Earth and Space Science

RESEARCH ARTICLE
10.1029/2020EA001623

Key Points:
- The most hazardous areas for tropical cyclones (TCs) induced rainfall are TCs within a distance of 200 km to the station
- TCs are more likely to bring torrential rainfall to a coastal station when they are in the southwest quadrant of the station
- TCs have almost no impact on rainfall when the azimuth is between 60 and 150° and distance is out of 200 km from the station

Supporting Information:
Supporting Information may be found in the online version of this article.

Correspondence to:
Q. Li, ql.li@siat.ac.cn

Abstract
Accurate prediction of tropical cyclone (TC) induced rainfall is of great importance to disaster prevention but quite challenging to operational forecasters. This study quantifies the spatial characteristics of the hourly rainfall caused by TCs at several individual weather stations over the south China coast. We use the historical TC datasets from 2004 to 2018 and the hourly rainfall data from six weather stations to investigate the stations' rainfall distribution characteristics induced by TCs within a distance of 700 km to the weather stations. The hourly rainfall data during the study period from six coastal stations: Zhuzilin (ZZL), Shekou Ferry Terminal (SFT), and Wutong Village (WTV) in Shenzhen, and Hong Kong Observatory (HKO), Sha Tin (SHA), and Tai Mo Shan (TMS) in Hong Kong are used to investigate the statistical relationship. Results show that the most hazardous areas for TC-induced rainfall are TCs within a distance of 200 km relative to the stations. High intensity TCs in the southwest quadrant may bring torrential rainfall to stations within 500 km distance, and low intensity TCs are likely to induce torrential rainfall to stations within 300 km distance when they are in the northeast and northwest quadrants. If TCs are over the region with the azimuth of 60–150° and distance out of 200 km to the six stations, there is almost no rainfall influence on those stations. The findings of this study are valuable to provide information for the local operational forecasters when predicting the potential rainfall along the south China coast due to future TCs.

1. Introduction

Why should we assume an association between extreme rainfall and landfalling tropical cyclones (LTCs)? The motive behind this is nature's most violent events induced by tropical cyclones (TCs) along the coastal regions (Dominguez & Magaña, 2018; Shu et al., 2018). The disastrous rainfall brought by TCs has received a great deal of attention because of the devastating damage such as human casualties, urban flooding, river overflow, landslides, and other forms of disastrous consequences (Li et al., 2015; Li, Lan, et al., 2016). According to (Ren et al., 2006), the extreme rainfall records associated with TCs in China are mostly in coastal regions. For example, some record-breaking intense rainfall events induced by TCs include 24-h accumulative rainfall of about 1,300 mm in southern Taiwan caused by Typhoon Morakot in 2009 (Yu & Wang, 2018). The resulting landslide covered up the whole Siaolin village of Taiwan and claimed about 600 people in this village alone (Hong et al., 2010).

Another catastrophic flooding event recorded a 24-h accumulative rainfall of 1,062 mm at Linzhung in Henan Province of Mainland China caused by landfalling Typhoon Nina in 1975, which brought about 26,000 fatalities and left approximately 10 million people without adequate shelter (Chen et al., 2004; Yang et al., 2017). In the North Indian Ocean basin, the TC named Nargis made landfall in Myanmar in 2008, which brought approximately 600 mm of rainfall, claiming a toll of 130,000 dead and missing and more than $10 billion US dollars in economic losses (Mcphaden et al., 2009). Floods from rainfall were the leading cause of death between 1970 and 2000 in the United States (Marchok et al., 2007). Therefore, such a significant influence highlights the importance of timely and accurate rainfall prediction and distribution forecasts due to landfalling TCs.

In recent years, the association between TC intensity and rainfall distribution has become a considerable interest topic (Yu & Wang, 2018). The stronger the TC intensity is, the higher the probability of heavy rainfall could occur (Rodgers & Pierce, 1995). In the prior decades or so, the TC track's prediction has significantly improved (Jun et al., 2017). However, improvements in the prediction of the rainfall intensity and
the rainfall distribution (the position of heavy rain, rainfall intensity, and spatial coverage) induced by TCs still lag behind (Knaff et al., 2005). For rainfall intensity, the hourly rainfalls of 0.1–1.5, 1.6–6.9, 7.0–14.9, 15.0–39.9, 40.0–49.9, and ≥50.0 mm are defined as light rain, moderate rain, heavy rain, torrential rain, downpour, and heavy downpour, respectively, according to the National Standard for Precipitation Grade Criterion in China (https://max.book118.com/html/2018/1028/8136000107001130.shtm). Sometimes, even when the TC track is well predicted, the rainfall intensity and distribution are often poorly predicted. Therefore, a better understanding of the factors that control the TCs’ rainfall distribution is crucial for real-time operational rainfall forecasts.

Some research studies on landfalling TC-rainfall presented that the amount of rainfall was often more substantial to the right side of the TC track as compared to the left in the north hemisphere owing to the dissimilar surface friction when TC approached the coast (Miller, 1964; Yue et al., 2015). The rainfall distribution caused by TC is asymmetric and mainly concentrates on one side of the TC track (Corbosiero & Molinari, 2003; Deng & Ritchie, 2018). Previous research (Dong et al., 2010) examined the link between TC tracks and the distribution of rainfall caused by TCs in the eastern United States and exposed that the rainfall distribution was more influential to the left side of the TC track due to its interaction between a TC and a westerly trough. These inconsistent statements show that accurately forecasting the amounts and localities of rainfall associated with TCs is a quite challenging task.

The distance between a TC and a station was found to have a significant influence on the rainfall at the station (Dominguez & Magaña, 2018; Li et al., 2015). When the TC moves far from the station, the chances of rainfall over the regions exponentially decrease (Kidder et al., 2005; Riehl & Malkus, 1961; Simpson & Riehl, 1981). Generally, the closer the TC distance is to the station, the more extreme rainfall could occur.

Different from the previous research of the rainfall distribution caused by TCs (Corbosiero & Molinari, 2003; Deng & Ritchie, 2018), which explores rainfall distribution relative to a TC’s position, this study will focus on the rainfall distribution relative to certain stations along the south China coast induced by TCs. The current study investigates the spatial characteristics of rainfall intensity, rainfall area, and the position of heavy rain at six weather stations along the southern coast brought by TCs within a distance of 700 km to the corresponding stations. Specifically, the main parameters considered in this study are the TC intensity, the TC distance, and the azimuth relative to the station. The remainder of this paper is organized as follows. The data and methodology are briefly described in Section 2. The results and discussions are presented in Section 3. Finally, Section 4 concludes the paper.

2. Data and Methodology

2.1. Study Area and Data

This study focuses on Shenzhen and Hong Kong to explore the hourly rainfall characteristics induced by TCs within 700 km to stations. The historical TC datasets for the period of 2004–2018, including TC intensity and TC position, were provided by China Meteorological Administration (CMA). The hourly rainfall data for the same period as the TCs data were obtained from six coastal automatic weather stations (AWSs), such as ZZL (Zhuzilin), SFT (Shekou Ferry Terminal), WTV (Wutong Village) in Shenzhen, and HKO (Hong Kong Observatory), SHA (Sha Tin), and TMS (Tai Mo Shan) in Hong Kong. The rainfall data at these six stations and the TC characteristics are used to build a statistical relationship. The schematic diagram of the study area (Shenzhen and Hong Kong) and the selected weather stations’ geographical features are shown in Figure 1 and Table 1.

2.2. Methodology

The leading factors which have a significant impact on both the amount and distribution of rainfall associated with landfalling TCs are the following: (a) TC intensity, (b) TC distance to the station, and (c) TC azimuth relative to the station, respectively (Dominguez & Magaña, 2018; Yu & Wang, 2018; Yue et al., 2015). The high intensity TC type mostly appears along the coastline and gradually decreases toward the inland areas. This is attributed to the fact that tropical cyclones tend to weaken after making landfall due to reduced...
energy supply and increased frictional effects (Yaukey, 2011). Generally, the TCs with higher intensities can induce more extreme rainfall in the region (Knight & Davis, 2009; Rao & Macarthur, 1994).

2.2.1. TCs Classification

TC intensity is defined as the sustained maximum wind speed near the center of a TC. According to the China Meteorological Administration (CMA), the TCs’ intensity is divided into six categories, as shown in Table 2 (Li, Xu, et al., 2016).

Due to the few numbers of Super Typhoons (SuTY) near the coastal area, SuTY is combined with severe typhoon (STY) and classified as super-severe typhoon (SSTY). Therefore, TCs are categorized into five levels in this study: SSTY, typhoon (TY), severe tropical storm (STS), tropical storm (TS), and tropical depression (TD). After TCs’ landfall, the overland durations of TS and TD are much longer than SSTY, TY, and STS. Therefore, we define TS and TD as weak TCs (or low intensity ones) in this study, while SSTY, TY, and STS are defined as intensive ones (or high intensity ones).

2.2.2. TC Distance to the Station

TCs will induce heavy rainfall if they are close enough to coastlines (Dominguez & Magaña, 2018). Generally, the closer is the TC distance to the station, the more extreme rainfall can become. Therefore, the station’s distance to the TC center is a crucial factor that can influence rainfall at the station. The distance can be calculated as follows (Maling, 1992; Meeus, 1991).

Table 1
Information of the Geographical Locations of the Six Automatic Weather Stations

| Weather station | Latitude (°N) | Longitude (°E) |
|-----------------|---------------|----------------|
| ZZL             | 22.54°        | 114.00°        |
| SFT             | 22.49°        | 113.93°        |
| WTV             | 22.59°        | 114.19°        |
| HKO             | 22.30°        | 114.17°        |
| SHA             | 22.40°        | 114.21°        |
| TMS             | 22.41°        | 114.12°        |

Abbreviations: HKO, Hong Kong Observatory; SFT, Shekou Ferry Terminal; SHA, Sha Tin; TMS, Tai Mo Shan; WTV, Wutong Village; ZZL, Zhuzilin.
In Equation 1, \( S \) represents the distance between the two positions (TC center and the weather station), \( R \) indicates the radius of the earth (in km), \( L_1 \) and \( \phi_1 \) are the longitude and latitude of the station, while \( L_2 \) and \( \phi_2 \) are the longitude and latitude of the TC center.

\[
S = R \times \frac{\pi}{180} \times \arccos\left[ \sin \phi_1 \sin \phi_2 + \cos \phi_1 \cos \phi_2 \cos (L_1 - L_2) \right] \quad (1)
\]

2.2.3. TC Azimuth Relative to the Station

The third most important parameter is the azimuth of the TC relative to the weather station that influences the rainfall distribution. According to (Miller, 1964), the amount of rainfall in the northern hemisphere was often more influential to the right side of the TC track as compared to the left when TC approached the coast. The azimuth of the TC relative to the station can be computed as follows (Maling, 1992; Meeus, 1991).

\[
\sin \alpha = \frac{\sin(90 - \phi_2)\sin(L_2 - L_1)}{\sin(\theta)} \quad (2)
\]

\[
\cos \alpha = \frac{\sin \phi_2 - \sin \phi_1 \cos \theta}{\cos \phi_1 \sin \theta} \quad (3)
\]

where \( \theta \) satisfies

\[
\cos(\theta) = \cos(90 - \phi_2)\cos(90 - \phi_1) + \sin(90 - \phi_2)\sin(90 - \phi_1)\cos(L_2 - L_1) \quad (4)
\]

With \( \cos \alpha \) and \( \sin \alpha \) known, we can get the value of \( \alpha \). It is worth noting that \( \alpha \) is a value from 0 to 360° in a clockwise direction. In this study, when \( \alpha \) is between 0 and 90°, we define the TC is in the first quadrant, and the TC is in the second quadrant when \( \alpha \) is between 90 and 180°, and the TC is in the third quadrant when \( \alpha \) is between 180 and 270°, and the TC is in the fourth quadrant when \( \alpha \) is between 270 and 360°.

2.2.4. Rainfall Distribution Figure for Stations

After computing the distance and azimuth of a TC relative to any AWS, the track of the TC relative to a station can then be plotted. Similar to Figure 3 in Li, Xu, et al. (2016), the origin of the coordinate refers to the location of a weather station. The TC position can be plotted on the polar coordinate with the computed distance and azimuth of the TC relative to any weather station. The color shade on the TC position refers to the hourly rainfall amount that the TC brings to the corresponding station. The contour plots can be created directly from the distances, azimuths, and hourly rainfalls. The corresponding referred algorithm calculation can be found on the website: https://www.originlab.com/doc/Origin-Help/Create-Contour-Graph#Algorithm_for_Creating_a_Contour_from_a_Worksheet.

3. Results and Discussions

As high intensity TCs move toward the coastal area and inland, the energy declines quickly. TCs’ intensity will generally downgrade to TS and TD, respectively. The correlation between TCs induced rainfall distribution and TCs’ intensity, TCs’ distance, and TCs’ azimuth is investigated in this section at the six weather stations.

3.1. TC Rainfall Distribution Induced by SSTYs

Figure 2 summarizes the spatial distribution of the hourly rainfall induced by SSTYs during 2004–2018 at the ZZL, SFT, and WTV in Shenzhen, and HKO, SHA, and TMS in Hong Kong. As shown in Figure 2, the dots with black color specify the locations of the historical TCs with SSTY intensity, whereas the rainfall intensity is displayed in various colors. The maximum hourly rainfall induced by TCs at six AWSs is denoted...
From Figure 1, it can be seen that the TCs in the second and third quadrants with the azimuth of 180°–250° are generally over the sea, while in the fourth and first quadrants with the azimuth of 0°–60° are generally over the land. The hourly rainfalls at the different weather stations corresponding to SSTYs intensity within a distance of 700 km are plotted in Figure 2. The outcomes from Figure 2 reveal that the SSTY is mainly located in the second and third quadrants of the six coastal stations, which are over the sea. The connection between TC intensity and rainfall in different radii of TCs was calculated by (Jiang et al., 2008), which indicated that rainfall within 150 km is more sensitive to TC intensity, especially over the sea, and insensitive to radii exceeding 400 km. The torrential (and above) rain brought by SSTYs can be seen within a distance of 200 km at all stations. In Figures 2a and 2c, SSTYs also induce torrential rainfall at the stations between 200 and 400 km in the third quadrant. In this quadrant, there is occasionally some hourly rainfall of around 10 mm hr$^{-1}$ at all these six stations brought by SSTY with a distance of approximately 600 km. The maximum hourly rainfalls induced by SSTY at these six stations are 48.1, 40.3, and 33 mm hr$^{-1}$, respectively. It is found from Figure 2 that there is no direct rainfall influence on the six stations induced by SSTY when the azimuth is between 60 and 150° with a distance out of 200 km from the station.

### 3.2. TC Rainfall Distribution Induced by TYs

The spatial distribution of the hourly rainfall induced by TYs for the same duration as SSTYs is illustrated in Figure 3. TYs within a distance of 200 km can be seen to bring torrential rain at all stations, except SFT. Figure 3 further shows TYs are likely to induce torrential and heavy rainfall between 200 and 500 km distances in the southwest quadrant, while the conditions are different when TCs are in the other three quadrants. The positions of the maximum hourly rainfall caused by TYs are similar for Figures 3d–3f in the third quadrant. Figures 3a and 3c display the maximum hourly rainfall within a 200 km distance near the station, while Figure 3b shows the maximum hourly rainfall in the first quadrant with a distance of 500–600 km.
This extreme rainfall in Figure 3b might be due to some local convective system, which is not rare in South China during this season. Figures 3c and 3f show some local rainfall in the fourth quadrant (270–330°) with a range of 100–300 km distance, but this kind of torrential rain is not induced by TYs, because no TY is passing near the region. These values are caused by interpolation. Discretion should be exercised here. Similar to SSTYs, there is no TY's influence on rainfall at the six stations when TY is at an azimuth of 60–150° and out of 200 km distance from the station.

3.3. TC Rainfall Distribution Induced by STSs

The spatial distribution of the hourly rainfall caused by STSs is shown in Figure 4. The majority of the torrential rain induced by STSs occurs within a distance of 200 km except for Figures 4b and 4f. STSs may bring patchy rain in the second and third quadrants within a distance of 200–700 km. As mentioned in the previous sections, the high intensity TCs often appear along the coastline and gradually decrease in the inland areas. This is because TCs tend to weaken after landing due to reduced energy supply and increased frictional effects (Feng & Shu, 2018). After those TYs making landfall and becoming STS, they might bring torrential rain to the nearby area, which can be seen in the first and fourth quadrants, especially for the station of ZZL (Figure 4a) and HKO (Figure 4d).

3.4. TC Rainfall Distribution Induced by TSs

Furthermore, the spatial rainfall distribution at the six weather stations of Shenzhen and Hong Kong induced by TSs is analyzed and shown in Figure 5. As seen from the figure, the rain instigated by this level of TCs is scattered. The locations of TSs are more widespread than other TCs, which can be seen in all quadrants within a distance of 700 km. As discussed in the previous section, such TCs in the first quadrant with the azimuth of 0–60° and fourth quadrants are already landed and move toward inland areas. Generally, it brings heavy rainfall to the stations when TCs are landed and close to their locations. As seen from Figure 5,
Figure 4. Same as Figure 2, but for severe tropical storms.

Figure 5. Same as Figure 2, but for tropical storms.
more rainfall is found within a 200 km distance in the quadrant from 0 to 90°. Similar to STSs, TSs may bring patchy rain to the six stations when they are in the third quadrant within a distance of 700 km.

### 3.5. TC Rainfall Distribution Induced by TDs

The spatial distribution of the hourly rainfall at those six stations associated with TDs presents a unique pattern at the different quadrants, as shown in Figure 6. Figures 6a, 6b, 6d, and 6e show that most of the torrential rainfall brought by TDs occurs within a distance of 200 km when TDs are closer to the stations' locations. Some of the precipitation can also be seen from Figures 6a and 6b at a distance over 600 km. However, the rainfall caused by this long-distance TD is not found in Figures 6c–6e and 6f. Therefore, this rainfall corresponding to the TDs with an azimuth of around 150° and a distance of nearly 700 km might be induced by the local convective system. Like the other kinds of TCs, the third quadrant is also a region for TDs that are prone to bring rainfall to the six stations; however, the rainfall level is generally milder than other TCs induced rain. Unlike other TCs, more TDs are found overland. Sometimes, this landed TD with a distance of more than 200 km might bring very intense rainfall (53.4 mm hr\(^{-1}\)) to the stations, such as shown in Figure 6b, especially when combined with the southwestern monsoon system (Cayanan et al., 2011). The distribution of rainfall caused by TD is irregular and not clear at all. Similarly, as with other TCs, there is generally no impact of TDs on rainfall when the azimuth is between 60 and 150° and the distance is out of 200 km from the stations.

### 3.6. Rainfall Frequency Induced by TCs

The analysis results in Sections 3.1–3.5 show that the rainfall at the six stations induced by TCs within the distance of 700 km to stations is unevenly distributed. When TCs are located in some quadrant, they are more likely to cause heavy rainfall at the stations, while TCs are located in another region, they almost have no rainfall impact on stations. In this section, we use the station of ZZL as an example to show precipitation frequency induced by different TCs. Figure 7 shows the rainfall frequency at the ZZL station induced...
by high intensity TCs (including SSTYs, TYs, STSs) in four quadrants with varying distances to the station. The numbers of 1, 2, 3, 4, 5, 6, 7 on the X-axis indicate the TCs distances of 0–100, 100.1–200, 200.1–300, ..., 600.1–700 km to ZZL station. The colors of dark blue, light blue, green, orange, and brown refer to 0 rain, light rain, moderate rain, heavy rain, torrential rain, and above, respectively.

Figure 7. Rainfall frequency at Zhuzilin (ZZL) station induced by high intensity tropical cyclones (TCs) (including super-severe typhoons, typhoons, severe tropical storms) in four quadrants with different distances to the station. The numbers of 1, 2, 3, 4, 5, 6, 7 on the X-axis indicate the TCs distances of 0–100, 100.1–200, 200.1–300, ..., 600.1–700 km to ZZL station. The colors of dark blue, light blue, green, orange, and brown refer to 0 rain, light rain, moderate rain, heavy rain, torrential rain, and above, respectively.

Figure 8 shows the rainfall frequency at the ZZL station induced by low intensity TCs (including TSs, TDs) in four quadrants with different distances to the station. Comparing to the high intensity TCs in Figure 7, the duration of low intensity TC to survive in the northwest quadrant is much longer. There is also a high chance for the low intensity TCs to bring rainfall to the station when they are in the third quadrant, but the probability is lower than that of the high intensity TCs. After TCs’ landfall, low intensity TCs have great chances to bring heavy rainfall to stations within a distance of 300 km to the station, as shown in Figures 8a and 8b.

Figures 2–6 show TCs almost have no impact on rainfall at the stations when the azimuth is between 60 and 150° and the distance is out of 200 km from the stations. Rainfall Frequency induced by TCs is further computed by using the ZZL station as an example. Figure 9 shows these rainfall frequencies due to SSTYs, TYs, STSs, TSs, and TDs, respectively. As shown in the figure, when TCs are over the region with the azimuth
Figure 8. Same as Figure 7, but for low intensity tropical cyclones.

Figure 9. Rainfall frequency at Zhuzilin station induced by super-severe typhoons, typhoons, severe tropical storms, tropical storms, and tropical depressions over the region with the azimuth of 60°–150° and with the distance out of 200 km from the station. The colors of dark blue, light blue, green, orange, and brown refer to 0 rain, light rain, moderate rain, heavy rain, torrential rain, and above, respectively.
between 60 and 150° and distance out of 200 km from the stations, the probability of no rainfall is 94.5%, and the probabilities of light rain, moderate rain, heavy rain, torrential rain and above are 3.3%, 1.4%, 0.58%, and 0.20%, respectively. These results confirm that there is almost no chance at the stations for rainfall disasters due to TCs when TCs are between azimuth 60–150° and out of 200 km distance to the stations.

4. Concluding Remarks

Tropical cyclone activities associated with torrential rainfall often cause disasters in South China. This study explores, for the first time, a full picture of spatial characteristics of TC-induced rainfall distribution at six automatic weather stations in Shenzhen and Hong Kong for the period of 2004–2018 associated with different TC-related parameters, including TCs’ intensity, TCs’ distance and TCs’ azimuth relative to the stations. Statistical analysis confirms that the most hazardous areas for the TC-induced rainfall are within a distance of 200 km to the station. Owing to the stochastic process of rainfall, high intensity TCs are likely to induce heavy rainfall in the range of 500 km distance to the station in the third quadrant. In comparison, low intensity TCs are prone to bring rain to the stations within a distance of 300 km when they are over land (in the first and fourth quadrants). When TCs are more remote than the above threshold, the chances of rainfall at the stations decrease. Results show that the stronger is the TC intensity, and the closer is the TC distance to the station, the more possible the extreme rainfall could occur. This study also found there is generally no rainfall influence on stations when TCs are over the region with the azimuth between 60 and 150° and distance out of 200 km from the stations.

Data Availability Statement

The data used for this paper can be available from the below repository: https://gitee.com/cas-shenzhen-x/SIAT.git.

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Acknowledgments

This research was funded by the Science and Technology Department of Guangdong Province (grant 2019B111101002) and the Innovation of Science and Technology Commission of Shenzhen Municipality Ministry with Grants JCYJ2018030518095450. Mr. Riaz Ali wishes to thank the Chinese Academy of Sciences (CAS) and the World Academy of Sciences (TWAS) for providing financial support through the 2018 CAS-TWAS President Fellowship Program.
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