Influence of urbanization on hourly extreme precipitation over China

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Abstract

The impact of rapid urbanization on the spatiotemporal pattern of short-term extreme precipitation in China remains unclear at the subnational scale. In this study, we present a general framework that measures urbanization-induced variation in hourly extreme wet season precipitation (April–October) from 1985 to 2012, with reference to a dynamic urban–rural station classification based on annual changes in urban extent. We found that urbanization in south China (<29° N) brings more extreme precipitation to urban areas than to suburbs, and reduces extreme precipitation continually over urban areas in parts of the north and northeast. Over 60% of provincial capital cities show significant changes in extreme precipitation due to urbanization, including smaller size cities separated from large urban clusters. Urbanization enhances extreme precipitation mainly in the local main part of the rainy season, which refers to May in the south (e.g. urban–rural differences of 0.70 mm h⁻¹ in Guangzhou) and July–September in the central and north (1.16 mm h⁻¹ in August of Beijing). Urbanization also increases hourly extreme precipitation at peak times in diurnal cycles. The results indicate that urbanization has caused overall more and more heterogeneous spatial patterns over China and concentrated distributions during the rainy season and peak time. These patterns warrant attention when assessing the risk of increased waterlogging and flash flooding in urban areas.

1. Introduction

Recent rapid urbanization worldwide resulted in an estimated 4.2 billion urban residents in 2018, accounting for 55% of the world population. This percentage is expected to reach 68% by 2050, as the world population approaches 10 billion (United Nations, Department of Economic and Social Affairs, Population Division 2019). The densification of urban inhabitants, together with associated socioeconomic hubs and assets concentrated in cities, is expected to increase urban vulnerability to extreme weather events as the global climate continues to warm and the hydrological cycle intensifies (IPCC 2021, Kumar 2021). In recent decades, many urban areas around the world have witnessed the consequences of extreme precipitation events—including those in East Asia where half of the world cities at high risk to hydrological and meteorological disasters are located (Gu 2019).

Short-term (sub-daily) precipitation extremes that cause waterlogging and flash flooding are some of the key urban hazards that directly affect public safety, well-being, and socioeconomic development...
China has experienced rapid urbanization since the 1980s (Güneralp et al. 2020), including high-developed urban agglomerations (Beijing–Tianjin–Hebei, Yangtze River Delta [YRD] and Pearl River Delta [PRD]) and many other provincial cities (e.g., Changchun, Chengdu, and Zhengzhou) (figure S1 available online at stacks.iop.org/ERL/17/044010/mmedia). During this period, China suffered many recent severe urban flooding episodes (Sang and Yang 2017). For example, on 21 July 2012, Beijing endured a mean rainfall depth of 170 mm in the city and 215 mm in the township in a 20 h period; and the heaviest recorded depth for the same period was 460 mm. This storm caused 79 deaths and losses of approximately 11.6 billion Yuan (Wang et al. 2013b). Another storm lashed Zhengzhou on 20 July 2021, bringing a maximum of 201.9 mm hourly rainfall to the Zhengzhou Station, leaving 292 dead in the whole event (Yin et al. 2022).

In addition to the high potential for devastation from extreme precipitation, increases in the urban extent are linked to altered precipitation characteristics via land–atmosphere interactions (Shepherd 2005, Han et al. 2014). Both analytical and modeling researches have revealed that urban environments can modify the spatiotemporal evolution of extreme precipitation events through inter-related mechanisms associated with, for example, urban heat or convection, atmospheric stability, urban canopy effects on evapotranspiration and wind channeling, aerosol creation/dispersal, and cloud formation (Thielen et al. 2000, Han and Baik 2008, Rosenfeld et al. 2008). Consequently, urban settings can play positive roles in precipitation extremes. For example, urban environments may invigorate vertical motions and convective systems, produce thermodynamic perturbations, and enhance moisture convergence (Rozoff and Cotton 2003). Conversely, the expansion of impervious urban surfaces can also have a negative effect by inhibiting the convective available potential energy and decreasing evapotranspiration (Zhang et al. 2009, Georgescu et al. 2012). However, diverse synoptic conditions and complex physiographic settings can largely influence the magnitude of urban effects on extreme precipitation (Freitag et al. 2018, Wang et al. 2021). Furthermore, the local changes in extreme precipitation due to urbanization combined with rainfall changes associated with a dynamic global hydrological cycle in a warming climate would either amplify or reduce precipitation extremes, contributing to uncertainty in the changing characteristics of extreme precipitation at various scales. Therefore, a comprehensive understanding of the relationship between hourly extreme precipitation and urbanization in rapidly urbanizing regions is urgently required to develop adaptive strategies and to promote more sustainable cosmopolitan environments. This issue is particularly relevant to China, where urban areas increased nearly three-fold from 1985 to 2015, with urban land areas increasing from 50 732 km² to more than 150 000 km² (Liu et al. 2020).

Despite the substantial progress in understanding the urban effects on extreme precipitation at coarse temporal scales (e.g. daily to annual), there remains uncertainty regarding how sub-daily precipitation extremes are affected by urban expansion. Many observational studies on precipitation extremes have focused on daily scales, mainly because of the paucity of long-term hourly precipitation records (Shastri et al. 2015, Singh et al. 2020). The insufficiency of emphasis on sub-daily phenomena is problematic because many extreme events that trigger urban flash flooding are intense, short-term events (Barbero et al. 2017). Another limitation of the literature is related to comparisons of precipitation at urban and adjacent rural stations, which do not have sufficient urban transformation data necessary to accurately distinguish the two types, because they vary in response to land-use change (Song et al. 2021). Most studies have classified urban and rural stations based on the static land cover distribution (Li et al. 2020), or distributions determined from a few discrete time stamps (Liao et al. 2018). Furthermore, the knowledge of the effects of urbanization on precipitation at multiple spatiotemporal scales in China remains limited, and most of the work has been performed for a few metropolitan areas, including Beijing, and those in the YRD and PRD in China (Li et al. 2015, Su et al. 2019). Few studies have investigated this problem at regional-to-national scales, as has been performed elsewhere (Trusilova et al. 2008, Shastri et al. 2015, Singh et al. 2020). Finally, the large variations determined in the literature (Kaufmann et al. 2007, Yan et al. 2020) raise questions on the transferability of results among regions and spatial scales.

Because of the aforementioned research gaps, we performed a comprehensive assessment of the long-term impacts of urbanization on hourly precipitation extremes over China for a 28 years period: from 1985 to 2012. We confined the analyses to the wet season, from April to October, which involves nearly all extreme precipitation events. We used an hourly precipitation dataset with a high degree of quality control and employed a dynamic urban–rural station classification approach that uses a high spatiotemporal-resolution map in the analysis. We then identified spatial variations in long-term changes in hourly extreme precipitation associated with urbanization. Finally, we examined how urbanization affects seasonality and diurnal patterns of extreme rainfall.

2. Materials and methods

2.1. Definition of hourly extreme precipitation indices
We used the hourly precipitation dataset developed by the National Meteorological Information Center of the China Meteorological Administration
Figure 1. Station distribution and study areas. (a) Spatial distribution of urban and rural stations in 1985 and (b) 2012 over China. Blue dots denote rural stations, and orange dots denote urban stations; six rapidly expanding areas, namely, Guangzhou, Hangzhou, Zhengzhou, Chengdu, Beijing, and Changchun, are indicated in panel (b), outlined in six black squares named (e)–(j), respectively; (c) urban area change in contiguous China from 1985 to 2012; (d)–(j) change in numbers of urban and rural stations for mainland China and six $3^\circ \times 3^\circ$ study areas from 1985 to 2012.

(https://data.cma.cn/en) to explore the changes in extreme precipitation variables. Due to limited data availability, the study period was set between 1985 and 2012 (Li et al. 2016, Jian et al. 2020). Nevertheless, this period adequately covers the development of urbanization in China. The dataset comprises observational hourly precipitation data from 2420 national meteorological stations over mainland China and has been subjected to a strict level of quality control, including climatological limit value tests, time consistency checks, and internal consistency checks (Li et al. 2016). We implemented further selection criteria for preprocessing. Any questionable or missing data in the dataset were excluded. Furthermore, a year was treated as complete for a station if it had >95% of available records from April to October. Stations were retained only if they had at least 15 complete years during the 28 years study period. Stations with relocation distances exceeding 20 km were also excluded to maintain spatial homogeneity (Zhai and Ren 1999). After quality control filtering, 1901 stations with valid long-term, hourly precipitation records were included in the analysis (figure 1(a)).

We adopted a threshold of 0.1 mm h$^{-1}$ to differentiate wet and dry hours (Li et al. 2016). We regarded the 95th percentile of all wet precipitation hours during the entire study period as the threshold that defined extreme precipitation. Following Jian et al. (2020), we then identified the following indices: the maximum hourly depth precipitation value (Max1h; unit: mm), number of extreme precipitation hourly records with rainfall depth > the 95th threshold (F95p; hours), mean precipitation intensity for the extreme hourly records (I95p; mm h$^{-1}$), and the ratio of extreme precipitation depth to total precipitation depth (P95p; %). We employed these indices to compare extreme urban and rural precipitation in the analyses at multiple spatiotemporal scales.

2.2. Classification of urban and rural stations

The potential contribution of urbanization to extreme precipitation is usually estimated by comparing the observed precipitation features of urban stations with those of adjacent rural stations (Li et al. 2020, Song et al. 2021). This method is mainly
based on the hypothesis that dominant precipitation-influencing factors (e.g. large-scale synoptic systems, topography, and land–sea interactions) cause nearly identical precipitation variability at local scales. To fulfill this hypothesis, we included in the calculation only the stations with an elevation difference of less than 500 m, to avoid orographic differences in the grid-scale analyses (see section 2.3 for detail; Liao et al 2018). By eliminating the potential impact of natural variability and topography as much as possible, we may regard the urban extent, which was previously a less dominant factor, as the dominant factor that leads to precipitation variation between urban and rural stations in a limited area (Zhao et al 2021).

We classified urban and rural stations dynamically by using global annual urban dynamics (GAUD) maps with high spatiotemporal resolution. The GAUD database, generated by Liu et al (2020) from numerous Landsat images on the Google Earth Engine platform, was used to identify high-precision urban extent changes around all 1901 meteorological stations. This state-of-the-art database describes annual changes in the global urban extent between 1985 and 2015 at a spatial resolution of 30 m. The GAUD maps have been demonstrated to be consistent and accurate (76% accuracy in humid regions between 1985 and 2000, 82% between 2000 and 2015; Liu et al 2020).

The framework for urban and rural classification is shown in figure S2. Referring to the earlier studies (Li et al 2020, Song et al 2021), we established a circular buffer—a 5 km radius—around each station, based on its location in the current year. After calculating the proportion of urban pixels inside each buffer, stations with more than 15% of urban pixels in the buffer were defined to be ‘urban’ in that year; otherwise, they were ‘rural’. These stations were reclassified annually. The threshold defining urban and rural areas was selected based on the following criteria after testing various combinations of buffers and thresholds (table S1). First, the number of urban stations in 1985 and rural stations in 2012 were sufficient to support long-term studies. Second, the number of stations that experienced rural-to-urban transitions should adequately capture China’s urbanization process during this period. According to our calculation, the total urban area in China expanded dramatically by 3222 km$^2$ per year from 1985 to 2012, a trend that accounts for nearly one-third of the global urbanization (9687 km$^2$) over the period (figure 1(c)). Area expansion was well reflected in our classification. In 1985, 288 of 1901 (15.14%) stations were urban, mainly scattered in north and northeast China (figure 1(a)). In 2012, this number increased to 885 (46.55%), as many rural stations located in northern, eastern, and southern China ‘transitioned’ into urban stations (figure 1(b)). In addition, 35.72% of the stations relocated at least once, potentially resulting in urban-to-rural or rural-to-urban transitions, together increasing urban stations by 21.0 per year (figure 1(d)). Overall, in the 28 years period, 34.67% of stations experienced urban–rural transitions due to the increasing urban area and station relocation.

### 2.3. Detection of the long-term trend of extreme precipitation

We used a 1° × 1° grid spacing as the basic analysis unit, as in Burke and Stott (2017) and Gu et al (2019). We considered the grid with all its surrounding grids (out of eight possible) as a 3° × 3° window (figure S3). A grid was deemed ‘valid’ if its window contained both urban and rural stations for each year during that period. For all indices considered, the individual values at each station in each year were calculated, and the time series of anomalies ($A_{\text{station}}$) was constructed as follows:

$$A_{\text{station}} = x_{\text{station}} - \bar{x}_{\text{station}},$$

where $x_{\text{station}}$ represents the time series, and $\bar{x}_{\text{station}}$ represents the long-term mean of the precipitation index. We then determined both the all-station anomaly means (including all rural and urban stations, $A_{\text{all}}$) and the urban–rural anomaly differences ($A_{\text{diff}}$) time series within each surrounding 3° × 3° window (i.e. a nine-grid block) and assigned the value to the central 1° × 1° grid. In the 28 years time series $A_{\text{all}}$, the all-station anomaly mean in year $i$ ($0 < i < 28$), $A_{\text{all},i}$, is defined as:

$$A_{\text{all},i} = \bar{A}_{\text{station},i},$$

where $\bar{A}_{\text{station},i}$ denotes the mean extreme precipitation anomalies of all stations in a valid grid for year $i$. The urban–rural difference time series of extreme precipitation anomalies ($A_{\text{diff}}$) in one valid grid was constructed as follows:

$$A_{\text{diff},i} = \bar{A}_{\text{urban},i} - \bar{A}_{\text{rural},i},$$

where $\bar{A}_{\text{urban},i}$ and $\bar{A}_{\text{rural},i}$ denote the annual mean precipitation anomalies for all urban and rural stations in a 3° × 3° window in year $i$, respectively.

We analyzed the annual trends in $A_{\text{all}}$ and $A_{\text{diff}}$ in each valid grid for the four hourly precipitation indices and used the nonparametric locally weighted regression smoother (Loess; Cleveland 1979) to alleviate the inter-annual fluctuation. After smoothing, a simple linear trend analysis was applied to trend detection, and a $t$-test was used to examine its significance at $\alpha = 0.05$.

### 2.4. Investigation of the seasonality and diurnal signals of extreme precipitation

To analyze the monthly and diurnal variations in the urban–rural differences in hourly precipitation extremes, we focused on six 3° × 3° windows...
covering six rapidly expanding areas (Guangzhou, Hangzhou, Zhengzhou, Chengdu, Beijing, and Changchun) (figure 1(b)). The number of urban stations in all of these areas in 2012 was at least double that in 1985 (figures 1(e)–(j)). Each area contained at least five urban stations and five rural stations throughout the study period. The four extreme precipitation indices of all urban and rural stations were averaged separately at the grid level for each month from April to October and each hour during the entire study period, and the differences between urban stations and rural stations were denoted as the urban–rural differences. Specifically, in diurnal studies, we selected four areas from the six and examined one month of each area with a larger urban–rural difference.

3. Results

3.1. Regional patterns in extreme precipitation changes

The all-station anomaly means \( A_{\text{all}} \) show overall positive trends across China for all four hourly extreme precipitation indices, with mean decadal increases of \( 0.48 \pm 0.12 \text{ mm decade}^{-1} \), \( 0.71 \pm 0.12 \text{ h decade}^{-1} \), \( 0.04 \pm 0.02 \text{ mm h}^{-1} \text{ decade}^{-1} \), and \( 0.73 \pm 0.11\% \text{ decade}^{-1} \) for Max1h, F95p, 195p, and P95p (figure 2), respectively. Although such increases are in line with assessments of global warming (IPCC 2012), prominent latitudinal heterogeneity in extreme precipitation changes exists between the southern and northern areas (figure S4). Significant trend increases were detected in some areas south of \( 35^\circ \text{N} \) for the following extreme precipitation variables: Max1h (>1.0 mm decade\(^{-1}\); figure 2(a)), F95p (>1.5 h decade\(^{-1}\); figure 2(c)), 195p (>0.15 mm h\(^{-1}\) decade\(^{-1}\); figure 2(e)), and P95p (>1.0\% decade\(^{-1}\); figure 2(g)).

By contrast, spatial variations in urban–rural differences in extreme precipitation anomalies \( A_{\text{ur}} \) tend to occur locally rather than zonally (figures 2(b), (d), (f) and (h)). Despite the urban–rural differences being not evident at a national scale, it is explicit that the urban–rural differences increase distinctly in most areas in the south (<29° N; figure S4) and a few areas in northern China, where the largest magnitude changes exceeded 2.0 mm decade\(^{-1}\) for Max1h and 0.3 mm h\(^{-1}\) decade\(^{-1}\) for 195p (figures 2(b) and (f)). Remarkable decreasing trends were observed in northeastern and central China. For the valid grids that contain provincial capital cities, significant trends of urban–rural differences for extreme precipitation occurred over two-thirds (16 out of 24) of the grids (table 1), with 11 grids experiencing changes in extreme intensity (Max1h or 195p), and nine grids showing changes in extreme frequency (F95p). Significant increasing trends of urban–rural differences for hourly extreme precipitation were observed in metropolitan areas such as Guangzhou (in the PRD), Shanghai, and Hangzhou (in the YRD), and smaller size provincial capital cities outside urban agglomerations (e.g. Shenyang, Fuzhou, and Zhengzhou) (table 1).

The local changes in hourly extreme precipitation affected by urbanization, if combined with the inter-annual variation in rainfall characteristics, could either strengthen or mitigate the extremes. The positive trends of both all-station anomalies and urban–rural differences (type 1; figure S6(a)) represent the role of urbanization in amplifying the intensification of extreme precipitation, principally in southern China (<29° N, blue areas in figure 2). In other words, these areas experienced an overall enhancement of extreme precipitation, with the discrepancy that extreme precipitation increased faster over urban areas than in rural areas. For example, the trend of the urban–rural difference for Max1h in Nanning was up to 4.17 mm decade\(^{-1}\), nearly three-fold higher than that for the trend of all-station anomalies (table 1). In addition, the trends of urban–rural differences for F95p in Guangzhou, Fuzhou, and Changsha were significantly positive and much higher than those of all-station anomalies (table 1). By contrast, the negative trends of both all-station anomalies and urban–rural differences (type 4; figure S6(d)) imply the amplification role of urbanization in decreasing extreme precipitation. This type mainly appears in the northeastern (>42° N) and parts of the north (orange areas in figure 2). For example, the trend of urban–rural difference for F95p in Shenyang is \(-2.60 \text{ h decade}^{-1}\), a value that is more than double for all-station anomalies \((-1.25 \text{ h decade}^{-1}\)). Moreover, the inconsistent trends between urban–rural differences and all-station anomalies (types 2 and 3; figures S6(b) and (c)) indicate that urban may serve as a ‘buffer’ to the inter-annual variation in precipitation extremes, and they are mainly located in the central and most parts of north China. The urban extent might mitigate the decadal changes in extreme rainfall frequency or intensity, resulting in a more slowly changing trend than in rural areas.

3.2. Changes in seasonality of extreme precipitation

The seasonality of urban–rural differences in hourly extreme precipitation indices was further investigated over six rapidly urbanized areas (figure 1(b); section 2.4). Generally, months with higher amounts of extreme precipitation (main rainy seasons) demonstrate a greater amplitude of urban–rural differences over these areas, especially for May–June in the south (e.g. Guangzhou) and July–September in the central and northern regions (e.g. Hangzhou, Zhengzhou, and Beijing). Our results generally show the inhibition of the frequency of extreme rainfall over urban areas
Figure 2. Spatial distribution of linear trend of extreme precipitation indices over China, 1985–2012. Linear trends of all-station anomalies and urban–rural differences are shown for (a), (b) Max1h, (c), (d) F95p, (e), (f) I95p, and (g), (h) P95p. Black crossings denote a significant trend at the 95% confidence level. Only the valid grids are shown.

For example, the largest descent of F95p in June (−1.75 h) for Guangzhou (figure 3(a)) was associated with the month with the highest frequency of extreme rainfall (6.85 h). A negative urban–rural difference in F95p was also observed in other regions. A few exceptions are the August and September for Hangzhou (0.63 and 0.98 h, respectively; figure 3(b)), and August for Beijing (0.46 h; figure 3(e)), when the enhancement role of urban areas is pronounced for both the frequency and...
Table 1. Linear trends of hourly extreme precipitation indices for valid grids with provincial capital cities over China: Max1h (unit: mm decade$^{-1}$), F95p (h decade$^{-1}$), I95p (mm h$^{-1}$ decade$^{-1}$), and P95p (% decade$^{-1}$). Grids are named for the corresponding capital cities, of which the locations and regions are presented in figure S5. Trends for all stations ($A_{el}$) and urban–rural differences ($A_{du}$) are presented. Bold numbers with star symbols denote significant trends at the 95% confidence level.

| Regions | Cities       | All stations |       | Urban–rural differences |       |
|---------|--------------|--------------|-------|-------------------------|-------|
|         |              | Max1h        | F95p  | I95p                    | P95p  |
| South   | Haikou       | 1.18         | 2.02* | 0.16                    | 0.70  | −0.39 | 2.35* | −0.56 | 0.95  |
|         | Nanning      | 1.44*        | 1.33  | 0.20                    | 0.90  | 4.17* | −0.54 | −0.08 | 0.11  |
|         | Guangzhou    | 1.72*        | 2.45* | 0.27*                   | 2.15* | 2.40* | 0.20  | 0.32* | 0.87  |
|         | Fuzhou       | 0.82         | 2.81* | 0.00                    | 1.89* | 3.20* | 1.72* | 0.25* | 1.37* |
|         | Changsha     | 0.82         | 1.59  | 0.16                    | 1.73* | 1.72* | 0.19  | 0.24* | 0.76* |
|         | Nanchang     | 0.84         | 1.73  | 0.11                    | 1.56* | 0.34  | −0.42 | −0.12 | −0.36 |
| Central | Chongqing    | 0.80         | 1.01  | 0.07                    | 1.33* | 0.33  | 0.10  | 0.05  | 0.21  |
|         | Hangzhou     | 1.65*        | 0.36  | 0.26*                   | 1.48* | 1.35* | −0.04 | 0.18* | 0.27  |
|         | Chengdu      | 0.03         | −0.22 | 0.00                    | 0.14  | 0.40  | −0.95 | 0.02  | −1.00 |
|         | Wuhan        | −0.12        | −0.57 | 0.02                    | 0.14  | −1.06 | 0.98* | −0.33* | 0.28 |
|         | Shanghai     | 1.52*        | −0.28 | 0.39*                   | 1.69* | 0.85  | −0.36 | 0.39* | 0.53  |
|         | Hefei        | 1.72*        | 1.27  | 0.20                    | 2.51* | 0.59  | −0.09 | 0.01  | 0.37  |
|         | Nanjing      | 1.81*        | 1.14  | 0.32*                   | 2.65* | 0.11  | −0.95* | 0.10  | −0.35 |
| North   | Xi’an        | 0.98         | 3.37* | −0.06                   | 1.73* | −2.11 | −1.12* | −0.28 | −1.75* |
|         | Zhengzhou    | −0.37        | 1.22  | −0.37                   | −0.12 | 1.09  | −0.64* | 0.28  | −0.52 |
|         | Ji’an        | 0.09         | 1.29* | −0.32*                  | −0.09 | 1.34* | 0.43* | 0.33  | 1.10* |
|         | Taiyuan      | 1.99         | 0.49  | 0.07                    | 0.45  | 0.90  | 0.55  | 0.14  | 0.97  |
|         | Shijiazhuang | −0.04        | 0.42  | 0.30*                   | −0.56 | 1.81* | 0.17  | 0.12  | 0.49  |
|         | Tianjin      | −0.04        | 0.35  | 0.22                    | −1.41 | 0.63  | −0.09* | 0.38  | 0.14  |
|         | Beijing      | −0.22        | −0.90 | −0.02                   | 1.62  | −0.78 | −0.49 | 0.04  | −1.25 |
|         | Hohhot       | −0.45        | 0.12  | 0.04                    | 0.37  | −2.23* | 0.05  | −0.37* | −1.23 |
| Northeast| Shenyang    | −2.05        | −1.25*| −0.51                   | −1.43 | 5.00* | −2.60* | 1.57* | −3.15 |
|         | Changchun    | −0.56        | 0.76  | −0.05                   | 0.44  | 0.70  | 0.13  | −0.14 | 0.36  |
|         | Harbin       | −1.33        | −1.24*| −0.15                   | −0.85 | −0.16 | −0.29 | −0.16 | −1.15 |

intensity of hourly extreme precipitation (figures 3, 4, and 7).

For extreme intensity, the higher amplitude is particularly obvious for the areas with positive trends of urban–rural differences in hourly extreme intensity (figures 4 and S7), for example, the larger urban–rural differences of I95p in May (0.70 mm h$^{-1}$) and September (0.94 mm h$^{-1}$) for Guangzhou (figure 3(a)), and Max1h (2.64 mm in August and 3.10 mm in September) and P95p (3.52% in August and 2.90% in September) for Hangzhou (figures S7(b) and S8(b)). Even for areas in central, north, and northeast China, where the urban–rural differences display weak signals, urban areas still generate more intense rainfall than rural areas in the main part of the rainy season. For example, the Zhengzhou area has the largest differences in I95p (1.50 mm h$^{-1}$) in July, when the mean intensity reaches 13.86 mm h$^{-1}$ (figure 4(c)). The Beijing area experiences more intense and a higher amount of precipitation in urban areas than rural areas in August, which is during the heart of the local rainy season (1.16 mm h$^{-1}$ for I95p, 2.49 mm for Max1h, and 4.87% increment for P95p; figures 4(e), S7(e), and S8(e)). The extreme precipitation intensity in urban areas still exceeds rural areas in July for Chengdu (0.44 mm h$^{-1}$; figure 4(d)) and Changchun (0.53 mm h$^{-1}$; figure 4(f)), although it is less pronounced than Zhengzhou and Beijing.

3.3. Diurnal nature of extreme precipitation changes

The diurnal signals of urban influence on hourly extreme precipitation were further detected in several cases, that is, specific months in these rapidly urbanized areas, during which the heaviest extreme precipitation occurs and displays a large amplitude of urban–rural differences. The selected cases were May for Guangzhou, July for Zhengzhou, July for Chengdu, and August for Beijing. Generally, the diurnal variations in the four hourly extreme indices were similar for urban and rural stations within each case and showed discrepancies among areas (figures 5, 6, S9 and S10). Guangzhou area has only one afternoon peak (13:00–17:00 LST). Zhengzhou and Chengdu exhibit early morning peaks (1:00–3:00 LST), and Beijing shows two peaks: at night (17:00–21:00 LST) and early morning. The enhanced impact of urban areas on extreme precipitation occurred mostly at a peak time. The F95p of urban stations in Guangzhou, Chengdu, and Beijing becomes higher than that for rural areas, and F95p in Zhengzhou was nearly identical to the rural frequency at peak time (figure 5). In the Guangzhou area, a positive urban–rural difference in extreme intensity is detected during the afternoon peak, with differences reaching 1.24 mm h$^{-1}$ in 16:00 LST and 0.99 mm h$^{-1}$ in 17:00 LST (figure 6(a)). Similar results were found in other locations, where urban areas were
Figure 3. Seasonality of the urban–rural difference of F95p (unit: hours) in the six regions, 1985–2012. (a) Guangzhou, (b) Hangzhou, (c) Zhengzhou, (d) Chengdu, (e) Beijing, and (f) Changchun. Bars denote the urban–rural difference (y-axis on the left); grey lines denote the total average F95p in the area (y-axis on the right). Error bars indicate the 95% confidence intervals of the mean difference.

Figure 4. Same as figure 3 but for the urban–rural difference of I95p (unit: mm h$^{-1}$) in the six regions.

associated with higher rainfall intensities than rural areas in the corresponding early morning and night peaks (figures 5 and S9). The combination of the increasing intensity and changing frequency caused a positive urban–rural difference in P95p (figure S10). Great differences occur at their respective peak times, with values of 3.17% in Guangzhou, 6.89% in Chengdu, 2.32% in Zhengzhou, and 3.99% in Beijing, respectively.

Discrepancies exist among different areas. In August in Beijing, precipitation intensification not only occurs at the peak time, but also almost the whole day, indicating an overall increase in extreme precipitation in urban versus rural areas during the local rainy season (figures 5(d), 6(d), S9(d), and S10(d)). In other cases, the results show a smaller urban effect on precipitation extremes during non-peak times. In addition, delays in the peak
precipitation time were observed in the Guangzhou area. Rural stations reached peak intensities at approximately 13:00 LST, and urban stations received peak precipitation at approximately 16:00 LST. Similar delays are found for Zhengzhou but are less obvious; for example, a 1 h delay can only be observed in the early morning peak for Max1h and I95p (figures 6(b) and S10(b)).
4. Discussion

We found that China has experienced significantly more extreme rainfall in the south, and a decreasing trend was detected in the north during the rainy season of the past decades. These distinct regional patterns were described in the literature (Li et al. 2016). Despite the impact of a large-scale synoptic system (e.g. the East Asian summer monsoon) that assists in the formation of such spatial variances, urbanization could also theoretically affect extreme precipitation characteristics (Sun et al. 2017). Urban impacts of a local nature, for example, have been determined in the form of urban acceleration in extreme precipitation in Guangdong Province (Yan et al. 2020) and Shanghai (Zhou and Yang 2001), and the promotion of an intensity decrease in Beijing (Li et al. 2015). By analyzing the urban–rural differences in hourly extreme precipitation indices across China with reference to an annual dynamic urban–rural station classification, we extended the knowledge of urban effects on extreme precipitation from a few metropolitan areas to regional and national scales.

We found that two-thirds of provincial capital cities have significant trends in urban–rural differences for hourly extreme precipitation. Furthermore, these differences and the underlying mechanisms of the urban influence on extreme precipitation differ among regions. Urbanization regulates the spatial heterogeneity of hourly extreme precipitation, enlarging the increasing (decreasing) rates of extreme precipitation in southern (part of north and northeast) China and mitigating the changes in extreme precipitation in central China (figure 2). Water vapor change due to energy alteration could be a key factor that accounts for the enhancement of urbanization in enhancing (declining) precipitation. Urban areas may produce more water vapor than rural areas resulting from the promotion of local moisture convergence under conditions with sufficient water supply (Zhang et al. 2019, Wang et al. 2021). Therefore, urban areas experienced more frequent and intense precipitation than rural areas as extreme precipitation continued to increase in the south (type 1; figure S6(a)). By contrast, urban areas can also produce less water vapor than rural areas and generate more convective inhibition energy, especially in the north (Zhang et al. 2009). As a result, the reduction in frequency is the major contributor to the faster precipitation decrease than before in some parts of north China. Expanding impervious surfaces and high water consumption in the city could be factors that further suppress extreme precipitation in regions where decreasing precipitation and cloud cover have been observed, for example, northeast China (Kaiser 2000, Wang et al. 2013a), where both intensity and frequency decrease with a decrease in rainfall. Urbanization in these two regions contributes to even less precipitation in urban areas as the region becomes dryer (type 4, figure S6(d)). The regional increases/decreases in extreme precipitation in central and parts of northern China are alleviated by urbanization locally by changing the precipitation frequency and intensity, increasing precipitation in drying areas and decreasing it in wetting areas (types 2 and 3; figures S6(b) and (c)).

In addition to distinct spatial patterns, the influence of urbanization on extreme precipitation demonstrates temporal variations. Seasonal variations between urban and rural stations were also investigated in the regional analyses of six rapidly urbanized areas. Urbanization enhancement of extreme precipitation generally shows a concentrated interannual variability that amplifies the extreme precipitation intensity in the main part of the local rainy seasons, referring to May in the south and July–September in the central and northern regions, which is consistent with previous results (Li et al. 2017, Su et al. 2019, Yan et al. 2020). Even in areas where urbanization slows the increasing rates (or speeds up the decreasing rates) of extreme precipitation, the enhancement of hourly extreme precipitation over urban stations during the main rainy season can still be detected. The effect is carried over to diurnal variability in that the enhancement impact of urban areas on extreme precipitation can be found mostly at the peak time. These results conform to the diurnal cycles in prior research (Plouhay and Lau 2010, Liu et al. 2021) and related studies on the urbanization effect on regional precipitation (Yuan et al. 2020). Urban areas tend to affect peak precipitation by increasing the intensity or frequency of extreme precipitation in most areas, leading to an increase in the proportion of extreme precipitation. Delaying urban precipitation is observed in diurnal variations, specifically in Guangzhou.

Mechanisms for the urban intensification of extreme precipitation might be attributed to two factors: land cover change and the urban heat island effect. An increase in surface roughness intensifies mechanical turbulence, which leads to enhanced convergence, intensifying convective precipitation (Li et al. 2021). Using the WRF model, Miao et al. (2011) proposed that urban land cover is responsible for breaking squall lines into convective cells and changing the thermal transport, leading to more concentrated precipitation in urban areas than in rural areas. Furthermore, the disturbed radiation budget and released anthropogenic heat over urban lands favor the formation of urban heat island circulation, promoting the upward transport of water vapor (Yang et al. 2019). Regarding precipitation delays, urban aerosols may be one of the affecting factors (Guo et al. 2015). Alternatively, the delay could also result from wind effects, as Chen et al. (2010) observed in Yangtze River Valley.
5. Conclusions

In conclusion, our findings highlight the potential increasing risks of waterlogging and flash flooding in urban areas. Urbanization exacerbates the spatial heterogeneity of extreme precipitation over China, producing more storm events and more rainfall in a single event. Impervious surfaces in cities and heavy rainfall together exacerbate waterlogging (Zhang et al. 2021). Moreover, the intensified extreme precipitation that occurs in the main local rainy seasons and greater peak precipitation times could increase local flash flooding or ponding. Notably, the urban enhancement for the wet season and the peak rainfall time not only occur in metropolitan locations but also in smaller size cities (e.g. Chengdu and Zhengzhou), indicating the importance of further investigations including minor cities. Large cities and small-scale cities are both susceptible to precipitation enhancement related to urbanization. However, research in these areas remains insufficient, and the underlying mechanisms require further research. Understanding these effects may provide insights into future hydrometeorology and hazard mitigation in urban areas.

Data availability statement

The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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Conflict of interest

The authors declare no competing interests.

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