

Research Article

Impact of Typhoons of Different Intensities on Short-Term Precipitation in the Middle and Lower Reaches of the Yangtze River in Summer

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According to China's reanalyzed meteorological dataset (CN05.1), a 6-h track intensity typhoon meteorological dataset in the Western Pacific, three types of short-term precipitation are described to study the impact of typhoons on summer rainfall of different intensities in the middle and lower reaches of the Yangtze River: short-term extreme precipitation (95% quantile), short-term heavy precipitation (75% quantile), and normal precipitation (below the lower limit of the 75% quantile threshold). The results show that the amount of short-term extreme precipitation is 1.8 and 3.7 times that of normal precipitation and short-term heavy precipitation, respectively. Considerable interannual and interdecadal fluctuations in the proportion of short-term heavy precipitation and extreme precipitation during summer are affected by typhoons, with a wide range of changes occurring between 1980 and 2000. The areas with high amounts of short-term heavy precipitation and extreme precipitation are distributed mostly in the middle and southern parts of the middle and lower reaches of the Yangtze River, whereas areas with a high amount of normal precipitation are distributed mostly in the southeastern parts of the river. The spatial distribution of the three intensities of rainfall affected by typhoons is consistent, with a gradual decrease from southeast to northwest; in addition, the spatial distribution of the proportion of total summer rainfall has similar characteristics. The three intensities of precipitation are affected by the spatial distribution of the typhoon path frequency, and the distribution of the high-value areas is essentially the same as that of precipitation. This indicates that most of the typhoons that affect summer precipitation pass through the middle and lower reaches of the Yangtze River.

1. Introduction

Precipitation, as an important physicochemical process of water circulation, plays a fundamental role in sustaining life on Earth [1]. It is also vital for livestock, crop irrigation, and forestry [2]. In addition, precipitation may reflect climate change on a regional or global scale (e.g., via flooding or drought). It has a large influence on the salinity of seawater and the wet deposition of air pollutants and aerosols in the lower atmosphere, which is closely related to the atmospheric environment [3].

Extreme precipitation is a type of catastrophic weather event that can easily cause serious consequences for the human population and the ecosystem. Large-scale extreme precipitation not only affects the industrial and agricultural

production but also poses a serious threat to social and economic development as well as the safety of peoples' life and property [4–6]. Therefore, the changes and causes of regional extreme precipitation have attracted widespread attention from walks of life and many scholars. Observational evidence since 1950 suggests that extreme precipitation events are increasing worldwide, especially in the Northern Hemisphere [7, 8]. These events are influenced by both natural (e.g., water vapor, temperature, El Niño–Southern Oscillation, the North Atlantic Oscillation, tropical cyclones (typhoons), sea-surface temperature anomalies, and monsoons) and human factors (e.g., greenhouse gases and urbanization) [9, 10]. Among them, tropical cyclones (typhoons) cannot be ignored. In the USA, China, Mexico, and Central America, typhoons have led to

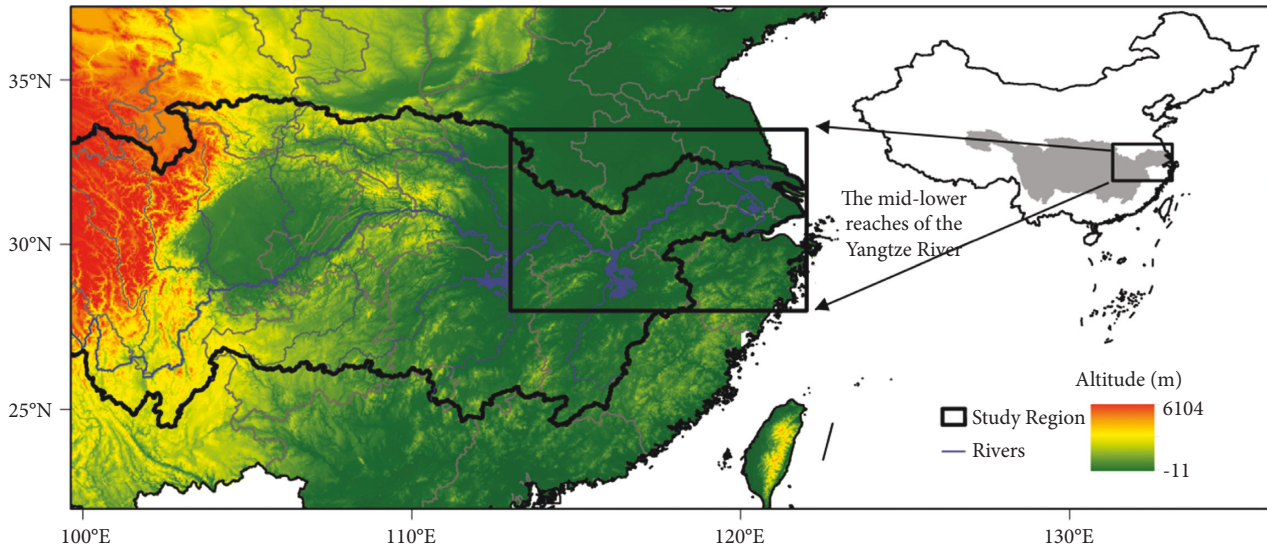


FIGURE 1: Location of the middle and lower reaches of the Yangtze River basin.

devastating flooding and set national records for extreme precipitation [11, 12].

To date, numerous studies have investigated the effect of typhoons on extreme precipitation [11–17]. However, few studies have examined the effects of typhoons on short-term extreme precipitation. Accurate and timely information regarding the impending short-term precipitation events can prevent financial losses and the loss of life. In particular, short-term precipitation forecasts, referred to 0–6 h of lead time, are acute for flashflood warning, flood forecasting, and other hydrological applications [18–20]. With the middle and lower reaches of the Yangtze River as study areas, this work aims to investigate the characteristics of short-term extreme precipitation and analyze the effects of typhoons on the different intensities of short-term extreme precipitation. Our research results can provide a reference for predicting short-term extreme summer rainfall in the middle and lower reaches of the Yangtze River and other areas of the world.

2. Materials and Methods

2.1. Materials. The middle and lower reaches of the Yangtze River (Figure 1) generally refer to the area from the north of Nanling to the south of the Qinling–Huaihe River and the east of Wushan (28° – 33.5° N, 113° – 122° E) [17]. This area is a key industrial and agricultural production base in China with continuous economic development and a high level of science, technology, and culture. Previous studies have demonstrated that the trends of total precipitation and extreme precipitation in the summer in the middle and lower reaches of the Yangtze River are influenced by changes in the intensity and frequency of typhoons [13–17].

This study utilized a high-resolution ($0.25^{\circ} \times 0.25^{\circ}$) grid dataset from China’s reanalyzed meteorological dataset (CN05.1) of daily precipitation. The CN05.1 dataset is based on the data obtained from more than 2,400 surface meteorological observation stations, including the variables of temperature and precipitation. Relevant studies have shown

that the descriptions of climatic extreme precipitation events in this dataset are consistent with the observations of extreme precipitation in eastern China [21, 22]. Therefore, the CN05.1 precipitation dataset could be used to reasonably analyze the changes in extreme precipitation in the middle and lower reaches of the Yangtze River and its impact mechanism. The study was conducted during the summer months (June–August) of 1961–2016. The typhoon data used was the typhoon path data set of the Tokyo Regional Specialized Meteorological Center–Typhoon Center (<https://www.jma.go.jp/jma/indexe.html>), including the path and intensity of the typhoons, obtained every 6 h. The selected study period was the same as that for the precipitation.

2.2. Definition of the Precipitation of Different Intensities.

There are multiple ways to define extreme precipitation. The Expert Team on Climate Change Detection and Indices of the World Meteorological Organization uses 95% and 99% quantile precipitation values as extreme precipitation thresholds [23]. Based on the commonly used definition of extreme precipitation, recent related studies have analyzed the various characteristics and physical causes of short-term extreme precipitation in the northeastern USA [24–26]. To distinguish the effects of typhoons on short-term precipitation of different intensities, this study refers to the method of defining short-term extreme precipitation in the northeastern USA and selected 75% and 95% quantile precipitation thresholds to define short-term heavy precipitation and extreme precipitation, respectively. The specific method is explained as follows.

Based on the criteria for selecting extreme precipitation in existing studies, total daily precipitation of ≥ 1 mm is accepted as effective precipitation [27, 28]. For each grid point in the study area, a one-week window before and after the precipitation event (i.e., a two-week window) is used to define a single short-term precipitation event [24]. Taking a 75%-quantile precipitation event (short-term heavy

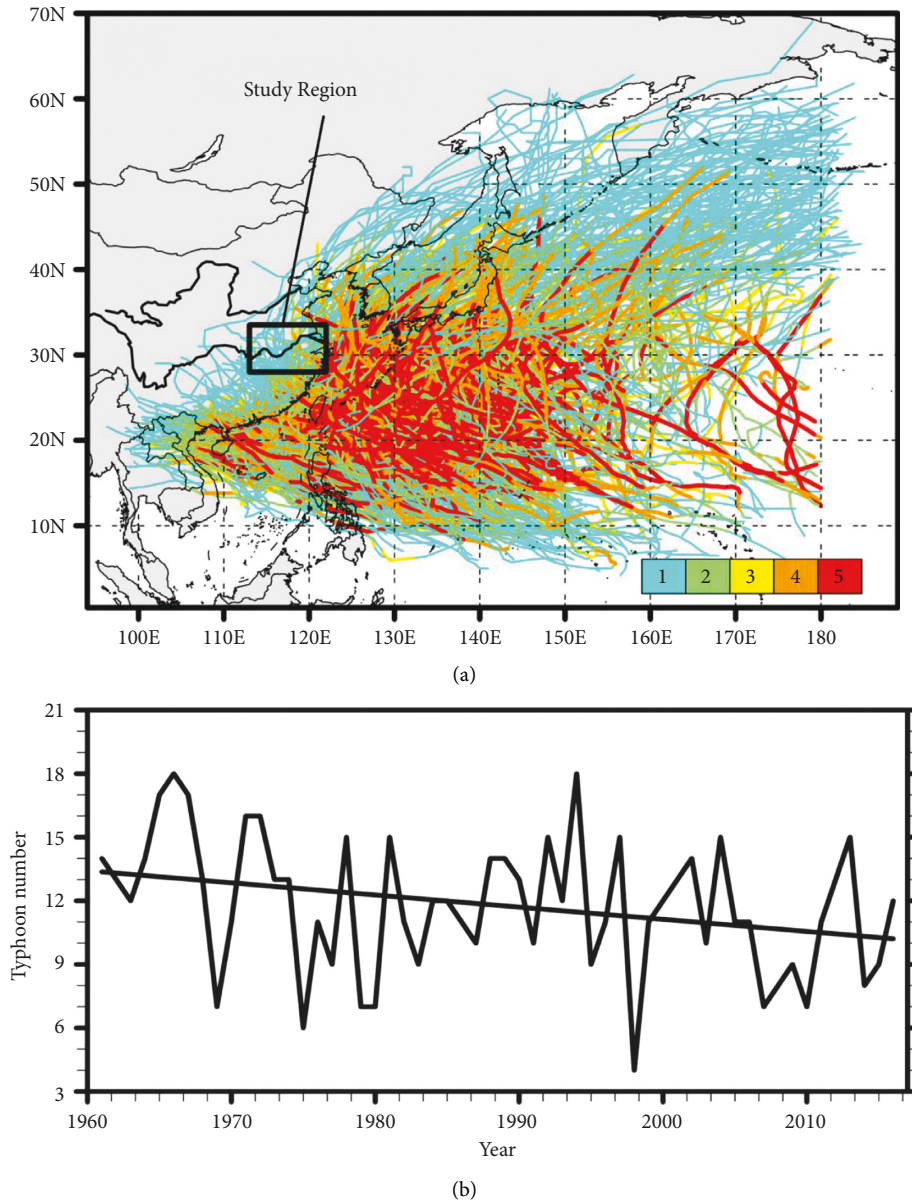


FIGURE 2: (a) All the typhoon tracks and (b) the time series of the number of typhoons during the summers of 1961–2016. Note. The straight line of the time series presents a linear trend. The same is true as follows.

precipitation event) as an example, one day’s precipitation must be within the $75\% \pm 5\%$ quantile precipitation threshold, and there should be no precipitation in the seven days before and after the precipitation event; if precipitation occurs before or after the event, then the daily precipitation should be $\geq 70\%$ of the quantile precipitation. When the threshold is set, the precipitation event is a short-term heavy precipitation event and precipitation events that do not meet the abovementioned conditions are not selected. A 95% quantile precipitation event (short-term extreme precipitation event) is defined as the total precipitation in a day with $\geq 90\%$ quantile precipitation threshold; the other conditions are the same as for the short-term heavy precipitation event [29, 30]. To further evaluate various influences of typhoons

on both heavy and general precipitation, events that have lower precipitation threshold than the lower limit of the short-term heavy precipitation event threshold ($< 75\%$) are defined as normal precipitation events.

The precipitation events influenced by typhoons are defined by internationally accepted methods [31, 32]; the area covered by a radius of ~ 500 km extending superficially by 5° from the center of the typhoon is the area affected by the typhoon. If an effective precipitation event occurs at any grid point in summer and is within the typhoon’s influence range, in the middle and lower reaches of the Yangtze River, the precipitation event at that grid point is treated as a precipitation event affected by the typhoon.

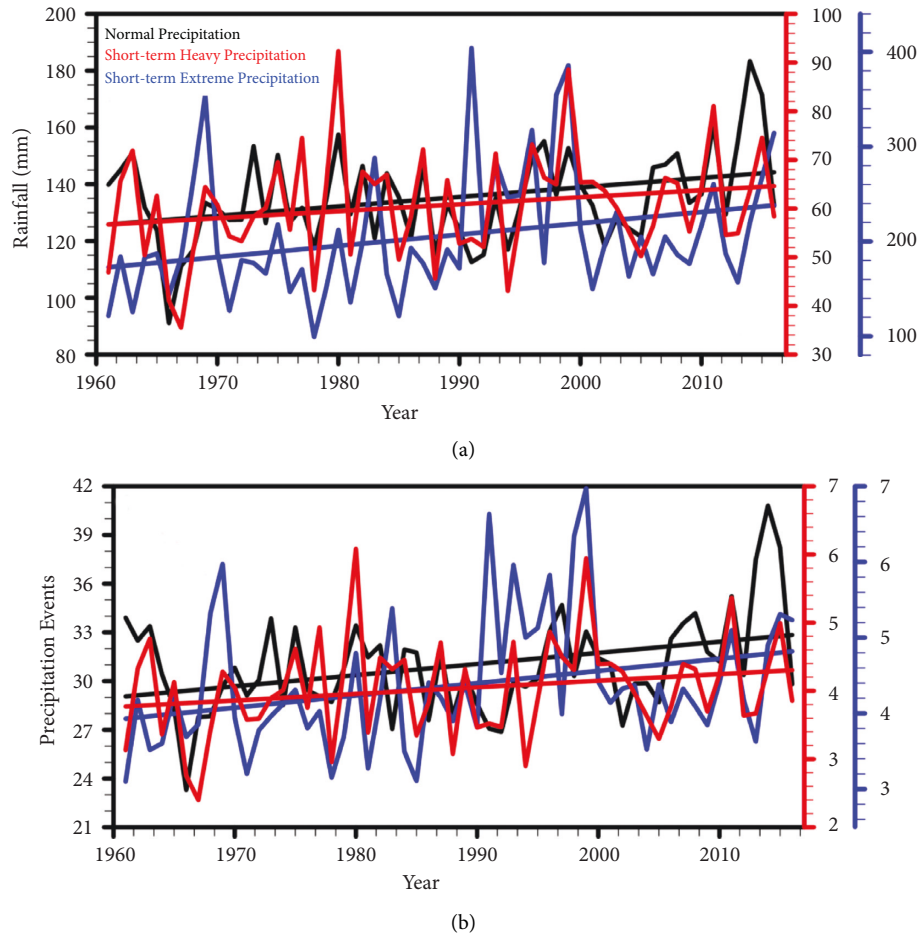


FIGURE 3: The time-series data of the (a) amount of precipitation and (b) number of precipitation events during the summers of 1961–2016.

3. Results and Discussion

3.1. Summer Typhoon Distribution and Changes.

Figure 2(a) shows that the areas with the most major typhoons are intensified in the coastal areas south of the Yangtze River (Fujian and Guangdong) and Hainan Province. After the typhoons create landfall, their intensity gradually weakens as they move inland, and they become their weakest in the middle and eastern parts of the middle and lower reaches of the Yangtze River. Figure 2(b) reveals that the number of typhoons in the Western Pacific in summer shows obvious interannual and interdecadal changes, with the largest range of changes during the 1970s and 1990s. The number of typhoons generally shows a decreasing trend (-0.6 times/10a) and passes the 95% significance test. Global warming increases the stability of the atmosphere and is not conducive to the formation and development of atmospheric convection. Therefore, in the context of global warming, although the number of typhoons decreases, their intensity does not; in addition, the volume of precipitation increases [33].

3.2. Temporal Changes in the Precipitation of Different Intensities.

The time-series data of the amount of precipitation and the number of precipitation events during the summers of 1961–2016 are shown in Figure 3. The amounts of normal precipitation, short-term heavy precipitation, and short-term extreme precipitation demonstrated specific interannual and interdecadal tendencies; the change trends were 0.33, 0.14, and 1.16 mm/a, with 99%, 89%, and 97% significance levels, respectively. Compared with the normal and short-term heavy precipitation, the amounts of short-term extreme precipitation demonstrated the largest variability, in 1970, 1991, and 1999 was relatively significant. The short-term extreme precipitation events had the largest amounts of precipitation, ~ 1.8 and 3.7 times the precipitation of normal and short-term heavy precipitation events, respectively. Unlike the precipitation amounts, the number of precipitation events demonstrated no substantial statistical changes (Figure 3(b)). The differences in the numbers of short-term heavy precipitation and extreme precipitation events were unnoticeable, while the number of normal-precipitation events revealed some differences. The total number of events was not more than seven times each year. The number of normal-precipitation events was ~ 5 –6 times that of the number of short-term heavy precipitation and extreme precipitation events. This result demonstrates that the intensity of short-term extreme precipitation is much greater than the intensity of normal and short-term

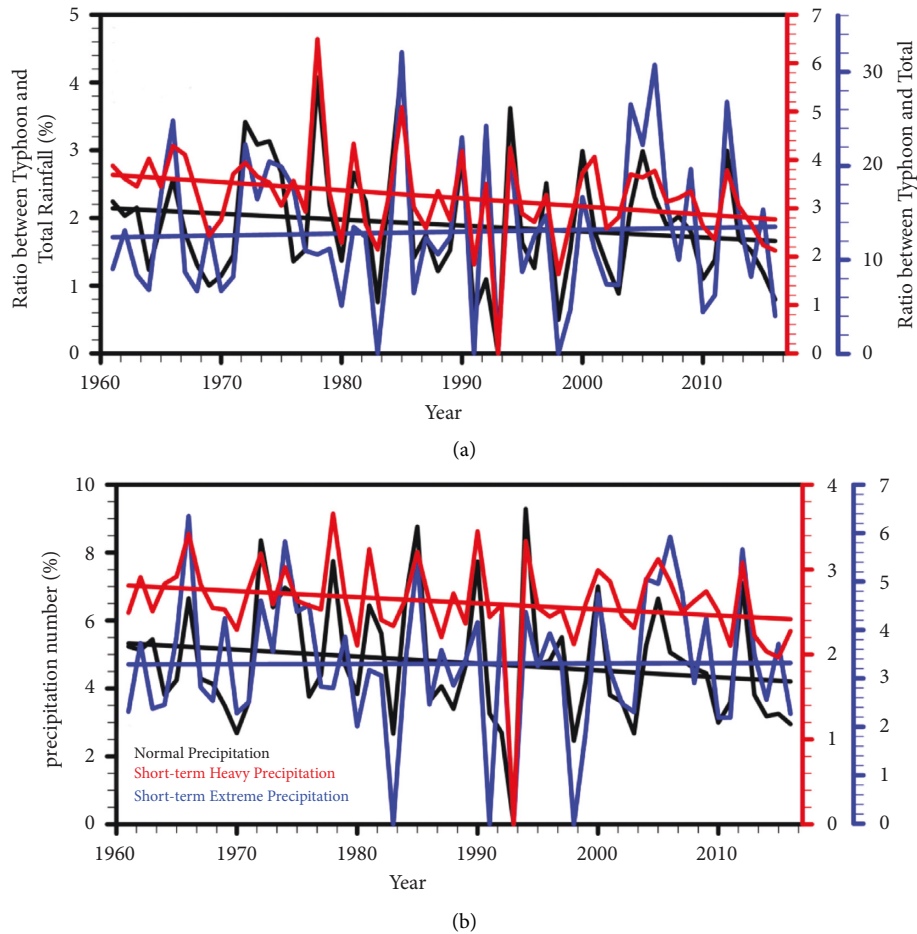


FIGURE 4: Time series of the (a) amount of precipitation and (b) the number of precipitation events induced by typhoons during the summers of 1961–2016.

heavy precipitation because it resulted in the largest amounts of precipitation.

3.3. Temporal Changes in the Precipitation Affected by Typhoons. The time series of summer typhoon-influenced precipitation as a percentage of total precipitation (Figure 4(a)) indicates that the three intensities of typhoon-affected precipitation had similar changes between 1980 and 2000, while the overall change of the short-term heavy precipitation and extreme precipitation events were opposite. In addition, both short-term events passed the 95% significance test. In terms of magnitude, typhoon-influenced short-term extreme precipitation is responsible for a major proportion of total summer precipitation. This is consistent with the conclusion that the entire proportion of precipitation is larger (Figure 3(a)).

Before 1980 and after 2000, the impact of typhoons on the three intensities of precipitation was quite different. Existing data show that the impact of typhoons on the different precipitation intensities is related to the intensity and path changes of the typhoons; in addition, the number and intensity of typhoons affecting southeastern China underwent major changes in the 1970s and 1990s [13, 32].

This is consistent with the interannual changes demonstrated by the number of typhoons occurring during the summers (Figure 2(b)). The number of typhoons in the 1970s and 1990s changed considerably. In some years, such as 1979, the impact of typhoons on both normal precipitation and short-term heavy precipitation was greater than that on short-term extreme precipitation. However, in 1983, 1991, 1993, and 1997, their impact on short-term extreme precipitation was zero. Except for 1993, when typhoons affected both normal precipitation and short-term heavy precipitation. Figure 4(b) demonstrates that the changes in the time series of the proportion of the summer short-term heavy precipitation and extreme precipitation events to the total number of precipitation events exhibit good consistency, although there are some obvious differences in specific individual years. The number of normal-precipitation events affected by typhoons is relatively large, as is the proportion of the total number of precipitation events. However, the years in which the typhoon affects more precipitation events are inconsistent with the years in which the typhoon affects the amount of precipitation. These results indicate that it is not the number of precipitation events that determine the proportion of precipitation influenced by the typhoon but the precipitation intensity of the typhoon.

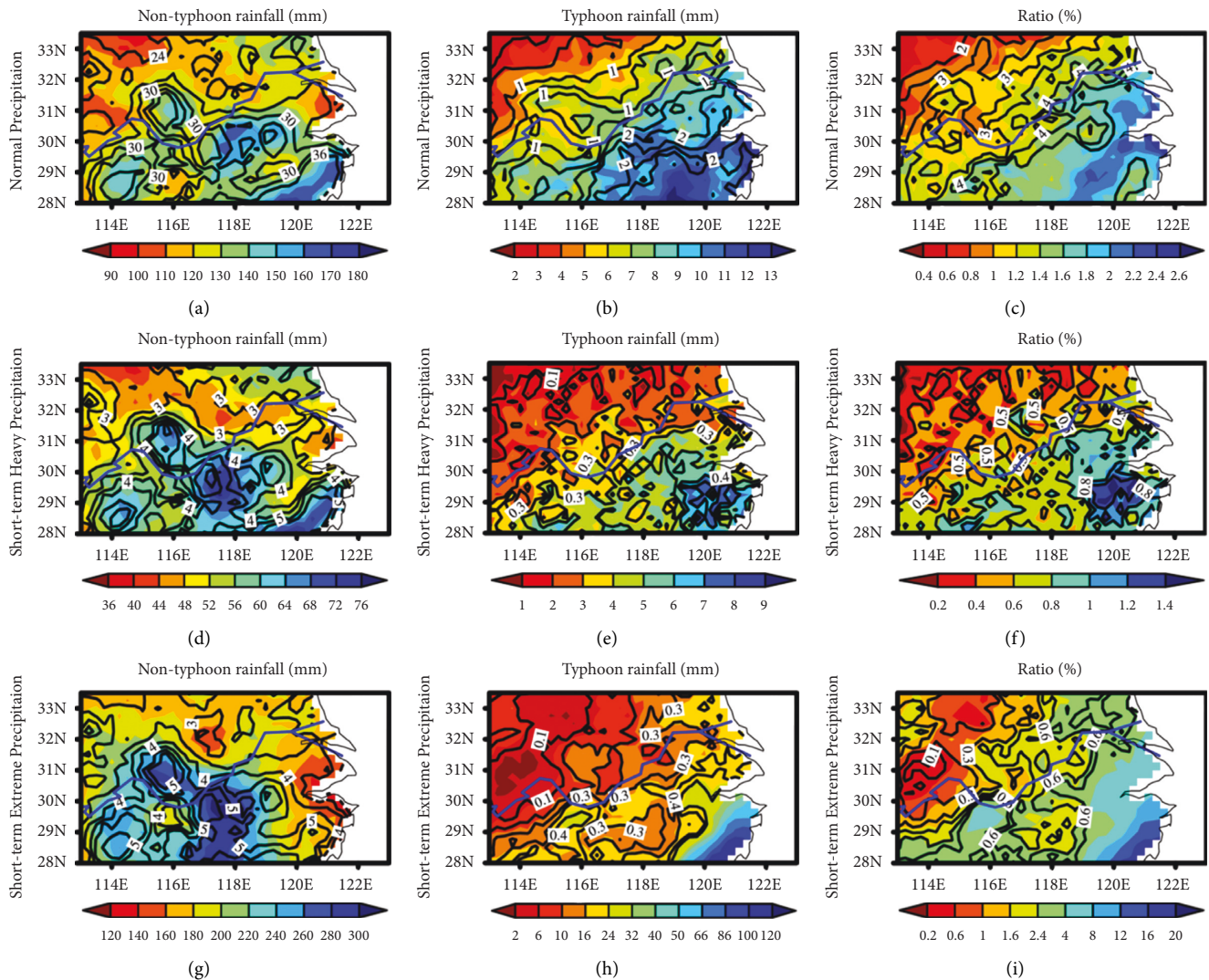


FIGURE 5: Spatial distribution of the summer precipitation events between 1961 and 2016. Note. The shading indicates the proportion of precipitation, the curve indicates the number of times precipitation occurred, and the ratio represents the ratio of the amount of precipitation affected by the typhoons to the total precipitation amount.

3.4. Spatial Distribution of the Precipitation of Different Intensities. Among the different intensities of precipitation not influenced by typhoons, the areas with a high amount of normal precipitation are mainly concentrated in the southeast and southwest of the middle and lower reaches of the Yangtze River, whereas the low-value areas are mainly distributed in the northwestern area (Figure 5(a)). The geographical distribution of the areas with high amounts of short-term heavy precipitation and extreme precipitation is similar to a certain degree. These areas are found in the south-central and southwestern parts of the middle and lower reaches of the Yangtze River, with the heavy precipitation areas primarily concentrated in the northwest and the extreme precipitation areas mostly distributed in the east and northeast (Figures 5(d) and 5(g)). In addition, it can be concluded from the geographical distribution that the average of short-term heavy precipitation in summers is less than the average values of the normal precipitation and

short-term extreme precipitation (Figures 5(a), 5(d), and 5(g)).

Among the different precipitation intensities influenced by typhoons, the areas with a high amount of normal precipitation are mostly intensified in the southeast of the middle and lower reaches of the Yangtze River, and they gradually decrease from the southeast to the northwest. Conversely, the areas with a low amount of normal precipitation are mostly distributed in the northwest (Figure 5(b)). The normal-precipitation areas are similar, but the precipitation amounts are relatively small (Figure 5(e)). The influence of typhoons on the short-term extreme precipitation events is mostly intensified in parts of the southeastern area of the middle and lower reaches of the Yangtze River, and it gradually decreases from the southeast to the northwest (Figure 5(h)). Among the three precipitation intensities, typhoons have a greater influence on short-term extreme precipitation, and the geographical

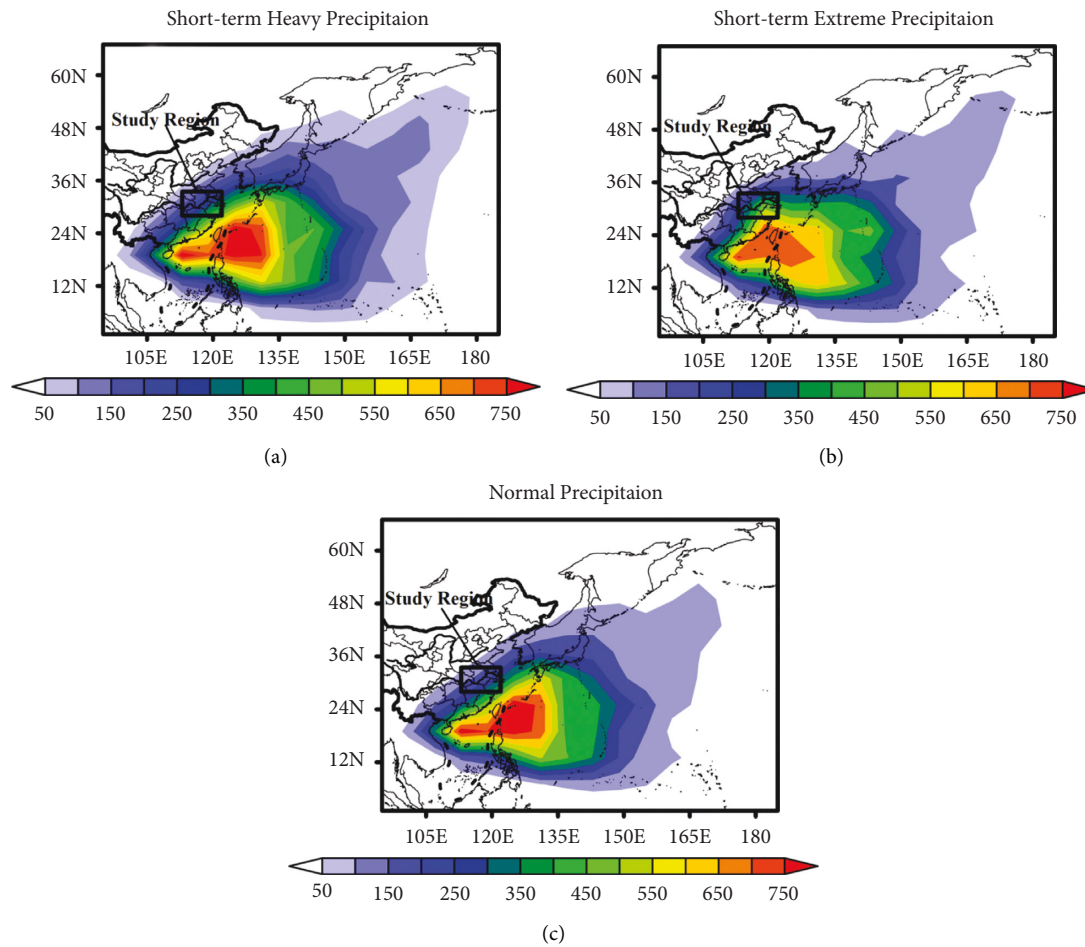


FIGURE 6: Spatial distribution of the frequency of typhoon tracks corresponding to the occurrence of different precipitation intensities.

distribution pattern is roughly the same as that of both normal and short-term heavy precipitation influenced by typhoons. In addition, this influence gradually decreases in a southeast–northwest direction (Figures 5(b), 5(e), and 5(h)). The proportion of precipitation of varying intensities influenced by the typhoons in total precipitation generally demonstrates a distribution that gradually decreases from the southeast to the northwest (Figures 5(c), 5(f), and 5(i)). This is consistent with the average distribution of typhoon-influenced precipitation. However, from the scale, typhoons have a substantial impact on short-term extreme precipitation, indicating that high-intensity short-term extreme precipitation is more likely to be produced after typhoons afford landfall. However, a minimal effect on short-term precipitation of general intensity is noted although the number of resulting normal-precipitation events is high.

3.5. The Frequency of Typhoon Paths Affecting the Precipitation of Different Intensities. The precipitation intensity of the area affected by a typhoon is closely related to the typhoon's path and intensity [13, 32]. To further investigate the impact of typhoons on the geographical distribution of precipitation in the middle and lower reaches of the Yangtze River in the summer, the geographical distribution of typhoon path

frequencies was analyzed thoroughly (Figures 6 and 7). The specific method for calculating the typhoon path frequency is as follows: during the period from 1961 to 2016, for each grid point in the study area, the number of typhoons that appeared in a $6^\circ \times 6^\circ$ area surrounding the grid point and the number of typhoons of different intensity precipitation days in all the years is summed up.

When a precipitation event occurs, the high-value area of the typhoon path frequency is concentrated mainly in the northwest Pacific (Figure 6). The typhoon path frequencies corresponding to normal precipitation and short-term heavy precipitation are similar to a certain extent. The high-value areas are distributed in a large range, and there is a branch of the high-value areas extending westward to Hainan Province (Figures 6(a) and 6(c)). The frequency of the typhoon paths corresponding to short-term extreme precipitation is relatively low (Figure 6(b)), indicating that there are few typhoons that influence high-intensity short-term extreme precipitation in the middle and lower reaches of the Yangtze River in summer. However, owing to high-intensity precipitation, the short-term extreme precipitation affected by typhoons is relatively high (Figures 3(a) and 5(a)). Figure 6 indicates that when the precipitation events occur in the middle and lower reaches of the Yangtze River in the summer, the typhoon path frequencies mostly appear in the

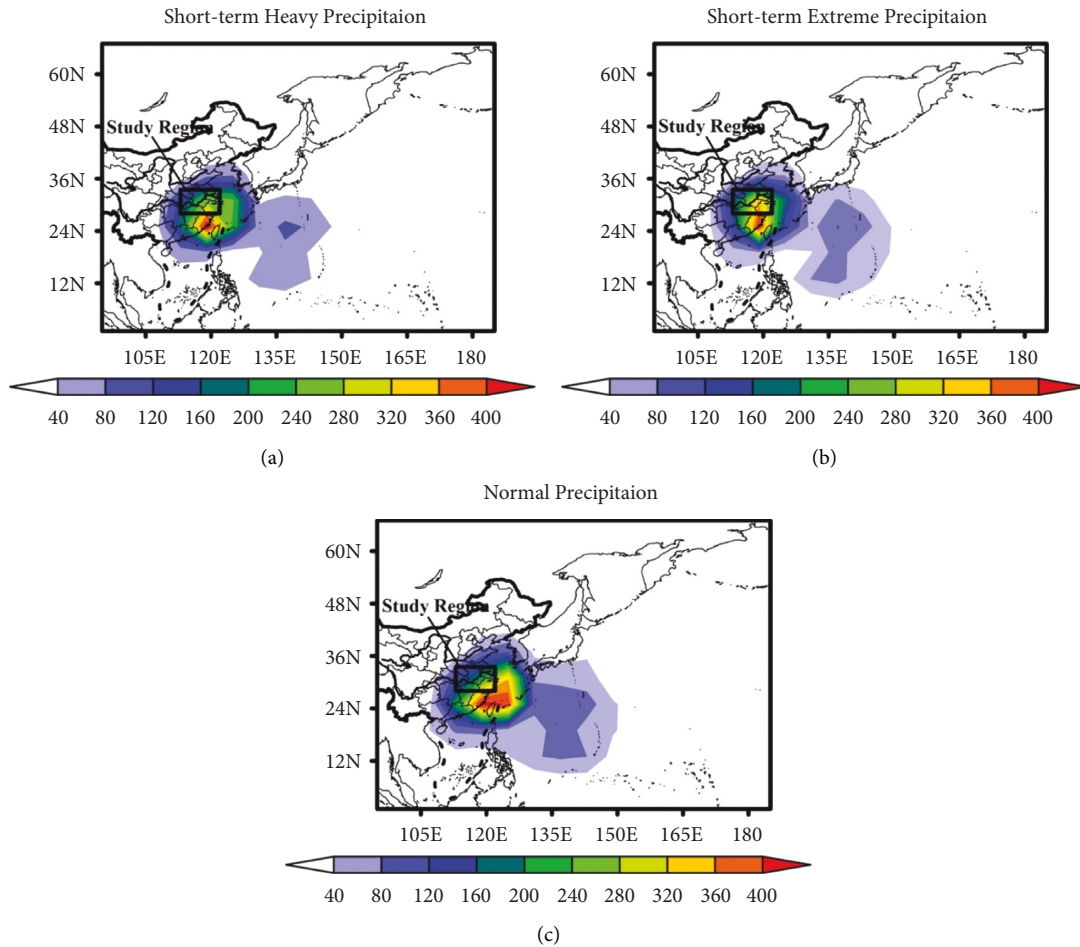


FIGURE 7: Spatial distribution of the frequency of typhoon tracks causing different precipitation intensities.

south and southeast regions of the study area. Combined with the summer typhoon path distribution map (Figure 2(a)), it can be observed that most of the typhoons that influence the summer short-term precipitation in the middle and lower reaches of the Yangtze River occur in the southeast of the area. This explains to a certain extent why the short-term extreme precipitation influenced by typhoons is concentrated mainly in the southeast of the middle and lower reaches of the Yangtze River (Figure 4).

Figure 7 shows the path frequencies of the typhoons that affect the precipitation of different intensities in the middle and lower reaches of the Yangtze River. Compared with Figure 6, the frequency of the typhoon paths demonstrated in Figure 7 does not meet the requirement that at least one grid point of the precipitation event in the study area is influenced by the typhoon. The frequency of the typhoon paths influencing normal precipitation is relatively high. The high-value areas are mostly concentrated in the southeast of the middle and lower reaches of the Yangtze River, whereas the frequency of typhoons in the study area is relatively low (Figure 7(c)). The frequencies of the typhoon paths influencing short-term heavy precipitation and extreme precipitation are similar, although the value of the high-value area of the former is larger than that of the latter

(Figures 7(a) and 7(b)). Compared with normal precipitation, more typhoon paths affect short-term heavy and extreme precipitation in the study area, indicating that when a typhoon passes through the middle and lower reaches of the Yangtze River, it is more likely to cause high-intensity short-term precipitation than the typhoons that do not pass through the middle and lower reaches of the Yangtze River. The intensity of short-term precipitation in summer in the middle and lower reaches of the Yangtze River is weakened when typhoons attempt to pass through the surrounding areas.

4. Conclusions

The effects of typhoons on the different intensities of short-term precipitation (short-term extreme precipitation, short-term heavy precipitation, and normal precipitation) in the middle and lower reaches of the Yangtze River were investigated, based on China's reanalyzed meteorological dataset (CN05.1) and a 6-h track intensity typhoon meteorological dataset in the Western Pacific. The results revealed that the precipitation contribution from short-term extreme precipitation events was higher compared with normal and short-term heavy precipitation events affected by typhoons,

which indicates that short-term extreme precipitation may lead to a greater risk of flooding; therefore, the prediction of short-term extreme precipitation is especially important. Furthermore, there were significant differences in the geographical distributions of the three types of short-term precipitation induced by the path frequencies of the typhoons. The above results also reflected the great significance of typhoons on the short-term precipitation; thus, the typhoons should not be ignored, especially while studying precipitation in the middle and lower reaches of the Yangtze River.

Data Availability

The data of typhoon were provided by the professional meteorological center of the Tokyo area, and the data of precipitation were provided by the National Meteorological Information Center of CMA.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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