Enhancement of Summer Monsoon Rainfall by Tropical Cyclones in Northwestern Philippines

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Abstract

The influence of tropical cyclones (TC) on the western North Pacific (WNP) summer monsoon flow—as well as the impact on rainfall in the Philippines during the months of June to September from 1958 to 2017—were investigated. High precipitation event (HPE) days with measured rainfall in the upper 85th, 95th, and 99th percentiles were determined using daily rainfall averages via data acquired from eight synoptic stations in northwestern Philippines. More than 90% of HPE days coincide with TC occurrence in the WNP, whereas landfalling TCs only account for 12.8–15.1% of HPE days. The present study looks at the non-landfalling TCs that are coincident with HPEs. The result shows that these non-landfalling TCs remotely play a key role that affects almost all local HPEs in northwestern Philippines.

Analysis of the TC tracks and their influence on southwesterly summer monsoon flow in Southeast Asia during HPE days shows that most of the TCs move along a line segment connecting northern Luzon and Okinawa, Japan. The composite low-level flow of all HPE days is characterized by a zonally-oriented eastward trough at the 1005–1007 hPa isobar along 20°N that extends to at least 135°E longitude over the northern half of the Philippines; a deepening of the monsoon trough in northern South China Sea also occurs. The 1005–1007 hPa trough induces an eastward shift on the southwesterly flow causing a 1.94–4.69 times increase in mean zonal wind velocity and 2.67–6.92 times increase in water vapor flux (via moisture conveyor belt) along western Luzon. In addition, increasing trends of 6.0% per decade in the mean annual number of HPE days per decade and 12.7% per decade in the annual total HPE precipitation are found to be significant in the upper 85th percentile of daily rainfall. These increases are attributed to the recent changes in WNP TC tracks.

Keywords summer monsoon; tropical cyclone; heavy precipitation events; the Philippines


1. Introduction

In the Philippines, the rainy season is officially declared at the onset of the tropical western North Pacific (WNP; 10–20°N, 110–160°E) summer monsoon period (Philippine Atmospheric, Geophysical and Astronomical Services Administration 2018; Wang 2002). The southwest monsoon, or in the local language “Haba-gat”, brings in warm moist air from the South China Sea (SCS; locally known as West Philippine Sea) along the western coastal regions of the Philippines. The southwest monsoon regime usually starts by the end of May or June and ends in September. A study by Asuncion and Jose (1980) found that approximately 43% of the country’s total rainfall occurs during this season. The onset of Habagat is also the basis used for planting calendars in most regions.
of the country, hence its importance for the management of national water resources and agriculture.

Previous studies found that there is a small but significant decreasing trend in rainfall during the summer monsoon period from 1960 to early 2010. This is likely caused by the weakening of westerly winds (Cruz et al. 2013; Villafuerte II et al. 2014). Simultaneously, the numbers of extreme events associated with the same monsoonal flow have been shown to be on the rise (Cinco et al. 2014). Other than the influence of the WNP monsoon on Philippine rainfall, TCs also play a major role in modulating summer monsoon rainfall in the Philippines. Kubota et al. (2017) found the summer monsoon onset tended to start earlier in May after the 1990s due to the influence of TC activity in the Philippine Sea and SCS. The variability of TC-induced rainfall is significantly correlated with total annual rainfall variability in northwestern Philippines. Also, the observed increasing trend in TC-induced rainfall since early 2000 led to the reversal of the reported decreasing summer monsoon rainfall trend. However, the rainfall contribution of TCs along the western Philippines is mainly due to the indirect effect of TCs, as their occurrence enhances the prevailing southwest monsoonal flow (Bagtasa 2017).

This TC-monsoon interaction resulted in heavy precipitation events along the western region of the Philippines. Cayanan et al. (2011) reported the influence of TCs on monsoonal winds and interactions with the Cordillera mountain range along western Luzon. Heisterman et al. (2013) used the then newly acquired Tagaytay C-band radar to map the rainfall distribution of a heavy precipitation event across the Manila Bay area in August of 2012. Referred to as the “2012 Habagat event”, this precipitation event was caused by the slow movement of Typhoon Haikui; located more than 1000 km away from Manila to the east of Taiwan, Typhoon Haikui caused a continuous strong monsoonal flow resulting in over 1000 mm of observed rainfall in Manila in a few days span. A year later, the “2012 Habagat event” was followed by a similar heavy precipitation that led to two heavy rainfall events with twenty-year return periods occurring on two consecutive years. During the “2013 Habagat event”, Tropical Storm Trami (locally named “Maring”) was similarly located to the east of Taiwan, strengthening the southwest monsoon flow which also led to widespread flooding, damaged properties, and loss of life in the Manila metropolis. Lagmay et al. (2015) discussed the influence of two volcanoes to the west of Manila on the spatial and temporal distribution of heavy rainfall in both the 2012 and 2013 Habagat events.

The interaction between TCs and the WNP southwestern monsoon flow can exhibit a significant effect on rainfall in certain parts of the Philippines. A researcher previously reported that the northwestern Philippines—the region where the highest TC-induced rain and TC rain contribution is found—is most affected by this TC-monsoon interaction (Bagtasa 2017). Furthermore, 44.8% of the Philippine population resides in this region (Philippine Statistics Authority 2017). This remote TC precipitation effect is usually discussed on national weather reports by the Philippine Weather Bureau, Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA). However, there is limited literature characterizing this underlying mechanism. The aim of this paper is to investigate the characteristics of TCs as well as the synoptic environment that induces heavy precipitation events along parts of the northwestern Philippines during the southwest monsoon season. The next section will describe the data and methodologies used to determine TC and monsoonal flow characteristics. The results discussed in Section 3 and Section 4 will summarize the present study.

2. Data and methodology

2.1 TC and rainfall data

In the present study, data from TCs that are formed in the WNP basin from 1958 to 2017 were gathered from the reanalyzed best track data via the website: Regional Specialized Meteorological Centre Tokyo Typhoon Center of the Japan Meteorological Agency (http://www.jma.go.jp/jma/jma-eng/jma-center/rsme- lp-pub-eg/trackarchives.html). Rainfall data from Asian Precipitation - Highly Resolved Observational Data Integration Toward Evaluation of the Water Resources (APRHODITE) Monsoon Asia, version 1101R2 (Yata-gai et al. 2012) from 1958 to 2007, and the National Climatic Data Center’s Global Summary of the Day (GSOD; http://www1.ncdc.noaa.gov/pub/data/GSOD) from 2008 to 2017 were also used. Reanalysis data of mean sea level pressure, total column water vapor flux, and 850 mb wind are from the Japanese 55-year Reanalysis (JRA55) project (Kobayashi et al. 2015), which is carried out by the Japan Meteorological Agency (JMA) at 1.25° grid resolution at 6-hour intervals (downloaded from https://rda.ucar.edu).

2.2 TC influence on rainfall

To determine if TCs influenced summer monsoonal flow in the designated region, daily rainfall data at selected synoptic stations along the western coast of
Luzon during June to September (JJAS) were used. These stations are within the climate Type I of the modified Coronas climate classification (Philippine Atmospheric, Geophysical and Astronomical Services Administration 2018). The climate Type I region, located along the western portion of the Philippines, has a distinct wet season from June to September and dry season that occurs during the remainder of the year. Thus, this region is most affected by the summer southwest monsoon period. The rainfall values of the selected stations are averaged as done in previous studies (Cayanan et al. 2011; Cruz et al. 2013). Table 1 summarizes the selected synoptic station ID, name, and locations. Figure 1 shows the station locations used in this study and the topography of the Philippines.

In the following analysis, HPE days were determined using the daily rainfall values in the upper 85th, 95th, and 99th percentiles and averaged using data from over 8 synoptic stations. It is noteworthy that a HPE percentile case would encompass the more extreme HPEs. After which, the characteristics of TCs that coincide with HPE days, as well as the prevailing synoptic environment, were analyzed.

3. Results and discussion

In this study, time periods of 1098, 366, and 73 days were determined as HPE time ranges, with daily mean rainfall in the upper 85th, 95th, and 99th percentiles respectively: hereafter referred to as HPE85, HPE95, and HPE99, respectively. Almost all HPE days (92.8 % for HPE85, 97.3 % for HPE95, and 100 % for HPE99) coincide with at least one TC occurring in the WNP region. Most of these TCs did not make landfall over any Philippine landmass. Only 140 out of the 1,098 HPE85 days (12.8 %), 50 out of the 366 HPE95 days (13.7 %), and 11 out of the 73 HPE99 days (15.1 %) experienced TCs that made landfall over the Philippines. The result in the present study is consistent with the previous finding of Cayanan et al. (2011), which found that 11 out of 13 (or 84.6 %) heavy rainfall events in western Luzon from 2002–2005 were caused by non-landfalling TCs over the ocean near the vicinity of Luzon, despite a different definition of heavy rainfall events. This suggests that while the presence of TCs in the WNP region is critical in inducing HPEs in the northwestern Philippines, heavy rainfall does not necessarily come from the immediate rainbands of a TC. In fact, since about 9 out of 10 HPEs coincide with non-landfalling TCs, the remote precipitation effect appears to be the dominant cause of HPEs. To further investigate this remote TC effect, HPE days that occur when any TC makes landfall over any Philippine landmass were removed in the following analysis.

Out of the 1,588 TCs that formed in the WNP from 1958 to 2017, 997 TCs occurred in the months of JJAS. Of which, 340 TCs (34.1 %) correlated to HPE85, 148 TCs (14.8 %) correlated to HPE95, and
28 TCs (2.8%) correlated to HPE99. Figures 2a, 2b, and 2c show the TC tracks for HPE85, HPE95, and HPE99 days, respectively. The presented TC tracks are not full tracks from the best track data, but they are tracks that are coincident with HPE days. For simultaneously occurring TCs in the WNP region, it is assumed that TCs closer to the Philippines exhibit more effect on local precipitation. Here, we removed TCs that occurred with a secondary TC when all of the location points more than 1,500 km from any Philippine landmass. This reduced the number of TCs in the analysis. However, the effect of TCs on the environment, if any, is still included in the examination of reanalysis data presented below. The resulting tracks show that HPE-induced TCs occurred within a region extending longitudinally from 100°E to 145°E and latitudinally from 10°N to 40°N. Figures 2d, 2e, and 2f show the corresponding normalized TC count density on the 2.5° × 2.5° resolution grid cells of Figs. 2a, 2b, and 2c, respectively. The density maps show that most TCs passed through the region located to the northeast of Luzon, or in the vicinity of a line segment connecting northern Luzon and Naha in Okinawa, Japan. In addition, the grid cells in the northern SCS also show considerable TC count. Most of the TCs in the northern SCS region occurred simultaneously with another TC in the WNP. Previous studies (Cayanan et al. 2011; Bagtasa 2017) on TC-monsoon-HPE interaction in the Philippines confined their analysis to the oceanic WNP region northeast of Luzon. The resulting TC tracks presented here extend the region of TCs hypothesized to cause heavy rainfall in the northwestern part of the Philippines.

In terms of intensity, Fig. 3 presents TCs classified using 6-hour interval central pressure data from the JMA best track dataset. Here, the Koba table (Koba et al. 1989) was used to relate TC central pressure with maximum wind speed. The central pressure values of TCs were partitioned as follows: > 1000 hPa are TCs with less than gale force wind and classified as a Tropical Depression (TD). Pressures of 1000 hPa to 988 hPa are classified as a Tropical Storm (TS), 988 hPa to 973 hPa as a Severe Tropical Storm (STS), 973 hPa to 910 hPa as a Typhoon (TY), and 910 hPa or less as category 4 or 5 Severe TY (STY). Table 2 shows the TC intensity count distribution (in percent-
age) for the three HPE cases. TDs and STYs comprise only of a small percentage of all HPE cases. Most TCs over the WNP Ocean—particularly to the northeast of Luzon where most TCs crossed—are of the STS or TY classification. STS and TY collectively make up a majority of TC categories at 52.3%, 49.2%, and 55.0% for HPE85, HPE95, and HPE99, respectively. However, simultaneously occurring TCs in the northern SCS are generally less intense at TS or STS categories.

Other than the presence of intense TCs to the northeast of the Philippines, weaker TCs or low-pressure systems in the northern SCS are also essential in inducing remote HPEs. Using the JRA55 reanalysis data, Fig. 4 shows the mean JJAS and composite environment of the three HPE cases. Climatological summer southwest monsoon data shown in Fig. 4a are characterized by a westerly low-level wind flow from the Indian Ocean through the Indochina region. This monsoon’s winds shift from westerly to a southwest-easterly direction in the central SCS as the winds meet the cross-equatorial jet at 110°E. The southwestward intrusion of the WNP subtropical high (not depicted in the figure) in the northern SCS in this season inhibits convection in most of the SCS. This intrusion also orients the monsoon trough in the southeastward direction from Indochina to Borneo, which places the area of active convection near the equator in the SCS (Chen et al. 2000). The summer monsoon is driven mainly by a variation in solar radiation and the differential heating of land and oceans. The area west of the Philippines is of particular interest to monsoon research as large variations in annual rain are found in this region; the onset of monsoons in this region signify the start of the large-scale Asian summer monsoon (Wang 2002).

Figures 4b, 4c, and 4d show the composite synoptic environment resulting from all HPE85, HPE95, and HPE99 days, respectively. The large environmental variability during HPE85 days did not show a signif-
significant (p < 0.05) difference from the JJAS mean zonal wind data and water vapor flux seen in the HPE95 and HPE99 days. Nevertheless, the three HPE cases show common characteristics in the prevailing environment during HPE days regardless of heavy rainfall ranking; these are as follows: 1) A strong cyclonic flow off the east coast of Taiwan. 2) A zonally-oriented eastward trough at the 1005–1007 hPa level extending to at least 135°E longitude along 20°N, which covers the northern half of the Philippines. 3) The induced trough displaces the low-level southwesterly wind flow from the central SCS to the Philippine Sea/western Pacific.
Ocean, thereby resulting to 4) a stronger zonal component of wind velocity and water vapor flux along the northwestern coasts of the Philippines. Lastly, 5) the deepening and stretching of the monsoon trough in the northern SCS that spans from northern Indochina to the Philippine Sea. TC presence in the northern SCS deepens the monsoon trough mentioned in (5). This region of low pressure enhances the convective activity in the area and confines the vertically-integrated westerly water vapor flux from the Indian Ocean along a narrow path within 10°N to 15°N in the SCS. This process significantly increased the zonal wind strength and the amount of eastward moisture transport along the SCS to the Philippine Sea over western Luzon. Kudo et al. (2014) referred to this water vapor transport as the “moisture conveyor belt” (MCB). The MCB forms when TC-induced westerlies overlap with monsoonal westerlies in the SCS. They serve as a pathway for WNP TCs to accumulate moisture from remote oceans. Other than the MCB, variations in summer monsoon westerlies can also produce short-term and sub-seasonal strong phasing due to diabatic warming in the confluent zone east of the Philippines (Holland 1995). This may explain why some HPE days did not coincide with a TC in the WNP. However, as the composite maps show the apparent presence of a TC and MCB in the HPE days, this leads to the conclusion that TCs to the northeast of the Philippines indeed caused most HPEs in western Luzon. The flux of moisture via the MCB is transported to the inner core of TCs and induces a release of latent heat near the eyewall. This typhoon-induced convective heating intensifies TCs further and induces equatorial Rossby waves (Fujiwara et al. 2017). In turn, the westward propagation of equatorial waves produces low-level westerlies in the SCS, which further intensifies the westerlies along the MCB. This TC-MCB feedback effect can sustain vapor flux into TCs. This vapor flux typically peaks at the start of the decay stage when TCs are located in the region southwest of Japan (Takakura et al. 2018). This explains why most HPE-inducing TCs are located in the region northeast of the Philippines.

The main difference between more extreme HPE cases is the eastward extent of the induced eastward trough (1005–1007 hPa) and the size of the closed isobar over the monsoon trough that extends from the northwest SCS to the northern Philippines. The synoptic environment during HPE99 days shows a larger extent of the 1002 hPa isobar that leads to a larger pressure gradient force, resulting in stronger monsoonal flow and a stronger MCB. The mean zonal component of the total column water vapor flux and 850 mb zonal wind are calculated along the northwestern Philippine coasts bounded by 12–18°N and 119–120°E. Upon comparison to the mean JJAS value of 65.9 kg m$^{-1}$ s$^{-1}$, the HPE85, HPE95, and HPE99 cases show the increased values in water vapor flux of 241.5 kg m$^{-1}$ s$^{-1}$, 415.3 kg m$^{-1}$ s$^{-1}$, and 521.6 kg m$^{-1}$ s$^{-1}$, respectively. From the JJAS mean, water vapor flux increased by 266.7 % for the HPE85 case, 530.5 % for the HPE95 case, and 691.9 % for the HPE99 case. Along the same region in the northwestern Philippines, the 850 mb mean zonal wind increased from 1.9 m s$^{-1}$ to 5.7 m s$^{-1}$ for the HPE85 case (194.3 % increase), 8.9 m s$^{-1}$ for the HPE95 case (365.1 % increase), and 10.9 m s$^{-1}$ for the HPE99 case (468.8 % increase). The increase in zonal wind and water vapor flux, coupled with the orographic forcing, is thought to produce precipitation along the western Luzon region (Cayan et al. 2011; Racoma et al. 2016).

Figures 5a and 5b show the mean annual HPE days per decade (for HPE85, HPE95, and HPE99) and the total annual HPE precipitation per decade, respectively. Statistically significant (p < 0.05) increasing trends are seen in the number of annual HPE days and total annual HPE precipitation amount per decade in the upper 85th percentile rain with r = 0.97 and r = 0.84, respectively. Annual HPE days per decade for the years 1960–1969 was at 20.7 days per year, while HPE days per decade from 2010 to 2017 (normalized to 10 years) was 26.9 days per year. This results in an increase of 29.8 % in the last 5 decades or an average of 1.3 days per year per decade. An even larger increase in the total annual HPE rainfall amount resulting from precipitation in the upper 85th percentile was observed. Total annual HPE85 rainfall increased by 63.5 % from 442 mm in the 1960’s to 722 mm in the current decade. No significant trends were observed for the HPE95 and HPE99 cases for both annual HPE days and total annual HPE rainfall amount. The increase in heavy local precipitation due to TC-monsoon interaction in the upper 85th percentile is likely due to an increase in TC count to the east of Taiwan in the recent two decades (Tu et al. 2009). This study showed that the presence of TCs in the WNP region east of Taiwan exhibits the most effect on remote precipitation in western Luzon. Changes in WNP sea surface temperature, low-level relative vorticity, precipitable water, and vertical wind shear (Chu et al. 2007) were shown to be strongly related to the northward shift of TC tracks (Wu and Wang 2004; Tu et al. 2009) toward the mid-latitudes of East Asia.
rather than a westward track to the SCS. This is particularly true for the decade after 2000. In the current decade, a higher TC count was also observed in the Philippine Sea, which likely contributed to an even higher number of annual HPE days and total HPE precipitation. The La Niña-like decadal cooling of the tropical Pacific (Kosaka and Xie 2013) may have reduced the frequency of anomalous anticyclone activity in the Philippine Sea (Lyon and Camargo 2009) that led to a larger TC count in the eastern Philippine region. In the future, as the thermal contrast between the eastern and western Pacific further intensifies, the northern hemisphere summer monsoon (Wang et al. 2012) coupled with the northward shift of TC tracks (Wu and Wang 2004) will likely cause more HPE days in a warmer globe.

4. Summary and conclusions

Tropical cyclones exhibit a significant influence on weather in the Philippines. The country’s geographic position at the western rim of the WNP basin makes it vulnerable to TC trajectories. Even though the wind speeds of TCs can be destructive, the rainfall provided by TCs provides a significant contribution to the country’s freshwater resources. According to a previous study, up to 54% of annual rainfall in the northwest region of the Philippines is TC-induced. Moreover, researchers have shown that most of TC-induced precipitation comes from TCs’ interaction with prevailing monsoons in the months of JJA (Bagtasa 2017). This study characterizes this TC-monsoon interaction. Three heavy rainfall cases were analyzed, namely precipitation in the upper 85th, 95th, and 99th percentiles of daily rainfall averaged from eight synoptic stations along the northwestern Philippines. More than nine out of ten HPE days coincide with TC occurrences in the WNP basin, indicating that TCs are essential in producing HPEs. Landfalling TCs only account for 12.8%, 13.7%, and 15.1% of HPE85, HPE95, and HPE99 days, respectively. Thus, this study focuses on the non-landfalling TCs that led to most heavy precipitation events in the northwestern Philippines. TC track density plots for all cases show that most TCs were in the vicinity of a line segment connecting northern Luzon and Okinawa in Japan. Composite synoptic conditions are shown to exhibit similar features that indicate TC enhancement via prevailing monsoons. These are summarized as follows: 1) cyclonic flow in the WNP east of Taiwan, 2) a zonally-oriented eastward trough at the 1005–1007 hPa isobar extending to at least 135°E longitude along 20°N, 3) displacement of southwesterly flow from the SCS to the Philippine Sea, 4) a 194.3–468.8% increase in zonal wind speed and 266.7–691.9% increase in total column water vapor flux along the northwestern Philippines, and 5) the deepening of the monsoon trough in the northern SCS, mostly due to simultaneously occurring TCs in that region. When the westerly wind produced by TCs to the northeast of the Philippines overlaps with the background monsoon westerlies in the SCS, strong moisture transport to the Philippine Sea is induced. Referred to as the “MCB”, this type of moisture intrusion has more influence on HPEs than climatological monsoon variability and is the main mechanism that produces nearly all HPEs in the northwestern Philippines.

An increase of 29.8% in the mean annual HPE85 days-per-decade and a 63.5% increase in total annual
HPE precipitation over the last five decades were observed. The increases in annual HPE days and precipitation are attributed to the increase in TC frequency to the east of Taiwan, which has shown to be one of the main factors in inducing remote TC precipitation to western Luzon. A third (34.1%) of all JJAS TCs in the WNP region resulted in HPE days with a rain amount in the upper 85th percentile. Thus, we can expect the number of HPE85 days to be sensitive to changes in TC activity in the WNP region; particularly, the northward shift of TC tracks that is linked to the warming of Pacific waters is most affected. In addition, rainfall anomalies were previously shown to be sensitive to SST anomalies to the west of Luzon (Dado and Takahashi 2017). The warming of SST and deepening of the ocean’s 26°C isotherm in the SCS (Sun et al. 2017) since 2000 may have also contributed to the higher HPE rainfall amount.

Heavy precipitation events resulting from TC–monsoon interaction presents a challenge to local weather forecasting in the Philippines. As shown in the present study, TCs induce remote precipitation in certain parts of the Philippines. However, not all non-landfalling TCs in the WNP basin enhance monsoon flow that leads to heavy precipitation events. In addition, the compounding effects of mesoscale orographic features (e.g., mountain range, volcanoes, etc.) that augment precipitation amounts (Lagmay et al. 2015) and modulate the local spatial and temporal distribution of heavy rainfall are difficult to quantify.

References


