

## Withdrawal of the Indian summer monsoon and its relation to the seasonal transition from summer to autumn over east Asia

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**सारांश**— FGGE स्तर III-b और ECMWF परिचालन विश्लेषण आंकड़ों का प्रयोग करते हुए वर्ष 1979 से 1984 के लिए अगस्त से नवम्बर तक भारतीय ग्रीष्म मानसून की वापसी की अवधि के दौरान दक्षिणी एशिया पर बड़े पैमाने के परिसंचरण के समय विकास का परीक्षण किया गया है। भारतीय ग्रीष्म मानसून की वापसी के दौरान आकस्मिक संक्रमण के तीन भिन्न स्तरों का पता लगाया गया है। तिब्बती पठार के आस-पास 200 मि.बार उष्णकटिबंधीय जेट प्रवाह की दक्षिणाभिमुखी बदलाव, भारतीय उपमहाद्वीप के आस-पास 850 मि.बार पश्चिमी पवनों का धीमा पड़ना भारत के पश्चिमी तट पर वर्षा में कमी, और/अथवा यूरेशियन महाद्वीप पर 300 मि.बार क्षेत्रीय माध्य तापमान का तेजी से गिरना, इन संक्रमणों पर लगभग एक साथ घटित होते हैं।

**ABSTRACT.** The time evolution of the large-scale circulation over south Asia during the withdrawal phase of the Indian summer monsoon from August to November is examined for the years from 1979 to 1984 using FGGE Level III-b and ECMWF operational analysis data. During the withdrawal of the Indian summer monsoon, three distinct stages of abrupt transitions are recognized. The southward shift of 200 mb subtropical jet stream round the Tibetan plateau, weakening of 850 mb westerlies around the Indian subcontinent, decrease of rainfall along the west coast of India, and/or sharp drop of 300 mb zonal mean temperature over the Eurasian continent occur almost simultaneously associated with these transitions.

### I. Introduction

The onset of the Indian summer monsoon is accompanied by distinct changes in the large-scale atmospheric circulation. It occurs almost simultaneous with the beginning of the early summer rainy season over east Asia, called 'Mei-yu' in central China and 'Bai-u' in Japan.

Little attention has been paid to the changes associated with the withdrawal of the Indian summer monsoon, although there is another rainy season in Japan, called 'Akisame' or 'Shurin' (autumn rain) in autumn. Chinese meteorologists noticed the relationship between the retreat of the Indian summer monsoon and the weather in China (Staff Members Academia Sinica, 1958). Reiter and Heuberger (1960) analyzed the synoptic situations of the 1954 monsoon retreat. Several studies suggested that the end of the summer monsoon is abrupt in the Himalayan regions. Ding *et al.* (1983) investigated the temperature changes over the Eurasian continent during the late summer of 1979 associated with the retreat of the Indian summer monsoon. Matsumoto (1988) revealed that the seasonal transition from late summer to autumn in Japan experienced four distinct stages like early summer situations presented by Yoshino (1965), and inferred that these stage transitions are closely related to the retreat of the Indian summer monsoon.

However, total descriptions of the withdrawal of the Indian or the Asian summer monsoon are still lacking. In order to realize the mechanism of the summer monsoon, it is also necessary to understand the physical processes associated with the retreat of monsoon, as well as the onset and/or the intraseasonal oscillation. In the present study, the author analyzed the large-scale circulation over the Eurasian continent from late summer to late autumn to describe the overall features of the monsoon withdrawal over south Asia and to relate them to the seasonal changes over east Asia.

### 2. Data and analysis procedure

The data used in this study are the FGGE Level III-b data set produced at the European Center for Medium Range Weather Forecasts (ECMWF) and the 1980 to 1984 ECMWF operational analysis fields. The details about this data set are described by Bengtsson *et al.* (1982). The wind fields are obtained by using observations from satellites, aircrafts, drifting balloons, as well as conventional synoptic observations. The 12 GMT temperature at 300 mb, the zonal wind at 200 mb and 850 mb and the meridional wind at 850 mb for the months from August to November are utilized.

The daily and 5-day precipitation amounts for the months from August to October are also utilized. Rain fall data are based on the FGGE Level II-c data sets

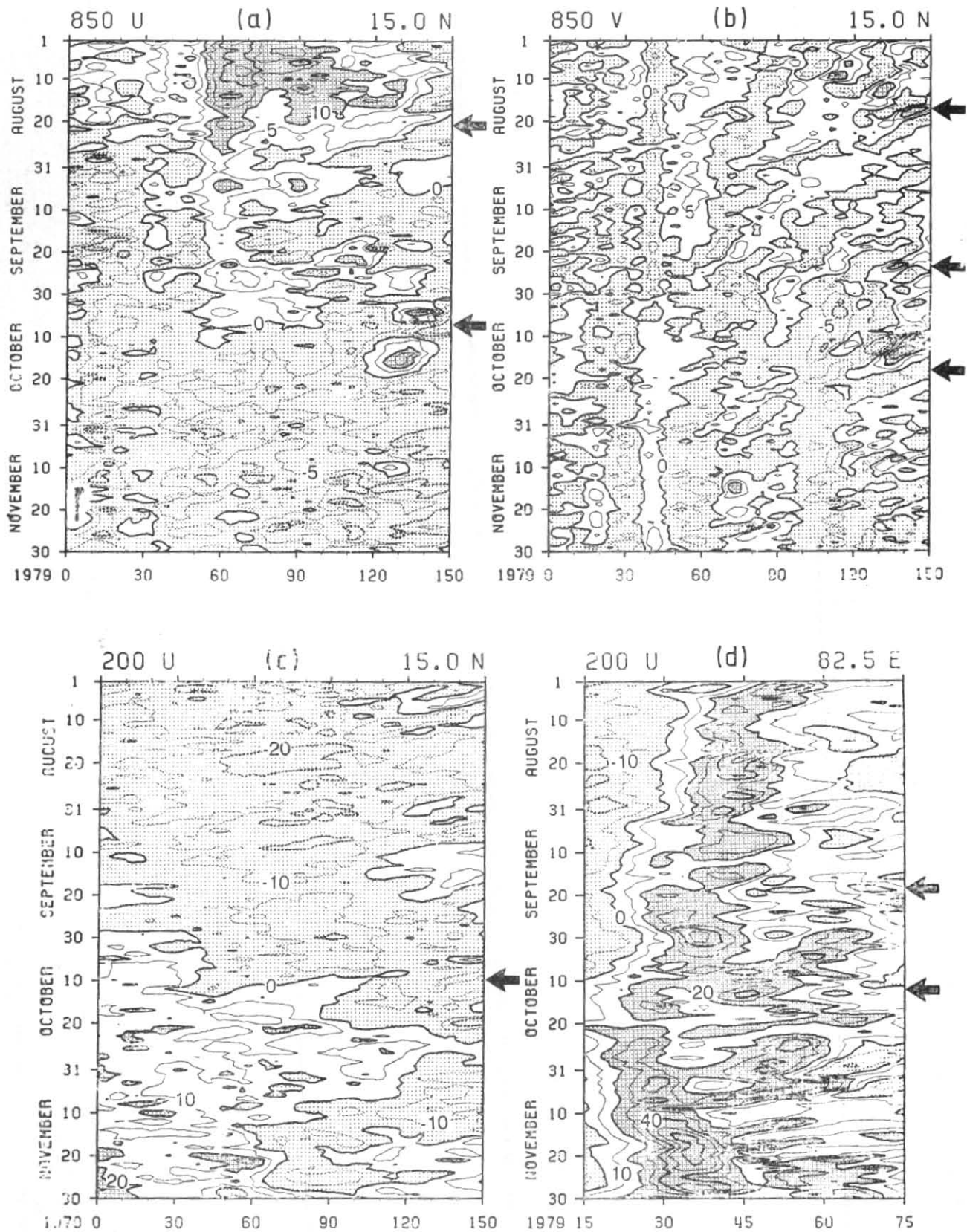


Fig. 1. Time-longitude sections of daily 850 mb zonal (a) and meridional wind (b) at 15° N, 200 mb zonal wind at 15° N (c), and a time-latitude section of 200 mb zonal wind at 82.5° E, averaged between 78.75° E and 86.25° E (d) in 1979. Contour intervals are 5 m/s for 850 mb and 10 m/sec for 200 mb. Regions of the easterlies (a, c) and northerlies (b) are light shaded. Heavy shadings denote the regions of westerlies greater than 10 m/s (a) and 20 m/s (c, d). Arrows in the right column indicate the date of marked changes.

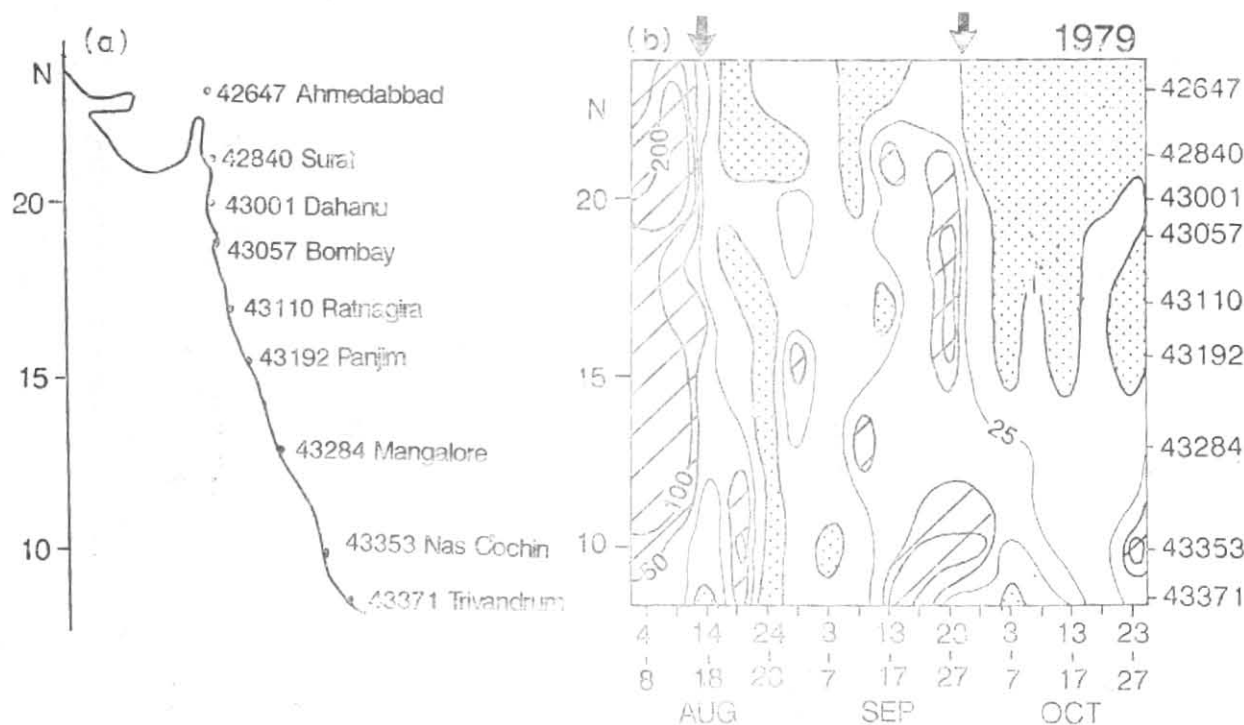


Fig. 2. A location map of stations (a) and a time-latitude section of 5-day total precipitation (mm) along the west coast of India in 1979 (b). Regions less than 1 mm are shaded and those more than 50 mm are hatched. Arrows are the same as Fig. 1.

compiled at the National Climatic Data Center, U.S.A. for 1979 and the *Indian Daily Weather Reports* published by the India Meteorological Department (IMD) for 1980 to 1984. Since the rainfall amounts in November are generally very small in the central part of India the rainfall data in November are omitted.

First, the FGGE year situations are analyzed for the region from  $0^{\circ}$  N to  $75^{\circ}$  N,  $0^{\circ}$  E to  $150^{\circ}$  E. Time-latitude or time-longitude sections based on daily data are constructed, as well as distribution maps of 10-day mean wind fields and 10-day total precipitation. Then the situations in the years from 1980 to 1984 are analyzed to obtain the common features and interannual variations of the summer monsoon withdrawal. Lastly relationship between the withdrawal of the Indian summer monsoon and seasonal transition from summer to autumn over east Asia are analyzed.

### 3. The situations during the withdrawal of the Indian summer monsoon in the FGGE year

Time-longitude sections of daily 850 mb zonal and meridional winds and daily 200 mb zonal wind at  $15^{\circ}$  N, and a time-latitude section of 200 mb zonal wind along the longitudinal strip of  $7.5^{\circ}$  width centred at  $82.5^{\circ}$  E are shown in Fig. 1 in order to present the time evolution of wind systems in both upper and lower troposphere.

Fig. 1 shows that several distinct changes in the wind systems occur during the investigated period which are shown by arrows on the right column of each figure. At  $15^{\circ}$  N the 850 mb westerlies weaken around 20 August over the Arabian Sea, the Indian subcontinent, and the Bay of Bengal (Fig. 1a). At the same time, the southerlies over the Arabian Sea retreat westward to  $60^{\circ}$  E (Fig. 1b). The 200 mb winds, however, show little changes during this period (Figs. 1c & d).

The southerlies around  $50^{\circ}$  E, which correspond to the wind systems related to the Somali jet, decay around 20 September. At the same time, the northerlies begin to prevail over the South China Sea (Fig. 1b). The axis of the 200 mb subtropical jet stream at  $82.5^{\circ}$  E which flows north of  $40^{\circ}$  N before 20 September, suddenly shifts southward to  $\sim 35^{\circ}$  N (Fig. 1d). This means that the subtropical jet stream flows over the Tibetan plateau after this date.

The most remarkable changes occur around 10 October. The 850 mb westerlies over the wide regions from  $60^{\circ}$  E to  $100^{\circ}$  E at  $15^{\circ}$  N are abruptly replaced by the easterlies. The prevailing wind over the Arabian Sea is the southeasterlies for the first ten days after this change. After 20 October, they are replaced by the northeasterlies which means the beginning of the northeast monsoon season. The changes of 200 mb wind systems also take place around 10 October. Easterlies are replaced by westerlies over the wide areas from  $30^{\circ}$  E to  $90^{\circ}$  E (Fig. 1c), accompanied by a sudden southward shift of the subtropical jet stream from  $35^{\circ}$  N to  $28^{\circ}$  N at  $82.5^{\circ}$  E (Fig. 1d). After this transition the subtropical jet stream flows around the southern periphery of the Tibetan plateau.

The 5-day total rainfall amounts along the west coast of India also experienced abrupt decreases in mid-August and late September (Fig. 2b). The latter period seems to correspond to the end of the summer monsoon season from the central part of the west coast of India. Murakami *et al.* (1986) noted that the withdrawal of the Indian summer monsoon in 1979 takes place around 27 September based on the harmonic analysis of the seasonal cycles to the outgoing longwave radiation (OLR) data.

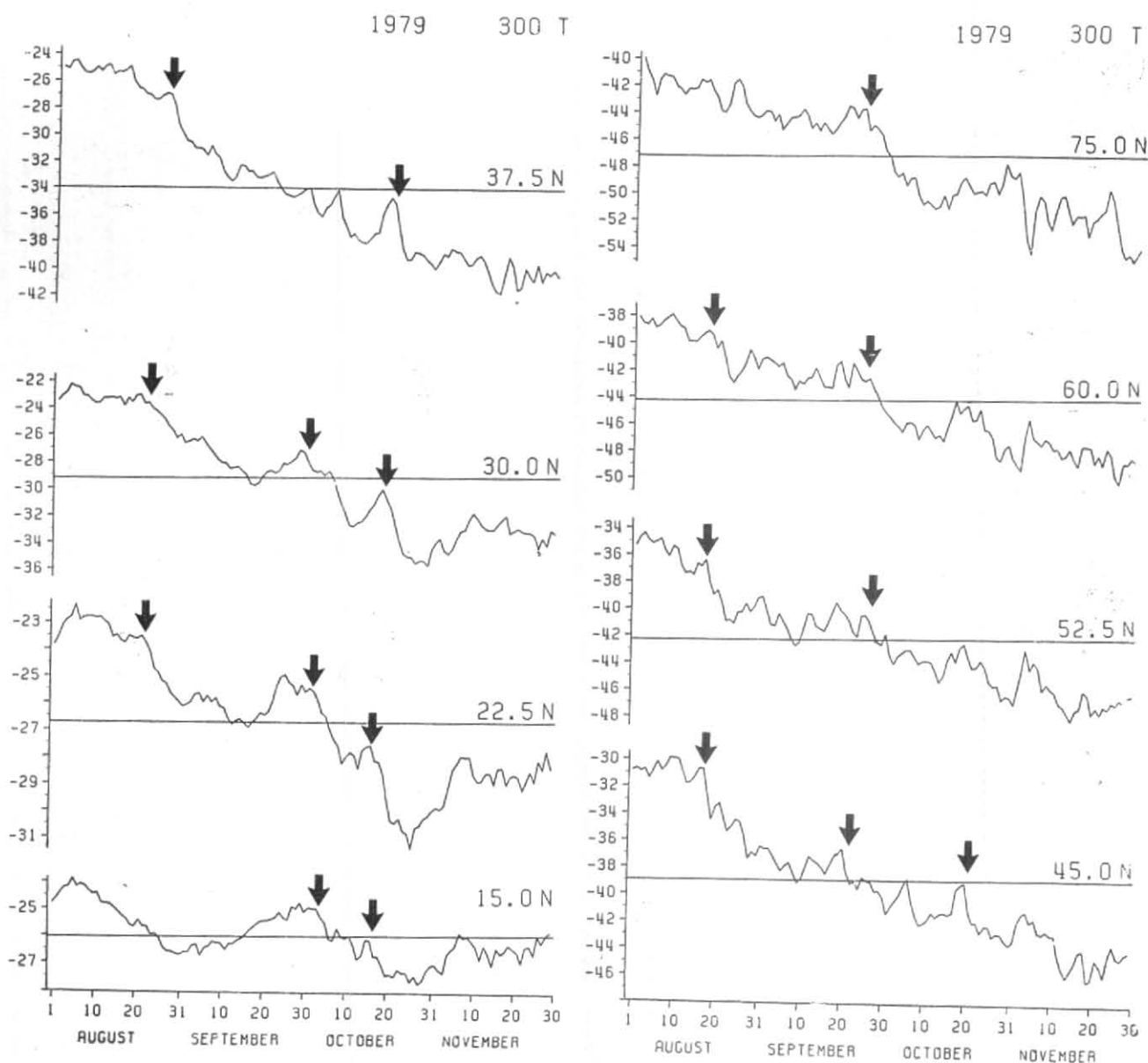


Fig. 3. Time-series of 300 mb zonal mean temperature averaged between  $0^{\circ}\text{E}$  and  $150^{\circ}\text{E}$  and at several selected latitudes. Arrows are the same as Fig. 1.

The time-series of zonal mean 300 mb temperature averaged between  $30^{\circ}\text{E}$  and  $150^{\circ}\text{E}$  at several latitudes over the Eurasian continent shows that several sharp drops occur simultaneously in the wide latitudinal belt (Fig. 3). The zonal mean temperature drops around 18 August at  $45^{\circ}\text{N}$ ,  $52.5^{\circ}\text{N}$  and  $60^{\circ}\text{N}$ , and around 23 August at  $22.5^{\circ}\text{N}$ ,  $30^{\circ}\text{N}$  and  $37.5^{\circ}\text{N}$ , as is shown by Ding *et al.* (1983). Other sudden drops take place around 22 September between  $45^{\circ}\text{N}$  and  $75^{\circ}\text{N}$ , and around 2 October between  $15^{\circ}\text{N}$  and  $37.5^{\circ}\text{N}$ . Further distinct drops occur around 16 October at  $15^{\circ}\text{N}$  and  $22.5^{\circ}\text{N}$ , and around 20 October between  $30^{\circ}\text{N}$  and  $60^{\circ}\text{N}$ . The dates of these sudden drops are in accordance with the changes of wind fields and rainfall amounts, although more minute investigations on the physical processes are necessary.

In summary, three distinct transitions in wind, thermal and rainfall fields occur during the withdrawal period

of 1979 Indian summer monsoon. These changes, which are observed in the time sections, are also recognized in the distribution maps of 10-day mean wind fields and 10-day total precipitation (not shown). Based on inspections of both time-series sections and distribution maps, schematic illustrations of the upper and lower tropospheric circulations are presented for each stage divided by the three distinct transitions (Fig. 4). The change pointed out by Ding *et al.* (1983) just correspond to the beginning of the monsoon withdrawal. The total withdrawal process continues for approximately two months after this first change.

#### 4. The wind, temperature and rainfall for the years from 1980 to 1984

In order to see the common features and the year to year variations of the Indian summer monsoon withdrawal the following time-sections are constructed for

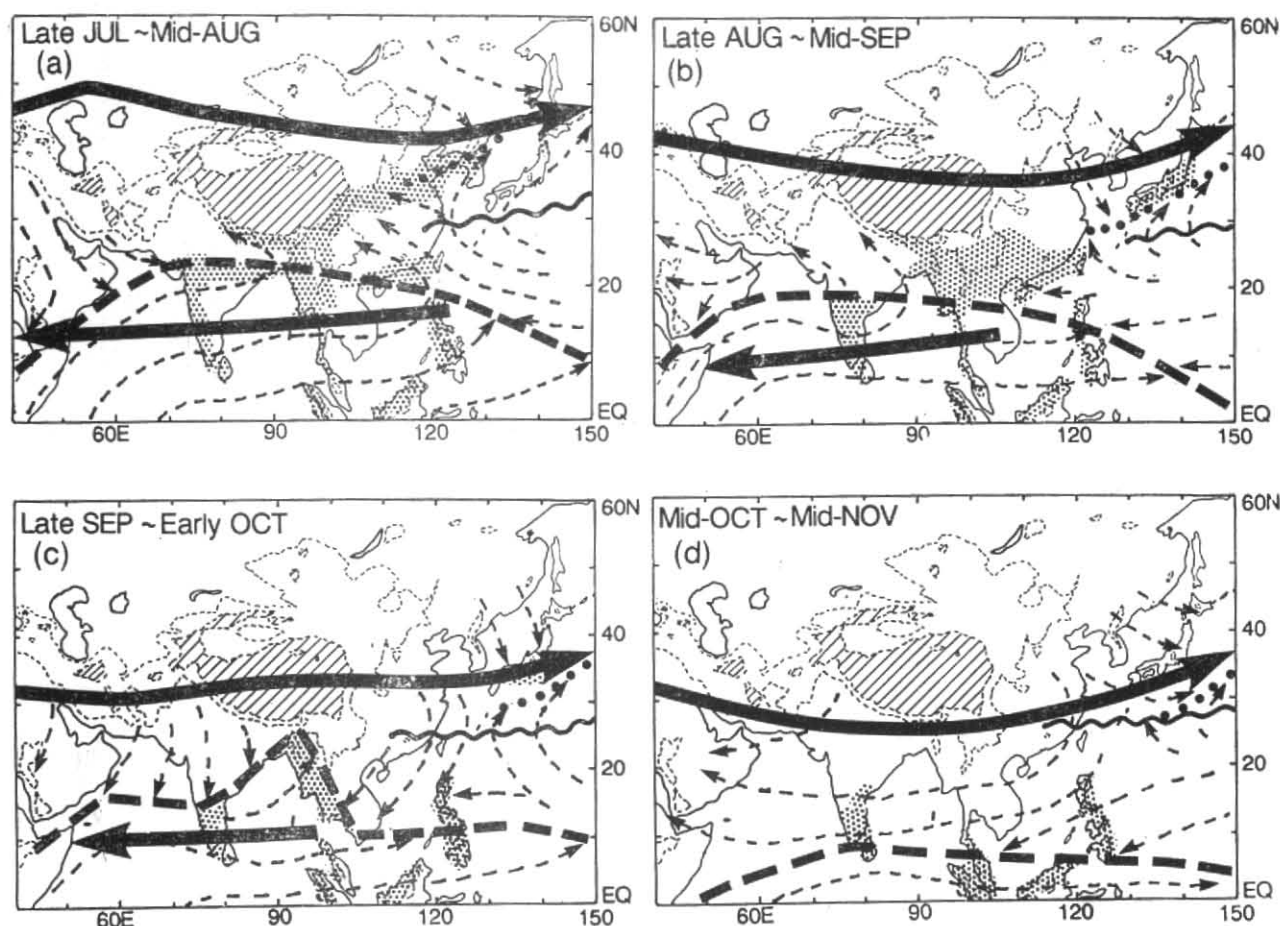


Fig. 4. Schematic illustrations of the large-scale circulation over south and east Asia from late August to November 1979. Thick arrows indicate axes of the jet stream at 200 mb. Thin dashed lines and dotted lines indicate locations of the ITCZ and the frontal zones at 850 mb respectively. The wave lines are the ridge lines of the subtropical anticyclone in the western Pacific. The shaded areas denote the heavy rain area exceeding 500 mm/day. Topographic contours are 1,000 m and 3,000 m and the regions higher than 3,000 m are hatched.

the years from 1980 to 1984 as in case in 1979; time-longitude sections of daily 850 mb zonal and meridional wind, those of 200 mb zonal wind at 15° N, time-latitude sections of 200 mb zonal wind at 80° E, averaged between 75° E and 85° E, those of 5-day total precipitation along the west coast of India and time-series of zonal mean 300 mb temperature averaged between 0° E and 150° E.

Although figures are not shown here, abrupt changes are clearly recognized twice or three times during the investigated period in every year. Approximate dates of the distinct changes in several meteorological elements for the period from 1979 to 1984 were found. The simultaneities of the changes in each meteorological elements are variable from year to year, however, several common features are recognized as follows:

(1) The rainfall amounts along the west coast of India suddenly decrease in late August. The 300 mb zonal mean temperature in mid and high latitudes sharply drops around this period (hereafter denoted by a first transition).

(2) The subtropical jet stream at 200 mb around 80° E suddenly migrates southward from 40° N to 35° N in late September. The 300 mb zonal mean temperature

also drops around this period, although the latitudinal zones of distinct changes are variable from year to year. The precipitation along the west coast of India, which increases again in mid-September, suddenly decreases around this period. The 850 mb westerlies at 15° N around the Indian subcontinent weaken and are replaced by the easterlies except in 1983 (hereafter denoted by a second transition).

(3) The rainfall amounts along the west coast of India increase again in mid-October in some years (1980, 1983 and 1984) and after few days they decrease drastically. 5-10 days after this decrease in the above years, or approximately 20 days after the second transition in other years, the subtropical jet stream at 200 mb displaces further southward to the south of 30° N, that is to the southern periphery of the Tibetan plateau in mid or late October. At the same time, 850 mb westerlies are completely replaced by easterlies around India at 15° N, and the zonal mean 300 mb temperature sharply drops (hereafter denoted by a third transition).

These results are consistent with those in 1979 described in the previous section, and also with those of Reiter and Heuberger (1960).

### 5. Relationship between the three distinct transitions and the oscillation of the monsoon activity

The activity of the Indian summer monsoon fluctuates with a periodicity of 30 to 50 days, associated with recurrent northward advancing clouds or rain bands from around the equator to  $\sim 30^\circ\text{N}$  (Yasunari 1979, Sikka and Gadgil 1980). Assuming the periods of heavy rainfalls along the west coast of India correspond to the active monsoon phases, the relationships between the monsoon activity and the transitional stages pointed out in the previous sections are as follows :

(1) The first and second transitions correspond roughly to the end of active monsoon phases.

(2) The third transition takes place in the weak monsoon phases.

In general, the Indian summer monsoon begins to withdraw from the northern limit in the beginning of September. Sikka and Gadgil (1980) stated that the maximum latitude in each northward moving cloud band decreases progressively after the beginning of September. The normal beginning date of the withdrawal from northwest India seems to be 5~20 days later than the first change in this study. This fact is interpreted as follows. After the end of the active monsoon phase in late August, the rain areas progress further northward to around the northern limit of the summer monsoon regions corresponding to the weak monsoon phase. Several days later, the weak monsoon phase ends and another heavy rain areas begin to move northward from the southern part of India, which corresponds to the beginning of the summer monsoon withdrawal from northwest India. Ananthakrishnan (1977) pointed out that the relative rainfall minimum in pentad rainfall is found around mid-August in several stations over north and central India. This rainfall minimum is possibly related to this first transition.

Little attention has been paid to the second transition in the process of monsoon withdrawal. In some years, however, both monsoon rains along the west coast of India and the monsoon westerlies around India retreat from wide regions at this transition. Therefore, the second transition should be more noted as one of the important processes of the withdrawal of the Indian summer monsoon.

The third transition coincides with the beginning of the northeast monsoon season and to be an important turning point of the seasons in south Asia, and seems to be a comparable change to the burst of monsoon during the onset phase. In general, the monsoon westerlies and rains weaken 10~20 days prior to this change.

As described above, distinct stepwise transitions are recognised during the withdrawal of the Indian summer monsoon. Three steps are superposed to the intraseasonal variations of monsoon activity. Subbaramayya *et al.* (1984) have shown that the advance of the Indian summer monsoon takes place primarily in three phases. Therefore, it is inferred that these three steps are common features in both the advance and the retreat of the monsoon.

Lastly, brief comments are added as to the synoptic aspects related to these changes. From inspections of daily 500 mb weather charts analysed by the Japan Meteorological Agency, these three transitions are

generally accompanied by the invasion of deep eastward moving troughs in mid-latitude westerlies into the Tibet-Himalayan region. Therefore, some interactions between mid-latitude westerlies and the monsoon withdrawal are inferred. Further study is needed, however, on this point.

### 6. Relationship between the withdrawal of the Indian summer monsoon and the seasonal transition over east Asia

Matsumoto (1988) divided four stages in the seasonal transition from late summer to autumn over east Asia. The best agreement is seen between the third transition in this study and the beginning of stage 4 by Matsumoto (1988). The second transition roughly coincides with the beginning of stage 3. The summer monsoon circulation in China ends at this period and the autumn rainy season in Japan called 'Akisame' or 'Shurin' also terminates. The first transition seems to precede several days prior to the beginning of stage 2. This time lag is well interpreted by the discussions in section 5. The beginning of stage 2, which falls on the autumn rainy season in Japan, is approximately coincided with the beginning of the monsoon retreat from northwest India, as stated by Matsumoto (1988).

Accordingly, the stepwise transitions in the withdrawal phase of the Indian summer monsoon are closely related to the seasonal transition from summer to autumn over east Asia.

### 7. Conclusions

The results obtained in this study are summarized as follows :

(1) During the withdrawal phase of the Indian summer monsoon, three remarkable stages of abrupt transitions are recognized in the large-scale circulation over south Asia.

(2) The first transition takes place in late August, accompanied by a sudden decrease in precipitation along the west coast of India and decrease in the 300 mb zonal mean temperature averaged between  $0^\circ\text{E}$  and  $150^\circ\text{E}$ . Approximately ten days after this transition, the retreat of the summer monsoon from northwest India begins.

(3) The second transition occurs in late September. The rainfall along the west coast of India, which increases again in mid-September, decreases drastically. This transition is corresponding to the end of summer monsoon rain along the central part of the west coast of India in some years. A weakening of monsoon westerlies around India, a southward shift of the 200 mb subtropical jet stream from  $40^\circ\text{N}$  to  $35^\circ\text{N}$ , and a sharp drop in 300 mb zonal mean temperature also occur at this transition.

(4) The third transition is most obvious and corresponding to the beginning of northeast monsoon circulation. This transition takes place in mid or late October and is an important turning point of the season in south Asia, comparable with the burst of monsoon. The 200 mb subtropical jet stream begins to flow around the southern periphery of the Tibetan plateau after this transition.

(5) These three transitions are in accordance with the seasonal transitions from summer to autumn over east Asia. Moreover, they are closely related to the intraseasonal low frequency oscillation of the Indian summer monsoon and passages of troughs in mid-latitude westerlies over the Tibet-Himalayan region.

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