Climatological Characteristics and Observed Trends of Tropical Cyclone–Induced Rainfall and Their Influences on Long-Term Rainfall Variations in Hong Kong

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ABSTRACT

This study examines the climatological features of tropical cyclone (TC) rainfall in Hong Kong in association with different TC-related parameters, and investigates the changes in TC rainfall, non-TC rainfall, and total rainfall during the past few decades in Hong Kong. On average, rainfall induced by TCs can account for about 25% of the total precipitation during summer and fall, and the contribution can be even greater in extreme cases. Composite analysis suggests that extreme TC rainfall is often related to TCs in closer proximity to Hong Kong, with higher intensity, and is associated with stronger convection and moisture convergence in the vicinity of Hong Kong.

Evaluations of the observed trends of different rainfall indices suggest that the rainfall variability in Hong Kong is considerably affected by the TC rainfall, which has a decreasing trend in frequency and intensity in recent decades. Taking out the TC rainfall from the total rainfall reveals that there is an increasing trend in daily rainfall frequency and intensity for non-TC rainfall in Hong Kong. Moreover, time-dependent generalized extreme value analysis of non-TC rainfall also reveals an increase in the return values of the maximum daily rainfall in Hong Kong. Results of this study suggest that, in order to obtain a more comprehensive picture of the long-term rainfall variations in Hong Kong, the contributions of TC rainfall should definitely be taken into account in the analysis.

1. Introduction

Located in the southeast coast of China, Hong Kong is a densely populated city with more than 7 million people. On average (1961–2010), there are about six tropical cyclones (TCs) affecting Hong Kong every year (Lee and Cheng 2012). In addition to damaging winds, the heavy downpour associated with TCs can also be hazardous and life threatening, resulting in severe landslides and flooding in low-lying areas. Some examples of torrential rain events induced by TCs in the western North Pacific (WNP) in recent years include Typhoon Morakot affecting Taiwan in 2008, Severe Tropical Storm Washi affecting Mindanao of the Philippines in 2011, and Typhoon Talas affecting Japan in 2011. Locally, the highest daily rainfall recorded at the Hong Kong Observatory (HKO) Headquarters was 534.1 mm, which happened on 19 July 1926. This phenomenal rainstorm was induced by a typhoon making landfall over the east of Hong Kong near Shantou on 18 July 1926 (Lee and Shun 2013). Moreover, the highest 6-h total rainfall and the 12-h total rainfall associated with this typhoon were 430.6 and 526.7 mm, respectively. Both of them are still the highest records to date. After the Second World War, Typhoon Sam was the wettest TC to affect Hong Kong. It brought more than 600 mm accumulated rainfall in August 1999 (Campbell 2005; HKO 2011). The heavy rain led to more than 300 cases of flooding and 160 landslides and resulted in four deaths, hundreds of injuries, and over $200 million in economic losses in Hong Kong (Campbell 2005). Because of such impacts, understanding and accurately predicting rainfall induced by TCs is of utmost importance for advanced planning and risk mitigation.

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The influence of climate change on extreme rainfall is also one of the major concerns of climate change adaptation and disaster preparedness. With the troposphere getting warmer, the maximum moisture content of the atmosphere increases with rising temperature. This will likely affect the chance of occurrence of such extreme rainfall events in the long term (Lenderink et al. 2011; Utsumi et al. 2011; Fujibe 2013). Previous studies have found that both the annual rainfall and the frequency of heavy precipitation events exhibit a long-term increasing trend in Hong Kong as well as in southern China (Zhang et al. 2009; Ginn et al. 2010; Wong et al. 2011). Based on the outputs of global climate models of the Intergovernmental Panel on Climate Change (IPCC), extreme rainfall events are also projected to be more frequent and intense in Hong Kong under future global warming scenarios (Parry et al. 2007; Lee et al. 2011). While most previous studies consider total rainfall as a whole, the influences of rainfall induced by TCs are relatively less explored. We know that TCs are an important rainfall source (Chin 1968), but it remains uncertain to what extent TC rainfall contributes to the overall rainfall variability in Hong Kong. Recently, more studies have begun to realize the importance of TC rainfall in shaping overall rainfall characteristics (Lau et al. 2008; Kubota and Wang 2009; Chang et al. 2012; Li and Zhou 2015). For instance, Lau et al. (2008) showed that TCs are responsible for an increase in extreme rainfall events in both the North Atlantic and the WNP, while Kubota and Wang (2009) revealed the substantial contributions of TCs to seasonal and interannual rainfall variability over the WNP. Chang et al. (2012) further stressed the nontrivial role of TCs in shaping the overall precipitation trends over China. Their results suggest that without explicit separation of TC rainfall, the overall trends in extreme rainfall tend to be either overestimated or underestimated in different parts of China. More recently, Li and Zhou (2015) found that TC rainfall varies concomitantly with total rainfall at interdecadal time scales and can account for more than 40% of the total rainfall anomalies over the coastal region of southeast China. In view of the significant role of TCs, a comprehensive study is thus essential to better understand the impacts and contributions of TCs to the overall rainfall variability in Hong Kong.

The objectives of this study are twofold: 1) to examine the climatological features of TC rainfall in Hong Kong in association with different TC-related parameters and 2) to investigate the changes in TC and non-TC rainfall as well as total rainfall during the past few decades in Hong Kong. The rest of this paper is organized as follows. Section 2 introduces the data and methodology used in this study; the climatology and characteristics of local rainfall induced by TCs are examined in section 3. Section 4 investigates the observed precipitation trends in Hong Kong by considering TC and non-TC rainfall components separately, while the possible causes associated with such changes are presented in section 5. Finally, section 6 discusses and summarizes the results.

2. Data and methodology

a. Data

Daily rainfall data recorded at the HKO Headquarters during 1961–2012 were used as local-scale observational data to investigate the climatology and trends of rainfall in Hong Kong. The TC dataset during the same period was acquired from the HKO at 6-h intervals. In addition, based on the availability of routine satellite observations, daily averaged $2.5^\circ \times 2.5^\circ$ outgoing longwave radiation (OLR), which is used as a proxy of convection, was archived from National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites for the period 1975–2012 (Liebmann and Smith 1996). Daily atmospheric data including wind and specific humidity during 1961–2012 were obtained from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996).

b. TC rainfall estimation

Until now, TC rainfall has commonly been defined as the rainfall recorded when TCs come within the effective radius of a station (Lau et al. 2008; Chen et al. 2010; Chen and Chen 2011; Chen et al. 2012; Kubota and Wang 2009; Li and Zhou 2015). Although values ranging from 250 to 1000 km have previously been used to define such a radius, no consensus has been reached regarding its optimum value. To estimate the effective radius of influence, Fig. 1 shows the mean daily rainfall recorded at HKO as a function of the distance between the HKO Headquarters and the TC center. A noticeable feature here is the exponential reduction in local rainfall with increasing distance from the TC center. The influence of TCs is most pronounced when TCs lie within a 300-km radius of Hong Kong. At distances greater than 300 km, however, the mean rainfall recorded in Hong Kong drops rapidly to 12 mm day$^{-1}$ with the curve starting to level off, indicating a significant weakening of TC influence on local rainfall beyond this range. Therefore, in this study, daily rainfall recorded in Hong Kong is classified as TC rainfall when TCs fall within a radial distance of 300 km from the station. Such a definition is also in line with that of most previous studies (Frank 1977; Rodgers et al. 2000; Chen et al. 2010; Chen and Chen 2011). The remaining precipitation is treated as non-TC rainfall and is obtained by subtracting the TC rainfall from the total rainfall. Non-TC rainfall in Hong Kong is typically associated with a surface monsoon trough, midtropospheric westerly jet,
active southwest monsoon, and land–sea breeze convergence as well as frontal systems.

c. Rainfall indices

A number of rainfall-related indices, which have been widely used in previous studies (e.g., Lee et al. 2011; Wong et al. 2011), have been employed to investigate the changes in precipitation in Hong Kong. These include the following:

1) annual rainfall frequency with daily rainfall greater than or equal to 100 mm (R100; units: days),
2) annual rainfall frequency with daily rainfall between 50 and 100 mm (R50; units: days),
3) annual rainfall frequency with daily rainfall between 1 and 50 mm (R1; units: days),
4) total annual rainfall frequency with daily rainfall greater than or equal to 1 mm (Rtotal; units: days),
5) annual maximum daily rainfall (Rmax; units: mm), and
6) mean daily rainfall intensity (RI; units: mm day$^{-1}$), which is derived from the annual rainfall total divided by the total annual rainfall frequency.

All these indices are extracted based on the rainfall data from the HKO Headquarters unless otherwise stated.

3. Climatological characteristics of TC-induced rainfall in Hong Kong

Before analyzing the observed rainfall trends in Hong Kong, we first examine the variations of local rainfall induced by TCs from a climatological perspective. The seasonality of TC rainfall, as well as different related factors, including TC tracks, TC intensity, and the background moisture circulations, will be illustrated and discussed one by one.

a. Monthly distribution

Figures 2a–f show the monthly distribution of the magnitude and frequency of total rainfall, non-TC rainfall, and TC rainfall in Hong Kong during 1961–2012. In general, all three types of rainfall depict clear seasonality, with both the amount and frequency attaining their corresponding maxima during boreal summer. The major rainy season
FIG. 2. Monthly distribution of the amount (mm month$^{-1}$) and frequency (days month$^{-1}$) of (a), (b) total rainfall; (c), (d) non-TC rainfall; and (e), (f) TC rainfall in Hong Kong during 1961–2012. (g), (h) The corresponding percentage contributions of TC rainfall to total rainfall. Rainfall frequencies with daily rainfall $\geq 100$ mm, $100 >$ daily rainfall $\geq 50$ mm, and $50 >$ daily rainfall $\geq 1$ mm, as well as their total, are denoted by green, red, blue, and purple lines, respectively. For (h), there was only one day in December on which over 100 mm of rainfall was recorded, which was brought by Typhoon Irma on 2 Dec 1974.
in Hong Kong spans May–September (Figs. 2a,b), with an average of 1809 mm of precipitation and 68 rainfall days recorded during this period, constituting about 79% and 67% of the annual total (2297 mm and 102 days), respectively. The seasonal variation of non-TC rainfall is similar to that of total rainfall, which reveals double peaks in both the precipitation amount and frequency in June and August (Figs. 2c,d). TC rainfall, on the other hand, increases remarkably after June and reaches its peak during July–September (Figs. 2e,f). An examination of the relative contributions of TC rainfall in Figs. 2g and 2h shows that the highest TC contribution occurs during summer and fall (July–October). On average, TCs can account for about 25% of the total rainfall during July–October (Fig. 2g), and the contribution can be even greater in extreme cases (Fig. 2h). As shown in Fig. 2h, more than 40% of the extreme rainfall days (daily rainfall ≥100 mm) in Hong Kong during summer and fall are actually contributed by TCs, suggesting the nonnegligible role of TCs in controlling the overall rainfall variability. The considerable contributions of TC rainfall to total rainfall may affect the overall interpretations of local rainfall trends, as will be discussed in more detail in section 4.

b. TC rainfall in relation to TC tracks and positions

To find out how the variations in TC tracks affect the magnitude of rainfall induced by TCs, composite analysis is carried out. TC rainfall is subdivided into three groups based on the intensity of daily rainfall. Cases with daily rainfall greater than or equal to 100 mm are classified as extreme, while those with daily rainfall between 50 and 100 mm and between 1 and 50 mm are considered moderate and weak cases, respectively. Figure 3 shows the distributions of TC tracks for each of the three TC rainfall groups, while Fig. 4 reveals the probability...
density estimates of TC locations during the TC rainfall days. Altogether there are 181 TCs that induce local rainfall in Hong Kong during 1961–2012. Among these, 26% (47 TCs) are extreme cases, while 22% (39 TCs) and 52% (95 TCs) are associated with moderate and weak local rainfall, respectively. It is observed that more than 50% of TCs that initiate more than 100 mm of daily rainfall make a direct hit in Hong Kong (Fig. 3b). Extreme rainfall tends to fall locally when TCs are situated at a mean position of 22.1°N, 113.8°E (Fig. 4a). On the other hand, a noticeable southward shift of the prevailing tracks can be seen for TCs with weaker local rainfall intensities (Figs. 3c–f). The majority of TCs tend to cluster in the area south of Hong Kong (21.6°N, 113.8°E) for moderate rainfall cases (Fig. 4b), while the mean TC location displaces farther southward, to 20.7°N, 114.4°E, for weak rainfall cases (Fig. 4c). These results indicate that TC rainfall in Hong Kong is rather sensitive to even slight changes in TC track and position. Overall, the closer the TCs are to Hong Kong, the more severe the local rainfall. A slight southward shift in the tracks and positions of the associated TCs will result in a substantial reduction in the amount of local rainfall in Hong Kong.

c. TC rainfall in relation to TC intensity

Another factor that may also affect TC rainfall is the TC intensity. Previous studies suggest that the instantaneous TC rainfall increases with storm intensity and that the inner-core mean rain rate of major hurricanes is about 2–3 times larger than that of a tropical storm (Rodgers et al. 1994; Rodgers and Pierce 1995; Jiang et al. 2008). As such, we also look into the relationship between TC rainfall severity and TC intensity. As illustrated in Fig. 5, heavier TC rainfall in Hong Kong is associated with TCs of higher intensity. The mean maximum sustained wind speed associated with extreme and moderate TC rainfall is 56 and 53 kt (1 kt = 0.5144 m s⁻¹), respectively, which are significantly greater than that of the weak rainfall group (47 kt) at 99% confidence based on the Student’s t test. The positive relationship between TC rainfall and TC intensity is basically in accord with previous studies (Rodgers and Pierce 1995; Jiang et al. 2008). Besides, Rodgers and Pierce (1995) previously noticed that the correlation between the mean rain rate and the maximum wind speed increases most significantly as TCs intensify from the stage of depression to tropical storm, while the correlation becomes weaker for more intense TCs. Similar to their results, the smaller difference in TC intensity associated with the extreme and moderate rainfall groups suggests that other factors, such as TC tracks and moisture circulations, might play a dominant role in modulating TC rainfall when TCs become more intense.
d. TC rainfall in relation to moisture circulations

Apart from the TC tracks and TC intensity, large-scale environmental circulations are also examined to see if discrepancies exist between different rainfall cases. Here, the OLR and the vertically integrated moisture flux and moisture divergence are used as a proxy for convection and moisture circulations (e.g., Frank 1977; Rodgers et al. 1994; Zhou and Chan 2005; Li et al. 2012). As shown in Fig. 6a, Hong Kong is situated at the center of the enhanced convection for the extreme rainfall cases. At the same time, it is also subjected to
strengthened southwesterly moisture flux from the Bay of Bengal and southeasterly moisture flux from the WNP (Fig. 6b), which results in an increased moisture convergence over the region, providing a favorable environmental background and rich moisture supply for heavy precipitation events. In contrast, for moderate and weak rainfall cases (Figs. 6c,e), the convective center is weakened and displaced southward in association with the concomitant southward shift in the TC tracks (Fig. 3). Meanwhile, further weakening in the moisture convergence can also be observed, with the moisture transport from the WNP being greatly suppressed (Figs. 6d,f). The weakening of convection and moisture transport is especially prominent for the weak TC rainfall cases, which greatly reduce the moisture content of TCs, leading to a decrease in TC rainfall in Hong Kong. Frank (1977) studied the water vapor budget of TCs in the WNP and found that water vapor convergence can explain almost 75% of the total precipitation within a radius of about 222 km from TC centers. Our results here are consistent with those of Frank (1977) and show that the strength and position of the convection and moisture convergence play an important role in controlling the amount of TC rainfall in Hong Kong.

4. Observed trends in TC, non-TC, and total rainfall in Hong Kong

Given the significant contributions of TC rainfall to the total rainfall in Hong Kong, this section proceeds to analyze the observed trends of different rainfall indices in Hong Kong by considering the TC and non-TC components separately. A linear regression method has been adopted to determine the trends of different indices and a two-tailed Student’s t test has been applied to test the statistical significance of the associated trends in this study (von Storch and Zwiers 1999; Ginn et al. 2010; Wong et al. 2011).

a. Annual rainfall frequency (R100, R50, R1, Rtotal)

Figure 7 depicts the variations of TC, non-TC, and total rainfall frequency during 1961–2012, while Table 1 summarizes the corresponding 52-yr linear trends. For daily rainfall ≥100 mm, the total rainfall reveals an insignificant 52-yr upward trend of 0.9 days (Fig. 7a). Thus, considering only the total rainfall will give the illusion that there was no obvious change with regard to the annual rainfall frequency in Hong Kong since 1960. Yet if we consider TC and non-TC components separately, a different picture emerges. A significant decreasing trend of 0.7 days (52 yr)−1 is found for the TC rainfall frequency (Fig. 7c), whereas the non-TC rainfall alternatively depicts a significant increasing trend of +1.5 days (52 yr)−1 during 1961–2012 (Fig. 7i). That is, the decreasing TC rainfall frequency actually results in an underestimation of the positive trends in the frequency of non-TC rainfall of approximately 67% (Table 1). In other words, the observed changes in R100 associated with non-TC rainfall should be far more vigorous than what we would expect by simply considering the total rainfall.

Similar results can also be obtained for R50, R1, and Rtotal. The TC rainfall frequency exhibits a negative tendency of −1.1, −0.6, and −2.4 days (52 yr)−1 with respect to R50, R1, and Rtotal, respectively, with the decreasing trends in R50 and Rtotal being significant at 95% and 90% confidence (Fig. 7 and Table 1). In contrast, the trends associated with total as well as non-TC rainfall are generally positive (except R1), with the rate of change of non-TC rainfall being greater than that of total rainfall (Table 1). Overall, TC rainfall frequency tends to vary inversely with the non-TC rainfall counterparts. The net effect is that rainfall induced by TCs cause a considerable underestimation of non-TC rainfall in Hong Kong, as shown clearly in Table 1.

b. Annual maximum daily rainfall and mean daily rainfall intensity (Rmax, R1)

Apart from the rainfall frequency, the annual maximum daily rainfall and mean daily rainfall intensity are also investigated to identify their corresponding changes in recent decades. As shown in Fig. 8 and Table 2, the annual maximum daily rainfall of total rainfall is characterized by a decreasing trend of −3.14 mm (52 yr)−1 in Rmax, even though the trend is not significant. Such a decrease in maximum daily rainfall is mainly attributed to the decrease in TC rainfall category which has a significant negative trend of −50.8 mm (52 yr)−1 in recent decades. However, after removing the TC rainfall, the non-TC rainfall actually demonstrates an overall increase in Rmax [+15.0 mm (52 yr)−1]. Similar opposite trends in TC and non-TC rainfall are also observed in RI. Compared to the insignificant change in the mean daily rainfall intensity of total rainfall [2.7 mm day−1 (52 yr)−1], the non-TC rainfall reveals a significant increasing trend of 4.6 mm day−1 (52 yr)−1 in RI when TC rainfall is removed. Overall, our results here show that the non-TC rainfall in Hong Kong has become far more intense than what we might have expected by merely considering total rainfall as a whole.

c. Return values and return periods of maximum daily rainfall

As an extension, it is also of interest to further investigate the variations of the return values and return
periods associated with the extreme daily rainfall in Hong Kong. The long-term trend of the probability of occurrence of maximum daily rainfall in Hong Kong can be determined by the time-dependent generalized extreme value (GEV) distribution technique (Coles 2001).

The time-dependent GEV distribution has three model parameters, including the location parameter $\mu$, the scale parameter $\sigma$, and the shape parameter $\xi$, which vary linearly with time and are suitable for modeling the changes in extreme values that may exhibit trends with

<table>
<thead>
<tr>
<th>Trend [day (52 yr)$^{-1}$]</th>
<th>Total rainfall</th>
<th>TC rainfall</th>
<th>Non-TC rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily rainfall $\geq 100$ mm (R100)</td>
<td>0.9</td>
<td>$-0.7^*$</td>
<td>1.5$^*$</td>
</tr>
<tr>
<td>100 $&gt;$ daily rainfall $\geq 50$ mm (R50)</td>
<td>1.9</td>
<td>$-1.1^*$</td>
<td>3.0$^{**}$</td>
</tr>
<tr>
<td>50 $&gt;$ daily rainfall $\geq 1$ mm (R1)</td>
<td>$-1.1$</td>
<td>$-0.6$</td>
<td>$-0.5$</td>
</tr>
<tr>
<td>Total (Rtotal)</td>
<td>1.6</td>
<td>$-2.4^*$</td>
<td>4.0</td>
</tr>
</tbody>
</table>

TABLE 1. The 52-yr linear trends of annual total rainfall frequency, TC rainfall frequency, and non-TC rainfall frequency in Hong Kong during 1961–2012. Trends that are statistically significant at 90% and 95% confidence are denoted by * and **, respectively.
respect to time (Kharin and Zwiers 2005; Feng et al. 2007; Wong et al. 2011). This technique has also been previously adopted for examining the changes in extreme daily rainfall in China (Feng et al. 2007), Hong Kong (Wong et al. 2011), and South Korea (Park et al. 2011). Readers can refer to Kharin and Zwiers (2005) or Wong et al. (2011) for detailed descriptions of the technique.

Figure 9 shows the GEV fits and the associated trends of the 10- and 20-yr return values of the maximum daily TC rainfall, non-TC rainfall, and total rainfall during 1961–2012. Both the 10- and 20-yr return values of the total rainfall demonstrate a significant decreasing trend of $-14$ and $-12\ mm\ decade^{-1}$, respectively (Fig. 9a). Nevertheless, when TC rainfall is removed, the 10- and 20-yr return values of non-TC rainfall have a significant upward trend of 12 and 15 mm decade$^{-1}$, respectively (Fig. 9c). Again, without further isolation of the TC and non-TC rainfall components, the increasing trend of the return values associated with non-TC rainfall will be masked. Figure 10 further shows the variations of the return values against return periods for TC rainfall, non-TC rainfall, and total rainfall in 1961 and 2012. It is observed that both TC rainfall and total rainfall are characterized by a lengthening of the return periods in 2012. Conversely, without the contribution of TCs, it is found that the return periods of non-TC rainfall are actually shortened in 2012 compared to those in 1961. For instance, the return period for maximum daily rainfall ≥350 mm associated with non-TC rainfall shortens from 28 years in 1961 to 13 years in 2012, whereas it otherwise would be expected to rise from 10 years in 1961 to 44 years in 2012 if only total rainfall were considered (Table 3). As such, explicit separation of total rainfall into TC and non-TC components can therefore provide a more accurate estimate of the rainfall variability in Hong Kong.

5. Attributions of TC and non-TC rainfall changes

To proceed further, it is also worth pointing out that the mutually opposite trends of TC and non-TC rainfall in Hong Kong can be physically explained by the corresponding changes in TC activity and background moisture supply. Following Yokoi and Takayabu (2013) and Murakami et al. (2013), the climatology (indicated by overbars) and changes (indicated by prime symbols) in TC passage frequency (TPF) in each $5^\circ \times 5^\circ$ grid in the WNP can be expressed as

<table>
<thead>
<tr>
<th>Trend</th>
<th>Total rainfall</th>
<th>TC rainfall</th>
<th>Non-TC rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual maximum daily rainfall [mm (52 yr)$^{-1}$]</td>
<td>$-31.4$</td>
<td>$-50.8^{*}$</td>
<td>$15.0$</td>
</tr>
<tr>
<td>Mean daily rainfall intensity [mm day$^{-1}$ (52 yr)$^{-1}$]</td>
<td>$2.7$</td>
<td>$-15.1$</td>
<td>$4.6^{**}$</td>
</tr>
</tbody>
</table>
TPF\((A)\) = \(\int_C g(A_0) \tilde{t}(A, A_0) \, dA_0\) \hspace{1cm} (1)

and

\[
\begin{align*}
\text{TPF}'(A) &= \int_C g'(A_0) \tilde{t}(A, A_0) \, dA_0 \\
&+ \int_C g(A_0) t'(A, A_0) \, dA_0 \\
&+ \int_C g'(A_0) t'(A, A_0) \, dA_0,
\end{align*}
\hspace{1cm} (2)
\]

respectively, where \(g(A_0)\) is the frequency of cyclogenesis in grid cell \(A_0\), \(\tilde{t}(A, A_0)\) is the probability that a TC formed in grid cell \(A_0\) passes through grid cell \(A\), and \(C\) is the domain of integration, which spans the entire WNP. The first term on the right-hand side of Eq. (2) indicates how the changes in TC genesis contribute to the anomalous TPF under the condition that the TC track is unchanged. The second term denotes the contributions from anomalous TC track, while the third term represents the nonlinear process associated with both the genesis and the track changes. In this way, changes in TPF can be decomposed and attributed to three factors, namely the genesis effect (first term), the track effect (second term), and the nonlinear effect (third term).

As shown in Fig. 11, the annual TPF exhibited a significant negative trend over southern China in the vicinity of Hong Kong during 1961–2012, which can be attributed primarily to the negative genesis and track effects over the WNP. In fact, similar changes in TPF have also been noted by a number of previous studies (Ho et al. 2004; Wu et al. 2005; Tu et al. 2009; Lee et al. 2012), which suggested that the change in prevailing TC tracks in the last few decades is likely due to the change in the steering flow pattern in the midtroposphere with an anomalous cyclonic circulation over eastern China. The anomalous westerlies over the northern part of the South China Sea (SCS) favor fewer TCs moving toward the SCS and more TCs recurving toward Taiwan, Japan, and the Korean peninsula. Since the northwestward-migrating TCs in the region just south of Hong Kong are often associated with heavier local rainfall (Fig. 3), a significant reduction in TPF over this region is one of the main reasons for the recent reduction in TC rainfall frequency and intensity in Hong Kong. The opposite increasing trend of non-TC rainfall in Hong Kong, however, is possibly related to the remarkable southward shift of the major rain belt from northern to southern China in recent decades, as reported extensively in a number of previous studies (Ding et al. 2008, 2009; Wu et al. 2010; Li et al. 2012). Consistent with such a shift, strengthening of
the moisture convergence is observed over southern China (Fig. 11e), contributing to the generally more frequent and intense non-TC rainfall during recent decades in Hong Kong.

6. Discussion and summary

This study examines the climatological features of TC rainfall in Hong Kong in association with different TC-related parameters and investigates the changes in TC rainfall, non-TC rainfall, and total rainfall during the past few decades in Hong Kong. On average, TC rainfall accounts for about 25% of the total rainfall in Hong Kong during summer and fall, and the contribution is even greater for extreme rainfall. Composite analysis suggests that extreme rainfall induced by TCs is often related to TCs that are in closer proximity to Hong Kong, have higher intensity, and are associated with stronger convection and moisture convergence in the vicinity of Hong Kong. On the other hand, a slight southward shift in the tracks and mean positions of the TCs and a weakening in moisture transport, especially from the WNP, will result in a substantial reduction in the amount of local rainfall in Hong Kong.

In addition, the observed trends of different rainfall indices in association with TC rainfall, non-TC rainfall, and total rainfall have also been assessed and evaluated. Here, we have shown that the rainfall variability in Hong Kong is significantly affected by TC rainfall, which has a decreasing trend in frequency and intensity in recent decades. By removing the TC rainfall from the total rainfall, the non-TC rainfall in Hong Kong shows a more prominent increasing trend in rainfall frequency and intensity. Moreover, time-dependent GEV analysis of non-TC rainfall also reveals an increase in the return value of the maximum daily rainfall in Hong Kong. Overall, our results demonstrate that non-TC rainfall in Hong Kong has become far more frequent and intense in recent decades than what we would expect by simply considering the total rainfall. Therefore, the contribution of TC rainfall should definitely be taken into account when analyzing the rainfall variability in Hong Kong in order to obtain a more complete picture.

To further account for the mutually opposite trends of TC and non-TC rainfall in Hong Kong in recent decades, the corresponding changes in TC activity and background moisture supply have been subsequently examined. It has

### Table 3. Return periods for maximum daily rainfall ≥350 mm associated with total rainfall, TC rainfall, and non-TC rainfall in Hong Kong in 1961 and 2012.

<table>
<thead>
<tr>
<th>Return period (yr) for maximum daily rainfall ≥350 mm</th>
<th>Total rainfall</th>
<th>TC rainfall</th>
<th>Non-TC rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961</td>
<td>10</td>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td>2012</td>
<td>44</td>
<td>55</td>
<td>13</td>
</tr>
</tbody>
</table>
been revealed that the recent reduction in TC rainfall frequency and intensity in Hong Kong can be attributed to the significant reduction in TPF over southeast China as a result of the negative genesis and track effects in the WNP, while the increase in non-TC rainfall is possibly linked to the strengthening of moisture convergence over southern China in association with the southward shift of the major rain belt in recent decades. Since there are considerable interannual and interdecadal variations in TC activity (Liu and Chan, 2008) and the available 52-yr TC data may still be relatively short for conclusively determining the associated long-term trends, further observations and research will still be required to understand the influence and contribution of natural variability and anthropogenic warming on TC track and rainfall changes in the WNP. It is also worth pointing out that this study only focuses on rainfall induced directly by TCs, while the remote effects of TCs on precipitation have not been considered.

![FIG. 11. Linear trends of (a) TC passage frequency anomalies, (b) the genesis effect \([\int g'(A_0) R(A, A_0) dA_0]\), (c) the track effect \([\int g'(A_0) R'(A, A_0) dA_0]\), (d) the nonlinear effect \([\int g'(A_0) R'(A, A_0) dA_0]\), and (e) 1000–300-hPa vertically integrated moisture flux divergence during 1961–2012. Unit for (a)–(d) is counts per decade and for (e) is \(10^{-5} \text{ kg m}^{-2} \text{s}^{-1} \text{ decade}^{-1}\). Dots denote trends that are statistically significant at 90% confidence.](image-url)
(Wang et al. 2009; Byun and Lee 2012). The remote influences of TCs on local rainfall and the interactions with different synoptic systems will be the main theme of our future research.

To recapitulate, this study has highlighted the importance of the explicit characterization of rainfall variability in Hong Kong in terms of the TC and non-TC rainfall components. The results are geared toward an improved interpretation and better understanding of the observed rainfall trends for risk and impact assessments in Hong Kong.

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