rd and high (96 W m$^{-2}$) on 25th. The mean net heat gain is 56 W m$^{-2}$.

In all the above zones, the computed values of incoming solar radiation ($Q_i$) is found to be higher than the climatological distribution of $Q_i$ in the study area (Hastenrath and Lamb, 1979) for November. The discrepancy between these two values is due to the different methods used for $Q_i$ computations. It is further noticed that the wind speed and the specific humidity gradients have contributed together to the variation of the latent heat flux on daily time scale. In each zone the variations of net heat gain and SST are well correlated with higher (lower) net heat gain coinciding with higher (lower) SST. The distribution of SST (Fig. 1) also supports this view with higher SSTs and higher surface heat gain occurring in the southern zone.
Fig. 4. Diurnal variation of the meteorological parameters and heat budget components on (A) 21 November, (B) 20 November and (C) 23 November corresponding to the northern, southern and eastern zones.

**Diurnal variation**

On a closer examination of the daily variations of the above parameters, it is seen that the daily variation of latent heat flux or evaporation is considerable in each of the zones. This has prompted us to examine the variation of the latent heat flux and evaporation and other parameters on diurnal time scale. For this purpose, the days with minimum and maximum latent heat flux in the each of the zones are considered. However, typical diurnal variations of the parameters for those days of higher latent heat flux, i.e., 21st, 20th and 23rd November representing the northern, southern, eastern zones respectively are presented in Figs. 4A, B & C respectively. No clear signal of diurnal variation of latent heat flux
or evaporation is noticed on the days of both high and low latent heat flux in the southern zone (Fig. 4B), and on the days low latent heat flux in the northern and eastern zones. This feature is mainly due to lack of clear signal of diurnal variation in wind speed and humidity. However, on the days of higher latent heat flux a clear signal of diurnal variation of latent heat flux with two maxima and two minima is noticed in both the northern and eastern zones (Figs. 4A & 4C). In the northern zone, the maxima of $Q_e$ occurred at 00Z and 15Z hours and minima occurred at 09Z and 18Z hours. In the eastern zone, the maxima of $Q_e$ are noticed at 00Z and 09Z hours and minima at 06Z and 15Z hours.

It is interesting to notice that the variation of $Q_e$ closely follows that of wind speed. This clearly shows the strong dependency of $Q_e$ on the wind speed over the specific humidity gradients at shorter time scales. However, this feature is masked on daily time scale probably due to prevailing spatial variations both in the wind speed and specific humidity gradients in each of the three zones.

In all the three zones of the study area, the daily variations of the meteorological parameters and heat budget components together with net surface heat gain are large. The overall distribution of the parameters are comparable with those of the climatological maps (Hastenrath and Lamb, 1979) for November except for $Q_i$ and $Q_N$. The higher rate of evaporation (0.4 cm day$^{-1}$) in the northern and eastern zones points out that the winter conditions are set over the region north of 15°N of the east central Arabian Sea during the observation period.

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