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NOTES AND CORRESPONDENCE

Baiu Rainfall Variability and Associated Monsoon Teleconnections

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Abstract

Century-long observations enable us to uncover an interesting out-of-phase variability between the first principal component of Baiu rainfall over the Japanese archipelago and the monsoon rainfall over India during the early summer season (June and July). The signatures of this contemporaneous relationship are clearly evident from analysis of long-period multi-source climate datasets. One of the findings suggest that the circulation near the subtropical region of the west Pacific Ocean tends to vary in-phase with that over the Indian subcontinent, so that an intensified (weakened) west Pacific subtropical high is accompanied by an intensified (weakened) Baiu circulation over Japan and a weakened (intensified) monsoon circulation over India. Additionally, the Baiu-Indian Monsoon relationship is well supported by middle and upper tropospheric circulation anomalies extending from the mid-latitude region of West-Central Asia up to the Far East. A pattern consisting of an anomalous low over the Caspian and Aral Sea region, a high over Mongolia and an anomalous low over Korea and Japan, tends to be associated with increased Baiu rainfall over Japan and decreased monsoon rainfall over India. An opposite configuration of the mid-latitude circulation pattern tends to accompany below normal Baiu rains over Japan and above normal monsoon rains over India. It is suggested that the two patterns oriented along the *(a) west Pacific southern oceanic* route and the *(b) mid-latitude continental* route yield a consistent dynamical basis for inferring the Baiu-Indian Monsoon rainfall teleconnections.

1. Introduction

It is well-recognized that the Baiu season, the early summer rainy season over Japan, is part of the larger Asian monsoon climate system which exerts profound impact on the lives of more than half the world's population. Countries in East Asia receive substantial rains in June and July (JJ) months under the influence of a "quasi-stationary subtropical frontal zone" (Ninomiya 1984; Ninomiya and Murakami 1987; Kato 1989; Kodama 1992) which forms along the northern edge of the Pacific subtropical high. The rainy season associated with this frontal zone is referred to as *Baiu* in Japan, *Mei-Yu* in the Yangtze river valley of China and *Changma* in Korea. Moisture from the tropical western Pacific Ocean (Murakami 1959) is transported into the Baiu frontal zone by low-level south-westerlies which feed several medium-scale cyclones, aligned

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along the Baiu front, so as to produce rainfall over Japan in the early summer months. Advection of moist and warm-air by the low-level winds is essential for generating convective instability and sustaining the convective activity along the Baiu front (Ninomiya 1980). The climatological evolution of the Baiu rainfall has been described by Yoshino (1966).

The onset of Baiu rainfall over southern Japan usually occurs around May 30, roughly coinciding with the commencement of the summer monsoon rains over Kerala in southern India (Ninomiya and Murakami 1987). While the Baiu season spans most of June and July, the monsoon rains over India usually last until the end of September. Therefore it is reasonable to regard June and July as the common rainy season both for Japan and India. The analysis of Yasunari (1979), based on the daily cloudiness data for the period (June–September) 1973, showed a negative correlation of the cloud amount between central India and that over southern Japan. In a recent paper by Krishnan et al. (2000), the authors had noted that "breaks" in the Indian summer monsoon are characterized by well-defined patterns of convection anomalies extending over a wide region of the Indian subcontinent and East Asia. Their results indicated that monsoon breaks are associated with suppresed convection anomalies located over north and central India; and extended eastward into Southeast Asia. During monsoon breaks, it was also noted that the convective anomalies had a general tendency to enhance over the equatorial Indian Ocean, eastern China, northwest Pacific and southern Japan. While monsoon breaks represent rainfall variations on the synoptic and intraseasonal time-scales, there is evidence from historical records which indicate that the seasonal summer rainfall over several Southeast Asian countries tend to vary in-phase with the seasonal monsoon rains over India (Kripalani and Kulkarni 1997). Convection and circulation changes near the Philippines region of the western Pacific are particularly relevant from the point of orienting the atmospheric flow over the Baiu region (Nitta 1987). In the light of the above results, it is motivating to inquire into the year-to-year variability of the Baiu rainfall and its associated configuration of the large-scale atmospheric patterns. For this purpose, we have performed a diagnostic study of precipitation observations and other climate datasets which are available over a fairly long time-period.

2. Patterns associated with Baiu rainfall variability

2.1 Relationship between Baiu and Indian Monsoon rainfall

Superposed on the Baiu seasonal cycle is the existence of significant year-to-year rainfall variations. In the recent past, Japan and Korea experienced an abnormally wet and cool summer during 1993; followed by a year of extraordinary drought and record breaking heat waves in 1994 (Kawamura et al. 1998; Park and Schubert 1997). The time-series of the first principal component (PC) of Baiu rainfall depicted in Fig. 1a indicates that such major wet and dry Baiu events have not been unprecedented in the last century. This time-series has been constructed using a PC analysis of rainfall observations over Japan obtained from the Global Historical Climatology Network dataset (Vose et al. 1992). The spatial distribution of the dominant component of Baiu rainfall variability, shown by the leading Empirical Orthogonal Function (EOF) in Fig. 1c, explains a substantial fraction of about 45% of the total rainfall variance over entire Japan

Fig. 1. (a) The first principal component (PC) of JJ rainfall during the period 1901–94 based on data from 16 stations in Japan. The PC1 time-series is scaled by a normalizing factor (360.51) so that all values lie in the interval $[-1, 1]$. Circles represent wet and dry Baiu events used for making composites. Red (green) bars represent Baiu events that have coincided with below (above) normal rain over North-Central India (NCI). (b) Time-series of the NCI rainfall variations during the period 1901–94. The time-series has been normalized by subtracting the climatological normal (461.3 mm) and dividing by the standard deviation (80.9 mm) of the JJ total rainfall averaged over the NCI region. Green (red) bars represent NCI rainfall departures that have coincided with negative (positive) values of PC1 of Baiu rainfall. (c) The first EOF component shown by coloured circles at the 16 station locations. (d) The wet minus dry (WMD) Baiu composite of JJ rainfall (mm) over Indian subdivisions constructed from the 16 wet and 16 dry Baiu events. The NCI rain is an area-weighted mean rainfall computed from those sub-divisions (encompassed by the red line) having anomalies less than -60 mm. The total area enclosed by the NCI region is about 1.23 Million Sq.km.

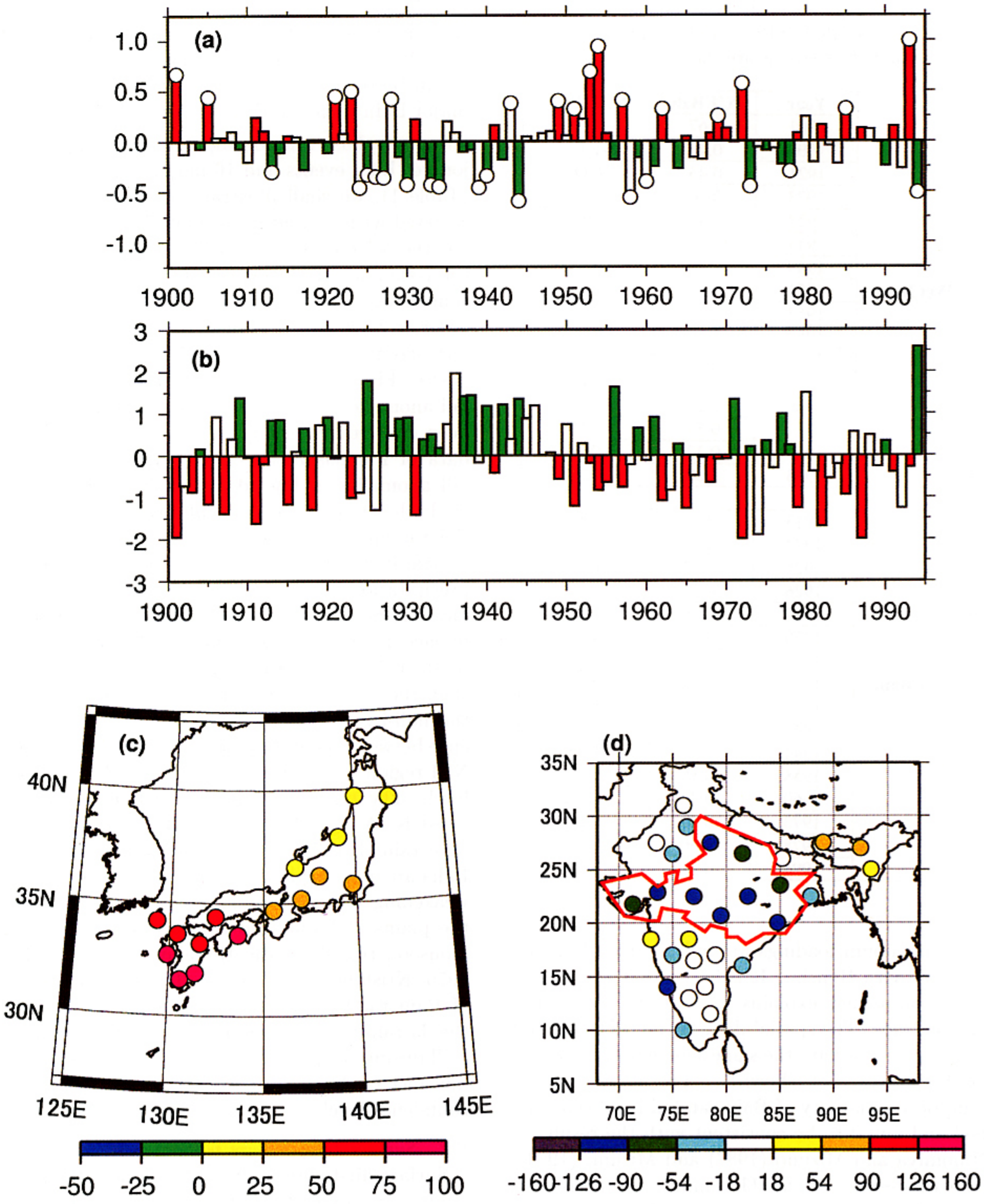
(a)
1.0
0.5
0.0
-0.5
-1.0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
(b)
3
2
1
0
-1
-2
-3
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
(c)
40N
35N
30N
125E
130E
135E
140E
145E
-50
-25
0
25
50
75
100
(d)
35N
30N
25N
20N
15N
10N
5N
70E
75E
80E
85E
90E
95E
-160
-126
-90
-54
-18
18
54
90
126
160

Table 1. The 16 wet and 16 dry Baiu events used for making composites. The corresponding values of the normalized time-series of PC1 of Baiu rainfall and the NCI rainfall variations are shown.

	Year	PC1 Baiu	NCI Rain
Wet Baiu	1901	0.67	-1.94
	1905	0.44	-1.15
	1921	0.45	-0.06
	1923	0.50	-1.01
	1928	0.42	0.48
	1943	0.38	0.39
	1949	0.40	-0.57
	1951	0.32	-1.21
	1953	0.69	-0.18
	1954	0.94	-0.83
	1957	0.41	-0.76
	1962	0.32	-1.08
	1969	0.25	-0.09
	1972	0.57	-1.99
	1985	0.32	-0.94
	1993	1.00	-0.28
Dry Baiu	1913	-0.30	0.85
	1924	-0.46	-0.88
	1925	-0.33	1.79
	1926	-0.35	-1.30
	1927	-0.36	1.22
	1930	-0.43	0.91
	1933	-0.43	0.51
	1934	-0.45	0.18
	1939	-0.46	-0.17
	1940	-0.34	1.18
	1944	-0.59	1.35
	1958	-0.56	-0.22
	1960	-0.40	-0.12
	1973	-0.45	0.20
	1978	-0.30	0.24
	1994	-0.51	2.59

with maximum loadings around Kyushu, Shikoku and southern Honshu. It is noted that the second EOF component explains 16% of the total rainfall variance. The spatial distribution of the EOF2 loadings do not have the same sign across the whole of Japan (fig not shown). The above spatio-temporal variability of Baiu rainfall has been verified and found to be consistent with the results of Ninomiya and Mizuno (1987) and Misumi (1994). The time-series of the JJ rainfall variations over North-Central India is shown in Fig. 1b. A particularly interesting aspect in Figs. 1(a,b) is that several major wet Baiu events in the last century have occurred in conjunction with decrease of monsoon rainfall over the plains of India. Conversely, several major dry Baiu events have been accompanied by above normal rains over India. Although, there have been some years when the PC1 of Baiu rainfall and the NCI rainfall have varied in-phase, it can be seen from Table.1 that 25 out of the 32 major Baiu events during the period 1901–94 show an out-of-phase relationship. By selecting 16 major wet Baiu events and 16 major dry Baiu events (Table 1), we shall illustrate composite maps associated with *wet minus dry* (WMD) Baiu events. All the selected events in Table 1 nearly exceed the 1-standard deviation (σ) of the normalized PC1 time-series. The wet event of 1969 was retained in order to have equal number of wet and dry cases although it was slightly short of σ. The WMD composite (Fig. 1d) shows the spatial pattern of rainfall anomalies over India. This composite plot has been constructed using the sub-divisional rainfall data of Parthasarathy et al. (1995). The rainfall anomalies in Fig. 1d are indicated by colored circles located within each sub-division. The negative rainfall anomalies over a large region of north-central India (NCI) indicate a decrease of monsoon precipitation. By performing a statistical t-test, we have verified (fig not shown) that the rainfall difference, between the wet and dry Baiu events, over most of the sub-divisions in the NCI region is less than the 5% significance level. This suggests that the null-hypothesis of insignificant rainfall difference between the wet and dry Baiu events, over the NCI region can be rejected with a high confidence level. The number of degrees of freedom for the t-test is $(N_{wet} + N_{dry} - 2) = 30$. The small positive rainfall differences appearing over northeast India are quite typical of situations associated with weakening of the summer monsoon activity over the plains of India, and a northward shift of the monsoon trough to the Himalayan foothills (Rao 1976; Krishnan et al. 2000). The PC1 time-series of Baiu rainfall shows a correlation of -0.4 with the JJ rainfall area-averaged over a wide region of NCI during the period 1901–94. The statistical significance of the above correlation exceeds the 99% confidence level.

2.2 Surface temperature pattern

Surface-air-temperature data (Jones 1994) over land areas, extending back up to the late nineteenth century, provide an excellent opportunity to examine signatures of the inverse relationship between the Baiu and Indian monsoon rainfall. The

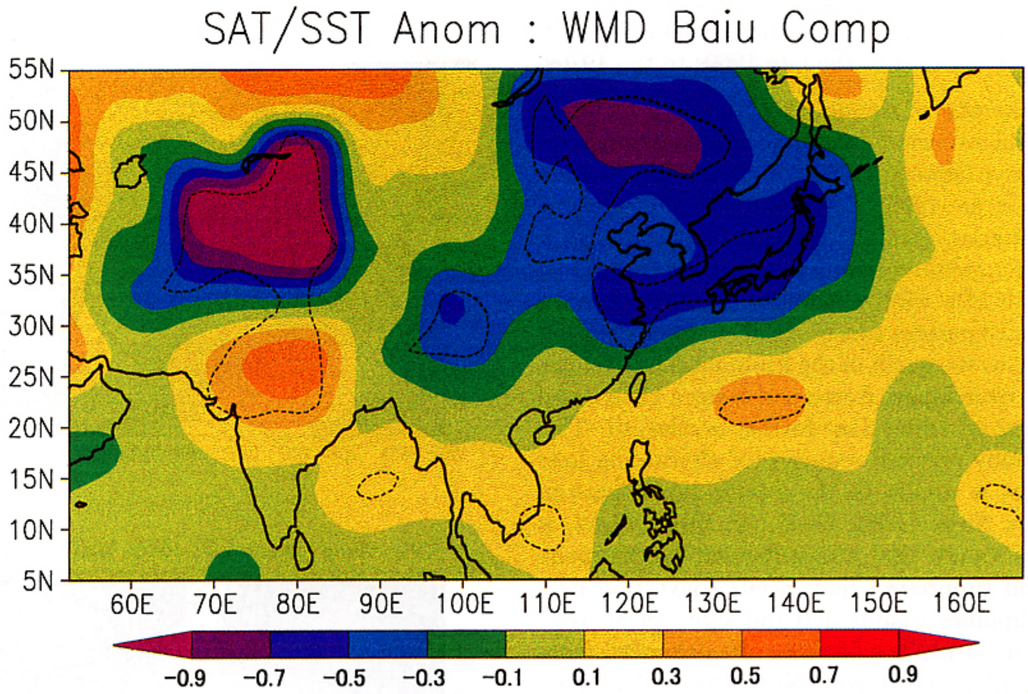

Fig. 2. The WMD Baiu composite of surface-air temperature (K) during JJ months based on the 16 wet and 16 dry Baiu events selected from Fig. 1a. The dotted contour line represents the 5% significance level, obtained from a statistical t-test for the difference between the wet and dry Baiu composites. The observed data over land regions is based on Jones (1994); and SST in the oceanic regions is based on Parker et al. (1995).

composite plot in Fig. 2 shows negative anomalies over Japan and adjoining region which are consistent with the increase of Baiu rainfall; while the positive anomalies over India corroborate with the decreased monsoon rains over the plains of India. The above pattern of surface-temperature anomalies is a further testimony that the Baiu and Indian monsoon rainfall relationship has been coherent during the last century. The negative anomalies over the mid-latitude region of West-Central Asia (Fig. 2) appear to be consistent with the regional atmospheric circulation anomalies, which will be discussed in the following sub-section. The statistical significance of the surface-air temperature change between the wet and dry Baiu composites, is shown in Fig. 2. The 5% significance level can be seen over Japan, the southern part of Korea, eastern and western China and north India; and the mid-latitude regions of West-Central Asia, northern China, eastern Russia, etc., indicating that the surface-air temperature change over these regions is statistically significant. Positive SST anomalies can be seen in Fig. 2 in the western Pacific Ocean around northeast of the Philippines with the maximum around 20–25°N latitude. An east-west SST gradient between the South China Sea and the region to the east of the Philippines can be seen to the south of 15°N. According to Kawamura et al. (1998) the east-west SST gradient between the South China Sea region (Region C; 5–15°N, 110–130°E) and the tropical western North Pacific region east of the Philippines (Region D: 5–15°N; 140–160°E) could be an important factor for contributing to the convection and low-level circulation changes over the Philippines and Baiu regions. Their results suggest that a negative value of the east-west SST gradient (Region D minus C) is favorable for suppressed convection in the vicinity of the Philippines. Conversely, a positive east-west SST gradient is favorable for enhanced convection around the Philippines. Further, Kawamura et al. (1998) noted that the interannual variations of the east-west SST gradient were significantly larger from the beginning of the 1980s to the early 1990s, as compared to the late 1960s to the 1970s.

2.3 Atmospheric circulation patterns

Atmospheric wind data from the National Center for Environment Prediction (NCEP) reanalysis (Kalnay et al. 1996) is used to illustrate patterns of atmospheric circulation that are associated with the Baiu rainfall variability. The WMD composite of 850 hPa wind anomalies (Fig. 3a) shows a north-south pattern consisting of an anomalous anticyclone to the north of the Philippines; a cyclonic anomaly over Japan, Korea and eastern China; and an anomalous anticyclone further northward. This meridionally oriented sequence of alternating lows and highs is similar to the Pacific-Japan pattern shown by Nitta (1986, 1987). In this context, it has been known that above (below) normal pressures and suppressed (enhanced) convection near the Philippines islands and the subtropical western Pacific Ocean are favorable for enhanced (subdued) rainfall over Japan (Nitta 1987). The modelling study by Kurihara and Tsuyuki (1987) describes this north-south pattern in the Far East as a dynamical outcome of Rossby wave dispersion (Hoskins and Karoly 1981). Another discernible feature in Fig. 3a is the easterly anomalies over India and the Arabian Sea, which indeed correspond to a weakening of the Somali jet and the southwest monsoon circulation (Krishnamurti and Surgi 1987). An anomalous low-level anticyclone can be noted over north and central India; while west-

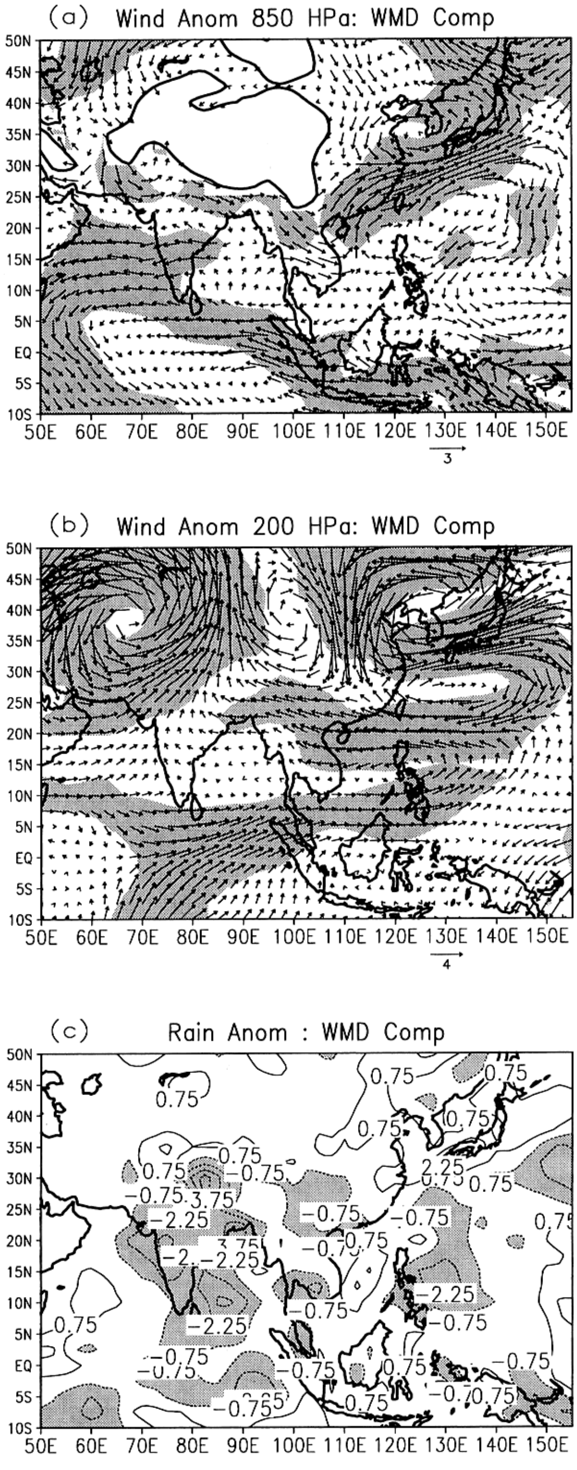

Fig. 3. The WMD Baiu composites for JJ months (a) 850 hPa winds (ms^{-1}). The orographic mask is shown by thick contouring. The light shading denotes regions exceeding the 95% confidence level for the magnitude of the WMD composite of wind vector anomaly at 850 hPa. (b) Same as Fig. 2a, except for 200 hPa winds. (c) Rainfall (mm/day). The NCEP winds were available from 1948 onwards. The WMD composites of winds are based on the major five wet (1953, 1954, 1962, 1972, 1993) and five dry (1958, 1960, 1973, 1978, 1994) Baiu events. The NCEP rainfall data was available from 1958 onwards. So the rainfall composite is based on three wet (1962, 1972, 1993) and three dry (1973, 1978, 1994) Baiu events.

erly wind anomalies can be seen intruding from the Afghanistan-Pakistan area towards northern India and the Indo-China region. The weakened southwest monsoon westerlies and the strengthened west Pacific subtropical anticyclone are accompanied by anomalous southerlies located to the west of the Philippine islands around 110°E. The enhanced southerlies over the South China Sea and the intensified westerlies along the subtropical Baiu front in Fig. 3a are consistent with the results of Matsumoto et al. (1971); and Akiyama (1973, 1975), who pointed out that heavy Baiu rainfall events tend to occur in association with enhanced southerly transport of moisture into the subtropical Baiu front. The statistical significance of the magnitude of the WMD composite wind vector, has been computed using the N-test (Gaussian test). The shaded areas in Fig. 3a show the region of 95% confidence of the magnitude of the WMD composite wind vector anomaly at 850 hPa. It can be seen that the magnitude of the low-level wind anomaly in Fig. 3a is statistically significant along the subtropical Baiu front, the Arabian Sea, peninsular India; parts of north India, and over regions of the southern tropical Indian Ocean and the western Pacific Ocean.

The WMD Baiu composite of winds at 200 hPa (Fig. 3b) shows a north-south pattern of anomalous anticyclone to the east of Taiwan and a cyclonic anomaly over Japan and Korea. The 95% confidence area obtained from a statistical significance test for the magnitude of the WMD composite wind vector anomaly at 200 hPa is shown by the shaded region in Fig. 3b. It can be seen that the shaded region exceeding the 95% confidence level stretches meridionally over the equatorial eastern Indian Ocean, the west Pacific subtropics, Japan and Korea and further north. Another conspicuous feature at the 200 hPa level is a pattern of mid-latitude cyclonic anomaly located to the east of the Caspian and Aral Seas; an anticyclonic anomaly near 100°E around Mongolia; and an anomalous cyclone further eastward over northeast Asia. It can be noticed that the magnitude of the WMD composite of the wind vector anomaly associated with this east-west oriented mid-latitude continental pattern exceeds the 95% confidence level as revealed by the shaded region in Fig. 3b. Further it is noted that this mid-latitude continental pattern appears at different tropospheric levels as well (fig not shown). However, the presence of elevated orography across Asia masks this circulation pattern at the lower levels. Meteorologists in India (Ramaswamy 1962; Keshavamurty and Awade 1974; Raman and Rao 1981; Krishnan et al. 2000) have alluded to anomalous lows in the middle and upper troposphere around the Caspian Sea region during weak episodes of the Indian monsoon activity; while in Japan instances of enhanced Baiu rainfall have been reported to coincide with blocking highs over the Mongol plateau and the Okhotsk region (Ninomiya and Muraki 1986; Ninomiya and Mizuno 1987; Wang 1992; Wang and Yasunari 1994). The east-west mid-latitude pattern in Fig. 3b has some resemblance with the pattern (but polarity reversed) noted by Lau et al. (2000). However their pattern was obtained by regressing the regional monsoon index over South Asia upon the 200 hPa wind field (Fig. 5 of Lau et al. 2000). Observational studies suggest that anomalous lows embedded in the mid-latitude westerlies over West-Central Asia are associated with advection of cold and dry air from the extra-tropics into the Indo-Pakistan region, which tend to inhibit the monsoon rainfall activity over the Indian subcontinent (Ramaswamy 1962; Keshavamurty and Awade 1974; Raman and Rao 1981). In the earlier discussions, we had seen a pattern of negative surface-air temperature anomalies over West-Central Asia and northeast Asia in Fig. 2. This feature seems to be broadly consistent with the possible occurrence of anomalous cold-air advection associated with the mid-latitude circulation pattern. The modelling study by Rodwell and Hoskins (1996) indicates that the summer monsoon heating can induce subsidence over regions of West-Central Asia. Further research work and numerical experiments are necessary in order to understand the possible role of monsoon-midlatitude interaction and the dynamics of the associated teleconnection patterns (Ambrizzi et al. 1995; Terao 1999).

For convenience we shall refer to the mid-latitude pattern in Fig. 3b as the Asian Continental Pattern (ACP), which can be characterized by a flow pattern index. The ACP index is derived from the 200-hPa circulation as a linear combination $([\zeta]_1 - [\zeta]_2 + [\zeta]_3)$ of the three relative vorticity (ζ) centers over West-Central Asia; Mongolia and the Far East. The first term represents the circulation averaged over West-Central Asia (50–85°E; 30–50°N); the second is vorticity averaged around the Mongolian region (85–110°E; 30–50°N) and the third term corresponds to the vorticity averaged over the Far East (110–145°E; 30–50°N). A positive ACP index corresponds to a pattern of low near the

Caspian-Aral Seas; a high over Mongolia and a low in the Far East. The polarities of the above three circulation centers are reversed during the negative phase of the ACP. It is noted that the ACP index during (1951–94) shows a high correlation of +0.59 with the PC1 time-series of Baiu rainfall; and a correlation of −0.64 with the rainfall over North-Central India. The WMD Baiu composite of rainfall (Fig. 3c) obtained from NCEP dataset shows negative rainfall anomalies over India; Thailand, Malaysia and the Phillipines. The negative anomalies of monsoon rainfall actually represent a decrease of moist-convection over the Indian subcontinent. In contrast, the situation in the Far East is rather different. The presence of a nearly barotropic trough over Korea and Japan is associated with an intensified subtropical Baiu front and a cyclonic anomaly anchored over this region (Fig. 3a–b). The rainfall composite (Fig. 3c) shows an increase of the Baiu rainfall over the Japanese archipelago. These anomaly patterns conform well with the inverse Baiu-monsoon relationship. It is realized that the rainfall anomalies obtained from the reanalysis dataset are not based purely on observations; but are also model dependent. Nevertheless the anomaly patterns provide a consistent picture among different atmospheric parameters. Moreover it must be pointed out that the anomalous decrease of the Indian monsoon rainfall is a robust feature and is well supported by long-period rainfall observations (Fig. 1d) over India.

3. Concluding remarks

A brief summary of the results of this study is presented below. Long-period observations provide evidence for the existence of an inverse relationship between the first principal component of Baiu rainfall over Japan and the monsoon rainfall over India during the early summer season (June and July). This relationship is supported by different atmospheric fields available from NCEP reanalysis during the post 1950 period. Based on this study, two possible teleconnection patterns are suggested. The first one manifests as a north-south pattern extending along the west Pacific southern oceanic route. In keeping with this feature it is seen that the circulation and rainfall over the subtropical west Pacific and Southeast Asia have a tendency to vary in phase with their Indian monsoon counterparts. Accordingly an intensified (weakened) subtropical anticyclone is associated with a stronger (weaker) Baiu circulation over Japan and a weaker (stronger) monsoon circulation over India. The second possible teleconnection pattern is the ACP, which extends across the mid-latitude regions of the Asian continent. It is seen that the positive phase of the ACP tends to be associated with decreased monsoon rainfall over India; and increased Baiu rainfall over Japan. The scenario is reversed for the negative phase of the ACP. Whether the teleconnections associated with the *southern oceanic route* and the *mid-latitude continental route* can work together jointly or independently, still needs to be resolved. It may be quite interesting to examine possible relationships between rainfall variations over different areas of the Asian monsoon region. The study by Nitta and Hu (1996) describes coherent variations of the summer rainfall in the middle-lower reaches of the Yangtze river with the rainfall over western part of Japan. It has been noted by Chen et al. (1992), that only rainfall in northern China shows positive correlation with the summer monsoon rainfall over central India. However the exact region over central India selected in the study of Chen et al. (1992) is not clearly evident from their paper. Moreover it is not clear to us what time-period and what months were used by Chen et al. (1992) for computing the correlations between the rainfall over China and central India. So it is not straightforward to compare our results with theirs. The present study has been largely qualitative and explorative. Nevertheless, the Baiu-Indian Monsoon rainfall relationship seems quite relevant for further investigation of some of the hitherto unknown teleconnection dynamics over the Asian continent.

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