Proc. Indian Acad. Sci. (Earth Planet. Sci.), Vol. 99, No. 3, September 1990, pp. 393–404.

Air-sea interaction over the tropical Indian Ocean during several contrasting monsoon seasons

M R RAMESH KUMAR and J S SASTRY

Physical Oceanography Division, National Institute of Oceanography, Dona Paula 403 004, Goa, India

MS received 26 December 1989; revised 19 May 1990

Abstract. Monthly mean anomaly fields of various parameters like sea surface temperature, air temperature, wind stress, effective radiation at the surface, heat gain over the ocean and the total heat loss between a good and bad monsoon composite and the evaporation rates over the Arabian Sea and southern hemisphere have been studied over the tropical Indian Ocean. The mean rates of evaporation on a seasonal scale over the Arabian Sea during a good and bad monsoon composites were equal (about $2{\cdot}48 \times 10^{10}$ tons/day). The evaporation rates over the southern hemisphere were greater during all the months. The mean evaporation rates over the southern hemisphere on a seasonal scale for the good and bad monsoon composites were $4{\cdot}4 \times 10^{10}$ and $4{\cdot}6 \times 10^{10}$ tons/day respectively. The maximum evaporation rates over the southern hemisphere were observed in August. The anomalies of wind stress, effective radiation at the surface and the heat gain over the ocean also exhibit large variations in August, as compared to other monsoon months.

Keywords. Air-sea interaction; Indian ocean; monsoon; anomaly; sea surface temperature; air temperature; wind stress.

1. Introduction

The summer monsoon period (June to September) plays an important role in the economy of a country as the annual rainfall for various meteorological subdivisions is mainly received during this period. The role of the sea surface temperature (SST) and the source of moisture for monsoon rainfall have been a controversial subject for years (Jospeh and Pillai 1986; Ramesh Kumar *et al* 1986; Shukla 1987; Cadet and Greco 1987; Sadhuram and Ramesh Kumar 1988; Kusuma Rao and Goswami 1988).

Sadhuram and Ramesh Kumar (1988) showed that the cross-equatorial flux from the southern hemisphere (SH) contributes to about 70% of the moisture transported across the west coast of India as compared to the evaporation over the Arabian Sea (AS). Ramesh Kumar and Sadhuram (1989) also showed that the evaporation rates over the AS during two contrasting monsoon seasons namely 1979 (bad monsoon year) and 1983 (good monsoon year) were of the order of $3{\cdot}66 \times 10^{10}$ and $3{\cdot}59 \times 10^{10}$ tons/day respectively which further substantiated the results of Sadhuram and Ramesh Kumar (1988). The present study aims at verifying the above results and examine whether any relationship exists between the evaporation over the AS or SH with the monsoon rainfall over India. In addition we present the anomaly fields of various surface meteorological parameters like SST, air temperature (AT), wind stress (τ), heat gain over the Ocean (HGO), effective radiation at the surface (ERS) and total heat loss between the good and bad monsoon year composites.

2. Data and methodology

The data for the present study were taken from the Bunker data set for the Indian Ocean (Bunker 1976), and the various surface meteorological parameters like SST, AT, wind speed, cloudiness, mixing ratio and sea level pressure etc., needed for computing the wind stress, latent heat flux, sensible heat flux and radiation heat flux have been extracted from it. Figure 1 gives the Marsden square (MSQ) numbers used in the present study and also the areas used for computing the evaporation for the AS and SH. The various parameters have been averaged over the 10° lat. and 10° long. girds over the tropical Indian Ocean (30°N to 30°S; 40°E to 100°E).

The rainfall data pertaining to the study were obtained from Shukla (1987) and the year were classified as good and bad if the normalized rainfall anomaly was

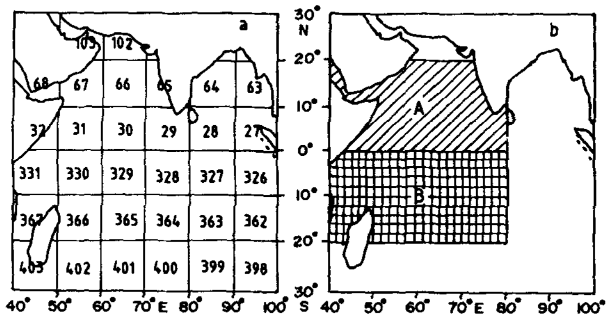

Figure 1a. Marsden square numbers used in the present study. **b** Study areas used to compute mean evaporation over Arabian Sea (area A) and southern hemisphere (area B).

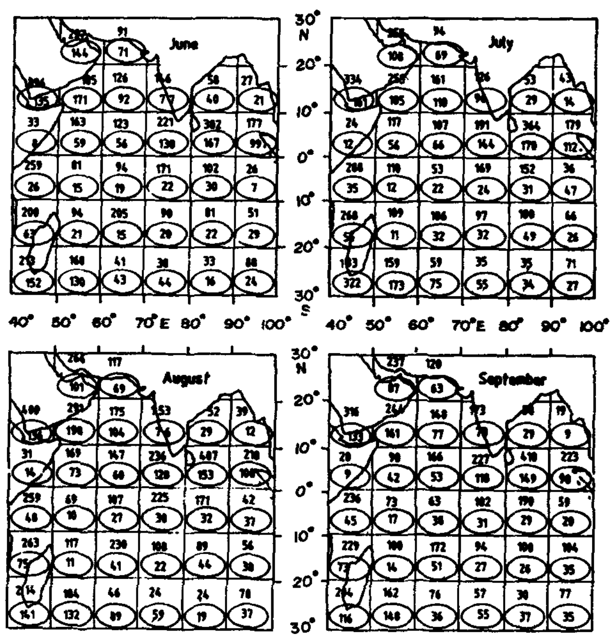

Figure 2. Mean monthwise distribution of data density for bad (open) and good monsoon (circled) composites.

> 1 s.d and < -1 s.d. respectively. Thus, the years 1953, 1956, 1959, 1961 and 1970 were chosen as the good monsoon years and 1951, 1965, 1968 and 1972 were chosen as the bad monsoon years for the period from 1948–1972.

The mean data density for the months June to September for the different Marsden squares is given in figure 2, for both, bad (open) and good (circled) monsoon composites. In general, it can be seen that the density of observations is greater over the traditional shipping lanes as compared to the other regions. The data density is also greater during the bad monsoon year composite as compared to the good monsoon composites. Further, it can be noticed that the observations are in general greater over the north Indian Ocean as compared to its southern counterpart. The data distribution seems to be sufficient to draw useful conclusions as suggested by Weare and Strub (1981).

The latent heat flux (LHF), sensible heat flux (SHF), wind stress, (τ) and the evaporation (E) have been computed following Bunker (1976), using the bulk aerodynamic formulae. The empirical equations used to compute the various fluxes are as follows

$$\tau = \rho_a C_d W^2, \tag{1}$$

$$\mathrm{LHF} = \rho_a L C_e (Q_s - Q_a) W, \tag{2}$$

$$\mathrm{SHF} = \rho_a C_p C_h (T_s - T_a) W, \tag{3}$$

$$E = \rho_a C_e (Q_s - Q_a) W, \tag{4}$$

where ρ_a is the air density; $C_d = C_e = C_h$ are the exchange coefficients; W is the wind speed at 10 m above the sea surface (ms^{-1}); Q_s is the specific humidity at T_s(gKg^{-1}); Q_a is the specific humidity at T_a(gKg^{-1}); T_s is the sea surface temperature (in °C); T_a is the air temperature (in °C) and C_p is the specific heat of air at a constant pressure.

The exchange coefficients suggested by Bunker (1976) for different wind speed and atmospheric stability conditions have been used for the present study. The fluxes have been computed from each individual ship observation and later averaged for different marsden squares for the months June, July, August and September.

The fluxes of solar radiation, infrared radiation have been computed as follows:

$$\mathrm{SW} = Q_0(1 - \alpha)(1 - aN - bN^2), \tag{6}$$

$$\mathrm{LW} = \varepsilon\sigma\theta_a^4(11{\cdot}7 - 0{\cdot}0023 e_a) + (1 - cN) + 4\varepsilon\sigma\theta_a^3(\theta_s - \theta_a) \tag{7}$$

where SW is the incoming solar radiation (Wm^{-2}), LW the outgoing longwave radiation (Wm^{-2}), Q_0 the shortwave radiation incident on the earth's surface on a cloudless day (from a table given in Kondratyev 1969 (Wm^{-2}), α the albedo of the sea surface (from Payne 1972), N the observed monthly mean cloudiness (tenths), a and b are empirical constants = 0·38 (following Bunker 1976), ε is the emissivity = 0·96, σ the Stefan Boltzmann's constant, θ_a is the average absolute temperature in air (in °K), θ_s the average absolute temperature of sea (in °K), e_a the vapour pressure of the air at 10 m above the sea surface and c the cloud cover coefficient.

The effective radiation at the sea surface (R) is the incoming solar radiation less the outgoing longwave radiation and is given by

$$R = \mathrm{SW} - \mathrm{LW}. \tag{8}$$

The net heat gain by the ocean (HGO) is given by net radiation absorbed minus the sensible and latent heat fluxes at the surface, and is given by

$$\mathrm{HGO} = R - \mathrm{LHF} - \mathrm{SHF}. \quad (9)$$

3. Results and discussion

In the present study we look at the mean evaporation rates over the AS and SH during the good and bad monsoon year composites along with the interannual variations for the above study areas. In addition we present the anomalies between the good and bad monsoon composites for SST, AT, τ, ERS, total heat loss and HGO (figures 3 to 8) for the tropical Indian ocean for the summer monsoon period.

Table 1 gives the onset dates and monsoon rainfall over India for the good and bad monsoon years used in this study. It can be noticed that the onset of summer monsoon along the Kerala coast itself exhibits very large variations (varying from 18 May to 18 June) and the monsoon rainfall also shows large fluctuations, varying from 653·2 mm to 1017·0 mm.

Table 2 gives the evaporation rates over the AS and SH respectively. The top values are for the AS area and the bottom values for the SH. From the table it can be seen that the evaporation values over the AS show a gradual decrease with onset of summer monsoon with the lowest values observed in September irrespective of the good or bad monsoon conditions over the Indian subcontinent. Another interesting feature is that the evaporation rates over AS relatively higher in June and July during good monsoon composite than a bad one. The reverse is true for August and September. If we consider the season as a whole, there is hardly any difference between the good and bad monsoon composite values. This was reported earlier by Ramesh Kumar and Sadhuram (1989) for 1979 (bad monsoon year) and 1983 (good monsoon year).

The evaporation rates over the SH were found to decrease with the progress of the southwest monsoon. A comparison between the evaporation rates over AS and

Table 1. Dates of onset of summer monsoon over the Kerala coast, the southern most part of India, for the good and bad monsoon years along with the monsoon rainfall over India.

Year	Date	Monsoon rainfall (mm)
1951*	31 May	736·9
1953	07 June	919·7
1956	21 May	979·5
1959	31 May	938·1
1961	18 May	1017.0
1965*	26 May	706·8
1968*	08 June	753·7
1970	26 May	939·4
1972*	18 June	653·2

*Refers to the bad monsoon years. (Source: Shukla, 1987).

Table 2. Evaporation rates over the Arabian sea (area A) (top values) and the southern hemisphere (area B) (bottom values).
(Units: 10^{10} tons/day)

Month	Bad composite B	Good composite G	Mean	Difference (G–B)
June	3·01 5·14	3·28 4·96	3·15 5·04	0·27 −0·18
July	2·74 5·21	2·79 4·60	2·77 4·91	0·05 −0·61
August	2·36 4·47	2·12 4·88	2·24 4·67	−0·24 0·41
September	1·82 3·57	1·72 3·14	1·77 3·36	−0·10 −0·43
Season	2·48 4·60	2·48 4·40	2·48 4·50	0·00 −0·20

Table 3. Evaporation rates for Arabian sea (open) and southern hemisphere (within brackets).
(Units: 10^{10} tons/day).

Year/ Month	June	July	August	September	Seasonal mean	Seasonal differences
1951	3·15 (4·35)	2·28 (4·85)	1·64 (3·56)	1·40 (2·89)	2·12 (3·91)	1·79
1953	3·43 (3·70)	2·78 (3·99)	1·83 (3·75)	1·63 (3·03)	2·42 (3·61)	1·19
1956	3·00 (4·96)	2·72 (5·04)	1·39 (4·70)	1·83 (1·90)	2·23 (4·15)	1·92
1959	3·00 (3·67)	2·68 (3·82)	2·31 (3·93)	1·27 (3·14)	2·32 (3·64)	1·32
1961	4·02 (6·14)	3·23 (5·26)	2·30 (4·83)	1·83 (2·92)	2·84 (4·79)	1·95
1965	2·82 (4·22)	2·82 (4·40)	2·30 (4·77)	1·69 (3·66)	2·41 (4·27)	1·86
1968	2·28 (5·11)	2·97 (6·04)	1·91 (4·99)	1·98 (4·28)	2·29 (5·10)	2·81
1970	2·96 (5·86)	2·55 (5·30)	2·79 (6·81)	2·22 (4·87)	2·63 (5·71)	3·08
1972	3·79 (6·83)	2·89 (5·49)	3·31 (4·44)	2·29 (3·13)	3·07 (4·97)	1·90
Mean	3·16 (4·98)	2·77 (4·91)	2·20 (4·64)	1·79 (3·31)	2·48 (4·46)	1·98

SH shows that they are in general greater over SH than in AS during all months irrespective of whether it is a good or bad monsoon composite. Another interesting feature is that the evaporation rates over SH during a bad monsoon composite show drastic reduction from July to August, and from August to September, whereas for a good monsoon composite the evaporation rates show a slight increase from July to August and then a similar decrease from August to September.

Table 3 gives the interannual variation of evaporation rates for the AS and SH. It is seen that there are both large interannual and intraseasonal variations in the evaporation rates. An important feature observed is that the evaporation rates from the SH are always greater than the AS especially for August (almost twice that of the AS value) and September. Thus it looks as if the moisture from the SH plays a crucial role in the monsoon activity over India, especially in August and September. This is important as it is in August that the maximum break in monsoon conditions occurs over the Indian subcontinent.

The mean moisture flux across the boundary wall between AS and SH for the years 1964 (normal), 1975 (good) and 1979 (bad) monsoon years is given in table 4. It is seen that the mean cross-equatorial flux across the boundary wall varies from year to year and with the maximum moisture flux transport into the AS during a good monsoon (almost twice that of a bad monsoon year). The probable reason for the lack of correlation between the evaporation rates over the AS or over SH with the monsoon rainfall over India appears to be that not all the moisture coming from the AS/SH is utilized for monsoon rainfall over India and that a reasonable amount would be used for the rainfall over southeast Asian countries. Hence only a detailed examination of the moisture flux coming into and leaving the Indian subcontinent can throw a better light.

3.1 *Sea surface temperature*

The SST were in general relatively higher over the north Indian ocean excepting the west and east coasts of India during June (figure 3). In the southern Indian ocean, the values were relatively higher and maximum anomalies were observed in the marsden square 400 and 401. In July, SST anomalies off the Somalia and Arabia were negative indicating active monsoon conditions. The region of maximum positive anomalies was observed in the Marsden squares 328 and 329 in August. By September, the entire north Indian Ocean showed negative anomalies with the maximum values off Somalia and Arabia coasts showing the effect of strong monsoonal cooling. Earlier studies of Ramesh Kumar *et al* (1986) and Joseph and Pillai (1986) have reported similar features for other years (namely 1979, 1983, 1972 and 1973).

Table 4. Moisture flux across the boundary wall between Arabian sea (area A) and southern hemisphere (area B) for normal (1964), good (1975) and bad (1979) monsoon years.

Month/year	1964	1975	1979	Mean
June	−3·38	−6·90	−3·23	−4·50
July	−4·36	−5·80	−2·99	−4·38
August	−3·89	−5·80	−2·71	−4·13
September	−3·01	−5·30	−1·46	−3·26
Mean	−3·66	−5·95	−2·60	−4·07

− ve values indicate inward flux into the area A.
Units: 10^{10} tons/day

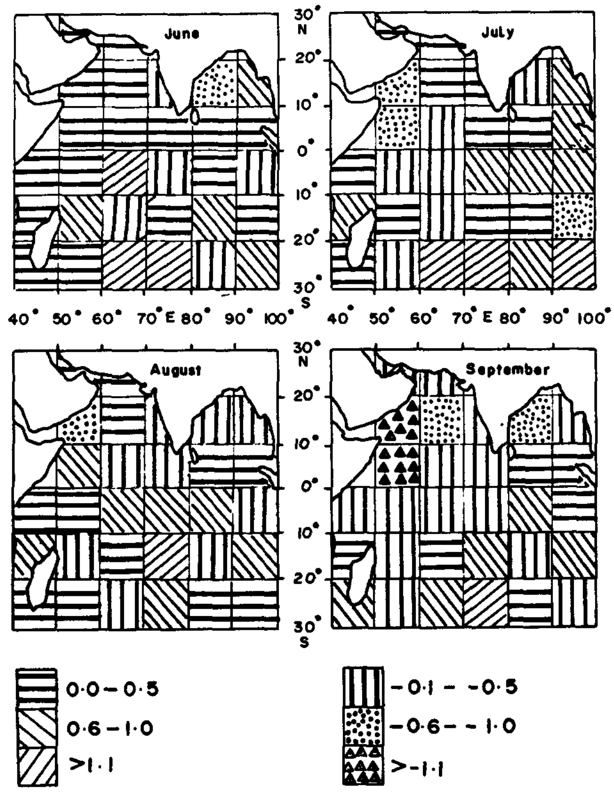

Figure 3. Sea surface temperature anomalies between good and bad monsoon composites (°C).

3.2 *Air temperature*

The air temperature in general followed the SST pattern. Maximum positive anomaly is observed in June in the MSQ 401 (figure 4). The small positive air temperature anomalies in the north Indian ocean turned into negative anomalies with the effect of strong monsoonal cooling, especially off the coasts of Arabia, Somalia and the west coast of India.

3.3 *Wind stress*

The wind stress anomalies were in general positive over the whole Indian Ocean except over a few locations like Arabian coast in June (figure 5). This picture underwent a dramatic change with active monsoonal circulation establishment in July, with large areas of negative anomalies especially in the belt 10°S–20°S. Another feature observed in August is that relatively larger positive anomalies were observed in the western Indian Ocean as compared to the eastern Indian Ocean indicating strong cross-equatorial flow during good monsoon years. Thus, it can be concluded that winds in August play a vital role in moisture transport across the equator, which is the month when the maximum break in monsoon conditions occur over India.

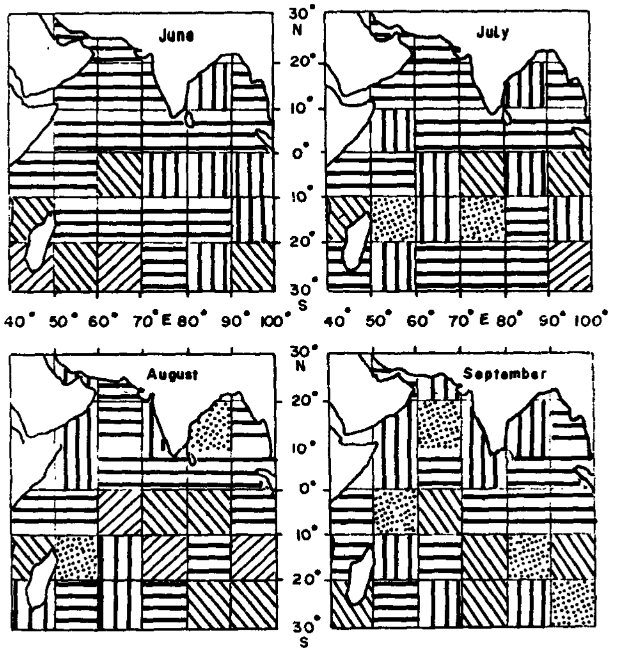

Figure 4. Same as figure 3 but for air temperature anomalies (°C).

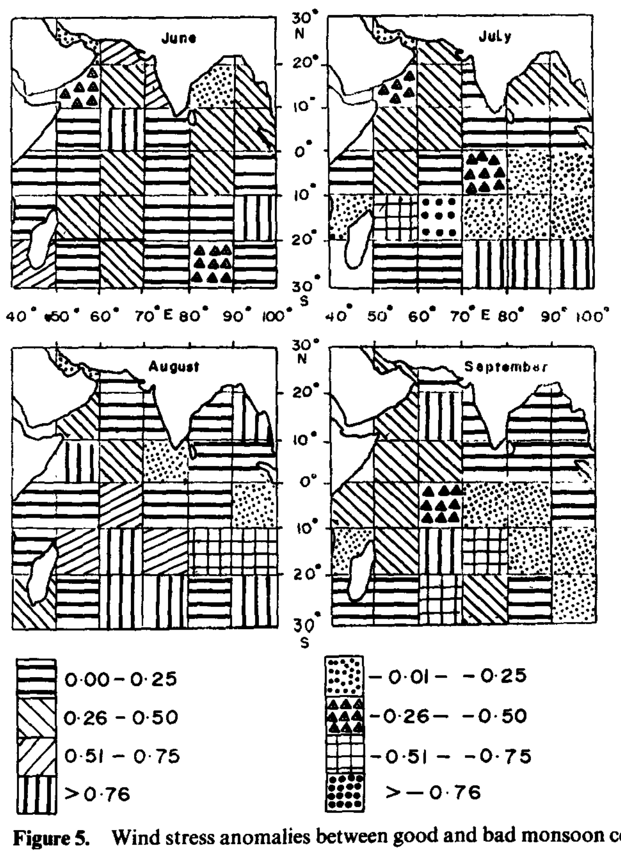

Figure 5. Wind stress anomalies between good and bad monsoon composites (dynes cm^{-2}).

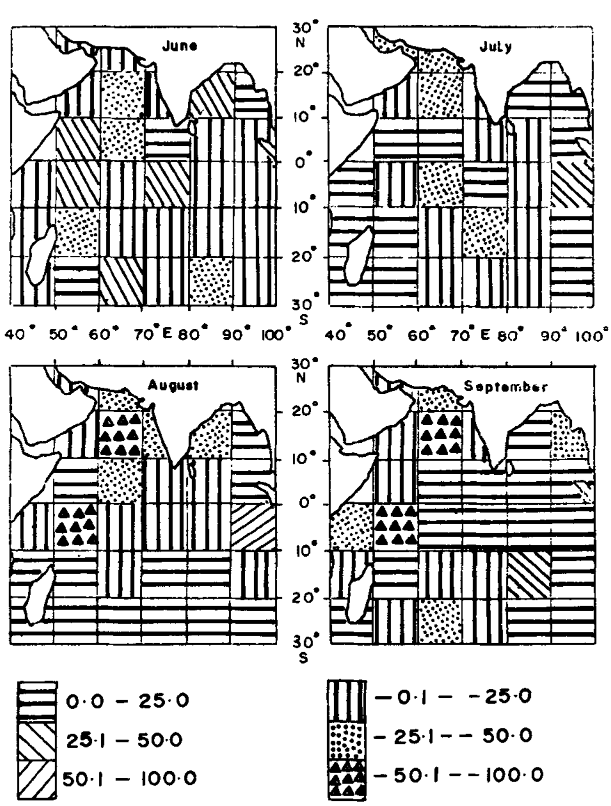

Figure 6. Net radiation anomalies at the sea surface between good and bad monsoon composites (Wm^{-2}).

3.4 *Effective Radiation at the surface* (*ERS*)

Figure 6 presents the net radiation anomalies between the good and bad monsoon composites for the Indian Ocean. An interesting feature is that the net radiation is in general greater during bad monsoon years as compared to the good monsoon years, which may be due to the effect of lesser cloudiness over the oceanic regions. Maximum anomalies were observed in the north Indian Ocean in August as compared to the other monsoonal months.

3.5 *Heat gain over the Ocean* (*HGO*)

The central AS and the westcoast of India (represented by MSQ's 66 and 65 respectively) exhibited negative anomalies throughout the season with the maximum values in September (figure 7). The east coast of India (represented by MSQ 64) undergoes drastic variations with the positive anomaly values decreasing by about 63 Wm^{-2} from June to July. Maximum variation occurs during July to August when it changes from 49 Wm^{-2} to -72 Wm^{-2}. These large variations over this area during these four months can be attributed to monsoon depressions which form during this period (June to September).

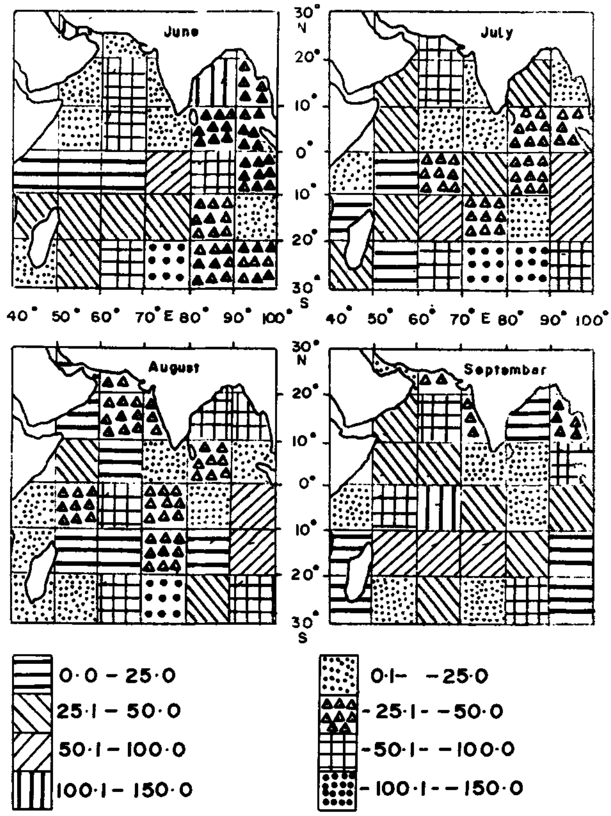

Figure 7. HGO anomalies between good and bad monsoon composites (Wm^{-2}).

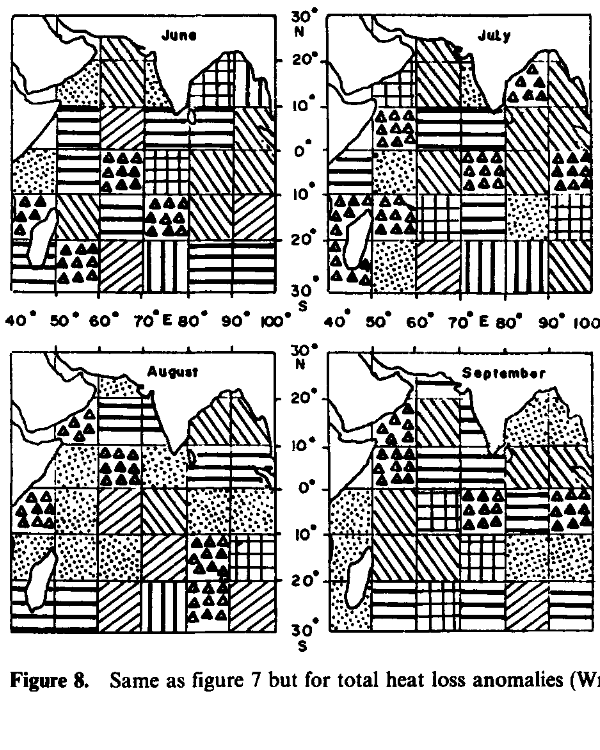

Figure 8. Same as figure 7 but for total heat loss anomalies (Wm^{-2}).

3.6 *Total heat loss* $(LHF + SHF)$

Figure 8 presents the total heat loss over the study area. The north Indian Ocean exhibits a complex picture with some areas showing positive anomalies and other areas negative anomalies. An interesting feature of this region is that the central AS exhibits positive anomaly throughout the season with minimum value in August and maximum value in September. The Arabian and Somalia coasts exhibit large negative anomalies once the monsoonal circulation has been established over the AS (i.e., from July onwards). These anomalies are directly linked to the strong cross-equatorial flow and therefore on the moisture transport towards the Indian subcontinent.

4. Conclusions

Air-sea interactions (SST, AT, τ, ERS, HGO, LHF + SHF) over the tropical Indian Ocean were studied in relation to the Indian summer monsoon activity. The evaporation rates over the AS and SH were analysed with reference to the monsoon activity over the Indian subcontinent. The evaporation rates on a seasonal scale were found to be the same over the AS irrespective of the monsoon activity over India. The southern hemispheric moisture was found to play a major role in the Indian monsoon activity during all months (June to September), with the evaporation being almost twice the AS amount in August, when the maximum break in monsoon conditions are observed over the Indian subcontinent.

Large negative anomalies of SST were observed over the Arabian and Somalia coasts indicating the effect of strong monsoonal cooling in July when the AS experiences active monsoon conditions. The anomalies of wind stress, ERS and HGO also exhibit maximum variability in August.

Acknowledgements

The authors are thankful to Drs C S Murty and S R Shetye for helpful suggestions and the two reviewers for useful suggestions in improving the manuscript.

References

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

Cadet D L and Greco S 1987 Water vapour transport over the Indian Ocean during 1979 summer monsoon. Part I: Water vapour fluxes; *Mon. Weath. Rev.* **115** 653–663

Joseph P V and Pillai P V 1986 Air-sea interaction over the north Indian Ocean—Part II: Monthly mean atmospheric and oceanic parameters during 1972 and 1973; *Mausam* **37** 159–168

Kondratyev K Ya 1969 *Radiation in the atmosphere* (New York and London: Academic Press)

Kusuma G Rao and Goswami B N 1988 Interannual variations of sea surface temperature over the Arabian Sea and the Indian monsoon: A new perspective; *Mon. Weath. Rev.* **116** 558–568

Payne R E 1972 Albedo of the sea surface; *J. Atmos. Sci.* **29** 959–970

Ramesh Kumar M R, Sathyendranath S, Viswambharan N K and Gangadhara Rao L V 1986 Sea surface temperature variability over north Indian Ocean – A study of two contrasting monsoons; *Proc. Indian Acad. Sci (Earth Planet. Sci.)* **95** 435–446

Ramesh Kumar M R and Sadhuram Y 1989 Evaporation over the Arabian Sea during two contrasting monsoons; *Meteorol. Atmos. Phys.* **41** 87–97

Sadhuram Y and Ramesh Kumar M R 1988 Does evaporation over the Arabian Sea play a vital role in the moisture transport across the west coast of India; *Mon. Weath. Rev.* **116** 307–312

Shukla J 1987 Interannual variability of monsoons: in *Monsoon* (eds) J S Fein and P L Stephens (New York: John Wiley)

Weare B C and Strub P T 1981 The significance of sampling biases on calculated monthly mean oceanic surface heat fluxes; *Tellus* **33** 211–224