Cloudiness Fluctuations Associated with the Northern Hemisphere Summer Monsoon

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Abstract

The broad-scale fluctuations of cloudiness over the Eastern Hemisphere during the northern summer monsoon were investigated by using daily satellite mosaic pictures taken from June 1 to September 30, 1973.

Spectral analysis revealed two dominant periodicities, of around 40 days and around 15 days. Cross-spectral, time-sectional, time-lag correlation and phase-lag vector analysis were applied to reveal the characteristics of these two modes in the time-space field.

The fluctuation of 40-day period shows marked northward movement of cloudiness from the equatorial zone to the mid-latitudes (around 30°E) over the whole Asian monsoon area, and southward movement over Africa and the central Pacific. The northward movement is most apparent over the India-Indian Ocean sector. The fluctuation of this mode is associated with the major "active"-"break" cycle of the monsoon over the whole Asian monsoon area.

The fluctuation of 15-day period shows similar features to that of 40-day period, but includes two clockwise rotations, one over India and Southeast Asia and the other over the western Pacific. A southward movement from the equatorial zone to the Southern Hemisphere middle latitudes is also prominent to the east and west of Australia. The fluctuation of this mode seems to correspond with the movements of equatorial, monsoon (or tropical), and westerly disturbances.

It is also suggested that the fluctuation of 40-day period may be closely connected with the global-scale zonal oscillation in the equatorial zone and that of 15-day period may exist as a result of meridional wave interactions.

1. Introduction

In recent years, many studies on the summer monsoon over and around India have revealed some predominant periodicities in the day-to-day fluctuations of rainfall, pressure and wind fields. Recently, M. Murakami (1977) summarized the results of these studies.

There exist at least two kinds of quasi-periodic variation in the summer monsoonal fluctuations over India and adjacent regions: one appears as a spectral peak with a period of around 5 days and the other as one with a period of around 15 days. The 5-day period was revealed by spectral analyses of wind and pressure fields (*e.g.*, Ananthakrishnan and Keshavamurty, 1970: Bhalme and Parasnis, 1975; M. Murakami, 1976 etc.). These studies show that this periodicity is most prominent in northern India and is related to the frequency of monsoon lows travelling from the Bay of Bengal to northern India.

The periodicity of around 15 days is found in rainfall and lower and upper wind and pressure fields over the whole of India, including the sub-Himalaya region (*e.g.*, T. Murakami, 1972; M. Murakami, 1976; Krishnamurti and Bhalme, 1976; Yasunari, 1976 etc.). Cloudiness over the tropical Indian Ocean also shows marked fluctuation with this period (Zangvil, 1975). Many of the authors also suggest that the fluctuation of this period range (around 15 days or quasi-biweekly) is closely related to the variation of the large-scale circulation systems associated with the SW monsoon.

However, as M. Murakami (1977) points out, these studies are limited to phenomena over the

Indian Ocean and Indian subcontinent region. Therefore, the fluctuations over the whole SW monsoon area (India, Southeast Asia and the western Pacific) should be investigated more extensively by the use of data obtained over a broader area. However, daily observations on temperature, moisture and wind field are still not sufficient, especially over the tropical ocean areas. In this sense, cloudiness data from meteorological satellites can provide immediate and invaluable information on the large-scale circulation systems, since cloudiness is one of the most important measures of monsoonal rainfall fluctuations. Moreover, recent studies (Krishnamurti and Bhalme, 1976; Webster *et al.*, 1977) have suggested that cloudiness over the monsoon area acts as a controlling factor of the large-scale monsoonal fluctuations.

T. Murakami (1976) made a statistical analysis of cloudiness fluctuation in the northern summer, by use of satellite cloudiness observations covering 8 years. By computation of time-lag correlations, he found that the spatial pattern of positive (negative) correlations moved northwards from the equatorial Indian Ocean to the Indian sub-continent at an average speed of 1° latitude/day. From the global point of view, he first revealed the interrelatedness of large-scale cloudiness perturbations over the tropical belt during the northern summer. However, a more precise description of monsoonal fluctuations, including the discussions of their periodicities, has not yet been made.

In this paper, an attempt will be made to clarify the time-spatial features and dominant modes of fluctuations of the northern summer monsoon over the Eastern Hemisphere, by use of daily satellite cloudiness data. We focus mainly on time scales longer than 10 days, which are thought to be associated with "break"-"active" phases of monsoonal fluctuations.

2. Data

Daily visible mosaic pictures (Mercator projection) of the Eastern Hemisphere (0°-180°E, 40°N-35°S), taken by the NOAA-2 satellite from June 1 to September 30, 1973 (122 days), were used. Monsoonal rainfall over India in this year is considered to be nearly normal (Saha, 1978). The brightness of each picture was measured in areas of 1° latitude × 2° longitude with an autodensitometer, which can measure light transmitted through the film from 0 to 30,000 density levels. Missing data were replaced by linear interpolation in time. Then, the number of areas where the brightness level corresponded to cumulus or cumulo-nimbus clouds was counted in each latitude-longitude block (5° latitude × 12° longitude). The counted values in each block were defined as the cloudiness of each block (5° latitude × 12° longitude).

3. Mean cloudiness and space correlations of cloudiness during the northern summer monsoon

Before discussing temporal fluctuations, we will describe the mean cloudiness and space correlations of cloudiness for the whole monsoon period.

Mean cloudiness of the four monsoon months (June to September) is shown in Fig. 1. Major monsoon cloudiness stays over the area from northern India to southeast Tibet, and over equatorial northern Africa. It is noteworthy that the maximum cloudiness over Asia appears over the Yunnang region (around 20°-25°N, 100°-105°E). Dense cloudiness also lies in a narrow band over southern Japan through the western

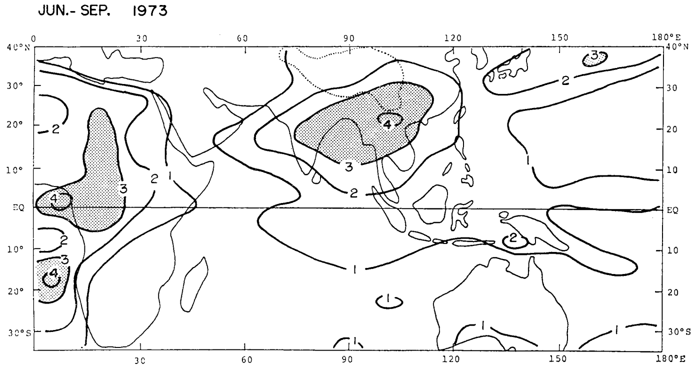


Fig. 1 Mean cloudiness for June through September, 1973. The cloudiness values greater than 3 (30%) are shaded.

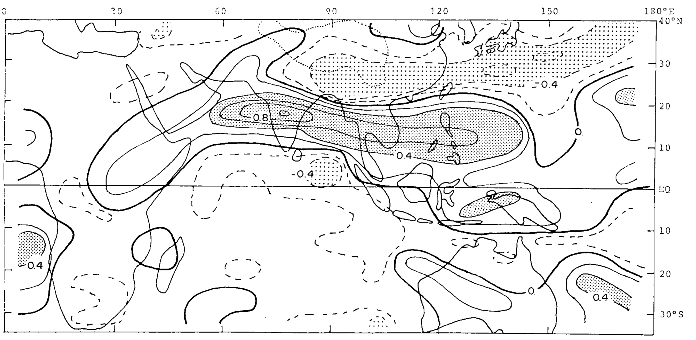


Fig. 2 Spatial distribution of correlation coefficients of cloudiness with a reference point over central India (17.5°N, 78°E). The values greater than 0.4 are shaded, and those less than −0.4 are dotted.

North Pacific. This cloudiness mainly resulted from quasi-stationary fronts in June (Baiu Season) and September. The two maxima of cloudiness over Asia and Africa are separated by the Arabian desert-Arabian Sea area.

The correlation coefficients of cloudiness were computed for a reference block over central India (15°-20°N, 72°-84°E). The result is shown in Fig. 2. A clearly bounded band of positive correlations extending eastward from central India to Southeast Asia and the Philippines is noted. From the Philippines it bends southeastward to New Guinea and extends eastward far into the equatorial Pacific. This band also extends westward to Africa. Another broad area of positive correlations exists from southern Australia to the southwestern Pacific and possibly beyond. In contrast, on either side of the east-west oriented marked positive band the correlation is negative with significant values over northern India, Tibet to the eastern North Pacific, and also over the equatorial Indian Ocean. It is well known that monsoon rainfall increases (decreases) over northern India and the southernmost part of India during "break" ("active") conditions over central India (*e.g.*, Hamilton, 1977, etc.). Therefore, the meridional contrast of the negative-positive-negative correlation pattern over and around India explains precisely the typical "break" (or "active") conditions of the Indian summer monsoon. This contrast of correlation pattern is most remarkable along the Tibet-Bay of Bengal line. But it is apparent in Fig. 2 that this pattern occurs simultaneously over East and Southeast Asia or more widely.

Thus, it is indicated that the cloudiness fluctuations associated with the northern summer monsoon are a phenomenon of the broad area from the Arabian Sea to the western Pacific and from the equator to the middle latitude zone.

4. Zonal and meridional structures of cloudiness fluctuations

In this section, we will investigate the nature of temporal fluctuations in zonal and meridional cross sections.

4.1 Time-longitude sections of cloudiness

Time-longitude sections were composed for each 5° latitude zone. In this analysis, cloudiness data for smaller blocks (5° latitude × 4° longitude) were used to examine zonal cloud movements of smaller scale. Latitude zones from 10°S to 40°N were examined, where cloudiness fluctuations associated with the northern summer monsoon are thought to be apparent. Through this analysis, it is expected to find eastward or westward moving (or quasi-stationary) cloud disturbances responsible for the monsoonal fluctuations, especially of quasi-biweekly or longer period ranges. The characteristic features of zonally propagating cloudiness, allow the latitude zones to be classified into three major groups.

(a) Equatorial zone (10°S-5°N)

In this zone, eastward moving cloud disturbances are predominant throughout the monsoon period. As a typical feature of this zone, the cross section of the 0°-5°S latitude zone is shown in Fig. 3. In this figure, almost all cloud disturbances first appear at around 60°E, develop while moving eastward over the Indian Ocean through Indonesia region, and finally decay at around 150°E. Major disturbances seem to appear with a period of around 30–40 days.

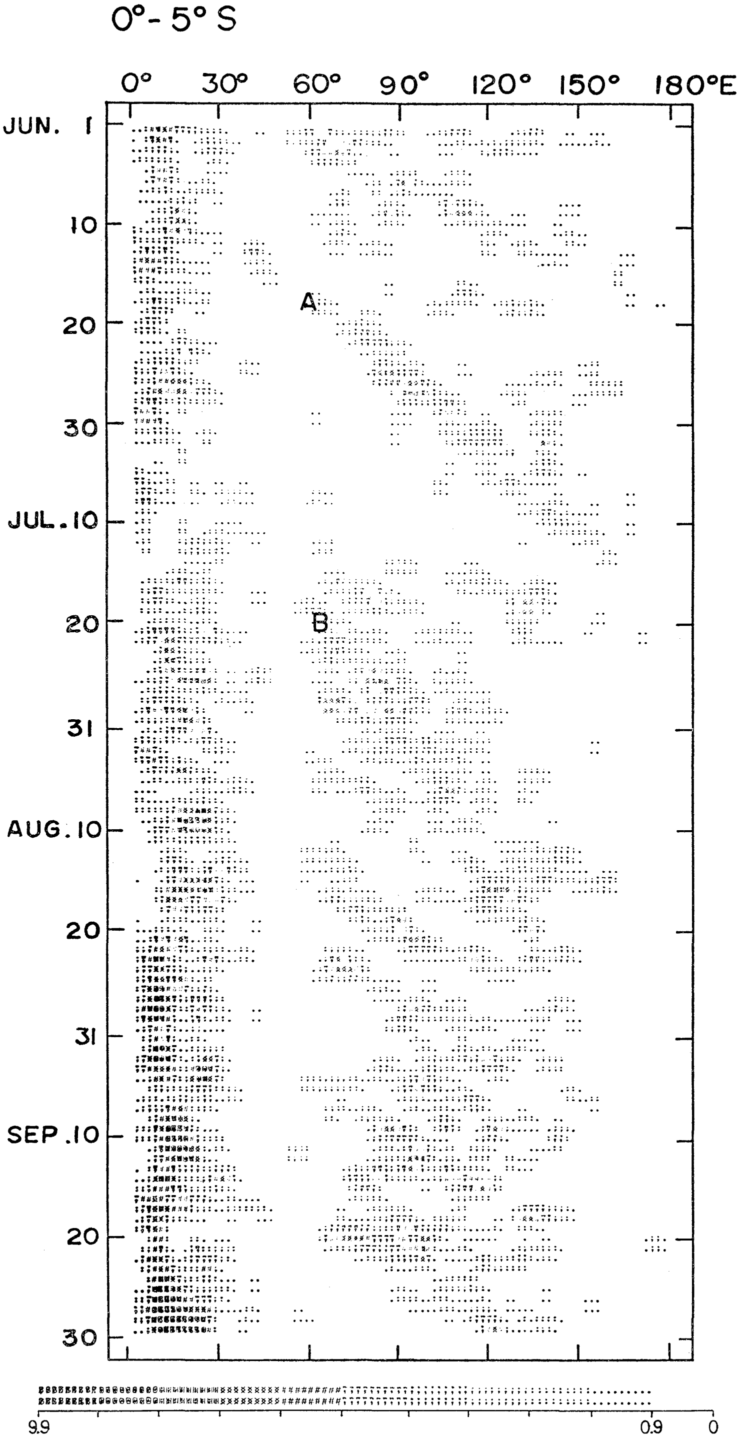
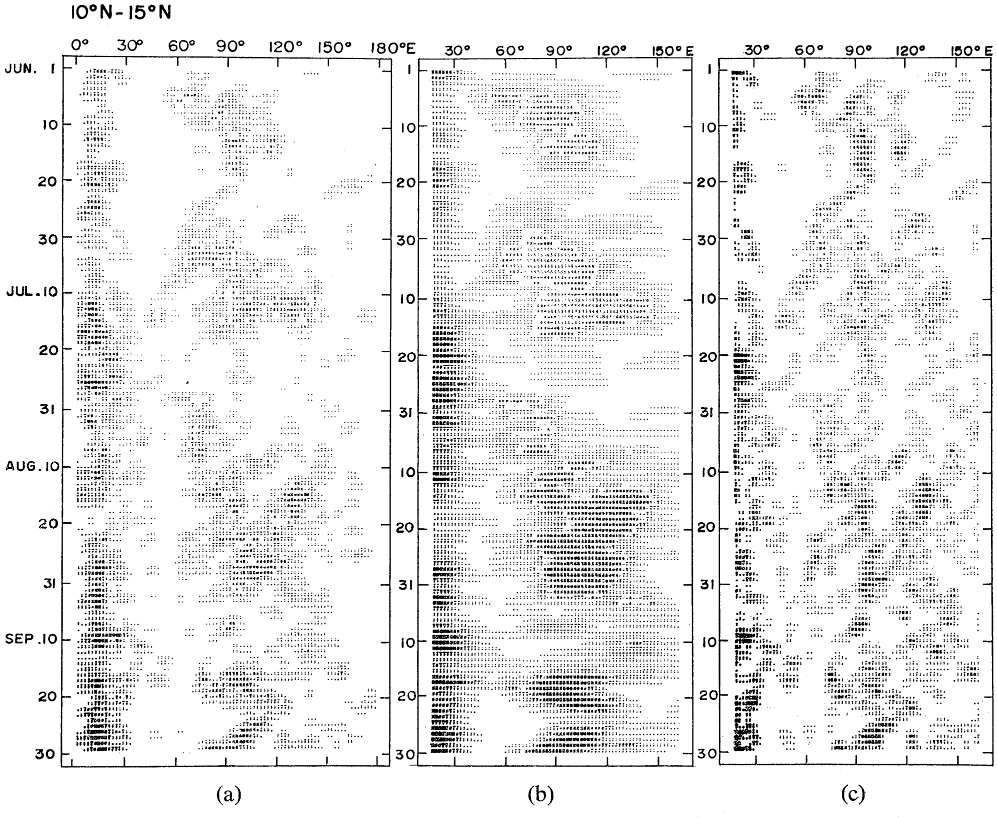


Fig. 3 Time-longitude sections of cloudiness for 0°–5°S latitude zone. Cloudiness is shown by a ten-level grey scale of half-tone display. The difference between adjacent levels corresponds to the cloudiness value of 0.9 as shown in the scale. See text for the symbols A and B.

Minor disturbances of shorter period also appear. These disturbances progress at a speed of roughly 4°–6° longitude/day. The former disturbances may be related to those noted by Madden and Julian (1972) and Zangvil (1975), since the eastward phase speed and estimated zonal wavenumber ($\simeq 2$) are similar to their results. In the 0°–5°N zone, though the major eastward disturbances still can be seen, westward cloud movements of smaller scale also overlap in the time section (not shown).

(b) Subtropical easterly zone (5°N–25°N)

The cloudiness in this latitude zone is closely related to the northern summer monsoon. As a typical pattern of this zone, time-longitude section of the 10°–15°N zone is shown in Fig. 4(a). Westward moving cloud systems corresponding to the easterly wave disturbances are dominant. Overlapping these moving cloud systems, there seems to be a broad-scale quasi-stationary cloudiness over the 60°E to 120°E longitude zone. These features become clearer on applying a zonal space filter to the original data. Here, the zonal running mean of 36° longitude was applied in order to separate the zonal scales larger and smaller than 36° longitude width. The larger-scale part thus obtained shows a quasi-stationary fluctuation, as shown in Fig. 4(b). The smaller-scale (or transient) part of cloudiness (Fig. 4(c)) shows westward movement at a phase speed of 3°–6° longitude/day, and with the zonal scales of 20°–40° longitude. The features of this transient cloudiness are similar to those of the disturbances studied by M. Murakami (1976) over the Bay of Bengal and northern India. The larger-scale (quasi-stationary) part of cloudiness (Fig. 4(b)) is located from 80°E to 100°E (over the Bay of Bengal and Indo-China), and fluctuates in its zonal width with a period of 30 to 50 days. Fig. 4(b) indicates that cloudiness fluctuations over Africa (0°–40°E), where maximum monsoon rainfall appears in this latitude zone, are roughly out of phase with those over Asia.



(a) (b) (c)

Fig. 4 (a) Same as Fig. 3 except for 10°–15°N latitude zone, (b) same as Fig. 4(a) except for zonally smoothed cloudiness, (c) same as Fig. 4(a) except for cloudiness of smaller scale. Note only positive deviations are illustrated by the grey scale in Fig. 4(b) and 4(c). The cloudiness difference between adjacent levels is 0.4 for Fig. 4(b), and 4(c).

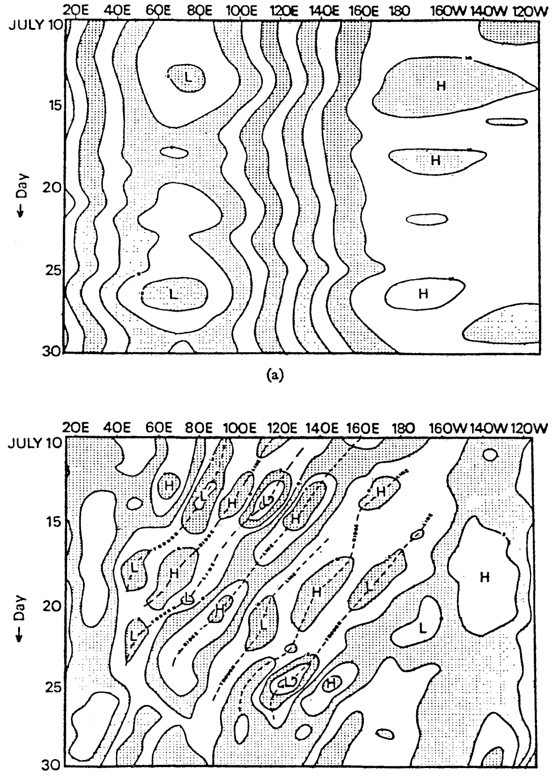


Fig. 5 Longitude-time sections of sea level pressure (mb) data at 20°N during July 1965 for (a) the sum of zonal wavenumbers 1 and 2, and (b) the sum of zonal wavenumbers 3–12. (after Krishnamurti *et al.,* 1977)

In the longitude-time sections of sea level pressure along 20°N, Krishnamurti *et al.* (1977) found the quasi-stationary part (wavenumbers 1 and 2) and the westward moving transient part (wavenumber 3 to 12) as shown in Fig. 5(a) and 5(b). Since the year of the data and the zonal space filter adopted are different from those used in the present study, Fig. 4(b) and 4(c) cannot be compared directly with Fig. 5(a) and 5(b), respectively. Nevertheless, it is noted that the westward transient cloud systems in Fig. 4(c) are similar to the disturbances in Fig. 5(b) and the quasi-stationary part of cloudiness (Fig. 4(b)) is located at about 20° longitude to the east of the quasi-stationary pressure trough of waves over India (see Fig. 5(a)).

(c) Mid-latitude westerly zone (25°N–40°N)

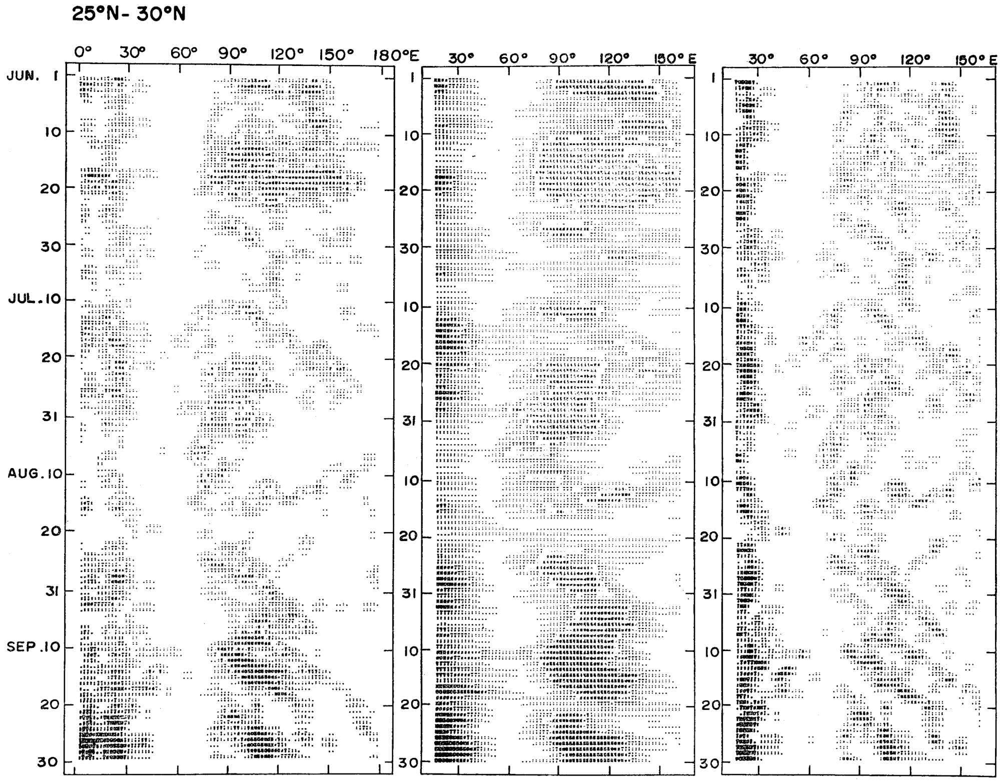
Through the whole monsoon period, eastward movements of cloudiness are predominant. Only in the 25°–30°N zone, westward movements can be seen in the short period from July to August, as shown in Fig. 6(a) and 6(c). These features show that even in the monsoon season the area stretching from northern India to the Tibetan Plateau is affected mostly by the mid-latitude westerly disturbances. In contrast, the large-scale part of cloudiness (Fig. 6(b)) exhibits quasi-stationary features over the 80°–120°E zone, with major fluctuations showing a periodicity of about 40 days and minor fluctuations a periodicity of 10 to 15 days. It should be noted that the upper level anticyclone (Tibetan High), one of the most dominant systems of the northern summer monsoon, lies over this area centered at around 30°N. The relation between Tibetan High and the westerly wave movements will be discussed later.

4.2 Time-latitude sections of cloudiness

Since the broad-scale monsoon circulation has been recognized as a local meridional (Hadley type) circulation, it follows that the fluctuations should also appear along the meridional plane. To confirm this, time-latitude sections of monsoon cloudiness were examined. To eliminate small-scale fluctuations, time-smoothing (of 5-day running mean) was applied to the original cloudiness data and the time-mean value of each latitude was subtracted from the smoothed data.

In the sectors from the Arabian Sea through the Bay of Bengal, remarkable northward movements of cloudiness are found from around 10°S to 30°–40°N, with a period of about 40 days. This feature is most distinct over the Indian subcontinent (72°–84°E) sector, as shown in Fig. 7. It is noteworthy that the meridional fluctuations of cloudiness accompanied by the major "active" and "break" phases over India appear not as oscillations but as a repetitive northward shift of cloudiness from the equatorial Indian Ocean to the Himalayas. The northward phase speed is about 1° latitude/day, which is almost the same value as that obtained by T. Murakami (1976). The maximum (or minimum) cloudiness simultaneously stays at the equatorial region and around the Himalayas, which is in good agreement with the well-known features of the "break" (or "active") phase of the monsoon over India. The first phase of the northward movements may correspond to the onset stage of the Indian summer monsoon.

In the Southeast Asian (96°–108°E) sector, northward movements of cloudiness with a period of around 30 to 50 days are also recognized over the latitude zone south of about 25°N, but over



(a) (b) (c)

Fig. 6 (a), (b), (c) same as Fig. 4(a), (b), (c), respectively, except for 25°–30°N latitude zone.

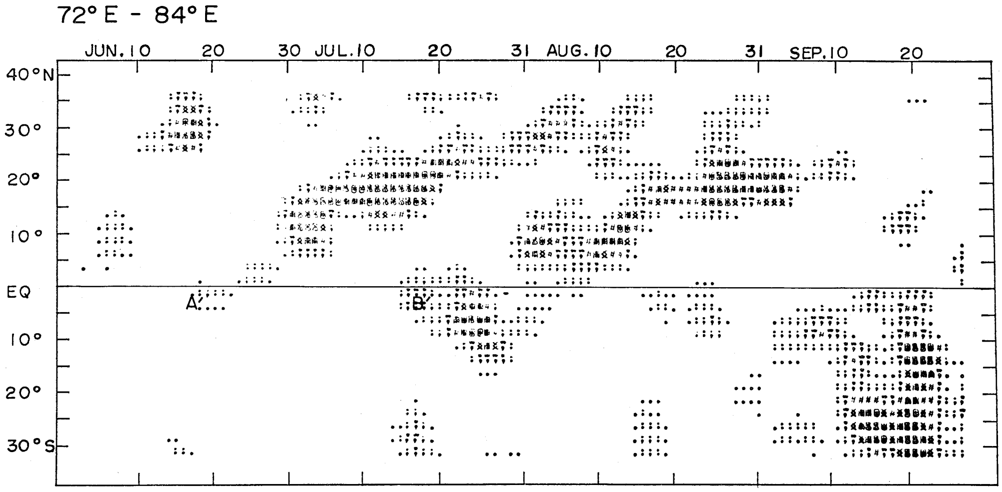


Fig. 7 Time-latitude sections of cloudiness for 72°–84°E longitude zone. Time means are subtracted from the smoothed cloudiness, and positive deviations are illustrated by the grey scale. The cloudiness difference between adjacent levels is 0.3. See text for the symbols A′ and B′.

the higher latitude zone (than 25°N) southward movements occur (data not shown).

In other areas, no systematic meridional fluctuations can be seen, partly because values and variances of cloudiness are very small. To examine more closely the statistical features of the meridional fluctuations of cloudiness, day lag-latitude sections of time-space correlations were made for all the longitudinal sectors. Time-space correlation coefficients $\gamma(\tau)$ were computed following the method of T. Murakami (1976). That is,

$$\gamma(\tau)=\frac{\frac{1}{T-\tau}\sum_{k} C_{ij}(t_k)C_{mn}(t_k+\tau)-\bar{C}_{ij}\bar{C}_{mn}}{\sigma_{ij}\sigma_{mn}},$$

where

$$\bar{C}_{ij}=\frac{1}{T-\tau}\sum_{k} C_{ij}(t_k)$$

The quantity $C_{ij}(t_k)$ denotes the smoothed cloudiness data at the reference block (i, j) on the k-th day, while $C_{mn}(t_k+\tau)$ represents the data at other blocks (m, n) on the $(k+\tau)$-th day. σ_{ij} is the standard deviation of $C_{ij}(k)$ for $k=1$ to T. T represents sample size; *i.e.*, $T=122$ days for the whole monsoon period of 1973 (June 1 to September 30). Day lag τ is taken from -50 to 50. In this case, a reference block was chosen from each longitudinal sector.

Fig. 8(a) shows the result for the African monsoon sector. Monsoon cloudiness over Africa

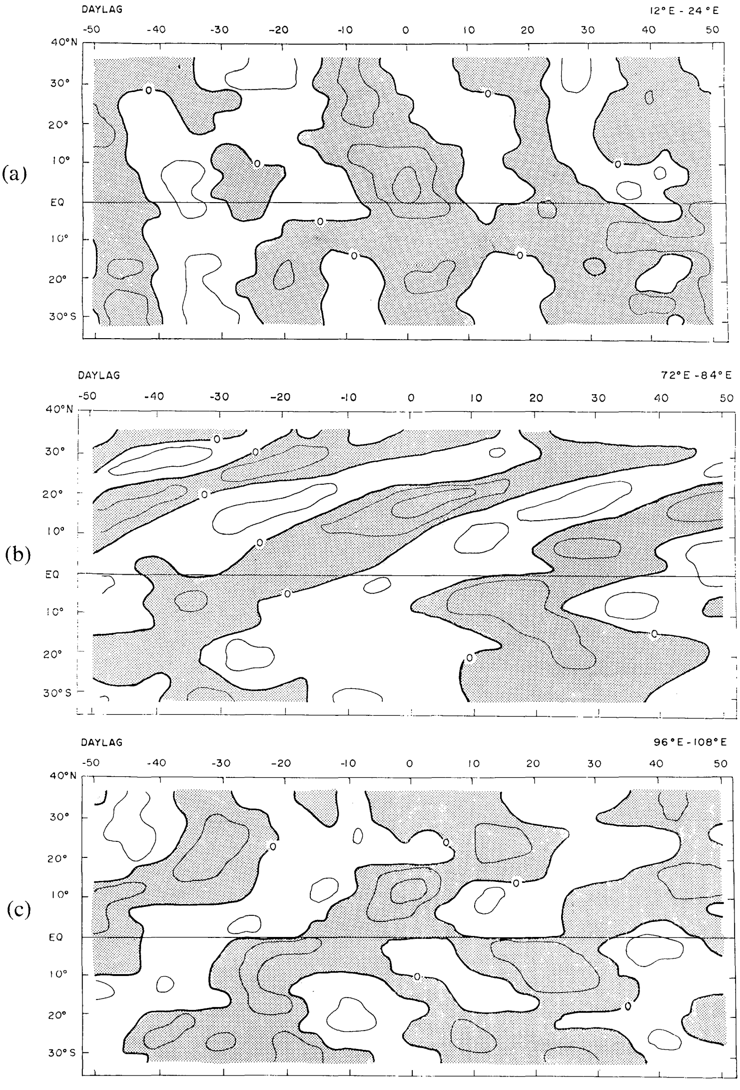


Fig. 8 Day lag-latitude sections of time-space correlation coefficients for the longitude zones of (a) 12°–24°E, (b) 72°–84°E and (c) 96°–108°E. Contour line interval is 0.4. Areas of positive values are shaded.

appears to be a standing (or slightly southward moving) fluctuation with a period of 25 to 30 days. A northward movement of the correlation pattern is apparent to the north of 10°S over the Indian sector (72°–84°E), with a period of about 40 days, as shown in Fig. 8(b). This feature is also seen over the Arabian Sea (60°–72°E) and over the Bay of Bengal (84°–96°E) sector (data not shown).

As mentioned, in the Southeast Asian sector, northward movement is limited to the south of 25°–30°N, and a southward movement is noted to the north (Fig. 8(c)). In the sectors further to the east, the correlation patterns again show nearly standing oscillation or slightly southward movement (data not shown). Throughout these meridional day-lag cross sections from the west to the east, the correlation patterns commonly show a mode of around 40 day period, except in the African monsoon sector. Over Africa (Fig. 8(a)) it seems that the major mode of oscillation is a period of 25 to 30 days or, more likely, of 50 to 60 days.

It is noteworthy that the major northward movements of cloudiness from the equatorial zone in Fig. 7 are initiated by eastward moving cloud systems like those shown in Fig. 3. Namely, the parts of cloudiness indicated by A and B in Fig. 3 are respectively the same as those marked A′ and B′ in Fig. 7. Thereafter, maximum cloudiness occurs in the subtropical easterly zone (5°–25°N), as shown in see Fig. 4(b). The final stage of the northward movements is attributed to the cloudiness brought by the mid-latitude westerly disturbances passing over northern India and the Tibet-Himalaya region, as referred to in Fig. 6.

The evidence presented here suggests the nearly synchronized movements of the eastward moving disturbances both in the equatorial and in the mid-latitude zone, which may be largely responsible for the monsoonal fluctuations at least over India and adjacent regions.

5. Quasi-periodical variations of cloudiness during the northern summer monsoon

In the previous section, the characteristics of temporal fluctuations of cloudiness were discussed in the zonal and meridional sections and the dominant periodicities of monsoonal cloudiness were roughly estimated.

In this section, spectral and cross-spectral analyses are applied to determine more exactly the features of the periodicities of the fluctuations and their phase-relationships in the time-space field.

5.1 *Dominant periodicities of cloudiness fluctuations over Asia and Africa*

To examine the predominant periodicities, spectral analysis by the maximum entropy method (MEM) was performed. This method has the advantage of giving far better resolution, especially for short-time records, than the conventional methods (Ulrych and Bishop, 1975; Hino, 1977 etc.). The time-period of each set of data is 122 days (from June 1 to September 30, 1973). Power spectra were obtained for 225 blocks over the Eastern Hemisphere (one block covers 5° latitude × 12° longitude).

Fig. 9 shows the result of power spectral analysis for central India (10°–15°N, 72°–84°E), which reveals strong concentrations of power, one with a 40-day period and one with a period of nearly two weeks. To examine statistically the spectral features of the northern summer monsoon area, histograms were constructed of the largest and second largest peaks of the power spectrum for each block of both the Asian monsoon area (60°–180°E, 10°S–40°N) and the African monsoon area (0°–48°E, 10°S–20°N), as shown in Fig. 10.

Over the Asian monsoon area (Fig. 10, upper), the predominant periodicities are of 40 days, 9–15 days, and around 2–3 days. In the histogram of the largest peaks only (denoted by shaded part in Fig. 10, upper), the 40-day period is predominant, which suggests that the fluctuation with this period is a fundamental mode over this area. The quasi-biweekly fluctuation is also confirmed in the cloudiness fluctuations. The large frequency

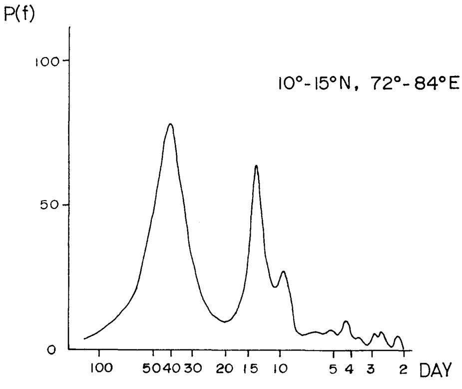


Fig. 9 Power spectra of cloudiness fluctuations for a block of 10°–15°N, 72°–84°E. Units are (cloudiness values)^2·day.

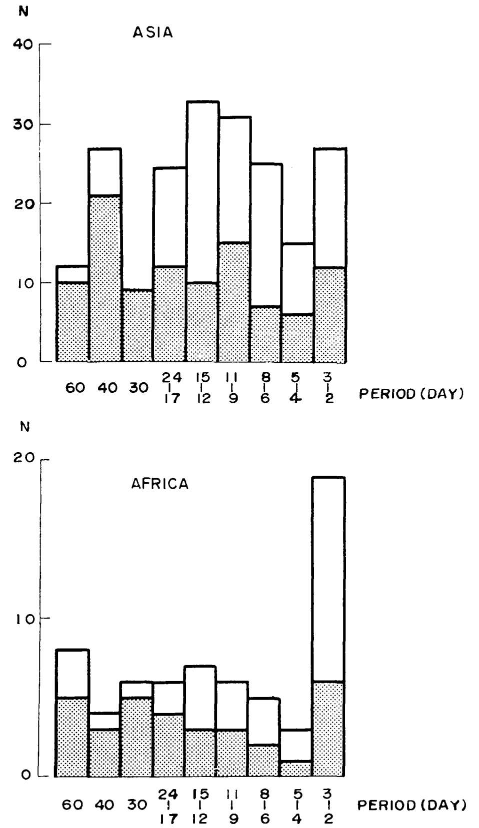


Fig. 10 Histograms of the largest and second largest peaks of the power spectra of cloudiness for each block over Asian monsoon region (upper) and over African monsoon region (lower). Those of the largest peaks are shown by shaded columns. Units are number of peaks.

of the 2–3 day period may be attributable to small-scale disturbances like those observed over the western Pacific (M. Murakami, 1971).

Over the African monsoon area (Fig. 10, lower), in contrast, a 2–3 day period is predominant. Orlanski and Polinsky (1977) also found this period range predominant in the spring season (March to May) over the African continent. They showed that the horizontal scale of these disturbances is of the order of 2,000 km. However, the horizontal scale of each unit-block (5°×12°) and the time interval of the data (once per day) in the present analysis seem to be too wide to discuss such a period range more in detail. Though not prominent, fluctuations of 60-day period occurred in relatively high frequency. These results suggest that the characteristics of cloudiness fluctuations over Africa are somewhat different from those over Asia.

The representative periodicities of large scale fluctuations over the Asian summer monsoon area are thus about 40 days and around 15 days. However, the fluctuation of around 15-day (or quasi-biweekly) period does not appear explicitly in the analysis of time-space correlations (see Fig. 8). This may be due to the far larger variances of the 40-day period, for the whole area in general, than those of the about 15-day period.

To eliminate the low frequency part of the fluctuations, a difference filter was applied to the smoothed cloudiness data. Namely, a filtered datum $C_f(t)$ by this method is,

$$C_f(t_k)=C(t_k)-C(t_k-1)$$

where $C_f(t_k)$ is smoothed cloudiness on the k-th day after operating 5-day running mean.

$C_f(t_k)$ values show a large frequency response with a period range from about 8 to 15 days. Time-space correlation coefficients were computed again for the filtered data to verify the time-space correlations of the mode of 10- to 15-day period. The day lag-latitude section for the Indian sector is shown in Fig. 11, revealing a remarkable northward phase shift over the Northern Hemisphere. A northward shift was also found over the Philippine sector (data not shown). Fig. 11 indicates that the northward phase shift of this period range is characterized by a phase speed of about 2° latitude/day with a latitudinal scale of about 20°. Thus, a mode of 10- to 15-day period is also likely to exist in the cloudiness fluctuations over India and Southeast Asia.

5.2 *Spatial behavior of the cloudiness fluctuations with the two dominant periodicities*

Here, the characteristics of the fluctuations of the two major modes (those of about 40-day and 15-day period) will be examined over the whole northern summer monsoon area.

First, a cross-spectral analysis was made to get the propagation characteristics of cloudiness movement in each period range, by the lag correlation method. In this computation, the total record length was 122 days, while the maximum lag number of 20 was used.

Fig. 12(a) shows the distribution of variance for the 40-day period and its phase angle relative to a reference point in central India. High variance values are distributed over India, Southeast Asia, south China and the western Pacific near Japan, where the large amount of monsoon cloudiness is also found (see Fig. 1).

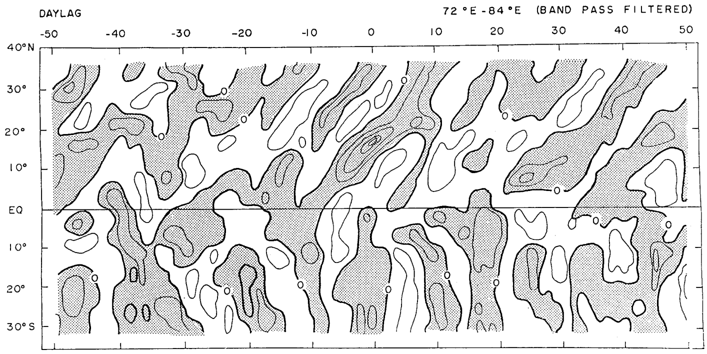
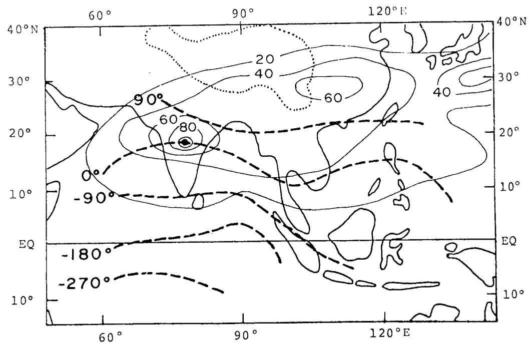


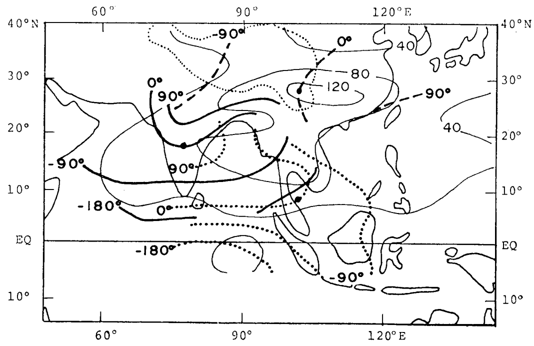
Fig. 11 Day lag-latitude sections of time-space correlation coefficients computed by the use of band-pass-filtered cloudiness. Details appear in the text.

40 DAY PERIOD



(a)

10- 20 DAY PERIOD



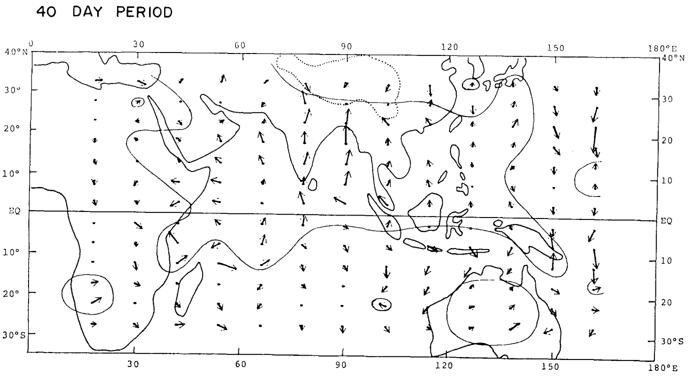
(b)

Fig. 12 Spatial distributions of variances (thin solid lines) and phase lag relations for (a) 40-day period, and (b) 10- to 20-day period range. Reference points are plotted with dots. Units of variances are (cloudiness values)^2.

The phase angle pattern indicates a very clear northward movement of cloudiness, especially over the Indian Ocean area, with a phase speed of about 1° latitude/day. Over the Malaysia-Indonesia region the movement seems to be northeastward. In Fig. 12(a), only the phase angles of cross spectra whose coherences are greater than 0.3 are illustrated. The feature of the northward movement over the Indian Ocean again corresponds well with the result of time-space correlation analysis made by T. Murakami (1976). Most of reports of spectral analyses so far conducted on the fluctuations of monsoon have not mentioned the 40-day period, partly because this period ($\simeq$40 day) is too long in comparison with the total length of the monsoon period (90–120 days) to be detected significantly by the conventional spectral analysis (such as lag-correlation method). Only Dakshinamurti and Keshavamurty (1973) have reported an oscillation with a period of around one month through the spectral analysis of winds at 850 mb level, by use of combined data for the four monsoon seasons. The time-sectional analysis mentioned here (see Fig. 4(b), for example) reveals that the maximum (minimum) cloudiness appears at intervals of 30 to 50 days. Thus, the periodicity they noticed may be related to that of around 40 days (or, roughly 30 to 50 days) reported here.

A phase relationship in the fluctuation of the quasi-biweekly mode was also investigated. Unfortunately, no systematic phase difference over a broad area with respect to a single reference block was found, probably because the periodicity of this mode was variable within a fairly wide period range, as expected from Fig. 10. The same feature of this fluctuation mode is also noted by M. Murakami (1976). Therefore, cross-spectral estimates for a 10- to 20-day period were averaged to obtain more appropriate phase relationships. In this case, significant phase angle relationships were found around some reference blocks over

(a)



(b)

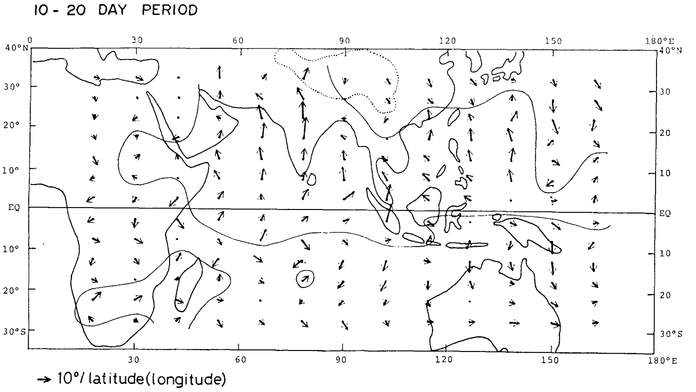


Fig. 13 Distributions of phase-lag vectors (see text) for (a) 40-day period and, (b) 10- to 20-day period. Length of each vector indicates phase-lag per one latitude-longitude degree, and solid lines show the rough boundaries of northward and southward components.

India and Southeast Asia. Fig. 12(b) shows the averaged phase differences with the three reference blocks (over central India, Malaysia and east Tibet). By combining these three patterns of phase difference, one may speculate that a wave of this mode located over the Malaysia-Indonesia region advances northwestward through the Bay of Bengal to India, and on reaching the Tibet-Himalaya region turns to the east, moving eastward as a mid-latitude westerly wave.

As described above, the cross-spectral analysis was partly successful in revealing the time-spatial behaviour of the two dominant modes over India and Southeast Asia. To examine the propagation characteristics over the whole northern summer monsoon area, a phase-lag vector analysis was conducted. Even though the spatial movement of cloudiness for each periodicity is somewhat complicated, the cross-spectral estimates for areas contiguous to a reference point were expected to show a high degree of coherence. Therefore, zonal and meridional phase-lags were calculated for each block by averaging phase-lags for two zonally or meridionally neighbouring blocks. Then, a phase-lag vector for each block was composed by using these two phase-lag values. It follows that a wave of each periodicity will propagate significantly where phase-lag vectors systematically change in the space field. Composite maps of phase-lag vectors for the 40-day period and the 10- to 20-day period are shown in Fig. 13(a) and 13(b), respectively. Averaged coherences for each block are greater than 0.5 for most of the blocks. In these figures, the arrows indicate the direction of propagation of the waves of each periodicity, and the length of the arrows represents the phase-lag per unit longitude-latitude degree.

The fluctuation of 40-day period (Fig. 13(a)) tends to be propagated mainly with north-south components over most part of the area. A broad northward movement is prominent over the whole Asian monsoon area, as enclosed by a solid line. The most remarkable and systematic northward movement is apparent over India and the Indian Ocean area, as repeatedly noted in the previous sections. Interestingly, a westward component is also marked over the Somalia-Arabian Sea region. To the east of the area of northward movement, namely over the central Pacific, southward movements are predominant. By combining these results with those of the time-space correlation analyses, the fluctuation of about 40 day period can be summarized as follows: major cloudiness appears over the southern equatorial zone from roughly 60° to 150°E in longitude (namely, over monsoon Asia in a broader sense), and gradually progresses northward as a whole and northwestward in the western marginal area (over the Arabian Sea). When the central part reaches around the Himalayas (about 30°E) after about 40 days, another major cloudiness appears over the southern equatorial zone, which again moves northward. The area where northward movement is predominant corresponds well with that of major monsoon cloudiness (see Fig. 1). This simultaneous northward (or northwestward) propagation of cloudiness with a period of around 40 days may be considered a quasi-periodical northward expansion of the ITCZ over the Asian monsoon area centered at 80°–90°E.

Fig. 13(b) shows the phase-lag vectors for the 10- to 20-day period, which have similar features to those of 40-day period. However, the following three differences can be recognized. First, relatively large eastward or westward components exist over the whole area, which result from zonally propagating waves of this period range over each latitude zone. Second, the northward movement of cloudiness over the Asian monsoon area differs somewhat. In the same manner as in Fig. 13(a), a wave progresses northward from the southern equatorial zone over the Indian Ocean, but first it propagates eastward or northeastward toward Southeast Asia, and then it turns northwestward toward the Bay of Bengal and India, as was speculated from the cross-spectral analysis (see Fig. 12(b)). By using zonal phase lags, the estimated zonal wavelength of the eastward propagating wave over the equatorial zone (0°–5°S) is 7,000–9,000 km (wavenumber $\simeq 4$ or 6). Marked northward movement also occurs over and around the Philippines. In contrast, a distinctive southward or southeastward movement occurs over the area from south China to the central Pacific, which may be attributable to the movement of mid-latitude westerly disturbances. In their spatial distribution the northward or northwestward movement and the southward or southeastward movement mentioned above appear as two clockwise rotations of this period range propagating over the whole Indian monsoon area (Bay of Bengal, India and Tibet) and over the western Pacific (including South China Sea and the Philippines). The similar clockwise rotation of surface pressure anomalies over India-Bay of Bengal region depicted by M. Murakami (1976) may be related to the clockwise rotation of cloudiness over the former area. The daily mosaic pictures show that monsoon disturbances marching northward or northwestward from the Bay of Bengal to northern India frequently cross the Himalayas and change into or merge with the mid-latitude westerly disturbances over Tibet. The northward movement around the Philippines seems to be derived from the formation and movement of tropical depressions and typhoons over this area.

The third difference is a systematic southward and southeastward (or anti-clockwise) propagation which is apparent from the equatorial zone around Indonesia and New Guinea. A series of daily mosaic pictures suggests that the propagation of cloudiness represents the movement of cloud vortices, which progress from the equatorial zone mentioned above southward to the Southern Hemisphere westerly zone, becoming extratopical vortices.

These results suggest that the cloudiness fluctuation of this period range (10 to 20 days) may be closely associated with the formation and movement of major monsoon or tropical disturbances.

6. Conclusions and remarks

Analysis of cloudiness fluctuations by several methods confirmed the existence of two major modes, with periodicities of around 40 days and around 15 days, and the behaviors of these two modes in the time-space field were investigated over the whole northern summer monsoon area.

The fluctuation of 40-day (or, roughly 30- to 50-day) period appears as a simultaneous northward movement over the whole Asian monsoon area (60°–120°E) from the southern equatorial zone to the zone at about 30°N. The northward movement is most apparent over the India-Indian Ocean area. The northward movement is initiated by eastward-propagating cloud disturbances developing over the equatorial Indian Ocean. These equatorial disturbances seem to correspond to those suggested by Madden and Julian (1972). According to their study, there is a convective disturbance propagating eastward from the Indian Ocean to the central Pacific, which is associated with a global-scale east-west pressure oscillation of 40- to 50-day period. They also speculated that strong zonal circulation cells exist to the east and west of the disturbance. It follows, therefore, that the upper level easterly and the lower level westerly wind (or the surface monsoon flow in the Indian Ocean) may be intensified (weakened) after (before) the passage of the disturbance, which is also suggested by Cadet and Olory-Togbé (1977). This speculation is consistent with the features around the India-Indian Ocean sector mentioned in the present paper. That is, when the disturbance approaches the Indian sector, the "break" conditions occur over India. At this stage, monsoon cloudiness shifts northward to the Himalayas. After passage of the disturbance toward Southeast Asia, monsoon cloudiness over India gradually moves northward from the south of India, and finally, in the "active" phase, almost continuous cloudiness extends from northern India southeastward to Southeast Asia and far beyond, at which time the disturbance has reached the western Pacific region.

In all events, it can probably be said that the "active" and "break" phases of the monsoon in the conventional meaning are related with the fluctuation of this period range.

As a possible cause of oscillations with this period range (40 to 50 days), Madden and Julian (1972) referred to a feedback mechanism between sea surface temperature and atmospheric circulation, which is known as atmospheric teleconnections (Bjerknes, 1969, etc.), or an evaporation-precipitation cycle over the trade-wind zone (Kraus, 1959). Whatever the physical process, it is feasible that the fluctuation of this mode during the northern summer results from a combination of the east-west oscillation over the equatorial zone with a feedback mechanism of (sensible and latent) heating and cooling caused by cloud cover which operates under conditions of meridional land-ocean contrast, since the northward movement of cloudiness is most prominent over the Tibet-India-Indian Ocean Sector.

The fluctuation with roughly a 15-day (or 10- to 20-day) period also appears totally as a northward movement over the Asian monsoon region. Similar to that of 40-day period, the northward movement seems to be initiated by the eastward-propagating waves over the southern equatorial Indian Ocean, whose zonal wavelengths are shorter (7,000–9,000 km) than those of the 40-day period. The propagation of this wave changes from eastward to northward over the northern equatorial zone, then to northwestward over Southeast Asia. Over the area from the head of the Bay of Bengal and south China to the western Pacific, a clockwise rotation is noticeable. The propagation of this wave is mainly related to the movements of major cloud disturbances. However, the same disturbance does not necessarily move from the equatorial zone up to the mid-latitudes. It is more plausible that in progressing eastward the equatorial wave disturbances excite the subtropical easterly wave in some way to produce monsoon disturbances over the Bay of Bengal or tropical depressions (or typhoons) over the western Pacific. These disturbances develop while moving northward to the Himalayas (or the western Pacific to the south of Japan) and then interact with the mid-latitude westerly waves to develop westerly disturbances. In the Southern Hemisphere, the propagation also represents the movement of some kind of tropical disturbances, which are generated over the equatorial area, move southward, and finally become the mid-latitude westerly disturbances. Very recently, mid-latitude troughs of great amplitude staying simultaneously at around 110°E over both hemispheres were suggested to play a large role in the "break" phases of Indian summer monsoon (Ramaswamy and Pareek, 1978). This synoptic feature may be considered to represent one phase of the fluctuation of this mode. Therefore, the fluctuation of this period range seems to be closely related to the mid-latitude westerly waves in both hemispheres, as well as to the equatorial waves.

Some problems can be pointed out for future study on the dynamical process of the meridional interaction of waves associated with this mode. It is plausible that monsoon (or tropical) disturbances play an important role in the development of the mid-latitude disturbances by injecting heat and moisture into the westerlies (Erickson and Winston, 1972). Conversely, the westerly waves of great amplitude might trigger the formation of equatorial disturbances, which may contribute to the monsoonal fluctuation as described previously. In this case, the problem may arise of how the westerly waves affect the equatorial flow through the "critical latitude".* Many theoretical studies have been made on this problem. For

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* In this paper, the "critical latitude" means the latitude at which the phase speed of a westerly wave is equal to the mean zonal flow.

example, M. Murakami (1974) used a model including non-linear wave interaction with the zonal flow to show that the equatorial Kelvin wave mode can be instigated by the westerly wave. But it remains to be proved whether the mode of the equatorial wave suggested here (around 15-day period, wavenumber of 4 to 6) can be excited. Additionally, more attention should be paid to the fact that the Tibet-Himalayas as a strong heat-source region for the monsoon system lies under the influence of the mid-latitude westerlies. As is commonly supposed (Flohn, 1968; Hahn and Manabe, 1975 etc.), cumulus convections over this region play an important role in the maintenance of the monsoon circulation. However, as examined in this paper, the convective activity over this region varies depending majorly on the westerly wave movements. In this context, the mid-latitude westerlies are considered to be one of the main controlling factors of the fluctuation of the monsoon system.

Here, such questions may arise as the interrelatedness of the two dominant modes. One may suppose that the mode of the 40-day period results simply from large amplitudes of the fundamental mode of about 15-day period which appear every two (or three) periods. The difference in phase speed of northward propagation of the two modes and in the zonal scale of the equatorial wave related to each mode is evidence that these two modes are independent each other, though further discussion may be needed. In this sense, the year-to-year features of the fluctuations of these modes should also be examined in connection with the activity of monsoon for each year. Moreover, to discuss the cloudiness fluctuations related to the dynamics and energetics of the monsoon, a similar analysis should be made by use of three-dimensional data on wind, temperature and moisture fields. The forthcoming MONEX is expected to reveal more completely the structures of the large-scale monsoonal fluctuations treated in this paper.

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北半球夏季モンスーン時における雲量変動の解析

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海陸を含めた広域モンスーンの変動を解析する手段として，気象衛星写真はきわめて有効と思われる。この論文では，緯度 1°，経度 2° ごとに読みとった可視域の輝度データをもとに，北半球夏季モンスーン時（1973年6月-9月）の雲量変動を東半球域について解析した。

スペクトル解析の結果，約40日と約15日の長周期変動が卓越していることがわかった。

時間断面解析，時差相関解析，位相差ベクトル解析等の手法を用いた結果，約40日周期の変動の位相は，インド亜大陸からベンガル湾を中心とするアジア南西モンスーン域で顕著に北上し，アフリカや中部太平洋域ではむしろ，南下する様相が明らかとなった。この変動は，広域にわたるモンスーン活動域の変動（又は ITCZ の南北方向の変動）に対応している。約15日周期についても，同様の位相の動きが認められるが，特にインドから中部太平洋域にかけての地域では，ベンガル湾と，フィリピン付近を中心とする2つの時計回りの回転性の動きが特徴的である。また，南半球では，オーストラリアの東，西部の海洋上において，中緯度へと南下する位相が現われている。これらの変動は，発達したモンスーン（又は熱帯）じょう乱，中緯度偏西風じょう乱の相互に関連した動きに対応している。

上記二つのモードの変動の力学的説明は未解決であるが，約40日周期については，南北方向の海陸の熱的コントラスト存在下における赤道域の大規模東西振動の役割が，約15日周期については，中緯度～赤道域における波動の南北方向の相互作用が，それぞれ重要な課題と考えられる。