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Relation between evaporation over the Arabian Sea and rainfall at the west coast of India during summer monsoon

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ABSTRACT. Quasi-synoptic latent heat fluxes have been computed over the Arabian Sea for the period 20 June to 19 July 1963. During this same period, the monsoon rainfall at the west coast of India was measured and found to be divided into three distinct phases : preintense, intense and postintense. Whereas the correlation between the latent heat of evaporation over the Arabian Sea and the intensity of rainfall at the west coast of India is generally good, the computations also show that precipitation over the central and eastern Arabian Sea exceeds the moisture that evaporates into the atmosphere from the Arabian Sea. The results of the study suggest that while latent heat exchanges over the Arabian Sea play a significant role in the rainfall patterns at the west coast of India, a cause-and effect relationship is not clear.

1. Introduction

Various studies have highlighted the individual characteristics of rainfall over the Indian subcontinent. A large number of Indian meteorologists believe that the topographic relief of the Indian subcontinent is the chief cause of both summer and winter precipitation; others have linked the migration of the so-called Inter-Tropical Convergence Zone (ITCZ) with the rainfall pattern of India, on the assumption that rain always accompanies the line of convergence. Colon (1964) has suggested that energy exchanges between the Arabian Sea and the monsoon air have considerable influence on the monsoon flow and the synoptic weather patterns over India. Findlater (1969) has suggested that variations in the cross-equatorial speed of a system of low-level jet streams which are closely associated with the ITCZ over the Arabian Sea and western India, have an important regulating influence on the rainfall over India. Recently, Walker (1975) has concluded that the monsoon rain system of western India can exist only by interaction with the convective troposphere. However, due to inadequate observational coverage of tracts west of India, most of the explanations have remained more or less conjectural.

The principal objective of this paper is to examine the relationship (if any) between the fluctuations of rainfall at the west coast of India, south of 20°N, and the synoptic-scale latent-heat exchanges over the Arabian Sea.

2. Analytical procedures and the available data

(a) *Region*

Fig. 1 shows the location of the Arabian Sea relative to the entire Indian Ocean and the bordering land masses.

For the purpose of this study, I selected a region (Fig. 1, hatched portion) characterized by a surface flow that always reaches the west coast of India (south of 20°N) during the summer monsoon period. Flow that deviated away from the west coast was excluded from consideration because it is not expected to have significant influence on the rainfall there, and the flow to the coast from the surrounding land masses was excluded to obviate the influence of factors other than air-sea exchanges over the Arabian Sea.

(b) *Time period*

This investigation covers the period from 20 June 1963 to 19 July 1963 (both days inclusive). I grouped rainfall data from all stations, an average of 32 km from the coastline into overlapping 2°-latitude intervals and computed five-day running averages of the daily rainfall data at these stations. Each average applies to the middle day of the corresponding five-day interval and is located (at the coast) at the middle latitude of the corresponding 2°-latitude interval. Fig. 2 shows the analysis of quasi-synoptic "daily" rainfall at the west coast of India. It is seen from the analysis that there are three distinct periods :

(*i*) The preintense period (20 June through 26 June 1963) of generally light rainfall

(*ii*) The intense period (27 June through 12 July 1963) characterized by heavy rainfall along the entire length of the west coast

(*iii*) The postintense period (13 July through 19 July 1963) when rainfall decreased considerably over most of the coastal region.

Thus, this investigation covers one complete cycle from a relatively dry period, through a very intense rainfall, to fairly dry conditions again.

(c) *Observations used in this study*

I have used the daily surface observations of sea-surface temperature, air temperature, dew point, and wind as reported by merchant ships for the computation of heat exchanges. Table 1 shows the number of observations available for this study. Since the data for *each* synoptic hour of observation are not adequate, I have considered *all* the available daily observations, irrespective of the hour of observation, for the period of study.

(d) *Processing of data*

Since marine meteorological data are usually concentrated along the shipping lanes, the distribution of observations is not sufficiently uniform to obtain a representative coverage of the region. To obviate this difficulty, the daily ships' observations are grouped in 5° latitude-longitude squares. I have computed five-day running means of meteorological parameters in each 5° square and have designated the data for the middle day of each five-day period, as the average. The five day average in each 5° square is located at the mean position of all the ships in that square. As a consequence of the above treatment of the data, this study is more quasi-synoptic than synoptic.

(e) *Rainfall data*

I obtained quasi-synoptic daily rainfall data at the coast using the procedure described above in (b).

Since there are no rainfall data over the Arabian Sea, I have used the merchant ships' reports of the occurrence of rainfall, both as present and/or past weather. These reports have been used to obtain percentage frequency of rainfall over the sea during the months of June and July 1963. Fig. 3 (b) shows that rainfall during both months was greatest near the coast of India and almost zero around 60°E longitude. This corresponds quite well with the climatological data of rainfall published by the Royal Netherlands Meteorological Institute in 1952 (Fig. 3a).

(f) *Comments*

Despite the limitations of measuring techniques used for measuring meteorological data from ships, I have considered the observations of air temperature, humidity and wind speed as representative of real conditions over the Arabian Sea. However, following Saur (1963), Ewing and McAlister (1960), and Wyrtki (1966), I have corrected the measured sea-surface temperature by —0·7°C.

3. Characteristics of the Arabian Sea summer monsoon

(a) *Winds*

The Arabian Sea branch of the summer monsoon has two currents, one crossing the west coast of India near 15°N and the other flowing eastward across the southern tip of the Peninsula to join the Bay of Bengal branch near Sri Lanka (Ceylon). Also, as shown by the daily surface charts, there is a high degree of steadiness in wind direction (southwest) over the Arabian Sea. While a speed maxima is always located in the northwest portion of the region, there are marked synoptic-scale variations in the wind speeds over the central and eastern parts of the sea. However, detailed analyses do not reveal any well-organized down wind propagation of speed maxima or minima (Miller and Keshavamurty 1966).

I computed quasi-synoptic daily divergence values for the preintense, intense and postintense periods and Fig. 4 (a, b, c) shows their patterns for 24 June (preintense), 2 July (intense) and 17 July (postintense) 1963, respectively. During the

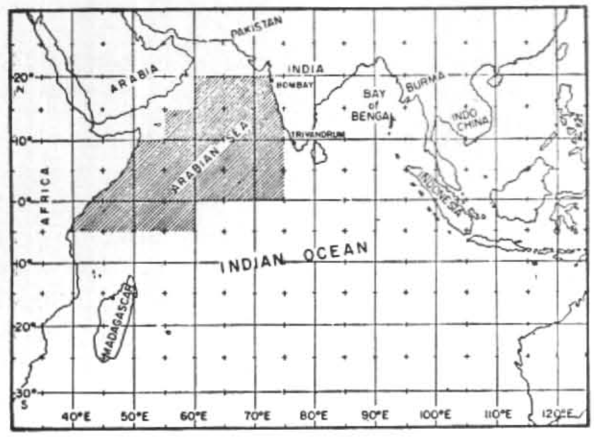


Fig. 1. Locator chart of the Arabian Sea; also shows the boundaries of the region considered in this study

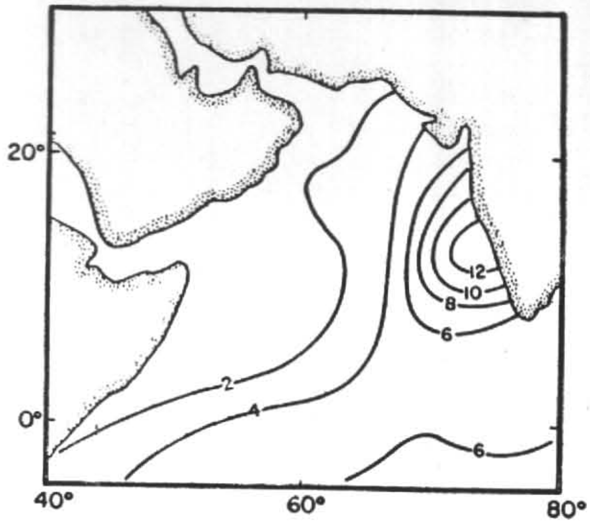


Fig. 3(a). Percentage duration of precipitation during summer from ships' observations (Royal Netherlands Meteorological Institute, 1952)

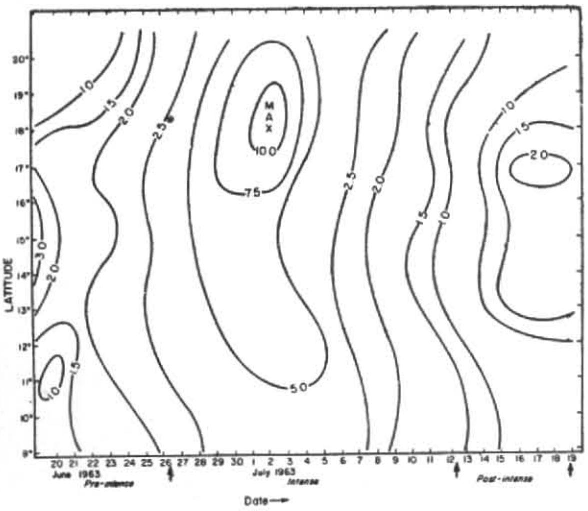


Fig. 2. Rainfall analysis along the west coast of India. Isohyets are in centimetres

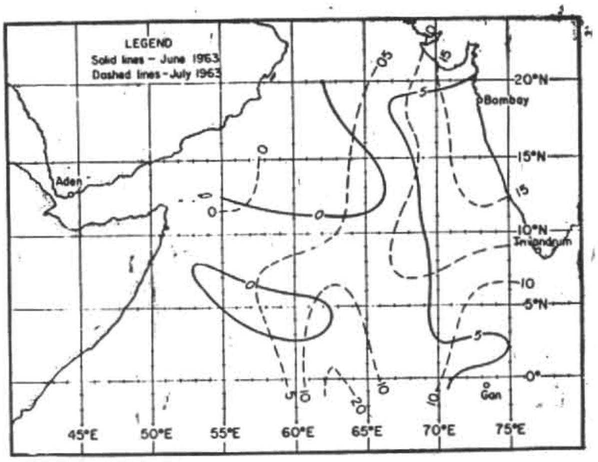


Fig. 3(b). Percentage frequency of the occurrence of rainfall over the Araban Sea during June and July 1963 (as reported by merchant ships)

TABLE 1

Total observations used in the study

Period	Total No. of observations	Available observations (%)			
		Air temp.	Sea surface temp.	Dew Point	Wind
June 20-June 30, 1963	639	100	85	85	100
July 1-July 19, 1963	998	100	87	87	98
Entire period (30 days)	1637	100	86	86	99

preintense and postintense periods, maximum convergence was confined to the southwest sector, Fig. 4 (a, c), while during the intense period it was located very near the coast (Fig. 4 b). As regards divergence, it was always located in the northwest and the southeast portions of the region though its intensity in the northwest was considerably greater during the intense and postintense periods.

(b) *Temperature*

Fig. 5 shows the distribution of the base of inversion over the Arabian Sea, as reported in the literature by Ramage (1966) and Colon (1964). Fig. 5(a) is based on 130 aerological soundings made during the summers of 1963 and 1965 and Fig. 5(b) is based on soundings made during the summer of 1963. Both figures show that the inversion is quite low over the western Arabian Sea and rises towards the coast of India, but it is not present near the coast itself. These features are also indicated by dropsonde soundings in the monsoon.

LIST OF NOTATIONS AND SYMBOLS

C_D	drag coefficient (dimensionless)
C_P	specific heat of air at constant pressure
E	evaporation of moisture
e_a	vapour pressure of air
e_s	saturated vapour pressure of air
L_e	latent heat of evaporation at the sea surface
P	precipitation
Q_E	latent heat transfer between ocean and atmosphere
Q_H	sensible heat transfer between ocean and atmosphere
T_a	temperature of air
T_s	sea surface temperature
V	scalar wind speed

(c) *Distribution of heat exchange*

The exchanges of sensible and latent heat between the Arabian Sea and the atmosphere were calculated from the bulk aerodynamic formulas

$$Q_E = L_e E = \rho L_e C_D \, (e_s - e_a) \, V \qquad (1)$$

$$Q_H = \rho C_P C_D \, (T_s - T_a) \, V \qquad (2)$$

by using the routinely measured meteorological parameters. I used a value of $2 \cdot 0 \times 10^{-3}$ for drag coefficient C_D.

The computations show that the sensible heat transport, on an average, is only about 9 per cent of the latent heat transport between the Arabian Sea and the atmosphere and, therefore, the analysis presented here pertains to latent heat transport only.

Fig. 6 (a, b, c) shows the patterns of average Q_E transport during the preintense, intense and postintense periods respectively.

During the preintense period, Fig. 6(a), a maximum of greater than 225 wm^{-2} is located near 55°E longitude within a belt of 5°to 10°N latitude. A minimum (less than 200 units) is located near the equator around 65°E. During the intense period, Fig. 6(b), two maxima (200 wm^{-2}) are seen: one in the west central Arabian Sea region and the other in the vicinity of 10°N, 65°E. Note that neither the position nor the value of the minimum has changed significantly from that of the preintense period, with the difference that the amounts transferred are less, especially near the coast of India.

The quasi-synoptic daily patterns of Q_E transfer during the nonintense periods are found to be more or less the same as the average transport for these periods. However, during the intense period, there are significant variations in the daily patterns and these differ considerably from the average picture of this period.

The differences of Q_E transfer between the three periods of varying rainfall intensity suggest some connection between Q_E and rainfall at the west coast of India. In order to probe this further, I examined the Q_E patterns (Fig. 7) and the rainfall variation at the west coast (Fig. 2) for five consecutive days (2 July to 6 July 1963). This analysis showed that the maxima was located very near the coast of India on 2 July, when the rainfall all along the coast was quite intense. During the next two days, this maxima moved off the coast and rainfall intensity along the coast decreased except near the Malabar coast where it continued to be fairly intense. On and after 4 July, the maxima of Q_E moved completely away from the coast and finally merged with a stationary maxima at 60°E on 6 July; at this time the rainfall intensity, all along the coast line, decreased very markedly.

The migrating nature of one of the two centres of maxima Q_E transfer during the intense period can perhaps be explained on the basis of temporal and spatial variations of the surface wind speed (V)

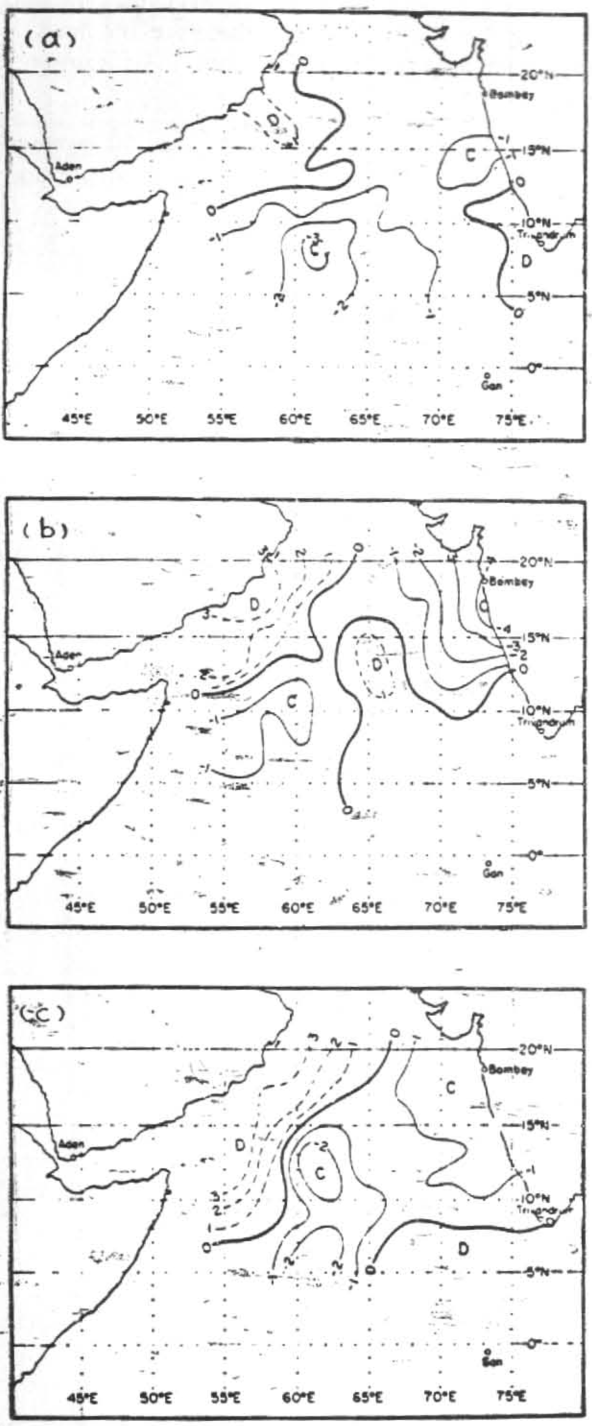


Fig. 4. Surface divergence patterns (in units of 10^{-5} sec^{-1}) over the Arabian Sea on (a) 24 June (b) 2 July and (c) 17 July 1963, representing respectively the preintense, intense and post intense periods.

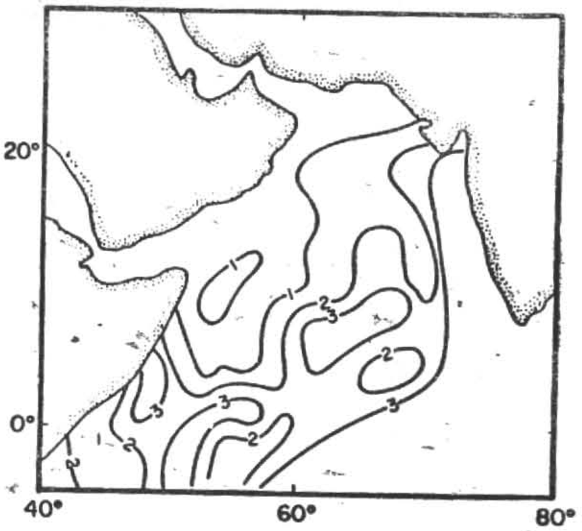


Fig. 5(a). Level of the inversion base (km) from 130 aerological soundings made during the summers of 1963 and 1964 (*after* Ramage 1966)

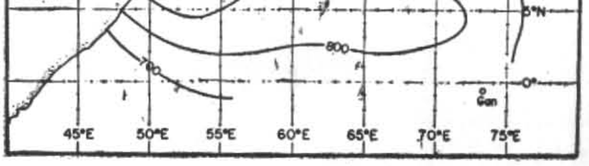


Fig. 5(b). Level of the inversion base (mb) from the aerological soundings made during the summer of 1963 (*after* Colon 1964)

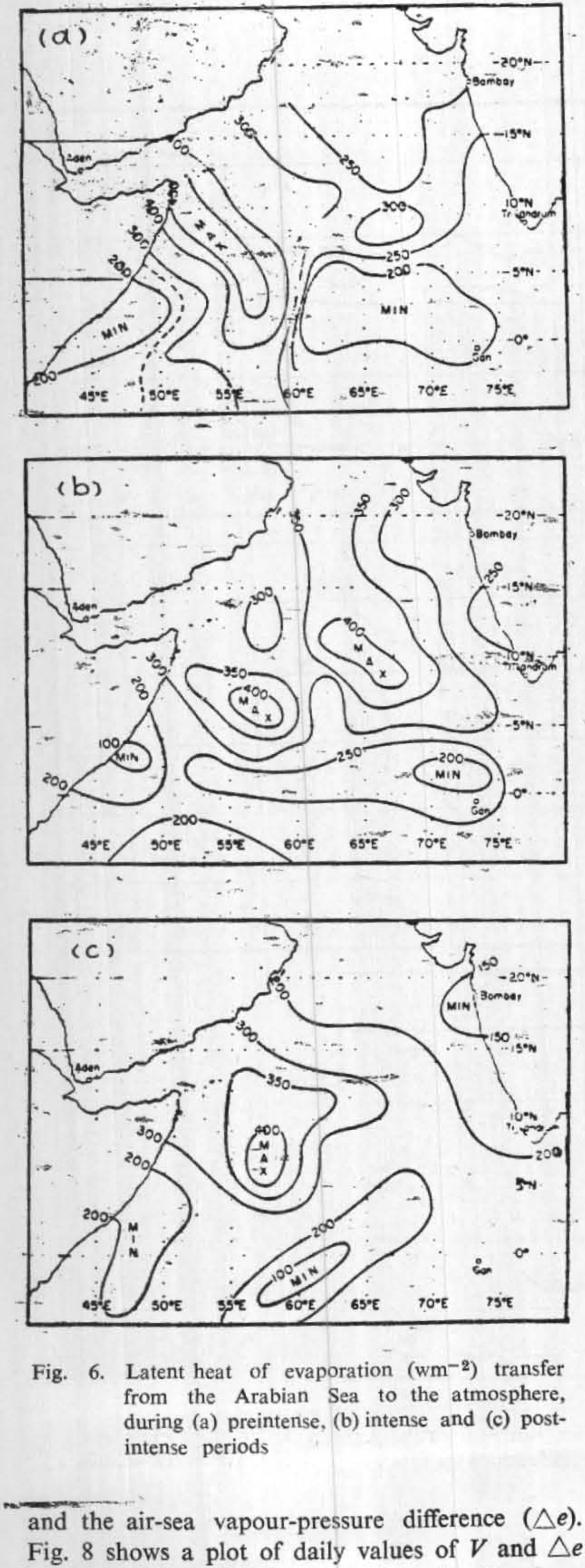


Fig. 6. Latent heat of evaporation (wm^{-2}) transfer from the Arabian Sea to the atmosphere, during (a) preintense, (b) intense and (c) postintense periods

and the air-sea vapour-pressure difference ($\triangle e$). Fig. 8 shows a plot of daily values of V and $\triangle e$ at three arbitrary locations —A, B, C (inset)— from 20 June to 19 July 1963, and one can see that the air-sea vapour pressure difference decreases when the wind speed increases. Also, the variation of V between intense and non-intense periods is much more marked than that of $\triangle e$, and V exercises a predominant influence on evaporation. This perhaps explains the existence of a maximum in this region during the intense period only. As regards its migrating nature, there does not appear to be a clear-cut explanation for this feature and I believe it is essentially due to air-sea interactions and their feed back effects.

4. Analysis of latent heat exchange over the Arabian Sea

The discussions in the preceding section imply a relationship between the quasi-synoptic daily pattern of latent heat exchange between the Arabian Sea and atmosphere and the variation in the intensity of rainfall at the west coast of India. In this section, I have examined this relationship in some detail.

(a) *Surface trajectories across the Arabian Sea*

A preliminary examination indicated that a parcel of air following the southwest monsoon flow took four to five days to traverse the region under consideration (Fig. 1) under intense monsoon conditions; it took more time to cover the same distance under non-intense conditions. I computed four-day surface trajectories from the surface wind data by using a successive approximation method suggested by Petterssen (1956, p. 27). Each trajectory was computed by working backwards from arbitrarily fixed points at the west coast of India, at intervals of 24 hours over a period of four days. Thus, several quasi-synoptic daily surface trajectories were computed for the preintense, intense and postintense periods and are shown in Fig. 9; these indicate the following features:

(*i*) In an equal time period (four days), the trajectories of the intense period had the longest passage over the Arabian Sea, whereas those of the pre-intense period were the shortest. This difference in the trajectories of the three periods could be be attributed to the fluctuations of wind speed from one period to another.

(*ii*) The trajectories of the preintense and postintense periods tended to diverge as they approached the coast of India but no such feature was found in the case of intense-period trajectories.

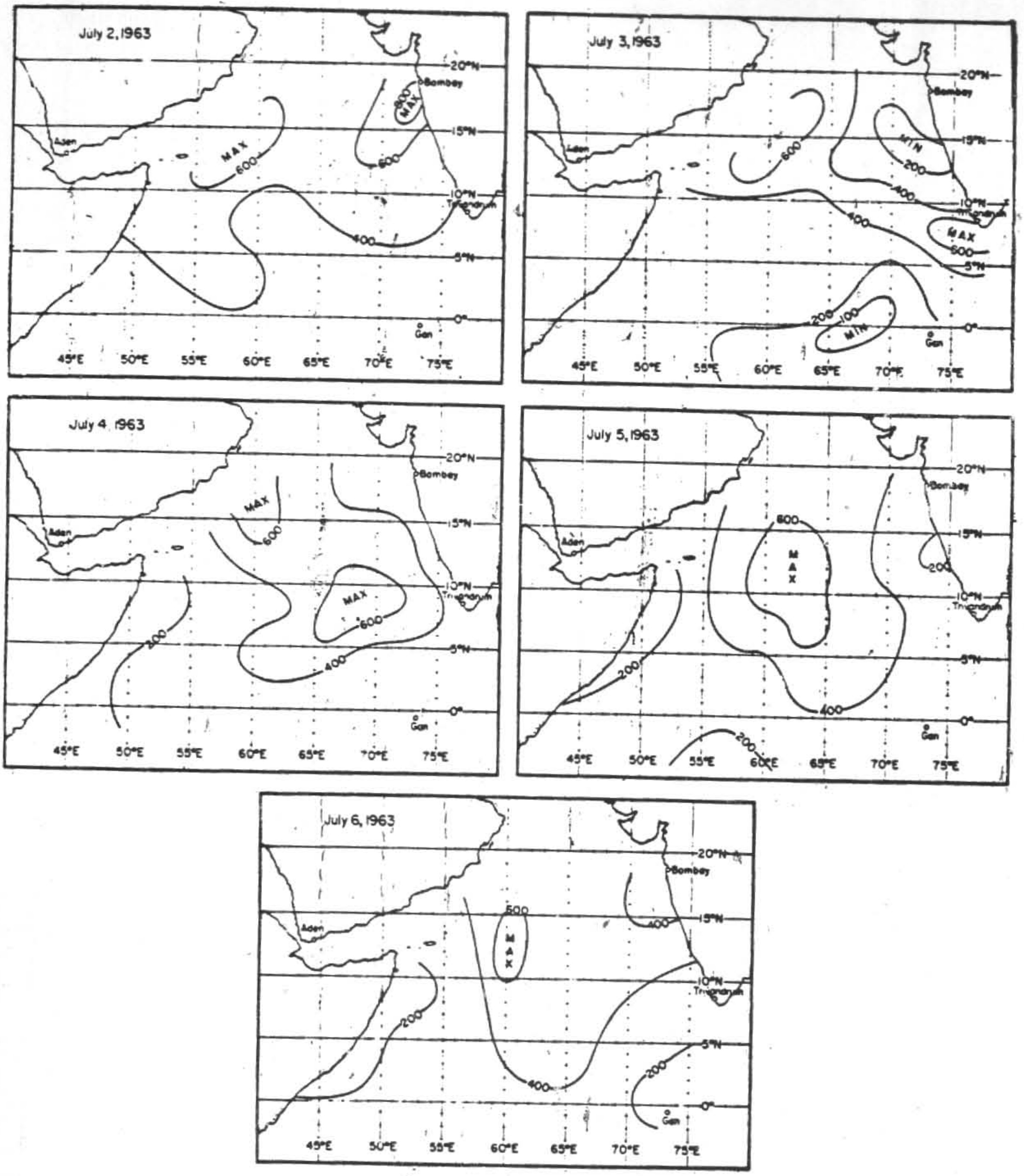


Fig. 7. The quasi-synoptic daily patterns of latent heat transfer (wm^{-2}) from the Arabian Sea to the atmosphere, during the period 2 July through 6 July 1963. The positions of the centres of maximum transfer, relative to the west coast of India, are also shown.

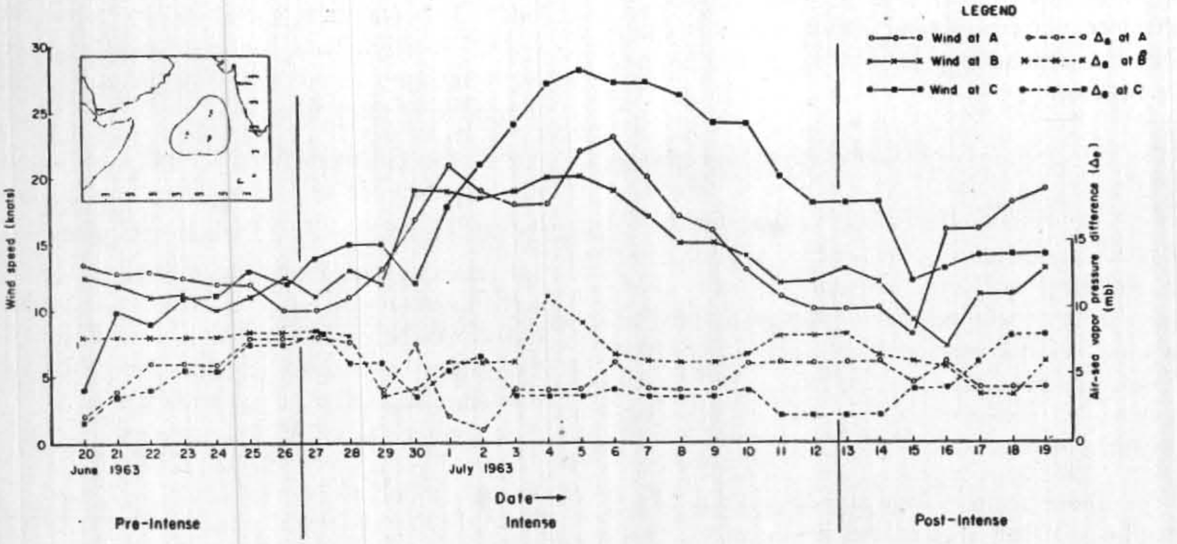


Fig. 8. Daily variations of the surface wind speed (knots) and the air-sea vapour-pressure difference (mb) at three locations (inset) lying in the region to the east of 60°E

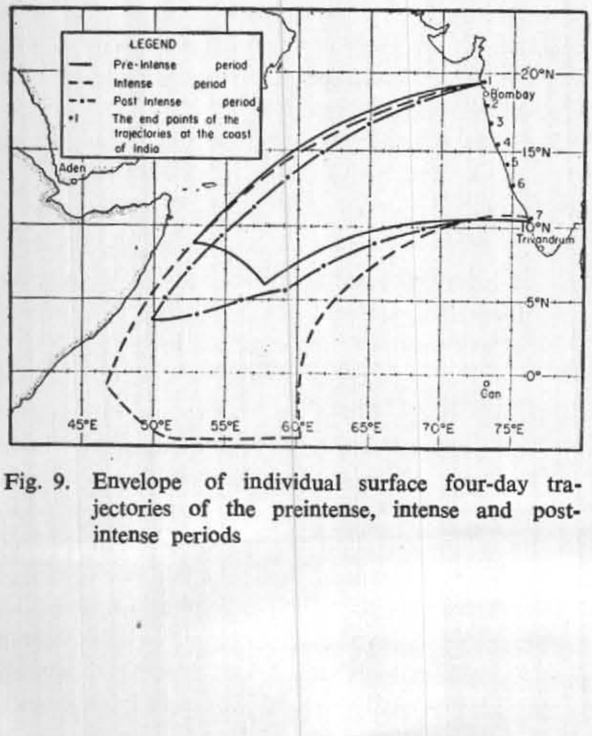
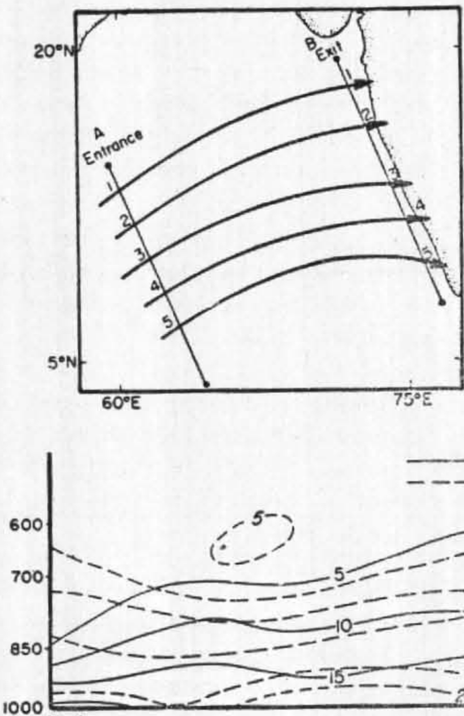


Fig. 9. Envelope of individual surface four-day trajectories of the preintense, intense and post-intense periods



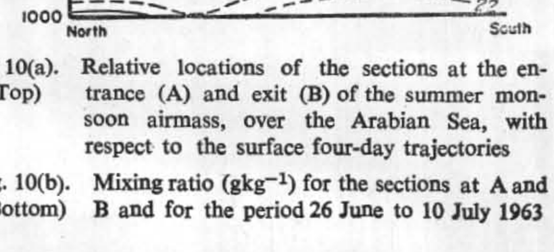


Fig. 10(a). (Top) Relative locations of the sections at the entrance (A) and exit (B) of the summer monsoon airmass, over the Arabian Sea, with respect to the surface four-day trajectories

Fig. 10(b). (Bottom) Mixing ratio (gkg^{-1}) for the sections at A and B and for the period 26 June to 10 July 1963 (*iii*) Whereas the starting points of the trajectories for the nonintense period lie in the region of low subsidence inversion (and almost zero precipitation), those of intense-period trajectories lie near the equator.

(b) *Modification of the summer monsoon airmass*

Fig. 10 (b) shows the average vertical distribution of mixing ratio (during the intense period) within an air mass with one boundary located in the region of minimal precipitation (low inversions) and the other near the west coast of India, Fig. 10(a). It can be seen that, as expected, the airmass reaches the coast of India with much greater moisture content.

The above features were also observed in typical soundings, which showed the presence of a well-mixed humid layer of air near the surface and clearly indicated considerable increase in moisture content and surface temperatures downstream. These modifications are indicative of the importance of subsidence inversion across the sea and also the exchange processes between the Arabian Sea and the monsoon air mass (Manabe 1957; Colon 1965). Unfortunately these findings cannot be generalized because the necessary upper air data for the non-intense period is not available.

(c) *Energy associated with summer monsoon airmass over the Arabian Sea (following the motion) and its relation to the rainfall at the west coast of India*

In the following discussions, the parcel concept has been applied to the monsoon air mass over the Arabian Sea and all references to changes in the energy content of the parcel should be treated as applicable to the entire air mass.

I considered an air parcel, of unit volume, being transported to the west coast of India along a four day surface trajectory. Thus, if this parcel started at a certain appropriate location on the Arabian Sea on 20 June 1963, it would arrive at the coast of India at the end point of the trajectory on 24 June 1963. It is obvious that the latent energy content (Q_E) of the parcel would change during this period. To study a relationship between the amounts of energy of the parcel and the rainfall when it reaches the coast, it is first necessary to estimate the total energy of the parcel at the end point of the trajectory.

For this purpose I assumed that —

(*i*) The Q_E energy acquired by a parcel at a certain location on a four-day trajectory is equal to the energy transferred from the sea to the atmosphere at that point, and

(*ii*) The potential, internal and kinetic energies of the parcel are negligible throughout its passage across the sea to the coast of India.

It may be noted that these assumptions have certain limitations. For example, it is quite unlikely that the parcel would be without any potential, internal and kinetic energies during its passage over the sea. Also, it is perhaps unrealistic to assign point values of Q_E transfer to a moving parcel.

On the basis of the above assumptions I obtained values of Q_E transfer at various points on a four-day trajectory, from corresponding quasi-synoptic daily analyses of Q_E exchange between the sea and the atmosphere. Fig. 11 (a, b, c, d) and Table 2 show the relationship between Q_E and rainfall for the three cases discussed above.

Correlation coefficients are higher (0·743 and 0·768) when the parcel is to the east of 60°E than when it is to the west. In the latter case the correlation coefficient is 0.411. While the above discussions clearly suggest a relationship between evaporation over the Arabian Sea and intensity of rainfall at the west coast of India, they do not enable us to determine a physical cause-and-effect relationship : for example, it is not possible to decide whether evaporation over the Arabian Sea causes an intensification of rainfall at the west coast of India or *vice versa*.

5. Balance between the evaporation of moisture from the Arabian Sea and the precipitation at and near the west coast of India

To obtain rainfall distribution over the Arabian Sea, I assumed rainfall. varies linearly between the regions of maximum and minimum rainfall frequency (Fig. 3); the former is at the west coast of India and the latter is in the western Arabian Sea. This assumption enabled me to obtain a quantitative estimate of precipitation over the Arabian Sea from the rainfall data at the coast of India. The distribution of precipitation thus obtained was analysed and subtracted graphically from evaporation. Fig. 12 (a, b, c) shows the

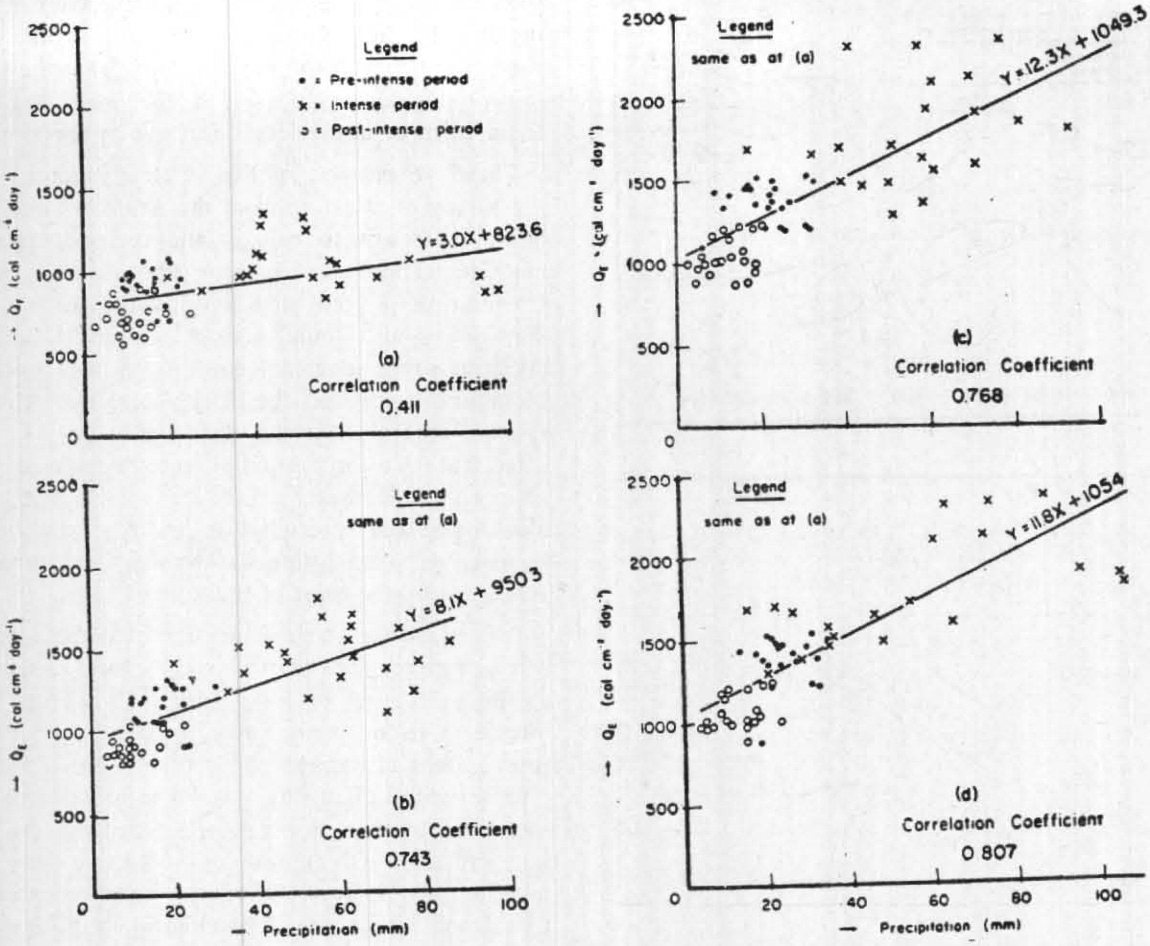


Fig. 11. Correlation between the Q_E transfer from the Arabian Sea to the atmosphere and the precipitation (cm day $^{-1}$) at the west coast of India for the four cases described in the text.

TABLE 2

Correlation coefficient between Q_E and P

No. of hours before the parcel reaches the coast	Correlation coefficient between Q_E and P
48	0·411
24	0·743
0	0·768

resulting evaporation *minus* precipitation (E—P) analysis for the preintense, intense, and postintense periods.

Fig. 12 (a, c), referring to non-intense periods, shows positive values for $E-P$ in the western part and negative values in the eastern part of the region. This implies that the atmosphere gained more moisture due to evaporation from the central Arabian Sea region than was lost through rainfall, and closer to the coast of India, precipitation exceeded the amount of moisture that evaporated into the atmosphere. Fig. 12 shows no positive E—P value during the intense period, and therefore, implies that rainfall exceeded evaporation over the entire region under consideration.

While it is difficult to suggest a physical explanation for these features, they may be attributed to the nature of the rain-producing mechanism as well as its capacity to raise or destroy the subsidence inversion in order that evaporated moisture be released as rain. It is probable that the mechanism is a convective scale activity which, in its turn, might be associated with synoptic disturbances at the surface.

However, some studies, notably Miller and Keshavamurty (1966), have shown that surface charts do

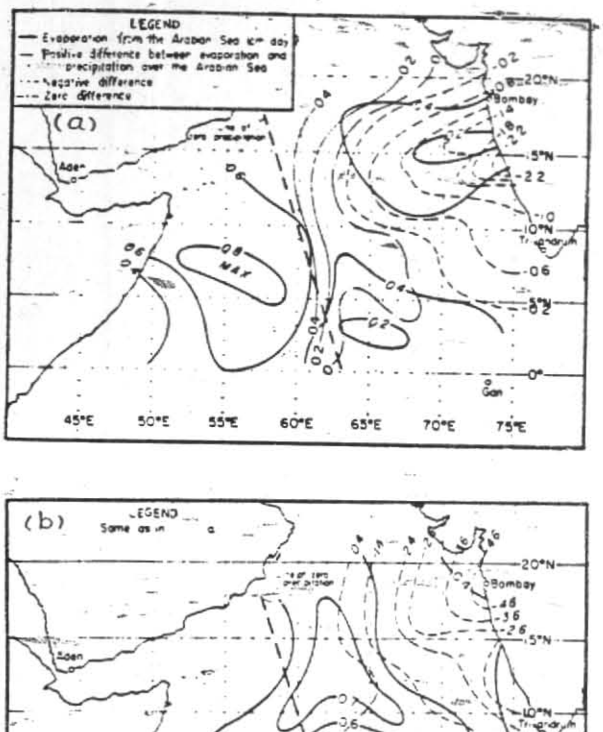


Fig. 12. Evaporation (cm day $^{-1}$) and evaporation *minus* precipitation patterns (cm day^{-1}) over the region of the Arabian Sea for (a) preintense, (b) intense and (c) postintense periods.

not indicate any disturbances over the Arabian Sea that can be associated with heavy rainfall along and near the coast of India. Moreover, the low-level flow along the northern portion of the west coast is divergent in the mean, though some of the heaviest rains frequently occur in this region. In fact, Ramage (1966) and Miller and Keshavamurty (1966) have concluded that the main rain-producing mechanism at the west coast of India exists at upper levels and not at the surface.

The *E—P* patterns of Fig. 12 clearly indicate that the supply of moisture from the Arabian Sea alone is not sufficient to explain the recorded rainfall amounts at and near and the west coast of India. In addition, I computed precipitable water from the dropsonde soundings of research aircraft taken at some selected locations off the coast of India and compared these with actually recorded rainfall at and near the coast. The results indicated that the recorded rainfall exceeded the amount of precipitable water. Venkateswaran (1956) has also found that precipitation exceeds evaporation by over 40 cm, during the season June through August, near the coast of India.

In view of the above, it appears that the amount of moisture required to explain the observed rainfall at the west coast of India, especially during the intense monsoon period must be sought from other sources in addition to the Arabian Sea. Jacobs (1951), while discussing the role of oceans as moisture suppliers for rainfall over land (in the northern hemisphere), also concluded that they are not the only source. However, while recognizing that Jacob's study was climatological, in this specific instance it seems quite certain that the hot and dry desert land-mass bordering the Arabian Sea, with subsiding air over it, cannot make any significant contribution of moisture to the monsoon atmosphere, though the southern India Peninsula might be expected to contribute some.

I would like to refer to the investigation of Ramage (1966), who found evidence that the Bay of Bengal constitutes the most significant source of moisture, in addition to the Arabian Sea, for rains over the west coast of India. Ramage has suggested that "the heavy rains over west India are unlikely without significant incursion of deeply moist air from the Bay of Bengal." Miller and Keshavamurty (1966), in one of the most detailed case studies of the Arabian Sea summer monsoon, reached a similar conclusion. They claimed that it is perhaps very significant that the rains over western India set in later than the rains of eastern India.

An examination of this hypothesis is beyond the scope of my study.

Acknowledgements

This work was part of the investigations of the meteorology of the Indian Ocean region, made possible by Grant GA-386 from the National Science Foundation.

Grateful appreciation is extended to the members of the IIOE group and the Department of Meteorology at the University of Hawaii. In particular, the author wishes to thank Dr. C.S. Ramage for his guidance throughout the duration of the research.

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DISCUSSION

C. RAMASWAMY : Does your paper support Dr. Pisharoty's hypothesis that monsoon rainfall is due to evaporation from the Arabian Sea?

AUTHOR : Yes.

COMMENT

P.R. PISHAROTY : While all water-vapour flux across the west coast of India need not be due to evaporation over the Arabian Sea, a significant contribution comes from the Arabian Sea. Especially since we saw that the trajectories of low level airflow (as shown in Daniel Cadet's paper) do not touch India but go round the Cape Comorin area.

Computations of latent heat flux based on the bulk aerodynamic formula need revision, as the vertical transport coefficients for momentum, heat and water vapour strongly depend on the stability conditions of the atmosphere. There is no satisfactory method of determining these transport coefficients except by the vertical eddy methods—u 'w', T 'w', q 'w'-values.