Interannual and Interdecadal Variations of the Western North Pacific Monsoon and Baiu Rainfall and their Relationship to the ENSO Cycles

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Abstract

Interannual and interdecadal variations of the Western North Pacific Monsoon (WNPM) and the East Asian Baiu rainfall are analyzed using 30-year (1963–1992) daily sea-level pressure, 30-year monthly and daily rainfall data for the East Asia, and 15-year (April 1978–December 1992) 5-day mean 1-degree latitude-longitude gridded GMS high-cloud-amount data. The relationship to the El Niño-La Niña cycles are investigated by using monthly sea surface temperatures (SST) data over a region defined by 4°N–4°S, 150°W–90°W in the equatorial Eastern Pacific (NINO3 SST) for a 30-year period from 1963 to 1992.

An analysis of interannual variations in intensity of the WNPM in late July shows high negative correlations with the NINO3 SST during a recent 15-year period from 1978 to 1992. In the La Niña (El Niño) years, strong (weak) WNPM are observed. For the Baiu rainfall, high positive correlations with the NINO3 SST are observed in July during this period. In the La Niña (El Niño) years, light (heavy) Baiu rainfall is observed. These correlations are the results of a delay of about 20 days in the onset dates of the WNPM and the peak dates of the Baiu rainfall between the La Niña and El Niño years. In the La Niña years, the early onset of the WNPM and early peak of the Baiu rainfall are observed. In the El Niño years, the late onset of the WNPM and late peak of the Baiu rainfall are observed.

The Baiu rainfall also shows a high positive correlation with the NINO3 SST during the early 15-year period from 1963 to 1977. However, difference in the dates of peak of the Baiu rainfall between the La Niña and El Niño years are smaller.

An analysis of the lag-correlations among the WNPM, the Baiu rainfall and the NINO3 SST shows that the SST leads the WNPM by 1 to 2 months. On the other hand, the Baiu rainfall leads (lags) the SST by 3 (2) months during a recent (early) 15-year period from 1978 to 1992 (1963 to 1977).

An autocorrelation analysis of the NINO3 SST shows that the biennial oscillation mode was pronounced during a 15-year period from 1963 to 1977. In a recent 15-year period, the low-frequency mode was dominant. These changes in the periods of the SST oscillations may be related to the recent increase in the correlations among the NINO3 SST and the WNPM and Baiu rainfall.

1. Introduction

In recent years, the Western North Pacific monsoon (WNPM) in summer has come to be recognized as a major tropical monsoon system. Tanaka (1992), using GMS high-cloud-amount data, determined the onset (retreat) dates of the northern summer monsoon over East, Southeast Asia and the western North Pacific. Matsumoto (1992) and Nakazawa (1992), using ECMWF wind and OLR data, showed that the WNPM extends up to 150°E. Wang (1994), using OLR data, determined the onset (retreat) dates of the global summer monsoon. Collectively, these studies showed that the onset of the WNPM is sudden and is observed around 25–29 July.

Murakami and Matsumoto (1994) analyzed the structure of the WNPM and concluded that the WNPM is driven by the combined effects of zonal asymmetry in the SST at 10° to 20°N and east-west heat contrasts between approximately 20°N and 30°N. Ueda *et al.* (1995) and Ueda and Yasunari (1996) analyzed the abrupt seasonal change of large-scale convective activity and the circulation pattern during the onset phase of the WNPM. They showed that the largest pressure changes during the onset are observed around 25°N, 140°E.

The East Asian Summer monsoon is characterized by the early summer rainy season called Baiu and Mei-yu in Japan and China respectively. The large-scale aspects of the Baiu front are analyzed by Akiyama (1973), who showed that the Baiu front over East Asia forms a belt-shaped zone of maxi-

mum cloudiness and coincides with the zone of maximum rainfall amount. The water vapor convergence within the frontal zone is shown to be mainly due to the southwesterly wind along the northwestern rim of the North Pacific Subtropical High.

The relationship between the monsoon and El Niño have been investigated in many studies: Yasunari and Seki (1992) showed that the occurrence of the El Niño is closely associated with the preceding weak Indian summer monsoon. For the East Asian monsoon, Tanaka (1987), Yatagai and Yasunari (1995) showed that the June–August rainfall in the North China region is positively correlated to the Indian monsoon rainfall. Shen and Lau (1995) found a negative correlation between the April–September rainfall near 30°N, 110°–120°E in China and the equatorial Central Pacific SST during the following autumn and winter.

In this study, we investigate interannual and interdecadal variations of the WNPM and the Baiu rainfall and their relationship to the equatorial Eastern Pacific SST during a 30-year period from 1963 to 1992. We first analyze the WNPM and its relationship to the El Niño event. Then we explore the East Asian Baiu rainfall and its relationship to the same events. The investigation of possible correlations among the WNPM, the Baiu rainfall and the tropical Pacific SST is the primary aim of this paper.

2. Data Sources

Four datasets (sea-level pressure, rainfall, high-cloud amount, and SST) are used in this study: The sea-level pressure data are extracted from the “Daily Weather Maps” published by the Japan Meteorological Agency (JMA) for a 30-year period from 1963 to 1992. The pressure values are read from the daily 12 Z GMT sea-level maps at a spatial resolution of 5° latitude-by-10° longitude for a region bounded by 40°N to 10°N, 110°E to 180°.

The daily and monthly rainfall data for Japan for a 30-year period from 1963 to 1992 are obtained from the “Monthly Report of the Japan Meteorological Agency”. The monthly rainfall data for China containing 160 stations from 1951 to 1994 are provided by the China Meteorological Administration. The monthly rainfall data for the Republic of Korea are extracted from the “Monthly Climatic Data for the World” published by NOAA.

The high-cloud-amount data are the 5-day mean 1-degree latitude-longitude grid data of the Geostationary Meteorological Satellite (GMS) created by the Meteorological Satellite Center of the JMA. The data from April 1978 to December 1992, which are same as Tanaka (1992, 1994), are used in this study.

The monthly SST data for a region bounded by 4°N to 4°S, 150°W to 90°W for a period from 1956 to 1994 are obtained from the JMA to monitor the

equatorial Eastern Pacific SST. This region (defined as NINO3 SST by the JMA) is a main region used by the JMA for monitoring the El Niño events. In the following discussion, the name “NINO3 SST” is used for equatorial Eastern Pacific SST.

For all daily data, 5-day averaged values are obtained. The 1-2-1 filter is then applied to all 5-day mean data to remove high frequency noise less than about 7.5 days. For the monthly NINO3 SST, the 1-2-1 filter is also applied to remove short-period fluctuations. For brevity, the term “smoothed” is not used in the subsequent discussions.

These data are divided into two 15-year periods from 1963 to 1977 and from 1978 to 1992 for an investigation of the interdecadal variations. The year of this division was based on the initiation of GMS observations in 1978 and an abrupt interdecadal warming of the tropical SST around 1977 (1979) reported by Nitta and Yamada (1989) (Wang, 1995).

3. Interannual variations of the WNPM and its relationship to the NINO3 SST

Ueda *et al.* (1995) and Ueda and Yasunari (1996) showed that the largest low-level pressure change during the onset of the WNPM is observed near 25°N, 140°E and the consequent rapid increase in the westerly winds is observed near 15°N, 140°E. In this study, the 5-day mean sea-level pressure difference between 10°N and 20°N at 140°E is used to monitor the strength of the westerly winds of the WNPM near 15°N (defined here as WNPM Index). The year-to-year change in the strength of the WNPM Index for a 15-year period from 1978 to 1992 is shown in Fig. 1. The onset of the WNPM was early (late) in 1978, 84, 85, 88 (1983, 87, 91, 92).

Figure 2 shows the interannual variations of the monthly NINO3 SST from 1956 to 1994. Using 0.6°C departure for a threshold value, defined here to include most of the early and late onset of the WNPM, there are 4 La Niña years (1978, 84, 85, 88), and 5 El Niño years (1982, 83, 87, 91, 92) in June of the calendar years during a 15-year period from 1978 to 1992. With the sole exception of 1982, all the La Niña (El Niño) years coincide with the early (late) onset of the WNPM (Fig. 1).

Figure 3 shows the autocorrelations of the NINO3 SST with respect to June. During a recent 15-year period from 1978 to 1992 (solid line), the low frequency mode of about 4 years is dominant. The biennial mode is nearly absent with near zero correlation at lead (lag) of about one year from a reference month. During the 15-year period from 1963 to 1977, the biennial mode was pronounced. There exists a strong persistence (autocorrelations over 0.9) in the SST from May to the following January. Hence large interdecadal differences in the interannual oscillation of the NINO3 SST are observed.

Fig. 1. Interannual variations of the WNPM monitored by the 5-day mean sea-level pressure difference between 10°N and 20°N at 140°E . Thin horizontal lines show the value of zero in the left-hand scale for each year. The interval between the adjacent year corresponds to a value of 10 hPa. The dark shaded areas show the periods of active WNPM defined as the periods of the westerly geostrophic winds near 15°N . The horizontal scale shows the dates of the last day of each pentad and the months.

Figure 4 shows the relationship between the WNPM Index during July 20–29 and NINO3 SST in June for a 15-year period from 1978 to 1992. There is a clear tendency (correlation = -0.87 ; 1 % level = 0.68) for strong (weak) WNPM in the La Niña (El Niño) years.

The significance level of the correlations is obtained by the method used by Chen (1982) and Davis (1976), where the autocorrelations between two continuous time series (samples) were used to estimate the reduction in the degree of freedom. All the significance levels of the correlations in this paper are tested by this method.

Figure 5 shows the lag-correlations between the WNPM Index during July 20 to 29 and the NINO3 SST. During a recent 15-year period, the maximum values of the correlations are observed for the May and June SST. Hence the SST leads the WNPM by about 1 to 2 months. During the 15-year period from 1963 to 1977, no significant correlation at the 5 % level is observed. Therefore significant correlations between the WNPM Index and the NINO3 SST are restricted to the recent 15-years from 1978 to 1992.

Figure 6 shows spatial patterns of the sea-level pressure for the 10-day period from 20 to 29 July. In the La Niña years (1978, 84, 85, 88) the WNPM is strong and the westerly wind extends east to 155°E between the latitudes from 10°N to 20°N . In the El Niño years (1982, 83, 87, 91, 92) the subtropical high extends west to 125°E and the trade wind is observed. A strong, moist southerly wind is observed near 25°N , 130°E . This synoptic pattern is observed during the Baiu rainy season in Japan. The difference between the El Niño and the La Niña years shows the largest pressure difference near 25°N , 140°E . The dots shown in Figs. 6a and 6b are the gridpoints where the difference is significant at the 95 % confidence by the application of a one-tailed student t-test. Hereafter all the differences in the sea-level pressure in this paper are tested by this method.

Figure 7 shows spatial patterns of the GMS high-cloud amounts for the 10-day period from 20–29 July. In the La Niña years (1978, 84, 85, 88) the active phase of the convection near 20°N , 150°E indicates the mature phase of the WNPM. In the El Niño years (1982, 83, 87, 91, 92) the active phase of the convection is observed south of 12°N and near the Baiu front located near 35°N . Figure 8 shows the correlation between the GMS high-cloud amounts and June NINO3 SST for the 10-day period from 20 to 29 July. The regions with significant correlation at 5 % level are shaded. A region with significant negative correlation near 20°N , 150°E with a maximum correlation of -0.92 at 19°N , 149°E shows that the WNPM is under the strong influence of interannual variations of the NINO3 SST. In addition, several regions with significant positive correlation exist near the Equator and north of 30°N .

4. Intraseasonal variations of the WNPM and their relationship to the NINO3 SST

In the preceding discussion, it was shown that the onset of the WNPM is early (late) in the La Niña (El Niño) years during the recent 15-year period from 1978 to 1992 (Fig. 1). In this section, intraseasonal variations of the WNPM and its relationship to the NINO3 SST are analyzed. Figure 9 shows the latitude-time cross-section of the GMS high-cloud amounts for the longitude 145°E to 154°E . Comparison of the La Niña (Fig. 9a) and

Fig. 2. Time series of the monthly NINO3 SST from 1956 to 1994. The short lines on the horizontal scale indicates December of the calendar year. The numbers on the horizontal scale are the calendar year.

Fig. 3. The autocorrelations of the NINO3 SST for June. The solid line (dots) shows the value for the 15-year period from 1978 to 1992 (1963 to 1977). $Y(0)$ denotes the year containing a zero-lag month. $Y(-1)$ ($Y(-2)$) denotes the year before (two years before) $Y(0)$. $Y(+1)$ ($Y(+2)$) denotes the year after (two years after) $Y(0)$.

El Niño (Fig. 9b) years shows that there is about a 20-day difference in the dates of the maximum values of the high-cloud amounts near 15° – 25° N. Figure 10 shows the correlation between the GMS high-cloud amounts and June NINO3 SST for the latitude-time cross-section shown in Fig. 9. The largest values of the significant negative correlations are observed near 15° – 25° N during late July which coincides with the early onset of the WNPM in the La Niña years. In addition, significant negative correlations are observed during late May–early June and late June. These negative correlations suggests that the clima-

tological intraseasonal oscillations with a period of about 25 to 30-days are enhanced in the La Niña years.

The lag-correlations between the WNPM and the NINO3 SST (Fig. 5) suggest that significant correlations between these two systems are restricted to a recent 15-year period from 1978 to 1992. The latitude-time cross-sections of the sea level pressure at 140° E from 25 June to 13 August (23 August for the El Niño years) are shown in Fig. 11 for a 15-year period from 1978 to 1992. The dots shown in Fig. 11 are the latitude-time periods where the difference is significant at the 95 % confidence by the application of a one-tailed student t-test. A strong westerly wind is observed between 10° N and 20° N in the La Niña years. The climatological onset date of the WNPM near 15° N is around 25–29 July. As discussed earlier, there are large differences of about 20-days in the onset dates of the WNPM between the El Niño and the La Niña years.

In the 15-year period from 1963 to 1977, the climatological onset date of the WNPM near 15° N is around 20–24 July. The onset dates of the WNPM were early (late) in 1967, 68 and 72 (1966, 74). With the sole exception of 1972, the NINO3 SST were near normal in these years. Therefore, the relationship between the onset of the WNPM and NINO3 SST is not significant in this period.

5. Interannual variations of the East Asian Baiu rainfall and its relationship to the NINO3 SST

The rainfall data over East Asia are used to investigate the long-term relationship between the Baiu rainfall and the NINO3 SST. The lag-correlation analysis between the monthly rainfall data over East Asia and the NINO3 SST showed that the largest

Fig. 4. Relationship between the June NINO3 SST and the WNPM during 20–29 July for the 15-year period from 1978 to 1992. The vertical scale on left shows the NINO3 SST anomalies in $^{\circ}\text{C}$. The horizontal scale shows intensity of the WNPM at 140°E .

Fig. 5. Same as Fig. 3, but for the lag-correlations between the WNPM during July 20 to 29 and the NINO3 SST.

numbers of the stations with significant correlations are observed between July rainfall and the NINO3 SST in September (May) for the 15-year period from 1978 to 1992 (1963 to 1977). Figures 12a and 12b shows the lag-correlation between the July rainfall in East Asia and September (May) NINO3 SST for the 15-year period from 1978 to 1992 (1963 to 1977). In both periods the highest correlation is observed in the vicinity of Kyushu Island and significant correlations (5 % level) are around 0.6 using the method dis-

cussed earlier) are observed in eastern China. These areas of high correlations coincide with the regions of heavy Baiu rainfall in July. These lag-correlation analyses show that the rainfall was leading the SST by about 3 to 4 (1 to 2) months in Japan (China) during a recent 15-year period.

6. Interannual variations of the Baiu rainfall in Northwest Kyushu and its relationship to the NINO3 SST

In the foregoing discussion, it was shown that the July rainfall over Kyushu Island has a high lag-correlation to the NINO3 SST. Since the onset of the WNPM is observed during July, it is necessary to investigate the intraseasonal time-scale rainfall to obtain the relationship between the Baiu rainfall and the synoptic pattern in East Asia. Therefore, 5-day mean rainfall data for 13 stations on Kyushu are used for the lag-correlation analysis with the NINO3 SST. Among these stations, the average of 4 stations (Saga 33.27°N , 130.30°E , Nagasaki 32.73°N , 129.87°E , Kumamoto 32.82°N , 130.72°E , Fukue 32.70°N , 128.83°E), hereafter called Northwest Kyushu, showed the highest lag-correlation with the NINO3 SST.

Figure 13 shows the time series of the composite 5-day mean Northwest Kyushu rainfall during June and July for the La Niña (solid line) and El Niño (dots) years. During 1978 to 1992 (1963 to 1977), the La Niña years are the composite of 1978, 84,

Fig. 6. Spatial patterns of the sea-level pressure for July 20–29. a) the La Niña years (1978, 84, 85, 88). b) the El Niño years (1982, 83, 87, 91, 92). c) the difference between the El Niño and La Niña years. The contour interval is 2 hPa for a) and b), and 1 hPa for c). The units are departure from 1000 hPa for a) and b). The dots in a) and b) show the grid-points where the difference between the El Niño and La Niña years is significant at the 95 % confidence by the students t-test.

85, 88 (1964, 71, 75), and the El Niño years are the composite of 1982, 86, 87, 91 (1965, 69, 72). The years selected for these composites are slightly different from that for the WNPM because October (May) NINO3 SST are used for selection to take advantage of maximum lag-correlations between the NINO3 SST and Northwest Kyushu rainfall during the 15-year period from 1978 to 1992 (1963 to 1977). Following Section 3, a 0.6°C SST departures was used for the threshold value. In the La Niña years for the recent 15-years, the negative October NINO3 SST departures were small (Fig. 2). Hence, 4 years with coldest SST were selected as the La Niña years which were found to be same as that for the June SST used in the WNPM. The largest difference in the rainfall between the La Niña and El Niño years was observed around July 5–24 (June 30–July 14) during 1978 to 1992 (1963 to 1977). The application of the students t-test showed that the rainfall difference for a 20-day (15-day) total rainfall for July 5–24 (June 30–July 14) is significant at the 95 % confidence during 1978 to 1992 (1963 to 1977).

Figure 14 shows the relationship between the Northwest Kyushu rainfall and the NINO3 SST. Except for 1991, all the El Niño years experienced heavy Baiu rainfall (Figs. 14a and 14b). Figure 14c shows the lag-correlations between the Northwest Kyushu rainfall and the NINO3 SST. The highest lag-correlation $+0.82$ ($+0.75$) was observed between the October–November (May with a secondary maximum in late autumn) NINO3 SST for the 15-year period from 1978 to 1992 (1963 to 1977). The 5 % level of significance for this correlation is 0.64 (0.59) for the 15-year period from 1978 to 1992 (1963–1977). Hence the Baiu rainfall leads (lags) the SST by 3 (2) months during the recent (early) 15-year period from 1978 to 1992 (1963 to 1977).

The spatial patterns of the sea-level pressure during the period of high rainfall correlation (July 5–24) between the Baiu rainfall and the NINO3 SST for the recent 15-year period from 1978 to 1992 are shown in Fig. 15. A La Niña composite (Fig. 15a) shows a transition between the Baiu pattern (Fig. 6b) and the mature phase of the WNPM (Fig. 6a). Compared to the Baiu pattern, the flow of the moist southerly winds is weak near 25°N , 130°E . A large area of weak winds is observed in the tropical and subtropical latitudes between the longitudes from 130°E to 150°E . This reduction in the winds is favorable for a rise in the SST and a subsequent increase in the convection and the onset of the WNPM.

An El Niño composite (Fig. 15b) shows the active phase of the Baiu season. The southwesterly winds near 30°N , 125°E and southeasterly winds near 25°N , 130°E are the important sources of the moisture for the very active Baiu front (Akiyama, 1975).

The difference between the El Niño and La Niña

Fig. 7. Spatial patterns of the GMS high-cloud amounts for July 20-29. a) the La Niña years (1978, 84, 85, 88). b) the El Niño years (1982, 83, 87, 91, 92). The scale for the cloud amount (percent) is shown on the left.

Fig. 8. Correlations ($\times 10$) between July 20-29 GMS high-cloud amounts and June NINO3 SST for the 15-year period from 1978 to 1992. Shaded areas show the gridpoints which are significant at the 5 % level.

Fig. 9. Latitude-time cross-section of the GMS high-cloud amounts at the longitudes from 145° to 154°E. The vertical scale shows the latitudes. The horizontal scale shows the months in the calendar year. a) the La Niña years (1978, 84, 85, 88). b) the El Niño years (1982, 83, 87, 91, 92). The scale for the cloud amount (percent) is shown on the left.

Fig. 10. Same as Fig. 9, but for the correlations (×10) between the GMS high-cloud amounts and June NINO3 SST. Shaded areas show the significant correlations at the 5 % level.

Fig. 11. Latitude-time cross-sections of the sea-level pressure at 140°E . a) the average for the 15-year period from 1978 to 1992. b) the La Niña years. c) the El Niño years. The units are departure from 1000 hPa. The dates shown in the horizontal scale are the last day of each pentad. The dots in b) and c) show the latitude and middle day of the pentad where the difference between the El Niño and La Niña years are significant at the 95 % confidence by the students t-test.

years (Fig. 15c) shows a significant positive (negative) sea-level pressure anomaly near $25^{\circ}\text{--}30^{\circ}\text{N}$, 140°E (40°N , $170^{\circ}\text{--}180^{\circ}\text{E}$).

The spatial patterns of the GMS high-cloud amounts during the same period as Fig. 15 are shown in Fig. 16. In the La Niña years (1978, 84, 85, 88), the active phase of the convection near 20°N , 150°E indicates a transition toward the onset of the WNPm. The convection associated with the Baiu front is weak near 33°N , 125°E and 35°N , 175°E . In the El Niño years (1982, 86, 87, 91), the active phase of the convection is observed along the Baiu front located north of 30°N and near the Philippines. Figure 17 shows the correlation between the GMS high-cloud amount and August NINO3 SST for a 20-day period from 5 to 24 July. The regions with significant correlation at the 5 % level are shaded. A region near 33°N , 125°E with a maximum positive correlation of 0.92 shows that the Baiu convection is under the strong influence of interannual variations of the NINO3 SST. The large-scale pattern of the correlation is similar to Fig. 8. However, the correlations near the Baiu front (20°N , 150°E) are higher (lower).

The sea-level pressure pattern (Fig. 15c) and GMS high-cloud amount correlation pattern (Fig. 17) suggest the propagation of anomalous Rossby waves, emanating from the convective region near the Philippines in the El Niño years. A wave train of anticyclonic cells near 25°N , 140°E and cyclonic cells near 40°N , 170°E in Fig. 15c is roughly aligned along a great circle that intersects the convective center near the Philippines where the positive correlations between the GMS high-cloud amount and the NINO3 SST are observed (Fig. 17). This pattern is similar to the analysis by Kawamura *et al.* (1996).

A similar analysis of the spatial pattern of the sea-level pressure during a 15-year period from 1963 to 1977 was carried out. The results indicate an intensification of the flow of the moist southerly winds near 25°N , 130°E in the El Niño years. However, the difference between the El Niño and La Niña years was statistically not significant.

The spatial patterns of the sea-level pressure suggest that the interannual variations in the NINO3 SST may be related to the ending dates of the Baiu season in the recent 15-year period from 1978 to 1992. We investigated this relationship using subjectively determined ending dates of the Baiu season obtained from the JMA for 11 regions in Japan for a 30-year period from 1963 to 1992. The lag-correlations between these dates and the NINO3 SST show that 3 regions (South Kyushu located near Kagoshima 31.55°N , 130.55°E (+0.78), North Kyushu located near Fukuoka 33.58°N , 130.38°E (+0.85), South Tohoku located near Sendai 38.27°N , 140.90°E (+0.68)) have significant

Fig. 12. Correlations ($\times 10$) between July rainfall in East Asia and NINO3 SST. a) the correlations between the rainfall during 1978–1992 and September NINO3 SST. b) the correlations between the rainfall during 1963–1977 and May NINO3 SST. The dots show the locations of the stations.

correlations to the August or September NINO3 SST in the recent 15-year period from 1978 to 1992. During the earlier 15-year period, significant positive correlation was not found for a time lag of less than one year.

7. The relationship between the mature phase of the WNPM and the end of the Baiu season in Japan

Ueda and Yasunari (1996) suggested that the onset and subsequent intensification of the WNPM coincides with the end of the Baiu season around Japan. However, this suggestion was made without the benefit of a statistical analysis between these two events.

We investigate this relationship using ending dates of the Baiu season determined by the JMA and the dates of the mature phase of the WNPM which are obtained from the sea-level pressure difference between 10°N and 20°N at 140°E . For the recent 15-year period, these data are shown in Fig. 1. The first maximum in the westerly winds during the July–September summer season was defined as the dates of the mature phase of the WNPM for each of the years. Significant correlations are found between ending dates of the Baiu season and the dates of the mature phase of the WNPM during the recent 15-year period from 1978 to 1992 at 5 regions (South Kyushu (+0.58), North Kyushu (+0.62), Hokuriku located near Niigata 37.92°N , 139.05°E (+0.64),

Fig. 13. Seasonal change in the composite 5-day mean rainfall during the Baiu season over Northwest Kyushu (average of Saga (32.25°N, 130.30°E), Nagasaki (32.73°N, 129.87°E), Kumamoto (32.82°N, 130.72°E), and Fukue (32.70°N, 128.83°E)). Solid line (dots) shows the La Niña (El Niño) years. a) the composite for the La Niña (El Niño) years of 1978, 84, 85, 88 (1982, 86, 87, 91). b) the composite for the La Niña (El Niño) years of 1964, 71, 75 (1965, 69, 72). The numbers shown on the horizontal scale are the last day of each pentad.

South Tohoku (+0.58), North Tohoku located near Aomori 40.82°N, 140.71°E (+0.60)) in Japan. During the 15-year period from 1963 to 1977, no significant correlation was found between these two dates. The dates of the mature phase of the WNPM have a significant correlation of +0.70 with July NINO3 SST during the recent 15-year period. No significant correlation was found in the earlier 15-year period. Therefore, the dates of the mature phase of the WNPM and the end of the Baiu season in Japan are correlated only when both of these events show high correlation to the NINO3 SST.

8. Summary

The analysis of interannual and interdecadal variations of the WNPM and the Baiu rainfall for a 30-year period from 1963 to 1992 showed high positive correlations between the Baiu rainfall and the

Fig. 14. Time series of the interannual variations of the Northwest Kyushu rainfall (solid line) and the NINO3 SST (dots), and the lag-correlations between the Northwest Kyushu rainfall and the NINO3 SST c). a) (b) shows the 15-year period from 1978-1992 (1963-1977). The rainfall amount is from July 5 to 24 (June 30 to July 14) for 1978-1992 (1963-1977). The scale on the left shows the rainfall in mm. The scale on the right shows the SST anomalies in °C. c) is same as Fig. 3, but for the lag-correlations between the Northwest Kyushu rainfall and the NINO3 SST.

Fig. 15. Same as Fig. 6, but for July 5-24. The El Niño years are 1982, 86, 87, and 91.

NINO3 SST. On the other hand, significant correlation between the WNPM and the NINO3 SST is restricted to the recent 15-year period from 1978 to 1992. During this period, early (late) onset of the WNPM and early (late) end of the Baiu rainfall are observed in the La Niña (El Niño) years. These dates are about 20 days later in the El Niño years.

The lag-correlations among the WNPM, the Baiu rainfall and the NINO3 SST show that the SST leads the WNPM by 1 to 2 months during the recent 15-year period from 1978 to 1992. On the other hand, the Baiu rainfall leads (lags) the SST by about 3 (2) months during the recent (early) 15-year period from 1978 to 1992 (1963 to 1977).

The NINO3 SST show biennial oscillation during the 15-year period from 1963 to 1977. In the recent 15-year period, the low frequency mode of about 4 years is dominant. These changes in the period of the oscillations of the NINO3 SST may be related to the recent increase in the correlations between the SST and the WNPM.

Yasunari and Seki (1992), using the Indian monsoon rainfall and Pacific SST data for the 21-year period from 1966 to 1986, suggested that these data show biennial oscillations. Shen and Lau (1995), using the rainfall data in China and tropical SST data for the 30-year period from 1956 to 1985, found similar biennial oscillations in these data. In both of these studies, more than half of their analysed periods are observations prior to 1978. Therefore, the low frequency mode in the recent 15-year period from 1978 to 1992 is not documented in these studies. Large interdecadal variations in the relationship among the WNPM, the Baiu rainfall and the NINO3 SST show that it is important to use long-term data and perform continuous update of these data for investigation of the stability of these relationships.

Ueda and Yasunari (1986), using the data from 1980 to 1994, suggested that the onset of the WNPM is closely related to early July SST in a local region in the western North Pacific. However, Lau and Sui (1997), using the data from November 1992 to February 1993, showed that the fluctuations of local SST on timescales of weeks to months are a response of the SST to the atmospheric low-frequency variability. Figure 10 shows that the first significant negative correlations between the GMS high-cloud amounts and June NINO3 SST are observed in late May-early June. Therefore the ENSO influence on the WNPM became significant well before July. These facts suggest that during the recent 15-year period from 1978 to 1992, the relationship to the ENSO cycles is the most important influence in interannual variations of the onset dates of the WNPM.

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Fig. 16 Same as Fig. 7, but for July 5–24. The El Niño years are 1982, 86, 87, and 91.

Fig. 17. Same as Fig. 8, but for the correlations ($\times 10$) between July 5–24 GMS high-cloud amounts and August NINO3 SST.

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梅雨降水量及び西太平洋における夏のモンスーンの年々及び長期変動と ENSO との関係

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東アジアにおける梅雨降水量及び西太平洋における夏のモンスーン (WNPM) の年々変動及び長期変動を 1963 年から 1992 年までの 30 年間の海面気圧・降水量及び 5 日平均 GMS 上層雲量データ (1978 年 4 月から 1992 年 12 月) を利用して調査した。これらの現象と ENSO との関係を 1963 年から 1992 年までの 30 年間の東部赤道太平洋海面水温 (NINO3 SST) を利用して調査した。

7 月下旬の WNPM の年々変動は、NINO3 SST と最近の 15 年間 (1978–1992) のみ高い負の相関があることがわかった。これは La Nina (El Nino) 年に WNPM は強く (弱く) なりやすいことを示す。7 月の梅雨降水量は、NINO3 SST と上記 15 年間に於いて高い正の相関があることがわかった。したがって La Nina (El Nino) 年に梅雨降水量が少なく (多く) なりやすいことを示す。これらの関係は最近の 15 年間については La Nina 年と比較して El Nino 年は WNPM の開始と梅雨降水量の極大が出現する日が 20 日ほど遅れることによる。

7 月の梅雨降水量は 1963 年から 1977 年の 15 年間にも NINO3 SST と高い正の相関があることがわかった。しかし La Nina 年と El Nino 年の梅雨降水量の極大の出現日の遅れの差は小さくなっていた。

NINO3 SST とのラグ相関を計算し、7 月下旬の WNPM は 5・6 月の NINO3 SST との負の相関が高かった。梅雨降水量は最近 (前期) 15 年間の 1978–1992 年 (1963–1977 年) の期間において、3 カ月遅い (2 カ月早い) 月の NINO3 SST と高い正の相関があることがわかった。

NINO3 SST の自己相関を調べると、1963–1977 年の 15 年間は、2 年周期が、1978–1992 年は 4 年位の長い周期が観測された。この周期の変化は、最近の 15 年間に SST と WNPM 及び梅雨降水量との相関が高くなったことと関係していると考えられるが、今後の調査が必要である。