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Wind stress and fluxes of sensible and latent heat over the Arabian Sea during ISMEX-1973

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ABSTRACT. During the Indo-Soviet Monsoon Experiment (ISMEX) in the year 1973, four Russian research vessels *Voeikov, Okean, Shokaliasky* and *Priliv* remained stationary at locations near 00·1°N, 49·6°E; 00·1°N, 60.0°E; 10.0°N, 60.0°E and 18·0°N, 67·0°E respectively from 28 June to 2 July 1973. Hourly surface observations were taken on board the ships during this period. From these observations hourly values of shearing stress of wind at the surface and vertical fluxes of sensible and latent heat at the air-sea interface are computed by using the bulk aerodynamic formulae. A variable drag coefficient with wind speed is used as suggested by Deacon and Webb (1962). Hourly values of the Richardson number (*Ri*) for the four locations are also computed.

It is found that the surface layers at locations near 00·1°N, 49·6°E; 10·0°N, 60·0°E and 18·0°N, 67·0°E show near neutral stability conditions. The wind stress values are comparatively smaller at the equatorial locations than those at the northern ones. A marked increase in the wind stress occurs in association with a surge in the monsoon current.

The sensible heat flux shows a well defined diurnal variation which is in close conformity with the diurnal variations of the air-sea temperature difference. Maximum positive flux occurs around mid-night or dawn hours and minimum around mid-day or afternoon hours. An actual reversal of direction of the sensible heat flux is found to occur at noon-hours particularly at the northern locations near 10·0°N, 60·0°E and 18·0°N, 67·0°E during the period of study. The latent heat flux remains positive at all times of the day and shows a relative decrease or increase with a decrease or increase in the wind speed. While the sensible heat flux shows a marked increase during disturbed weather period, the latent heat flux shows a decrease during the same period.

1. Introduction

The dynamic and thermal properties of the atmosphere and ocean are directly affected by the air-sea transfer of momentum, heat and water vapour. The transfers are nearly independent of height in the atmospheric surface layer, a layer extending from the sea surface to a height of about 50 m. This enables one to infer the fluxes at the air-sea interface from the measurements at a convenient height above the sea level.

During the Indo-Soviet Monsoon Experiment (ISMEX) in the year 1973, oceanographic and meteorological observations were made on board the Russian research vessels *Voeikov, Okean Shokaliasky* and *Priliv*. These vessels remained stationary at locations near 00·1° N, 49·6°E; 00·1°N, 60·0°E; 10·0°N, 60·0°E and 18·0°N, 67·0°E respectively from 28 June to 2 July 1973 and took hourly observations. These observations have been used to compute the shearing stress of wind at the surface and fluxes of sensible and latent heat at the interface by using the bulk aerodynamic formulae given as —

$$\tau_0 = \rho C_D U_a^2 \tag{1}$$

$$Q_s = \rho c_p C_T (\theta_0 - \theta_a) U_a \tag{2}$$

$$Q_e = \rho L C_q (q_0 - q_a) U_a \tag{3}$$

where, τ_0 is the shearing stress of wind at the surface Q_s, and Q_e are respectively the eddy vertical transports of sensible and latent heat, which are directly proportional to the differences between the potential temperatures ($\triangle\theta$) and specific humidities ($\triangle q$) measured at the surface and at a height a above the surface, usually taken as 10 m. C_D, C_T and C_q are nondimensional bulk aerodynamic coefficients and are sometimes referred to as the drag coefficient, Stanton number and Dalton number respectively. U_a is the wind speed in mps at the height a, c_p the specific heat of air at constant pressure, L the latent heat of vaporisation and ρ the air density.

Roll (1965) has discussed the derivation of the above equations and suggests that $C_D \approx C_T \approx C_q$ over the sea for near neutral condition. C_D depends upon the height of the observation of wind and

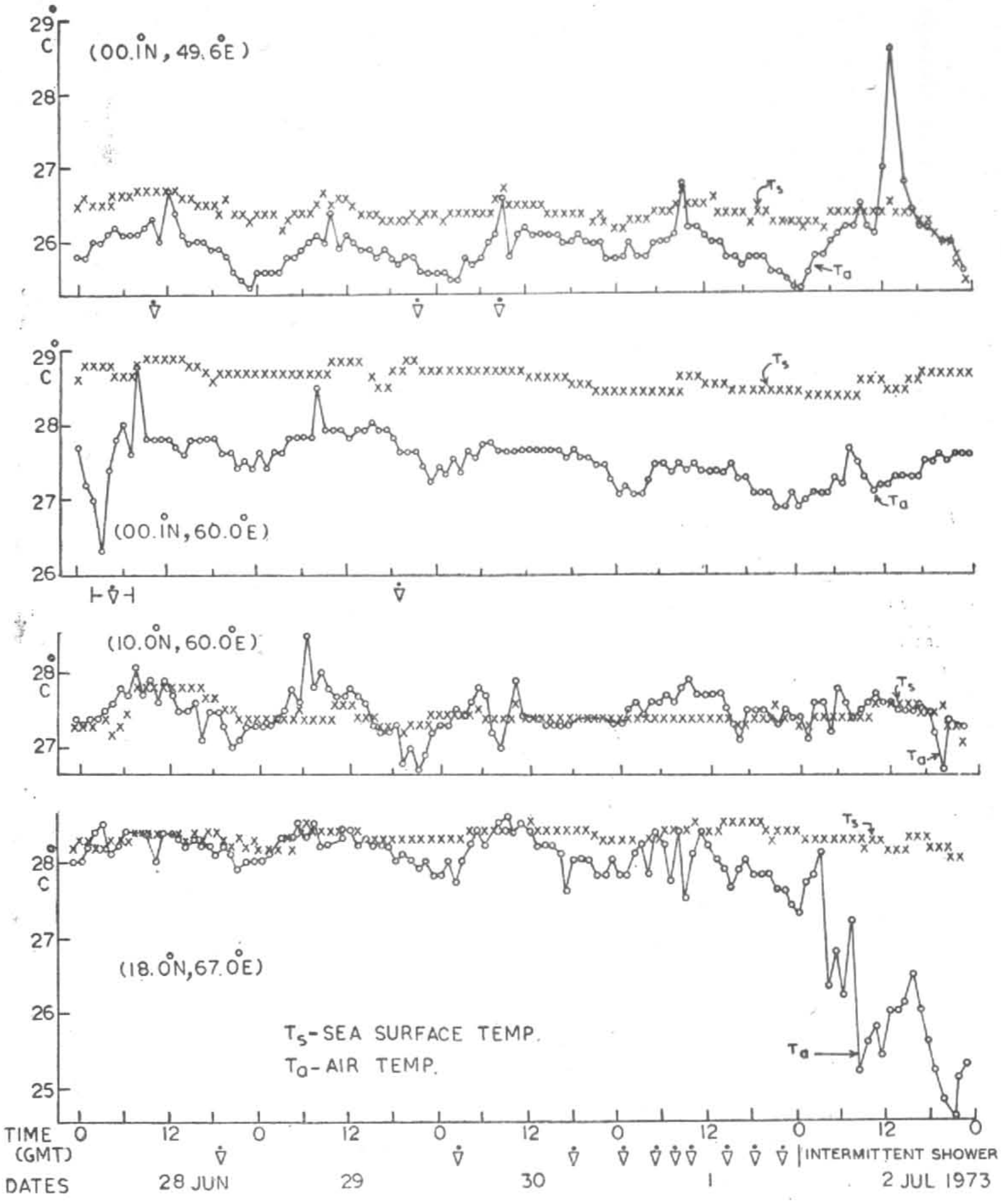

Fig. 1. Hourly observations of sea surface temperature (T_s) and air temperature (T_a) during 28 June to 2 July 1973

also upon the character of the sea surface. Several quasi-empirical and quasi-theoretical relations between the wind speed U_a and the drag coefficient, C_D have been worked out by various workers, reviews of which have been given by Wilson (1960), Hidy (1972) and Pond *et al.* (1974). It appears that C_D is about $1\cdot5\times10^{-3}$ for light winds ranging from 3 to 10 mps. Recent estimates of C_T and C_q by Hicks (1972) from eddy flux method give both equal to about $1\cdot4\times10^{-3}$ for same wind speed range. Pond *et al.* (1971) however give a rather high value of $C_T=(2\cdot7\pm0\cdot06)\times10^{-3}$ (mean ± standard deviation) and $C_q=(1\cdot23\pm0\cdot17)\times10^{-3}$ from BOMEX data for wind speeds ranging from 4 to 7 mps.

Dependence of the transfer coefficients on thermal stability and other parameters is not yet accurately known due to limited number of field experiments and range of conditions encountered. In a recent study Kondo (1975) has, however, shown that in the case of light winds, the effect of stability on transfer coefficients is large even when the air-sea temperature difference is small.

In the present study equality of the three transfer coefficients ($C_D=C_T=C_q$) has been assumed in the computations of air-sea momentum exchanges and fluxes of sensible and latent heat. This assumption is valid for near neutral conditions but may give less satisfactory results in a highly unstable or stable surface layer. The following relationship is used for the drag coefficient (Deacon and Webb 1962) which gives a linear increase in the drag coefficient with wind speed.

$$C_{10} = (1.00 + .07\times U_{10})\times10^{-3} \qquad (4)$$

Based on this formula C_D ranges between 1×10^{-3} and 2.4×10^{-3} for wind speeds ranging upto 20 mps which agrees well with others estimates (Roll 1965).

The degree to which conditions in the surface layer departed from neutral stratification at the four observing locations was assessed by computing the hourly values of the Richardson number (R_i) by using the following relation :

$$R_i = \frac{g}{T_m}\left(\frac{\triangle T}{\triangle Z} + \Gamma\right)\Big/\left(\frac{\triangle U}{\triangle Z}\right)^2 \qquad (5)$$

where, g is the acceleration due to gravity, T_m is the mean temperature (°K) between surface and the height Z (10 m) above the sea surface, $\triangle T/\triangle Z$ is the actual lapse rate of temperature in the surface layer, Γ is the dry-adiabatic lapse rate (0·98°C/100 m) and U is the wind speed **at 10** m level.

Prevailing weather conditions — From the hourly observations recorded at the four locations it is found that the weather was generally cloudy with broken skies. The low cloud amount varied from 2 to 5 okta with mainly cumulus clouds of little or moderate vertical extent (code 1 or 2). At the eastern equatorial location near 00·1° N, 60. 0° E, intermittent showers however occurred from 0300 GMT to 0600 GMT on the 28th (Fig. 1) when cumulonimbus clouds (code 3) were observed. At the central location near 10·0° N, 60.0° E no large convective activity was observed during the period of study. The sky was covered with 2-4 okta of cumulus clouds (code 1 or 2). At the northernmost location near 18·0° N, 67·0° E weather activity was nearly similar till 30th as observed at the other three locations, but an increase in the convective activity took place after 1200 GMT of 30 June. The low cloud amount increased to 4-6 okta with mainly cumulonimbus clouds (code 3 or 9). Intermittent showers, however, occurred on 2 July.

Surface winds were generally steady at all the locations. At the equatorial locations the winds blew from S to SSW. Higher speeds were observed at the western equatorial location (range 7 to 11 mps) than at the eastern one (range 3 to 10 mps). At the central location the winds were mainly from a SW direction with speeds ranging from 10 to 18 mps. At the northernmost location the winds blew from WSW to W with speeds, ranging from 5 to 13 mps. On the last day of observation, the surface wind showed a change both in direction and speed when it blew from NW with a lesser speed of about 6 mps.

2. Variation of sea surface temperature and air temperature

The sea surface temperature (T_s) shows a diurnal variation, though not very well defined, with a range of about 0·4° C (Fig. 1). The diurnal variation of air temperature (T_a) is large and has a range of about 1°C. A comparison of the two curves shows that there is a lag of 2 to 3 hours in the diurnal heating and cooling of the sea surface relative to the air. Maximum sea surface temperature occurs sometimes in the afternoon/evening hours and minimum in the midnight/early morning hours. The air temperature reaches its maximum and minimum 2 to 3 hours earlier. There is, however, a significant departure from the average picture in the disturbed weather conditions (*e.g.*, at 00·1°N, 60·0°E from 28/03 GMT to 28/06 GMT and to 18·0°N, 67·0° E after 04 GMT on 2 July), when the air temperature has shown a much wider variation than the sea surface temperature. Disturbed weather period is consistently cooler. Reduced insolation due to cloud cover, direct cooling of air by rain showers, as well as descent of cooler air from aloft, all contribute to the large cooling of the air at the interface.

No large variations in the specific humidity values both at the sea surface (q_s) and of air (q_a) are observed at the four locations during the period of study. Both T_s and q_s are larger at the eastern equatorial location near 00·1°N, 60. 0°E than at the western equatorial locations. Still larger values of both T_s and q_s are observed at the northernmost location near 18·0° N, 67·0°E.

Table 1 shows the daily average values of (T_s—T_a) and (q_s—q_a) at the four locations. It may be seen that both (T_s—T_a) and (q_s—q_a) are comparatively larger at the eastern equatorial location near 00·1°N, 60·0°E than at the other three.

Stability conditions — Hourly values of the Richardson number (R_i number) computed by

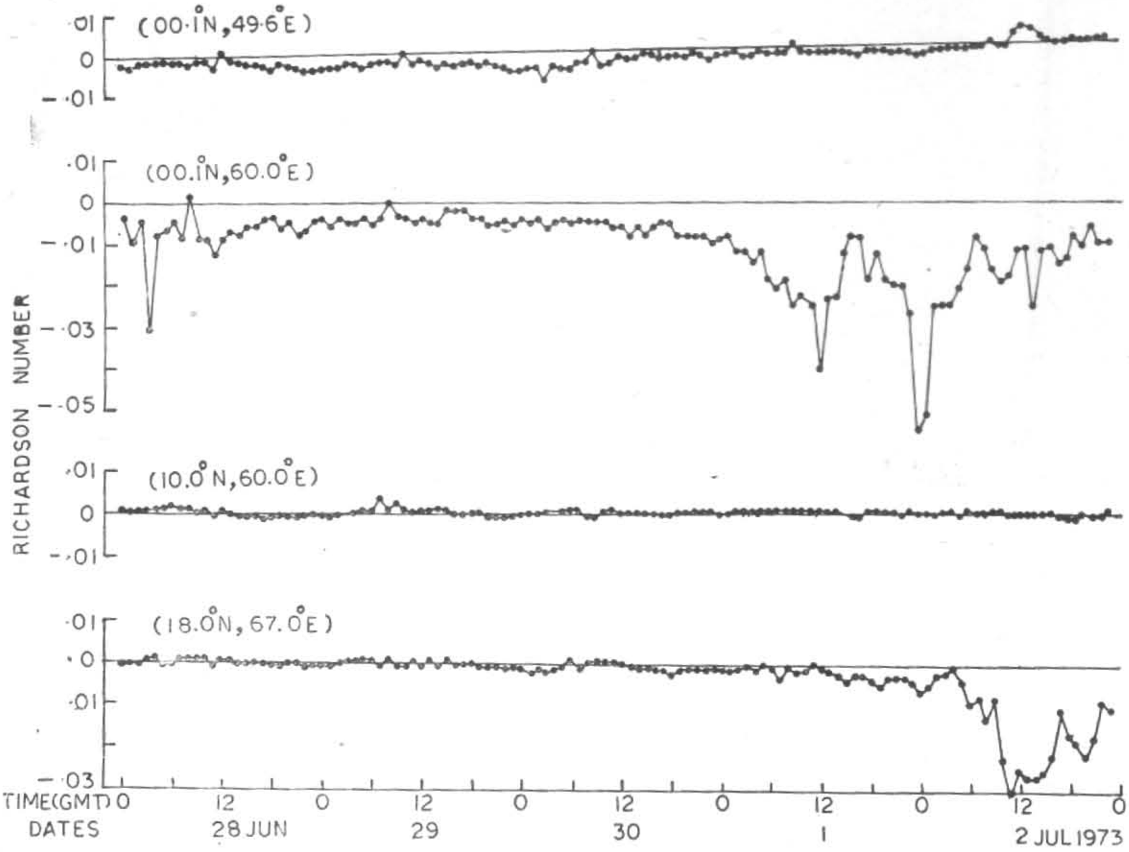

Fig. 2. Hourly values of Richardson number (Ri)

TABLE 1

Daily averages of $T_s - T_a$ (°C), $q_s - q_a$ (gm/kg), U_a (mps), τ_o (dynes/cm²), Q_s (cal/cm²/day), Q_e (cal/cm²/day) and Bowen ratio during 28 June to 2 July 1973

Date (1973)	T_s-T_a	q_s-q_a	U_a	τ_o	Q_s	Q_e	Bowen ratio	T_s-T_a	q_s-q_a	U_a	τ_o	Q_s	Q_e	Bowen ratio
Location — Near 00·1°N, 49·6°E								Location — Near 10·0° N, 60·0° E						
28 Jun	0·56	5·06	3·71	1·45	16·0	419·6	0·038	0·06	4·17	11·67	2·93	−1·7	525·9	−0·003
29 Jun	0·57	5·48	7·25	0·94	12·9	354·8	0·037	—0·07	3·72	11·63	2·93	−7·7	467·2	−0·017
30 Jun	0·49	4·52	7·25	0·95	10·4	294·4	0·037	0·01	4·13	11·25	2·68	−4·0	496·7	—0·007
1 Jul	0·47	4·86	9·21	1·68	15·0	440·9	0·033	−0·13	4·45	12·75	3·67	−12·4	467·3	−0·020
2 Jul	0·03	3·54	9·50	1·78	−1·4	335·1	—0·015	0·00	5·44	15·42	5·83	−5·9	1037·7	—0·007
Location — Near 00·1°N, 60·0°E								Location — Near 18·0°N, 67·0°E						
28 Jun	1·15	7·41	6·88	0·86	26·7	444·5	0·060	0·10	4·80	10·54	2·31	0·6	523·3	0·001
29 Jun	0·95	7·00	8·08	1·21	26·8	526·3	0·050	0·12	4·87	9·75	1·93	2·1	475·4	0·003
30 Jun	1·10	7·38	7·42	1·02	28·4	497·5	0·056	0·26	5·16	9·50	1·79	7·1	486·4	0·015
1 Jul	1·27	7·71	5·00	0·43	19·8	408·8	0·063	0·45	5·40	9·17	1·66	12·5	484·1	0·028
2 Jul	1·23	7·34	5·13	0·45	19·2	303·4	0·064	2·09	5·73	7·29	1·05	56·1	383·8	0·141

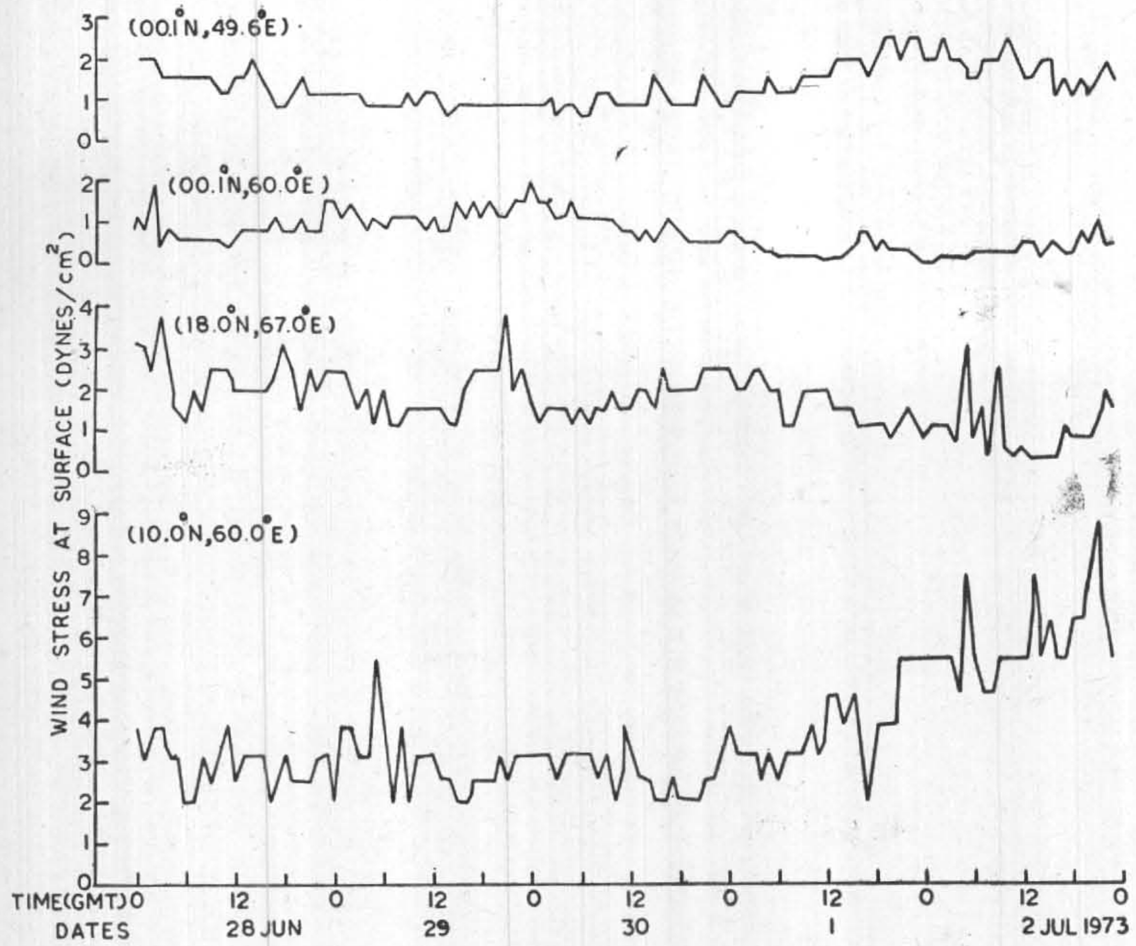

Fig. 3. Hourly values of wind stress at the surface (dynes/cm²)

using equation (5) for the four locations are shown in Fig. 2. The R_i numbers fall within a range of −0·007 and +0·004 (except in showers) at the three locations, *viz.*, 00·1°N, 49·6°E; 10·0°N, 60.0°E and 18·0°N, 67·0°E. Stability conditions prevailing at the eastern equatorial location near 00·1°N, 60·0°E appear to be different from these at the other three. At this location the R_i numbers fall within a larger range of −0·05 and +0·001. Large negative R_i numbers indicate a greater instability in the surface layer. A marked increase in the instability during the last two days of observations at this location, in the absence of any disturbed weather conditions, is mainly due to a relative decrease in the wind speed rather than a large lapse rate of temperature in the surface layer, while at the other three locations the surface winds are relatively stronger, and a comparatively large wind shear in the surface layer keeps the R_i numbers within a reasonable range. Conditions are, therefore, relatively close to neutral stratification at these locations. For this range of stability (R_i numbers lying between −0·007 and +0·004) found at these locations with the actual observed maximum range of air-sea temperature difference between +2·1 and −1·0 (except in showers), it may be inferred that the stability depends more upon wind speed rather than upon actual lapse rate of temperature. Therefore, the stronger the wind, the more closely governing conditions for using the bulk formulae are met. When the wind approaches calm and the air-sea temperature difference remains large, as is observed at the eastern equatorial location near 00·1°N, 60·0°E, the formulae are likely to give unsatisfactory results.

3. Wind stress at the surface

The wind stress values are comparatively smaller at both the equatorial locations than those at the northern ones (Fig. 3). A marked increase in the surface stress is observed at locations near 00·1°N, 49·6°E and 10·0°N, 60·0°E after 29 June. This increase in the stress may be in association with an increase in the monsoon activity after the 29th (surge in the monsoon

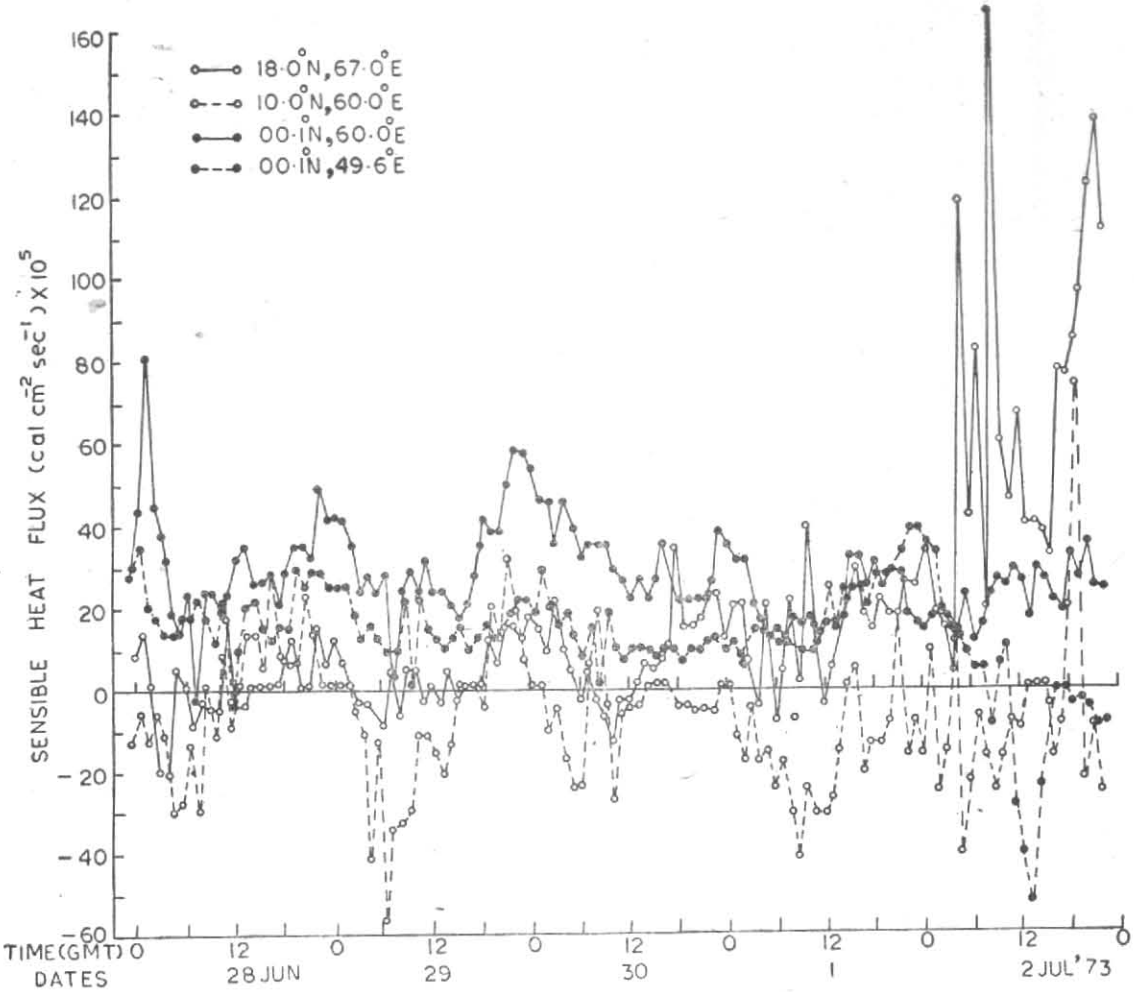

Fig. 4. Hourly values of sensible heat flux [(cal/cm²/sec) × 10⁵]

current), as was actually observed by an increase in rainfall activity along the west coast after this date. At the northernmost location (near 18·0°N, 67·0°E) a relative decrease in the wind stress values is observed after 30 June. Formation of a north-south trough off the west coast is also indicated by the northwesterly winds prevailing at this location on 2 July.

At the eastern equatorial location near 00.1°N, 60·0°E the surface stress shows a marked decrease after 30 June when a marked increase in the instability in the surface layer is observed. Since the stability has a marked effect on the stress coefficient (Derbyshire 1955), the stress values obtained at this location by using Eq. (1) are likely to be in error and may be an underestimate during this period.

4. Fluxes of sensible and latent heat

The sensible heat flux (Q_s) shows a well defined diurnal variation with maximum positive flux occurring around mid-night or dawn hours and minimum around mid-day or afternoon hours (Fig. 4). This is in close conformity with the diurnal variation of air-sea temperature difference observed at the four locations.

The flux of sensible heat has generally remained positive at the western equatorial location near 00·1°N, 49·6° E during the first four days of study and becomes negative after 1100 GMT on the last day. At the eastern equatorial location the heat flux has, however, remained positive during all the five days. At the northern locations the sensible heat flux shows nearly a sinusoidal variation with time, positive and negative fluxes occurring alternately during early morning and afternoon hours. This kind of a variation of the heat flux in the surface layer has an important bearing on the instability of the subcloud layer and the development of convective clouds. Minimum sensible heat transfer from sea to air in the afternoon hours causes minimum thermal turbulence in the surface layer and consequently there

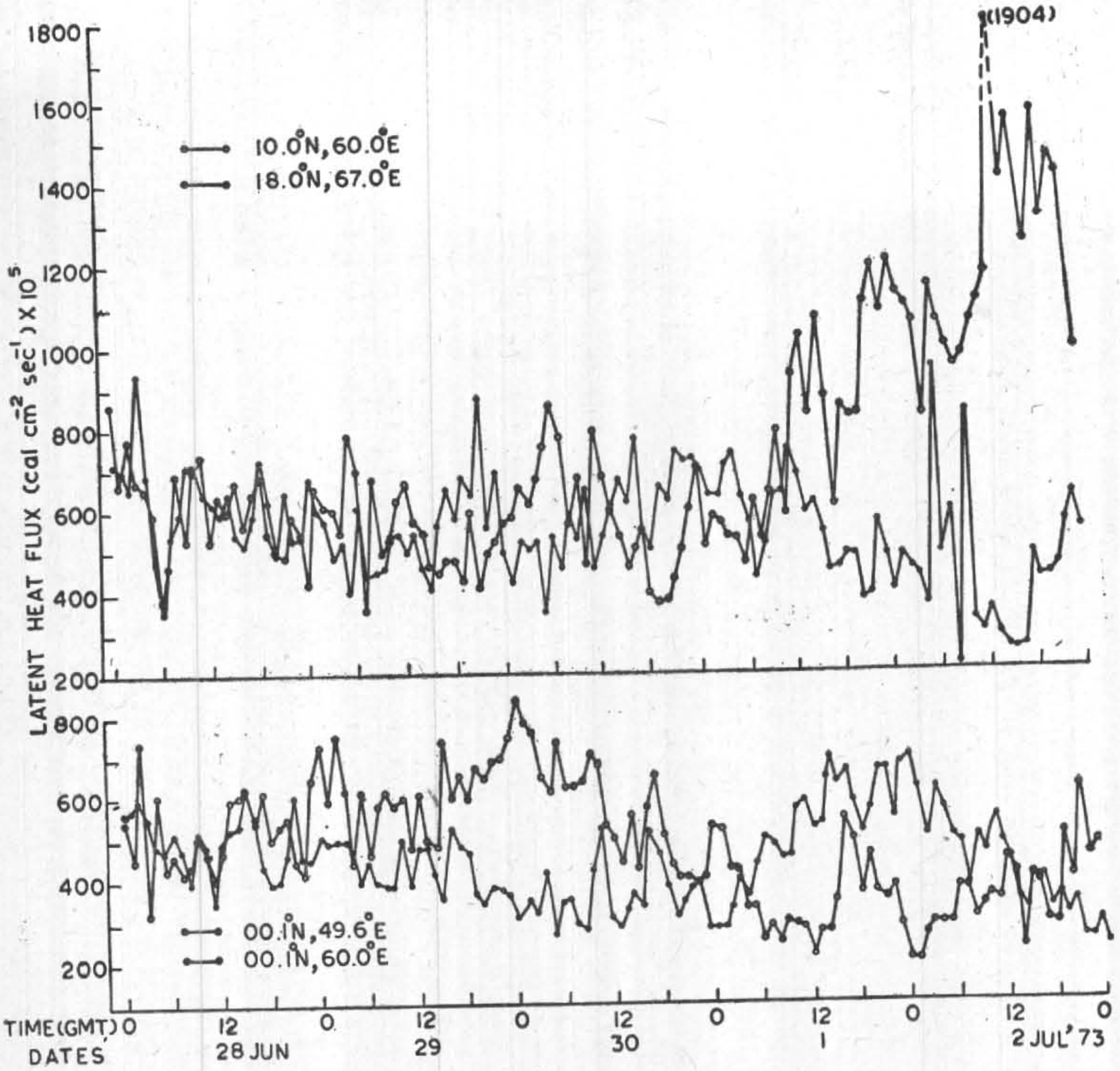

Fig. 5. Hourly values of latent heat flux (cal/cm^2/sec) $\times 10^5$

is a minimum of cloudiness observed during these hours.

A comparison of the four curves shown in Fig. 4 suggests that large Q_s values are obtained through increased air-sea temperature difference (Fig. 1) rather than the wind speed (Fig. 3). From Table 1 it may be seen that the daily average values of the heat flux are comparatively larger at the equatorial locations than those at the northern ones, where relatively lighter winds prevailed during this period but with larger air-sea temperature difference. This aspect becomes more clear when we compare the fluxes at the two locations at the equator. At the northernmost location near 18·0°N, 67·0°E, a significant increase in the sensible heat flux is observed on the last day of observations. This marked increase in the heat flux is in association with the disturbed weather condition prevailing at this location which caused a large air-sea temperature difference, although the prevailing surface winds during this period were comparatively lighter. A feature of interest observed at the central location near 10·0°N, 60·0° E is that the average heat flux comes out to be negative on all the five days. Incidentally, there has been a complete lack of convective activity at this location during this period.

The flux of latent heat Q_e is always positive at the four locations (Fig. 5) and is one order higher in magnitude than the sensible heat flux. No well defined diurnal variation is noticed in it but a relative decrease or increase in the latent heat flux is generally associated with a decrease or increase in the wind stress at the surface.

Day to day variations in average latent heat flux are not large at the equatorial locations (Table 1). At the central location near 10.0°N, 60·0° E, however, a marked increase in the heat flux is observed on the last day. This is mainly because of a significant increase in the surface wind speed on this day. At the northernmost location near 18·0° N, 67·0°E, the latent heat flux shows a decrease on the last day of observation, particularly during disturbed weather period. The flux values for this period may be an underestimate as variations in the drag coefficient with stability have not been taken account of in the the present computations. Garstang (1967) has shown that when a drag coefficient with a dependence on stability is used, then the changes in the drag coefficient produce an increase in the latent heat transfer during disturbed weather conditions even though the wind speeds and specific humidity differences are similar to those of undisturbed condition. However, from the present data set, it is difficult to use a variable drag coefficient with stability.

Estimates of the sensible and latent heat fluxes at the northern locations from the present study show a good agreement with those obtained from IIOE data for the two July months of 1963 and 1964 (Met. Atlas of the IIOE 1972). A comparatively higher values of the fluxes are, however, found at the equatorial locations in the present study.

5. Bowen ratio

Hourly values of the Bowen ratio Q_s / Q_e were computed for the four locations during the period of study. These values are found to vary from —0·305 to 0·220.

Daily average values of the Bowen ratio for these locations are given in Table 1. The averages fall within the range generally found at lower latitudes (Sverdrup 1951). At the eastern equatorial location near 00·1° N, 60·0°E, the daily averges are positive and remain nearly same on all the five days. Higher values of the Bowen ratio are found at this location than those at the western equatorial location, indicating a higher rate of sensible heat exchange at this location than that at the western one during the period of study. At the central location near 10·0°N, 60·0°E, the average Bowen ratio remains negative on all these days and is small in absolute value. At the northern location near 18·0°N, 67·0°E, the average Bowen ratio shows a progressive increase with time. Large values of the Bowen ratio are found at this location on the last day of observations, particularly in association with disturbed weather conditions.

6. Conclusion

Present study brings out the following noteworthy points :

1. Conditions are close to neutral stability in the surface layer at locations near 00·1°N, 49·6°E; 10·0°N, 60·0°E and 18°N,67·0°E. Since stability depends more upon the wind speed rather than the actual lapse rate of temperature in the surface layer, it can be inferred that prevalence of stronger surface winds over a large part of the Arabian Sea during the monsoon season would maintain a near neutral stability in the surface layer.
2. The sensible heat flux shows a well defined diurnal variation. Maximum positive flux occurs around mid-night or dawn hours and minimum around midday or afternoon hours. An actual reversal of sign in the flow of sensible heat has been observed at noon hours at the northern locations near 10·0°N, 60·0°E and 18·0°N, 67·0°E.
3. A marked increase in the sensible heat flux occurs during disturbed weather period. A decrease in the latent heat flux is, however, observed during the same period.
4. The latent heat flux remains positive at all times of the day and shows a relative decrease or increase with a decrease or increase in the wind speed.

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