Proc. Indian Acad. Sci. (Earth Planet. Sci.), Vol. 96, No. 2, September 1987, pp. 123–133

Turbulent fluxes over east-central Arabian sea during MONEX

K K VARMA and N N RAMAN
College of Fisheries, Panangad, Cochin 682 506, India

MS received 2 June 1986; revised 18 April 1987

Abstract. Fluxes of momentum, latent heat and sensible heat at fixed stations in the east-central Arabian sea during MONEX were studied. Observations at the same locations at different periods as well as simultaneous observation at different locations were compared. During the advance of monsoon, momentum flux showed remarkable increase. Latent heat loss from sea also increased while sensible heat flux, in general, changed direction to become a gain by the sea. SST decreased by about 1.5°C and air temperature decreased by about 1°C during the advance phase. A north-south difference in SST in the study region seemed to be favourable for the genesis of onset vortex of monsoon. The possible differential effect of this storm at two different locations, depending upon the SST before the storm, is also discussed.

Keywords. MONEX; turbulent fluxes; onset vortex.

1. Introduction

Air-sea interaction is one of the factors that influence monsoons. Different aspects of air-sea interaction over Indian Ocean in general and the monsoon regions in particular have earlier been studied (Colon 1964; Pisharoty 1965; Hastenrath and Lamb 1979; Reddy *et al* 1984a; Rao 1984). In the present investigation, based on MONEX data, turbulent air-sea fluxes across sea surface at fixed locations in east-central Arabian sea in pre-onset and advance phases of monsoon have been examined. The possible differential effect of onset vortex at different locations has been discussed.

2. Data and methods

The locations and periods of observation and reference numbers used for each set of observation are given in table 1 (see figure 1). Surface meteorological data collected during MONEX from these locations were utilized for computing fluxes of momentum (τ), sensible heat (Q_s) and latent heat (Q_e) using bulk aerodynamic formulae

$$\tau = \rho C_D U^2, \quad (1)$$

$$Q_s = \rho C_H C_P (T_s - T_a) U, \quad (2)$$

$$Q_e = \rho C_E L (q_s - q_a) U. \quad (3)$$

Here ρ is the density of air, C_p the specific heat at constant pressure, L the latent heat of evaporation, T_s the SST, T_a the air temperature at deck level and q_s and q_a

Table 1. Locations and periods of observations.

Name of ship	Number	Location	Period of observation	Phase of monsoon
Darshak	I	9°N 68°E	2.5.79 to 12.5.79	Pre-onset
Darshak	II	8·9°N 68°E	26.5.79 to 3.6.79	Pre-onset
Darshak	II–A	12°N 68°E	4.6.79 to 5.6.79	Pre-onset
Darshak	III	9°N 68°E	21.6.79 to 23.6.79	Advance
Deepak	IV	15°N 65°E	17.5.79 to 8.6.79	Pre-onset
Deepak	V	15°N 65°E	19.6.79 to 25.6.79	Advance

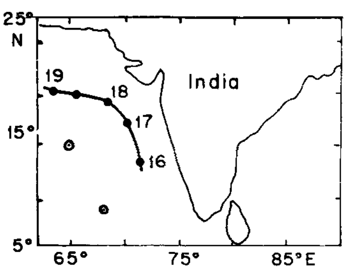

Figure 1. Station location and track of the storm showing the dates.

the specific humidities at these levels. U is the wind speed at deck level, C_D the drag coefficient and C_H and C_E the exchange coefficients for sensible heat and water vapour respectively. Fluxes computed at 6 hr intervals were used to obtain average daily fluxes.

2.1 *Exchange coefficients*

Although early studies assumed a single and constant value for C_D, C_H and C_E, subsequent investigations revealed that a single value is not adequate for computing different fluxes. Several investigators earlier indicated that C_D was not constant but increased with wind speed (Smith and Banke 1975; Garratt 1977; Smith 1980; Wu 1980; Large and Pond 1981) which agreed with the suggestion by Charnook (1955) based on theoretical considerations. C_D obtained by Smith (1980) was $(0{\cdot}61 + 0{\cdot}063\ \mathrm{U}) \times 10^{-3}$. Somewhat similar relationships were seen by Smith and Banke (1975) and Garratt (1977). Smith (1980) indicated that drag coefficient appeared to be nearly constant for winds below 10 m $\sec^{-1}$ but increased rapidly at higher wind speeds. Stability of the atmosphere also influences the air-sea flux and hence exchange coefficients. Stable stratification inhibits turbulence and decreases the flux. Under unstable conditions turbulent exchange is enhanced by buoyancy. Stability is mainly caused by vertical temperature gradient. The effect of moisture on stability is significant only in near neutral conditions of atmosphere (Launiainen 1979). Smith (1980) found a dependence of C_D on stability but a quantitative functional relationship was not obtained. Kondo (1975) plotted the exchange coefficients as a function of wind speed and air-sea temperature difference.

Various workers had suggested that $C_H = C_E$. According to most experiments this is still valid (Launiainen 1979). Pond *et al* (1974) obtained $C_H = C_E = 1{\cdot}5 \times 10^{-3}$ for normal temperature conditions and Smith (1974) got $1{\cdot}2 \times 10^{-3}$ for C_H and C_E. Hicks (1972) found both coefficients to be $1{\cdot}4 \times 10^{-3}$. C_H does not depend strongly on wind speed but depends on stability (Smith 1980). Friehe and Schmitt (1976) found that $C_E > C_H$. Exchange coefficients were reviewed by Garratt (1977), Bunker (1976), Smith (1980) and Friehe and Schmitt (1976). Extensive micrometeorological observations made using an automatic sea mast in the Gulf of Finland and various theoretical aspects of air-sea turbulent fluxes were discussed by Launiainen (1979).

Bunker (1976) presented C_D and C_E in the form of tables for different wind speeds and air-sea temperature differences and suggested that values of C_E could also be used for computation of Q_s. For studying wind stress over world oceans, Hellerman and Rosenstein (1983) developed a polynomial for C_D using the values of Bunker (1976). C_E presented by Bunker (1976) was used for latent and sensible heat computations by Rao *et al* (1978), Weare (1983) and Reddy *et al* (1984 a) using climatological data, and by Reddy *et al* (1984 b) and Anto *et al* (1982) using MONEX data. For the present study also, C_D and C_E, which varied with wind speed and air-sea temperature difference, were extracted from the tables given by Bunker (1976).

3. Results

3.1 *Observations at same locations*

3.1a *Observations at 9°N 68°E*: Observations from this location were taken on periods I, II and III. Observations made (at 12°N 68°E) between these observations are indicated as IIA (table 1).

I 2.5.1979 to 12.5.1979: During this period (figure 2) wind stress was generally low (< 0·90 dy. cm^{-2}) excepting on the last two days when it increased to about 1·5 dy. cm^{-2}. Latent heat of evaporation mostly followed the trend of τ and varied between 130 and 570 cal. cm^{-2} day^{-1}. Heat loss by sensible heat ranged between 5 and 45 cal. cm^{-2} day^{-1}. The increasing trend of fluxes was due to increase in wind speed associated with a cyclone in Bay of Bengal. SST varied between 29·8°C and 31·0°C and air temperature was always less than SST by about 1°C.

II 26.5.1979 to 3.6.1979: Calm weather prevailed during this period. Stress was about 0·60 dy. cm^{-2} on 26th May and decreased considerably on subsequent days. Latent heat was generally about 200 cal. cm^{-2} day^{-1} except on 26th when Q_e was 400 cal. cm^{-2} day^{-1}. Sensible heat loss of about 30 cal. cm^{-2} day^{-1} observed on 26th decreased on the following days. Both followed the pattern of momentum variation. SST varied between 30°C and 31°C. Air temperature was in general less than SST.

Observations for the next two days (IIA-table 1) at 12°N 68°E also showed low values of τ, Q_e and Q_s. SST was about 30·5°C and air temperature also had similar values.

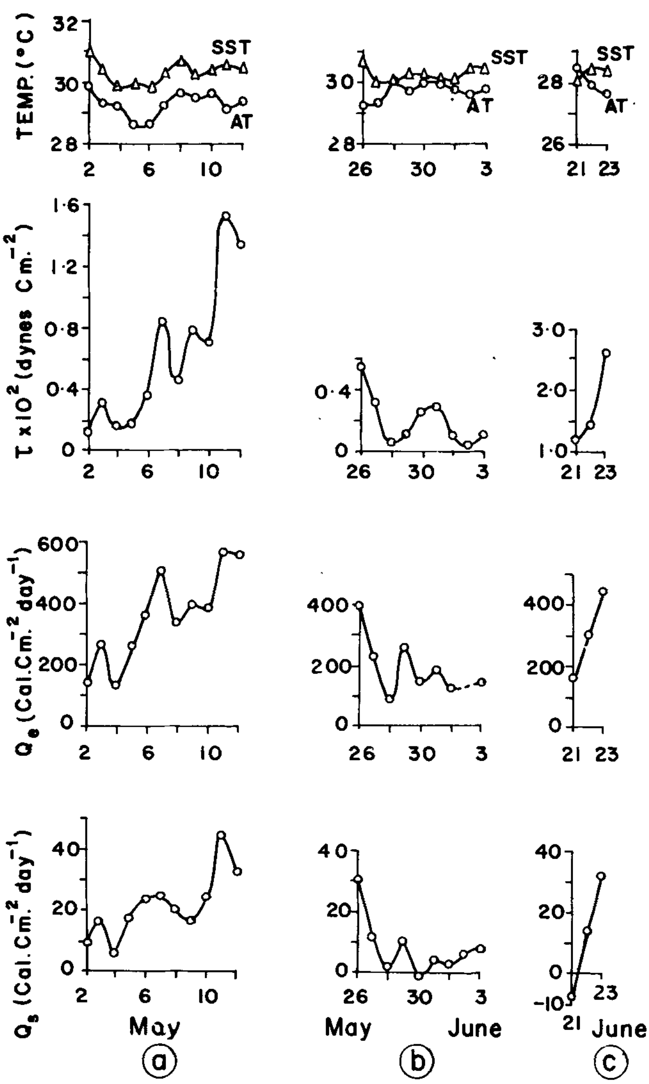

Figure 2. Variation of fluxes and temperature at southern station.

III 21.6.1979 to 23.6.1979: These observations were made after the monsoon had set in, in the wake of an onset vortex which formed east of the station and moved away, intensifying into a storm. As compared to the earlier occasions, wind stress was higher (1·1 to 2·5 dy. cm^{-2}). The Russian ships which had formed a polygon south of this station also experienced an increase in wind speed associated with the storm (Shajahan 1980). Latent heat on the first day (~ 150 cal. cm^{-2} day^{-1}) was similar to those during the earlier undisturbed weather conditions. Low evaporation, despite higher wind speed, was due to the presence of moist air as deduced from wetbulb depression. While wetbulb depression was about 3·8°C during undisturbed situation, it decreased to about 1·3°C on 21st June. However, on the following days wetbulb depression increased to about 2·7°C and this, together with increasing wind speed, resulted in increase of Q_e. On the first day of observation, slight gain of sensible heat by the sea was noticed and on the next two days the sensible heat loss steadily increased to about 30 cal. cm^{-2} day^{-1}. SST had recorded a fall from the values of the previous set of observations and was about 28·5°C. Air temperature was slightly greater than SST on the first day and decreased to values less than SST on the next two days.

3.1b *Observations at 15°N 65°E*: Two sets of observations (designated IV and V) were made from this station (table 1). As this station was nearer to the track of the onset vortex, these two observations will show situations before and after the storm.

IV 17.5.1979 to 8.6.1979: During this period (figure 3), wind speed was low with the stress varying between 0·02 and 0·8 dy. cm^{-2}. Latent heat, in general, followed

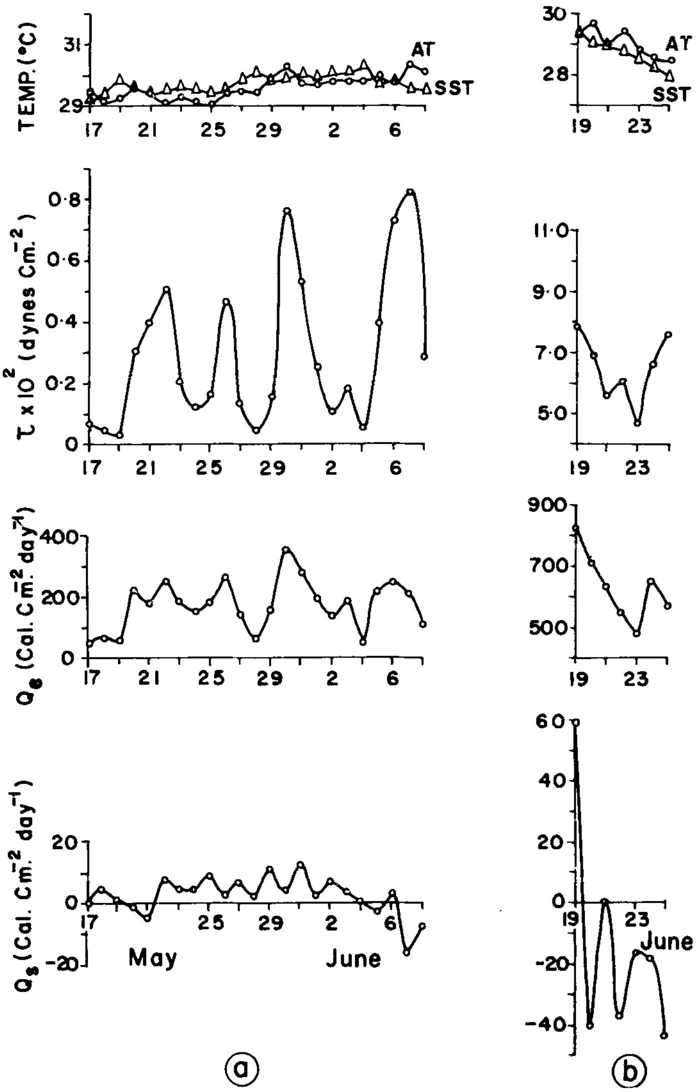

Figure 3. Variation of fluxes and temperature at northern station.

the pattern of variation of stress and ranged between 40 and 350 cal. cm^{-2} day^{-1}. Sensible heat exchange was also low and varied between −17 and 13 cal. cm^{-2} day^{-1}. From 25th May onwards SST showed a slight increase of about 0·5°C and decreased from 4th June onwards. Air temperature was, in general, less than SST by about 0·5°C. From 25th May onwards air temperature increased suddenly by about 1·3°C upto 30th. From 6th to 8th June, the air temperature was greater than SST by about 0·8°C. This is because of a fall in SST as well as an increase in air temperature noticed on these days.

V 19.6.1979 to 25.6.1979: The onset vortex mentioned earlier had passed near the station two days before this set of observations commenced. Convective weather was present and the monsoon had set in. Wind stress was high and varied between 4·5 and 8·0 dy. cm^{-2}, with the minimum value on 23rd June. Nyenzi (1980) while studying zonal time sections of wind along 65°E during MONEX (the present longitude) had observed high westerly wind from 14th June to the end of the month with a break on 24th June at 850 mb surface. Latent heat was high and varied between 480 and 820 cal. cm^{-2} day^{-1}. Minimum evaporation was observed when the wind speed was minimum. During this period, the air at this location was generally less moist (wetbulb depression of about 3°C) compared to southerly station. This, along with very high wind speed caused high evaporation. Sensible heat varied between −45 and 55 cal. cm^{-2} day^{-1}. SST was 29·3°C on the first day of observation and progressively decreased by about 1·5°C on the subsequent days. Air temperature was, in general, greater than SST and showed a progressive decrease.

3.2 *Simultaneous observations*

As seen earlier, there are occasions when observations were made simultaneously at two locations. To make comparisons easier relevant parts are again presented in figure 4.

3.2a Observations at 9°N 68°E and 15°N 65°E from 26.5.1979 to 3.6.1979: The pattern of stress variations was similar at both the locations although slightly higher values were encountered at the northern location. In general, the variation of latent and sensible heats at both stations was comparable. SST was greater by about 1°C at the southern location on 26th and was more or less equal at both locations on the following days. The same data at the southern location (Shajahan 1980) also showed a decrease in SST after 26th. Although the present observations at the southern station was completed on 3rd June, the observation by Russian ship *Volna* at a closeby station (9·2°N 66·7°E) presented by Shajahan (1980) indicated equally high SST. However, the northern location (see § 3·1b) showed a decrease in SST from 4th June, thus exhibiting a north-south gradient in SST. Air temperature was in general comparable at both the stations.

3.2b Observations at the above locations from 21.6.1979 to 23.6.1979: As compared to the previous occasion, stress was greater at both locations. However, of the two stations, wind energy was considerably higher at the northern station. During this period of observation, wind stress decreased at the northern station while it showed a slight increase at the southern location. The decrease at the northern station is

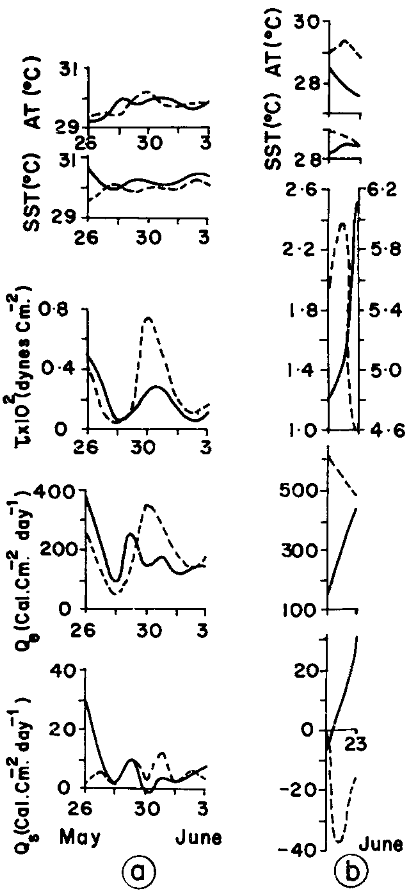

Figure 4. Variation of fluxes and temperature during simultaneous observations. (———— southern station and - - - - - northern station)

associated with the fall in wind speed along 65°E (Nyenzi 1980). The meridional sections of wind further east, presented by Nyenzi (1980) do not exhibit this fall in wind speed. The southerly station which was located at 68°E thus did not show the decrease in wind speed. Evaporation was greater at the northern station and at both the stations, in general, latent heat followed the pattern of wind stress. While there was a heat gain due to sensible heat at the northerly station on 22nd and 23rd, there was a heat loss at the southern location. Both SST and air temperature were higher at northern station.

4. Discussion

According to the terminology used during MONEX (FGGE 1981) the present observations can be classified as those during 'pre-onset' and the beginning of 'advance' phases of monsoon. Average fluxes for the two phases are presented in table 2. Average wind stress increased remarkably during the advance phase to

Table 2. Average fluxes during pre-onset and advance phases of monsoon.

	Pre-onset phase	Advance phase
No. of observations	185	38
Air temperature (°C)	29·6	28·7
SST (°C)	30·0	28·6
τ (dy.cm^{-2})	0·4	5·3
Q_e (cal. cm^{-2} day^{-1})	219·0	546·0
Q_s (cal. cm^{-2} day^{-1})	8·0	−8·0

about 5·3 dy. cm^{-2}. Similar values associated with increase in monsoon activity were observed in the Arabian sea by Pant (1977). Average fluxes of latent heat and sensible heat during pre-onset phase were about 220 and 10 cal. cm^{-2} day^{-1} respectively. These values, in general, agreed with those by Hastenrath and Lamb (1979) for May. During advance phase, average fluxes were about 550 cal. cm^{-2} day^{-1} and −10 cal. cm^{-2} day^{-1} for latent and sensible heats respectively. Daily average fluxes of similar magnitude were reported from this area by Pant (1977) during ISMEX. Present fluxes were larger than the climatological average for June presented by Hastenrath and Lamb (1979) and the average for monsoon months of certain years by Saha (1970) and Saha and Suryanarayana (1972). This is because the present observations were made soon after the passage of a storm. Studying GATE data Senguin and Kidwell (1980) found that synoptic scale fields contained large fluxes. With the onset of monsoon, SST decreased by about 1·5°C. Using climatological data Rao *et al* (1976) had noticed a fall in SST of about 1·0°C in east-central Arabian sea from May to June. Air temperature also decreased after the onset of monsoon.

During this year, monsoon had set in under the influence of onset vortex which first appeared as a trough over Lakshadweep on 7th June. After becoming well marked, it persisted there till 13th June, then intensified into a depression over east-central Arabian sea by 16th June and later into a cyclone (Mukherjee and Paul 1980). During this period SST distribution in this area also underwent changes. At northern station from 4th June till the end of observations (8th June) SST decreased to about 29·2°C and became less than air temperature. SST at Russian polygon presented by Shajahan (1980) showed higher values (> 30°C) at 9·2°N 66·7°E and 7°N 66·7°E till 12th June and a decrease at a station further south (4°N 66·7°E) during this period. The situation in east-central Arabian sea was thus conducive for higher air-sea exchange at 7°N and 9°N with reduction towards north and south. This might have been one of the factors that contributed to the intensification of onset vortex. Mandal *et al* (1984) had shown that high SST which can result in large evaporation was one of the favourable conditions for observed intensification of a cyclone in Bay of Bengal. The genesis region of this vortex coincided with the area where SST exceeded 31°C (Ramesh Babu and Sastry 1984).

Another interesting observation is the slightly higher SST at the northern station during the first few days (21st and 22nd June) after the storm, explained in 3·2b. Although northerly station was nearer to the track of the storm (figure 1), both stations were under the influence of the storm. Jet-like speeds existed during the storm over extensive areas (FGGE 1981). Hence a plausible explanation for the slightly higher SST at the northern station could be the differential impact of the storm on the locations depending on the thermal structure obtained before the storm. Elsberry and Raney (1978) had shown that cooling due to storm would be greater when the mixed layer is shallow and would be less when the mixed layer is deep. SST in the present study and those recorded by Russian polygon (Shajahan 1980) indicates variation in thermal structure. Observations II at 9°N 68°E recorded higher SST upto 3rd June. A nearby station occupied by Russian ship *Volna* (9·2°N 66·8°E) continued to record high temperature upto 12th June. Present observations (III) at 15°N 65°E indicated a fall in SST from 4th June onwards. Before storm, the higher surface temperature at the southerly station would have inhibited the formation of deep mixed layer while the decreasing SST at the northern station would have induced convection and deeper mixed layer. Ramesh Babu and Sastry (1984) had shown deeper mixed layer exceeding 40 m at stations close to the present northerly station (15°N 65°E) just before the vortex crossed the area. Such variations in mixed layer depth might have caused a differential effect of the storm and resulted in increased cooling and lower SST at the southerly station soon after the passage of the storm.

5. Conclusions

Wind stress and evaporation increased during advance phase of monsoon. Sensible heat was less than latent heat by an order of magnitude. While sensible heat was lost from sea during pre-onset it was gained by sea during advance phase. North-south SST gradient in early June might have contributed to the formation of onset vortex. Southerly station, where SST was greater before the vortex, had registered greater surface cooling as a result of this storm.

Acknowledgements

The authors thank Dr M J Sebastian for his keen interest and Dr P G Kurup, Head of the Oceanography and Meteorology Division, University of Cochin for a critical reading of the manuscript. Thanks are also due to the India Meteorological Department for the supply of data. Authors are thankful to the referees for valuable comments for improving the paper.

References

Anto A F, Rao L V G and Somayajulu Y K 1982 Surface layer conditions of the atmosphere over western Bay of Bengal during MONEX; *Indian J. Mar. Sci.* **11** 15–20

Bunker A F 1976 Computations of surface energy flux and annual air-sea interaction cycles of north Atlantic oceans; *Mon. Weather Rev.* **104** 1122–1140

Charnook H 1955 Wind stress on water surface; *Q. J. R. Meteorol. Soc.* **81** 639–640

Colon J A 1964 On interactions between the southwest monsoon current and the sea surface over the Arabian sea; *Indian J. Meteoroi. Geophys.* **15** 183–200

Elsberry R L and Raney S D 1978 Sea surface temperature response to variations in atmospheric wind forcing; *J. Phys. Oceanogr.* **8** 881–887

FGGE 1981 Summer MONEX field phase report; *FGGE Operations Report* **8** Section 2 WMO, Geneva

Friehe R L and Schmitt 1976 Parametrization of air-sea interface fluxes of sensible heat and moisture by bulk aerodynamic formulae; *J. Phys. Oceanogr.* **6** 801–809

Garratt J R 1977 Review of drag coefficients over oceans and continents; *Mon. Weather Rev.* **105** 915–929

Hastenrath S and Lamb P J 1979 *Climatic atlas of Indian Ocean Part II: The oceanic heat budget;* (Madison; University of Wisconsin Press)

Hellerman S and Rosenstein M 1983 Normal monthly wind stress over the world ocean with error estimates; *J. Phys. Oceanogr.* **13** 1093–1104

Hicks B B 1972 Some evaluation of drag and bulk transfer coefficients over water bodies of different sizes; *Boundary-Layer Meteorol.* **3** 201–213

Kondo J 1975 Air-sea bulk transfer coefficients in diabatic conditions; *Boundary – Layer Meteorol.* **9** 91–112

Large W F and Pond S 1981 Open ocean measurements of flux in moderate to strong winds; *J. Phys. Oceanogr.* **11** 324–336

Launiainen J 1979 Studies of energy exchange between the air and sea surface on the coastal area of the gulf of Finland; *Finn. Mar. Res.* **246** 3–110

Mandal G S, Gupta G R and Mookerjee N 1984 Orissa cyclone 1–4 June 1982; *Vayumandal* **14** 5–11

Mukherjee A K and Paul D K 1980 Influence of Arabian sea cyclonic systems on the onset of monsoon; *Results of summer MONEX field phase research part A; FGGE Operations Report* **9** WMO, Geneva 62–67

Nyenzi B S 1980 Influence of low tropospheric flow on the onset of summer monsoon flow over India in June 1979; *Results of summer MONEX field phase research part A; FGGE Operations Report* **9** WMO, Geneva 68–80

Pant M C 1977 Wind stress and fluxes of sensible and latent heat over the Arabian sea during ISMEX 1973; *Indian J. Meteorol. Hydrol. Geophys.* **28** 189–196

Pisharoty P R (ed) 1965 Evaporation from Arabian sea and the Indian southwest monsoon; *Proceedings of the symposium on the Indian Ocean expedition of meteorological results*; Meteorological results of IIOE (Bombay: India Meteorological Dept.) 43–54

Pond S, Fissel D B and Paulson C A 1974 A note on bulk aerodynamic fluxes for sensible heat and moisture fluxes; *Boundary – Layer Meteorol.* **6** 333–339

Ramesh Babu V and Sastry J S 1984 Summer cooling in the east-central Arabian sea – A process of dynamic response to the southwest monsoon; *Mausam* **35** 17–26

Rao D P, Sarma R V N, Sastry J S and Premchand K 1976 On the lowering of surface temperatures in the Arabian sea with the advance of southwest monsoon; *Proceedings of the symposium on tropical monsoon*, (Pune: Indian Institute of Tropical Meteorology) 106–115

Rao R R 1984 A case study on the influence of summer monsoon vortex on the thermal structure of upper central Arabian sea during onset phase of MONEX-79; *Deep Sea Res.* **31** 1511–1521

Rao R R, Somanadhan S V S and Nizamuddin S 1978 Study of the influence of surface energy budget of north Indian ocean on the behaviour of Indian summer monsoon; *Indian J. Meteorol. Hydrol. Geophys.* **29** 253–258

Reddy K G, Rao M V, Prassad P H and Rao G R L 1984a Net energy exchange at the surface over the Arabian sea during the summer monsoon; *Mausam* **35** 499–502

Reddy K G, Rao M V, Prassad P H and Rao G R L 1984b Fluxes of sensible and latent heat over the Arabian sea during MONEX-79; *Indian J. Mar. Sci.* **13** 134–135

Saha K R 1970 Zonal anomaly of sea surface temperature in equatorial Indian ocean and its possible effect on monsoon; *Tellus* **22** 403–409

Saha K R and Suryanarayana R 1972 Mean monthly fluxes of sensible heat and latent heat from surface of the Indian ocean; *J. Mar. Biol. Assoc. India* **14** 663–670

Senguin W R and Kidwell K B 1980 Influence of synoptic scale disturbances on surface fluxes of latent and sensible heat; *Supplement I to Deep Sea Res. Part A* **26** 51–64

Shajahan Shah Md 1980 An evaluation of near surface fluxes of momentum, sensible and latent heat in the Arabian sea during the onset phase of monsoon; *Results of MONEX field phase research part A; FGGE Operations Report* **9** WMO, Geneva 187–206

Smith S D 1974 Eddy flux measurements over lake Ontario; *Boundary – Layer Meteorol.* **6** 235–255

Smith S D 1980 Wind stress and heat flux over the ocean in gale force winds; *J. Phys. Oceanogr.* **10** 709–726

Smith S D and Banke E K 1975 Variation of sea surface drag coefficient with wind speed; *Q. J. R. Meteorol. Soc.* **101** 665–673

Weare B C 1983 Interannual variation in net heating at the surface of the tropical Pacific ocean; *J. Phys. Oceanogr.* **13** 873–885

Wu J 1980 Wind stress coefficients over sea surface near neutral conditions – A revisit; *J. Phys. Oceanogr.* **10** 727–740