Role of Tropical Cyclones along the Monsoon Trough in the 2011 Thai Flood and Interannual Variability

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ABSTRACT

The atmospheric circulation patterns that were responsible for the heavy flooding that occurred in Thailand in 2011 are examined. This paper also investigates the interannual variation in precipitation over Indochina over a 33-yr period from 1979–2011, focusing on the role of westward-propagating tropical cyclones (TCs) over the Asian monsoon region. Cyclonic anomalies and more westward-propagating TCs than expected from the climatology of the area were observed in 2011 along the monsoon trough from the northern Indian subcontinent, the Bay of Bengal, Indochina, and the western North Pacific, which contributed significantly to the 2011 Thai flood. The strength of monsoon westerlies was normal, which implies that the monsoon westerly was not responsible for the seasonal heavy rainfall in 2011. Similar results were also obtained from the 33-yr statistical analysis. The 5-month total precipitation over Indochina covaried interannually with that along the monsoon trough. In addition, above-normal precipitation over Indochina was observed when enhanced cyclonic circulation with more westward-propagating TCs along the monsoon trough was observed. Notably, the above-normal precipitation was not due to the enhanced monsoon westerly over Indochina. Therefore, the 2011 Thai flood was caused by the typical atmospheric circulation pattern for an above-normal precipitation year. It is noteworthy that the effect of sea surface temperature (SST) forcing over the western North Pacific and the Niño-3.4 region on total precipitation during the summer rainy season over Indochina was unclear over the 33-yr period.

1. Introduction

In 2011, severe flooding in Thailand during the postmonsoon season caused substantial human and economic damage. Komori et al. (2012) showed that rainfall in each month of the rainy season (from May to October) exceeded climatological norms, and that this was a primary cause of the Thai flood. The aim of this study is to

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better understand the characteristics of atmospheric circulation during the rainy season of 2011 around Indochina through an investigation of the interannual variations in precipitation and related atmospheric circulations over a period of more than 30 yr.

Interannual variations in precipitation for the whole Asian monsoon and for regional Asian monsoon regions have been investigated in many previous studies. Indochina is located at the boundary of two monsoon regions, the South Asian and western North Pacific monsoons. Wang and Fan (1999) proposed two separate monsoon indices for the South Asian and western North Pacific monsoons, based on observations indicating that interannual variations in precipitation in these two regions were not correlated. Furthermore, Wang et al. (2001) showed that long-term changes or interdecadal variations in precipitation over these two regions were also distinct.

Some studies have examined interannual variations in total precipitation over Indochina. Chen and Yoon (2000) suggested that high rainfall over Indochina was related to an enhancement of the westward-propagating tropical cyclones (TCs) in the Asian summer monsoon season trough and changes in the sea surface temperatures (SSTs) over the Niño-3.4 region. Zhang et al. (2002) suggested that a similar mechanism occurred, but only for the onset phase of the rainy season. They suggested that the above-normal rainfall in May and June over Indochina was caused by the activity of westward-propagating TCs, which were associated with cold SST anomalies over the central and western Pacific. In the peak rainy season, interannual variation in September precipitation over Indochina has been explained in relation to the activity of TCs (Takahashi and Yasunari 2008; Takahashi et al. 2009), although these studies focused solely on peak seasonal precipitation. However, the factors controlling this interannual variation in rainy seasonal precipitation are not yet understood.

Climatologically, the rainy season over the Southeast Asian monsoon can be characterized as two subseasons divided by the climatological monsoon break in late June (Takahashi and Yasunari 2006). Rainfall in the first half of the rainy season (from May to June) is brought by typical monsoon southwesterlies, whereas rainfall in the second half of the season (from July to September) is due to active TCs. Takahashi and Yasunari (2008) estimated that 70% of precipitation over Thailand is caused by TCs in September. In fact, peak precipitation over Indochina occurs in September (Matsumoto 1997; Takahashi and Yasunari 2006). Note that Takahashi and Yasunari (2008) indicated that weaker TCs, such as tropical depressions (with wind up to $17\,\mathrm{m\,s^{-1}}$), have also contributed to the peak seasonal precipitation. In this study, the term TC includes these weaker TCs.

Westward-propagating TCs coupled with convective activity in the rainy season over tropical Asian monsoon regions have been reported in previous studies (e.g., Chen and Chen 1993; Chen and Yoon 2000; Fukutomi and Yasunari 1999; Yokoi and Satomura 2005). Yokoi et al. (2007) showed that the dominant time scales of precipitation in the first and second halves of the rainy season of the Southeast Asian monsoon were 30–60 and 10–20 days, respectively. Hence, these studies support the idea that the basic rainfall system over Indochina can be characterized as westward-propagating TCs. It is therefore possible that the activity of the westward-propagating TCs is a key factor in determining interannual variation in rainfall over Indochina.

This study describes the atmospheric circulation pattern that caused the seasonal heavy precipitation and subsequent flooding in Thailand in 2011. To understand the heavy seasonal precipitation in 2011, we statistically investigated the interannual variations in total precipitation in the summer rainy season over Indochina over a 33-yr period. We focused on the activity of westward-propagating TCs. In addition, we considered whether the 2011 Thai flood was caused by an untypical or a commonly occurring atmospheric circulation pattern in the above-normal precipitation years. Furthermore, the role of SSTs over the Niño-3.4 region on the interannual variation in total precipitation of the summer rainy season over Indochina is discussed.

Section 2 describes the data used in this study. Section 3 presents our results regarding the 2011 Thai flood and interannual variation in seasonal precipitation, atmospheric circulation, and TC activity. Finally, the impact of SSTs on the interannual variation in seasonal precipitation is discussed in section 4, and our conclusions are presented in section 5.

2. Data

Komori et al. (2012) reported above-average precipitation in 2011 at 15 weather stations. To better understand the spatial and temporal distributions of precipitation in 2011, we used daily rainfall data from 56 stations in Thailand (Fig. 1), which were compiled by the Thai Meteorological Department. The data spanned 1979–2000 and included 2011. Climatological means were calculated over 23 yr, from 1979 to 2000 and again in 2011. To produce precipitation time series for Thailand (north of 12°N), we averaged data from 53 stations (Fig. 1). The average precipitation index was referred to as the ''all-Thailand rainfall'' (ATR).

To analyze large-scale rainfall on a daily time-scale across Indochina, the Global Precipitation Climatology Project 1° Daily Precipitation (GPCP-1DD; Huffman

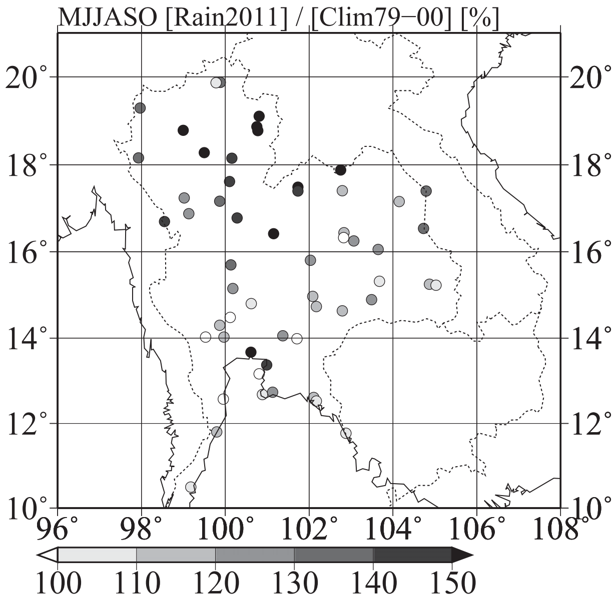

FIG. 1. Spatial distribution of 2011 precipitation expressed as the percentage of climatological precipitation (1979–2000) that fell from May to September.

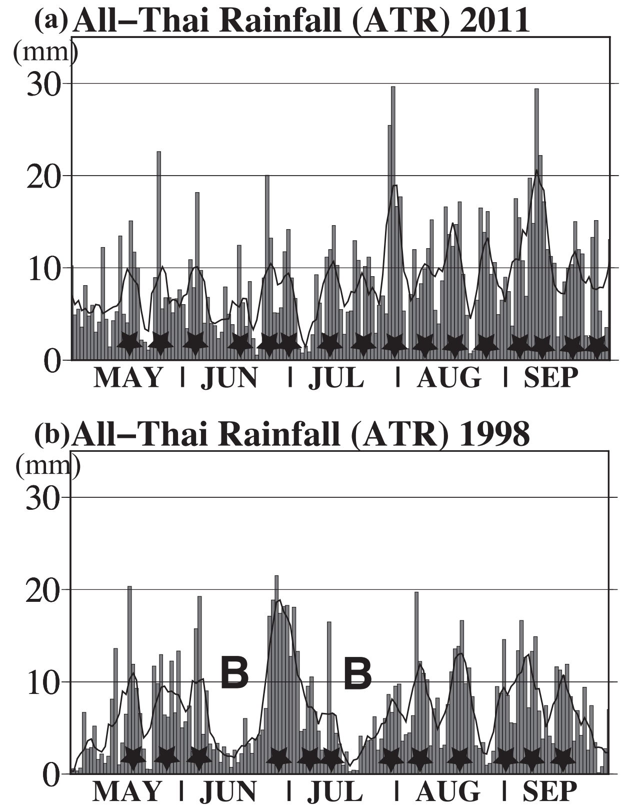

FIG. 2. Time series of daily all-Thailand rainfall (ATR) in (a) 2011 and (b) 1998. ATR data were generated by averaging precipitation data from 53 stations north of 12°N (Fig. 1). Black line indicates 5-day running mean. Star symbols indicate precipitation events. The letter B shows longer monsoon breaks.

et al. 2001, version 1.2) dataset was also used. This provides daily, global 1° × 1° gridded fields for total precipitation from October 1996 to December 2011. This study also used satellite-derived rainfall data from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997) over 33 yr from 1979 to 2011 for statistical analysis of the interannual variation in precipitation with monthly, global 2.5° × 2.5° gridded fields.

To investigate the differences in precipitation activity between wet and dry years, 2011 and 1998 were selected as the highest and lowest precipitation years, respectively, because of the limitations of the daily global precipitation dataset. We show the daily time series of ATR (Fig. 2) and the longitude–time sections of GPCP-1DD precipitation along 12°–20°N (Fig. 3) in both years.

To examine the atmospheric circulation that caused the heavy precipitation and subsequent severe flooding and interannual variation in precipitation over Thailand, we used the Japanese 55-year Reanalysis (JRA-55; Ebita et al. 2011) dataset, including zonal and meridional winds (u, v) and streamfunction (ψ) at 850 and 200 hPa. The Joint Typhoon Warning Center (JTWC) TC track dataset was also used to examine the interannual variation in TC activity. The JTWC TC track datasets include tropical storms (with winds of 18–32 m s^{-1}) and some tropical depressions (with winds up to 17 m s^{-1}). We also used Extended Reconstructed SST (ERSST) version 3 (Smith et al. 2008) datasets, which have a spatial resolution of 2°, to discuss the impact of SST on precipitation over Indochina.

3. Results

a. *2011 Thai flood*

1) HIGH PRECIPITATION IN 2011

Figure 1 shows a spatial map of rates of precipitation in 2011 to the climatological precipitation. High precipitation was observed over Thailand from May to September at most stations. The seasonal mean precipitation was particularly high over the northwestern part of Thailand. The rates of monthly precipitation (expressed as the ATR) were 105.6%, 100.5%, 124.1%, 121.3%, and 127.5% of the climatological monthly precipitation for May, June, July, August, and September, respectively. As demonstrated, precipitation was higher than climatological mean data for all months, but particularly so in the second half of the summer rainy season. To understand whether this high precipitation over Thailand in 2011 was caused by an atypical atmospheric circulation pattern or not, we investigate the 33-yr interannual variation in precipitation over Indochina in sections 3b and 4a.

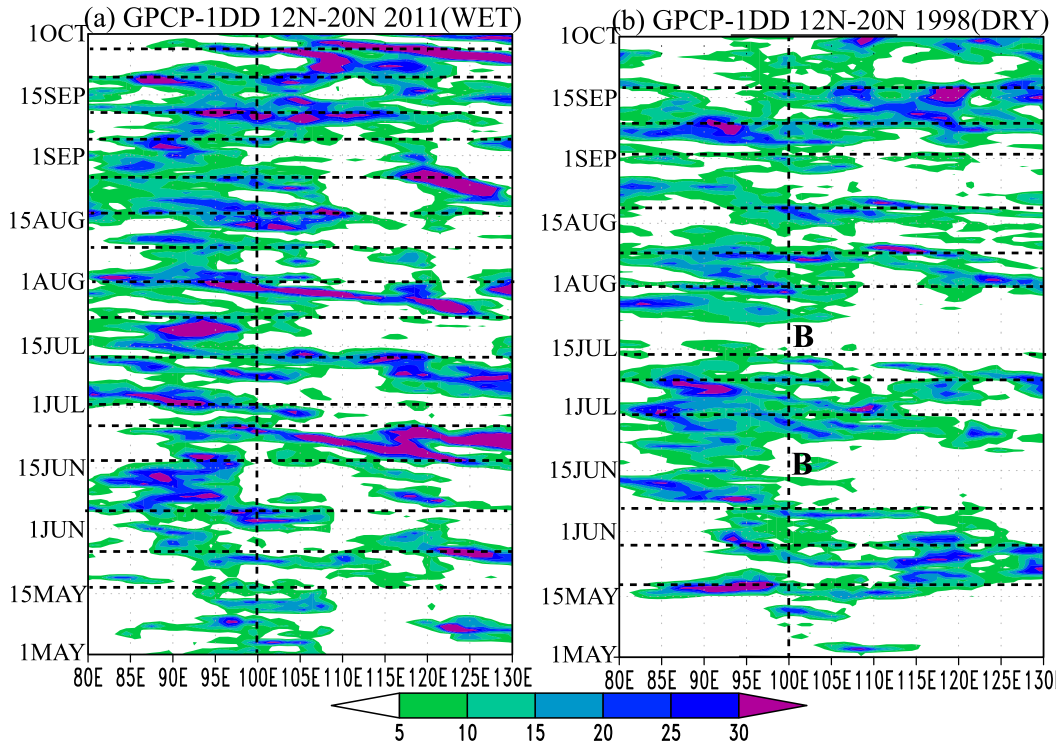

FIG. 3. Time–longitude cross section generated from the GPCP-1DD daily precipitation (mm) dataset in (a) 2011 and (b) 1998 along the latitudinal band between 12° and 20°N. The target region located around 100°E is shown by a vertical dashed line. Precipitation events in Fig. 2 are also indicated by horizontal dashed lines.

2) Westward-propagating precipitation systems

The ATR time series in 2011 showed frequent precipitation events throughout the five months from May to September (Fig. 2a). Three or four precipitation events per month were observed from June to September in 2011, indicating that precipitation events occurred frequently during the rainy season in 2011. However, two long monsoon breaks were observed in mid-June and July in 1998 (Fig. 2b). In addition, the major climatological rain peak in September was unclear in 1998. These longer monsoon breaks and the below-normal rainy peak in September were characteristics of the 1998 rainy season.

Figure 3 shows that many westward-propagating precipitation signals were found in both 2011 and 1998. Many westward-propagating precipitation signals were observed over Thailand (approximately 100°E) from May to September. These signals originated from the western North Pacific or over the east of Indochina (Fig. 3). The timing of arrival or approach of these precipitation activities basically corresponded with the high precipitation of the ATR (see the horizontal dashed lines in Fig. 3).

In 2011, many westward-propagating precipitation signals were consistently observed from June to September, which corresponded with the precipitation events observed in the ATR. Compared to the westward-propagating precipitation signals in 2011, fewer precipitation signals were observed in 1998 during the longer monsoon breaks in mid-June and July and September. Climatologically, the major precipitation peak, which is caused by westward-propagating TCs, tends to occur in September (Takahashi and Yasunari 2006). In conjunction with the long monsoon breaks in mid-June and July and the below-normal precipitation peak in September, the westward-propagating rainfall activity over Indochina experienced a temporary lull. Over Indochina, the frequency of westward-propagating precipitation systems, which are probably the westward-propagating TCs, differed greatly between the summers of 1998 and 2011.

3) Enhanced cyclonic circulation and TC activity along the monsoon trough in 2011

To investigate the characteristics of atmospheric circulation and TC activity over and around Indochina in 2011, 5-month mean anomalies in the 850-hPa streamfunction were investigated based on climatological values from 1979 to 2011, and TC tracks from May to September

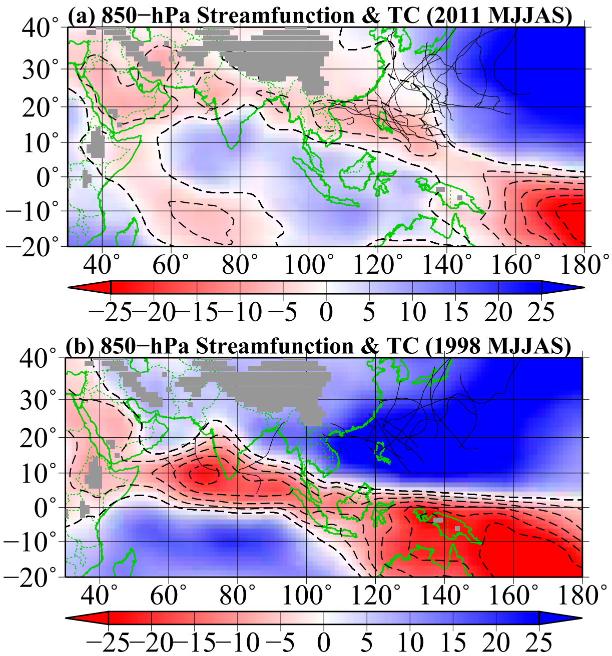

FIG. 4. Five-month mean anomalies in streamfunction at 850 hPa from May to September (a) 2011 and (b) 1998, based on climatological data from the 33-yr period from 1979 to 2011. Only contours below 0 $m^2 s^{-1}$ are plotted (cyclonic anomalies) and the interval is $5 \times 10^5 m^2 s^{-1}$. JTWC TC tracks from May to September are also plotted in black and the green lines outline land areas.

in 2011 and 1998 (Fig. 4). Negative streamfunction anomalies were observed along the monsoon trough from the northern Indian subcontinent, the head of the Bay of Bengal, Indochina, and the western North Pacific. In addition, more TC tracks were observed along the monsoon trough in 2011 than in 1998. However, positive streamfunction anomalies were found along the monsoon trough in 1998 (Fig. 4b). Note that there were clearly fewer TCs in 1998 than in 2011, particularly on the eastern coast of Indochina. These results imply that cyclonic anomalies with many TCs along the monsoon trough were a major contributing factor to the heavy precipitation over Thailand in 2011.

We also confirmed that the TCs along the monsoon trough in Fig. 4 corresponded to the westward-propagating precipitation systems, which were observed in Fig. 3 (not shown). However, not all of the westward-propagating TCs were categorized as tropical storms, severe tropical storms, or typhoons while over the western North Pacific. Hence, weaker TCs, such as tropical depressions, contributed to the total precipitation, as reported by Takahashi and Yasunari (2008). In addition, it is difficult to understand the changes in TC activity from a comparison of two specific years, given the random nature of TCs. To determine if the 2011 Thai flood could be explained by the typical atmospheric circulation pattern in high precipitation years, we statistically investigated the interannual variation in precipitation and atmospheric circulation over a 33-yr period.

b. *Interannual variation of rainy seasonal precipitation over a 33-yr period*

1) A ZONALLY EXPANDED CYCLONIC CIRCULATION SIGNAL ALONG THE MONSOON TROUGH

To statistically investigate the atmospheric circulation that controlled interannual variation in total precipitation from May to September over and around Indochina, we generated regression maps showing interannual variation in precipitation and circulation in the lower troposphere with area-averaged precipitation. To obtain a robust result, we conducted a regression analysis over 33 yr from 1979 to 2011, based on CMAP data over Indochina (12.5°–20°N, 97.5°–107.5°E), because the observations by rain gauges were limited to 23 yr. This is referred to as the reference region of precipitation. Based on CMAP data, the time series of interannual variation in precipitation over Thailand from May to September showed that 2011 was one of the heaviest precipitation years (Fig. 5a). This was consistent with our results for the ATR analysis based on rain gauge observations (not shown). The interannual correlation coefficient between the two precipitation datasets over 23 yr from 1979/2000 and 2011 was 0.83. Similar results were obtained when we used the area-averaged 53-gauge precipitation dataset instead of the CMAP dataset.

Figure 5b shows the regression of the 5-month mean precipitation from May to September and low-level circulation at all grid points in the Asian monsoon region against the normalized CMAP dataset over Indochina. High correlations and highly regressed precipitation values are observed across the northern Indian subcontinent, the head of the Bay of Bengal, Indochina, and the western North Pacific. This indicates that interannual variation in total precipitation during the rainy season over Indochina was synchronized with that over the zonally expanded area. This zonally expanded area corresponded to the monsoon trough. Interannual variation in total precipitation during the rainy season showed a broad spatial structure along the monsoon trough over the Asian monsoon region. No significant correlation was observed over central or southern India.

The regression coefficient in the 850-hPa winds and streamfunction showed zonally expanded signals along the monsoon trough (Fig. 5c). Negative streamfunction

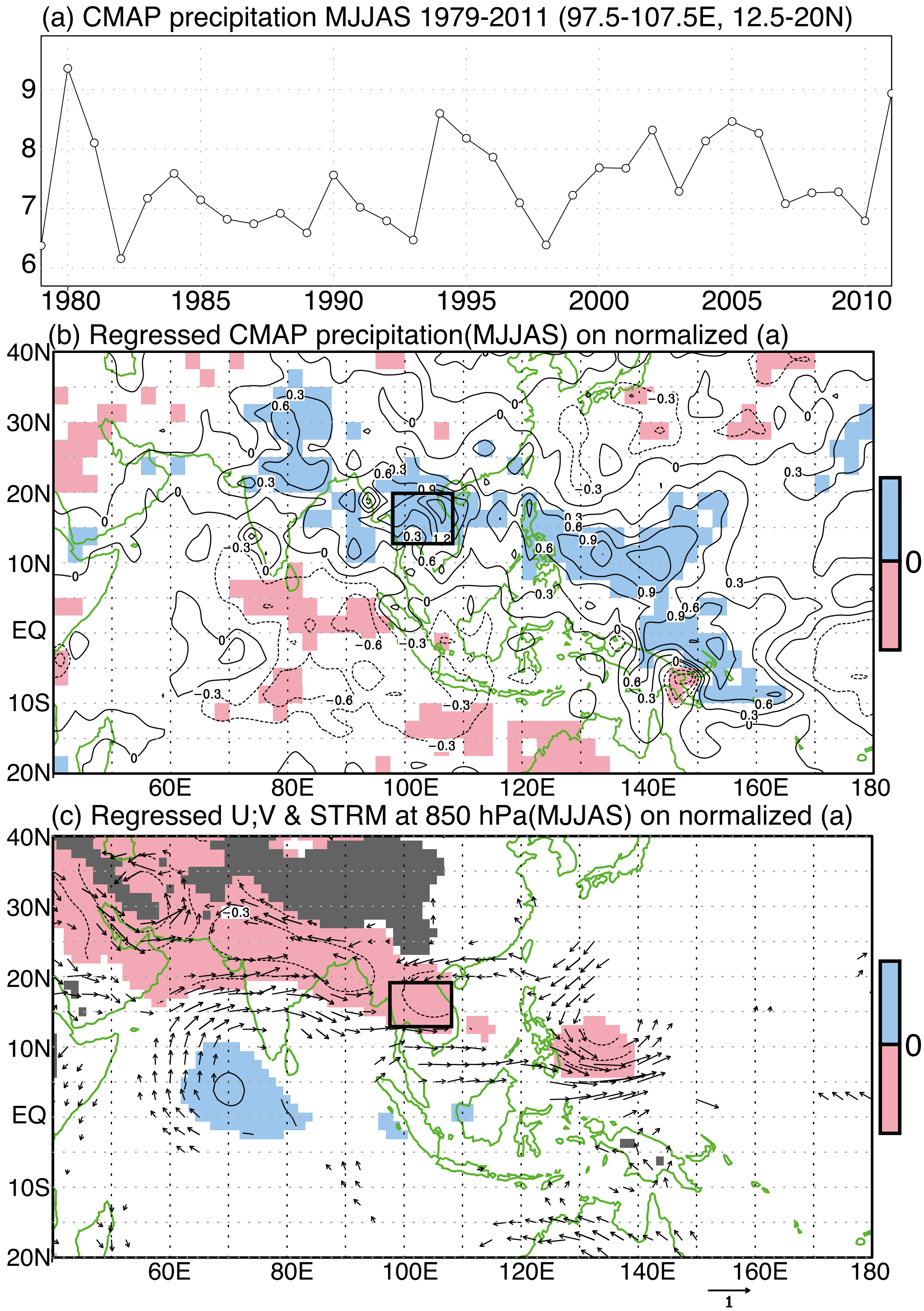

FIG. 5. (a) Precipitation time series generated from the CMAP dataset for the rainy season (May–September) over the reference region of Indochina (12.5°–20°N, 97.5°–107.5°E) from 1979–2011. The reference region is used for the regression analysis in (b),(c) and is indicated by a solid rectangle in these panels. (b) Regression of CMAP data during the rainy season against the normalized data (mm day^{-1}) shown in (a) from 1979 to 2011. (c) As in (b), but for the 850-hPa zonal and meridional winds and streamfunction (colors) during the rainy season. Areas with colors in (b) and plotted vectors (winds; m s^{-1}) and contours and colors (streamfunction; 10^6 m^2 s^{-1}) in (c) are statistically significant at the 90% level, as determined by correlation coefficients based on 31 degrees of freedom (df).

signals along the monsoon trough with above-normal precipitation over Indochina were observed. Thus, when above-normal precipitation occurred over Indochina, cyclonic circulation strengthened over the monsoon trough region. This suggests that interannual variation in total precipitation during the rainy season over Indochina is controlled by the mean seasonal strength of cyclonic circulation along the zonally expanded monsoon trough.

Westerlies were stronger south of Indochina, while easterly anomalies were observed over the northern Indochina. Thus, no significantly enhanced monsoon westerly was observed over the reference region, which probably indicates that the above-normal precipitation over Indochina was not directly induced by the enhanced monsoon westerlies over Indochina. In addition, the zonally expanded precipitation and low-level cyclonic circulation along the monsoon trough were consistent with the primary route of westward-propagating TCs, originating from the western North Pacific to the Bay of Bengal, which will be examined in the next section.

2) Association between cyclonic anomalies and westward-propagating tropical cyclones

In 2011, many westward-propagating precipitation systems were observed along the zonal band of 12°–20°N (Fig. 3), which basically corresponds to the monsoon trough. In addition, cyclonic circulation anomalies with many TCs were found along the monsoon trough in 2011 (Fig. 4). To investigate the robust relationship between cyclonic circulation and TC activity along the monsoon trough from the Indian subcontinent, the head of the Bay of Bengal, Indochina, and the western North Pacific, we produced composite maps of TC tracks and frequency for the five wettest years and driest years (Fig. 6). The five wettest years were 1980, 1994, 2002, 2005, and 2011, and the five driest years were 1979, 1982, 1989, 1993, and 1998, based on Fig. 5a. The TC frequency was calculated from the 6-h TC track dataset. TC frequency was defined as how often TCs were observed at each grid point, which was expressed as the number of days across the entire 5-month period from May to September.

High TC frequencies were observed along the monsoon trough and over the western North Pacific in the climatology (Fig. 6d) and even in the driest years (Fig. 6b). This indicated that many TCs occur along the monsoon trough during the summer monsoon season. The climatological correspondence between the TC activity and cyclonic circulation of the monsoon trough shows their close linkage.

Higher TC frequencies east of Indochina and over the western North Pacific were observed in the five wettest years compared with lower TC frequencies in the five driest years. Figure 6c shows the differences in TC frequency, and clearly indicates higher frequencies over the monsoon trough in the wettest years. These higher TC frequencies east of Indochina, and over the

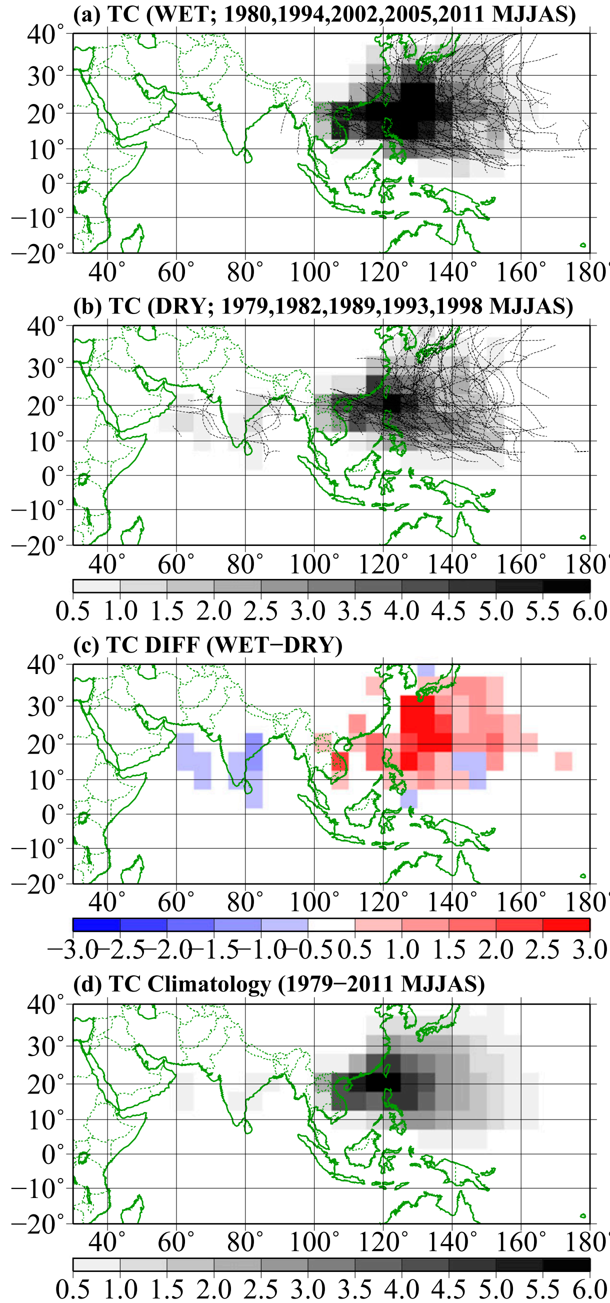

FIG. 6. JTWC TC tracks and the TC frequency [days (5-month)$^{-1}$] from May to September across a given bin (5° increments) for (a) the five wettest years (1980, 1994, 2002, 2005, and 2011) and (b) the five driest years (1979, 1982, 1989, 1993, and 1998). (c) Difference in TC frequency between the five wettest and five driest years [(a) minus (b)]. (d) Climatology of TC frequency from 1979 to 2011. The unit is the number of days per rainy season (from May to September).

western North Pacific, were consistent with the low-level cyclonic circulation signal (Fig. 5c). This supports the notion that enhanced TC activity (Fig. 6c) and the 5-month-averaged cyclonic signal (Fig. 5c) along the monsoon trough are linked. However, lower TC frequencies were observed over the northern Indian Ocean in the wetter years. The relationship between the weaker TC activity in the wettest years over the Arabian Sea and the eastern Indian subcontinent and the atmospheric circulation anomalies was not clear, although there are far fewer TCs over the northern Indian Ocean than over the eastern side of Indochina.

4. Discussion

a. 2011 Thai flood

In the previous section, we investigated the characteristics of precipitation and atmospheric circulation in 2011 and 1998, and performed a statistical analysis for a 33-yr period. These results demonstrated that interannual variation in atmospheric patterns, including TC activity, explains the precipitation over Indochina. One of the aims of this study was to determine if the 2011 Thai flood was caused by a typical atmospheric circulation pattern for a high precipitation year. From both the case study for 2011 and the statistical analysis of a 33-yr period, an increase in precipitation over Indochina was commonly determined to be responsible for the enhanced cyclonic circulation with many TCs along the monsoon trough. We also confirmed that similar results were obtained when we conducted the same analyses for Figs. 5 and 6 even excluding the 2011 rainy season. The correspondence between the two analyses implies that our mechanism for the typical interannual variation is applicable to the 2011 Thai flood. Hence, the 2011 Thai flood was not caused by an atypical atmospheric circulation pattern.

We should also examine whether these severe floods are likely to increase in future. Multiple global climate models have projected a decrease in the number of TCs around Indochina, which may be due to the decrease in the total number of TCs over the western North Pacific (Yokoi et al. 2013). However, the number of weaker TCs, such as tropical depressions, may also influence total precipitation over Indochina. Thus, further investigations are necessary to generate future projections for precipitation over the Southeast Asian monsoon regions.

b. ENSO forcing of precipitation over Indochina

Many previous studies have suggested that the interannual variation in precipitation over the overall Asian monsoon area and individual Asian regional monsoon areas is correlated with SSTs over the Niño-3.4 region (e.g., Webster and Yang 1992; Webster et al. 1998; Wang et al. 2001). However, this relationship remains unclear over Indochina because the relationship varies greatly from region to region and seasonally. The influence of SSTs over the Niño-3.4 region on the total precipitation over Indochina during the rainy season is not understood. Here, we show the regression coefficients in SSTs against normalized CMAP data for May–September (Fig. 5a) over 33 yr (Fig. 7).

No significant SST signals were observed over the Philippine Sea or the central or eastern Pacific. Significant SST signals were observed only over the western North Pacific near the date line. The spatial pattern of the SST signals did not resemble typical SST anomalies caused by El Niño–Southern Oscillation (ENSO), and the statistical relationship between ENSO and total precipitation during the rainy season over Indochina remains unclear. Although the relationship between SSTs over the Niño-3.4 region and precipitation over Indochina was somewhat clearer in May and October (not shown), the SSTs over the Niño-3.4 region contributed little to the total precipitation over Indochina during the rainy season on an interannual time scale.

To confirm the impact of SSTs over the Niño-3.4 region on the Asian monsoon, Fig. 7b shows the regression of total precipitation data during the rainy season (May–September) and low-level circulation at all grid points in the Asian monsoon region against SST data over the Niño-3.4 region. High correlations and highly regressed precipitation values are seen across the central equatorial Pacific, western equatorial Pacific, and the Maritime Continent, indicating that precipitation and low-level circulation vary with ENSO. However, the impact is unclear over the South and Southeast Asian monsoon regions. This also indicates that the impact of ENSO on the Asian monsoon is limited, particularly over Indochina and the Indian subcontinent.

Goswami et al. (1999) showed a weak correlation between SSTs over the eastern Pacific, namely ENSO, and precipitation variations in the Asian monsoon region, including Indochina. In addition, Kripalani et al. (1995) used detailed statistical analyses to show that rainfall variation over Thailand was correlated with that over India on interannual time scales. Our results are consistent with these previous studies, implying that remote SST forcing from the Niño-3.4 region on precipitation over Indochina is weak. However, Chen and Yoon (2000) claimed that SSTs over the Niño-3.4 region impacts Indochina through changes in TC activity. These discrepancies may be explained by long-term

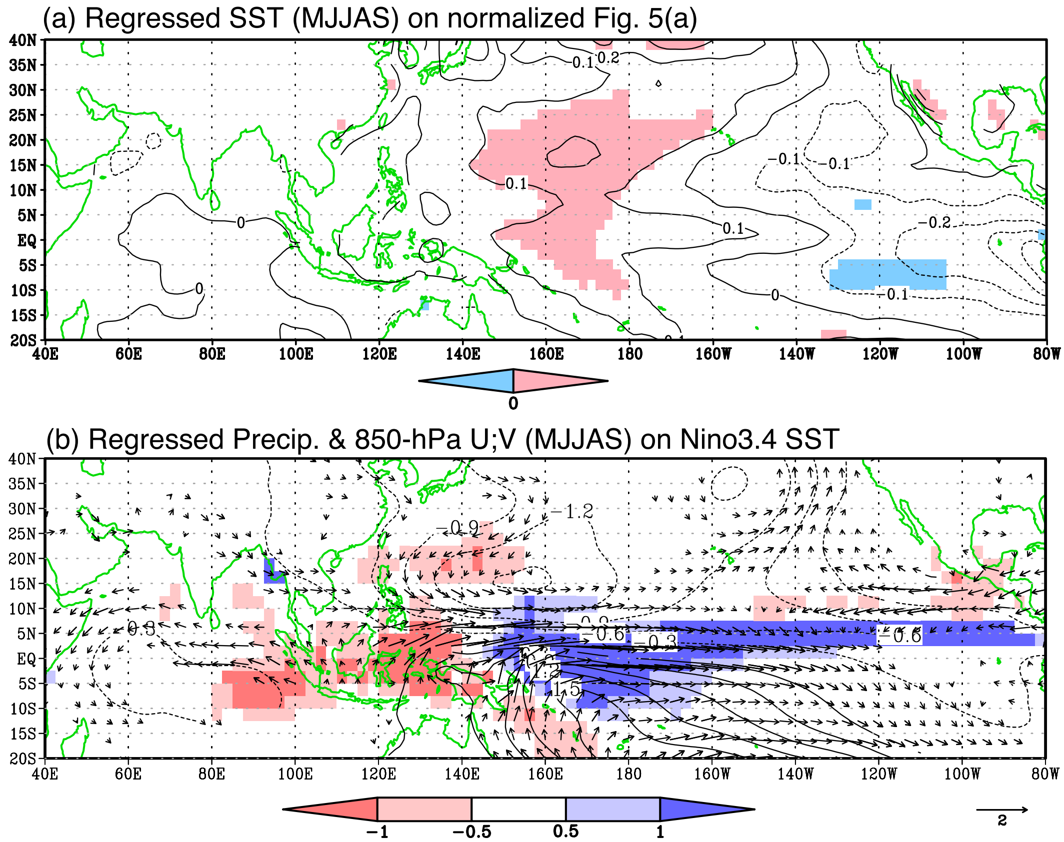

FIG. 7. (a) Regression of rainy season SST data onto the normalized data (K) shown in Fig. 5a from 1979 to 2011; pink indicates positive and blue negative values. (b) Regression of the rainy season 850-hPa zonal and meridional winds (vectors; $m s^{-1}$), streamfunction (contours; $10^6 m^2 s^{-1}$), and precipitation (color; $mm day^{-1}$) onto the normalized SST data for the Niño-3.4 region from 1979 to 2011. Colors in (a) and plotted values in (b) are statistically significant at the 90% level, as determined by correlation coefficients based on 31 degrees of freedom (df).

or decadal changes in the ENSO–monsoon system, based on previous work by Goswami et al. (1999) showing that this relationship has been changing. Indeed, over the last 33 yr, high precipitation years over Indochina occurred primarily in the 2000s (Fig. 6a). The results of Chen and Yoon (2000) may be significant only for the decades that they studied.

Our statistical analysis showed that the impact of ENSO was not a major determinant of interannual variation in precipitation during the rainy season over Indochina. Also note that the SST anomalies over the western North Pacific and over the Niño-3.4 region during the 2011 rainy season were small and not typical of the ENSO pattern (not shown).

c. *Seasonal mean monsoon trough and tropical cyclone activity*

Our results show that interannual variation in precipitation over Indochina is primarily controlled by 5-month mean enhanced cyclonic anomalies with frequent TC activity along the monsoon trough. On an interannual time scale, the 5-month mean cyclonic anomalies along the monsoon trough corresponded to frequent TC activity there. This idea is consistent with previous work showing that the spatial pattern of the dominant mode of intraseasonal variability of low-level winds is similar to that of interannual variability of seasonal mean winds over the Indian monsoon region (Goswami and Mohan 2001). The authors concluded that the similarity between spatial patterns in the two parameters (variability) indicates that the higher frequency of active monsoon conditions would result in a stronger than normal seasonal mean. In addition, Fujinami et al. (2011) showed that the activity of intraseasonal disturbances controlled seasonal mean precipitation over Bangladesh. However, the physical mechanism that controls the activities of TCs or the intraseasonal variations of atmospheric circulation over the Asian monsoon region is still unclear. The mechanism generating this interannual variation in

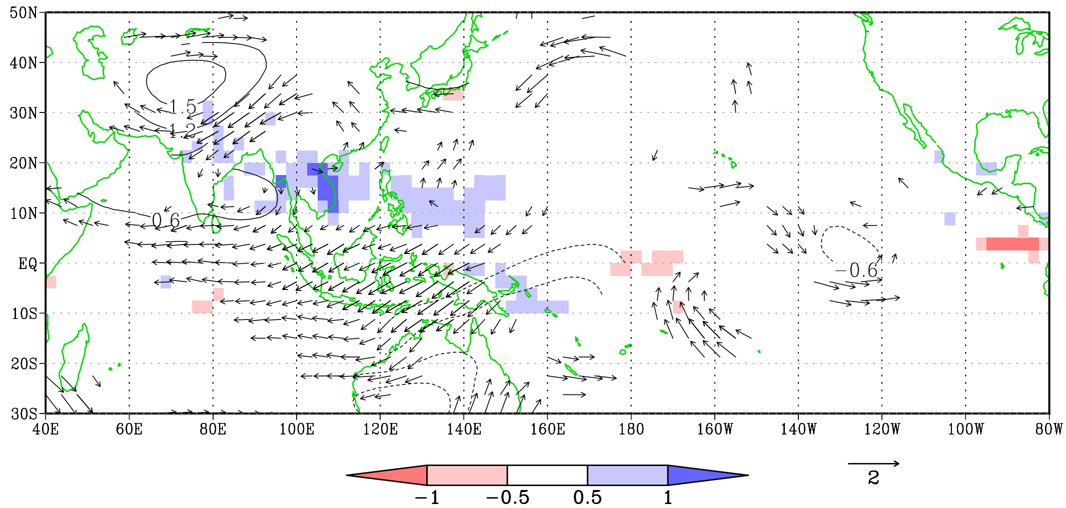

FIG. 8. Regression of the rainy season 200-hPa zonal and meridional winds (vectors; m s^{-1}) and streamfunction (contours; 10^6 m^2 s^{-1}) and CMAP precipitation (color; mm day^{-1}) onto the normalized data in Fig. 5a from 1979 to 2011. The plotted values are statistically significant at the 90% level, as determined by correlation coefficients based on 31 degrees of freedom (df).

westward-propagating TCs along the monsoon trough will be the subject of additional studies.

d. Regional differences in interannual variability

This subsection investigates the relationship among interannual variations in the regional components of the Asian monsoon, such as over the Indian subcontinent, over the western North Pacific, and over the monsoon trough. Wang et al. (2001) demonstrated differences in interannual variability in precipitation in the Indian and western North Pacific monsoon regions. Interannual variation in the western North Pacific monsoon was associated with that of the East Asian monsoon. The western North Pacific monsoon modulated the subtropical high over the western North Pacific, the eastern Asian subtropical front, the Okhotsk high, and precipitation over the Great Plains of the United States. The authors concluded Indochina should be included within the western North Pacific monsoon regions, although their results were not statistically significant. However, our results show that the interannual variability in Indochina differs from that in the western North Pacific, particularly in terms of the effect of ENSO. In addition, the spatial structures of the variation in interannual precipitation over Indochina, which were synchronized with those along the monsoon trough, are very different from those of both the Indian and western Pacific monsoons.

Figure 8 shows the regression coefficients for 200-hPa winds and streamfunction onto the normalized CMAP data (Fig. 5a) over 33 yr (May–September). This allows investigation of the atmospheric response in the upper troposphere to the interannual variations in seasonal mean precipitation totals along the monsoon trough. Enhancement of anticyclonic circulation was observed over the Tibetan Plateau. This may have been the result of increased precipitation along the monsoon trough, which can be explained by the Rossby wave response to the enhanced latent heating along the monsoon trough due to vigorous TC activity. No significant atmospheric response to the enhanced latent heating along the monsoon trough was observed over the western North Pacific or North America. This was significantly different from the atmospheric response of the convective activity over the western North Pacific, as shown by Wang et al. (2001). However, the atmospheric response to the enhanced latent heating along the monsoon trough was somewhat similar to the atmospheric response of the convective activity over the Indian monsoon region, as shown by Wang et al. (2001). This may indicate that the interannual variability in precipitation along the monsoon trough or over Indochina is more similar to that of the Indian monsoon than to that of the western North Pacific monsoon, although the spatial structures of interannual precipitation variation were different. Of course, because Indochina is located between the Indian subcontinent and the western North Pacific, the interannual variability in seasonal precipitation over the monsoon trough is possibly similar to both regions. These results suggest the possibility that the interannual variation in precipitation along the monsoon trough is independent of the interannual variability in seasonal precipitation over the Asian monsoon region.

e. Relationship between the seasonal march of precipitation and interannual variation

Our results showed that interannual variation in precipitation over Indochina is primarily explained by westward-propagating TC activity along the monsoon trough that appears from the Arabian Sea, the Indian subcontinent, the head of the Bay of Bengal, Indochina, and the equatorial Philippine Sea. This pattern can be observed in the first and second halves of the Asian summer rainy season, although Takahashi and Yasunari (2006) showed the climatological atmospheric pattern changes from the first half of the Asian summer rainy season (May–June) to the second half (July–September). Our previous studies showed that water vapor transport by the monsoon southwesterly was important in the first half of the rainy season, while in the second half was associated with TC activity. Interannual variation in precipitation over Thailand was controlled by zonally expanded cyclonic circulation along the monsoon trough, namely the frequent occurrence of westward-propagating TCs, throughout the rainy season. Interestingly, the atmospheric patterns that control total precipitation during the rainy season can differ from those of the climatological atmospheric pattern in the first half of the rainy season.

5. Conclusions

This study examined the characteristics of atmospheric circulation patterns, which induced heavy precipitation throughout the rainy season, and the subsequent severe flooding that occurred in Thailand in 2011. To determine whether the 2011 Thai flood was an unusual event or an occasionally occurring heavy rainfall event, we also investigated interannual variation in precipitation over Indochina for the 33-yr period from 1979–2011. This analysis was carried out using ground- and satellite-based rainfall observations, atmospheric reanalysis datasets, and TC tracks.

The average precipitation recorded by 53 stations in Thailand throughout the rainy season from May to September in 2011 was higher than in any other year in the 22-yr period from 1979–2000. Westward-propagating precipitation systems (i.e., westward-propagating TCs) from the western North Pacific to Indochina were periodically observed from mid-May to September. When these TCs approached Thailand, heavy precipitation was observed. In 2011, enhanced cyclonic circulation with many TCs along the monsoon trough was observed.

Interannual variation in total precipitation from May to September over Indochina was synchronized with that over the zonally expanded area from the northern Indian subcontinent, the head of the Bay of Bengal, Indochina, and the Philippine Sea. The zonally expanded area corresponded to the monsoon trough. Interannual variation in total precipitation during the rainy season over Indochina was explained by cyclonic circulation anomalies with the activity of westward-propagating TCs along the monsoon trough. Enhanced cyclonic anomalies corresponded to the vigorous TC activity along the monsoon trough. Note that the monsoon westerlies did not strengthen with increased precipitation over Indochina, indicating that they were not responsible for the interannual variation in that region. In addition, the interannual variation in total precipitation during the rainy season over Indochina showed no statistical correlation with SSTs over the western North Pacific and Niño-3.4 regions, which indicates that SSTs in these regions did not control the heavy precipitation over Indochina.

The correspondence between the case study in 2011 and the 33-yr statistical analysis implies that the 2011 Thai flood and the occasional above-normal precipitation events were also explained by the same mechanism. Therefore, the frequent TCs along the monsoon trough were a major contributing factor to the heavy precipitation over Thailand in 2011. In addition, the interannual modulation of TCs along the monsoon trough controls the interannual variation in precipitation over the Southeast Asian monsoon region. The above-normal precipitation over Indochina due to the enhanced monsoon westerlies was not applicable to this region.

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