Climatological Characteristics of Tropical Cyclone Rainfall in Vietnam

(Tentative summary version)

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ABSTRACT

The tropical cyclones (TCs) are one of the most destructive atmospheric phenomena, bringing dangers such as disastrously heavy rainfall and flooding. Vietnam is one of the countries strongly affected by the TCs which are originated within the South China Sea (SCS) or coming from the western North Pacific (WNP). The features of rainfall associated with TCs have not been fully understood in Vietnam, as well as its role to the climatic variation.

The main objectives of this study which aims to explore are:

1. The climatological characteristics of the TC rainfall in Vietnam from 1961–2008.
2. Long-term trends in TC rainfall over Vietnam region from 1961–2008.
3. An insight view of TC-induced rainfall in Central Vietnam.

First, the characteristics of the climatological seasonal TC rainfall in Vietnam, including the amount, the TC rainfall ratio, and heavy rainfall events (TC_R50) were explored. The results show the distribution of TC rainfall, TC rain ratio, and the ratio of heavy rain days varies spatially and temporally. The TC rainfall amount in the central region is higher than that in other regions, with a peak in October–November. The northern region has maximum TC rainfall from July to September, whereas the total rainfall in the south is due mainly to non-TC rainfall. The TC rain ratio varies from 0 to ~25% with a maximum value occurring from 16° to 18°N in September. The northern region receives a maximum TC_R50 ratio value up to 20% from July to October, whereas the southern region receives a low TC_R50 ratio value throughout

the year. The maximum value of TC_R50 ratio occurs in September, October in the mid–central region. Distinct differences in El Niño and La Niña phases were found for both the TC rain ratio and TC_R50 ratio. During El Niño (La Niña) years, the TC rain ratio and TC_R50 ratio significantly decrease (increase) in October–November in the central region, particularly in the 15º to 17ºN region. The results also emphasize that the La Niña phases more strongly affect TC rainfall than the El Niño phases, particularly in central Vietnam.

Next, the long-term trends in TC rainfall in the whole Vietnam and four sub-regions, namely REG1 (north of 20ºN), REG2 (17º–20ºN), REG3 (12º–17ºN), and REG4 (south of 12ºN) were investigated for the years from 1961 through 2008. A significant increasing trend with 90% and 95% confidence levels of TC rainfall amount (TCRA) and TC heavy rainfall (TC_R50) is observed clearly at most stations in central coastline. For regional trends, little trends are detected in REG1, REG2, and REG4, while the significant increase is found in REG3 for both TC rainfall amount and TC heavy rainfall days. TCs formed in the WNP contributed more than TCs inside the SCS to that trend during the study period. A larger frequency of negative anomaly of TCRA and TC_R50 indices is seen in the mid-1970s and before 1982 in REG3. On the other hand, a larger frequency of positive anomaly of these indices is seen after 1983, in particular, during the 1990s with a peak in 1990. An increasing trend of heavy rainfall in the central-south Vietnam and a decreasing trend of that index in North Vietnam in the last half of the past century were found in the previous study. These results suggest that the cause of the increasing trend of heavy rainfall in the central–south Vietnam can be explained partly by TC rainfall, while the decreasing trend in north region is due to non-TC rainfall.

Finally, more detailed characteristics on the changes in TC rainfall and TC activity for the whole period 1961–2008 in the central part of Vietnam were explored. By applying a regime detection algorithm for TC rainfall, two change-points were found. The results show that TC rainfall including amount and heavy rainfall events increase significantly during the active period 1983–2000 in the central part of Vietnam. The differences in TC rainfall between ID2 (1983–2000) and two inactive periods ID1 (1961–1982) and ID3 (2001–2008) are compared. The results show that the increase in TC rainfall in the period 1983–2000 with the contribution of rainfall accumulated from TCs formed in the WNP in October. The increase of the TC frequency in the SCS/WNP led to an increase in TC rainfall in the period 1983–2000 in the central part of Vietnam. In comparison with the period 1961–1982, both sea surface temperature (SST) and atmospheric variables play a role in TC development in the SCS/WNP during the period 1983–2000. The reason caused an increase TC rainfall during this period not only the number of TCs affecting REG3 but also the number of TC landfall. In comparison with the period 2001–2008, the high of TC number affecting REG3 leading more TC rainfall during the period 1983–2000 is not caused by SST changes, while the role of other atmospheric factors are not very clear.

I. Introduction

The tropical cyclones (TCs) are one of the most destructive atmospheric phenomena, bringing dangers such as disastrously heavy rainfall and flooding. These effects can cause overtopping and erosion of dikes and sand dunes, and lead to saltwater intrusion of farmland with water masses destroying the crop. Understanding the effects of TCs or typhoons is the great interest in order to develop protection methods for preventing such damage. The damage caused by TCs has been recorded in many parts, in particular Asian-Pacific countries. In China, Zhang et al. (2009) pointed out about 4.5 billion U.S. dollars and 472 deaths were caused by landfalling TCs on average each year from 1983–2006. Luong et al. (2011) showed that 7% of deaths and 36% of destroyed and damaged houses in Vietnam over the period 1989–2010 were caused by storms.

The western North Pacific (WNP) and South China Sea (SCS) region is the most active TC basin in the world with an annual average of about 30 TCs, accounting for nearly one third of the global TCs activity. During the last decade, the activities of TCs over the WNP/SCS have received much attention of many scientists (e.g. Chan 1985, 2000; Dong 1988; Wang and Chan 2002; Liu and Chan 2008; Goh and Chan 2010). El Niño–Southern Oscillation (ENSO) is known as the most significant climate variation that affects interannual variability in TC activity over the WNP in many different ways. The interannual variation in TCs over the WNP was also found focusing on the relation with ENSO. Chen et al. (1998) noted that the frequency of TC formation increased (decreased) in El Niño (La Niña) years during summer season in the southern part of the WNP. Wang and Chan (2002) found while TC life became longer, TC tracks tended to curve northward during El Niño years.

In Southeast Asia, during the summer of an El Niño developing year, the number of TC making landfall increased, however, the number was significantly less than normal in September–November (Wu et al. 2004; Fudeyasu et al. 2006; Lyon and Camargo 2008). In addition, according to Zhan et al. (2011), the SST in the eastern Indian Ocean may also influence the TC genesis frequency over the WNP. The modulation of typhoon associated with ENSO found in the WNP was also reviewed in Kubota (2012). During El Niño, typhoon genesis location tended to shift southeastward, typhoons became more intense and had longer life span. In addition, the effect of the Madden-Julian Oscillation, the Quasi-Biennial Oscillation, and the Pacific-Japan pattern on the typhoon number in the WNP was also reviewed in his study.

Some recent studies have also investigated the interdecadal variation of TC activity (Matsuura et al. 2003; Ho et al. 2004; Yeh et al. 2010; Maue 2011; Liu and Chan 2012). For example, Matsuura et al. (2003) analyzed the interdecadal variability of TC over the WNP during the years 1951 to 1999, and found that there were two weakened periods (1951–1960 and 1973–1985), and two enhanced periods (1961–1972 and 1986–1994). They suggested that favorable condition for deep convections was detected during the high period. Yeh et al. (2010) displayed a decadal change in relationship between TC in the WNP and the tropical Pacific SST. They showed that SST and heat content factors played important roles in the period 1979–1989, while the keynote factors in the period 1990–2000 were the atmospheric conditions. Recently, Liu and Chan (2012) examined the interdecadal variation of the TC activity over the

WNP and found inactive TC activity after 1998. The reason for that was the strong vertical wind shear and strong subtropical high observed together apparently lead to unfavorable atmospheric conditions for TC genesis. However, according to Kubota (2012), one of the problems which caused many discrepancies in the previous studies about the interdecadal variability of TC activity over the WNP was TC datasets.

Rainfall associated with TC has a strong impact on environment and it can cause freshwater flooding disasters. Therefore, it is of great interest to understand how climate change could be affecting the rainfall from TCs. Over the last decade, the rainfall associated with TC (hereafter called TC rainfall) has received considerable attentions by many scientists in the world. For example, Rodgers et al. (2000) estimated monthly TC rainfall in the North Pacific using Special Sensor Microwave Imager (SSM/I) observations for an 11-yr period from 1987 to 1998 (few available data in 1990). They found that TCs contributed 12% of the climatological rainfall over the WNP from June to November.

Englehart and Douglas (2001) investigated the role of tropical storms over the eastern North Pacific in the rainfall climatology of western Mexico and showed that tropical storm-associated rainfall normally constitutes 20 to 60% of rainfall along the Mexico’s Pacific coast. In more extreme cases, they found that such rainfall could contribute as much as 25 to 30% to seasonal rainfall totals in western interior locations. Gleason (2006) estimated the characteristics of TC rainfall in the United States between 1950 and 2004. They found that coastal and near-coastal regions received 8 to 16% and 4 to 12% of the precipitation by TCs, respectively.

Ren et al. (2006) reported that the ratio of annual TC precipitation to total annual rainfall was 20 to 30% in most of Taiwan and along the coast of China south of 25ºN, using rain gauge data over China during 1971–2004. Kubota and Wang (2009) investigated the effect of TCs on seasonal and inter-annual rainfall variability over the WNP by analyzing rainfall data at 22 rain gauge stations. They showed that along 125ºE and between 18º and 26ºN, TC rain accounted for 50 to 60% of the total rainfall during the TC season from July to October. In addition, they described some characteristics of TC rainfall during the developing phases of El Niño and La Niña. They found in El Niño years little changes in autumn rainfall over the WNP islands. Recently, Sugino and Satomura (2010) mapped precipitation due to typhoons in the period 1998–2004 over Indochina, based on Tropical Rainfall Measuring Mission (TRMM)-3B42 data. They showed that the maximum precipitation occurred along the eastern coast of Indochina, with the precipitation amount over land decreasing as the distance from the coast increased.

Some more recent studies have also examined the variation of TC activity and rainfall-related TCs. Kim et al. (2006) examined the heavy rain associated with TCs landfalling in the Korean Peninsula during August–September from 1954 to 2005. They found that the average accumulated heavy rainfall at 12 stations across the Korean Peninsula in these two months increased significantly from the period 1954–1977 to the period 1978–2005. Takahashi and Yasunari (2008) reported a long-term decreasing trend in rainfall over Thailand in September, using daily rainfall from Thailand, Regional Specialized Meteorological Center (RSMC)-Tokyo and Joint Typhoon Warning Center (JTWC) TC tracks, and the 40-year Reanalysis dataset of the European Centre for Medium-Range Weather Forecasts from 1950−2000. They noted that September rainfall over Thailand was strongly influenced by TCs (including tropical depressions and residual lows) propagating westward from the SCS and the WNP to Indochina Peninsula and suggested that the weakening of TC activity over the Indochina Peninsula was probably a main factor in the statistically significant long term decrease in September rainfall over Thailand.

Ikema et al. (2010) studied the daily rainfall variation of Okinawa, south-eastern Japan, for 1982–2005 using a probability distribution function for each year. Their analysis revealed that the frequency of light (0-3 mm/day) and heavy (26-50 mm/day) rainfall events had a statistically significant decreasing trend, while extreme (>75 mm/day) rainfall events have been increasing. They found that such increases could be attributed to the increase in the rainfall amounts per typhoon, especially in September. They interpreted this as partially due to a slowing of the mean translation speed of typhoons near Okinawa in the latter half of the record. The study by Park et al. (2011) also found that TC-induced rainfall for TCs landfalling in Korea and Japan during June–October increased significantly from the decade 1977–1988 to the decade 1997–2008. Lee et al. (2012) depicted a decrease in the TC frequency in the SCS from 1961 to 2010 based on the best track data of four main weather agencies, but that trend was not statistically significant at 5% level for most datasets. They mentioned that large differences in datasets do not allow for detecting the long-term trend of TC intensity in the SCS.

Apart from the long-term trend of TC frequency, their results showed that no significant trend on the TC-induced extreme rainfall was found in Hong Kong area. Chang et al. (2012) showed the trends of TC rainfall and monsoon rainfall over the

China summer monsoon region from 1958 through 2010 have been distorted by WNP typhoons, which brought rainfall with decreasing frequency and increasing intensity.

Located along the east coast of the Indochina Peninsula with a substantial latitude extent from 8º to 22ºN in the north–western Pacific Ocean, Vietnam is one of the most disaster-prone countries in the world, in which TC is one of the factors causing frequent disasters in the country. According to Garcia (2002), Vietnam is struck by an average of four to six typhoons per year. They are originated within the SCS or coming from the WNP in general. Some previous studies have examined the variation of rainfall and TC activity, between rainfall and ENSO for Vietnam. Heavy rainfall has also received much attention by many researchers in Vietnam. Yokoi and Matsumoto (2008) pointed out the heavy rainfall event occurred in central part in early November 1999. They found that the coexistence of cold surge originating from North China and southerly wind anomaly over the central SCS associated with a tropical depression was important for the occurrence of that event. Takahashi et al. (2009) used a 30-year simulation for September from 1966 to 1995 and found a weakening TC activity over the region, which caused the observed long-term decrease in September rainfall along the eastern coast of Vietnam. Yen et al. (2011) analyzed the observational-based data in Vietnam and concluded that central Vietnam had more (less) rainfall in the La Niña (El Niño) years. Wu et al. (2011) analyzed a heavy rain event in northern part of Vietnam in October 2008 and showed that the Asian winter monsoon and tropical disturbances played major roles for that event.

The trend of rainfall in Vietnam was also noted in some previous studies (e.g. Manton et al. 2001; Endo et al. 2009). An increasing trend of heavy rainfall index in

Central Vietnam and a decreasing trend of that index in North Vietnam in the last half of the past century were noted in Endo et al. (2009). The reason for that trend was unknown. In addition, they did not mention the role of rainfall from TCs on that trend in these studies. Some Vietnamese scientists studied the variation of TC activity in the coastal regions during 1945–2007 (e.g. Vu et al. 2010). She found that the number of typhoon had the increasing trend in all regions, and the frequency of typhoon in El Niño years is lower than that in La Niña years.

From the climatological aspect, rainfall or heavy rainfall caused by the TCs has not been sufficiently explored in Vietnam. In fact, little has been known about the TC rainfall and its relationship with some large scale oscillations, as well as its variability in Vietnam. Therefore, the main objectives of this study which aims to investigate are:

1. The climatological characteristics of the TC rainfall in Vietnam from 1961–2008.
2. Long-term trends in TC rainfall over Vietnam region from 1961–2008.
3. An insight view of TC-induced rainfall in Central Vietnam.

The body of this dissertation consists of six sections. Chapters I and II describe the general information, data and methodology, respectively. Each main section (Chapters III to V) contains its objectives, results, and conclusions. Chapter III focuses on the climatological characteristics of the TC rainfall, including the amount, the TC rain ratio, and the ratio of heavy rainfall caused by TCs from 1961–2008 for the coastal region of Vietnam and its features in ENSO years. Chapter IV addresses the long-term trends in TC rainfall in the whole Vietnam and some sub-regions from 1961–2008. The main results in Chapters III and IV have been accepted in the journal papers as Nguyen et al. (2012) and Nguyen et al. (2013), respectively. Chapter V describes an insight view of TC rainfall in central Vietnam and the relationship of TC frequency with the SST and atmospheric variables. The final Chapter VI summarizes the major objectives, provides some discussions and conclusions. A complete list of references is included at the end of this dissertation.

II. Data and methodology

2.1. Datasets

The SCS is a part of the WNP, defined here as the ocean body between 0º and 25ºN and 100º and 120ºE (Goh and Chan 2010). TCs in the SCS are formed in two ways. Some originate within the region, while others enter from the WNP. To investigate TCs and associated rainfall in this region, two main data sources have been used: (1) TC best-track data from the UNISYS website (http://weather.unisys.com) provided through JTWC and (2) daily rainfall observed at 58 meteorological stations (Table 2.1) operated by the Vietnamese National Hydro-Meteorological Service (VNHMS). Figure 2.1 shows the location of these stations, in which 15 stations located along the coast indicated by red dots are used in Chapters III. TCs are defined from the stage of tropical depression and tracked until they are downgraded again to the tropical depression stage (Kubota and Wang 2009).

The reason to choose UNISYS over different available best track datasets such as RSMC-Tokyo, International Best Track Archive for Climate Stewardship (IBTrACS) and the Shanghai Typhoon Institute (STI) is simply based on our familiarity with the data. Song et al. (2010) mentioned that differences in TC tracks among these data sets are negligibly small, while TC intensities could be relatively different. Therefore, which best track data sets to use is not a challenging problem because only TC tracks information is required in this study.

TC best-track and daily rainfall data are selected for the same period (1961–2008) and information on ENSO years is obtained from Kubota and Wang (2009) (Table 2.2). The ENSO monthly SST anomalies used in this study were obtained from the Niño 3.4 region (5°N–5°S, 170–120°W) from NOAA's Climate Prediction Center. In addition, the following data are also used: NCEP/NCAR Reanalysis1 (Kalnay et al. 1996) and the extended reconstruction sea surface temperature (SST) produced by the National Climatic Data Center (Smith et al. 2008). From the horizontal wind fields, the vertical wind shear (VWS) is defined by the formula: $\sqrt{(U200-U850)^2+(V200-V850)^2}$, where U, V and number show zonal wind, meridional wind, and pressure level, respectively.

2.2. Methodology

2.2.1. Definition of TC rainfall

Previous study used different distances from the TC center to define TC-induced rainfall. Englehart and Douglas (2001) found that in 90% of cases over western Mexico, TC rainfall occurs within 550-600 km from the center of the TC. Gleason (2006) estimated the characteristics of TC rainfall in the United States based on a simple partition method to consider rainfall associated with TCs. He treated any rainfall less than or equal to 600 km from the center of the storm as TC rainfall. Kubota and Wang (2009) assumed that the daily rainfall as a function of the distance between the TC center and stations and TC-induced rainfall could be estimated from station data when a TC was located within the radius of influence (1000 km). Hattori et al. (2010) showed the contribution of TCs to the seasonal change patterns of rainfall in the WNP, based on the Japanese long-term reanalysis/JMA Climate Data Assimilation System (JRA-25/JCDAS) dataset (Onogi et al. 2007). In their study, TC rainfall was defined as the rainfall within 500 km of the center of the TC. This distance was also applied in Ren et al. (2006) to explore the change in TC precipitation in China.

To estimate the TC rainfall, this study also adopted the conception of an effective radius for the definition of TC rainfall (same as in Kubota and Wang 2009). In Figure 2.2, the distribution of daily TC rainfall (DR) is indicated by the black solid line. DR is averaged over 15 meteorological stations which are shown by the red dots in Figure 2.1 from the TC center to a 1000 km radius. Thus, there are 48 DR datasets corresponding to 48 years from 1961 to 2008 for each distance binned into 100-km intervals. The red curve is DR fitted by the third-order polynomial function, while the straight blue line is DR mean at the different distances for the whole 48-year period. The rainfall showed a maximum of 87mm/day within a radius of 100km, it decreased rapidly with the distance away from TC center. DR mean and the fitted curve seem to change little when the distance is greater than 600 km. Thus, it was reasonable for us to choose the distance of 600 km from the TC center to the station to identify TC rainfall in this study. The individual TC rainfall values were summed for each month at selected stations. The non-TC rainfall was defined as the difference between the total rainfall and the TC rainfall, while the TC rain ratio was defined as the TC rainfall divided by the total rainfall. In addition, heavy rainfall events caused by TCs were defined as days in which the daily rainfall amount exceeded 50 mm/day (TC_R50). In fact, 50 mm/day is the heavy rainfall threshold currently used by the forecasters of the National Center for Hydro-Meteorological Forecasting of Vietnam, similar to the criteria of the central Weather Bureau of Taiwan (Chen et al. 2007). TC_R50 ratio was defined as TC_R50 divided by the total heavy rainfall days (the sum of TC_R50 and non TC_R50). Finally, the TC frequency was defined as the number of TCs that approached the station within the 600 km distance from the TC center.

In Chapter IV, eight TC rainfall indices described in Table 4.1 were calculated for each station for annual timescale. In order to explore the role of TCs formed in the SCS/WNP on the trends of some indices, TC rainfall amount (TCRA) and TC_R50 were calculated separately for each station and each basin. To obtain the regional indices, the annual indices were averaged over the meteorological stations in each of sub-regions.

2.2.2. Statistical analysis

The bootstrapping technique detailed by Efron and Tibshirani (1993) was applied to estimate anomalies during El Niño and La Niña years (Chapter III). The confidence intervals for bootstrap estimates were obtained using the percentile method (at 90% confidence level). The significance of the trend was calculated by using the non-parametric Mann-Kendall method and the slope of trends were estimated by applying Sen’s estimator (Hirsch et al. 1982; Helsel and Hirsch 2002). The statistical significance levels at 90% and 95% were used for the trend analysis in Chapter IV. In addition, a two-sample Student’s t-test (Snedecor and Cochran 1989) was applied to find the significance of the different mean value between the two periods in Chapter V.

2.2.3. Regime shift detection

To detect the regime shifts of TC rainfall, the regime detection algorithm developed by Rodionov (2004) was applied in Chapter V. This method can identify significant change in the sequential running means with a certain cut-off length based on the Student’s t-test. A regime is detected if the difference in the two means is significant at a fixed confidence level.

III. A climatological study of tropical cyclone rainfall in Vietnam

3.1. Objectives

This part aims to explore the characteristics of the climatological seasonal TC rainfall in Vietnam, including the amount, the TC rainfall ratio, and heavy rainfall events. Apart from that, the differences in these parameters also are investigated during ENSO years for the coastal region of Vietnam.

3.2. Results

3.2.1. Climatological seasonality of TC rainfall

a. TC rainfall amount

Figure 3.1 shows the mean distribution of TC rainfall, non-TC rainfall, and total rainfall amounts for each month at eight selected stations in three Vietnam coastal regions: north, central, and south. At most stations, TC rainfall is zero from December to May. In the northern part of Vietnam (from 20ºN northward), the maximum TC rainfall occurs from July to September. In the central region (approximately from 12º to 20ºN), the stations (including the ones not shown in Figure 3.1) have two total rainfall peaks. The first peak, which occurs in May, coincides with the active south–west monsoon period in the region. The second highest peak total rainfall appears in October–November, coinciding with the TC rainfall peak. In the central region, the non-TC rainfall amount contributes significantly to the total rainfall. This suggests that in addition to TC activity, other weather systems such as inter-tropical convergence zone (ITCZ) displacement, boreal summer and winter monsoon play an important role in this region (e.g. Chen et al. 2012, Yokoi and Matsumoto 2008). For the mid–central region (located between 15º and 17ºN), Hue is the most typical station and has the highest TC rainfall (152 mm) in October among all analyzed stations in Vietnam. This result for the TC rainfall amount in the central region is close to the satellite data analyses by Jiang and Zipser (2010). However, in the southern part (from 12ºN southward), the total rainfall is due mostly to non-TC rainfall. This region has both the minimum TC rainfall and minimum total rainfall in all of Vietnam. There, the rainy season coincides with the southwest monsoon season from May to October.

b. TC rain ratio and TC_R50 ratio

The time-latitude sections of the monthly mean TC frequency and TC rain ratio are presented in Figures 3.2a and 3.2b. The distribution of these factors is different from region to region and month to month. As indicated in Figure 3.2a, the TC season starts from May–June. High TC frequency occurs in the central region from September to November, with a peak in October. From Figure 3.2b it can be seen that TC rain ratio contributes from 0 to 25%, with the highest value found in the region of 16º to 18ºN in September. At three stations located in the mid–central region, the TC frequency reaches the maximum value in October, but the TC rain ratio in October is smaller than that in September because the total rainfall in October becomes maximum (Figure 3.1). From 18ºN northward, even though the TC frequency has a maximum value in September, the maximum TC rain ratio shifts to July, while the stations located south of 16ºN have maximum ratios in November. In addition, the TC rain ratio south of 16ºN reaches a maximum value in November due to both the high TC frequency and the low total rainfall.

Heavy rainfall events that can cause flooding and extensive damage, occur frequently during the rainy season in central Vietnam (Yokoi and Matsumoto 2008). To what extent do TCs contribute to these events? Figure 3.2c shows the time-latitude section of the monthly mean TC_R50 ratio. The value of TC_R50 ratio varies from north to south along the coastal line. TC_R50 ratio starts to increase in May, becoming greater during July–November. The northern region receives a maximum TC_R50 ratio value up to 20% from July to October, whereas the southern region receives a low TC_R50 ratio value throughout the year. The maximum value of TC_R50 ratio occurs in September, October in the mid–central region. This area also has the highest TC frequency (Figure 3.2a) in the same period. Hence, TCs play an important role both in rainfall and heavy rainfall events in that region.

During the TC season in Vietnam (from June to December, not shown), the mid–central region receives the maximum TC frequency (six cases), TC rain ratio (~26%), and TC_R50 ratio (~26%). These values decrease northward and southward along the Vietnamese coast.

3.2.2. Linkages with ENSO years

The association between ENSO and TC activity over the SCS/WNP is well documented. Wang and Chan (2002) noted that the interannual variability of TC formation in the WNP is strongly affected by ENSO phases. Goh and Chan (2010) showed that the total number of TCs entering the SCS from the WNP is below normal during El Niño events but above normal during La Niña events. Kubota and Wang (2009) also reported that the seasonal TC rain ratio differs between El Niño and La Niña years.

In order to study the linkages of TC rainfall with ENSO years, the bootstrapping technique detailed by Efron and Tibshirani (1993) was applied. In this study, 1000 bootstrap replication of size $n_{\text{ElNiño}}=18$ and $n_{\text{LaNinña}}=13$ were generated to estimate anomalies during El Niño and La Niña years, respectively.

In Figures 3.3 and 3.4, we examined the anomalies of TC frequency, TC rain ratio, and TC_R50 ratio during El Niño and La Niña years, respectively. The contour shows the mean bootstrap value of the anomalies while color shading shows areas where the anomaly is positively (negatively) significant at the 90% confidence level.

Figure 3.3a (Figure 3.4a) shows that during El Niño (La Niña) years, TCs are significantly less (more) frequent than the climatology in October and November across all regions, which is in agreement with previous studies (Goh and Chan 2010; Wu et al. 2004). The decrease (increase) in TC frequency leads to a significant decrease (increase) of up to 20% in the TC rain ratio in October and November from 13ºN northward (Figures 3.3b and 3.4b). During El Niño years, a significantly positive TC rain ratio anomaly appears in the mid–central region in September while negative TC rain ratio anomalies appear in July. Similar to TC rain ratio, an increase in TC_R50 ratio also occurs in mid–central region in September (Figure 3.3c). Significant negative (positive) TC_R50 ratio values are also found in the central region during late autumn in El Niño (La Niña) years (Figures 3.3c and 3.4c).

Compared to the TC season (June to December) total distribution (not shown), less (more) TC frequency can be seen in all the coastal regions in Vietnam during El Niño (La Niña) years. The TC rain ratio and TC_R50 ratio also decreases (increases) during El Niño (La Niña) years, except at stations located in the northern region. Anomalies in the TC rain ratio and TC_R50 ratio in La Niña years are higher than those in El Niño years in the central region. The La Niña phases strongly affect TC rainfall, particularly in central Vietnam.

3.3. Conclusions

By analyzing the TC best-track data from the UNISYS website archive and the daily rainfall data from 15 meteorological stations in the period 1961–2008, we explored the role of TCs in the rainfall climatology of the Vietnam coastal region. The distribution of TC rainfall, TC rain ratio, and the ratio of heavy rain days varies spatially and temporally. The TC rainfall amount in the central region is higher than that in other regions, with a peak in October–November. The northern region has maximum TC rainfall from July to September, whereas the total rainfall in the south is due mainly to non-TC rainfall. The TC rain ratio varies from 0 to ~25% with a maximum value occurring from 16º to 18ºN in September. The mid–central region of Vietnam receives the maximum TC_R50 ratio in September–October and also has the highest TC frequency in the same period.

Distinct differences in El Niño and La Niña phases were found for both the TC rain ratio and TC_R50 ratio. During El Niño (La Niña) years, the TC rain ratio and TC_R50 ratio significantly decrease (increase) in October–November in the central region, particularly in the 15º to 17ºN region. Our results also emphasize that the La Niña phases more strongly affect TC rainfall than the El Niño phases, particularly in Central Vietnam.

This study has not addressed the long-term change in TC-induced rainfall and changes in the atmospheric circulation forced by ENSO events. Further studies are needed to investigate these problems, to identify variations in TC rainfall, and to explain the differences between ENSO phases described here.

IV. Long-term trends in tropical cyclone rainfall inVietnam

4.1. Objectives

As noted in Chapter I, the contrastive long-term trend of heavy rainfall occurrences in north and south regions was explored in Endo et al. (2009). And the role of heavy rainfall accumulated from TCs to that features has not been fully understood. Therefore, this part aims to indentify the long-term trends in TC rainfall from 1961 to 2008 in the whole and some sub-regions of Vietnam.

4.2. Results

4.2.1. Temporal trends in TC rainfall in whole region

Figure 4.1 shows the temporal trends of annual TC rainfall amount (TCRA) and TC heavy rainfall days (TC_R50) over the whole Vietnam for the 48 years period using the non-parametric Mann-Kendall test. For the contribution of TCs to the annual rainfall (TCRA), most of the stations located along the coastline show the increasing trend, but only 6 out of 58 stations have significant increasing trend in mid- and south-central area (Figure. 4.1a). Over much of north–Vietnam and south there is little change in TCRA with some areas showing increasing or decreasing trend (not significant at the 90% and 95% levels). For TC_R50, the positive significant trend at 90% and 95% confidence levels of some stations is also found in the same region with TCRA, but no trend is detected at all stations in the south of 12ºN and in the north of 20ºN (Figure. 4.1 b).

4.2.2. Temporal trends in TC rainfall in four sub-regions

Four sub-regions namely REG1, REG2, REG3, and REG4 are defined as the location of the stations in the north of 20ºN, 17º–20ºN, 12º–17ºN, and south of 12ºN, respectively (Figure 4.3). The regional definition is based on the similarity of TC rainfall climatology and the trend of that (as shown in Figures. 4.1 and 4.2).

Table 4.2 shows the annual trends of the eight rainfall indices for four sub-regions: REG1, REG2, REG3, and REG4 at 90% and 95% confidence levels. The indices that do not show any significant trends are rainfall and heavy rainfall accumulated form TCs formed in the SCS (TCRA_SCS and TC_R50_SCS), while rainfall derived from TCs formed in the WNP (TCRA_WNP) has increased significantly in REG3 and REG4 (1.62 mm/year and 0.16 mm/year, respectively). REG1 is the region which received the significant negative trend for non-TC rainfall indices with slope trend of 5.1 mm/year and 0.05 days/year for non-TCRA and non-TC_R50 indices, respectively. Figures 4.4a and 4.4b show the annual time series anomalies of non-TCRA and non-TC_R50 in REG1; the linear trends show a significant decrease during 1961–2008. TCRA in REG1 also shows an increase with slope trend about 0.64 mm/year but not significant. REG2 does not show any significant trend in all indices. REG3 is the region with the largest number of significant positive trends for both TC rainfall and non-TC rainfall. To complement these results of TC rainfall, Figures 4.5a and 4.5b show the time series of TCRA and TC_R50 anomaly in REG3 during the 1961–2008 period; the significant increase of these indices are indicated by linear trends. There is a significant positive correlation between TCRA and TC_R50 (r=0.98, approximately) at 95% confidence level. It means that the increase of TC rainfall amount is mainly contributed from heavy rainfall days caused by TCs in REG3.

Table 4.2 also shows that rainfall coming from the contribution of TCs formed inside the SCS does not show any trend, while a significant increasing trend is found with the contribution of TCs entering the SCS in this region. Since TCRA_SCS/TC_WNP is one component of TCRA (similar with TC_R50), overall, it can be concluded that TCs formed in the WNP contributed more than TCs inside the SCS to that trend during the study period. Endo et al. (2009) noted that the contrastive long-term trend of heavy rainfall occurrences in Vietnam with the decrease (increase) occurs in the north (south) regions (similar to the location of REG1 and REG3). However, they did not separate the trend of TC rainfall from non-TC rainfall and the reason for that feature was unknown. These results suggest that the cause of the increasing trend in REG3 can be explained partly by TC rainfall, while the decreasing trend in REG1 is due to non-TC rainfall. A larger frequency of negative anomaly of TCRA and TC_R50 indices is seen in the mid-1970s and before 1982 in REG3. On the other hand, a larger frequency of positive anomaly of those indices is seen after 1983, in particular, during the 1990s decade with a peak in 1990. As documented by Goh and Chan (2010), the number of TCs entering and formed in the SCS during the warm Pacific Decadal Oscillation (PDO) and El Niño phase tends to be below normal and above normal during the negative PDO and La Niña phases.

According to Yen et al. (2011), Central Vietnam has more (less) rainfall (TC rainfall and non-TC rainfall) in La Niña (El Niño) years. As a result in Chapter III, during El Niño (La Niña) years, TC rainfall and TC_R50 significantly decrease (increase) in October–November in the central region. The results suggest that non-TC rainfall in this region has also a correlation with ENSO. ENSO monthly SST anomalies obtained from the Niño 3.4 region are averaged for October and November to find relationship between rainfall indices and ENSO for Central region (REG3). The correlation coefficient of rainfall indices in REG3 and ENSO 3.4 from 1961 to 2008 is explored in Table 4.3. The coefficient is shown in bold and one asterisk indicates statistical significance at the 95% level. Negative significant correlation was found for TCRA, TC_R50, and non-TCRA. This result shows that not only TC rainfall but also non-TC rainfall in Central Vietnam has a negative relationship with ENSO.

Leung et al. (2005) and Goh and Chan (2010) indicated that the decline of TC activity in the SCS is likely due to the decrease of TCs entering the SCS from the WNP, in particular after the mid-1990s. The increase of TC rainfall in REG3 during the period 1983-2000 could be directly linked to the changes in TC characteristics in not only frequency but also tracks and intensity. The variability of TC rainfall during this period should be addressed in the next study.

4.3. Conclusions

The long-term trends in TC rainfall was investigated in the whole Vietnam and four sub-regions, namely REG1 (north of 20ºN), REG2 (17º–20ºN), REG3 (12º–17ºN), and REG4 (south of 12ºN) using the TCs best-track data provided through JTWC and daily rainfall records at 58 meteorological stations observed by Vietnamese National Hydro-Meteorological Service for the years from 1961 through 2008. A significant increasing trend with 90% and 95% confidence levels of TC rainfall amount (TCRA) and TC heavy rainfall days (TC_R50) indices is observed clearly at most stations in central coastline during the study period. For regional trends, little significant trends are detected in REG1, REG2, and REG4, while the significant increase is found in REG3 for both of TCRA and TC_R50. The increase of TC rainfall amount is mainly contributed from heavy rainfall days caused by TCs in REG3. The contrastive long-term trend of heavy rainfall occurrences in REG1 and REG3 was noted in Endo et al. (2009). These results suggest that the cause of the increasing trend of heavy rainfall in

REG3 can be explained partly by TC rainfall, while the decreasing trend in REG1 is due to non-TC rainfall. A larger frequency of positive anomaly of TCRA/TC_R50 is seen during the period 1983–2000 in the mid– and south–central regions in Vietnam.

V. An insight view of the tropical cyclone-induced rainfall in Central Vietnam

5.1. Objectives

As pointed out in Chapter IV, a larger frequency of positive anomaly of TC rainfall including amount and heavy rainfall events was seen after 1983, in particular, during the 1990s decade in Central part of Vietnam. A regime detection algorithm was applied to find the active (inactive) periods in TC rainfall for this region. The main objective of this chapter continues to explore more detailed characteristics on the change in TC rainfall and TC activity in the whole period 1961–2008. Aside from that, we address the differences in oceanic factor and atmospheric variables for both the active (inactive) periods in TC activity.

5.2. Results

5.2.1. Change in rainfall and tropical cyclone activity in Central Vietnam

In this chapter, Central Vietnam is defined as the region located from 12ºN to 17ºN (REG3). Figure 5.1 shows map of six meteorological stations located along the coast line in this region (blue stars) and the locations of tropical cyclone centers (red dots) every 6 hours during 1961–2008. TC rainfall including TC rainfall amount (TCRA) and heavy rainfall days (TC_R50), and TC frequency of six meteorological stations are calculated with the same method in Chapter II. Minute results are omitted in this tentative version.

VI. Discussions and conclusions

This chapter provides some discussions, and conclusions of this dissertation.

6.1. Discussions

In Chapter III, climatological seasonal march of TC approaching frequency, rainfall amount and ratio related to TC, and frequency of heavy rainfall events related to TC over Vietnam, and interannual variability of these statistics related to ENSO are described. The distribution of TC rainfall amount, TC rain ratio, and the ratio of heavy rainfall events varies spatially and temporally. The results showed that the mid–central region receives the highest TC rainfall and also has the highest TC frequency. Meanwhile, the seasonality of total rainfall in the south of 12ºN region is mainly determined by non-TC rainfall. These results are close with the findings of Rodgers et al. (2000) and Jiang and Zipser (2010). However, in their studies, the contribution of heavy rainfall from TCs has not been mentioned. In the present study, Hue station located near 16ºN has the highest TC rainfall (152 mm) in October. This result in the present study is greater than that in Jiang and Zipser (2010) (Figures 3.1 and 6.1). Rodgers et al. (2000) estimated TC rainfall in the North Pacific using SSM/I observations and found that Central Vietnam received significant TC rain ratio (over 20%). When compared with Figures 3.2c and 6.2 of Rodgers et al. (2000), it seems that the value in the present study is lower than that found in Rodgers et al. (2000), although maximum value was found up to 25%. These discrepancies may be related to the difference in the study periods. As pointed out by Liu and Chan (2012), the period from 1998 to 2006 selected by Jiang and Zipser (2010) is considered as the inactive period of TC activity in the WNP. Meanwhile, Rodgers et al. (2000) selected an 11-yr period from 1987 to 1998 (few available data in 1990) for their study. This period is pointed out as the active period of TC activity by Liu and Chan (2012) and Nguyen et al. (2013). The different results also may be related to the different method in the present study and their studies.

As mentioned above, ENSO is the strongest interannual climate phenomenon on a global scale. In this chapter, the distinct differences for both the TC rain ratio and TC_R50 ratio are found in El Niño and La Niña phases. During El Niño (La Niña) years, the TC rain ratio and TC_R50 ratio significantly decrease (increase) in October–November in the central region, particularly in the 15º to 17ºN region. The TC rain ratio is shown with a significant increase of up to 20% in October and November (Figure 3.4b) in La Niña years. The impact of ENSO on the TC rainfall in the WNP was also noted in some previous studies. Kubota and Wang (2009) found that the interannual variability of the TC rainfall is primarily modulated by ENSO. Rodgers et al. (2000) noticed that TC rainfall is increased during El Niño years. In general, their result was consistent with Jiang and Zipser (2010) but with some differences were found, such as in the SCS and Gulf of Mexico. One of the reasons causing these differences in the present study and their studies may be due to the difference in the number of study years as discussed above and the used datasets. Further studies are needed to improve understanding of the causing the difference of TC rainfall between ENSO phases in this region.

In Chapter IV, we investigated the long-term trends in TC rainfall in the whole Vietnam and four sub-regions, namely REG1 (north of 20ºN), REG2 (17º–20ºN), REG3 (12º–17ºN), and REG4 (south of 12ºN) for the 48-year period from 1961 through 2008. Endo et al. (2009) examined that the contrastive long-term trend of heavy rainfall occurrences in Vietnam with the decrease (increase) occurs in the north (south) regions (similar to the location of REG1 and REG3); the reason for that feature has not been mentioned. Moreover, they did not separate the trend of TC rainfall and non-TC rainfall. In the present study, TC rainfall shows an increase in all sub-regions in Vietnam over the past 48 years with a significant increasing trend found in REG3 (Table 4.2). This result is consistent with Vu et al. (2010), who found that the number of TCs in all regions in Vietnam had the increasing trend. A significant decrease (increase) of non-TC rainfall is also found in REG1 (REG3). Although, there is no significant trend in TC rainfall for annual scale in the north and south regions over the last few decades, it should be noted that for the seasonal trend, as well as the exact cause of the decreasing (increasing) trend of non-TC rainfall in these regions are found. In Central Vietnam, a significant correlation was found for TCRA, TC_R50, and non-TCRA with ENSO3.4. This result shows that not only TC rainfall but also non-TC rainfall in this region has a negative relationship with ENSO, except non-TC_R50. From the results of long-term trend in TC rainfall and non-TC rainfall in REG3, it is confirmed again that La Niña phases more strongly affect rainfall in Central region than the El Niño phases.

In Chapter V, we investigated the detailed change in rainfall amount and heavy rainfall events related with TC for the period ID2 (1983–2000) in the central part of Vietnam (REG3).

Chen et al. (2012) also found that the increase in southern China summer rainfall around 1993 was accompanied by an increase in TCs that were formed in the SCS. This feature identified by their study may be related to the increase of TCs found in this study. They also concluded that the reason for the increase in TCs in the SCS may be attributable to an increase in local SST. The different results between the present study and the previous study may be related with the method. Since the present study only examined the change of the oceanic and atmospheric factors only for October, while three months June–July–August were selected in Chen et al. (2012).

The frequency of TCs formed in the SCS (the short dashed line), TCs formed in the WNP (the dashed line), and total TCs (the solid line) that bring rainfall to the central part of Vietnam from 1961 to 2008 were displayed in Figure 6.3. During the period 1990–2000, the number of TC_SCS increased (decreased) after 1995. In contract with the TC_SCS, the number of TC formed in the WNP decreased (increased) at the same time. In order to look at the change of TC frequency and TC rainfall before/after 1995 for the two sub-periods 1990–1995 and 1996–2000, Figures 6.4 and 6.5 are created. It is interesting to see that the changes of those around 1995 with the high values of TC rainfall accumulated from TCs formed in the WNP occurred in the 1990–1995 period, on the other hand, the low values occurring in the 1996–2000 period for TC rainfall accumulated from TCs formed in the SCS. The characteristic of the change of TC rainfall and TC frequency in these two sub-periods also should be explored in further studies.

6.2. Conclusions

In the present study, we firstly explored the characteristics of the climatological seasonal TC rainfall in Vietnam including the amount, the TC rainfall ratio, and heavy rainfall events (TC_R50) for the years from 1961 through 2008. The relationship of ENSO with TC rainfall was also detected.

Next, we investigated the long-term trends in TC rainfall in the whole Vietnam and four sub-regions: REG1 (north of 20ºN), REG2 (17º–20ºN), REG3 (12º–17ºN), and REG4 (south of 12ºN) for the 48-year period.

Finally, we examined the detailed characteristics on the change in TC rainfall and TC activity for the whole period 1961–2008 in the central part of Vietnam. A regime detection algorithm was applied to find the active (inactive) periods in TC rainfall for this region. Aside from that, we addressed the differences in oceanic factor and atmospheric variables for both the active (inactive) periods in TC activity.

By analyzing two main data sources, TC best-track provided through the Joint Typhoon Warning Center and daily rainfall observed at 58 meteorological stations operated by the Vietnamese National Hydro-Meteorological Service, the main results of the present study are as follows:

1. The TC rainfall amount in the central region is higher than that in other regions, with a peak in October–November. The northern region has maximum TC rainfall from July to September, whereas the total rainfall in the south is due mainly to non-TC rainfall.
2. The TC rain ratio varies from 0 to ~25% with a maximum value occurring from 16º to 18ºN in September. The northern region receives a maximum TC_R50 ratio value up to 20% from July to October, whereas the southern region receives a low TC_R50 ratio value

throughout the year. The maximum value of TC_R50 ratio occurs in September, October in the mid–central region.

3. During El Niño (La Niña) years, the TC rain ratio and TC_R50 ratio significantly decrease (increase) in October–November in the central region, particularly in the 15° to 17°N region. The results emphasize that the La Niña phases more strongly affect TC rainfall than the El Niño phases, particularly in central Vietnam.
4. A significant increasing trend with 90% and 95% confidence levels of TC rainfall amount (TCRA) and TC_R50 is observed clearly at most stations in central coastline.
5. For regional trends, little trends are detected in REG1, REG2, and REG4, while a significant increase is found in REG3 for both of TCRA and TC_R50. The increase of TCRA is mainly contributed from TC_R50 caused by TCs in REG3. TCs formed in the WNP contributed more than TCs formed inside the SCS to the increasing trend in REG3.
6. A larger frequency of negative anomaly of TCRA and TC_R50 is seen in the mid-1970s and before 1983 in REG3, on the other hand, a large frequency of positive anomaly of those indices is seen after 1983, in particular, during the 1990s with a peak in 1990.
7. The results suggest that the cause of the increasing trend of heavy rainfall in the central–south Vietnam can be explained partly by TC

rainfall. The decreasing trend of that in north region is due to non-TC rainfall.

8. The increase in TC rainfall in the period 1983–2000 in REG3 is accompanied with the contribution of rainfall accumulated from TCs formed in the WNP in October. A possible reason for that feature is the number of TCs affecting and the number of TCs landfall this region has increased.
9. In comparison with the period 1961–1982, the results suggest that both sea surface temperature and atmospheric variables play a role in TC development in the SCS/WNP leading to an increase of TC rainfall during the period 1983–2000.

The interactions of TCs with other synoptic or sub-synoptic systems also can induce heavy rainfall, however, we have not mentioned them in this study. Further studies are needed to investigate such interactions for all sub-regions in Vietnam.

The findings of the present study can provide important knowledge on the spatial and temporal distribution of rainfall from tropical cyclones over Vietnam. This study also shows that ENSO is strongly related with TC rainfall, in particular, heavy rainfall in the central part of Vietnam. However, to have greater understanding, further studies should also be performed and compared with other data types, such as RSMC Tokyo-Typhoon Center, IBTrACS, because the present study only used the station data and TC best-track by JWTC.

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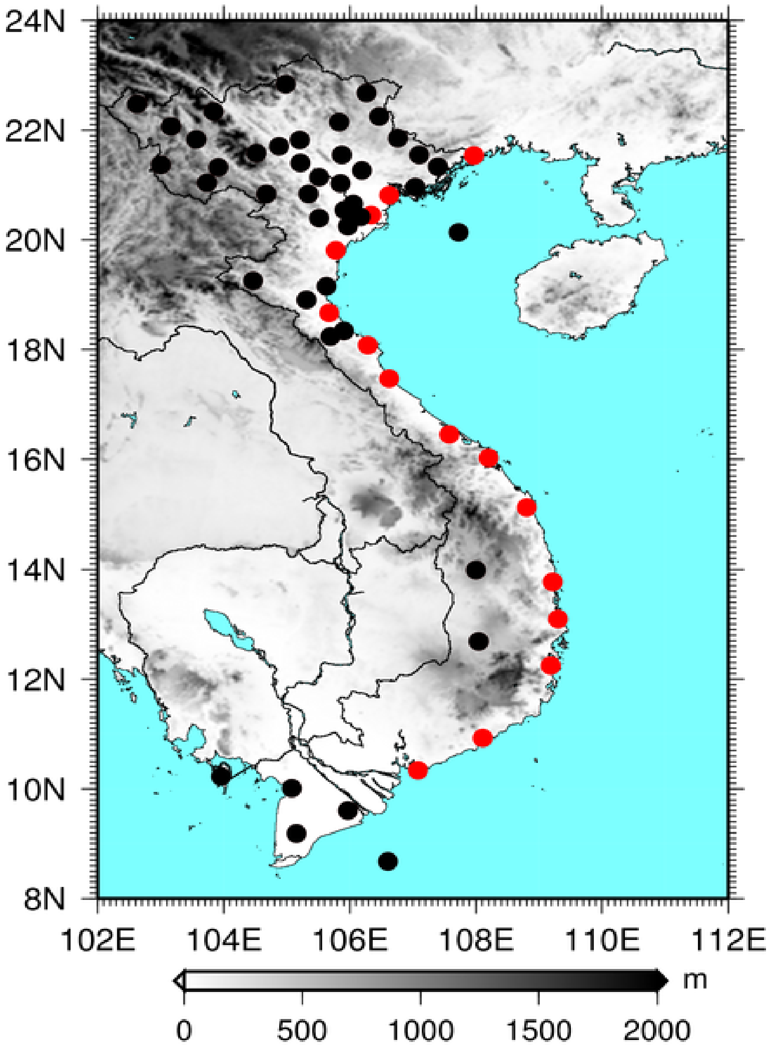


Figure 2.1. Locations of 58 selected meteorological stations in Vietnam used in this study. The red dots show the locations of 15 meteorological stations used in Chapter III.

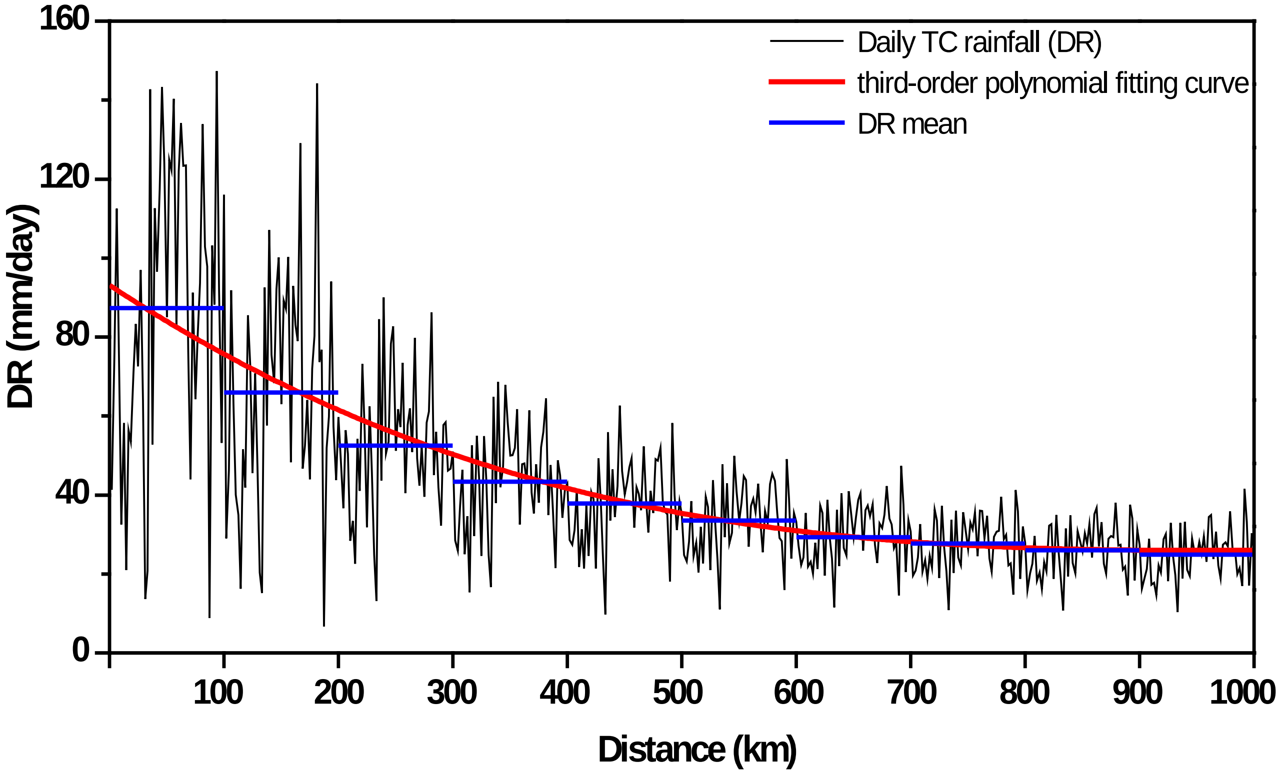


Figure 2.2. The distribution of daily TC rainfall (DR) averaged from 15 meteorological stations which are shown by the red dots in Figure 2.1 from TC center to a 1000 km radius (the black solid line). There are 48 DR datasets corresponding to 48 years (1961–2008) for each distance binned into 100-km intervals. The red curve is DR fitted by the third-order polynomial function, while the straight blue line is DR mean at the different distances for the whole 48-year period.

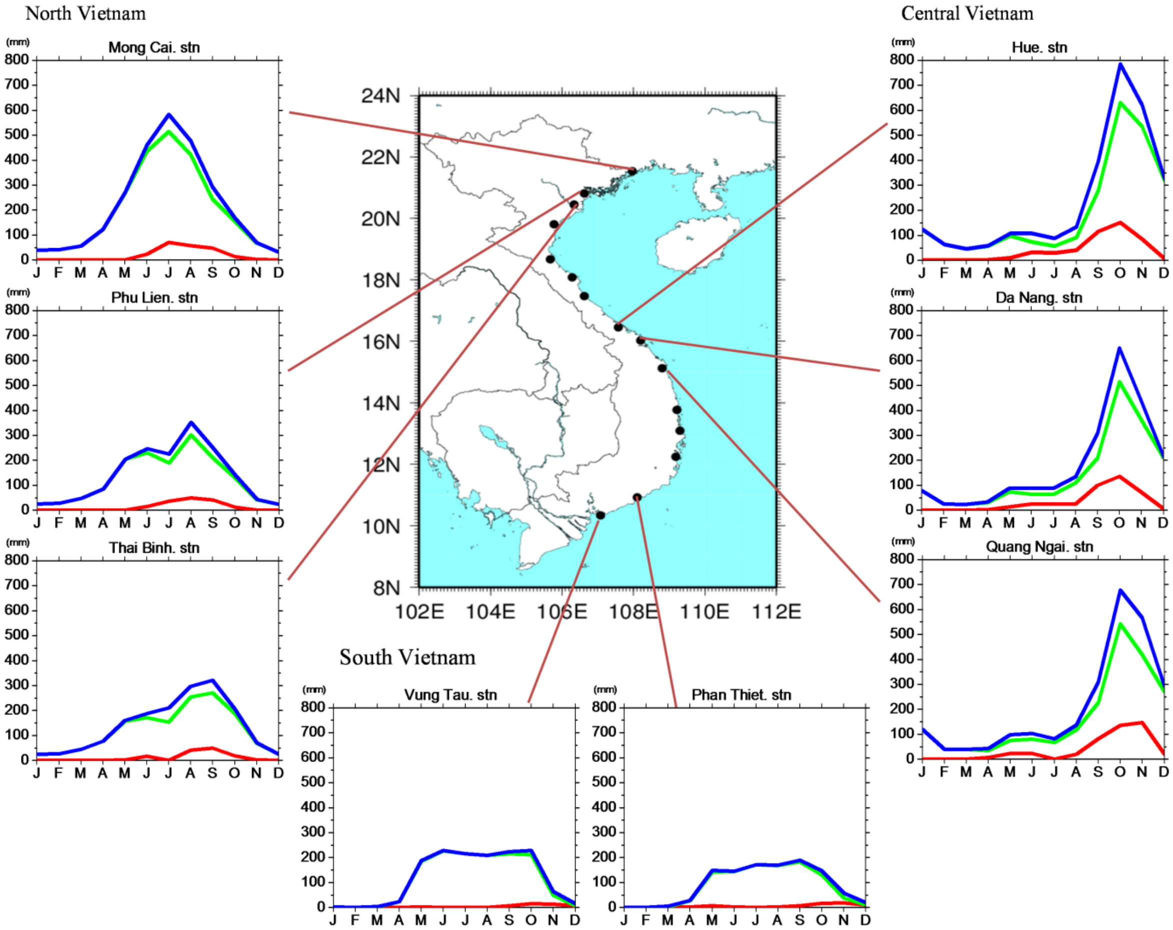


Figure 3.1. Monthly climatological distribution of the total rainfall (blue), TC rainfall (red), and non-TC rainfall (green) of eight weather stations located in three Vietnam coastal regions (units are in mm). The dots show the locations of the stations used in Chapter III.

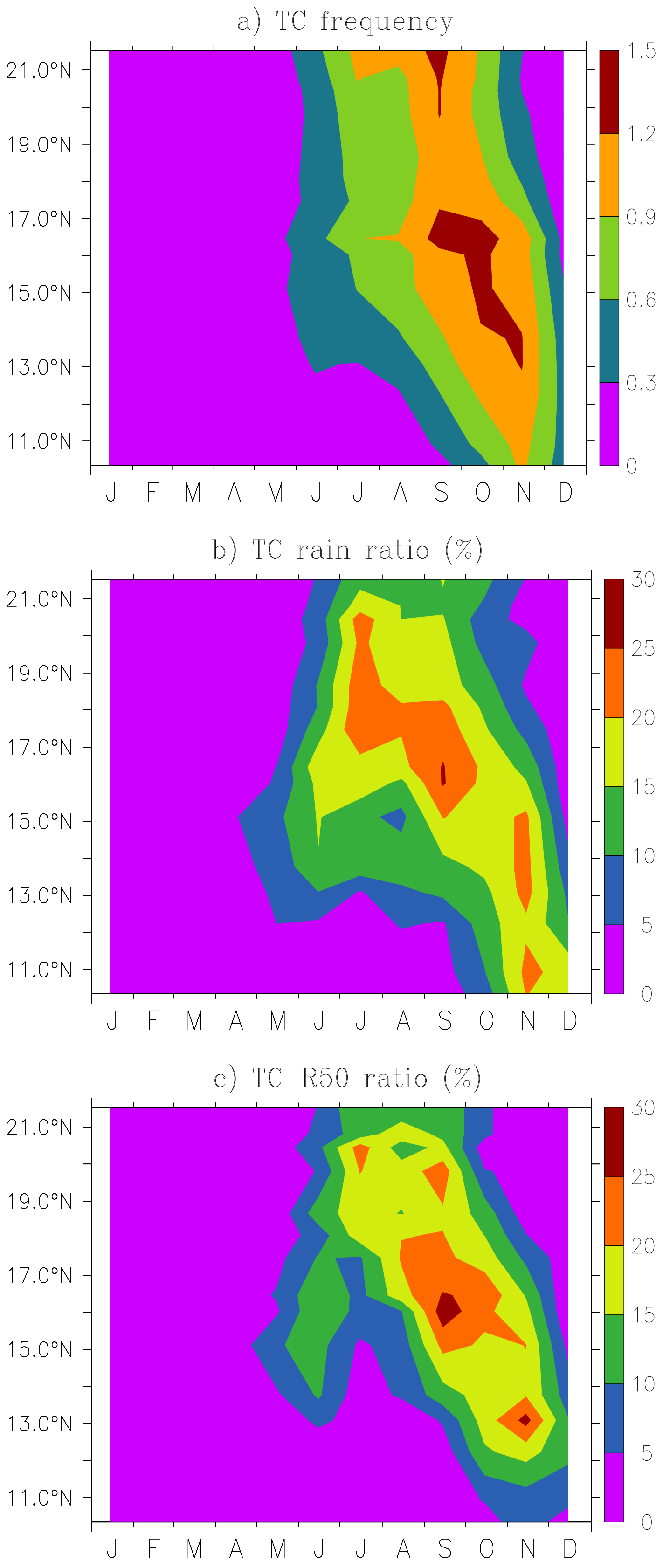
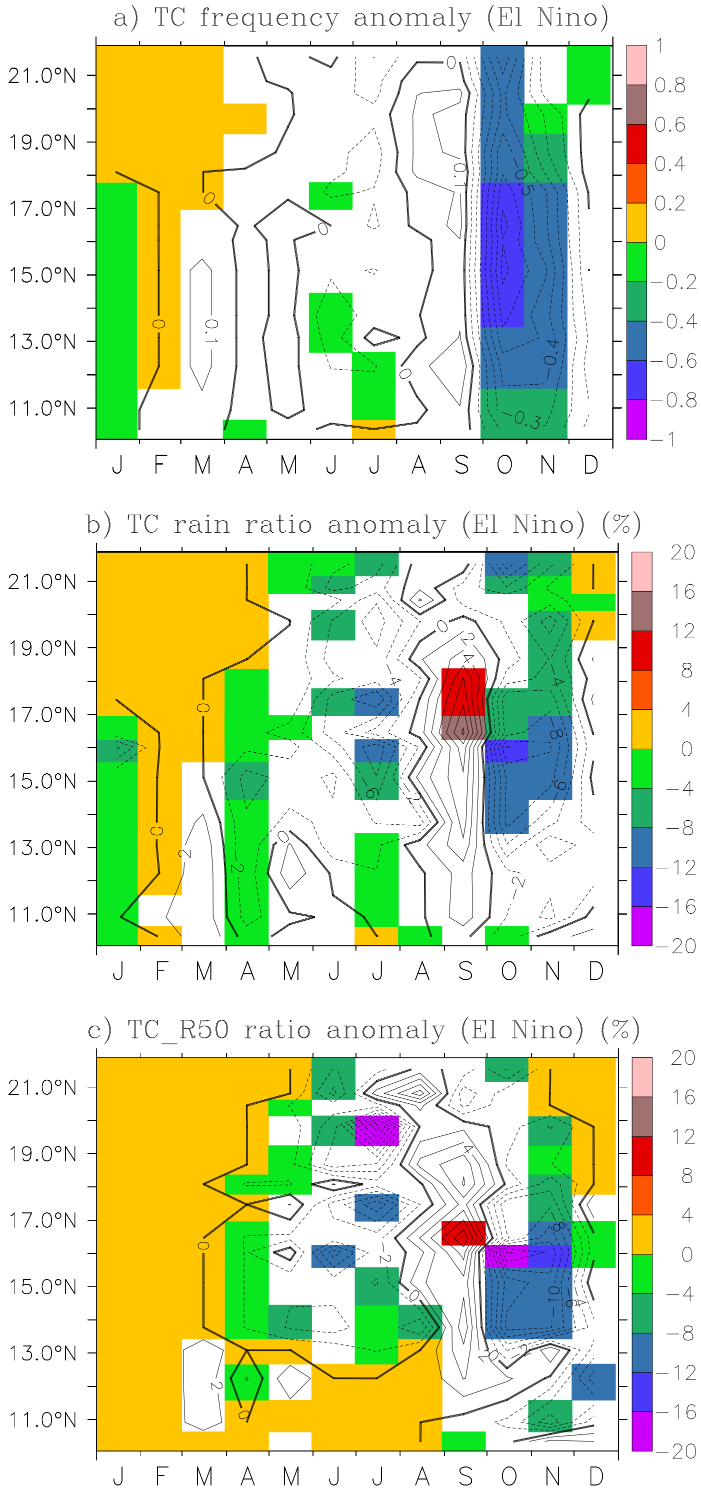


Figure 3.2. Time-latitude sections of (a) TC frequency, (b) TC rain ratio, and (c) TC_R50 ratio along the Vietnam coast.



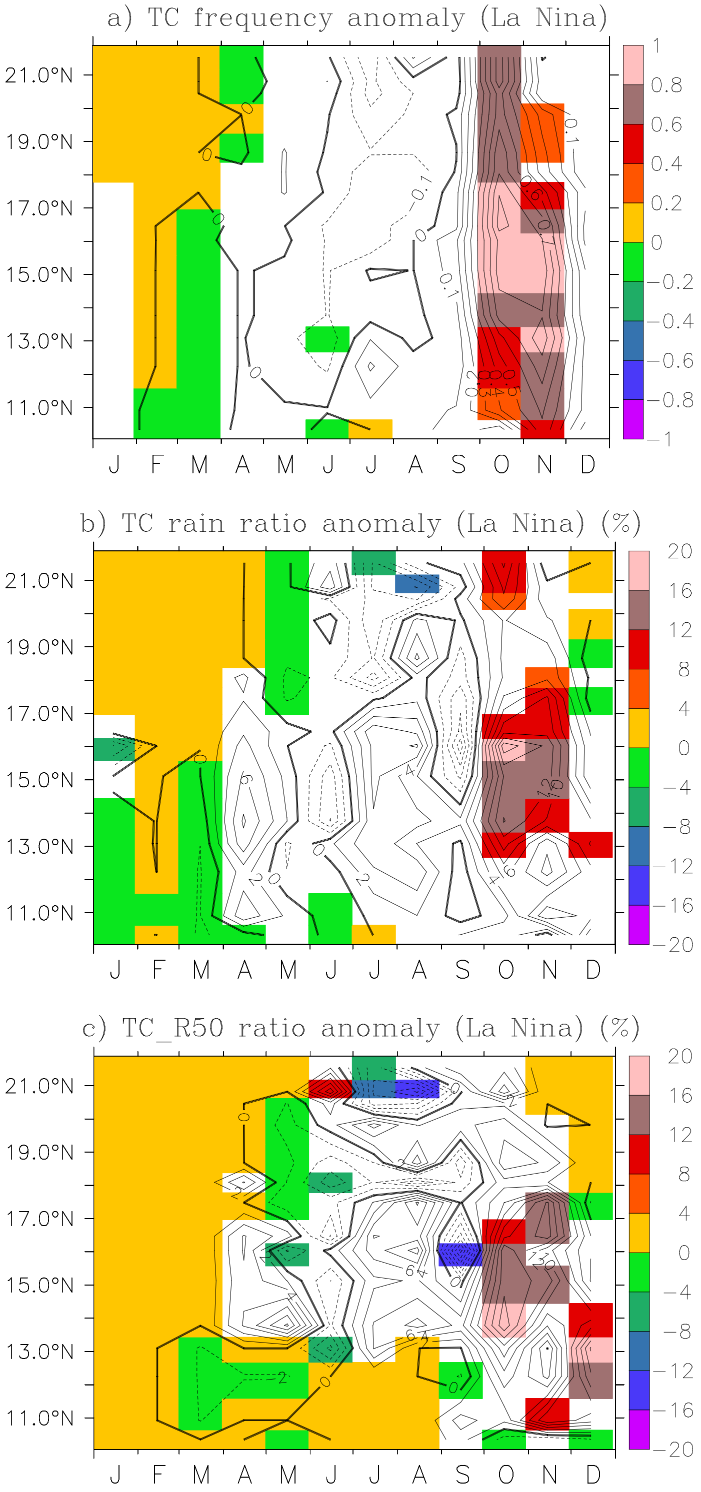
a) TC frequency anomaly (El Nino)

b) TC rain ratio anomaly (El Nino) (%)

c) TC_R50 ratio anomaly (El Nino) (%)

Figure 3.3. Time-latitude sections of the bootstrap means (contour) of (a) TC frequency anomaly, (b) TC rain ratio anomaly, and (c) TC_R50 ratio anomaly in El Niño years. Color shading shows areas where the anomalies are positively (negatively) significant at the 90% confidence

level and the color levels also indicate the bootstrap means of each anomaly.



a) TC frequency anomaly (La Nina)

b) TC rain ratio anomaly (La Nina) (%)

c) TC_R50 ratio anomaly (La Nina) (%)

Figure 3.4. Same as Figure 3.3, but for La Niña years.

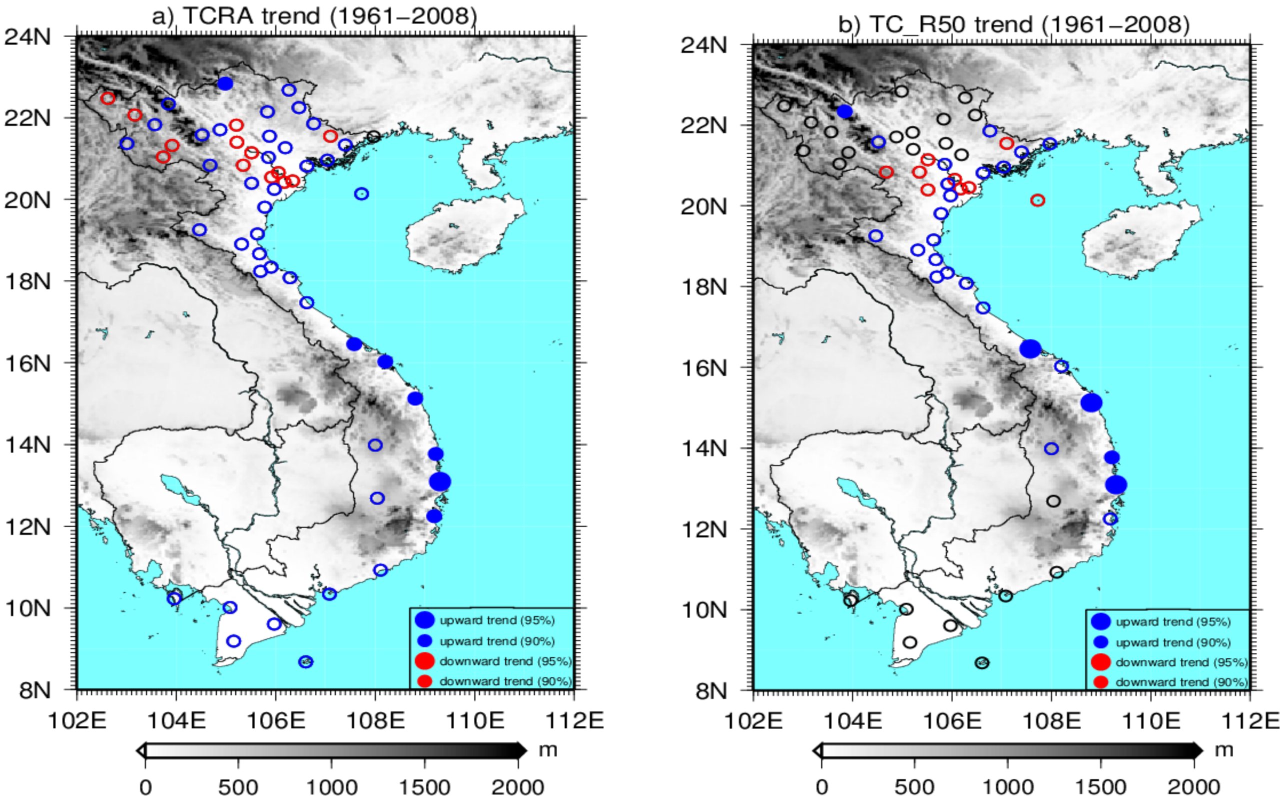


Figure 4.1. Trends of (a) TCRA and (b) TC_R50 for 58 stations in Vietnam, 1961–2008. Blue (red) symbol indicates increasing (decreasing) trend where small (big) filled circles are statistically significant at 90% (95%) confidence level. Open circles are not significant in any of these levels. Black open circles represent stations with no trend.

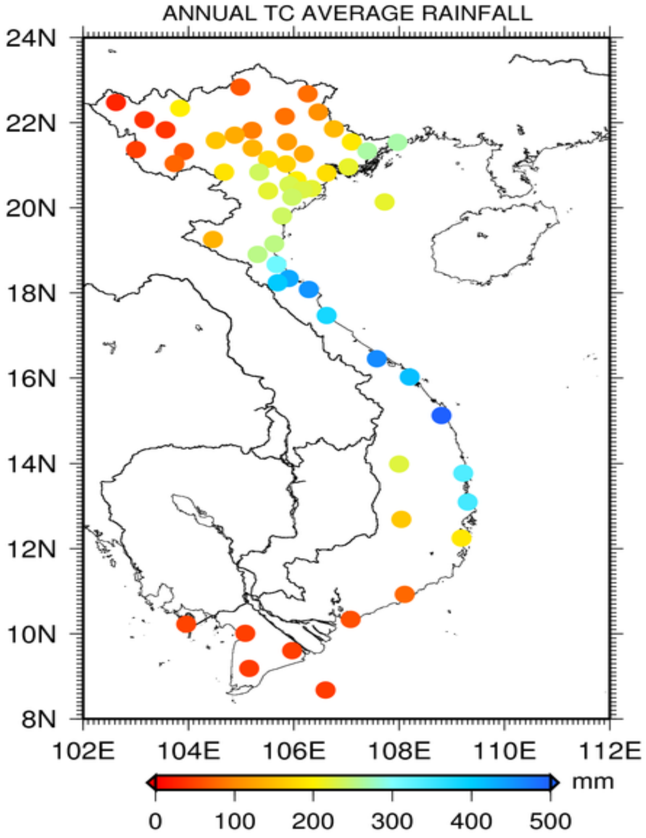


Figure 4.2. Annual TC average rainfall of 58 meteorological stations considered in Chapter IV.

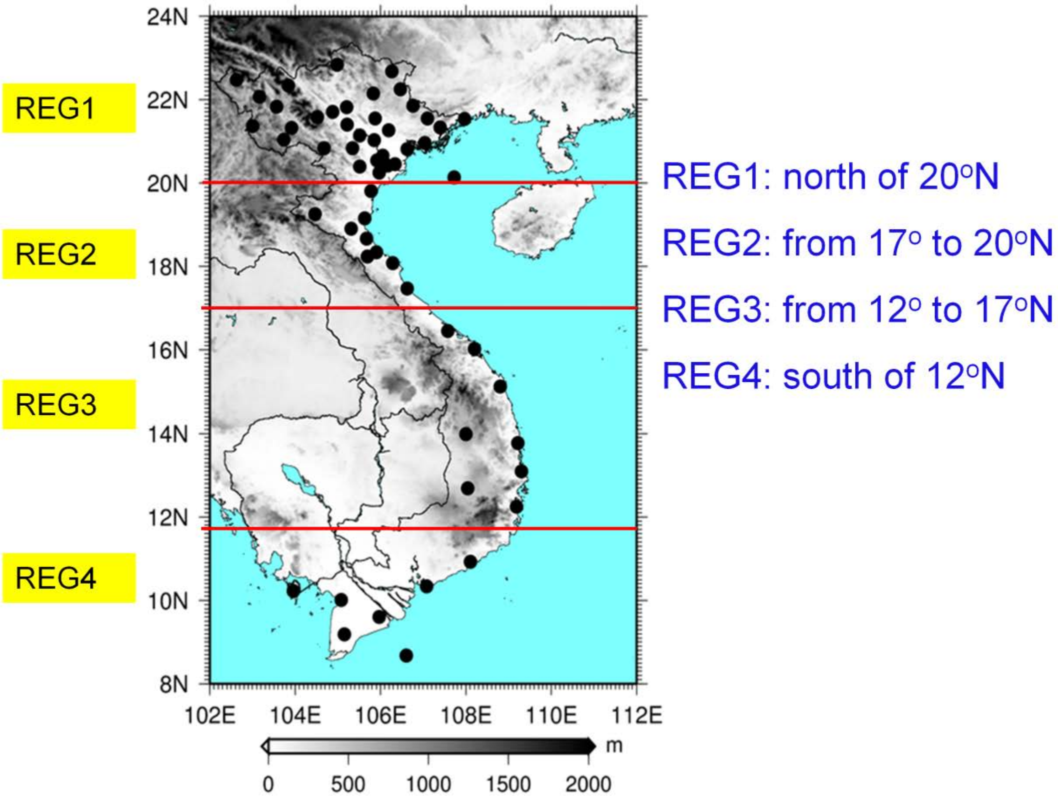


Figure 4.3. Definition of four sub-regions in Vietnam used in Chapters IV and V.

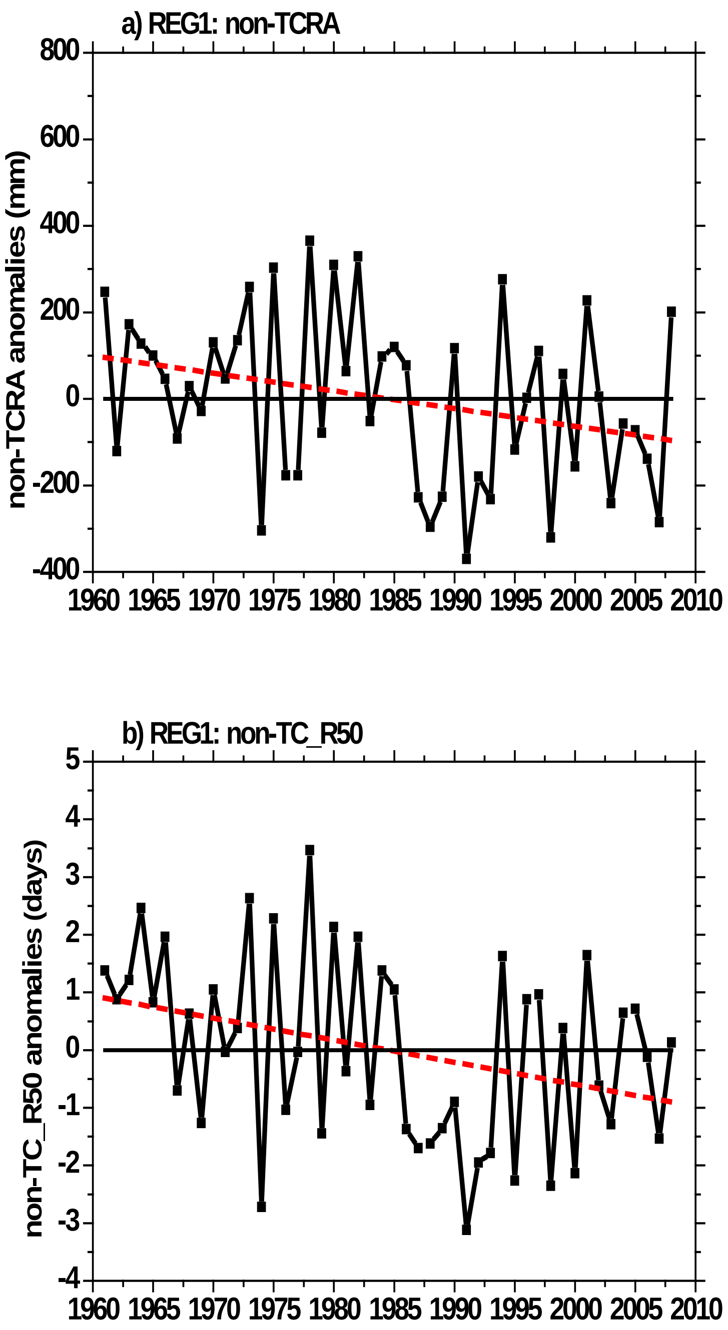
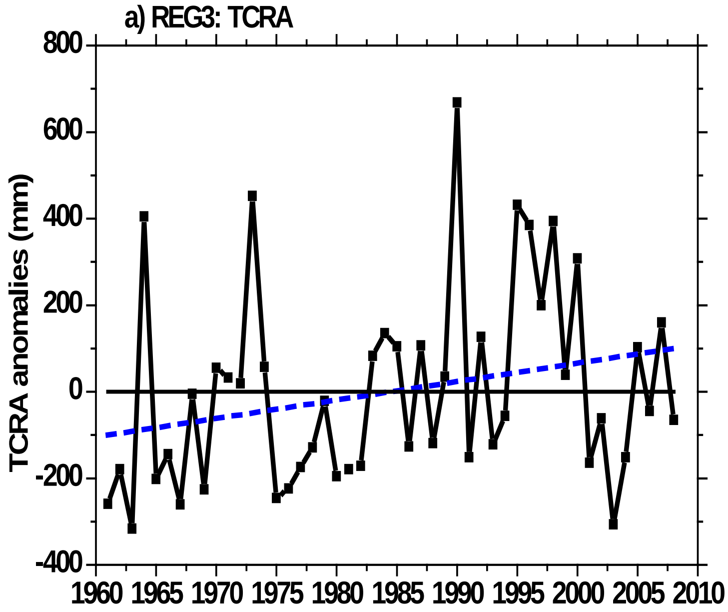


Figure 4.4. Annual time series for anomalies and linear trends (dashed lines) of (a) non-TCRA and (b) non-TC_R50 in REG1.



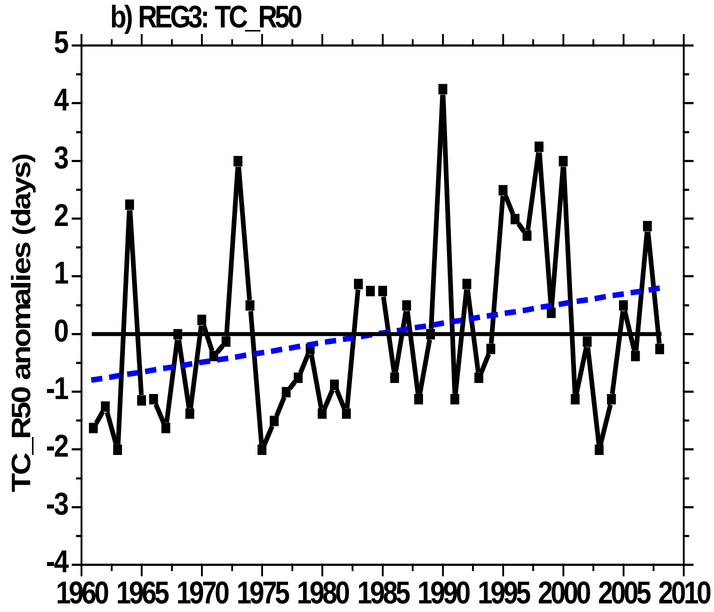


Figure 4.5. Annual time series for anomalies and linear trends (dashed lines) of (a) TCRA and (b) TC_R50 in REG3.

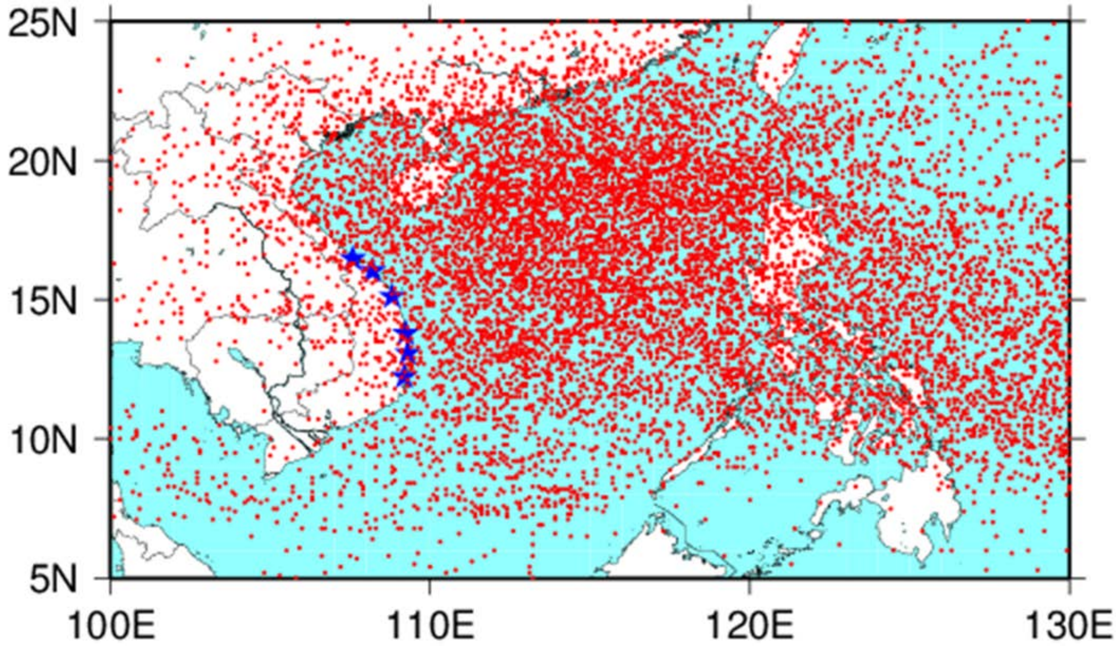


Figure 5.1. Map of six meteorological stations in Central Vietnam (blue stars) and the locations of tropical cyclone centers (red dots) every 6 hours during 1961–2008.

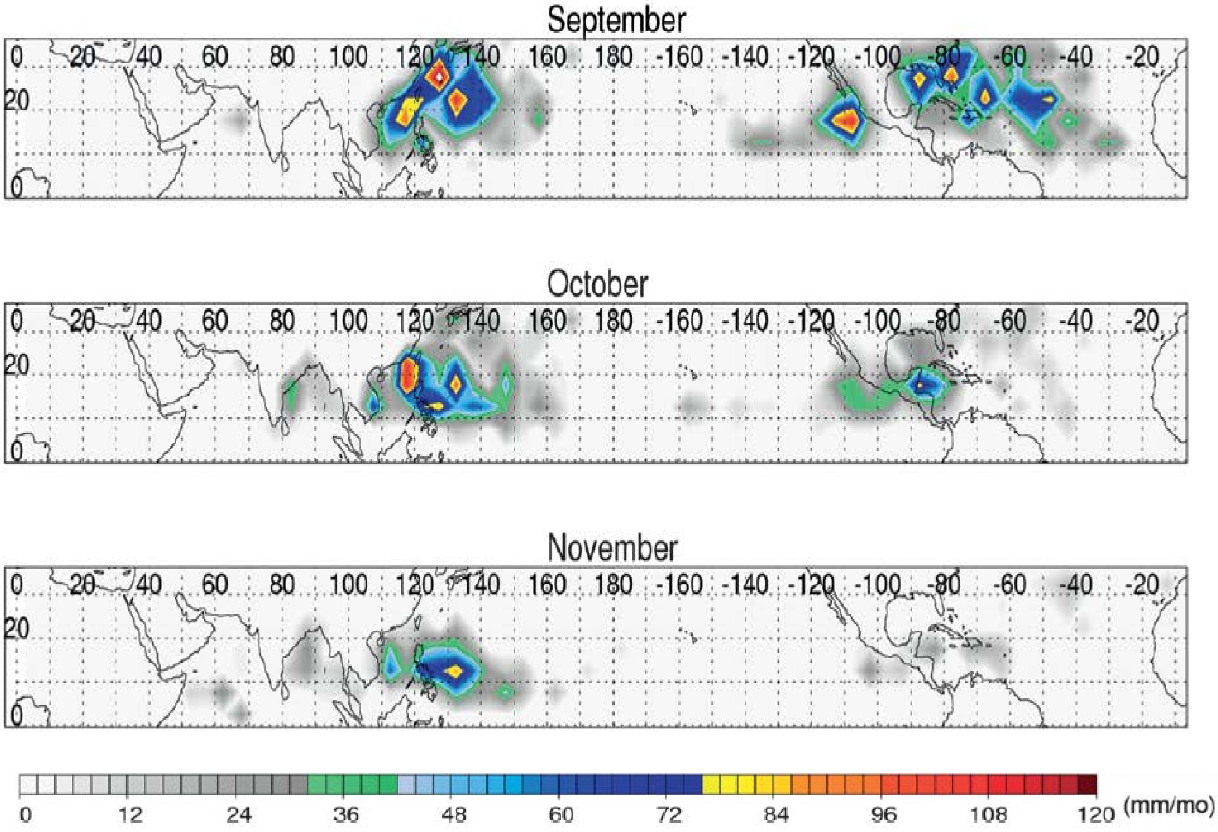


Figure 6.1. Seasonal TC rainfall for the months of Sep–Nov for the years of 1998–2000 and 2002–2006 by Jiang and Zipser (2010).

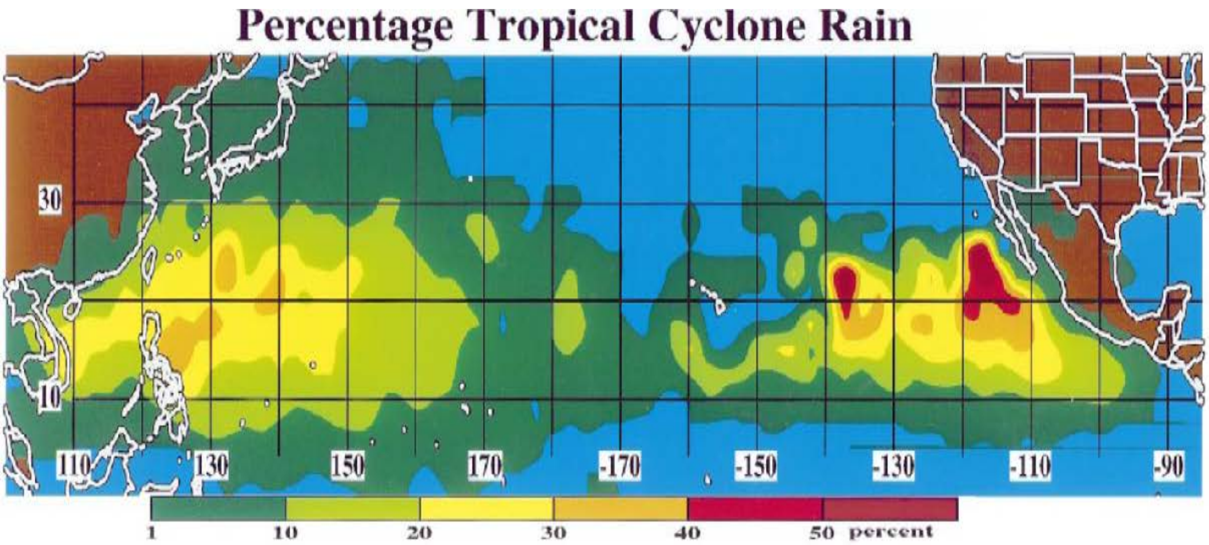


Figure 6.2. Mean monthly TCs rainfall percentage for the months of Jul–Nov 1987, Jun–Nov 1988–1989, and 1991–1998 by Rodgers et al. (2000).

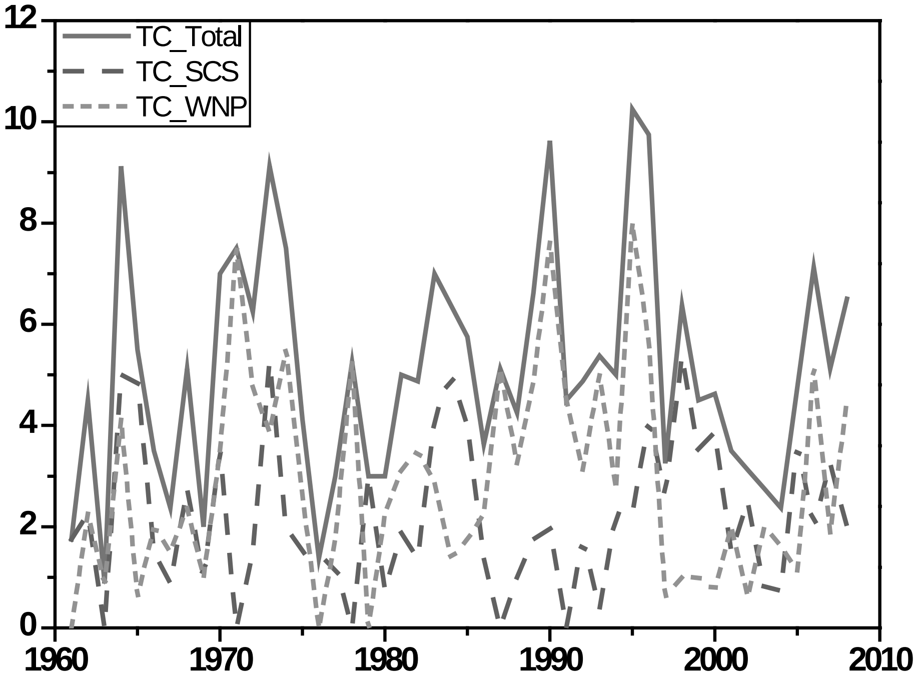


Figure 6.3. Annual time series for the TC frequency that brings rainfall to Central Vietnam (REG3).

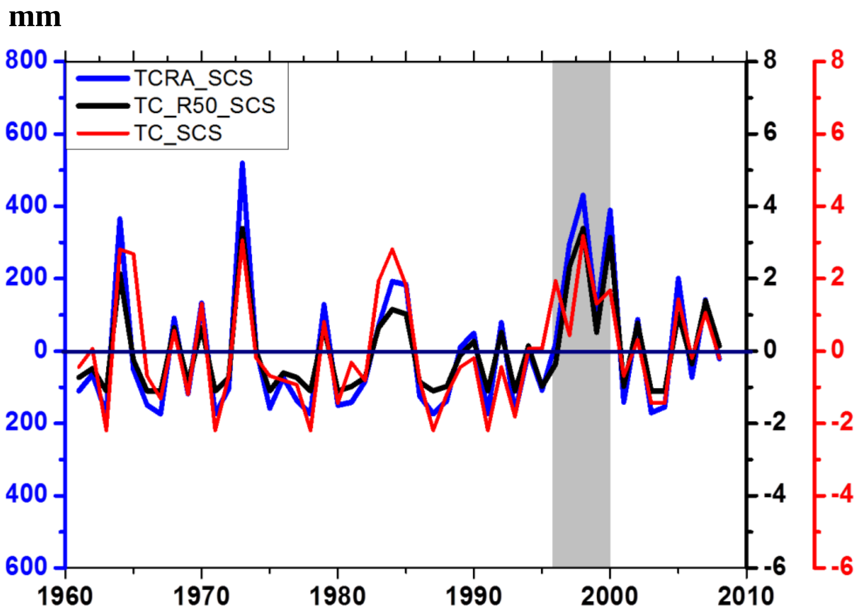


Figure 6.4. Annual time series for anomalies of TCRA (blue line), TC_R50 (black line), and TC frequency that brings rainfall (red line) in Central Vietnam (REG3) accumulated from TC formed in the SCS.

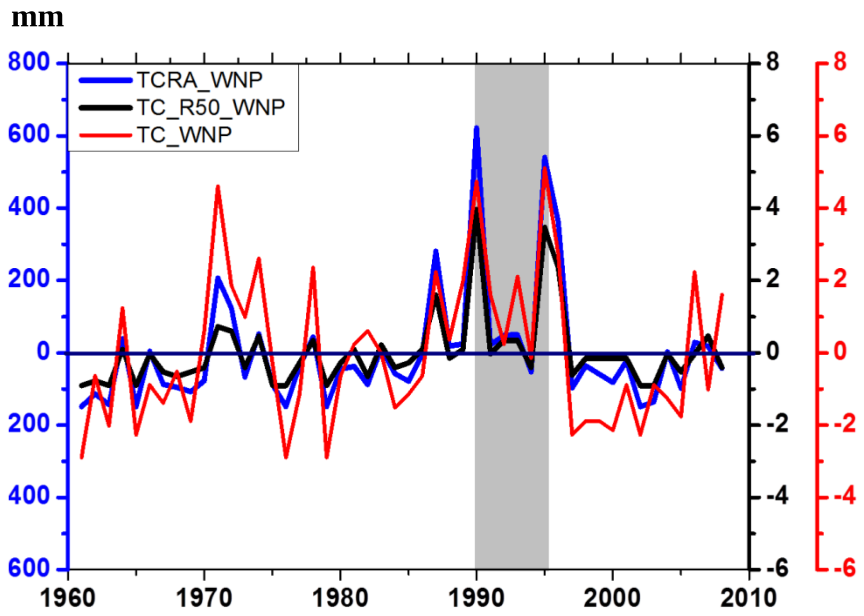


Figure 6.5. Annual time series anomalies of TCRA (blue line), TC_R50 (black line), and TC frequency that brings rainfall (red line) in Central Vietnam (REG3) accumulated from TC formed in the WNP.

Table 2.1. List of 58 selected meteorological stations in Vietnam used in this study (in which 15 selected meteorological stations used in Chapter III are marked by a bold asterisk)

No.	Station	Lon. (ºE)	Lat. (ºN)	Elev. (m)
1	Ha Giang	104.98	22.83	118
2	Cao Bang	106.26	22.67	260
3	Muong Te	102.62	22.47	300
4	Sapa	103.84	22.34	1570
5	That Khe	106.47	22.25	275
6	Bac Can	105.83	22.15	174
7	Lai Chau	103.16	22.07	244
8	Lang Son	106.76	21.85	258
9	Quynh Nhai	103.57	21.83	150
10	Tuyen Quang	105.21	21.82	42
11	Yen Bai	104.88	21.7	56
12	Van Chan	104.52	21.58	257
13	Thai Nguyen	105.87	21.55	36
14	Dinh Lap	107.1	21.55	174
15	**Mong Cai***	107.97	21.53	7
16	Phu Ho	105.22	21.4	36
17	Dien Bien	103.01	21.37	479
18	Tien Yen	107.4	21.33	0.2
19	Son La	103.92	21.32	600
20	Bac Giang	106.19	21.27	7
21	Son Tay	105.51	21.14	7
22	Song Ma	103.74	21.04	330
23	Ha Noi	105.85	21.03	6
24	Bai Chay	107.04	20.96	87
25	MocChau	104.68	20.84	958
26	Hoa Binh	105.34	20.83	23
27	**Phu Lien***	106.62	20.81	3
28	Hung Yen	106.05	20.65	4
29	Ha Nam	105.92	20.54	3
30	Vu Ban	105.51	20.4	20
31	**Thai Binh***	106.34	20.45	3
32	Nam Dinh	106.17	20.42	3
33	Ninh Binh	105.97	20.25	2
34	Bach Long Vi	107.73	20.13	6
35	**Thanh Hoa***	105.78	19.81	7
36	Tuong Duong	104.47	19.26	90
37	Quynh Luu	105.63	19.15	3
38	Do Luong	105.31	18.9	15
39	**Vinh***	105.67	18.67	3
40	Ha Tinh	105.9	18.34	3
41	Huong Khe	105.69	18.24	10
42	**Ky Anh***	106.29	18.08	3
43	**Dong Hoi***	106.62	17.47	8
44	**Hue***	107.58	16.46	17
45	**Da Nang***	108.2	16.03	7
46	**Quang Ngai***	108.81	15.12	8
47	Pleiku	108	13.98	800
48	**Quy Nhon***	109.22	13.77	6
49	**Tuy Hoa***	109.3	13.09	12
50	BuonMeThuot	108.04	12.68	490
51	**Nha Trang***	109.19	12.24	10
52	**Phan Thiet***	108.11	10.92	8
53	**Vung Tau***	107.08	10.34	4
54	Phu Quoc	103.96	10.22	3
55	Rach Gia	105.08	10.01	2
56	Soc Trang	105.97	9.6	3
57	Ca Mau	105.15	9.18	2
58	Con Dao	106.6	8.68	3

Table 2.2. List of ENSO years in the period 1961–2008 used in this study

El Niño years	**La Niña years**
1963	1964
1965	1970
1968	1971
1969	1973
1972	1974
1976	1975
1977	1984
1979	1988
1982	1995
1986	1998
1987	1999
1991	2000
1993	2007
1994	
1997	
2002	
2004	
2006	

Table 4.1. TC rainfall indices used in this study

Index	Description	Unit
TCRA	Annual TC rainfall amount	mm
TC_R50	Number of days with TC daily rainfall ≥50 mm	days
TCRA_SCS	Annual TC rainfall amount when TC was formed in the SCS	mm
TC_R50_SCS	Number of days with TC daily rainfall ≥50 mm when TC formed in the SCS	days
TCRA_WNP	Annual TC rainfall amount when TC was formed in the WNP	mm
TC_R50_WNP	Number of days with TC daily rainfall ≥50 mm when TC was formed in the WNP	days
non-TCRA	The difference between total rainfall and TCRA	mm
non-TC_R50	The difference between total number of days with daily rainfall ≥50 mm and TC_R50	days

Table 4.2. Sen's slope trends of eight rainfall indices over four sub-regions in Vietnam during 1961–2008

Index/Region	REG 1	REG 2	REG 3	REG 4
TCRA	0.64	1.74	**4.64****	0.43
TC_R50	0.00	0.01	**0.03***	0.00
TCRA_SCS	0.00	1.46	1.8	0.00
TC_R50_SCS	0.00	0.01	0.01	0.00
TCRA_WNP	–0.08	0.00	**1.62***	**0.16****
TC_R50_WNP	0.00	0.00	**0.01***	0.00
non-TCRA	**–5.1****	–3.51	3.35	1.19
non-TC_R50	**–0.05***	–0.02	**0.05***	0.00

(Note: Statistically significant trends are shown in bold and one (two) asterisks indicate statistical significance at the 90% (95%) levels. Units are mm/year and days/year for TCRA and TC_R50, respectively).

Table 4.3. Correlation coefficient of rainfall indices in REG3 and ENSO3.4 from 1961 to 2008. Statistical significance at the 95% confidence level is shown in bold and one asterisk.

Index	ENSO3.4
TCRA	**-0.31***
TC_R50	**-0.30***
non-TCRA	**-0.31***
non-TC_R50	-0.27