On the Maximum Cloud Zone and the ITCZ over Indian Longitudes during the Southwest Monsoon

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ABSTRACT

An investigation is presented of the daily variation of the maximum cloud zone (MCZ) and the 700 mb trough in the Northern Hemisphere over the Indian longitudes 70–90°E during April–October for 1973–77. It is found that during June–September there are two favorable locations for a MCZ over these longitudes—on a majority of days the MCZ is present in the monsoon zone north of 15°N, and often a secondary MCZ occurs in the equatorial region (0–10°N). The monsoon MCZ gets established by northward movement of the MCZ occurring over the equatorial Indian ocean in April and May. The secondary MCZ appears intermittently, and is characterized by long spells of persistence only when the monsoon MCZ is absent. In each of the seasons studied, the MCZ temporarily disappeared from the mean summer monsoon location (15–28°N) about four weeks after it was established near the beginning of July. It is reestablished by the northward movement of the secondary MCZ, which becomes active during the absence of the monsoon MCZ, in a manner strikingly similar to that observed in the spring to summer transition. A break in monsoon conditions prevails just prior to the temporary disappearance of the monsoon MCZ. Thus we conclude that the monsoon MCZ cannot survive for longer than a month without reestablishment by the secondary MCZ. Possible underlying mechanisms are also discussed.

1. Introduction

The Indian longitudes (70–90°E) are characterized by a large seasonal excursion of the maximum cloud zone [MCZ (Sadler, 1975)] from its mean winter location slightly south of the equator to the mean summer location near 20°N (Hubert *et al.*, 1969), in association with a similar excursion of the near-equatorial trough (Ramage, 1974). This monsoonal response can be attributed to the presence of a radiative source over the Indian continent in the Northern Hemisphere summer. In addition to the seasonal scale, the predominant time scales for the variation of the rainfall over the region are known to be the diurnal, synoptic (2–5 days) and a larger scale ranging from 2–5 weeks (Ramage, 1971). Prediction of temporal variations over the last two timescales is one of the central problems of monsoon meteorology. Clearly, detailed investigations of the observed variation of important components of the monsoon during the monsoon season are necessary for understanding the vagaries of the monsoon. We have undertaken such a study for the variation of the MCZ and the 700 mb trough over the Indian longitudes.

The daily variation of the MCZ over 70, 80 and 90°E based on NOAA satellite imagery has been investigated for the years 1973–77 during April to October. The variation of the location of the 700 mb trough is also studied for this period. We find that the details of the seasonal transitions as well as the fluctuations within the season vary from year to year. However, within this variability, certain features which occur year after year can be identified. Since such common features are likely to be fundamental components of the variations of the monsoon, their elucidation is our major aim here.

The data analysis is described in Section 2. The seasonal variation of the MCZ and the characteristics of different epochs of the MCZ in the transition phases are discussed in Sections 3 and 4, respectively. The fluctuation of the MCZ during the peak monsoon months of July and August are considered in Section 5. The relationship of the ITCZ to the MCZ as defined here is discussed in Section 6. Finally, Section 7 contains suggestions (of a somewhat speculative nature) of the possible mechanisms which could "explain" the observations presented.

2. Data

The environmental satellite imagery from the scanning radiometer data (visible) published by the NOAA Environmental Data Service were used in

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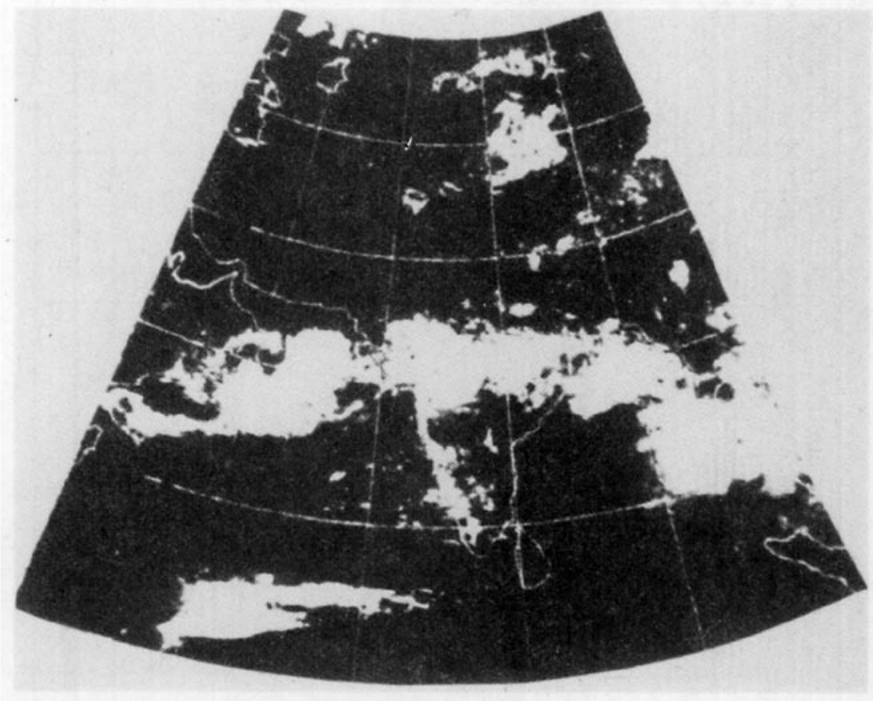

FIG. 1. The MCZ on 8 July 1973.

the study of cloud bands. The maximum cloud zone (MCZ hereafter) is taken to be that cloud band which has the maximum brightness, is predominantly zonal, and has a longitudinal extent of at least 10° (e.g., Fig. 1). On some occasions the MCZ comprises cloud clusters linked by regions of less intense cloud brightness, while on other occasions it is equally bright at all longitudes at which it occurs. Daily values of the latitudes of the northern limit, the axis, and the southern limit of the MCZ were read off at longitudes 70, 80 and 90°E from the cloud mosaics for the period April–October 1973–77. Since the MCZ is a well-defined large-scale band surrounded to the north and south by cloud-free regions, it is easily recognizable in satellite imagery. We expect the inaccuracies in our visual estimates to be about 1° latitude. These errors are unlikely to affect the conclusions since our major interest is in the analysis of the large-scale fluctuations of the MCZ. The data gaps were few and, in general, cloud data were available over the region of interest for more than 29 days in any month.

The latitudinal position of the 700 mb trough at these longitudes for the period of interest was obtained from the daily weather charts prepared by the Poona Weather Central of the India Meteorological Department. During the monsoon season (June–September) when the trough is located north of 15°N and is associated with vortices, the estimation of its axis is expected to be accurate to about 1° in latitude. However, in April and part of May when the trough is in the region south of 8°N, the estimation is likely to be less reliable since most of the reporting stations are located to the north of this latitude. As such, we consider the trough data only for the months of May–September.

3. Seasonal features

Fig. 2 depicts the monthly averages of the number of days on which the axis of the MCZ occurred at different latitudes during 1973–77 along 80 and 90°E. It is seen that the region between 0–10°N is favorable for the occurrence of the MCZ from April to October, although the belt 15–25°N is more favorable during June–September. This is also the case at 70°E. Thus we find that in the summer mean distribution over 70–90°E there are two MCZ's—one over the continent in the north and the other over the ocean to the south. Hereafter, we refer to the northern one as the monsoon MCZ and the oceanic one as an equatorial or secondary MCZ. Srinivasan (1968) and Sikka and Dixit (1972) have also reported the presence of this secondary MCZ which is seen near 5°N in the seasonal distribution of mean brightness presented by Hubert *et al.* (1969).

During June–September, the low-frequency belt between 7 and 13°N separates the northern MCZ from the southern one. We take the latitude of minimum occurrence along 90°E in this band, *viz.*, 7°N in June and September and 13 and 11°N in July and

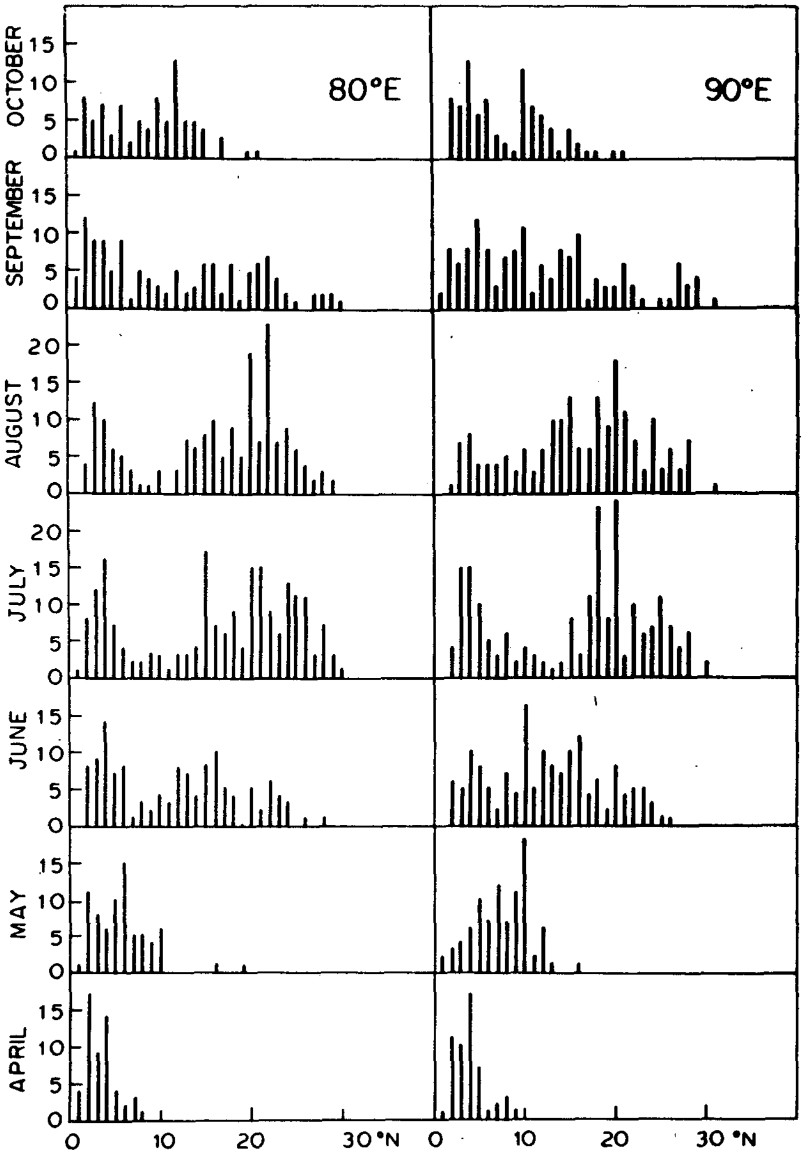

FIG. 2. Monthly mean of the number of days on which the axis of the MCZ occurred at different latitudes during 1973–77 along 80 and 90°E.

August, respectively, as the dividing latitude between these two MCZ's.[1] The mean monthly values of the latitude of the axis and the widths of the two MCZ's at 80 and 90°E are shown in Fig. 3. The standard deviations at 90°E are also indicated. The width of this band is maximum in July. In July and August the northern MCZ fluctuates predominantly in the region 15–25°N within which the monsoon trough is also known to fluctuate. Hence, in the discussion of the behavior of the MCZ during these peak monsoon months, we refer to the zone north of 15°N as the monsoon zone and that south of 15°N as the equatorial region. For the years 1973–77, we find that on 74% of the days in July and August, an MCZ is present in the monsoon zone, while on 34% of the days a secondary MCZ is present in the equatorial zone (Fig. 2). Of the number of days on which the MCZ is present in the monsoon zone, the secondary band is simultaneously present on 46% of the days.

4. Cloud band characteristics

The daily variation of the latitude of the axis and the width of the MCZ at 90°E is shown in Fig. 4.

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[1] The results obtained about the mean locations, widths, etc., of the two MCZ's are not sensitive to the particular choice of the dividing latitude, since the frequency of occurrence in the band 7–13°N is rather small.

The general characteristics of the variation of the MCZ at 70 and 80°E are similar to those at 90°E. The location of the 700 mb trough is also shown. When the trough and MCZ are both present, the correlation coefficients between their axes are 0.92, 0.85 and 0.80 at 70, 80 and 90°E, respectively.

The seasonal transitions, as well as the fluctuations during the peak monsoon (July–August), are seen to be rather complex. The MCZ is not present everyday either in the northern or equatorial regions. Rather, at any given longitude, it appears on a certain day at a particular latitude, persists for a certain length of time (with fluctuations in position) and then disappears. We find it useful to consider each such spell as a unit which we call an "MCZ epoch," with given date and latitude of origin and life span. The variation of the MCZ at any longitude is then described in terms of this unit as successive occurrences of MCZ epochs with specific life-history parameters.

One of the most conspicuous features of the cloud bands, which is seen in all the phases of the monsoon, is their tendency to move northward. This northward movement occurs either as a northward shift of a continuous MCZ or by generation of large clusters in the region to the north of the existing MCZ generally over the oceanic longitudes of 70 and 90°E, and subsequent generation of a continuous MCZ there. Often the northward movement is not gradual but occurs as an abrupt shift a day or two after the MCZ has persisted at the same latitude for a few days.

That the tendency for northward movement is statistically significant is seen from the following analysis. We filter the high-frequency fluctuations of the latitude of the axis of the MCZ by taking 3-day running means within each epoch. The change in the latitude of the axis per day (ΔL) is then obtained from these smoothed data for all the epochs. From this, changes of small amplitude ($|\Delta L| \leq 1$) are omitted (since these are within the error of location of the axis) and the frequency distribution of northward and southward displacement per day is obtained. This showed that out of 224 occasions on which northward or southward movement occurred, on 170 occasions (76%) it was northward whereas on 54 occasions (24%) it was southward. The null hypothesis of equal probabilities is strongly rejected at the 10^{-6} level. The 99% confidence interval obtained from the binomial distribution is 0.18–0.32 for probability of southward movement, indicating that the probability of northward movement is more than twice that of southward movement. Similar analysis for July–August also indicates that the probability of northward movement is significantly more than that of southward movement.

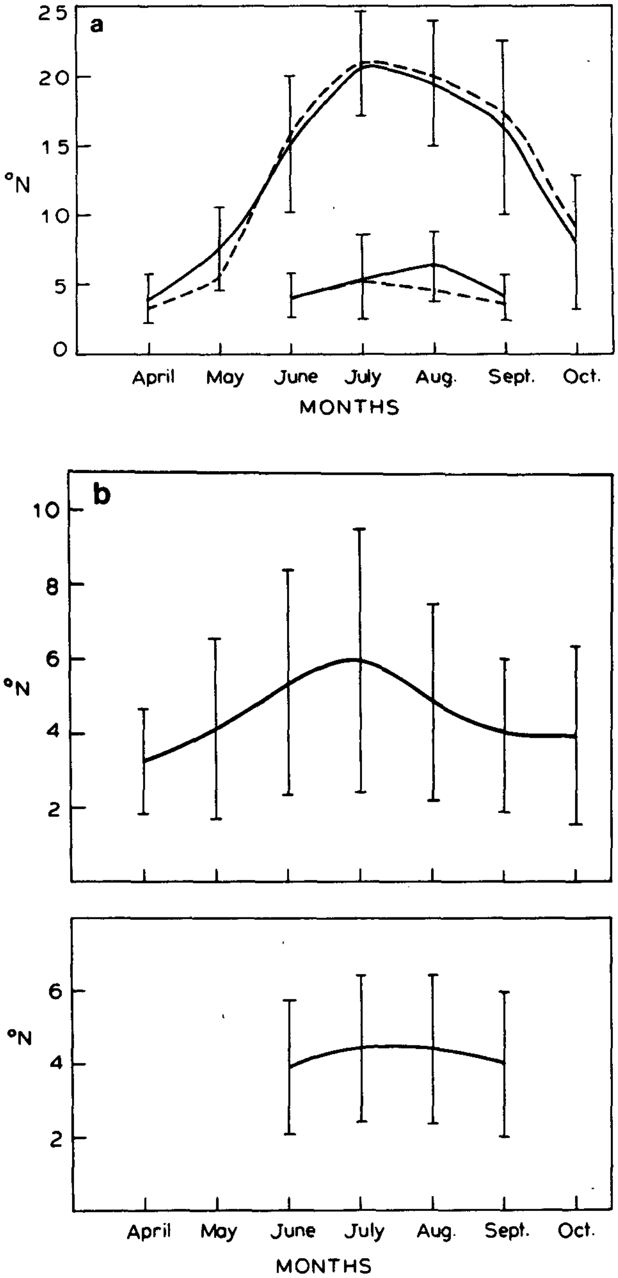

FIG. 3. (a) Monthly mean location of the axes of the northern and southern MCZ (solid line, 90°E; dashed line, 80°E). The standard deviation at 90°E is also shown. (b) Monthly mean width of the northern (top) and southern MCZ's at 90°E. The standard deviation is also shown.

The presence or absence of significant northward movement within the life span of an epoch is included as another feature specifying the nature of an MCZ epoch. Northward movement > 7° latitude within the life span of an MCZ epoch is considered significant since the standard deviation of its axis is less than 7° for every month (Fig. 3). Such epochs are refered to as northward moving epochs. As the general characteristics of the variations of the MCZ are found to be similar at all the longitudes, we

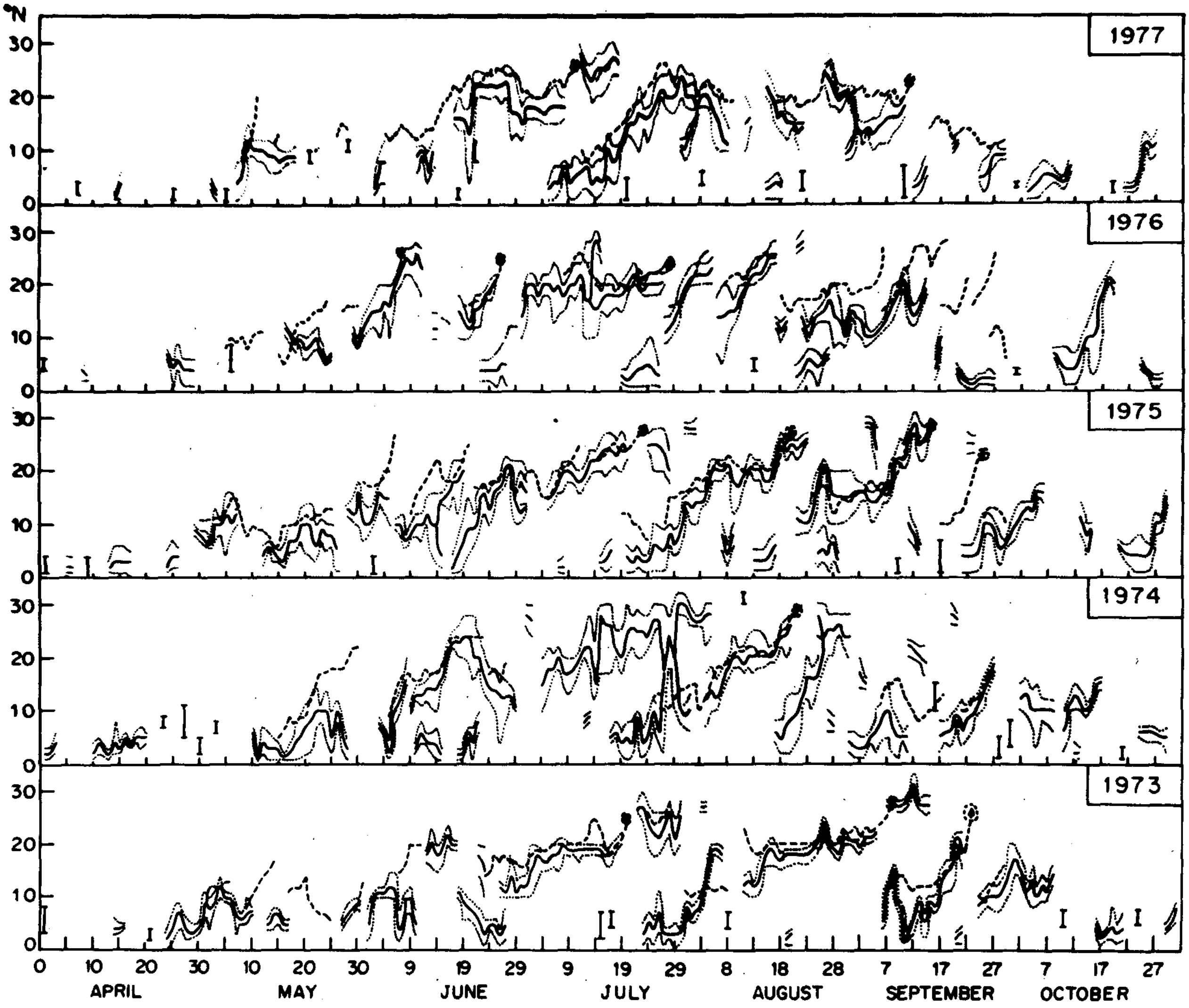

FIG. 4. Daily variation of the latitude of the axis of the MCZ (solid line); northern and southern limits (dotted line) of the MCZ; and the location of the 700 mb trough (dashed line) at 90°E during 1973–77.

restrict our discussion here to the features of the MCZ epochs at 90°E.

a. Life history parameters of MCZ epochs during April–October

The latitude and date of origin of an MCZ epoch is defined by the latitude and date at which it first appears at the given longitude. This appearance may be a result of the generation of a new cloud band at the location, or an advection of a band generated in the region to the east or the west. Generally over the oceanic regions south of 15°N at 70 and 90°E the appearance is associated with the generation of new bands. The frequency of occurrence of all the MCZ epochs and the northward moving ones with different latitudes of origin during April–October is shown in Fig. 5.

Fig. 6 depicts the number of MCZ epochs with different life spans. Epochs with life span of one day, and also gaps of one day in occurrence of the MCZ within an epoch, have been ignored. It is seen that northward moving epochs have the longest life spans; all epochs with life span greater than or equal to 18 days and 80% of those with life span greater than or equal to 10 days are of this type.

b. Month-to-month variations.

Table 1 gives the percentage of MCZ epochs originating in different latitudinal intervals during different months. Note that the latitudinal distribution of generation frequencies becomes bimodal in the peak monsoon months of July and August with one mode near the equator and another near 15°N. We find that 70% of the bands in July and 88% of

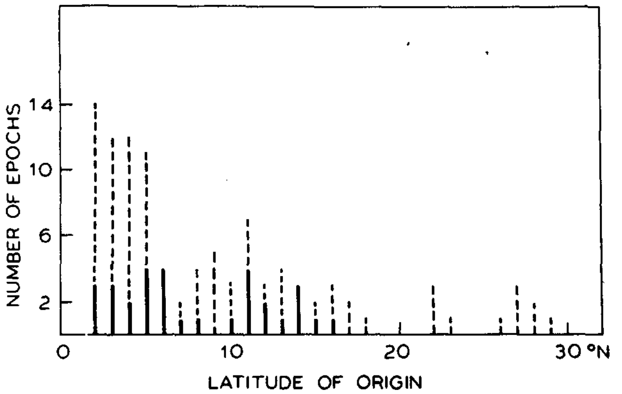

FIG. 5. Number of MCZ epochs with given latitude of origin during April to October: solid line indicates epochs with significant northward movement; dashed line all other epochs.

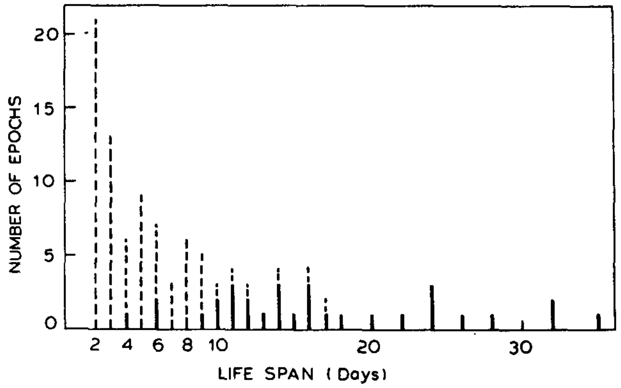

FIG. 6. Number of MCZ epochs with given life-span during April–October: solid line indicates epochs with significant northward movement; dashed line all other epochs.

the bands in August are generated in the equatorial region south of the monsoon zone. The few bands originating to the north of 25°N occur as a result of southwestward extension of midlatitude bands from northern China and Japan.

The percentage of epochs with life spans in different intervals for each month are given in Table 2. The MCZ epochs are characterized by short life spans of less than a week in April, while epochs with larger life span (2–3 weeks) occur during May–September. In July and August a few epochs with even longer life spans of about four weeks are observed.

c. *Seasonal transitions*

1) SPRING TO SUMMER TRANSITION

The northward shift of the MCZ from its mean location near 5°N in April and May to 20°N in July–August is accomplished by the successive generation of northward moving epochs in the equatorial region. The average rate of northward progression is 1° latitude per day. It is seen from Fig. 4 that the maximum latitude attained by each such band generally is farther northward than that of the preceding one. After one or more surges of this type the MCZ gets established near 20°N at all longitudes considered, toward the end of June or the beginning of July. It is interesting that this mode of northward shift of the MCZ is similar to the northward progression of monsoon rains over India which is also accomplished in surges, each surge taking the rainbelt farther northward.

2) SUMMER TO AUTUMN TRANSITION

This transition begins with the final disappearance of the monsoon band from the region north of 20°N toward the beginning of September. During this transition, the maximum latitude attained in each northward moving epoch decreases progressively.

d. *July–August epochs: Importance of northward moving bands*

The MCZ epochs in July–August can be classified into three types comprising those generated in the equatorial region which do not cross over into the monsoon zone (type I), those generated in this region which cross over into the monsoon zone (type II), and those generated within the monsoon zone (type III). We find that epochs of type I are characterized by short life-spans (mean 4 days), those of type III by somewhat longer life-spans (mean 6

TABLE 1. Percentage of epochs starting in different latitude intervals.

	Latitude (°N)									
Month	1–3	4–6	7–9	10–12	13–15	16–18	19–21	22–24	25–27	28–30
Apr	78	11	11							
May	11	67	22							
Jun	22	17	11	17	11	22				
Jul	31	6	0	12	19	6	0	6	12	6
Aug	26	16	16	16	16	0	0	5	5	0
Sep	10	35	5	15	5	5	0	10	5	0
Oct	23	46	15	15						

TABLE 2. Percentage of epochs with life span in given intervals.

Month	2–4	5–7	8–10	11–13	14–16	17–19	20–22	23–25	26–28	29–31	32–34	35–37
	Life span (days)											
Apr	67	22	0	11								
May	22	11	22	11	11	22						
Jun	28	28	22	5	11	0	5					
Jul	31	6	19	0	12	0	6	6	6	6	6	6
Aug	42	16	10	10	5	5	0	0	5	0	5	
Sep	45	10	5	15	15	0	0	10				
Oct	41	41	17									

days) and the northward-moving ones of type II by the longest life-spans (mean 22 days). It is interesting that the mean duration between successive generation of northward moving bands during April–October is also 22 days. Part of the life of the type II epochs is spent in the equatorial region and part in the monsoon zone. For the five seasons studied, type II bands accounted for about 82% of the days on which the MCZ was present in the monsoon zone and 78% of the days on which it was present in the equatorial region. Thus, type II epochs dominate the contribution of the other epochs in both the zones during July–August.

During these peak monsoon months there are fluctuations in the location and the intensity of the MCZ in the monsoon zone with spells of varying duration in which it is absent over this zone. Such cloud-free spells terminate either due to the formation of a cloud band within the zone, i.e., *in situ* generation by type III epochs or by northward movement via epochs of type II. We find that on nine occasions the revival occurred by *in situ* generation, whereas northward moving bands of type II accounted for the other 13 revivals. Results of Sikka and Dixit (1972) for 1966–70 seasons are similar in this respect.

5. Mid-season disappearance and revival of the monsoon MCZ

a. General pattern

We find that the following sequence of events takes place after the establishment of an MCZ in the monsoon zone in all the five seasons studied. For the first two to four weeks after establishment, this MCZ fluctuates within the monsoon zone persisting almost day after day (with only one or two short spells of 2–3 days duration in which it is absent) and then disappears. A secondary band is generated in the equatorial region more or less simultaneously with this disappearance. In three of the five seasons studied, 4–8 days later, a cloud band appeared in the region north of 25°N as a result of the westward extension of a midlatitude band from China or Japan. The secondary band in the equatorial region continued to persist, coexisting with this northern band throughout the latter's life span of 4–7 days. Soon after the disappearance of the MCZ from the monsoon zone (which implies the disappearance of this northern band in the three seasons in which it occurred or the disappearance of the band established toward the beginning of July in the other two seasons), the secondary MCZ begins to move northward. This northward movement lasts for about one week and leads to the reestablishment of the MCZ in the monsoon zone either via the band that moved northward persisting in the monsoon zone or via another northward moving MCZ epoch generated in its wake. This sequence of events occurred at least once in every season, and twice in the seasons of 1973 and 1975 (Table 3). The period between the establishment of the MCZ in the monsoon zone and the appearance of the secondary band which was responsible for the reestablishment in the monsoon zone can be calculated from Table 3. It varies from 25 to 33 days for the seven cycles with a mean of 28 days and standard deviation of 2.7 days. The largest value of 33 days occurred in the season of 1974 in which the disappearance of the monsoon MCZ was preceded by a merger with a northward moving equatorial MCZ which occurred 25 days after the establishment in the monsoon zone. These observations suggest that the monsoon MCZ does not survive for longer than one month after its establishment in the monsoon zone without interaction with or reestablishment by northward moving epochs of the secondary MCZ.[2]

It is seen from Fig. 4 that during spells in which the monsoon MCZ was continuously present for periods of two weeks or more (with the exception of that preceding the merger in 1974) the secondary MCZ appeared rather intermittently with each epoch being characterized by short life spans. The secondary MCZ persists for longer periods only when the monsoon MCZ disappears.

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[2] A referee has drawn our attention to a recent investigation by Yasunari (1979) of satellite-derived cloudiness during the season of 1973 using spectrum analysis. He finds that of the two dominant modes, one is characterized by a 30–50 day period. Fluctuations of this mode show northward movements which are significant over the Indian longitudes and seem to be of the type described here as an important feature of the transients of the MCZ.

TABLE 3. Cycles of midseason disappearance and revival.

Year	Cycle	Life-span of band in the monsoon zone after establishment	Life-span of band generated north of 25°N	Life-span of the secondary band responsible for re-establishment	Period during which this secondary band moved northward
1973	I	2–19 Jul	22–30 Jul	23 Jul–7 Aug	30 Jul–7 Aug
	II	14 Aug–5 Sep	9–15 Sep	6–21 Sep	14–21 Sep
1974	I	3 Jul–5 Aug	—	2–20 Aug	6–10 Aug
1975	I	25 Jun–20 Jul	24–28 Jul	20 Jul–22 Aug	29 Jul–7 Aug
	II	3–22 Aug	1–5 Sep	21 Aug–13 Sep	6–13 Sep
1976	I	30 Jun–27 Jul	—	28 Jul–3 Aug	28 Jul–1 Aug
1977	I	21 Jun–9 Jul	11–17 Jul	5 Jul–8 Aug	18–26 Jul

b. Case history of reestablishment in the season of 1975

To illustrate a typical sequence of the reestablishment of the monsoon MCZ by a northward moving epoch of the secondary MCZ, we discuss below some features of the nature of the MCZ and the synoptic situations during the period 14 July–7 August 1975. Details of the location of the MCZ and the 700 mb trough along 80 and 90°E, are shown in Fig. 7. With the disappearance of the monsoon MCZ on 20 July, the secondary MCZ formed and

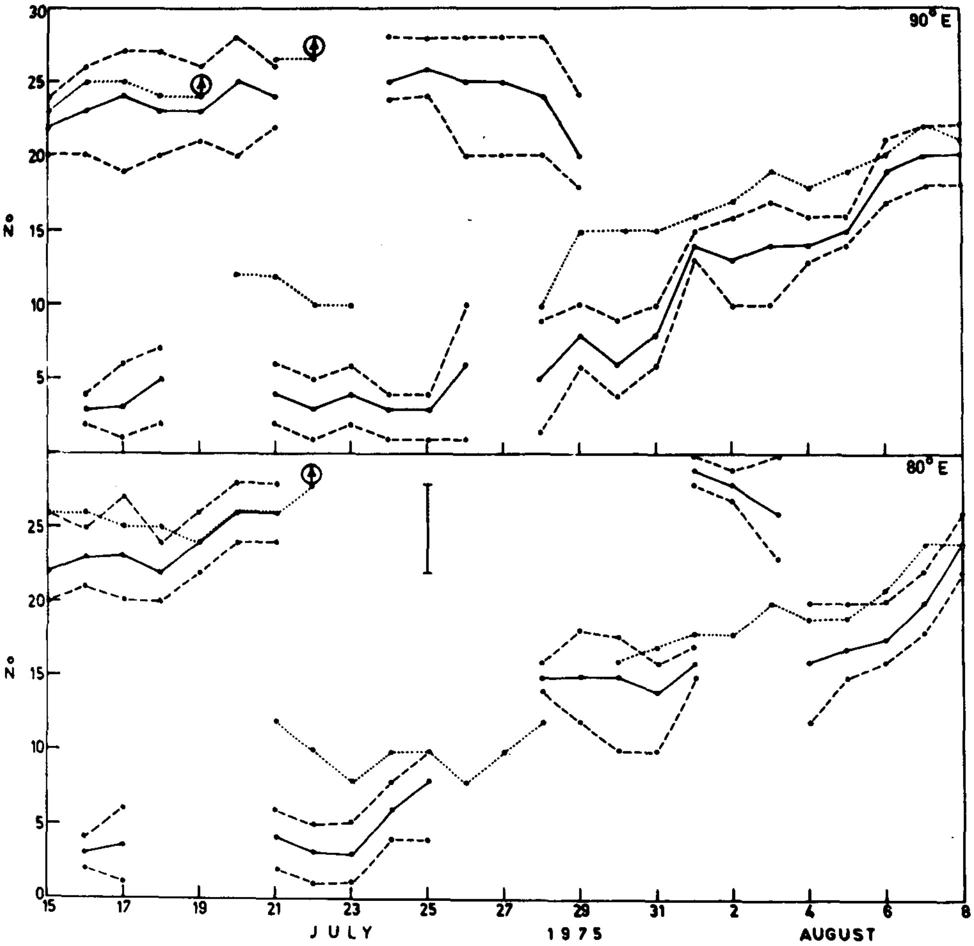


FIG. 7. Daily variation of the latitude of the axis of the MCZ (solid line); northern and southern limits (dashed line) and the location of the 700 mb trough (dotted line; the arrow implies a shift to the foothills) for the period 15 July–8 August 1975 at 90°E (above) and at 80°E (below).

TABLE 4a. Major features of the behavior of the MCZ during 14 July–8 August 1975 at 80°E.

Feature	Life span	Starting latitude (°N)	Ending latitude (°N)
1. Northward movement within the monsoon zone	14–21 Jul	22	26
2. Pulse of northward movement of the equatorial MCZ	21–25 Jul	4	8
3. Formation of the MCZ near the monsoon zone	28 Jul–1 Aug	15	16
4. Pulse of northward movement of the MCZ leading to reestablishment near the seasonal mean	4–8 Aug	16	24

moved northward, reestablishing the monsoon MCZ near its mean location by 7 August.

At 90°E the northward movement is continuous but it is not uniform, with large changes or jumps occurring on three occasions. At 80°E the MCZ appears in three spells with northward movement in the first and the last (Table 4a). The major synoptic events of the period 14 July–8 August are summarized in Table 4b. The noteworthy features are as follows:

1) The northwestward movement of a monsoon depression to the foothills followed by a "break monsoon" situation.

2) Establishment of a trough of low pressure and a region of cyclonic vorticity in the region south of 11°N with formation of disturbances in this zone during the break.

Koteswaram (1950) and Mukherjee and Natarajan (1968) have also suggested that during break monsoon the equatorial zone becomes favorable for formation of disturbances at 700 mb.

3) Northward shift of this zone accomplished by successive formation of three disturbances each generated to the north of the previous one and moving northwestward.

It appears that the northward movement of the MCZ during 21 July–8 August is associated with lower tropospheric transient disturbances (3–5 in Table 4b). The 700 mb charts for one day in the life history of each of the three disturbances are shown in Fig. 8. The satellite mosaics for the last phase of northward propagation during the reestablishment are shown in Fig. 9. The similarity in the nature of MCZ transients at 70, 80 and 90°E suggests large-scale organization.

We consider next the nature of the temporal variation of the sea level pressure departure from normal and the 900 mb relative vorticity over this large scale. The basic data for this are obtained by picking the daily values of the pressure departure from (5-day) normals and the wind at 2.5° intervals from 5–27.5°N and 70–90°E from analyzed charts. The variation of the zonal mean of the computed pressure departure and relative vorticity over this longitudinal belt are shown in Fig. 10. The northward propagation of the negative pressure anomaly and maximum relative vorticity is consistent with that of the other features documented earlier. Weekly weather reports of the India Meteorology Department for this period also show northward shift of the rainbelt from the southern peninsula during 23–30 July, to central India for the week ending 13 August. All these results lend support to our suggestions about the process of the reestablishment of the monsoon MCZ by northward movement (Section 5a).

6. Intertropical convergence zone (ITCZ) and the MCZ over the Indian longitudes

The monsoon trough is a principal feature on the synoptic charts of the lower and middle troposphere over India in the summer season. During July and August the 700 mb trough is approximately along 22°N between 70 and 90°E. The trough zone is characterized by the occurrence of maximum cyclonic vorticity and convergence in the lower troposphere (Anjaneyalu, 1969) and maximum nonorographic precipitation over India (Raghavan, 1973). In addition, there is a close association between the monsoon cloud band over India and the 700 mb trough (Bedi and Sikka, 1971; Bhaskar Rao *et al.*, 1972). Our data also indicate a high

TABLE 4b. Major synoptic features for 14 July–8 August 1975.

Major events	Life span	Starting position	Final position
1. Low which became a depression	16–22 Jul	23°N, 88°E	29°N, 76°E
2. Break monsoon situation	23–29 Jul		
3. Cyclonic circulation between 900–700 mb	22–28 Jul	8°N, 84°E	15°N, 70°E
4. Low pressure area extending up to 700 mb	30 Jul–1 Aug	16°N, 87°E	18°N, 80°E
5. Low which became a depression	2–8 Aug	17°N, 87°E	24°N, 81°E

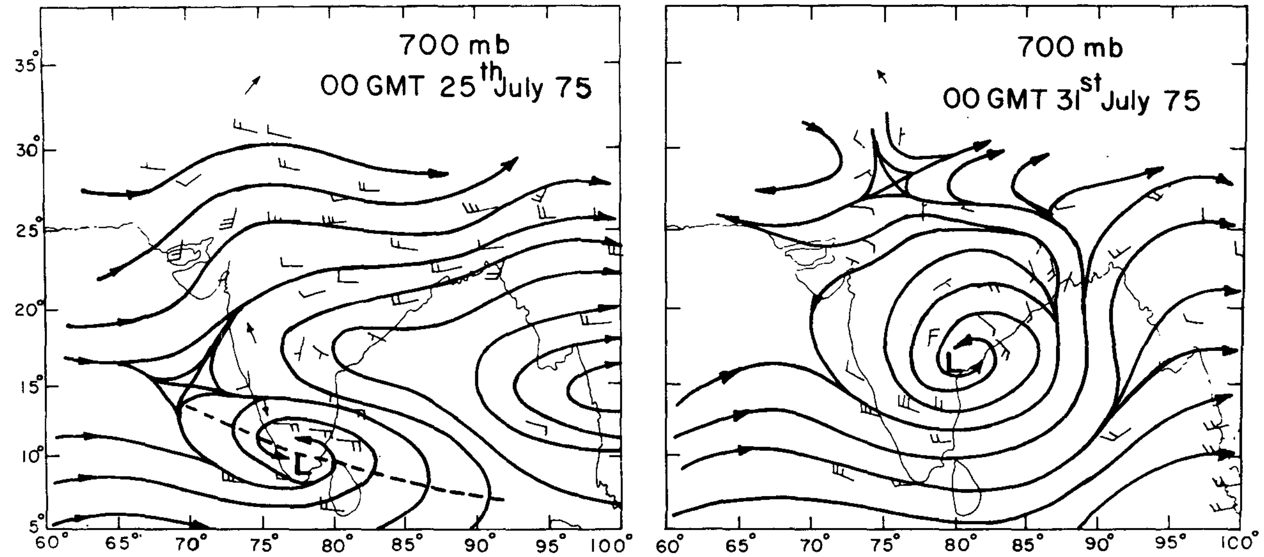
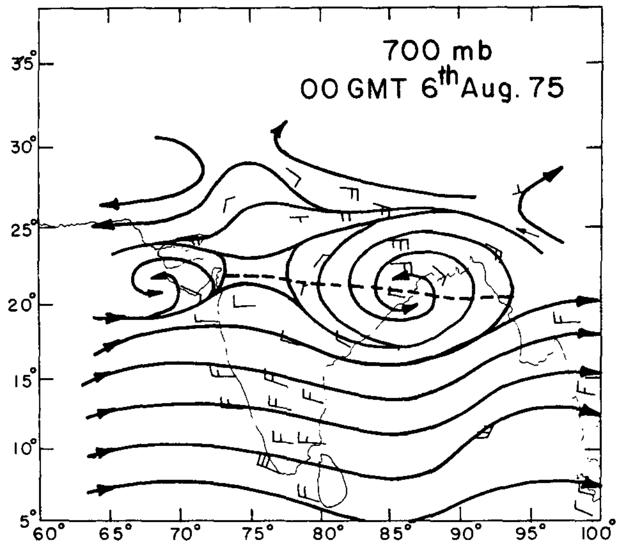


FIG. 8. Streamlines at 700 mb for 25 July, 31 July and 6 August 1975 at 0000 GMT.



correlation between the axes of the MCZ and 700 mb trough on a day-to-day basis. Putting all these together, it becomes clear that the organized moist convection associated with the monsoon trough may be attributed to a continental ITCZ over the region. This surmise is consistent with the characteristics of an ITCZ, *viz.*, the presence of a prominent zonally oriented region of moist convection in the tropics associated with high cyclonic relative vorticity and convergence. Thus the monsoon MCZ could be considered as a manifestation of a continental ITCZ and the secondary MCZ of an oceanic one.[3]

We find that the establishment of the continental ITCZ in the beginning of July is accomplished by northward progression of the oceanic ITCZ. The observed northward migration is not gradual but is brought about in surges. An examination of the synoptic charts for the periods in which northward surges occurred showed them to be associated with the formation and northward movement of synoptic-scale disturbances originating in the oceanic ITCZ.

In Section 5a we have shown that right in the middle of the season, about four weeks after its first establishment, the monsoon MCZ disappears from the monsoon zone. Northward moving epochs of the secondary MCZ generated within a few days of the disappearance of the monsoon MCZ lead to the reestablishment of the latter. Epochs preceding this temporary disappearance of the monsoon MCZ were found to be associated with the commencement of break monsoon conditions on examination of the daily weather charts. Thus, it appears that although during most of the active monsoon period the continental ITCZ is dominant, at least once in the middle of every season the oceanic ITCZ becomes dominant in a spell characterized by break monsoon conditions.

7. Discussion and interpretation

The major features of the behavior of the ITCZ during the summer over the monsoonal region studied here are as follows:

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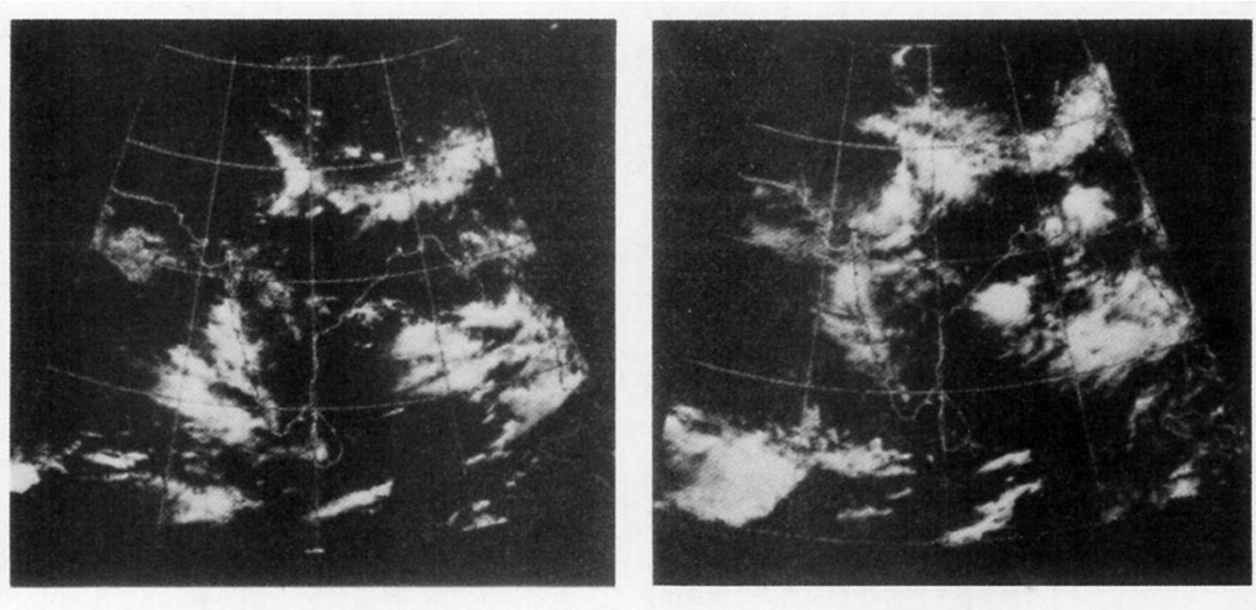
[3] Since on occasions there are two MCZ's simultaneously present over the same longitudinal belt, it is clear that the convergence in only one of them can be intertropical. Nevertheless, the term ITCZ is used here to denote a system with the above characteristics.



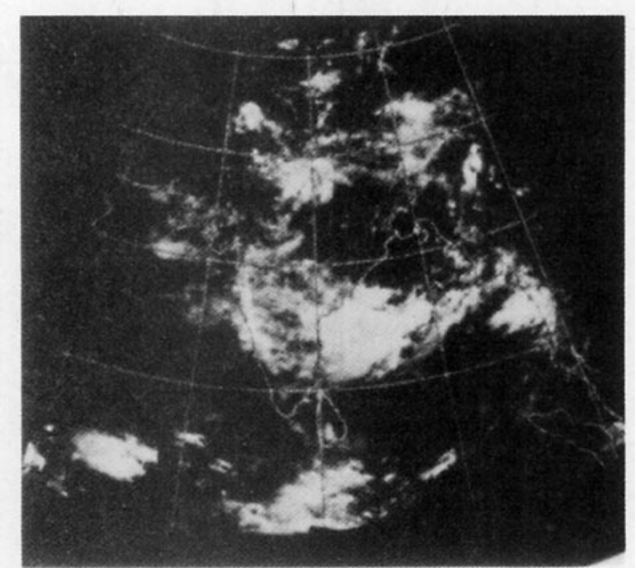


FIG. 9. Satellite mosaics for 2–8 August 1975.

1) The presence of two ITCZ's—a continental one in the north on a majority of the days and (sometimes simultaneously) an oceanic one in the equatorial belt of the Northern Hemisphere. Epochs of the oceanic ITCZ are characterized by long life spans only when the continental ITCZ is absent.

2) The important role played by northward moving epochs generated over the warm oceanic equatorial zone in the transition phases as well as the peak monsoon months.

3) A time-scale of about four weeks which has emerged as being the maximum period for which the continental ITCZ can survive after its establishment near the seasonal mean location without interaction with or reestablishment by an oceanic ITCZ. Within this period, after a temporary disappearance, the monsoon MCZ is regenerated by formation of disturbances within the monsoon zone. At the end of this period, a spell characterized by the absence of the continental ITCZ occurs and revival from this situation is brought about by northward moving epochs of the secondary ITCZ.

Now we speculate about possible mechanisms responsible for such behavior of the ITCZ over the Indian longitudes by considering these aspects one by one. First, it is known that the location of the ITCZ is determined by the interplay of various factors such as the location of the radiative heat source (which would also be that of the maximum sea surface temperature for the oceans) and boundary-layer pumping and moisture availability (Charney, 1969; Manabe, 1969a,b; Pike, 1971; Manabe *et al.*, 1974). The situation in summer over the Indian longitudes is complex with the radiative source region lying over the large land mass in the tropics and the maximum sea surface temperature occurring in the equatorial regions (Saha, 1971). Thus, the atmosphere is faced with the choice of forming an ITCZ in the warm oceanic regions near the equator or over the heated continent to the north or a combination of both. It is seen that the choice made

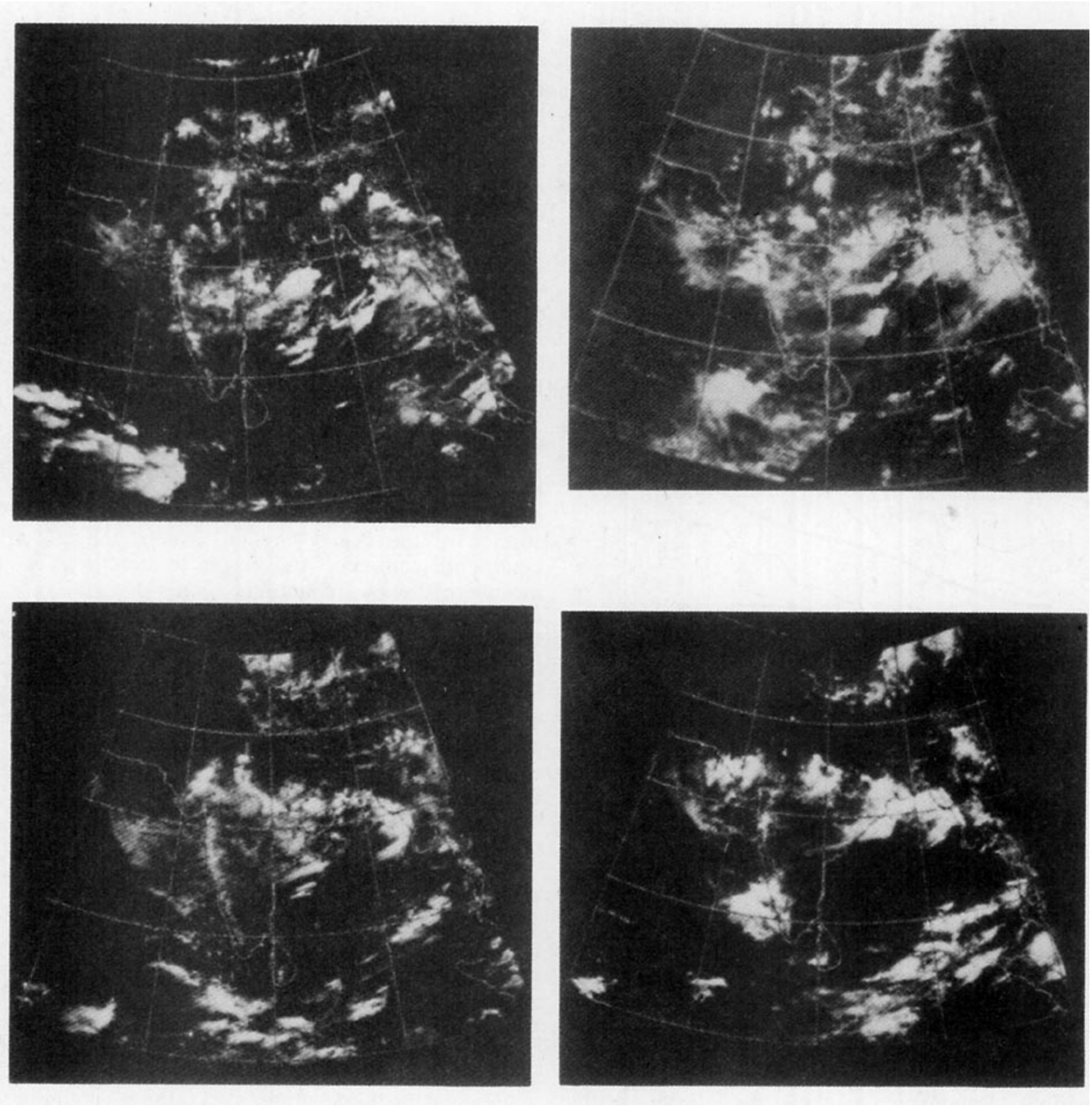
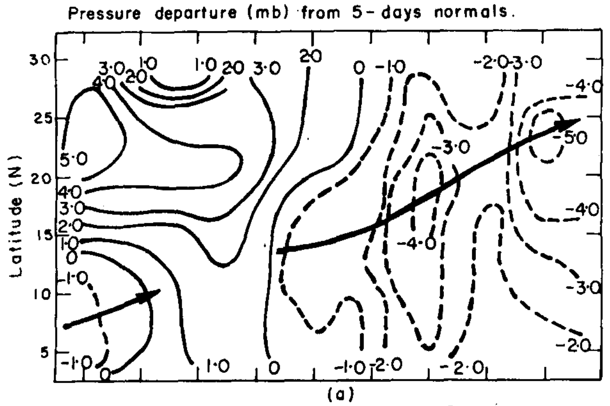


FIG. 9. (*Continued*)

consists of a combination of both, with the continental ITCZ being dominant most of the summer.

Webster *et al.* (1977) have developed a relatively simple coupled atmosphere-ocean model to investigate the role of land-ocean contrasts, and ocean-atmosphere interaction in determining the planetary-scale monsoon. When effects of clouds were incorporated into this primitive equation model, it yielded two zones of maximum precipitation in the summer—one over the continent near its southern boundary and one over the ocean near 5°N. The oceanic zone became prominent only when there was no precipitation in the continental zone. This result is consistent with the first aspect noted above.

We find that throughout the period April–October, even in the peak monsoon months, a vast majority of bands are generated over the oceanic region south of the monsoon zone. Thus, although the continental location is more favorable for oc-



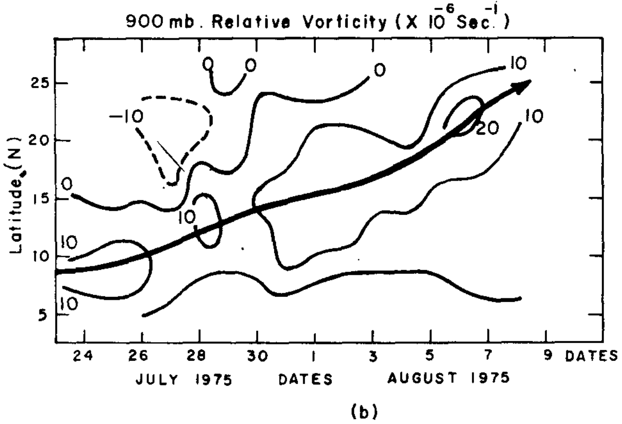


FIG. 10a. Meridional profile of sea level pressure departure (mb) from 5-day normal, averaged for 70–90°E, for the period 23 July–8 August 1975.

FIG. 10b. As in Fig. 10a except for 900 mb vorticity ($\times 10^{-5}$ s^{-1}).

currence during the peak monsoon months, the generation remains largely oceanic and hence the major contribution to the maintenance of the monsoon MCZ in the monsoon zone comes from the northward moving epochs.

To interpret the last aspect, it is necessary to first understand the basic cause of fluctuations with periods of about two weeks in the intensity of the continental ITCZ. One factor worth considering in this respect is the long-term effect of deep convective clouds associated with the ITCZ. The radiative effect of increased clouds is twofold. On the one hand, the albedo is increased and the reduction in solar input tends to cool the surface. On the other hand, the emission of longwave radiation to space is reduced because the "surface" as seen through the atmospheric window is of lower temperature. Increased cloud also blocks the atmospheric window and returns additional longwave radiation to the ground. Whether the net result is a cooling or warming depends on various factors such as the cloud temperature, its geographical position, etc. Results of Schneider's (1972) investigation of a simple radiation flux model indicates that the net flux difference due to an increase in cloudiness is negative at latitudes equatorward of 40°. If this result also holds for the clouds in the ITCZ, we expect the strength of the radiative source to decrease due to the clouds, thus implying the presence of a negative feedback on the ITCZ, over time scales of the order of two weeks or so.

In a simplified form the action of the clouds may be represented as follows: Initially when the ITCZ is getting established near the radiative source we expect a positive feedback from clouds because the latent heat released in the clouds leads to the intensification of the ITCZ by CISK (Charney and Eliassen, 1964). However over long time scales, the negative effect of increased albedo dominates the positive effects of increased absorption of longwave radiation and a negative anomaly of the radiative heat flux will appear. As suggested by Monin (1972, p. 112) as a result of this negative anomaly—"The surface of the ocean (in our case of the moist continent) will cool and begin to cool the atmosphere; downward motions will develop in the atmosphere and the clouds will begin to disappear. With a decreased amount of clouds the ocean (again, land in our case) will undergo an increased warming, the conditions with which we began will be established and the whole process repeated." Such a process could lead to fluctuations between active and weak spells in the monsoon. In this regard, it is interesting that fluctuations in the intensity of the precipitation occur in Webster *et al.*'s (1977) model only when clouds and the hydrological cycle are incorporated into it.[4] Krishnamurthy and Bhalme (1976) also attribute the prominent 10–15 day periodicity they found in the fluctuations of all the components of the monsoon system they studied, including rainfall, to the effect of clouds. Thus, it appears that the fluctuations in the monsoon could be attributed to the effect of clouds.

Let us assume for a moment that the above hypothesis for fluctuations is correct, and attempt to understand the third feature listed at the beginning of this section. We suggest that this behavior arises due to a special constraint experienced by an ITCZ located on land, *viz.*, a moisture constraint. A few days after the establishment of the ITCZ with the associated high rainfall, conditions at the moist surface of the land may not be very different from those at an oceanic surface. However, subsequently there may be a slow but steady depletion of moisture

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[4] We have just learned of a subsequent study of a similar model by Webster and Chou (1980) in which they find that the revival of the monsoon circulation from weak phases (which alternate with active phases on a time scale of the order of two weeks) occurs with the poleward movement of the rising limb of the equatorial Hadley cell. This is strikingly similar to the observations reported here.

(through absorption by soil, runoff, etc.), so that at the end of about one month the conditions at the land surface become markedly different from those at the oceanic surface. At this point a break occurs either due to the negative feedback of clouds or to moisture depletion or a combination of these factors. When cloud-free conditions restore the strength of the radiative heat source, the monsoon cannot revive without replenishment of the moisture. In fact, conditions become similar to those prior to the onset and revival occurs by a process which is also strikingly similar, i.e., by northward movement of the oceanic ITCZ.

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