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The 10 to 20-day westward propagating mode and "Breaks in the Monsoons"

By T. N. KRISHNAMURTI and PHILIP ARDANUY, *Department of Meterology, Florida State University, Tallahassee, Florida 32306, U.S.A.*

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ABSTRACT

This study utilizes daily surface pressure data records for a 40-year period (1933 to 1972). The dominant transient modes of the wave number frequency spectra of surface pressure along the latitudes of the monsoon trough (i.e., 20° to 30° N) are determined from a longitude–time composite of roughly 3 months of surface pressure data for ten separate episodes of Breaks in the monsoons. This data base is composited relative to a reference (0, 0) which denotes the day of commencement of the Break in rainfall over central India and the longitude of central India (i.e., 75° E). These dominant modes, as determined from this composited data, exhibit interesting westward as well as eastward propagating modes. Furthermore, some of the salient modes exhibit steady variations of phase from one day to the next. The period of Breaks in the monsoon rainfall is shown to coincide with a pressure rise associated with the arrival of a ridge of the dominant modes over the reference origin (0, 0). The remaining 30 years of data are next subjected to a test of a hypothesis that the steady propagation of phase of a dominant westward propagating mode can be used to extrapolate, and thus to predict, the arrival of this ridge. The tests show that a 10-day linear extrapolation of the phase to Day 0 exhibits considerable skill in locating the ridge of the "Monsoon Breaks" over central India. In over 70% of the cases examined we note that the arrival of the ridge coincides with a period of the observed Breaks in the monsoon. Suggestions for casting this problem in a truly predictive frame are made, the results of which will be reported in a separate study.

1. Definition of "Breaks in the Monsoons"

The phrase "Breaks in the Monsoons" is an accepted terminology for describing an inactive spell in the monsoon rainfall over Central India (Hahn and Manabe, 1975). In his text on Southwest Monsoons, Rao (1976), provides the following definition for this phenomenon:

> There are periods when the monsoon trough is located close to the foot of the Himalayas which leads to a striking decrease of rainfall over most of the country but increases along the Himalayas and the southern Peninsula. Such a situation is referred to as the Break in Monsoon.

2. Introduction

Fig. 1a, b illustrates the daily rainfall totals over Central India (averaged between 73° to 82° E and 12° to 25° N) for two individual years, i.e. 1967 and 1972. The periods of "Breaks" in the rainfall are apparent in these diagrams. Also shown in these diagrams is the curve of the long term mean calandar day rainfall based on 40 years of daily rainfall records. The present paper is devoted to an investigation of planetary scale propagating waves and their role in the regional "Breaks" of the monsoon rainfall over Central India. Our study is an observational approach based on 40 years of daily surface pressure data sets.

Our present knowledge on the Breaks in the Monsoons may be summarized as follows:

(i) An examination of 80 years (1888–1967) of rainfall records over India led Ramamurthy (1969) to define the observational characteristics of "Breaks" of summer monsoon over India.

His major findings are:

(a) The most frequent duration of Breaks is 3 to 4 days.

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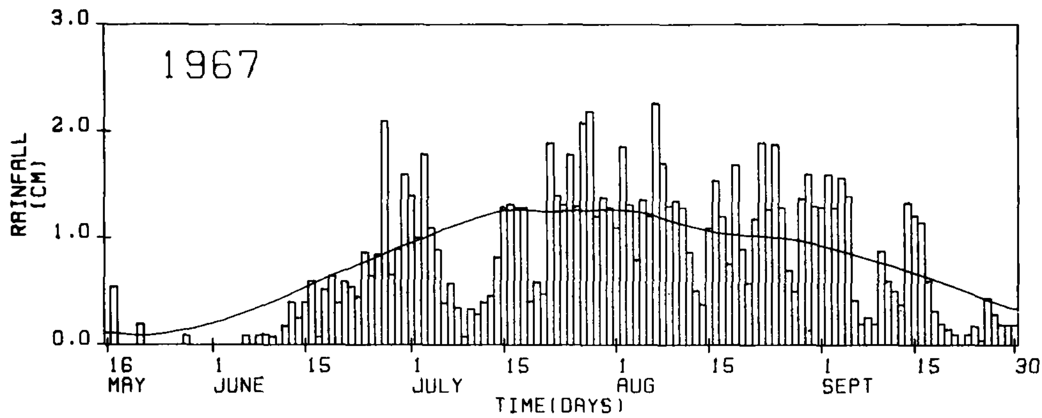

Fig. 1a. Daily rainfall totals (in centimeters) during 1967 over central India. The solid curve denotes long term mean calendar day rainfall.

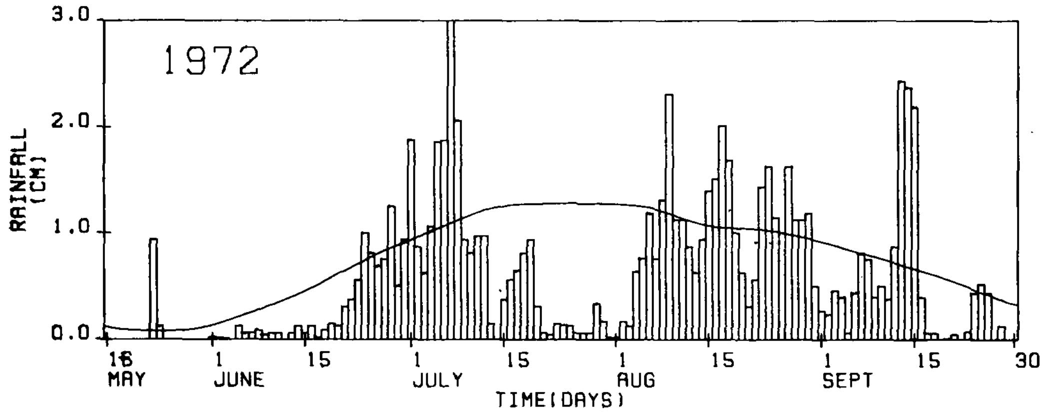

Fig. 1b. Daily rainfall total (in centimeters) during 1972 over central India. The solid curve denotes long term mean calendar day rainfall.

(b) The longest Breaks last from 17 to 20 days.

(c) The average duration of Breaks is around 6 days.

(d) Breaks are more common in August than in other months of the monsoon season.

(e) Pressure rise of the order of 4 mb is noted during Breaks over Central India.

(f) During 12 out of a total of 80 years there were no reported Breaks in the Monsoons.

(ii) M. Murakami (1976), and Krishnamurti and Bhalme (1976) have noted an alteration between active and inactive monsoon spells. They found that during years of near normal rainfall, the period of alternation between active and inactive spells is around 2 weeks. Murakami further noted an interesting counterclockwise rotation of the surface pressure cells (highs and lows) with this 2-week period over India. Krishnamurti and Bhalme also noted from power spectral analysis of 100-day data records a near 2-week periodicity for such elements as cloud cover, rainfall and intensity of the lower and upper tropospheric monsoon currents.

(iii) T. Murakami and Frydrych (1974) have also distinguished between active and inactive periods from spectral analysis of upper tropospheric winds and have noted similar periodicities.

(iv) During periods of Breaks, the axis of the monsoon trough over Northern India is known to move northward towards the mountains. The rainfall belt around 20° N also moves northward to the foothills of the Himalayas with the migration of the trough. This is associated with a northward propagation of a lower tropospheric anticyclonic belt from the near equatorial latitudes towards Central India (Rao, 1976). During the Breaks two rainfall belts are usually observed. One of these is located near 25° N and the other is found near 7° N.

(v) The lower level cross-equatorial jet over the Arabian Sea has been investigated by Findlater (1969), Hart et al. (1978), Krishnamurti et al. (1976). Presently available data sets are inadequate to define its structure over the Arabian Sea during different periods. Observations over Western India show that during "Breaks" a northern branch of the Arabian Sea current (near 20° N) is more intense compared to the southern branch around 5° N (Rao, 1976). During active monsoon periods the converse is usually found.

(vi) Krishnamurti and Bhalme (1976) attributed the alternations between active and "Break" spells of the monsoons to cloud feedback and associated large scale radiative effects. The active spells produce widespread cloud cover, a reduction in the shortwave radiation and a gradual stabilization of the lower troposphere, thus inhibiting the further growth of deep convection. A cycle between a stabilizing and a destabilizing phase was postulated as a natural oscillation of the monsoons forced by its own heating cycle.

A formal test of the above hypotheses was presented by Webster et al. (1977). In this study the inclusion of cloud feedback in a planetary scale numerical model is shown to produce intra-seasonal oscillations with active and "Break"-like conditions with shifts in the circulations and rainfall patterns quite analogous to what is known from observations presently.

None of the aforementioned studies have examined the zonal or meridional (inter-hemispheric or middle latitude) interactions of the monsoons. It is conceivable that the "Breaks" may be preceded by the zonal and/or meridional propagation of anomalies of high pressure at sea-

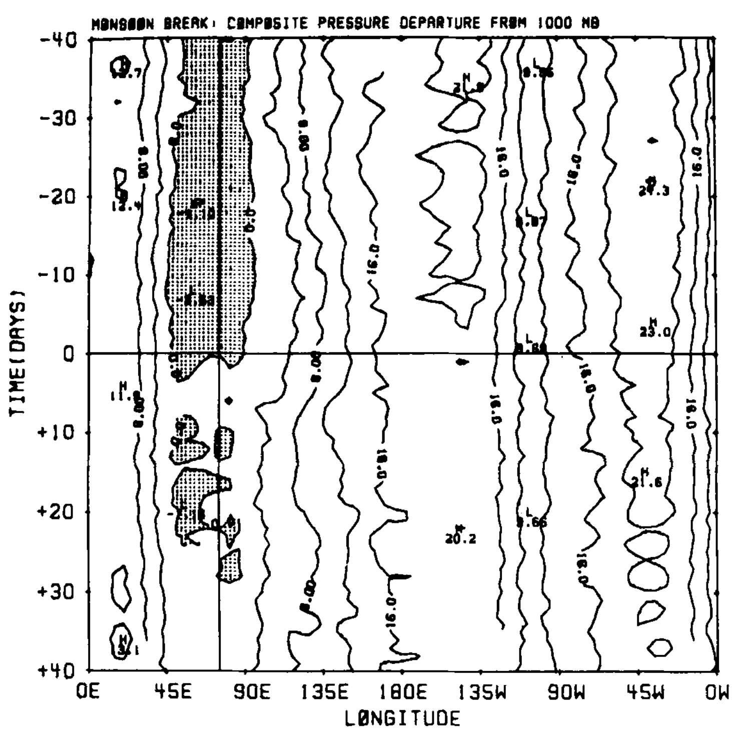

Fig. 2. A longitude–time (x–t) diagram for 20° N to 30° N latitude belt of surface pressure based on 10 years of composited Breaks. 0 along ordinate denotes reported date of first occurrence of Break. Vertical line along 75° E is the reference longitude over central India. Departures from 1000 mb are analyzed in intervals of ±4 mb. Strippled region denotes pressure less than 1000 mb.

level into the monsoonal regions. The data sets presently available limit the scope of present study to an investigation of "zonal interactions" in the lower troposphere from the sea-level pressure data.

3. Data sources

The 40 years of daily surface pressure records are obtained from the Northern Hemisphere sea-level pressure daily charts by the U.S. National Climatic Center as Asheville. This data set is resolved by a 5° longitudinal separation. The period covered is from 1933 through 1972.

3.1. *A time dependent compositing technique*

We shall here show a composite x–t diagram for the pressure during the "Breaks in the Monsoons", where x is the zonal direction around the globe along a reference latitudinal belt (20° to 30° N)

Table 1. *A tabulation of "Break" periods based on Ramamurthys' (1969) data sets*

Year	Period of reported "Break"	Length of reported Breaks in days	Assigned category	Success (S) or failure (F) in extrapolative prediction
1933	Aug 13–Aug 20	8	C	
1934	July 11–July 18	8	C	
1935	Aug 8–Aug 10	3	T	S
1937	Aug 8–Aug 15	8	C	
1939	July 25–July 28	4	T	S
1941	July 16–July 24	9	C	
1942	Aug 7–Aug 10	4	T	S
1946	July 9–July 11	3	T	F
1946	Aug 29–Sept 3	6	T	S
1947	July 6–July 9	4	T	S
1947	Aug 3–Aug 10	8	C	
1948	Aug 1–Aug 3	3	T	S
1949	July 19–July 23	5	T	S
1949	Aug 21–Aug 25	5	T	S
1950	Aug 15–Aug 24	10	T	F
1951	Aug 24–Aug 29	6	C	
1952	July 9–July 12	4	T	F
1953	July 24–July 26	3	T	S
1954	July 18–July 29	12	C	
1954	Aug 21–Aug 25	5	T	S
1955	July 22–July 29	8	C	
1956	Aug 23–Aug 26	4	T	S
1957	July 27–July 31	5	T	S
1958	Aug 10–Aug 14	5	T	F
1959	Aug 16–Aug 18	3	T	S
1960	July 16–July 21	6	T	S
1962	Aug 18–Aug 22	5	T	S
1964	July 14–July 18	5	T	F
1964	July 28–Aug 3	7	T	S
1965	July 6–July 8	3	T	S
1965	Aug 4–Aug 15	12	C	
1966	July 2–July 11	10	C	
1966	Aug 23–Aug 27	5	T	S
1967	July 7–July 10	4	T	F
1972	July 21–Aug 3	14	T	F

and t is the time coordinate increasing from Day −40 to Day +40. The reference Day 0 denotes the starting day of the Break in the Monsoon rainfall over Central India from the reports of Ramamurthy (1969). The cases selected for the construction of the composite structure on the x–t plane are identified by the letter "C" in Table 1. Sea-level pressure for 10 years of episodes of Breaks are composited in the time longitude section shown in Fig. 2. This composite is an arithmetic mean of the longitude time sections of sea-level pressure for the individual cases. The dominant features in this composited diagram are the quasi-stationary monsoon trough (shaded area) centered around 75° E and the subtropical highs over the Pacific (140° W) and Atlantic (40° W) oceans. The isopleths shown in Fig. 2 are pressure departures from 1000 mb. The period of the Break in this diagram may be identified from Day 0 to Day 7. During this period the pressure along 75° E shows a rise of roughly 4 mb. This diagram is dominated by these quasi-stationary features, however there exist a number of very interesting transients whose amplitudes are much smaller which can be defined via wave number frequency spectral analysis.

The extraction of, and the characteristics of these transients will be discussed in further detail in Sections 4 and 5 below.

3.2. *Break cases not considered in present study*

Ramamurthy's tabulation of Breaks, during the 40-year period between 1933 to 1972 includes:

(i) several minor Breaks lasting less than 3 days:
(ii) several cases of successive Breaks that occurred as frequently as one per week.
(iii) those cases for which we could not obtain continuous daily surface pressure records.

These are not included in the present study. This excludes 7 cases out of a total of 42 cases from the original tabulations. We exclude very short Breaks that last for one or two days because our interest here is on events lasting for periods of the order of one week. Similarly, minor breaks which occur in close succession were excluded.

4. Wave number frequency spectra

A composite wave number frequency spectral analysis of the individual cases comprising the x–t diagrams was carried out to determine the dominant transient waves associated with the Breaks in the Monsoons. The technique for spectral analysis is that proposed by Hayashi (1971, 1973). There we determine the Fourier coefficients using Fast Fourier Transforms for each day along the latitude circles. The conventional autocorrelation lag method is next applied to the Fourier coefficients to evaluate the power spectra, cospectra and quadrature spectra for the time coordinates. This analysis is carried out separately for the positive (ω+) and the negative (ω−) frequencies. This procedure enables us to plot the power spectral estimates as a function of wave number and period for the eastward and the westward moving wave components separately.

5. Dominant modes of the "Composite Break"

Fig. 3 illustrates the wave number frequency spectra for the surface pressure based on 81 days of data illustrated above in Fig. 2. Here the power spectral density is expressed as a function of the horizontal wave numbers 1–6 and period or frequency. The diagram contains two panels; larger amplitudes in the left panel describe westward propagating modes, while the larger amplitudes in the right panel describe eastward propagating modes. If, however, the amplitudes on the left and the right panel are of comparable magnitudes, then those scales are quasi-stationary. In the diagram (Fig. 3), we note several interesting features:

(i) A dominant westward propagating mode is located in the *10 to 20-day time period.* A large contribution in this asymmetric mode is found for the zonal *wave numbers 3, 4, 5, 6.* Although wave numbers 7 through 13 also exhibit this asymmetry, their amplitudes, however, are quite small. A number of earlier studies have emphasized the westward propagating mode in the 10 to 20-day range (Krishnamurti and Bhalme, 1976; M. Murakami, 1976; Murakami and Frydrych, 1974).

(ii) The power spectral density in the 20 to 30-day range for the wave numbers 3, 4, 5 and 6 is also large for the westward propagating modes.

(iii) In the time frame of 3 to 6 days we note rapid westward propagating modes for the zonal wave number one. We identify this mode with that demonstrated earlier by Madden and Julian

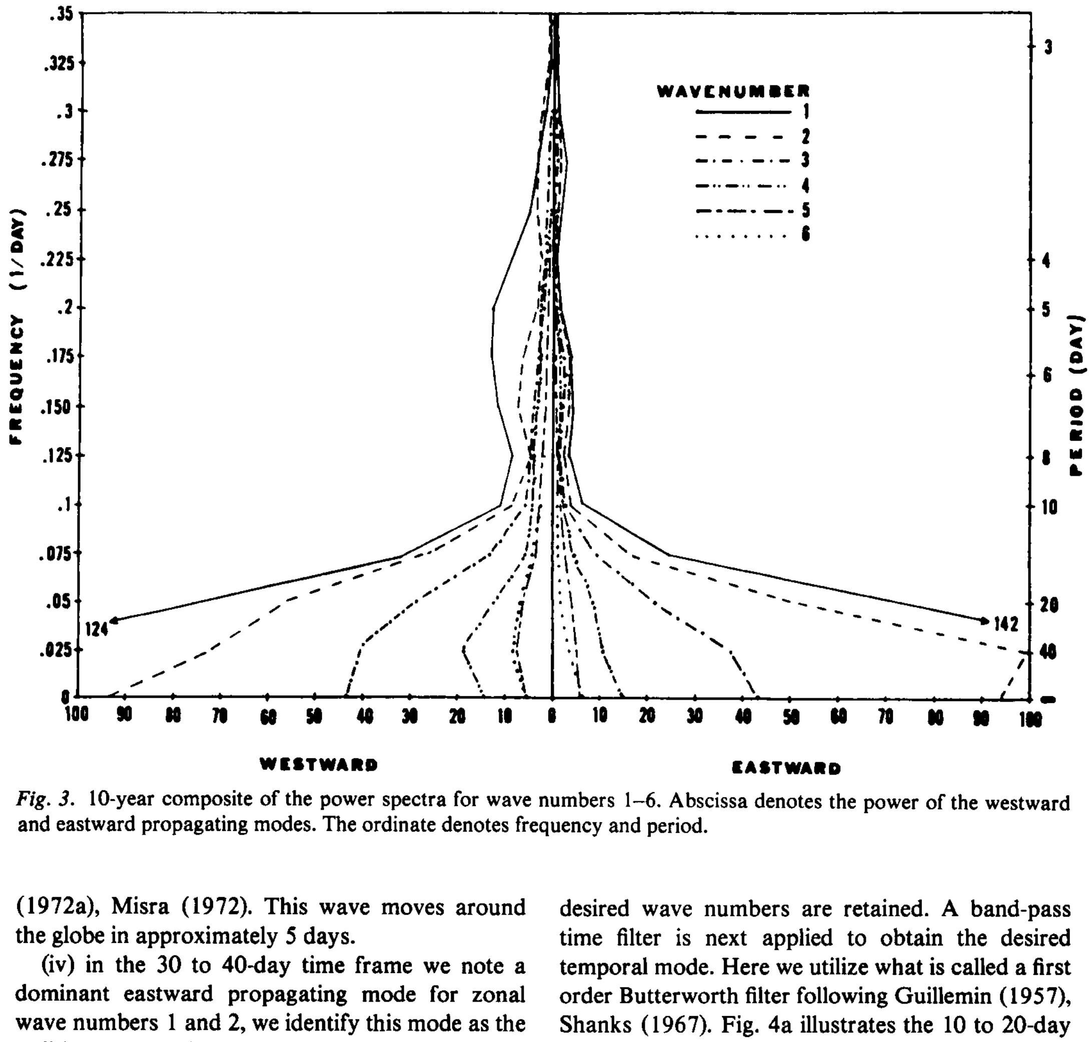

Fig. 3. 10-year composite of the power spectra for wave numbers 1–6. Abscissa denotes the power of the westward and eastward propagating modes. The ordinate denotes frequency and period.

(1972a), Misra (1972). This wave moves around the globe in approximately 5 days.

(iv) in the 30 to 40-day time frame we note a dominant eastward propagating mode for zonal wave numbers 1 and 2, we identify this mode as the well-known transient whose properties were extensively studied by Madden and Julian (1971, 1972b).

In this study we shall not be addressing the few thousand kilometer scale tropical waves in the period range of 3 to 6 days, although we recognize the existence of considerable atmospheric fluctuations on this scale. We feel that these are not directly relevant to the problem of the Breaks in the Monsoons for the time scales of interest here.

Figs. 4a, b, c, d illustrate longitude–time (x–t) diagrams of these dominant modes extracted from the composited data set. The illustration of dominant modes require a space–time filter of the data sets. This is accomplished by first subjecting the data to a spatial Fourier analysis where only the desired wave numbers are retained. A band-pass time filter is next applied to obtain the desired temporal mode. Here we utilize what is called a first order Butterworth filter following Guillemin (1957), Shanks (1967). Fig. 4a illustrates the 10 to 20-day mode for zonal wave numbers 3 through 6. The shaded area shows a trough (or low pressure) passage while the clear area illustrates a ridge (or high pressure) passage. The amplitude of this mode (for the composited data set) is of the order of 0.5 mg. However, for individual years the local amplitudes have been noted to be as large as 1.8 mb. The wave is clearly westward propagating for the most part during the 80 days. The reference origin denotes the date of "reported Break" over Central India. For the 10 to 20-day mode the period between Day −5 through +5 at the reference longitude is characterized by a pressure rise. This feature will be used in the present study. Fig. 4b illustrates the corresponding illustration for the 20 to 30-day mode for the composited data

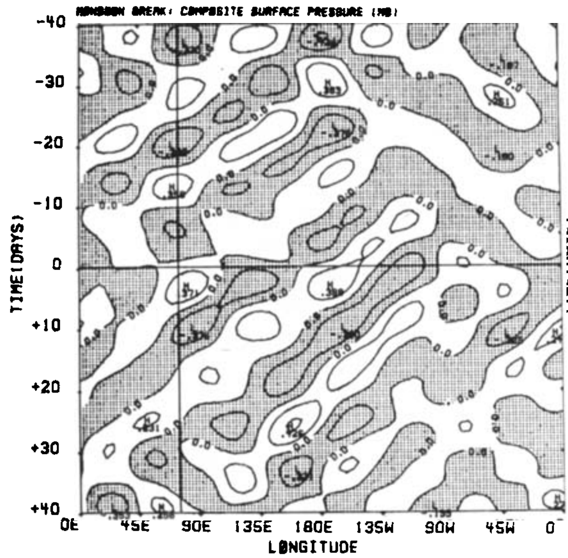

Fig. 4a. Longitude–time (x–t) diagram of the filtered 10 to 20-day pressure data for the zonal wave numbers 3 through 6. Contour interval ± 0.2 mb. Strippled region shows negative pressure values. Vertical and horizontal reference lines denote central India longitude and day of occurrence of reported Break.

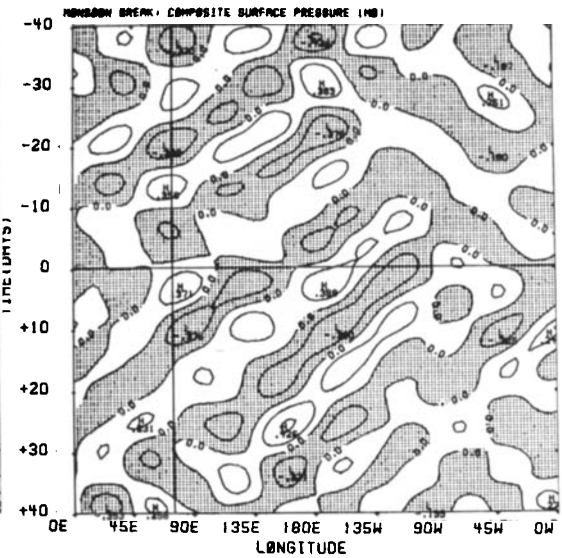

Fig. 4c. Same as Fig. 4a for the 30 to 40-day mode for zonal wave numbers 1 and 2.

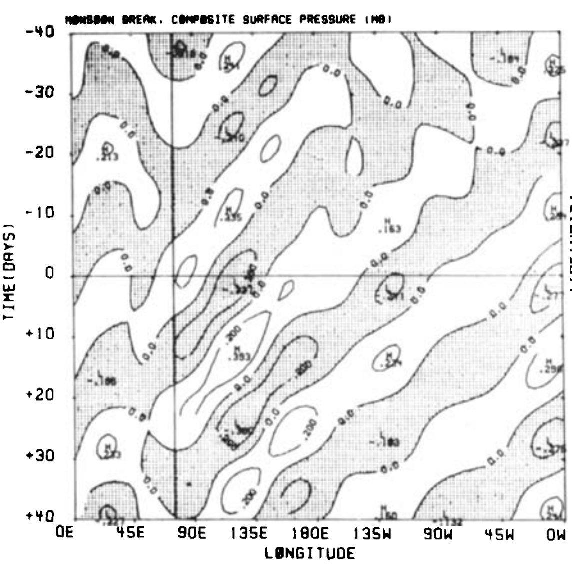

Fig. 4b. Same as Fig. 4a for the 20 to 30-day mode.

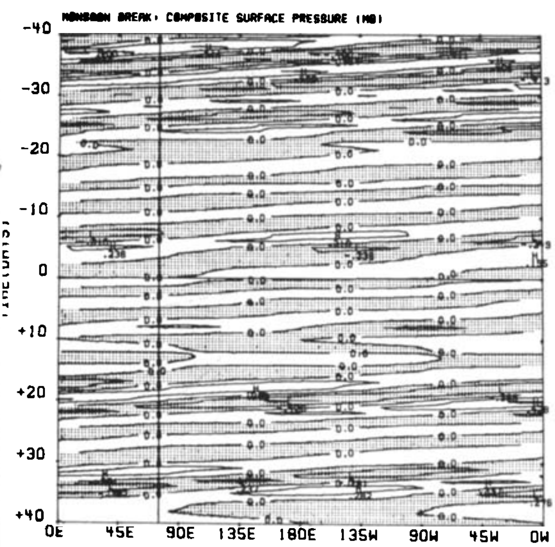

Fig. 4d. Same as Fig. 4a for the 3 to 6-day mode for zonal wave number 1.

sets. Well-defined westward propagating modes are evident in this time period. The amplitude of this composited wave is less than that for the 10 to 20-day mode in the vicinity of the "reference origin". This mode is however noted to be somewhat more pronounced subsequent to the Break.

Fig. 4c illustrates the eastward propagating long wave (wave numbers 1 and 2) for the 30 to 40-day period. The amplitude of this composited wave is comparable to those illustrated above for the 10 to 20-day periods. The ridge passage occurs some 5 days after the reported date of Break in the Monsoons. This is a fast eastward moving wave whose speed of propagation is around 9° longitude/day. Finally, in Fig. 4d we illustrate the rapid westward propagating 3 to 6-day period long wave (zonal wave number 1). This wave travels around the world in 3 to 6 days and has a rather small amplitude, however its passage does leave a clear signature on the composited total pressure field. This is evident when one superimposes Fig. 4d on Fig. 2. The small amplitude oscillations in Fig. 2 that seem to occur in the time scale of 3 to 6 days coincide with the passage of the wave shown in Fig. 4d in most instances.

It is also noteworthy that the period of Break coincides with the rise of pressure for each of the salient modes illustrated here.

6.

6.1. *Predictive skill in the extrapolation of phase*

The steady westward propagation of phase for the 10 to 20-day mode (shown in Fig. 4a) for the composited data sets, as well as individual cases, suggests that this feature could be used to predict the phase at some future time in an extrapolative sense. Although the 30 to 40-day mode of wave numbers 1 and 2 also exhibits a steady change of phase in the composite, individual cases show more variability, making such an extrapolation of phase less reliable. Thus, we shall use the 10 to 20-day mode as a frame of reference in this study. In this section we examine cases extracted from 30 years of daily pressure records not included in the above.

In Table 1 the symbol T identifies these episodes of the Breaks in the Monsoons which were subjected to "the extrapolation of phase". For this purpose we construct longitude–time (x–t) diagrams of the dominant modes of the composite spectra. This analysis is carried out using data sets that start at Day −90 and terminate at Day −10 (i.e., 10 days prior to the Break) for each of the breaks "T".

For the test cases, where an extrapolation of phase is carried out the period of the predicted Breaks could be defined during the period of pressure rise between the dates of arrival of the trough and that of the subsequent ridge at the reference longitude for the 10 to 20-day mode. If the date of the commencement of the observed Break coincides with the dates of the predicted Breaks we have designated this as a successful prediction at this stage. In Fig. 5a through h we illustrate some of the successful extrapolative predictions. In these diagrams, the ordinate denotes time (from Day −35 to Day −10), while the calculations are based on data sets from Day −90 to Day −10. Thus no pressure information for a 10-day period, immediately prior to the Break, is included in these test cases. The abscissae in these diagrams denotes longitude. The isopleths are drawn from intervals of ∓ 0.25 mb.

In Table 1, on the far right column, we have identified the successes (S) and Failures (F). These are based on the extrapolations of phase illustrated in Figs. 5 (a through h). In summary we note that out of a total of 25 cases there were 18 successes, which is 72% of the cases examined here.

6.2. *Interpretation of test cases that failed*

Among these 25 test cases there were 7 failures. The simple linear extrapolation of the phase of a westward propagating wave in the 10 to 20-day time period fails to provide a pressure rise around Day 0 for these Breaks. The failure in these cases could be due to one of several reasons:

(i) The global pressure data for some of these episodes may not be reliable, since the global tropical observations prior to 1950 did not have an "adequate" coverage.

(ii) Some of the dates of reported Breaks in the tabulations of Ramamurthy (1969) are open to question. We believe that this may be true for 1958 and 1972. In these cases we noted that a rise in the sea-level pressure over the region of the monsoon trough did not occur on the dates of the reported Break. If we arbitrarily shift the reported date of Breaks by a few days to make it coincide with the dates of pressure rise at sea-level, then these cases appear to be reasonably predicted by the extrapolation of phase of the 10 to 20-day wave. This arbitrary adjustment or shift of the date is certainly open to question. The reasons for these failures are still somewhat obscure.

(iii) Our analysis, furthermore, shows that the 10 to 20-day wave is not the dominant westward propagating wave in each and every episode. In fact, in a few cases, where we noted a failure in the

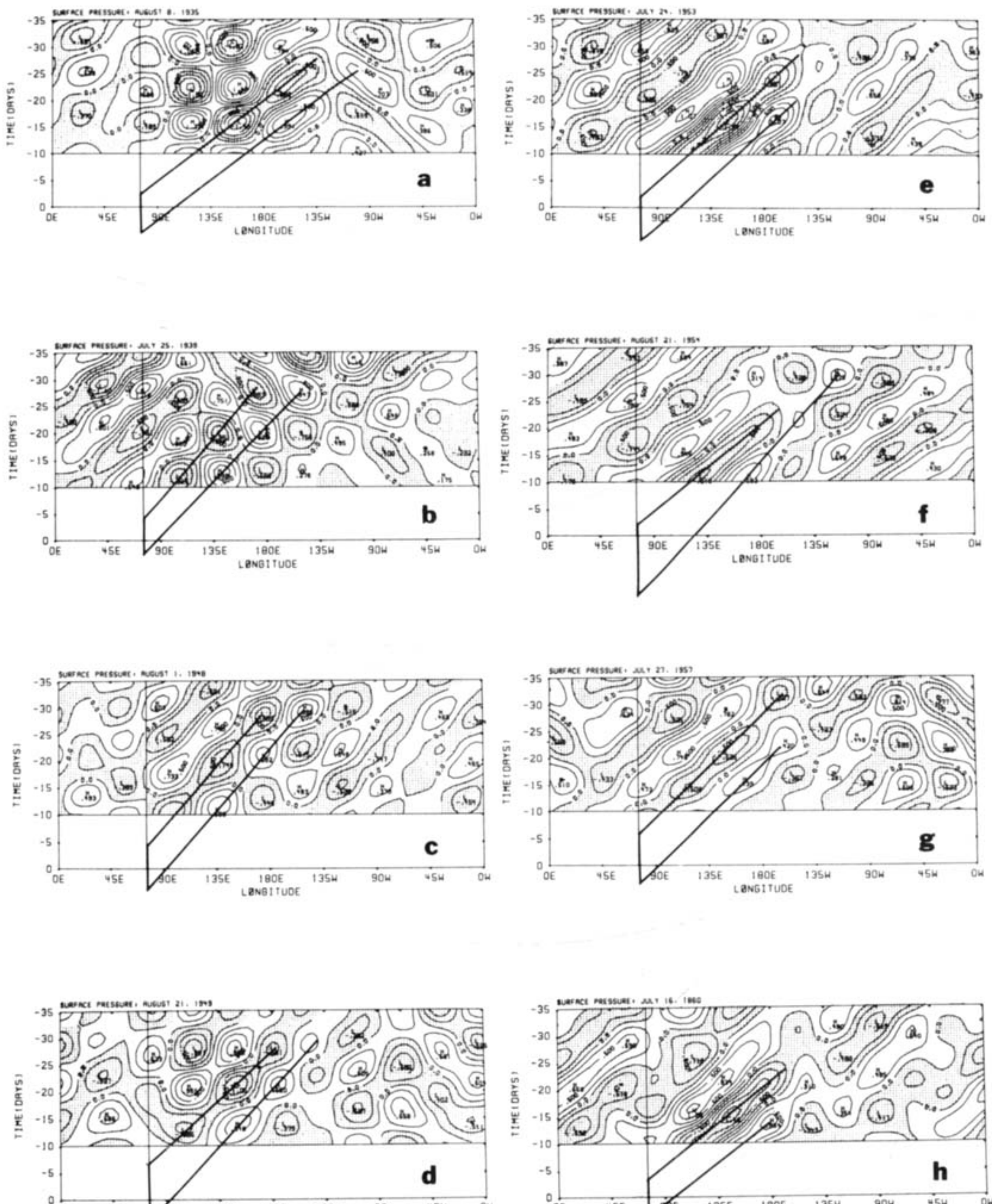

Fig. 5a–h. Longitude–time (x–t) diagram of surface pressure for the 10 to 20-day mode for zonal wave numbers 3 through 6 for test cases indicated on the top of the diagrams (also identified in Table 1). Ordinate denotes days starting at 35 days and terminating 10 days prior to the occurrence of a reported break. The extrapolation of a trough–ridge system is indicated by a pair of sloping straight lines. Isopleths are drawn for ± 0.25 mb. The stippled area denotes the troughs.

extrapolation of the 10 to 20-day mode, another mode (also a westward propagating wave) was, in fact, the dominant mode.

(iv) Although the ridge passage of the dominant mode often coincides with the reported date of Break, this ridge does not necessarily provide a sufficient condition for a Break.

7.

7.1. *Limitations of present approach*

Although the proposed approach does not use any observations for a 10-day period prior to the date of the commencement of reported Breaks, this method is not presently designed for prediction in field operations. The statistics presented here are experimental test predictions which strongly suggest that the 10 to 20-day mode has a steady quasi-linear propagation of phase. This approach has a relative success in over 70% of the test cases of Breaks that occurred over a 30-year period. In this study we have primarily explored the potential of a single dominant mode of the composited data. Thus, we did not perform a wave number frequency analysis for each of the test cases separately in order to assess the prevailing dominant mode.

If the extrapolated wave, with its accompanied pressure rise, passed near the origin then we classified the case as success. In the 10-day test prediction diagrams we were anticipating the arrival of a wave around the reference origin (0, 0). In reality, there are always several other troughs and ridges on these x–t diagrams which pass the reference longitude in succession. In making real time predictions one is faced with the problem of determining if any of these waves will be associated with "The Break in the Monsoons". Our test predictions merely confirm that one of the waves of the 10 to 20-day period is very often associated with the Break. Our success is due in part to the "knowledge" that a Break in fact does occur in the ensuing 10 days. This "knowledge" has been used to tag one of the trough–ridge systems on the x–t diagram which was then extrapolated. In real time predictions this "knowledge" will not be available.

7.2. *Future test predictions*

Here we propose the design of test predictions that assume no future "knowledge" as to when the Break in fact occurs. We assume that the date of onset of monsoons over Central India is known. The test prediction commences with data sets from Day −80 to Day 0, where Day 0 denotes the date of onset of the monsoons. A wave number frequency analysis of these 81 days of data (from an x–t diagram along the latitudes of the monsoon trough) would determine the dominant modes. An x–t diagram of the dominant modes will contain several candidate trough–ridge systems. The first prediction of "Breaks in the Monsoons" would then be made on the basis of a linear extrapolation of the first trough–ridge system to the reference longitude.

The normal date of onset of monsoons is around June 10th (Rao, 1977) and the normal date of commencement of a major Break in the Monsoons is around August 10th (Ramaswami, 1972). Thus we believe that the probability of success in the prediction of the Break based on the arrival of the first trough–ridge system would be somewhat small. In the event of a failure, we focus on the arrival of the next wave to the reference longitude. We know update our data base for the next several days prior to carrying out the next extrapolative phase prediction. This data base extension can be carried out to a date which is roughly 10 days prior to the projected arrival of the next wave at the reference longitude. Our analysis shows that there are only 3 or 4 possible trough–ridge systems in these x–t diagrams of the dominant mode in a given monsoon season, hence the probability of success after an initial failure in prediction becomes much higher. We must also recognize the fact that in the past 80 years there were no reported Breaks during 12 years, Ramamurthy (1969). Test predictions along these lines are presently being carried out for the years 1968 through 1978. We also expect to carry out this exercise during the forthcoming 1979 GARP Monsoon Experiment (MONEX). Results of these studies will be reported in the future.

This study has relied on two observational findings from long records of tropical data sets:

(i) The existence of a 10 to 20-day westward propagating mode, and
(ii) The steady propagation of phase by this mode over very long periods.

A dynamical theory for these observational findings is presently lacking and we consider this as an important unsolved problem.

8. Acknowledgements

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РАСПРОСТРАНЯЮЩАЯСЯ НА ЗАПАД ВОЛНА С ПЕРИОДОМ 10–20 СУТОК И РАЗРУШЕНИЕ МУССОНОВ

В работе используются ежедневные данные по приземному давлению для 40-летнего периода (с 1933 по 1972 г.). Доминирующие нестационарные моды пространственно-временного спектра приземного давления вдоль широт, где наблюдается муссонная ложбина (20–30° N), определяются по долготно-временному набору данных по приземному давлению за период приблизительно три месяца для десяти различных случаев разрушения муссонов. Этот набор данных был составлен относительно точки отсчета (0,0), за которую был принят день начала ослабления дождя над центральной Индией и долгота центральной Индии (т.е. 75° E). Эти доминирующие моды, определенные по этим составным данным, представляют собой интересные моды, распространяющиеся как на запад, так и на восток. Более того, некоторые хорошо прослеживаемые моды обнаруживают постоянные изменения фазы от суток к суткам. Показано, что время прекращения дождя в муссоне совпадает с повышением давления, связанным с приходом гребня доминирующей моды в отсчетную точку (0,0). Оставшиеся 30-летние данные были использованы

для проверки гипотезы, что постоянное распространение фазы доминирующей моды, бегущей на запад, может быть использовано для экстрополяции и, тем самым, предсказания прихода гребня. Испытания показали, что 10-дневная линейная экстрополяция фазы достаточно хорошо локанизует гребень, связанный с разрушением муссона над центральной Индией. В более чем 70 % изученных случаев мы заметили, что приход гребня совпадает со временем наблюдаемого разрушения муссона. Были сделаны попытки по превращению этой задачи в реальную прогностическую схему. Результаты будут опубликованы отдельно.