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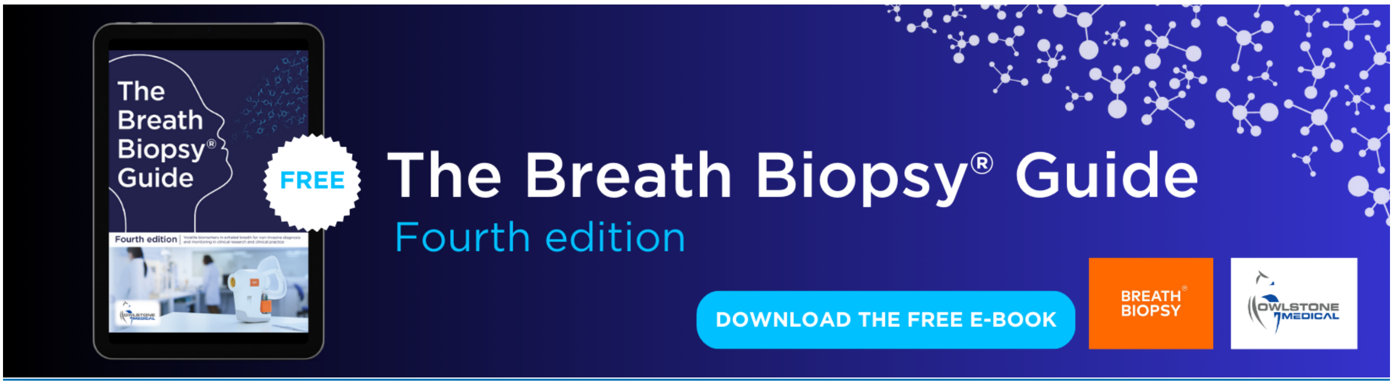

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Changes in precipitation frequency and intensity in the vicinity of Taiwan: typhoon versus non-typhoon events

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Abstract
The hourly rainfall at 21 ground stations in Taiwan is used to investigate changes in the frequency, intensity, and duration of rainfall, which can be divided into typhoon and non-typhoon rainfall, in the period of 1970–2010. As a whole, the frequency of rainfall shows a decreasing trend for lighter rain and an increasing trend for heavier rain. Also, the typhoon rainfall shows a significant increase for all intensities, while the non-typhoon rainfall exhibits a general trend of decreasing, particularly for lighter rain. In rainfall intensity, both typhoon and non-typhoon rainfall extremes become more intense, with an increased rate much greater than the Clausius–Clapeyron thermal scaling. Moreover, rainfall extremes associated with typhoons have tended to affect Taiwan rainfall for longer in recent decades. The more frequent, intense and long-lasting typhoon rainfall is mainly induced by the slower translation speed of the typhoons over the neighborhood of Taiwan, which could be associated with a weakening of steering flow in the western North Pacific and the northern South China Sea.

Keywords: typhoon, rainfall extreme, frequency, intensity, climate changes, global warming

1. Introduction

In the past few decades, the global hydrological cycle has been undergoing major changes, which include precipitation amount, frequency, intensity and duration (see, e.g., Trenberth *et al* 2007). These changes, particularly in rainfall extremes, can cause severe droughts and floods, which have tremendous impacts on the ecosystem and human societies. Various studies show a shift in distribution toward more intense rainfall events, i.e., less light rain and more heavy rain (see, e.g., Hsu and Chen 2002, Fujibe *et al* 2005, Lenderink and Meijgaard 2008, Liu *et al* 2009, Min *et al* 2011). These changes are not only found in observations but also in climate model simulations, and are mainly attributed to global warming (see, e.g., Emori and Brown 2005, Kharin *et al* 2007, Meehl *et al* 2007, Sun *et al* 2007, O'Gorman and Schneider 2009, Allan *et al* 2010, Sugiyama *et al* 2010, Kao and Ganguly 2011, Chou *et al* 2012).

Under global warming, two major effects can influence rainfall frequency and intensity: the thermodynamic and dynamic contributions (Emori and Brown 2005, Held and Soden 2006, Chou *et al* 2009b), due to changes in water vapor and vertical motion, respectively. Changes in atmospheric water vapor roughly follow the Clausius–Clapeyron thermal scaling at constant relative humidity with a rate of around 7% per 1 °C surface warming (Allen and Ingram 2002, Trenberth *et al* 2003), so the thermodynamic contribution is close to but slightly smaller than the rate of 7% per 1 °C surface warming (O'Gorman and Schneider 2009, Chou *et al* 2012). The dynamic contribution, on the other hand, is generally negative to precipitation, which is associated with the weakening of tropical circulation (Held and Soden 2006, Vecchi and Soden 2007, Chou and Chen 2010). However, the dynamic contribution could be positive to rainfall extremes (Sugiyama *et al* 2010, Chou *et al* 2012), so changes in the intensity of rainfall extremes are often found to be greater than the Clausius–Clapeyron thermal scaling (Lenderink and Meijgaard 2008, Liu *et al* 2009, Min *et al* 2011).

Changes in rainfall intensity and frequency could vary with space, due to the dynamic contribution (Chen *et al* 2012), which could be related to the local boundary condition and large-scale environment. In other words, rainfall intensity and frequency may not always increase even with uniform surface warming. In this study, we focus on rainfall in Taiwan, which is located in the western North Pacific–East Asian (WNP–EA) sector. Over the WNP–EA region, the Asian monsoon and typhoons are the two most important systems for producing precipitation (Chou *et al* 2009a, Chen *et al* 2010), with the typhoon-induced rainfall accounting for 50–60% of the total rainfall between 18°N and 26°N along 125°E during the July to October period (Kubota and Wang 2009). Taiwan is located in a region dominated by two prevailing typhoon tracks (Tu *et al* 2009), and the typhoon-related rainfall accounts for 47.5% of the total annual rainfall (Chen *et al* 2010). Hence, the rainfall should be influenced by not only global warming-induced thermodynamic and dynamic contributions, but also changes in typhoon characteristics in the WNP, such as the translation speed and prevailing track. Thus, we should first separate Taiwan rainfall into typhoon-induced rainfall and others, i.e., non-typhoon rainfall.

In this study, we briefly introduce the data sets used here. In order to distinguish rainfall with and without typhoon influence, typhoons that affect Taiwan rainfall are also defined in section 2. The changes of typhoon and non-typhoon rainfall frequency, intensity and duration between the two epochs of 1970–89 and 1990–2009 are then examined in section 3. A discussion of the causes for these changes is given in section 4, followed by conclusions.

2. The data and method

In order to quantitatively calculate changes in rainfall frequency and intensity, hourly rainfall at 21 ground stations obtained from the Central Weather Bureau (CWB) in Taiwan was used in this study. These stations are distributed throughout the entire Taiwan region, and therefore they are able to represent the changes of rainfall characteristics in Taiwan to a fair extent. The best track typhoon data set from the Joint Typhoon Warning Center (JTWC) was also used to distinguish typhoon and non-typhoon rainfall from the hourly rainfall used here. Both data sets cover the period of 1970–2010.

Figure 1(a) shows the spatial distribution of typhoon frequency climatology in the WNP and the South China Sea (SCS) in the period of 1970–2010. The contour interval is 0.5 per year per grid box (2.5° × 2.5°). Taiwan is located within the major typhoon activity region and around the turning point

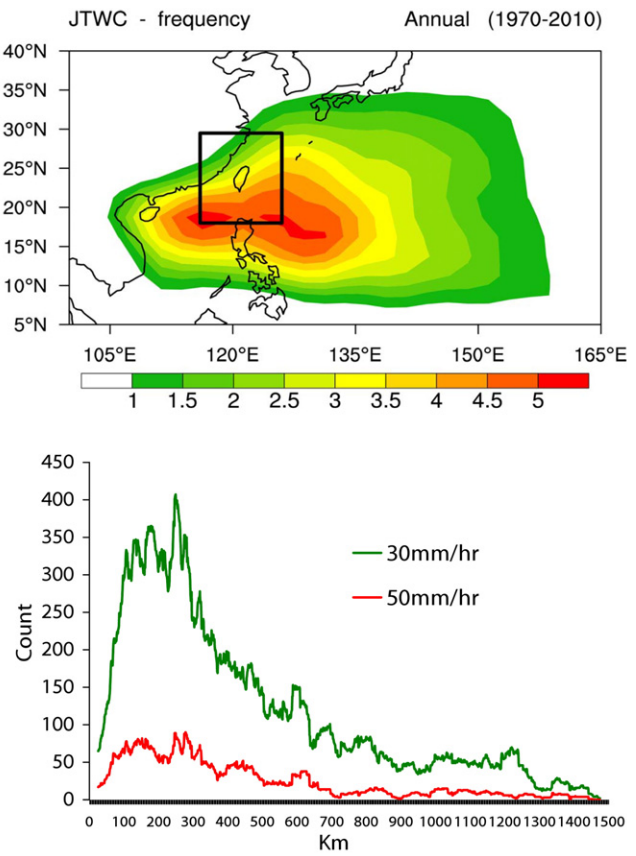

Figure 1. (a) Typhoon frequency climatology in the western North Pacific and South China Sea averaged over the period of 1970–2010. The contour interval is 0.5 per year per grid box (2.5° × 2.5°). The black box (18°N–29.5°, 116°E–126°E) represents the region where typhoons can affect rainfall in Taiwan. (b) The number distribution of rainfall extremes as a function of the distance between the ground station in Taiwan and the typhoon center: green and red for rainfall intensity ≧30 and 50 mm h^{-1}, respectively.

of two prevailing typhoon tracks: one goes to the west into the SCS and the other travels to Korea and Japan (Tu *et al* 2009). Therefore, the rainfall frequency and intensity in Taiwan will be affected by typhoons, particularly in the boreal summer, the main typhoon season in this region.

There are several ways to define the typhoon rainfall. A typhoon is a nearly circular storm with a typical radius of about 200–300 km, in which the wind speed exceeds 34 knots. Typhoons can sometimes extend as far as 400–500 km away from the storm center in the WNP (Merrill 1984, Liu and Chan 1999). Thus, a bigger domain is commonly used to define typhoon-related rainfall. Chu *et al* (2007) used a rectangular box of 21°–26°N and 119°–125°E for typhoons invading Taiwan, instead of the actual geographic domain of Taiwan. Chen *et al* (2010) defined typhoon rainfall as when the corresponding typhoon center lies within the area of 19.5°–27.5°N and 117.5°–124.5°E.

In this study, we used a different definition since our focus is mainly on typhoon-induced rainfall extremes. Figure 1(b) shows the probability distribution of the hourly rainfall over 30 (green) and 50 (red) mm h^{-1} with respect to the distance between the typhoon center and the corresponding ground station in Taiwan. The distance shown in figure 1(b) is an 11-point smoothing with a spatial resolution of 1 km. Most heavy rainfall (≧30 and ≧50 mm h^{-1}) is observed when the typhoon center is within 500 km from the corresponding ground station, with the maximum number occurring between 100 and 300 km. The frequency of heavy rain significantly decreases when typhoons are more than 500 km away from the ground station. On the basis of this result, we first define the box of 18°N–29.5°N and 116°E–126°E (the black box in figure 1(a)) as the typhoon-influenced region. We note that the results that will be shown later are not sensitive to the box that we choose here. Once the typhoon center is within this region, the day is then regarded as a typhoon day, and the associated rainfall is defined as typhoon rainfall. The rainfall in the rest of the year, on the other hand, is defined as non-typhoon rainfall, which includes rainfall not only in summer but also in other seasons.

3. Changes in precipitation frequency, intensity and duration

Figure 2(a) shows precipitation (hourly) frequency (per station per year) in each precipitation intensity bin for total rainfall (green line), typhoon rainfall (red line) and non-typhoon rainfall (blue line) in the period of 1970–89. The bin width is 1 and 10 mm h^{-1} for hourly rainfall less and greater than 50 mm, respectively. The frequency of precipitation decreases as the corresponding intensity increases. We note that the big jumps around 50 mm h^{-1} are due to the change in the bin width. The frequency of typhoon rainfall is less than that of non-typhoon rainfall, particularly for light rain.

The relative changes in precipitation frequency between two 20-year epochs, i.e., 1990–2009 and 1970–89, are shown in figure 2(b). The changes are normalized by the global-mean surface temperature difference between these two periods, which is 0.46 °C, calculated from the Climate Research Unit (CRU) surface temperature (Brohan *et al* 2006). When examining the total rainfall without making a division into typhoon and non-typhoon rainfall, the frequency of relatively light rain (less than 5 mm h^{-1}) is clearly reduced, while the frequency of relatively heavy rain (greater than 5 mm h^{-1}) is increased. However, the changes are very different for typhoon and non-typhoon rainfall. For typhoon rainfall, the frequency increases in all intensity bins, with a rate of more than 100% per 1 °C surface warming for most intensity bins, and most of the cases are statistically significant (table 1). For non-typhoon rainfall, on the other hand, the frequency tends to reduce for most intensity bins, especially for lighter rain (table 1). In other words, the decrease in the frequency of lighter rain is associated with non-typhoon events and the increase in the frequency of heavier rainfall is associated with typhoon events (figures 2(b) and 3).

Figure 4 shows changes in the intensity of rainfall extremes, the heaviest 1%, between 1990–2009 and 1970–89. The precipitation intensity is averaged over each percentile bin, with a bin width of 0.01%. Figure 4(a) shows the climatology of the intensity of rainfall extremes in the period

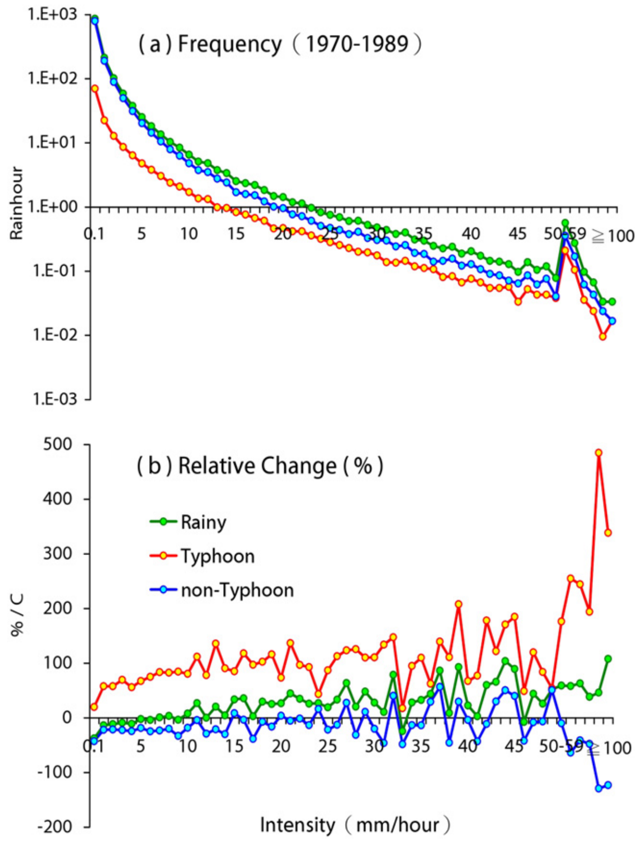

Figure 2. (a) Climatology of rainfall frequency in the period of 1970–89. The bin width of precipitation intensity is 1 and 10 mm h^{-1} for rainfall intensity smaller and greater than 50 mm h^{-1}, respectively. The unit for frequency is per station per year. (b) The relative changes in frequency between 1990–2009 and 1970–989, which are normalized by the global-mean surface temperature difference between these two epochs. Green, red and blue curves are for total, typhoon and non-typhoon rainfall, respectively.

Table 1. The linear trends and the corresponding confidence level for different rainfall intensities (<1 mm h^{-1}, 10 mm h^{-1}, 20 mm h^{-1} and ≥40 mm h^{-1}) associated with total, typhoon and non-typhoon rainfall, respectively. The unit for trends is hour/decade.

Category	Rainy	Typhoon	Non-typhoon
<1 mm h^{-1}	−1351.7 (>99%)	32.4 (46%)	−1376.3 (>99%)
10 mm h^{-1}	4.1 (58%)	6.3 (99%)	−4.5 (80%)
20 mm h^{-1}	1.5 (64%)	1.5 (94%)	0.0 (13%)
≧40 mm h^{-1}	5.6 (95%)	4.4 (95%)	0.0 (15%)

of 1970–89. The intensity ranges from 20, 17 and 35 mm h^{-1} to 95, 89 and 116 mm h^{-1} for total, non-typhoon and typhoon rainfall, respectively. It is clear that typhoon rainfall is much stronger than non-typhoon rainfall, with a difference of around 20 mm h^{-1} for almost every percentile bin. However, non-typhoon rain events occur much more frequently than

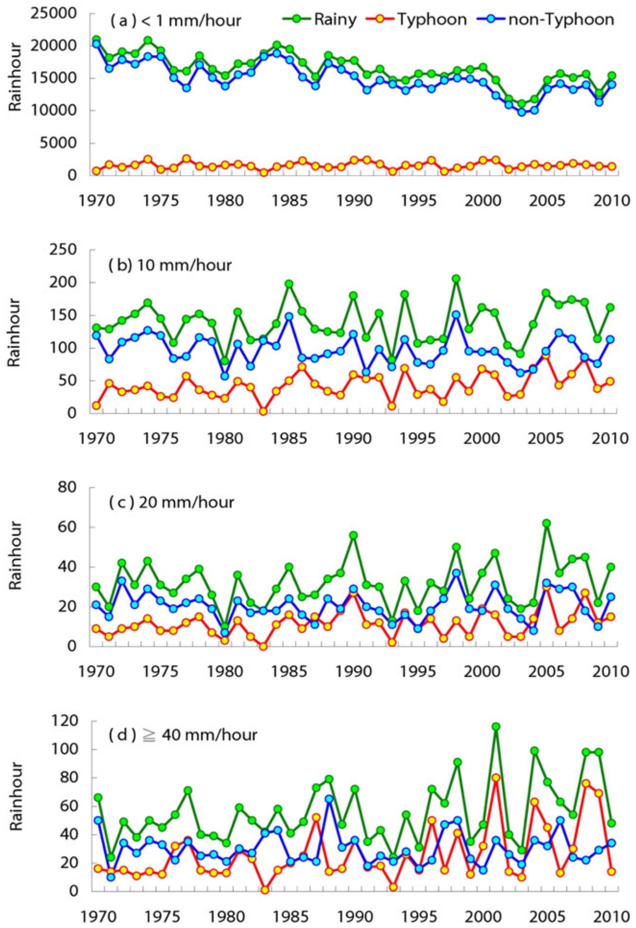

Figure 3. Time series of rainfall frequency in 1970–2010 for the bin of (a) less than 1 mm h^{-1}, (b) 10 mm h^{-1}, (c) 20 mm h^{-1} and (d) equal to and greater than 40 mm h^{-1}. Green, red and blue curves are for total, typhoon and non-typhoon rainfall, respectively.

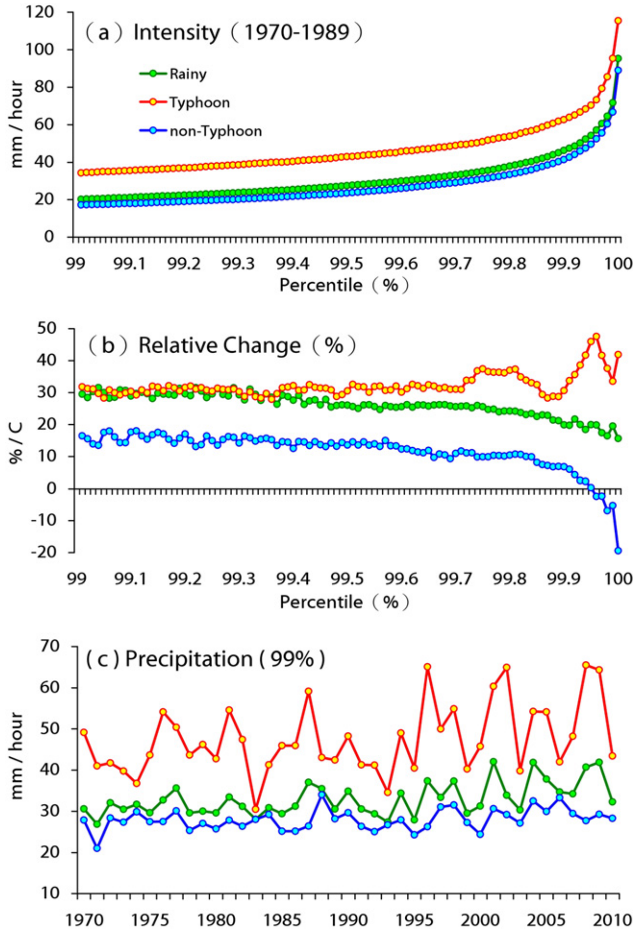

Figure 4. (a) Climatology of precipitation intensity for rainfall extremes (the 99th percentile) in the period of 1970–89, with the bin width of 0.01%. The unit for precipitation intensity is mm h^{-1}. (b) The relative changes in the intensity of rainfall extremes between 1990–2009 and 1970–89, which are normalized by the global-mean surface temperature difference. (c) Time series of rainfall intensity averaged over the entire 99th percentile in 1970–2010. Green, red and blue curves are for total, typhoon and non-typhoon rainfall, respectively.

typhoons (figure 2(a)), so the distribution of rainfall intensity for total rain events (green) is similar to that for non-typhoon rain events (blue).

Next, we examine the changes in precipitation intensity between 1990–2009 and 1970–89 (figure 4(b)), which are normalized by the global-mean surface temperature difference between these two periods, the same normalization as was applied to precipitation frequency in figure 2(b). Both typhoon and non-typhoon rainfall are intensified. The relative changes averaged over the entire 99th percentile for total, non-typhoon and typhoon rainfall are around 25%, 8% and 30% per 1 °C surface warming, respectively. The intensified rate of typhoon rainfall intensity gradually increases with the percentile bin, while that for non-typhoon rainfall reduces as the percentile increases, and even becomes negative after the 99.95th percentile, which results in a slight decrease of the enhanced rate of precipitation intensity for the total rain events.

To further examine precipitation extremes, figure 4(c) shows the time series of rainfall intensity averaged over the entire 99th percentile in the period of 1970–2010. All three rainfall types show upward trends in the past four decades, which is consistent with the result shown in figure 4(b). For total rain events, the increased rate is around 1.7 mm h^{-1} per decade. The intensities of typhoon and non-typhoon rainfall increase at rates of about 2.5 and 0.6 mm h^{-1} per decade, respectively, with the statistical significance passing the 5% level. Moreover, it is clear that the interannual variations (variances) for these three rainfall types all tend to increase with time.

Rainfall extremes can result in severe damage. Persistent rainfall extremes can cause even greater damage to the environment and the local economy. Figure 5 shows the frequency of rainfall extremes with a longer duration: 6 h for most rainfall extremes and 3 h for the strongest one, 50 mm h^{-1} (figure 5(e)). In general, persistent rainfall extremes are mainly associated with typhoons, even though non-typhoon systems can also induce some. For long-term variations, persistent rainfall extremes clearly occur more frequently in recent years, particularly in the past decade, i.e., the 2000s. In other words, rainfall extremes last longer. Moreover, the increase in frequency is greater for heavier rainfall extremes, i.e., 30 and 50 mm h^{-1}. These increases

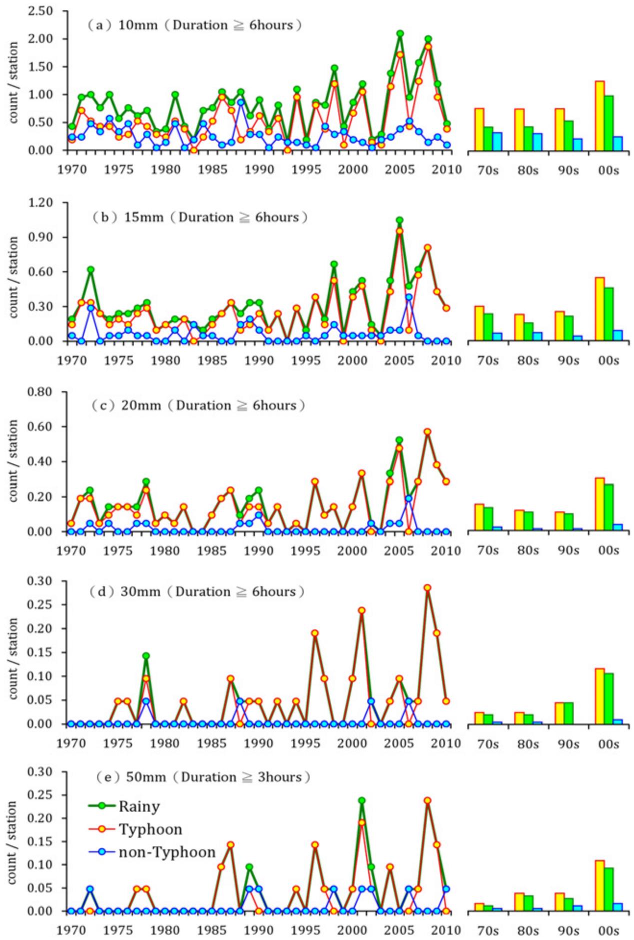

Figure 5. Time series of the frequency for various intensities of persisted rainfall extremes: (a) 10, (b) 15, (c) 20, (d) 30 and (e) 50 mm h^{-1}. The persistence duration is 6 h for intensity less than 50 mm h^{-1} and 3 h for intensity of 50 mm h^{-1}. Green, red and blue curves are for total, typhoon and non-typhoon rainfall, respectively. The panels on the right are averages for each decade.

in the frequency of persistent rainfall extremes are mainly associated with typhoons. Thus, typhoon rainfall is not only becoming more frequent and intense, but also persisting for longer.

4. Causes for changes in Taiwan rainfall

From the results discussed above, it is clear that changes in rainfall characteristics in Taiwan are different for non-typhoon and typhoon events. Thus, we examine possible causes for these changes in rainfall separately.

4.1. Non-typhoon rainfall

Previous studies (Chou *et al* 2012, Chen *et al* 2012) examined climate model simulations and showed that the thermodynamic contribution is the major effect for inducing changes in precipitation frequency. It tends to increase the frequency of heavy precipitation and reduce that of light precipitation. Non-typhoon rainfall does show a reduction in frequency for lighter rain, but there are no clear changes in heavier rain (figures 2(b) and 3 and table 1), even with a decrease for rainfall greater than 50 mm h^{-1}. This implies that effects other than the thermodynamic contribution are also important. This is an interesting topic, especially for the decrease of the heaviest rain, and will be our future work.

For intensity, the thermodynamic contribution also tends to enhance precipitation intensity, while the dynamic effect varies with space (Chen *et al* 2012). Since most non-typhoon rainfall is intensified and greater than the Clausius–Clapeyron thermal scaling, which is around 7% per 1 °C warming, except for those cases greater than the 99.95th percentile, both thermodynamic and dynamic effects should positively contribute to precipitation intensity. The positive dynamic effect could be due to convective feedback for heavy rain (Sugiyama *et al* 2010, Chou *et al* 2012). We note that the reduction in the intensified rate of non-typhoon rainfall with percentiles should be further examined since it contradicts what was found in previous studies for climate model simulations (see, e.g., Sugiyama *et al* 2010, Chou *et al* 2012).

4.2. Typhoon rainfall

Typhoon-induced rainfall frequency increases for all intensity bins (figure 2(b)), while the intensity for precipitation extremes is enhanced and much greater than that of non-typhoon rainfall (figure 3(b)). This implies that effects other than the thermodynamic and dynamic contributions should dominate. Thus, we next examine typhoon characteristics, including the number of typhoons and the translation speed.

The number of typhoons that affect Taiwan rainfall, which is around 8 per year, is examined first (figure 6(a)). There is no clear long-term trend, even though the averaged number is slightly higher in the past two decades. The number of typhoon days, which are defined for those days on which typhoons have an influence on Taiwan rainfall at least over one station, shows a clear upward trend (figure 6(b)). There are 23 days per year in the 1970s, but the number increases to 30 days per year in the 2000s. This implies that the time of each typhoon affecting Taiwan rainfall becomes longer. For each individual typhoon, the time affecting Taiwan rainfall does indeed become longer in the 2000s (53.6 h) than in the 1970s (45.4 h), with a linear increased rate of about 3.3 h/decade.

What causes this increase in typhoon-influenced time in Taiwan? Figure 6(d) shows the change in the translation speed for those typhoons affecting Taiwan rainfall. The translation speed is defined as the distance of the typhoon track within the domain of 18°N–29.5°N and 116°E–126°E (the black box shows this in figure 1(a)) divided by the time for which typhoons stay in the domain. In other words, it is the mean translation speed within the domain. A downward trend is found in the past four decades, with an average of 16.2 km h^{-1} in the 2000s and 17.3 km h^{-1} in the 1970s. The linear trend found using a rank regression method (Chou *et al* 2007) is about −0.45 km h^{-1} per decade. In other words, the typhoons that affect Taiwan rainfall tend to move more slowly in recent years, which is consistent with a weakening of steering flow over the western part of the WNP and the northern

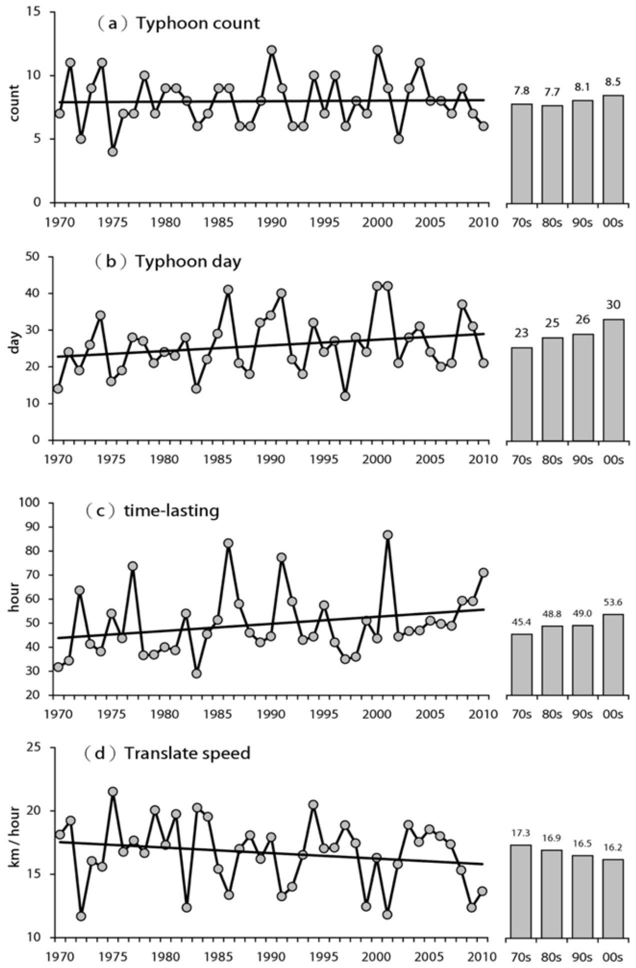

Figure 6. Time series of (a) the number of typhoons, (b) typhoon days, (c) the time affecting Taiwan rainfall for each typhoon and (d) typhoon translation speed in the vicinity of Taiwan (18°N–29.5°N, 116°E–126°E) in the period 1970–2010. The panels on the right are for decadal averages and those on the left are for annual averages. Solid lines represent the corresponding linear trend.

part of the SCS (Chu *et al* 2012). This slowing down of typhoons can cause an increase in the frequency and duration of typhoon-related rainfall extremes, which is consistent with the finding from observations (figures 2 and 5). This shift toward more typhoon rainfall extremes could be a part of the causes for the intensification of typhoon rainfall shown in figure 4. Moreover, the slowing down of typhoons could also intensify precipitation due to the orographic effect (Hsu *et al* 2012), contributed by the many mountains in Taiwan being 3000 m or greater in height.

5. Conclusions

In this study, we examined changes in the frequency, intensity and duration of rainfall extremes in Taiwan in the period of 1970–2010. In general, a decreasing trend of frequency is found for lighter rainfall, and an increasing trend for heavier rainfall. On dividing the total rain events into typhoon and non-typhoon types, the changes are seen to become very different from those without differentiating the rainfall types. Typhoon rainfall occurs more frequently for every precipitation intensity bin, while non-typhoon rainfall tends to be less frequent. In other words, the less frequent lighter rainfall found in total rain events is mainly associated with non-typhoon events, while the more frequent heavier rainfall is related to typhoons. Meanwhile, both typhoon and non-typhoon rainfall extremes tend to be intensified at a much greater rate than the Clausius–Clapeyron thermal scaling, with a greater rate for typhoon than for non-typhoon rainfall. Rainfall extremes that can persist for a longer period of time also tend to occur more frequently. These long-lasting rainfall extremes are mainly associated with typhoons. Overall, rainfall extremes in Taiwan, which are mainly associated with typhoons, tend to become more frequent and intense, and also persist longer. These changes are mainly due to the slower-moving typhoons in the neighborhood of Taiwan, which are induced by the weakening of steering flow in this region.

Acknowledgments

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