

Does Evaporation over the Arabian Sea Play a Crucial Role in Moisture Transport across the West Coast of India during an Active Monsoon Period?

Y. SADHURAM AND M. R. RAMESH KUMAR

National Institute of Oceanography, Dona Paula, Goa, India

(Manuscript received 25 March 1987, in final form 30 April 1987)

ABSTRACT

In the present study interannual variability of the contributions of evaporation and moisture flux from the Southern Hemisphere towards the moisture transport across the west coast of India is examined. The mean rates of evaporation and precipitation over the Arabian Sea during the southwest monsoon season are 2.78 and 2.21 ($\times 10^{10}$ tons/day, MKS, respectively). This suggests that the possible contribution from evaporation towards the moisture flux across the west coast of India is less significant. On a seasonal scale the ratio between cross-equatorial flux and the moisture transport across the west coast of India is found to be dominant irrespective of the monsoon activity. Only detailed information on evaporation and precipitation fields over the Arabian Sea under different phases of a monsoon could shed light on this problem.

1. Introduction

The Indian subcontinent receives about 70% of its annual rainfall during the summer months of June through September. Moisture availability and its advection by the prevailing summer monsoonal winds could be the principal means for this observed rainfall. The moisture required for such a voluminous quantity should come from either the adjoining Arabian Sea or the Southern Hemisphere. During the past, several investigators, based on limited available meteorological data, have examined the role of evaporation from the Arabian Sea and the interhemispheric moisture transport. These studies have led to the realization of the importance of either or both of these modes of transport.

Utilizing the data collected during International Indian Ocean Expedition (IIOE), Pisharoty (1965) examined the moisture budget and found evaporation from the Arabian Sea to be the main contributor for the Indian summer monsoon rains. Later with some additional upper air data along the equator, Saha and Bavadekar (1973) concluded that 70% of the moisture flux from the Southern Hemisphere accounts for the bulk of the moisture required for monsoon rains. Based on the evaporation and the satellite-derived precipitation over the Arabian Sea for the 1973 and 1974 monsoon seasons, Rao et al. (1981) reported that nearly 40% of the total evaporation accounted for the precipitation over the Arabian Sea while the balance is trans-

ported across the west coast of India. The validity of the relative roles of both evaporation and cross-equatorial flux have been substantiated by Greco (1984); however, the studies of Hastenrath and Lamb (1980), Cadet and Reverdin (1981a,b) and Cadet and Greco (1986) stressed the importance of interhemispheric transport of moisture flux.

The intraseasonal variations of moisture budget over the Arabian Sea have also been examined by many researchers (Sikka and Mathur 1965; Ramamurthy et al. 1976; Ghosh et al. 1978; Howland and Sikdar 1983; Murakami et al. 1984 and Cadet and Greco 1986). While the importance of evaporation over the Arabian Sea is suggested by Ghosh et al. (1978) and Murakami et al. (1984), the role of cross-equatorial flux was emphasized by Howland and Sikdar (1983) and Cadet and Greco (1986). The later studies also highlighted the dramatic changes in the moisture and kinematic fields during different phases of a monsoon. The present study attempts to address the relative roles of evaporation from the Arabian Sea and the cross-equatorial flux towards the moisture transport across the west coast of India during the 1979 monsoon season and the variability of these parameters under normal, active and weak (defined with reference to the rainfall activity along the west coast of India) monsoon seasons.

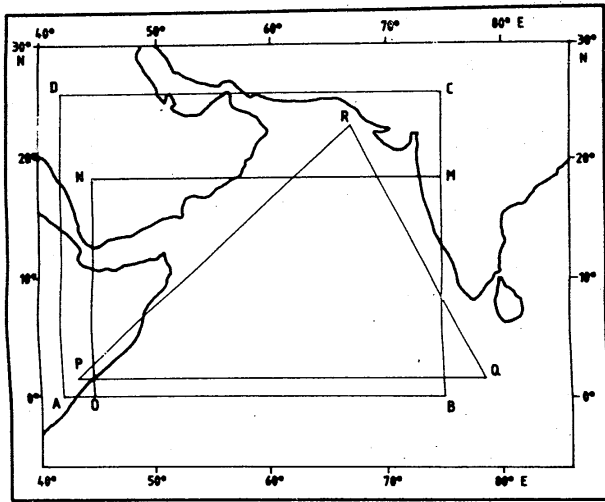
2. Data and methodology

Moisture budget over the Arabian Sea could be expressed as

$$E - P = FE + FW + FS + FN, \quad (1)$$

where E and P denote the total amounts of evaporation and precipitation over the Arabian Sea respectively;

Corresponding author address: Dr. Y. Sadhuram, Physical Oceanography Division, National Institute of Oceanography, Dona Paula, Goa 403 004, India.



ABCD - 1964 . PQR - 1975 . OBMN - 1979
 FIG. 1. Areas of moisture budget over the Arabian Sea.

FE, FW, FS and FN represent the total moisture flux across eastern, western, southern and northern boundaries (Fig. 1).

The rate of evaporation for 1979 monsoon season is computed from the bulk aerodynamic formula,

$$E = \rho C_e (e_s - e_a) U, \quad (2)$$

where ρ represents density of air (1.2 kg m^{-3}); e_s and e_a represent saturated vapor pressure at sea surface temperature and vapor pressure at deck level (obtained

from dewpoint temperature) respectively; and U represents wind speed (m s^{-1}) at anemometer level. The drag coefficient C_e is taken as 1.4×10^{-3} for wind speeds $< 13 \text{ m s}^{-1}$ and 1.6×10^{-3} for wind speeds $> 16 \text{ m s}^{-1}$ as suggested by Rao et al. (1981) and found consistent with those of Meyer and Rao (1985).

Data on sea surface temperature, dewpoint temperature and wind speed pertaining to 1979 monsoon season were taken from the Indian Daily Weather Reports. The density of observations in each $5^\circ \times 5^\circ$ grid are shown in Fig. 2. To compute the rate of evaporation over the study area, weighted averages of the data have been taken. The rate of precipitation is computed from the above E values together with the net moisture flux divergence presented by Murakami et al. (1984).

To study the variability of these parameters for the years 1964 and 1975 the data has been extracted from the studies of Saha and Bavadekar (1973) and Cadet and Reverdin (1981a). The spatial boundaries considered for these datasets vary markedly in that the vertical extent varies from 300 to 500 mb with the lateral boundaries as shown in Fig. 1. It may be mentioned here that the moisture budget computations by Cadet and Reverdin for 1975 utilizes the concept of equivalent moisture heights obtained from the coastal upper air data.

3. Results and discussion

Figure 3 shows the distribution of the wind speed over the Arabian Sea during the 1979 monsoon season. Winds are quite strong (maximum of 14 m s^{-1}) with

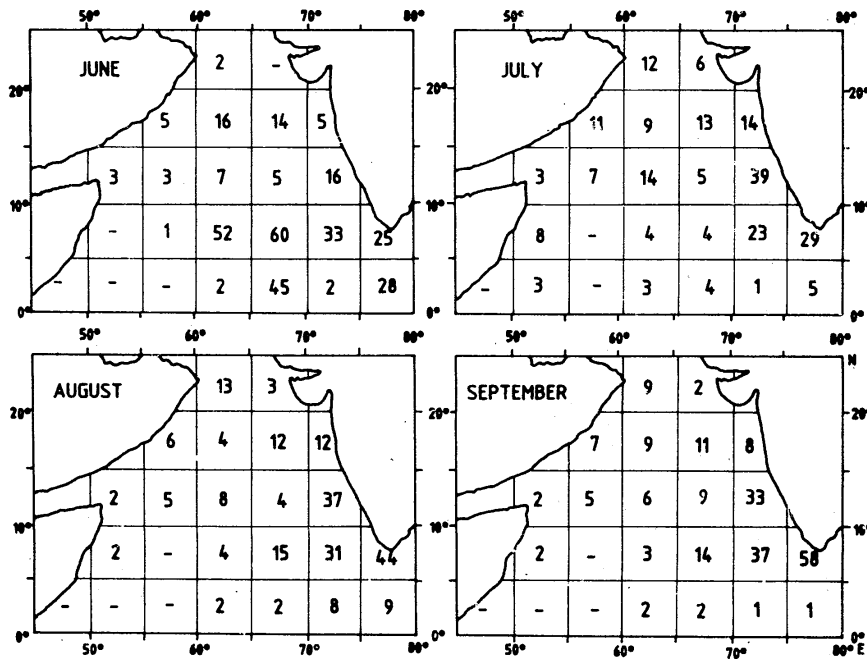


FIG. 2. Density of observations used in the computation of evaporation during the 1979 monsoon season.

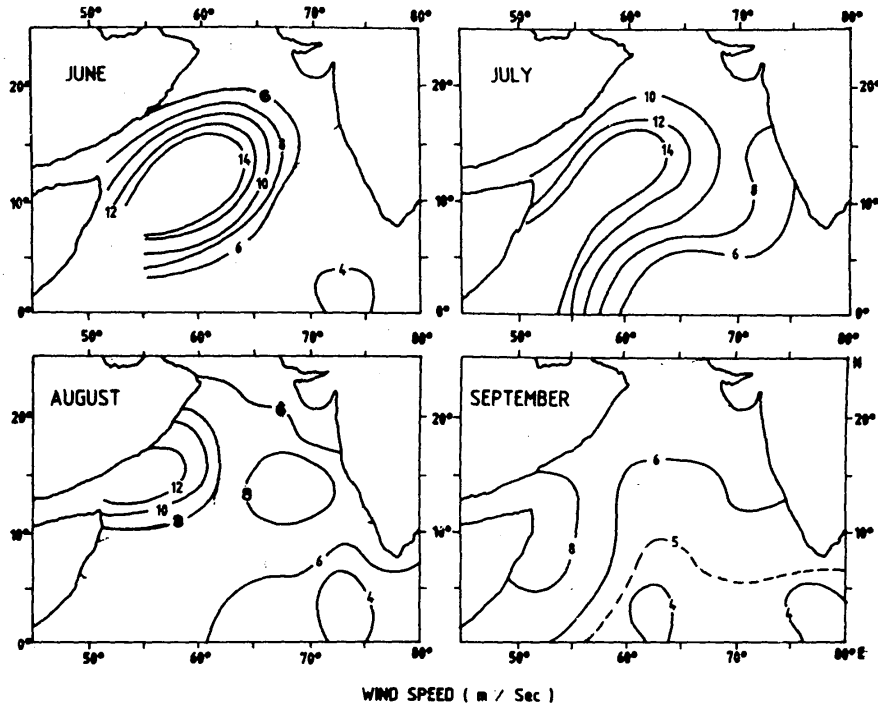


FIG. 3. Distribution of wind speed over the Arabian Sea during the 1979 monsoon season.

its core oriented in the SW-NE direction over the western and central Arabian Sea during June and July. By August the strength of these winds reduced markedly and by September they were more or less uniform over the entire area.

The vapor pressure gradients (Fig. 4) are high during June compared with the rest of the months. Higher vapor pressure gradients are confined to the south-eastern Arabian Sea which could be attributed to the warmer sea surface temperature in that region.

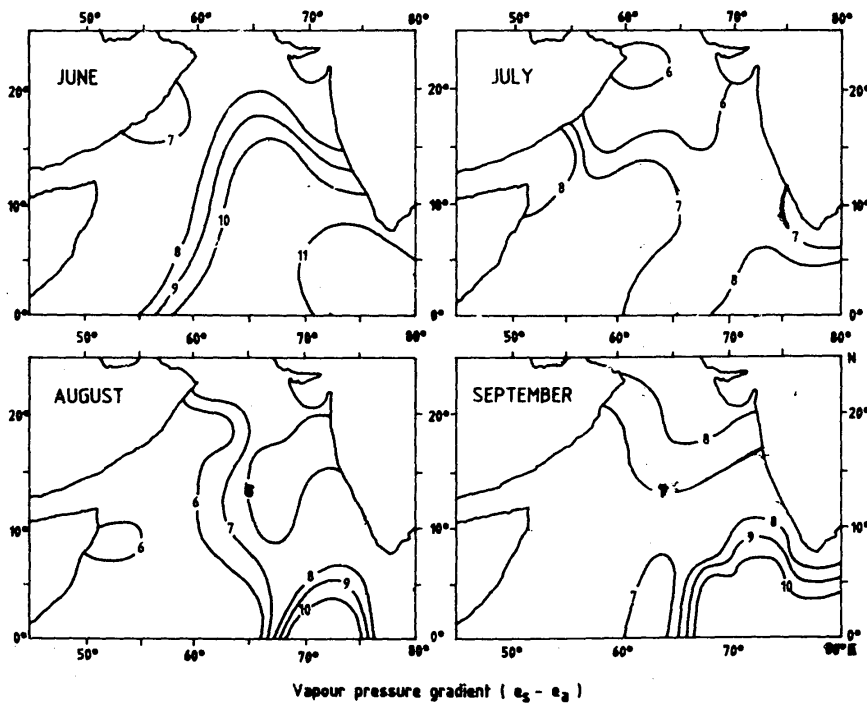


FIG. 4. As in Fig. 3 but for vapor pressure gradient ($e_s - e_a$ mb).

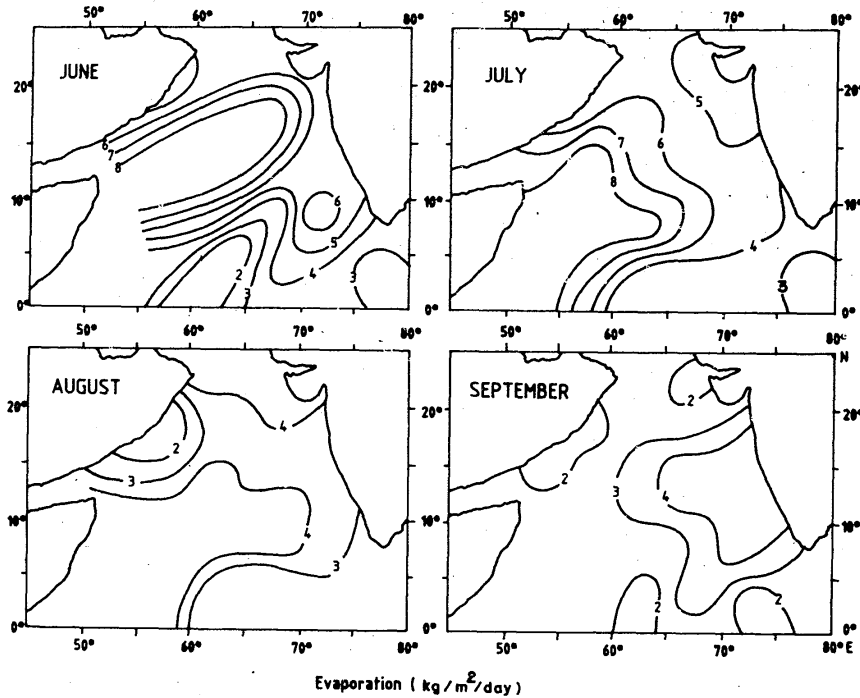


FIG. 5. Same as in Fig. 4 but for evaporation ($\text{kg m}^{-2}/\text{day}$).

Evaporation during June and July is quite high over western and central regions (Fig. 5) of the Arabian Sea. The rates of evaporation showed a decrease in August and September as a result of the low wind speeds together with weak vapor pressure gradients (Figs. 3 and 4). Even though the vapor pressure gradients are strong over the southeastern Arabian Sea, the rate of evaporation is low during the entire season which could be due to the weak winds (4 to 5 m s^{-1}) observed in this region.

These computations, as a whole, clearly indicate higher evaporation associated with strong winds during June and July. By August and September a noticeable decrease is seen even though higher vapor pressure gradients prevail in the SE region. The zone of maximum gradient in vapor pressure appear to have been advected from the west to the east from June through September. This feature may be attributed to the fall in sea surface temperature associated with the cold upwelled waters off the Somali coast.

For the year 1979 the evaporation and precipitation rates over the Arabian Sea are presented in Table 1. The rate of evaporation indicates a gradual decrease with the progress of the monsoon but with a sharp fall from July to August. This rapid fall could be largely due to the overall decrease in the wind field (Fig. 3) and partly due to advection of cold waters from the Somali coast. Precipitation rates are closer to evaporation rates and these almost balance each other. The values of E and P when compared with the rates of

1964 (normal) and 1973 (active) monsoons show marginal variation arising due to the differences in the methods of approach in computing the precipitation rates. For example, Rao et al. (1981) computed precipitation rates from satellite data and found that the estimates are 50% lower than the observed rainfall and that this factor need not be constant for the entire area. From the table it is obvious that more than 80% of the evaporation contributes towards precipitation irrespective of the monsoon activity, and this ratio more or less maintains within the season also. The overall means of evaporation and precipitation are 2.78 and 2.21 ($\times 10^{10}$ tons/day) respectively. From these values

TABLE 1. Rates of evaporation (top) and precipitation (bottom) over the Arabian Sea for different years. Unit: 10^{10} tons/day.

Month	1964	1973	1979	Mean
Jun	3.5	2.55	3.18	3.08
	2.5	2.19	3.16	2.62
Jul	3.2	2.98	3.02	3.07
	2.7	1.60	2.98	2.43
Aug	2.5	3.10	2.12	2.57
	2.1	—	1.67	1.88
Sep	2.4	—	1.86	2.13
	1.7	—	2.09	1.89
Mean	2.9	2.88	2.55	2.78
	2.25	1.89	2.48	2.21

TABLE 2a. Moisture flux across different boundary walls (*-ve* inward; *+ve* outward), rates of evaporation and precipitation over the Arabian Sea for different monsoon seasons. Unit: 10^{10} tons/day.

	1964				1975				1979			
	J	J	A	S	J	J	A	S	J	J	A	S
FW	0.11	0.50	-0.67	0.15	0.80	1.40	0.60	0.90	-0.31	-1.19	-0.66	0.45
FN	-1.21	-1.53	-1.46	-1.27	—	—	—	—	-0.35	-0.23	-0.49	-0.67
FE	4.99	5.87	5.75	4.95	9.20	7.40	8.70	7.20	3.91	4.45	4.31	1.45
FS	-3.38	-4.36	-3.89	-3.01	-6.90	-5.80	-5.80	-5.30	-3.23	-2.99	-2.71	-1.46
E	3.50	3.20	2.50	2.40	3.90	3.60	3.40	3.30	3.18	3.02	2.12	1.86
P	2.50	2.70	2.10	1.70	0.80	0.60	-0.10	0.50	3.16	2.98	1.67	2.09

it can be inferred that only 20% is the contribution available from evaporation towards the moisture transport across the west coast of India. The contributions from the different boundary walls are presented in the Tables 2a and 2b.

Table 2a shows the data compiled from different moisture budget studies cited earlier. It should be emphasized here that the 1975 monsoon season was comparable with 1973 as far as rainfall activity over the west coast of India is concerned. Fluxes across the eastern and southern boundary walls fluctuate from 3.5 to 8.1 and 2.65 to 5.95 units, respectively (Table 2b). The fluxes across other boundaries are considerably lower. The contribution from the southern boundary to the eastern boundary shows higher consistency irrespective of monsoon activity and has a mean value of about 70%. From the overall seasonal means the ratio between *E* and *FE* is about 57%. Logically, this figure enables us to conclude that the role of evaporation is equally important. But from Table 1 it is noticed that the possible contribution from evaporation is less than 20%. This latter figure is roughly one-third of the former (57%) in which the contribution of evaporation towards precipitation over the sea is ignored. Giving due weightage for the precipitation which accounts for about 80% of the evaporation from the Arabian Sea, the moisture flux from the Southern Hemisphere appears dominant and forms an important factor in the summer monsoon rainfall. However, it is difficult to give greater emphasis, at this stage, to this factor because, at present, no reliable information is available

on the spatial distributions of evaporation and precipitation (observed) over the Arabian Sea under different phases of the monsoon season. These factors are very essential to quantify the exact contributions of evaporation and interhemispheric flux towards moisture transported across the west coast of India. The authors feel that the differences of opinion on this particular subject are mainly due to the lack of systematic data—a prerequisite for better understanding of the moisture source for the Indian monsoon. Hence, it is felt that in order to examine the relative roles of evaporation and cross-equatorial flux in the Indian summer monsoon rainfall, a systematic data collection program must be initiated—preferably at an international level.

4. Conclusions

- The rates of evaporation and precipitation during 1979 monsoon are found to balance each other, indicating an insignificant role of evaporation towards moisture transport across the west coast of India.
- Irrespective of monsoon intensity the ratio of interhemispheric flux to moisture transport across the west coast of India has been found to be dominant and consistent on a seasonal scale.
- Measurements of evaporation and precipitation over the Arabian Sea under different monsoon phases could help unravel the complexities regarding the moisture source through a planned large-scale experiment at an international level.

Acknowledgments. We are grateful to the Director and Dr. J. S. Sastry, N.I.O. for their support and encouragement. We are thankful to Dr. C. S. Murthy, N.I.O., and Dr. D. L. Cadet, Laboratoire de Meteorologie Dynamique du CNRS, 91128 Palaiseau Cedex, France, for their valuable suggestions. The authors thank the reviewers for their helpful suggestions.

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TABLE 2b. Seasonal means of the parameters in TABLE 2a and the percentage ratio between *FS:FE* and *E:FE*.

	1964	1975	1979
FW	0.02	0.93	-0.42
FN	-1.37	—	-0.44
FE	5.39	8.13	3.53
FS	-3.66	-5.95	-2.60
E	2.90	3.55	2.55
FS/FE	68.00	73.00	74.00
E/FE	54.00	44.00	72.00

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