TROPICAL CYCLONE RAINFALL STRUCTURE AFFECTING INDOCHINA PENINSULA AND LOWER MEKONG RIVER BASIN (LMB)

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Abstract. Indochina Peninsula is located in between Bay of Bengal (BoB) and South-China Sea (SCS). This region is affected frequently from Tropical Cyclones (TCs) formed in North Indian Ocean (NIO), South-China Sea (SCS), and North West Pacific Ocean (NWP). This research analyzed the structure of the rainfall over Indochina Peninsula and its relationships with TCs from the aforementioned sources. Principle Component Analysis (PCA) was performed to investigate the dominant rainfall area produced from those TCs. Spatial and Temporal structures of rainfall from the TCs is analyzed to understand their propagation. The results show that the dominant TC rainfall area covers Central Vietnam which contributed around 25\% to total rainfall in the region. However, the contribution of this TC rainfall over LMB is likely less than 20\% where Laos’s territory receives highest contribution (20\%). Furthermore, from the three source areas, TCs formed in SCS produce the highest rain rate when they develop into typhoon intensity stage of Joint Typhoon Warning Center (JTWC)’s scale. The average duration of TC rainfall over Indochina Peninsula is 81.28 hours, and over LMB is 66.22 hours. Thus, same as other regions in the Indochina Peninsula, LMB is affected by TC rainfall with considerable scales both spatially and temporally that may lead to significant hydrometeorological hazards.

1. Introduction

1.1. Background

The Tropical Cyclone (TC) is one of the most destructive natural phenomena that bears hydrometeorological hazards such as devastating wind gust, storm surge along the coastline area, and flood-triggering heavy rainfall. Flooding due heavy rainfall is known to cause the most prolonging effect.
to human society because overtopping water can inundate villages, public service facilities such as school and hospital, farmland and roads resulting in large amount of economic lost. More severe flood events even cause a large number of deaths, and ecological degradation. For example, flood from Typhoon Ketsana in 2009 caused 182 deaths and 357000 displacements in LMB’s countries (Dartmouth’s record). Therefore, it is important to understand the effects of TCs or Typhoons over the region for characterizing the hazards and developing better countermeasure in future disaster risk reduction planning or action.

With regard to flood hazard, Mekong River Commission’s working paper (2011-2015) published in 2012 described the causes of flood in LMB to be connected with two major weather phenomena including widespread and extended rains of Southwest Monsoon, and short and more localized rainfalls resulting from remnants of tropical weather systems that propagate east from West Northern Pacific disturbance. Among these two source of rainfall, tropical weather system is more severe phenomenon and irregular events. Located in between Bay of Bangal and South-China Sea (SCS), Indochina Peninsula is affected frequently by Tropical Cyclones (TCs) form in Indian Ocean (IO), South-China Sea, and North-Western Pacific Ocean (NWP). These TCs land or approach Indochina regions every year, and they bring along heavy rainfall which produce flood to river basins located inside these region, mainly LMB.

A climatological study of tropical cyclone by Nguyen-Thi et al. (2012a) shows that the maximum tropical cyclone (TC) rainfall occurs from July to September in the northern region of Vietnam, and peak TC rainfall occurs from October to November in the central region. The long-term trends in tropical cyclone rainfall in Vietnam has also been studied by Nguyen-Thi et al. (2012b), in which they found a significant increasing trend with 90% and 95% confidence levels of TC rainfall amount and TC heavy rainfall days at most of the stations in central coastline during (1961-2008). On the other hand, Takahashi et al. (2008) observed the decreasing trend in rainfall during the late summer monsoon season (September) over Indochina from 1951 to 2000 and associated changes in tropical cyclone activity during these years. They estimated that 70 % of the rainfall amount in September was associated with TCs in Thailand, and they also interpreted the cause of decreasing trend of rainfall over Indochina Region from 1951 to 2000 as associated with the reduction of cyclonic activity during these period. Furthermore, by investigating the interannual variation in precipitation over Indochina over a 33-years period from 1979-2011, Takahashi et al. (2015) pointed out that cyclonic anomalies and more westward-propagating tropical cyclones than expected from the climatology of the area were observed in 2011. These anomalies, along with the monsoon trough from the north Indian subcontinent, the Bay of Bengal, Indochina, and the western Pacific, contributed significantly to the 2011 Thai flood. Apart from the trends and interannual variation of the TCs in Indochina Peninsula and LMB, studies on spatial and temporal structures of the associated rainfall are still limited.

1.2. Study Purposes and Scope

This study aims to explore the rainfall structure: the spatial and temporal distribution of the TC events that influence Indochina region. More than that, the comparison of rainfall structure produced by TCs formed in North Western Pacific, South China Sea (SCS) and Indian Ocean will be done in this study as well.

This study focuses on Tropical Cyclone rainfall that occurred in Indochina Peninsula. This research limits to the TCs tracking toward Indochina Peninsula or nearby region during the period 2000-2013. From best track data of Joint Typhoon Warning Center (JTWC) during this period, 91 TCs are selected with the suspect of producing rainfall to Indochina Peninsula (additional material A). Therefore, these 91 TC events will be used in this study.
2. Data and Methodology

2.1. Data

Four important kinds of data are required for this study including rainfall data, Atmospheric Circulation data, Tropical Cyclone Track, and cloud activity data. Rainfall from TRMM 3B42 is chosen to fulfil this study for its higher resolution in time and also can be access publically. The version 6 of TRMM provided precipitation data with three hourly temporal resolutions and $0.25^\circ \times 0.25^\circ$ spatial resolution from 1998 until June, 2011. However, the scope of this study is from 2000 to 2013, thus two more years’ data is needed. To solve this problem, the continuous version of TRMM 3B42 (version 7) is available until present time (2015). Therefore, data of TRMM 3B42 version 7 from July, 2011 until 2013 is used to fulfil the data range in scope of this study; then the rainfall data problem is solved. Atmospheric circulation is investigated using the 40-year Reanalysis (ERA-40, Uppala et al. 2005) dataset of the European Center for Medium Range Weather Forecasts (ECMWF). TC track data is obtained from Japan Meteorological Agency (JMA), Indian Meteorological Department (IMD), and Joint Typhoon Warning Center (JTWC). Cloud activity data is obtained from regional satellite observation (GMS, GEOS-9, and MTSAT) with spatial resolution of 5 km and 1 h temporal resolution available from 1979-present (Blersh and Probert, 1991 and Meteorological Services Center Japan, 1997).

2.2. Methods

2.2.1. Study Area

The study area of this research is located in Indochina Peninsula which covers 5 countries namely Myanmar, Laos, Thailand, Cambodia, and Vietnam. The specific geographic location is within the longitude range from $93.125^\circ$E to $109.125^\circ$E, and within the latitude range from $8.125^\circ$N to $23.125^\circ$N (Figure 4). The map of LMB is included in the map of Figure 4 which is symbolized with red polygon inside Indochina Peninsula.

2.2.2. TC-Induced-Rainfall Extraction and Total TC-Rainfall Calculation Method

Method to extract cyclone-induced rainfall was adapted from a previous study by Nguyen-Thi et al. (2012) who study was about climatology of TC rainfall in Vietnam. This team based on the study by Englehart and Douglas (2001) who found that 90% of cases over western Mexico, TC rainfall occurs within the radius of 600 km from the center of the TC, and the study by Gleason (2006) who treated any rainfall less than or equal to 600 km radius from the center of the storm as TC rainfall. These studies apply the area inside the circle area as TC-induced rainfall.

In this current study, we try to adapt the above method to be fit with our available gridded TRMM data with spatial resolution of $0.25^\circ \times 0.25^\circ$. We treat the rainfall occurred inside a square box which half of the box’s side has distance of 6° or 600 km from the TC center or best track location as TC-induced rainfall (Figure 1). This adaptation helps simplify the calculation algorithm of TC-induced rainfall which will be used for some analysis of this study.

In the calculation of total TC rainfall, two important kinds of data are used: track position data from JTWC and TRMM 3B42 rainfall data. Since the track data is recorded in 6-hourly time step and TRMM data is in 3-hourly time step, calculation seems to encounter inconsistency. Thus, 6-hourly track data of JTWC is interpolated to get 3-hourly time step. The total TC rainfall is calculated from summation of rainfall occur only inside the TC-induced rainfall box for the life time period of TC along the interpolated track position. Figure 2 shows an example rainfall inside the box along the track position. The total TC rainfall for each event in this study is constructed.
2.2.3. Weak TC Detection Method

Weak TC detection is a method adapted by Takahashi et al. (2008) who also adapted from Fudeyasu et al. (2006). Takahashi et al. (2008) identified the TCs around Indochina domain using 700-hPa relative vorticity, following the method of Fudeyasu et al. (2006), but they included the explanation why they also applied the above-mentioned relative vorticity to Indochina domain. Takahashi et al. (2008) treated any grid of the 700-hPa relative vorticity exceeded 3.0 ×10^{-5} s^{-1} within the Indochina domain as TC event. In their illustration of this method, they also used some other parameters to see the phenomena such as 850-hPa winds and geopotential height. Therefore, this method is also continuously adapted for this study. Although JTWC track data include weak TCs, such as tropical depression, the quality of weak TC data is not homogeneous for all events. This make a difficulty in recording the duration of TC over Indochina Peninsula. Thus, weak TC detection method adapted by Takahashi et al. (2008) is useful to solve this problem.

The usage of this method in this study is to confirm the movement and the continuation of TC rainfall over the study area after termination of track of JTWC, which is important for duration recording of TC rainfall. We make the same plot as that method, but we omit the relative vorticity replacing with rainfall parameter. The rainfall occur under the swirling wind and close geopotential height is considered as TC rainfall. With this plot, we can observe the movement TC rainfall, and the time when the TC stop producing rainfall to the study area (Figure of this plot is shown in section IV of additional material B).

2.2.4. Method to Record Affection Duration of TC Rainfall

The duration counted from the time when TC start to produce rainfall until the time when TC stop producing rainfall to our study area is call “affecting duration of TC rainfall” which is used as terminology for this study. The duration of TC rainfall is recorded using specific method which will be described below.

First of all, we divide Indochina Peninsula into four bands along latitude where band I is started from latitude 8.5 °N and band IV is ended at latitude 23 °N (The illustration about these bands is shown at section I of additional material B). Then, the approximated location of starting point and ending point of Indochina Peninsula and LMB for each band is determine on one grid of TRMM resolution on longitude. After that, we try to determine the starting time and ending time of TC rainfall for each band and for both Indochina Peninsula and LMB. To see clearly the propagation of TC rainfall, Hovmöller diagram of time and longitude with rainfall average within latitude range of each band. In order to see the time point when TC rainfall starts and ends, the time series plot of rainfall at four point such as starting and ending point of Indochina Peninsula and that of LMB is attached with Hovmöller diagram.
By doing this, we can easily determine the time point. However, the bothering from other rainfall source causes difficulty to decide whether that time point is TC rainfall or not. To solve this problem, we use two sources to confirm the existence of TC rainfall during that time point. First, we confirm with visible image of cloud from MTSAT to see if the cloud still exists over our suspected area during that suspected time point or not. Second, we confirm with the plot adapted from weak TC detection method as mention in the above section (section 2.2.3). This plot is the overlap of three parameters namely wind direction arrow, contour of geopotential height, and shaded color of TRMM rainfall. If the rainfall occurs within the domain of swirling wind and close geopotential height contour, we treat it as TC rainfall, and at that time point TC still produce rainfall to the study area. Continuing do like this for every band, we get the time point of starting and ending of TC rainfall over both Indochina Peninsula and LMB of every band. Then, the recorded time point of the four bands is sorted from earliest to latest. Thus, the earliest time point is the starting time of TC rainfall for the whole Indochina Peninsula and LMB, and the latest time point is the ending time of TC rainfall for the whole Indochina Peninsula and LMB. Then we can calculate the affecting duration of TC rainfall over our study area (The example of this method is shown in additional material B).

3. Results and discussion

3.1. Dominant TC Rainfall Area

![Figure 3 Principle Component Analysis (PCA) of annual total TC rainfall (2000-2013). a- the percentage explained of variance of 50 leading mode of PCs, b- the first mode of PCs (EOF1), c- the second mode of PCs (EOF2). The red polygon in the map is the LMB.](image-url)
The area in Indochina Peninsula and LMB where the rainfall produced from TC occurred more frequent is an interesting finding in this analysis. That most frequent TC-rainfall occurrence area is defined as dominant TC rainfall area which can be captured by Principle Component Analysis (PCA). In this study, the total annual cyclone-induced rainfall is analyzed with PCA to capture the dominant TCs’ rainfall area. The method to extract TC-induced rainfall is already mentioned in section 2.2.2 above. The total TC-induced annual rainfall is calculated from the summation of all total TC-induced rainfall of all events occurred in the same year from all 91 TC events in this study. Then, the annual time series of TC rainfall is obtained for every grid. Operating PCA on that data matrix, the result is shown as following.

Figure 3 shows the result of PCA on the annual total TC rainfall. The explained percentage of 50 leading PCs is illustrated in the plot of Figure 3a. This plot shows that two leading modes is significant with explained percentage of 33 %, and 29 % of total variances, respectively. Thus, these two modes contain the most variability of TC rainfall which are sufficient to show dominant TC rainfall area over Indochina Peninsula. The spatial pattern information of TC rainfall based on the PAC of TC annual total TC rainfall (2000-2013) contains in loading of PCs. The loading of first mode (EOF1) indicates that during 2000-2013 the dominant TC rainfall occurred over central Vietnam within latitude 15 °N-20 °N (Figure 3b). This area is considered as a center of dominant TC rainfall (highest positive loading in the area) for the first mode. The loading value is positive deep inland of Indochina until Laos, Thailand and Cambodia, but this value reduce gradually from the center of dominant point (Central Vietnam). This suggests a reduction of degree of dominant of TC rainfall from Eastern part to Western part of Indochina Peninsula.

However, the loading of second mode (EOF2) shows the offset of dominant loading area southward (Figure 3c). This means that the second mode suggest the dominant TC rainfall area is located southern part of Vietnam within latitude range 11 °N and 14 °N. This location is considered as a dominant TC rainfall center for the second mode of EOF. Similar with first mode, the loading value is positive deep inland of Indochina until central part of Cambodia. This positive loading value spread out until southern Laos, and eastern and southern part of Thailand. Likewise, that positive value decrease gradually westward from the dominant center. This suggests a reduction of degree of dominant of TC rainfall from Eastern part to Western part of Indochina Peninsula similar as what happen in first mode. Another positive loading value is also observed at western part of Indochina region that is to say in the territory of Myanmar, but it is the lowest positive loading value comparing to eastern part. This is the TC rainfall effect from North Indian Ocean.

3.2. Contribution of TC rainfall over Indochina Peninsula and LMB

The center of contribution percentage is located on the sea near Hainan Island, China which is around 35% in average (Figure 4). This contribution becomes less when moving toward east Indochina Peninsula to less than 25%. The highest contribution of TC rainfall over land of Indochina Peninsula is located in central Vietnam with value of 25 % which is a consistence location with PCA. Along the coastline of central Vietnam, the contribution is ranking from 15-25 % in average. At Northern Vietnam coastline, Southern Laos, and some part of South Vietnam the contribution is around 10-15 % of total rainfall. The contribution becomes less if go deeper inland of Indochina Peninsula that is to say parts of Laos, Eastern Thailand, Cambodia, North and Southern Vietnam. This contribution is less than 10 % in average. If consider in LMB, the TC rainfall contributes less than 20 % and the highest contribution occur in Laos territory. At western part of Indochina Peninsula, TC rainfall contribute very little rainfall (less than 2 %) resulting from two factors: 1) less TCs approach Indochina from Northern Indian Ocean (6 cases among 91 cases in this study), and 2) the more total annual rainfall (the denominator of percentage calculation) from the south-west monsoon rainfall.
3.3. Significant TC Rainfall Source

This analysis is achieved from longitude-intensity plot as shown in Figure 5. The rain rate is averaged for each TC event in the selected cyclone list (additional material A) and composite to the corresponding TC intensity recorded by JTWC. After that the latitudinal averaging within latitude 5.125°N-23.125°N is performed over that composited averaging. Then the longitudinal average rain rate for all TC intensity stages is obtained. The subplots of that rain rate value along longitude are organized in order of its intensity by weakest intensity at the bottom and highest intensity at the top of the figure (Figure 5). The feature of that organised subplot is considered in this study as the longitude-intensity plot. This plot shows the location of highest rain rate for the corresponding TC intensity. The TC rainfall source which pronounce the highest rain rate to the vicinity of Indochina Peninsula is considered as significant TC rainfall source to the region.

Figure 5 shows the result of this analysis. TCs formed at North-West Pacific produce more rain rate of more than 1 mm/hr averaging at longitude around 125°E-130°E when the cyclones develop to super typhoon stage (Figure 5a). This means that this TC rainfall source produce more rain rate to the Philippines islands during supper typhoon. Moreover, this rain rate reduces to less than 0.7 mm/hr in average when they arrive at Indochina Peninsula at latitude around 110°E. Figure 5b shows that TCs formed in north Indian Ocean produce rain rate of less than 0.8 mm/hr in average at the western part of Indochina Peninsula at longitude around 93°E when cyclones develop to Typhoon stage; seem not go deeper inland of Indochina that is to say not more than 95°E.

However, TCs formed in SCS produce more rain rate of around 1 mm/hr in average in vicinity of eastern Indochina Peninsula of longitude around 105°E to 110°E when the cyclones develop to Typhoon Stage (Figure 5c).

Therefore, this analysis suggests that the TCs formed in SCS produce the highest rain rate to Indochina Peninsula when the TC intensity develop to Typhoon intensity class of JTWC’s scale. The TC rainfall produced from TCs formed in NIO is the second highest rain rate to Indochina Peninsula.

Figure 4 14-year mean (2000-2003) contribution Percentage of TC rainfall to total annual rainfall over Indochina Peninsula. Color shaded is the percentage of contribution of TC rainfall to total rainfall. Contrib %=(TC rainfall / Total rainfall)×100. The red polygon is the LMB territory.
Figure 5: Latitudinal average cyclone rain rate in mm/hr, composite to TC intensity of the three different sources of TCs: a. North-West Pacific, b. Indian Ocean and c. South China Sea (Average rainfall duration recorded by JTWC and averaged within latitude 5.125°N-23.125°N). Note: DB - Disturbance stage, TD - Tropical Depression stage, TS - Tropical Storm stage, TY - Typhoon stage, and ST - Super Typhoon stage. Vertical axis and horizontal axis of each panel is a rain rate and longitude, respectively. Green box is the location of Indochina Peninsula.
3.4. Affecting Duration of TC rainfall over Indochina Peninsula and LMB

The affecting duration of TC rainfall over Indochina Peninsula is the duration counted from the time that TC start to produce rainfall on the peninsula until the time that TC decay or exit the peninsula. The method to record this duration was already mentioned in section 2.2.4 and additional material B.

The results of this recorded affecting duration and statistical analysis on that duration are shown in Figure 6. Bar plot of duration of all 91 TCs spending on the Indochina Peninsula is illustrated in Figure 6a. The average duration of TCs producing rainfall on Indochina Peninsula is 81.28 hours, and the maximum and minimum duration is 237 hours and 12 hours, respectively. Furthermore, the average duration TC rainfall over LMB is around 66.22 hours with the maximum and minimum duration of 174 and 9 hours, respectively (Figure 6b).

From box plot analysis, we can see that the distribution of duration data is not so sparse because the box is tight that is to say the first quartile, second quartile (median), and third quartile not range far from each other for both Indochina Peninsula and LMB. Anyway, two cases are seen outliers in both Indochina’s box plot and LMB’s box plot (Figure 6c). This means that there are two extreme cases in term of affecting duration of TC rainfall in both Indochina Peninsula and LMB. This is very consistent with the bar plot of duration of TC rainfall that two cases are seen higher than the others in both Indochina and LMB. Those cases are the TC number 49 and number 90 (List of those TCs is included in additional material A). Thus, these two cases are considered as extreme in term of affecting duration.

The TCs in this study produce rainfall to both Indochina and LMB very long time of average more than 3 days, and 2 days, respectively. This result is consistence with the study of Sugimoto and Satomura (2010) who suggest this long-lived time of Typhoon over Indochina resulting from the supply of water vapour from the nearby regions.

4. Conclusion

Indochina Peninsula is affected frequently from Tropical Cyclone from three different sources including North Indian Ocean, South-China Sea (SCS), and North-West Pacific Ocean (NWP). This study has been exploring about the TCs’ rainfall structure spatially and temporally.

The result from PCA suggest TC rainfall in Indochina Peninsula frequently happen at central Vietnam as the first variability and the southern Vietnam as the second variability. Those locations are the center of TC rainfall for each TC rainfall pattern. The degree of dominant of these TC rainfall decrease gradually westward and it occupies most of LMB.

More than that the contribution percentage of TC rainfall to total annual rainfall over Indochina Peninsula is less than 25 %. The contribution is becoming less if go deeper inland of Indochina Peninsula that is to say parts of Laos, Eastern Thailand, Cambodia, North and Southern Vietnam. If consider over LMB, the TC rainfall contributes less than 20 % and the highest contribution occur in Laos territory. The cyclones formed in SCS is significant TC rainfall source to Indochina Peninsula. This source produces highest rain rate when the cyclone develops to Typhoon stage.

In addition, the TCs affect the Indochina Peninsula and LMB very long time with average duration of around 3 days and 2 days, respectively. Two TC events are seen extreme in term of affecting duration.

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