Climatic Study on the Summer Tropical Easterly Jet at 200 hPa

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ABSTRACT

The low latitude easterlies at 200 hPa in summer (May–October) is analysed climatically during the 13–year period from 1968 to 1980, with a special emphasis on the relationships between the anomalous tropical easterly jet stream over South Asia and the low latitude atmospheric circulation, and also the summer monsoon precipitation in India. The compositing analysis shows that the tropical easterly jet stream over South Asia has five anomalous patterns at 200 hPa i.e. the western pattern, middle pattern, eastern pattern, two–branch pattern and multi–core pattern. Evidence has shown that the precipitaion in India anomalously increased during the anomalous period of the western pattern and the middle pattern, but reverse case is true in the eastern pattern. Some different anomalies of the precipitation in different area of India were found during the other two anomalous pattern.

I. INTRODUCTION

The tropical easterly jet stream (hereafter called TEJ) in the upper troposphere is one of the most important components of summer monsoon system in the India and the East Asia monsoon region, which has a close relationship to the seasonal changes of the low latitude atmospheric circulation and summer monsoon activity in the South Asia (Tao, et al., 1957; Yeh, et al., 1958; Krishinamurti, et al., 1976; Chen, et al., 1983). The strongest TEJ was usually found to be located at the 150–100 hPa level. The climatic studies on the fluctuations of the TEJ at 100 hPa and summer monsoon have been carried out by some authors (Kobayashi, 1974; Tanaka, 1982). Tanaka (1982) pointed out that the interannual fluctuations of the TEJ at 100 hPa were caused by the severe influences of the middle latitude atmospheric circulation in addition to following the low latitude seasonal evolution and that there exist some relationships between the TEJ and the typhoon over West Pacific; the intensity of the TEJ and the summer monsoon precipitation presented positive correlation in South Asia and years with major El Nino were found to be the years with weak TEJ and the precipitation decreased anomalously. Yang (1980) has studied the splitting phenomenon of the 100 hPa TEJ. Chen et al. (1980) suggested that there are two TEJs over the South Asia, the north branch being located at 100 hPa (15° N–20° N) and the south branch being found at 150 hPa near 8° N. Zhu et al. (1984) found out that the seasonal evolutions of the TEJ in 1979 presented 7 patterns which showed large differences during maintenance period. All of the above results indicate that the intensity and position of the steady TEJ in summer have apparently intraseasonal variations and interannual fluctuations; the low latitude circulations may also play an important role in the anomaly of the TEJ except middle latitude circulations. Based on 13–year 200 hPa wind data, in the present study, we will mainly discuss the relationship between anomalous TEJ and low latitude anomalous circulations. The changes of the precipitation distributions in India and the weather in South Asia in relation to the anomalous TEJ are also investigated.

II. DATA AND COMPUTATIONAL METHODS

The primary resource of global low latitude (45 ° N–45 ° S) wind data (u, v) with 5 longitude–latitude horizontal resolution during the period of 1968–1980 for May–September was provided by National Meteorological Center (NMC). It is reasonable to use the zonal wind to represent the TEJ because the stability (ratio between the zonal wind and vector wind) of the easterlies can reach 95% in summer. The arithmetic mean of zonal wind along the monthly mean TEJ axis for four months (June–September) is used as a measure of intensity of the TEJ in this month of the year. The deviation ($u', v', \vec{v}'$), which are the difference between the monthly mean and 13–year mean, are used to investigate the anomaly of the atmospheric circulation. An inspection of the monthly mean fields and anomaly fields for 52 months (June–September, 1968–1980) in total shows that TEJ can be divided synoptically into five patterns: western pattern, middle pattern, eastern patern, two–branch pattern, multi–core pattern which are related to the broad–scale anomaly of the low latitude circulations. Therefore, the compositing analysis technique is used to investigate the monthly mean wind and deviation fields of the five TEJ patterns in the low latitude area (20 ° S–40 ° N, 20 ° W–160 ° E). During the period of the anomalous TEJ patterns, anomalous changes characterized by percentage of the precipitation anomaly in five parts of India (Fig. 5), computed from the daily area average data sets (June–September, 1968–1980) provided by the Meteorological Department of India, are listed in Table 2. According to the fluctuations of the TEJ intensity (Fig. 1), five strong (weak) TEJ years are picked up (Table 3) for each month (June–September) and the difference in the precipitation (subtracting the composite value for years of weak TEJ from the value for years of strong TEJ) is listed in Table 4.

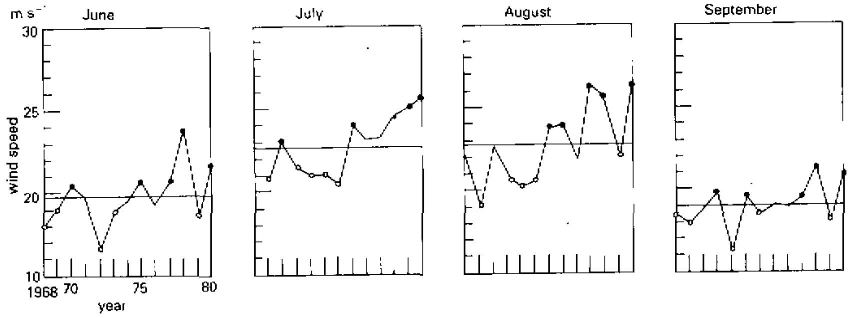

Fig. 1. 200 hPa mean TEJ intensity for a period from 1968 to 1980. Solid circles are for the strong easterly years and the open circles are for the years of weak easterly. Horizontal solid line is 13–year mean of the TEJ intensity.

III. THE GENERAL FEATURES AND SEASONAL EVOLUTIONS OF THE SUMMER EASTERLIES AT 200 HPA

The summer tropical easterlies at 200 hPa is basically located within the zonal belt from 10 ° S to 30 ° N (Fig. 2) (Ding, et al., 1988). The asymmetric distribution of the easterlies that is characterized by wider zone in the Eastern Hemisphere than in the West Hemisphere is apparent and TEJ forms in a narrow latitudinal belt (5 ° N–10 ° N) from 40 ° W to 160 ° E. The positions and intensities of the three cores of the TEJ, which are situated respectively over the southern tip of the Indo–China peninsula, Indian peninsula and Arabian peninsula. change with the seasonal evolutions of the circulations in low latitude. In May, a weak easterly core is first built at the southern tip of Indo–China peninsula; easterlies are stronger over the region of 2.5 ° S–18 ° N, 40 ° W to international date line. The remarkable changes of easterlies occur in June: two TEJ cores over the southern tip of the Idian peninsula and Arabian peninsula are all built at their mean positions, respectively; the easterlies expands northward to 25 ° N and dominates the south part of the Tibetan Plateau; among the three TEJ cores, the strongest is the Indian one (15.2 $m\ s^{-1}$) and the weakest is that over Arabian peninsula (14.2 $m\ s^{-1}$); the speed over Indo–China reaches 15.0 $m\ s^{-1}$.However, the southward expansion of the easterlies is not apparent; the easterlies is still weaker in Africa and global easterlies does not form at low latitude. Another remarkable evidence is that the TEJ over the region from the South China Sea to the West Pacific begins to split in June. The global easterlies, which expands northward to its northernmost latitute (32 ° N) and southward to its southernmostlatitude (13 ° S) in July and August, is built in July and maintains until September. In July and August, it should be noted that the TEJ strengthens but migrates scarcely and that a change in position of the strongest core of TEJ is observed i.e. the strongest easterly wind speed (18.9 $m\ s^{-1}$) is over Arabian peninsula in July, but the strongest core (19.0 $m\ s^{-1}$) is rebuilt over India in August which is also the strongest speed in summer. The speed of the core over Indo–China peninsula is the weakest one in these two months. On the other hand, the TEJ extends westward apparently and the axis is located in south of 10 ° N over West coast of Africa during that time. As another seasonal change in summer which is not so apparent as it is in June, the easterlies withdraws southward to south of 25 ° N and westerlies appears in southern part of Tibetan Plateau and the TEJ core over Arabian peninsula first dissipates in September. In October, easterlies withdraws further to south of 15 ° N and westerlies rebuilds in the middle of the Pacific and Atlantic in equatorial region. However, the TEJ core over India still persists, but the strongest speed moves over Indo–China peninsula.

The meridional wind is weaker except for the wind in the three main cross–equatorial flow region of the global easterlies belt, i.e., two southward cross–equatorial flows are over the South Asia monsoon region and the region from East Pacific to the Gulf of Mexico, and the northward cross–equatorial flow is found near the international date line (Fig. 3). The most remarkable cross–equatorial flow near 100 ° E, which scarecely changes except that the speed strengthens in July and August, may be associated with the north–easterly wind coming from east side of the South Asia high. It should be noted that the expansion of the cross–equatorial flow associated with the seasonal evolution and summer monsoon activity is

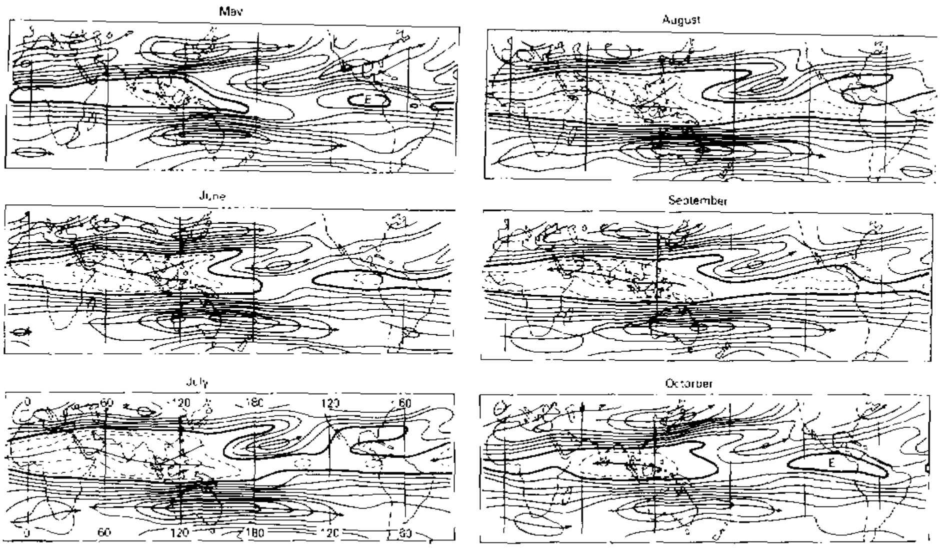

Fig. 2. Mean 200 hPa zonal wind field (1968–1980). The isopleths are drawn at an interval of 5 m s^{-1}. $u<0$ is denoted by dashed line; $u=0$ is represented by thick solid line

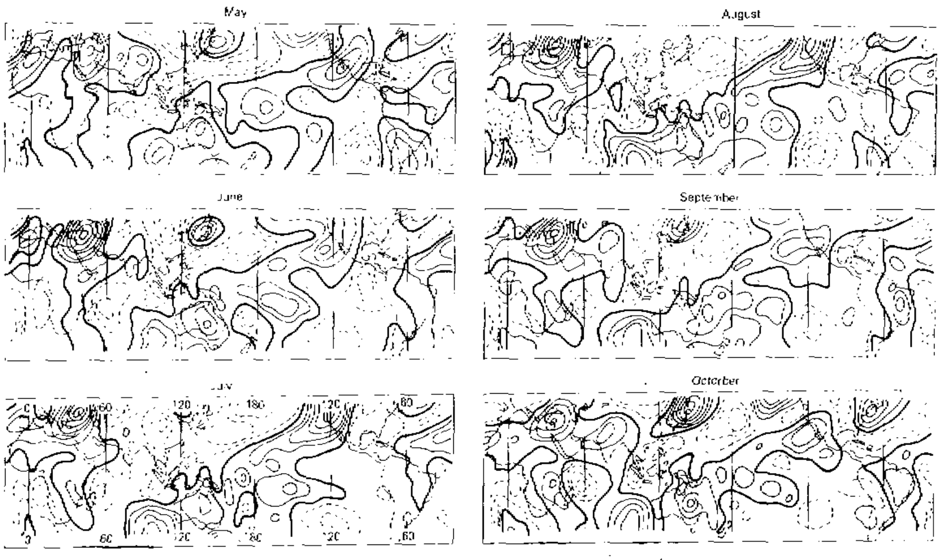

Fig. 3. Same as Fig.2 but for meridional wind with isopleth interval of 2 m s^{-1}.

quite different for both sides of 100° E. The southward cross–equatorial flow to west of 100° E is basically located at south of 5° N in May and begins extending northward and reaching 15° N in June. It is strongest from July to August and returns back to near–equatorial region in September. Inversely, the southward flow to east of 100° E does not cross equator until July and returns back to the North Hemisphere in October. The northern wind from East Pacific to the Gulf of Mexico is quite different from the South Asia monsoon region in that it can extend to higher latitude of the Southern Hemisphere from higher latitude of the Northern Hemisphere. The range of the southward cross–equatorial current is very wide in spite of the weak easterlies there. On the other hand, the flow crossing equator northward near international date line is generally located in equtorial region; it expands and may reach 20 ° N from Southern Hemisphere from June to August.

IV. ANOMALOUS TEJ AND THE SUMMER MONSOON PRECIPITATION IN INDIA

The intraseasonal changes of the TEJ at 200 hPa, which are characterized by the intensity anomaly of the TEJ core and the anomaly of the positions of the TEJ axis, are very apparent. A division of five anomalous TEJ patterns based on the monthly average positions of the TEJ cores for 52 months is shown in Table 1.

Table 1. Frequency of Occurrence of Five TEJ Patterns for the Period of 1968–1980. *W, M, E, T, S* represent the Western Pattern, Middle Pattern, Eastern Pattern, Two–branch Pattern and Multi–core Pattern, respectively.

Months / Years	6	7	8	9
1968	M	M	S	E
1969	E	W	W	M
1970	E	D	D	E
1971	M	S	M	E
1972	E	E	S	M
1973	S	S	S	S
1974	S	D	D	M
1975	D	S	S	S
1976	S	S	D	E
1977	E	D	S	S
1978	D	D	S	D
1979	E	D	D	D
1980	W	W	W	W

There is no noticeably preferable frequency of occurrence for each TEJ pattern except that the western pattern prevails continuously from June to September in 1980 and multi–core pattern prevails for four summer months of 1973. The numbers of cases when the western pattern, middle pattern and eastern pattern occur, respectively, are basically equal and the frequency is almost 11–13%. An apparent character we can see from Fig. 4 is that there is only one TEJ core along the axis for these three patterns, which is over the Arabian peninsula, India peninsula and Indo–China peninsula, respectively. They are very close to the climatic mean position except that the core of the western pattern has a eastward shift by 15 longitude and southward shift by 5 latitude. The western pattern is the strongest TEJ with a maximum mean speed of 20.7 m s^{-1}; the easterlies can extend southward to 17 ° S and eastward to 160 ° E; India is at the right hand side of the entrance of the TEJ center. The easterlies of the middle pattern covers the region of 40 –140 ° E with the maximum mean wind speed only 16.5 m $s^{-1}$and is weaker but wider over the South China Sea and West Pacific; India is just at the right side of the TEJ center. The eastern pattern often occurs in June and September. The TEJ axis basically lies at 5 ° N and the strongest mean wind speed is about 16.0 m s^{-1}. India is at the right hand side of the exit of the TEJ center. The two–branch TEJ pattern mainly ocurrs in midsummer. The southern branch TEJ mainly maintains at equator and can enter Southern Hemisphere; the TEJ center lying over the Kalimantan Island (5 ° N, 110 ° E) with maximum mean speed of 16.4m s^{-1}deviates from the climatic mean center over the Indo–China peninsula by 10 longitude. There are two TEJ cores on the northern branch lying over the southern tip of India peninsula and Arabian peninsula, respectively; the center over India (19.7 m s^{-1}) is stronger than that over Arabian peninsula and a frequency of occurrence of 25% is seen from Table 1 for this TEJ pattern. The highest frequency of occurrence of 30% is obtained from the cases of multi–core TEJ pattern, which has more than two centers within it generally. The compositing TEJ cores of this pattern are in accordance with the climatic average distribution of the TEJ according to the compositing map (Fig. 4e). The strongest center (17.2 m s^{-1}) is over the southern tip of Arabian peninsula.

The distributions of the zonal wind anomaly computed further for the five TEJ patterns are shown in Fig. 5 (subtracting Fig. 2 from Fig. 4). The deviation is very large for each pattern except the multi–core TEJ pattern. The deviation distribution for the western pattern shows two large negative centers over the Arabian Sea and South Indian Ocean; the former makes a strong easterly maximum move further westward and the latter makes the easterlies reach a more southern latitude over the South India Ocean. Meanwhile, the positive departure belt which crosses Tibetan Plateau from Arabian region to Japan explains why the easterlies of this pattern can only reach a lower latitude near 20 ° N and another positive departure belt, where the easterlies is anomalously weak over the region from South India to South China Sea, is also distinct. Some similar anomaly distributions of the middle pattern and eastern pattern may be observed, mainly in low latitude region (10 ° S–20 ° N). In the region from African continent to Western Pacific (10 ° N–20 ° N, 20 ° W–120 ° E), the anomaly for middle pattern is positive, but it is negative in equatorial region from Africa to the Bay of Bengal (10 ° S–10 ° N, 20 ° W–90 ° E). The anomaly in the latitudinal belt of 10 ° N–20 ° N for the eastern pattern is also positive.but extends to 160 ° E; the anomaly over the West Pacific Ocean may be associated with the activities of the TUTT. The relationship between the negative anomaly of zonal wind and inactive typhoon spell in West Pacific had been discussed by Ding et al. (1983) in detail. It can be seen that the anomaly to the east of 120 ° E (10 ° N–20 ° N) is negative (Fig. 5). In equatorial region (10 ° S–10 ° N), a similar expansion of the negative anomaly for eastern pattern is clearly seen. The zonal wind deviation distribution of the two–branch pattern is almost inverse to that of the middle pattern, so that it may be associated with an inverse anomalous atmospheric circulation. This fact is confirmed in Fig. 6. The anomalous circulations of the middle pattern are the large cyclone (intensification for cyclone, weakening for anticyclone) over South China and the maritime continent and the anticyclone over North India , which is favorable for the intensification of the easterlies over the southern tip of India; Another anomalous system is the weak cyclone over the region from Iran Plateau to west coast of Africa. Inversely, the anomalous systems of the two–branch TEJ pattern are the large anticyclone lying over east coast of China and maritime continent and the cyclone centered over equatorial India Ocean. Also, an apparent anticyclone is found over Iran. The formation of the two– branch TEJ pattern may be related to the increase of the cyclonic circulation (or decrease for the anticyclonic circulation) over equatorial region. The remarkable anomalous systems of the eastern pattern are the huge cyclonic circulation located

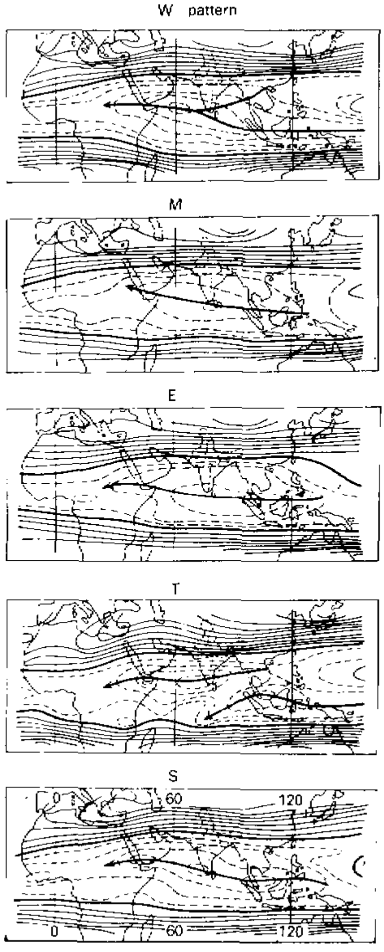

Fig. 4. Composite monthly mean zonal wind field for five TEJ patterns. Isopleth interval: 4 m s^{-1}. Dashed line denotes $u<0$. Thick solid line represents $u=0$.

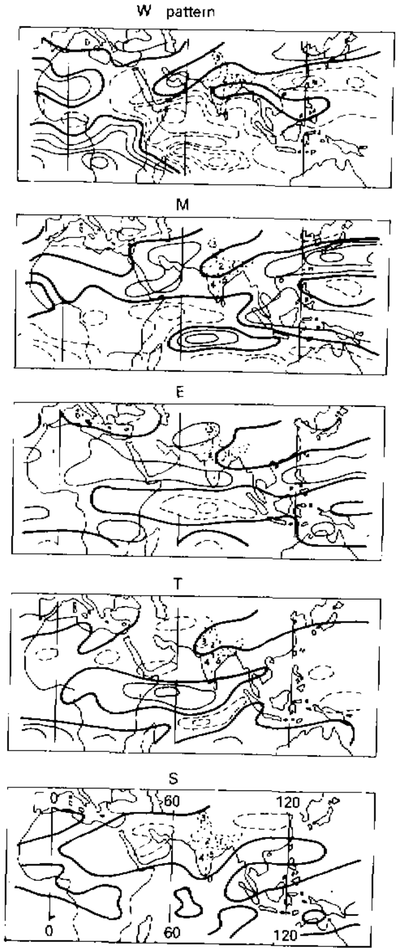

Fig. 5. Composite zonal wind anomaly field. Isopleth interval: 2 m s^{-1}. $u'<0$: dashed line, $u'=0$: thick solid line. A division of 5 subregions for India in the map is: 1. north–east India, 2. mid–India, 3. north–west India, 4. west coast of India, 5. east coast of India.

to west of 80° E, i.e., the region from the Mediterranean Sea to Iran and the anticyclonic circulation centered at equatorial India Ocean, southern tip of Indo–China peninsula and southwestern part of China. The former makes the easterlies decelerate to south of it and the latter makes the jet strengthen in south of Indo–China peninsula and form the particular easterlies distribution. For the western pattern, the easterlies strengthens in the west of Indiapeninsula that results from the anomalous circulations of the anticyclones over south of the Mediterranean Sea and South Indian Ocean. Also, the cyclone is over India. The anomalous anticyclonic circulation centered at Iran Plateau and South Africa is noticeable for the multi–core TEJ pattern.

We can see that the anomalous circulation of the middle pattern over the Pacific is in accordance with the condition of few typhoons and the anomalous circulation over the Pacific for the two–branch pattern is in accordance with the condition of many typhoons. The anomalous circulation of the eastern pattern is also basically the same with that of many typhoons. Ding, et al. (1983) pointed out that the anomalous cyclone over the West Pacific during the period of few typhoons, is caused by the TUTT which extends westward and enters the region south of 20° N. The contributions made by the migrating of the TUTT slightly eastward and northward than its mean position and the full development of the equatorial high ridge possibly result in the anomalous anticyclone over the West Pacific during the period of many typhoons. Some relationships between typhoon and TEJ have also been discussed by Tanaka (1982). Furthermore, Ding et al. pointed out that an almost inverse distribution of the India summer monsoon precipitation occurs in the period of many typhoons and few typhoons. During the period of many typhoons, the summer monsoon breaks in India and much more precipitations distribute over eastern India and the Southern Hymalayan foothills. The inverse situation happens during the period of few typhoons. It is well known that the TEJ in the upper troposphere is the return flow of the summer monsoon in the South Asia region where the air flow crosses the equator at 200 hPa and flows southward (Fig. 3). Thus, the strengthening of the flow can be considered as a measure of the low level summer monsoon activity. The meridional wind anomalies (Fig. 7) show that the basically inverse distributions of the India precipitation during the period of few and many typhoons are associated with the anomalies of large scale circulations over South Asia monsoon region; the anomalous north–easterly wind at the right hand side of the anticyclone over the Gulf of Aden strengthens the cross–equatorial flow over India, which implies a stronger summer monsoon activity during middle pattern. Because the anticyclone is located farther to east than that of middle pattern, the positive meridional wind anomaly over India makes the southward cross–equatorial flow weaken, which reflects a weaker summer monsoon activity during the period of eastern pattern. During two–branch TEJ pattern, the South China and India, except north–west part of India, are dominated by anomalous south–east wind and the southward cross–equatorial flow weakens. An apparent difference as compared with the eastern pattern is the north wind anomaly over north–west part of India during the period of two–branch pattern, which is more remarkable over west part of India during the period of western pattern. We can see that the climatic mean southward cross–equatorial flow would weaken over the region from Indo–China peninsula to the West Pacific for the positive anomaly there during the western pattern. The meridional wind anomaly is small during the period of multi–core TEJ pattern.

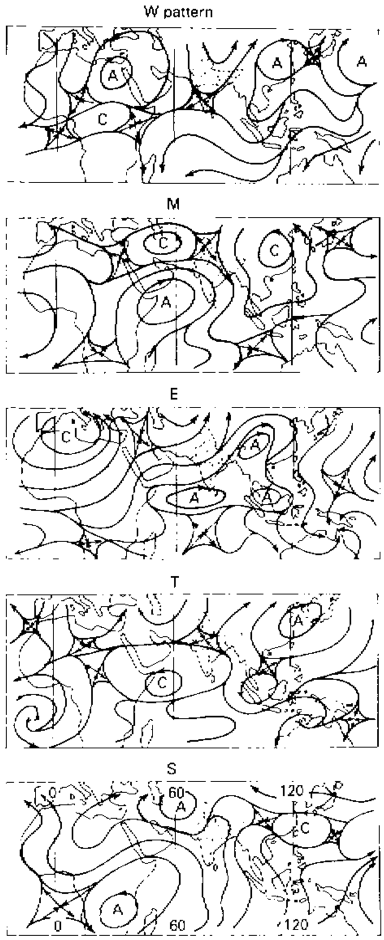

Fig. 6. Compositing anomaly streamlines for five TEJ patterns. (subtracting 13–year mean vector wind field from the compositing vector wind field for each TEJ pattern).

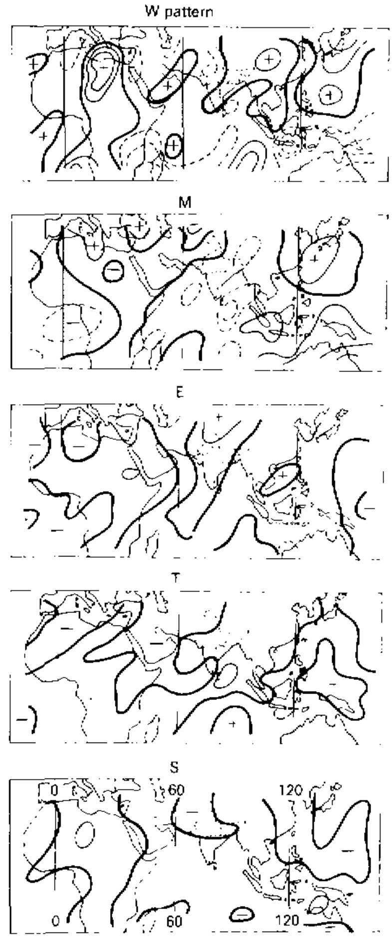

Fig. 7. Same as Fig. 3, but for the meridional wind with isopleth interval of 2 m s^{-1}.

Table 2 shows the anomaly changes of the precipitation in India for each TEJ pattern. The precipitation in the five subdivisions of India increases by 5–10% during the period of middle pattern. However, it decreases by 10–17% during the period of eastern pattern. During the period of two–branch pattern, the precipitation of India increases slightly in addition to the remarkable increase occurring in the region of west coast of India. During the period of western pattern, the precipitation in north–east and west coast of India increases. Also increases the precipitation in north–east and mid–India during the period of multi–core pattern. These results make sure further that there exists much better correlation between upper tropospheric TEJ and the summer precipitation in India, particularly for the middle pattern and eastern pattern. The investigation into the precipitation differences in India (Table 4) between the years of strong easterlies (greater than long term mean) and the years of weak easterlies (Table 3) indicates that the precipitation increases noticeablely during the years with strong easterlies. During the drought year of 1972 (major El Nino year) and 1979 weak TEJ was found . The increase in precipitation on the average may have 34 mm per day which is a considerable magnitude of increase in the area average precipitation. The increase of precipitation in the region of west coast of India is relatively great in every month and the largest increase is found in June. The increase of precipitation in North India (area 1, 2, 3) is larger in September.

Table 2. Precipitation Anomaly Percentage for Five Subregions in India during Each Anomalous TEJ Pattern. The precipitation data are taken from the daily mean precipitation data for 5 subdivisions of India for June through September of 1968–1980 compiled by Indian Department of Meteorology.

	1	2	3	4	5
W	5%	14%	−2%	3%	−2%
M	11%	8%	7%	12%	5%
E	−12%	−16%	−15%	−10%	−17%
D	1%	−6%	2%	13%	−5%
S	∓1%	4%	12%	−11%	−2%

Table 3. A List of Years Used for the Compositing Computation of the Precipitation in India for Strong TEJ and Weak TEJ. Strong (weak) TEJ is defined as those 5 years when TEJ intensity is greater (less) than the 13–year mean value.

Months	6	7	8	9
	1970	1970	1974	1971
Strong	1975	1975	1975	1973
TEJ	1977	1978	1977	1977
Years	1978	1979	1978	1978
	1980	1980	1980	1980
	1968	1969	1973	1968
Weak	1969	1971	1969	1969
TEJ	1972	1972	1971	1972
Years	1973	1973	1972	1974
	1979	1974	1979	1979

Table 4. Difference in the Precipitation in India between the Years of Strong TEJ and the Years of Weak TEJ Positive values indicate increases in the precipitation when the TEJ is strong. (unit: mm)

	1	2	3	4	5
6	2.8	15.1	6.2	34.0	4.0
7	3.3	3.5	11.6	13.7	8.2
8	−4.6	7.3	6.0	30.8	6.3
9	11.9	10.1	9.6	7.6	1.7

V. CONCLUSION

Based on long–term wind data set (1968–1980), some climatic analyses of the summer upper tropospheric easterlies at 200 hPa and of the relationship between the upper tropospheric tropical jet stream at 200 hPa and the precipitation in India in particular, are carried out. The following results have been obtained:

1. The summer tropical easterlies at 200 hPa is located in the latitudinal belt of 10° S–30° N and forms the TEJ over the region of Africa and Asia (5° N–15° N, 40° W–160° E). Three TEJ cores are observed at the southern tip of the Arabian peninsula, India peninsula and Indo–China peninsula, respectively. The core over the Indo–China peninsula first forms in May. Distinct changes in the easterlies occur in June and September. In June, the TEJ cores over India and the Arabian peninsula build up following the strengthening of the easterlies. In July and August, the global easterlies forms and strengthens further. The easterlies withdraws southward beginning in September and the TEJ weakening is indicated by the dissipation of the TEJ core over the Arabian peninsula. However,the cores over India and the Indo–China peninsula still maintains in October. There exist three main cross–equatorial flows in low latitude region at 200 hPa: the southward flows over the South Asian monsoon region and the region from the East Pacific to the Gulf of Mexico and the northward flow near international date line. Apparent seasonal evolutions are also found in the cross–equatorial flows.

2. Five anomalous TEJ patterns, i.e., western pattern, middle pattern, eastern pattern, two–branch pattern and multi–core pattern are found from the statistics of 52 cases. The first three patterns have only a TEJ core, over east of the Arabian peninsula and the southern tips of India peninsula and Indo–China peninsula, respectively. The axis of the southern branch of the two–branch pattern is basically at equator, which has a TEJ core over Kalimantan Island. Two cores of the northern branch of the two–branch pattern are over the southern part of India peninsula and Indo–China peninsula, respectively. Three cores of the multi–core pattern are found near the long term mean positions of the TEJ cores.

3. The anomalous TEJ patterns are related to the intraseasonal changes of the low latitude atmospheric circulation, i.e., the anomalous changes of the TUTT, the Tibetan high and the tropical anticyclones in Southern Hemisphere. For the middle pattern, there is an anomalous cyclone and an anticyclone over the region from West Pacific to East China and over the Arabian Sea, respectively. Some almost inverse anomalous circulations are found during two–branch pattern. The formation of the eastern pattern is associated with the anomalous

cyclone over the Mediterranean Sea–Iran Plateau. The anomalous anticyclone over the region from the equatorial Indian Ocean to the south–western part of China also plays an important role. For the period of western pattern, the anomalous circulations are the cyclone over the Tibetan Plateau and the anticyclone developed anomalously over the South Indian Ocean. The anticyclone and cyclone over the Tibetan Plateau and South Africa are the most remarkable anomalous atmospheric systems for the multi–core TEJ.

4. The anomalous TEJ contributes a lot to the weathers in the South Asia and West Pacific region in summer. Anomalous circulation over West Pacific is found typical of few typhoons during the period of the middle pattern, while the precipitation anomalously increases in India. An inverse situation is found during the period of the eastern pattern. A more apparent precipitation increase occurs in the west coast of India during the western pattern. The anomalous circulation over West Pacific is identified with the condition of many typhoons for the two–branch pattern, while the precipitation increases in north–east, north–west and west coast of India. The precipitation anomaly is also apparent during the period of the multi–core pattern.

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