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Asymmetrical Shift Toward Less Light and More Heavy Precipitation in an Urban Agglomeration of East China: Intensification by Urbanization

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Key Points:

- Changes in rainy-season precipitation over the YRD show an asymmetrical shift toward less light and more heavy precipitation
- This asymmetrical shift has been amplified by rapid urban expansion in recent decades
- Urbanization contributes to 44.4% of the decrease in light precipitation and 26.4% of the increase in heavy precipitation

Supporting Information:

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

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Abstract Under global warming, projected changes in precipitation have shown an asymmetrical shift from light to heavy precipitation over China. However, the role of urbanization in this shift remains unknown. Here, we show that increases in total rainy-season (May-September) precipitation over the Yangtze River Delta (YRD) urban agglomeration of East China are characterized by decreasing light precipitation and increasing heavy precipitation during 1961–2019. This asymmetrical shift toward heavier precipitation is even more prominent in urban than rural areas. Areas with faster urban expansion rates exhibit stronger negative (positive) trends in light (heavy) precipitation. Urbanization contributes to 44.4% (26.4%) of the decreasing (increasing) light (heavy) precipitation in the urban areas of the YRD. We suggest that urban managers should consider potential adverse impacts of this asymmetrical shift, which may favor increases in both the frequency of heatwaves and waterlogging.

Plain Language Summary China has experienced rapid urbanization in recent decades, alongside decreases in light precipitation and increases in heavy precipitation. This shift in precipitation patterns is also observed in the Yangtze River Delta (YRD), a typical densely populated region of China. Over the period 1961–2019, urban areas of the YRD have witnessed intensifying precipitation characterized by sharper decreases in light precipitation as well as sharper increases in heavy precipitation than rural areas. We estimate that 44.4% of the decrease in light precipitation and 26.4% of the increase in heavy precipitation in urbanized areas can be attributed to urbanization.

1. Introduction

Precipitation-temperature relations are regulated by the Clausius-Clapeyron (C-C) equation (Wang et al., 2017; Westra et al., 2014), whereby the water vapor holding capacity of the atmosphere increases by 6–7% for each degree of warming. This scaling relationship theoretically explains increasing precipitation intensity in a warming climate (Donat et al., 2016; Giorgi et al., 2011; Gu et al., 2017; Ingram, 2016). For example, Donat et al. (2016) found that both wet and dry regions of the world have witnessed increasing heavy precipitation using in situ and model data. Conversely, most areas of the globe have also observed a decreasing trend in light precipitation in recent decades, such as North America (Dai et al., 2020), Europe (Qian et al., 2010), and Asia (Ma et al., 2015; Ren et al., 2015; Wu et al., 2017; Zhou et al., 2020). Ma et al. (2015) found that China witnessed more heavy precipitation (≥50 mm/day) and less light and moderate precipitation (<10 and 10–25 mm/day, respectively) during 1960–2013, which shows an asymmetrical change for different categories of precipitation intensity. Both lower-tropospheric warming and decreasing water vapor content are responsible for this reduction in light precipitation (Dai et al., 2020; Giorgi et al., 2011; Wu et al., 2015). Additionally, greater changes per unit warming are found in light and heavy precipitation than in medium-intensity precipitation (Ma et al., 2015).

Since atmospheric temperature warming drives this asymmetrical change in light and heavy precipitation, local urbanization, which leads to a higher temperature in urban than surrounding rural areas (known as the urban heat island (UHI) effect (Kong et al., 2020; Ren & Zhou, 2014; Ren et al., 2008; Sun et al., 2016), may further affect this asymmetry. Previous studies have widely investigated UHI effects on heavy precipitation (Gu et al., 2019a, 2019b; Li et al., 2020; Singh et al., 2016; Wang et al., 2018; Yang, Ren, et al., 2017). For example, Li et al. (2020) found that extreme precipitation increased 3 times more in urban than rural areas in Kuala Lumpur, Malaysia using observed and modeled evidence. Additionally, several studies have detected an urban dry island (UDI) effect (Li et al., 2021; Liu et al., 2009; Luo & Lau, 2019; Yang, Ping, et al., 2017), where urbanization may lead to reductions in relative humidity and amplification of vapor pressure deficit (VPD). This drying atmospheric moisture and enhanced VPD make it harder for light precipitation to occur in urban areas (Dai et al., 2018, 2020; Ren et al., 2016; Yang et al., 2021). Yang et al. (2021) showed that the frequency of light precipitation (hourly 0.1–0.3 mm) is significantly smaller in the central urban area of Beijing relative to the surrounding rural areas, and they attributed this spatial pattern to the remarkable decrease in relative humidity, the increase of cloud base height and a denser aerosol concentration in the urban areas. From the above-mentioned researches, we hypothesize here that the asymmetrical change in different categories of precipitation intensity may therefore be caused or intensified by urbanization. Whether or not this hypothesis is confirmed by observed evidence should be investigated, because other processes associated with urbanization (such as surface roughness, anthropogenic aerosols, and evapotranspiration) may also alter precipitation occurrence and distribution (Freitag et al., 2018; Han et al., 2014; Li et al., 2020; Zipper et al., 2017).

The Yangtze River Delta (YRD) is densely populated, economically developed, and represents a typical highly urbanized region in eastern China. Given that the YRD contributes 11% of the population and 25% of Gross Domestic Product (GDP) of China (Zhu et al., 2016) for just 2.2% of the land surface area, it is frequently chosen as a typical region to investigate strong urbanization effects (Jiang et al., 2020; Lu et al., 2019; Luo & Lau, 2019; Wang et al., 2021; Yang, Leung, et al., 2017). Here, we assess the potential effect of urbanization on the asymmetrical change in light and heavy precipitation within the urban agglomeration. Because this asymmetry may be causing increases in extreme hydro-climatic events, our results could provide a valuable reference for understanding large-scale changes in extreme precipitation patterns and for improving urban planning and design in other regions of the globe beyond eastern China.

2. Study Region and Data

The YRD region includes 27 cities (total areas: 301,700 km^2) within the Shanghai, Jiangsu, Zhejiang, and Anhui provinces (Figure 1a; Luo & Lau, 2019). It has experienced rapid urbanization since the 1980s, with urban areas expanding at a rate of 973 km^2/yr during 1980–2015 (Figure 1a). Previous studies have found enhanced extreme precipitation and prominent reductions in humidity in the summer due to strong urban effects in YRD (Jiang et al., 2020; Lu et al., 2019; Luo & Lau, 2019; Wang et al., 2021).

We obtained a quality-controlled and homogenized daily data set for 2,481 weather stations from the National Meteorological Science Data Center. This data set includes observations since the 1950s for eight variables, including precipitation, surface air temperature, and relative humidity. The locations of the stations are provided for each year, so any effects of site migration on the identification of urban stations can be considered. A station is retained for the following analyses if it has observations over 1961–2019 and a missing rate during the rainy season (May-September) of no >5%. After filtering, 126 stations remain in the YRD region (Figure 1a).

The actual evapotranspiration during 2000–2019 is estimated using a coupled diagnostic biophysical model (i.e., PML_V2). The performance of PML_V2 has been evaluated and validated with other estimated evapotranspiration data sets and in situ observations (Zhang et al., 2016, 2019). The spatial and temporal resolutions of PML_V2 are 500 m and 8 days, respectively. This PML_V2 data set has been widely used in previous studies

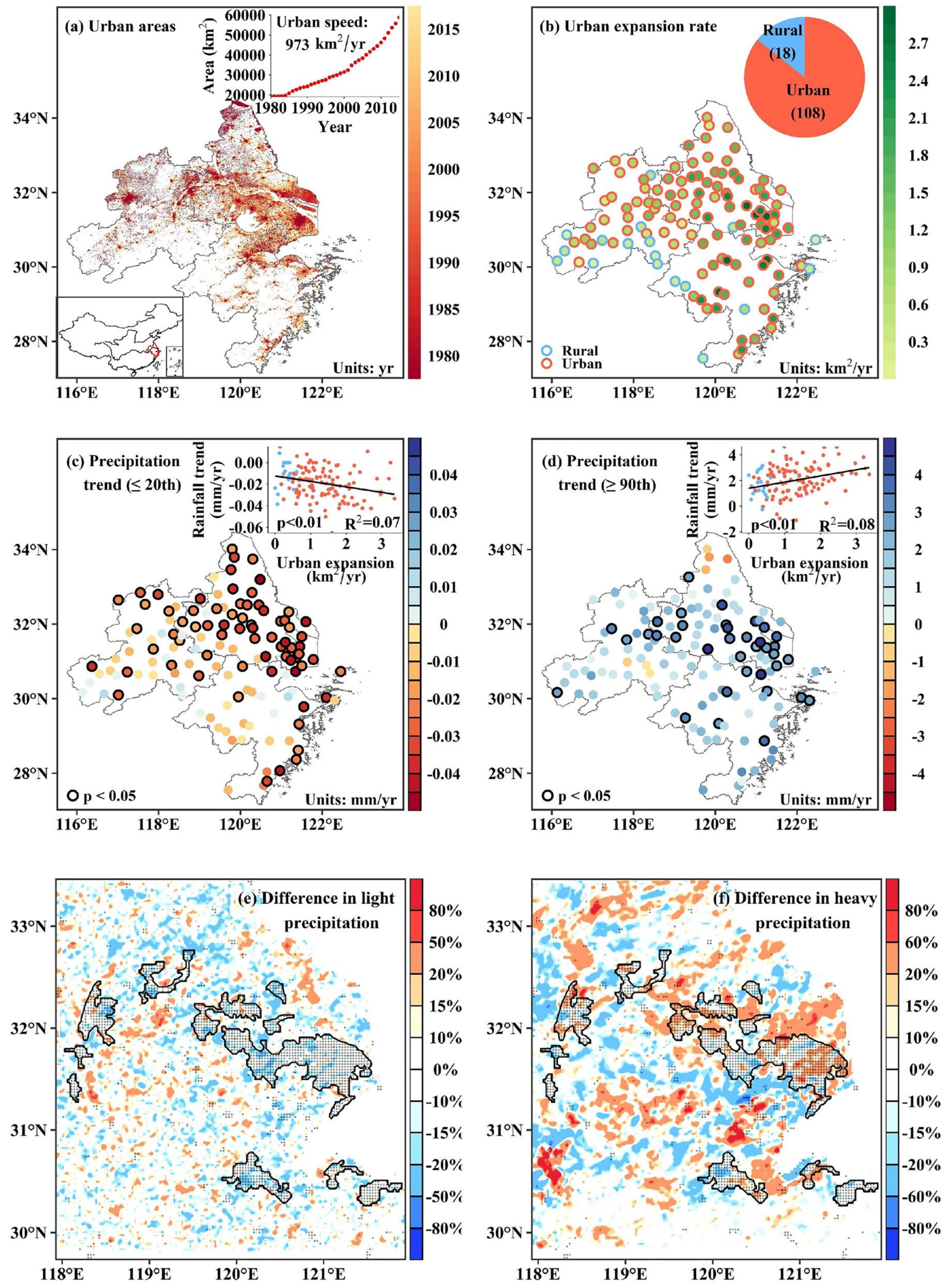
(a) Urban areas
Urban speed: 973 km²/yr
Area (km²)
Year
Units: yr
(b) Urban expansion rate
Rural (18)
Urban (108)
Rural
Urban
Units: km²/yr
(c) Precipitation trend (≤ 20th)
Rainfall trend (mm/yr)
p<0.01 R²=0.07
Urban expansion (km²/yr)
p < 0.05
Units: mm/yr
(d) Precipitation trend (≥ 90th)
p<0.01 R²=0.08
(e) Difference in light precipitation
(f) Difference in heavy precipitation

Figure 1.

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(Elnashar et al., 2021; Huang et al., 2020; Zhang et al., 2020), and more details on the model can be found in Zhang et al. (2019). Hourly K-index data indicating atmospheric instability and thunderstorm potential are obtained for 1961–2019 from the ERA5 reanalysis data with 0.25° spatial resolution.

Land use/land cover (LULC) data for China in each year of 1980–2015 were produced by Xu et al. (2020). The 30-m LULC data set was generated based on multiple satellite images, including Moderate Resolution Imaging Spectroradiometer (MODIS) and 30-m Landsat TM/ETM+/OLI. The quality of the LULC data set has been evaluated and assessed, and urban areas are explicitly mapped in each year (Xu et al., 2020).

3. Methods

3.1. Definition of Different Categories of Precipitation Intensity

Most heavy precipitation in the YRD region occurs in the rainy season (May-September) and therefore, daily precipitation during this season is selected for the following analyses. A rainy day is defined as total precipitation exceeding 0.1 mm. The 10th, 20th, …, 90th, and 95th quantiles of the rainy days in the rainy season of the climatological period (1961–1990) are taken as the thresholds to define precipitation intensity. Annual total precipitation in each category of precipitation intensity (i.e., 0th–10th, 10th–20th, …, and ≥95th) is calculated during the rainy season of 1961–2019 at each station. The nonparametric modified Mann-Kendall method (Hamed & Rao, 1998) is employed to detect changes within each category.

3.2. Dynamic Identification of Urban and Rural Stations

We identify urban stations by considering both site migration and dynamic urbanization, using the annual locations of weather stations and annual LULC data. For each station, a 7-km circular buffer is established in each year of 1980–2015 (see Figure S2a in Supporting Information S1 for an example), and the percentage of urban area in this buffer is calculated. For each station, the annual change in urban area (unit: km^2/yr) within the 7-km circle is taken as the urban expansion rate. The radius is set to 7 km because previous studies have suggested that this radius is the optimal radius to identify urban stations in the YRD region (Luo & Lau, 2019; Yang, Leung, et al., 2017). Similar to these two previous studies, we test the correlations between urban expansion rates estimated in buffers with a radius of 1–10 km and changes in different categories of precipitation intensity (Figure S1 and Text S1 in Supporting Information S1). We find that the correlations tend to be stable for a radius ≥7 km.

For each year, a station is identified as an urban station if the percentage of urban area within the 7-km buffer is >20%. This percentage is consistent with previous studies (Luo & Lau, 2019; Yang, Leung, et al., 2017). However, several studies chose other percentages to identify urban stations, such as 33% (Liao et al., 2018; Ren & Zhou, 2014), so we also test whether our results are sensitive to urban station identification using other percentages (20%, 25%, …, 50%). We identify 26 urbanized stations (in all years from 1980), 82 urbanizing (where the station became urbanized during 1980–2015), and 18 rural stations (in all years from 1980; Figure 1b, Figures S2b–S2i and S3 and Text S1 in Supporting Information S1).

3.3. Quantification of Urbanization Effects

By dynamically classifying stations as urban and rural, changes in total precipitation are estimated in urban and rural stations over the period 1961–2019, i.e., P_U and P_R, respectively, for different categories of precipitation intensity. The urban effect is quantified by $|P_U - P_R|$, and the contribution of urbanization is estimated

Figure 1. Spatial distributions of (a) urban areas, (b) urban expansion rate, (c and d) precipitation trend, and (e and f) difference in light and heavy precipitation over the Yangtze River Delta (YRD). Panel a shows annual urban area from 1980 to 2015. Panel b shows urban expansion rates within a 7-km radius in rural and urban (including both urbanized and urbanizing) stations. Panels c and d show trends in total precipitation below and above the 20th and 90th quantiles during the rainy season of 1961–2019 at all stations, respectively. Inset scatterplots in c and d show linear regressions between the precipitation trends and urban expansion rates. In the scatterplots, blue (orange) dots indicate values from rural (urban) stations. In panels e and f, light/heavy precipitation is the daily value ≤5 mm/≥50 mm, and the difference is calculated as ((Urb2010 values − Urb1988)/Urb1988) from the WRF experiment. The areas enclosed by black lines in e and f are the main urban areas, and the stipples indicate the difference of light (heavy) precipitation between the two WRF experiments is significant at the 0.05 level in the urban areas.

by $\left|\frac{P_U - P_R}{P_U}\right| \times 100\%$, as in previous studies quantifying the urbanization effect on and contribution to surface air temperature (Luo & Lau, 2019; Ren & Zhou, 2014).

3.4. Model Experiments

The Weather Research and Forecasting (WRF) modeling system (version 3.6) is employed to simulate urban impacts on precipitation over the YRD region. LULC data for the year 1988 (Urb1988), 2000 (Urb2000), and 2010 (Urb2010) are utilized as surface boundary conditions, respectively. The June-August precipitation is simulated over the YRD region in 2001, 2003, and 2005 under the two surface boundary conditions. The 3 years are chosen for their consistent summertime temperature with the climatological mean temperature. Detailed information on the WRF physical parameterizations, experiment designs, and model evaluations can be found in Cao et al. (2016).

4. Results and Discussion

During 1961–2019, the YRD urban agglomeration has undergone rapid urbanization especially since the 2000s (671 km^2/yr during 1980–2000 and 1,712 km^2/yr during 2001–2015; Figures 1a and 1b). Over the same period, the YRD is dominated by increasing trends in total rainy-season precipitation (Figure S4 and Text S2 in Supporting Information S1). These increases in total precipitation are most prominent in the stations with higher urban expansion rates (e.g., stations in Shanghai and surrounding areas). The significant positive regression relation ($p < 0.01$) between increasing total precipitation trends and urban expansion rates (see scatterplot in Figure S4d in Supporting Information S1) suggests that the faster the urban expansion, the greater the rise in total precipitation. The increase in total precipitation is confirmed by positive trends in all quantile ranks (i.e., 10th, 20th, …, 90th, 95th, 100th values of each year), but the increasing rates are uneven and rise exponentially for higher percentiles (Figure 2a). This exponentially rising feature in the increasing rates of all quantile ranks is most obvious in urbanized areas, followed by urbanizing areas, and rural areas (Figure 2b, Figure S5a and Text S2 in Supporting Information S1). For each of the 82 urbanizing stations, the year when the station turned from rural to urban is used to divide the whole period (i.e., 1961–2019) at a given station into two subperiods (i.e., rural and urban). The exponential rise is more obvious during the urban period than during the rural period (Figure S6a and Text S2 in Supporting Information S1). The above results demonstrate that total precipitation over the YRD shows an asymmetrical increase in heavy precipitation and urbanization plays an important role in this asymmetrical increase.

We further investigate how this asymmetrical increase affects the precipitation amounts for different intensities. The 10th, 20th, …, 90th, and 95th percentiles of rainy days during 1961–1990 are calculated and then the precipitation amounts of ≤10th, 10th–20th, …, and ≥95th in each year are counted. We find that precipitation totals below low quantiles exhibit distinctly negative trends, especially for the two categories of ≤10th and 10th–20th percentiles (mean rates are −6.3% per decade and −7.3% per decade, respectively; Figure 2c). Precipitation trends in the medium categories (i.e., 20th–30th, …, 60th–70th) are slightly negative (with a mean rate of −1.3% per decade), and then switch to increases in the 70th–80th percentile category. A sharp increase is found in the precipitation amounts above high quantiles (i.e., the 90th–95th and ≥95th percentiles exhibit mean rates of +1.6% per decade and +7.1% per decade, respectively). This clearly indicates an asymmetrical shift toward heavier precipitation over the YRD in the rainy season, in line with previous studies (Ma et al., 2015; Wu et al., 2015).

It is worth noting that this asymmetrical shift is more evident for urbanized and urbanizing stations than that for rural stations (Figure 2d and Figure S5b in Supporting Information S1). Specifically, the precipitation totals in low quantiles (≤10th and 10th–20th) decrease faster at urban stations, while the totals in high quantiles (90th–95th and ≥95th) increase faster at urban stations. For the 82 urbanizing stations, precipitation totals also decrease below low quantiles and increase above high quantiles during the urban period relative to the rural period (Figure S6b in Supporting Information S1), demonstrating that the difference in precipitation trends (seen for low and high quantiles) between rural and urbanized stations is not due to other spatial differences such as elevation (Figure S3b in Supporting Information S1). For the medium-intensity precipitation totals, we observe smaller differences in their changes between urban and rural stations and between urban and rural periods (Figure 2d, Figures S5b and S6b in Supporting Information S1). These results imply that urbanization effects mainly occur in the low and high tails of the probability distribution of precipitation, in other words, urbanization tends to suppress light precipitation and enhance heavy precipitation.

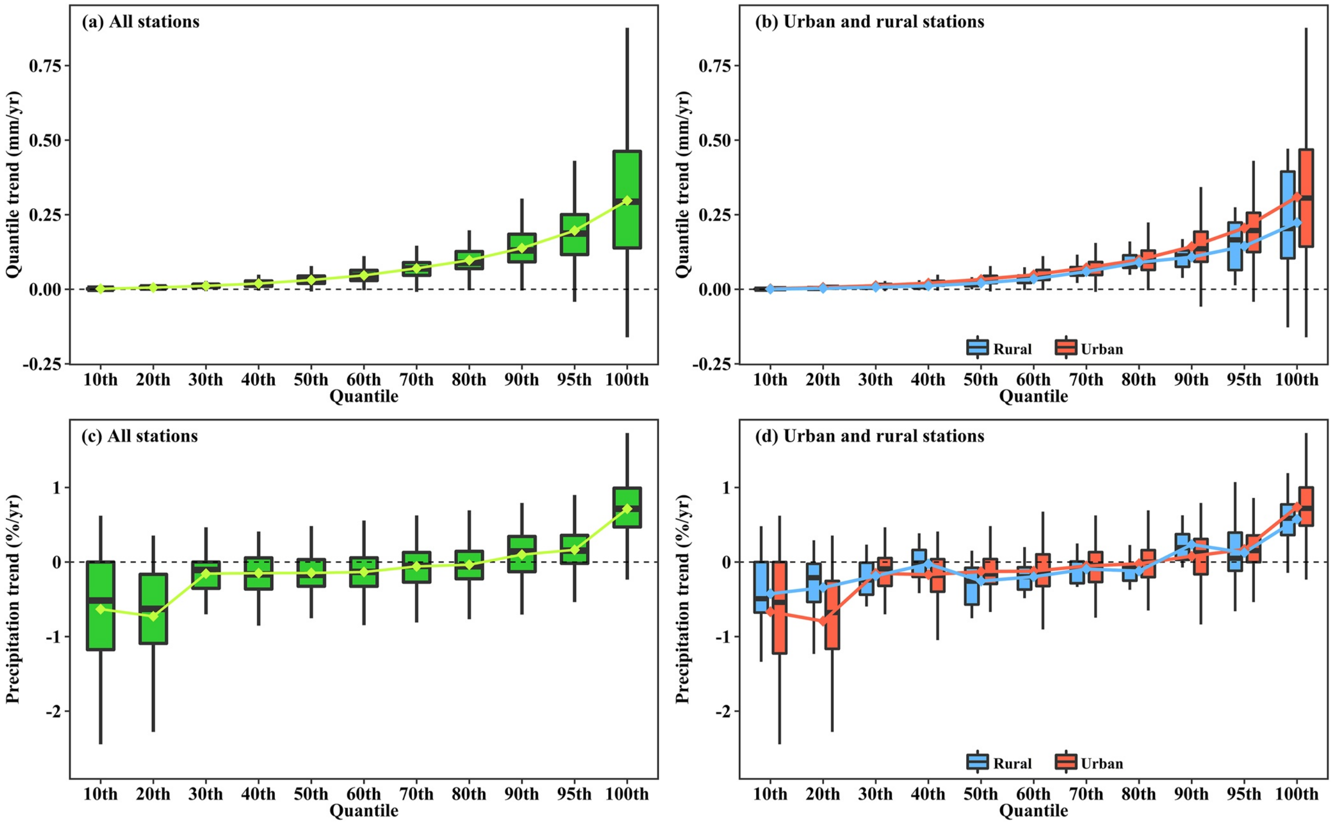

Figure 2. Distribution of trends in precipitation quantiles and total precipitation for different categories of precipitation intensity during the rainy seasons of 1961–2019 over the Yangtze River Delta (YRD). In a and b, taking the 10th quantile as an example, we calculate the 10th quantile of rainy days in each year for each individual station, and obtain a time series of this quantile. The trend (units: mm/yr) in this time series is estimated using the modified Mann-Kendall method. In c and d, we calculate the 10th, 20th, …, 90th, and 95th quantiles of rainy days during 1961–1990 for each station, and then compute total precipitation ≤10th, 10th–20th, …, and ≥95th quantile in each year. Trends (units: %/yr) in total precipitation for different categories of precipitation intensity are estimated for all stations. In b and d, urban stations include urbanizing and urbanized stations.

We now exclusively examine the changes in light (≤20th) and heavy (≥90th) precipitation during the rainy seasons (Figures 1c and 1d). A widespread reduction in light precipitation is observed over the YRD, and this reduction is particularly pronounced in the northeastern YRD (Figure 1c). Almost all stations, show increasing trends in heavy precipitation, and the most prominent increases are seen in the eastern YRD (Figure 1d). The spatial patterns of changes in both light and heavy precipitation are very similar to the spatial distributions of urban areas and urban expansion rates (see Figures 1a and 1b). These similarities in spatial patterns are further confirmed by significantly negative (positive) regression relations between the trends in light (heavy) precipitation and urban expansion rates (see scatterplots in Figures 1c and 1d). When taking values ≤10th (≥95th) and ≤25th (≥85th) percentiles as quantiles to define light (heavy) precipitation (Figures S7 and S8 in Supporting Information S1), the spatial patterns of the changes in light and heavy precipitation are not altered.

We further compare simulated summertime light (heavy) precipitation between the Urb2010 and Urb1988 experiments run using the WRF model (Cao et al., 2016). We take 5 mm (50 mm) as the thresholds to identify light (heavy) precipitation. In comparison with the Urb1988 experiment, urban areas exhibit a decrease in light precipitation (i.e., −4.07%) and an increase in heavy precipitation (+4.84%) under Urb2010 (Figures 1e and 1f). This is consistent with what we found in the observations.

We plot time series of regionally averaged light/heavy precipitation for urbanized, urbanizing, and rural stations in the YRD to assess their consistency (Figure 3 and Figure S9 in Supporting Information S1). Regionally, light precipitation (≤20th percentile) at rural stations exhibits a statistically significant decrease at a rate of 0.12 mm per decade. The negative rate at urbanized and urbanizing stations is almost twice as high (0.21 and

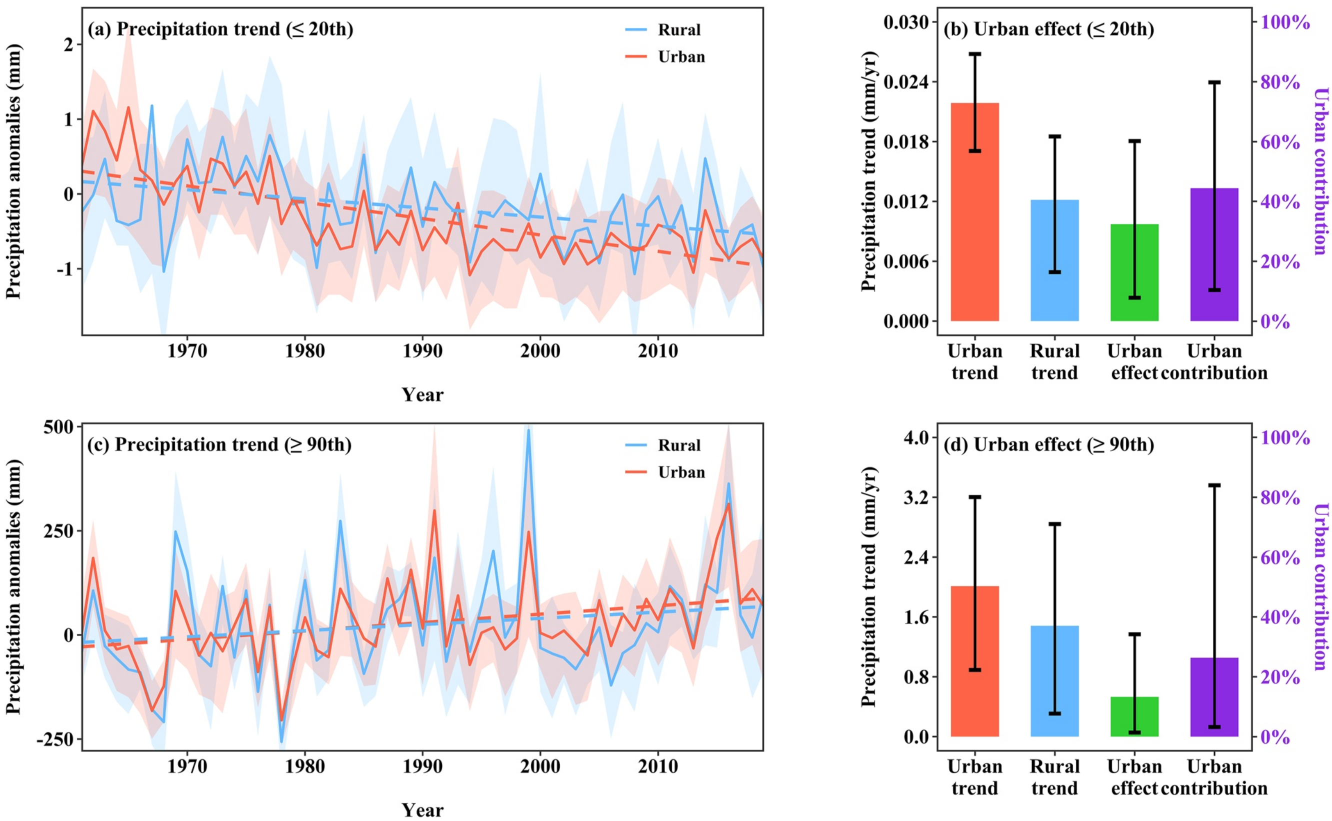

Figure 3. Time series of total precipitation below and above the 20th and 90th percentiles during the rainy season of 1961–2019 over the Yangtze River Delta (YRD). Blue and red solid lines in a and c are average values of rural and urban (urbanized and urbanizing) stations. Light blue and red ribbons are the corresponding 25–75% ranges of these average values. Blue and red dashed lines are the corresponding linear trends of these average values. In b and d, red and blue bars are the slopes of the red and blue solid lines in a and c, respectively. Green and purple bars are the urban effect and urban contribution, respectively (see Section 3). Error bars indicate the 90% confidence intervals.

0.23 mm per decade, respectively) than at rural stations. In contrast, heavy precipitation (≥90th percentile) significantly increases at a rate of 14.8, 20.2, and 21.8 mm per decade at rural, urbanizing, and urbanized stations, respectively.

In our study, we identified urban stations if the percentage of urban areas in the 7-km buffer is >20%. This percentage is relatively conservative in comparison with previous studies (e.g., Liao et al., 2018; Ren & Zhou, 2014) where the percentage is set as 33% or larger. We try to set the percentage as 35% and identified 46 rural stations. The samples of urban and rural stations are changed, while results of urban impacts on light and heavy precipitation are not altered (Figure S10 in Supporting Information S1). The difference in sample size between 82 urbanizing, 26 urbanized, and 18 rural stations may also affect the results. We employ a bootstrap approach to sample an equal number of 18 stations (equivalent to the number of rural stations) from the 82 urbanizing and 26 urbanized stations, respectively, and estimate the precipitation trend from each group of 18 stations. We repeat this process 1,000 times, and find there is a significant difference between rural/urban/urbanizing categories, irrespective of the sample size (Figure S11 and Text S2 in Supporting Information S1).

To reduce the impact of any regional confounding factors, we pair rural and urban stations by selecting urban stations that are located within a 100-km buffer of rural stations (Gu et al., 2019b; Luo & Lau, 2018). The above analyses are repeated based on the paired rural-urban stations (Figures S12–S14 and Text S3 in Supporting Information S1). We test the results when choosing 75 and 125 km as the radius, respectively, and obtain consistent results. Because the LULC data used in this study only cover the period 1980–2015, we also test our results during this period (Figures S15–S16 and Text S4 in Supporting Information S1). The finding that urbanization enhances the asymmetrical shift toward heavier precipitation can be still observed.

We finally quantify the contribution of urbanization to the decrease in light precipitation (≤20th percentile) and increase in heavy precipitation (≥90th) in urban areas (Figures 3b and 3d). Urbanization (combining urbanized and urbanizing stations into one group) contributes to 44.4% of the decline in light precipitation and 26.4% of the increase in heavy precipitation over the YRD. We also evaluate these contributions and obtain consistent results, when taking ≤10th (≥95th) and ≤25th (≥85th) as quantiles to define light (heavy) precipitation (Figure S17 in Supporting Information S1). Moreover, there is little sensitivity to the buffer radius and percentage of urban to total areas (Figure S17 and Text S5 in Supporting Information S1).

As suggested by previous studies, this asymmetrical shift in precipitation can be linked to temperature warming (Dai et al., 2018, 2020; Giorgi et al., 2011; Ma et al., 2015). Therefore, we assess the mechanisms driving UHI impacts on light precipitation changes in the YRD (Figure 4a and Figures S18 and S19 and Text S6 in Supporting Information S1). During light-precipitation days (≤20th), we find the surface air temperature increases by +0.24 and +0.10°C per decade in the urban and rural areas of the YRD, respectively. The faster increase in surface air temperature enlarges the atmospheric moisture demand in urban areas. This enlarged water demand is reflected by the increase in potential evapotranspiration (estimated by using the Penman-Monteith equation (Nyolei et al., 2021) in the urban areas (+0.4 mm per decade)), while the trend in rural areas is negative (−7.89 mm per decade). However, impervious surface expansion inhibits actual evapotranspiration from soils and plants (Zipper et al., 2017), resulting in a greater decrease of actual evapotranspiration (−23.02 versus −15.46 mm per decade for urban versus rural areas, respectively). On the one hand, the greater reduction of local evapotranspiration leads to faster decreasing relative humidity (−1.3 versus −0.43% per decade) and increasing VPD (+0.59 versus +0.23 hPa per decade) in urban areas relative to rural areas. This leads to the formation and development of an UDI effect in urban areas (Unkasevic et al., 2001; Yang, Ping, et al., 2017). Luo and Lau (2019) discussed other factors such as urban roughness and vegetation degradation linked with this UDI effect. The drier moisture and stronger VPD lead to a lower probability of precipitation occurrence (Dai et al., 2020; Giorgi et al., 2011; Ren et al., 2016) and thus a faster decline in light precipitation in urban areas. On the other hand, the reduction in urban evapotranspiration decreases local precipitation recycling (i.e., the percentage of precipitation sourced from local evapotranspiration) and then constrains the transformation of water vapor to precipitation (Wang et al., 2018).

During heavy-precipitation days (≥90th percentile; Figure 4b and Figures S20 and S21 in Supporting Information S1), although there is no obvious difference in trend magnitudes of surface air temperature between urban and rural stations (+0.16 versus +0.14 °C per decade), the atmospheric water holding capacity increases faster in urban than rural areas (+0.33 versus +0.22 hPa per decade in saturated vapor pressure). An enlarged atmospheric water holding capacity could result in stronger heavy precipitation in urban areas, when the condition for large-scale moisture transport and moisture convergence is met in the rainy season. Besides this thermal and moisture effect, the thermodynamic effects of the UHI and land surface roughness may further drive instability in the lower atmosphere, enhancing horizontal convergence and intensifying convective systems in urban areas (Freitag et al., 2018; Gao et al., 2021; Li et al., 2020; Lorenz et al., 2019). Gao et al. (2021) found high sensitivity of heavy precipitation to the land surface alteration. We show that the K-index (an index used for indicating atmospheric instability) is growing more than twice as fast in the urban areas of the YRD as in the rural areas (0.25 versus 0.11 K per decade).

We finally compared surface air temperature, relative humidity, and VPD (surface air temperature and saturated vapor pressure) during light (heavy) precipitation days between the Urb2010 and Urb1988 experiments (Figures S22–S25 and Text S7 in Supporting Information S1). Changes in these variables under Urb2010 relative to Urb1988 confirm the above results based on observations.

Previous studies pointed out that light and heavy precipitation in the urban areas show different responses to the same factor, such as surface heat fluxes and tropospheric aerosols (Holst et al., 2016; Li et al., 2019). Urbanization contributes to increased urban surface sensible heat fluxes, which results in a stronger UHI effect and heavier precipitation but has less impact on light precipitation (Holst et al., 2016). The heavy air pollution from aerosol particles in urban areas of the YRD has become a primary environmental concern in recent decades (Zhu et al., 2021), and the light (heavy) precipitation in urban areas tends to be suppressed (enhanced) under the same cloud thickness condition (Li et al., 2019).

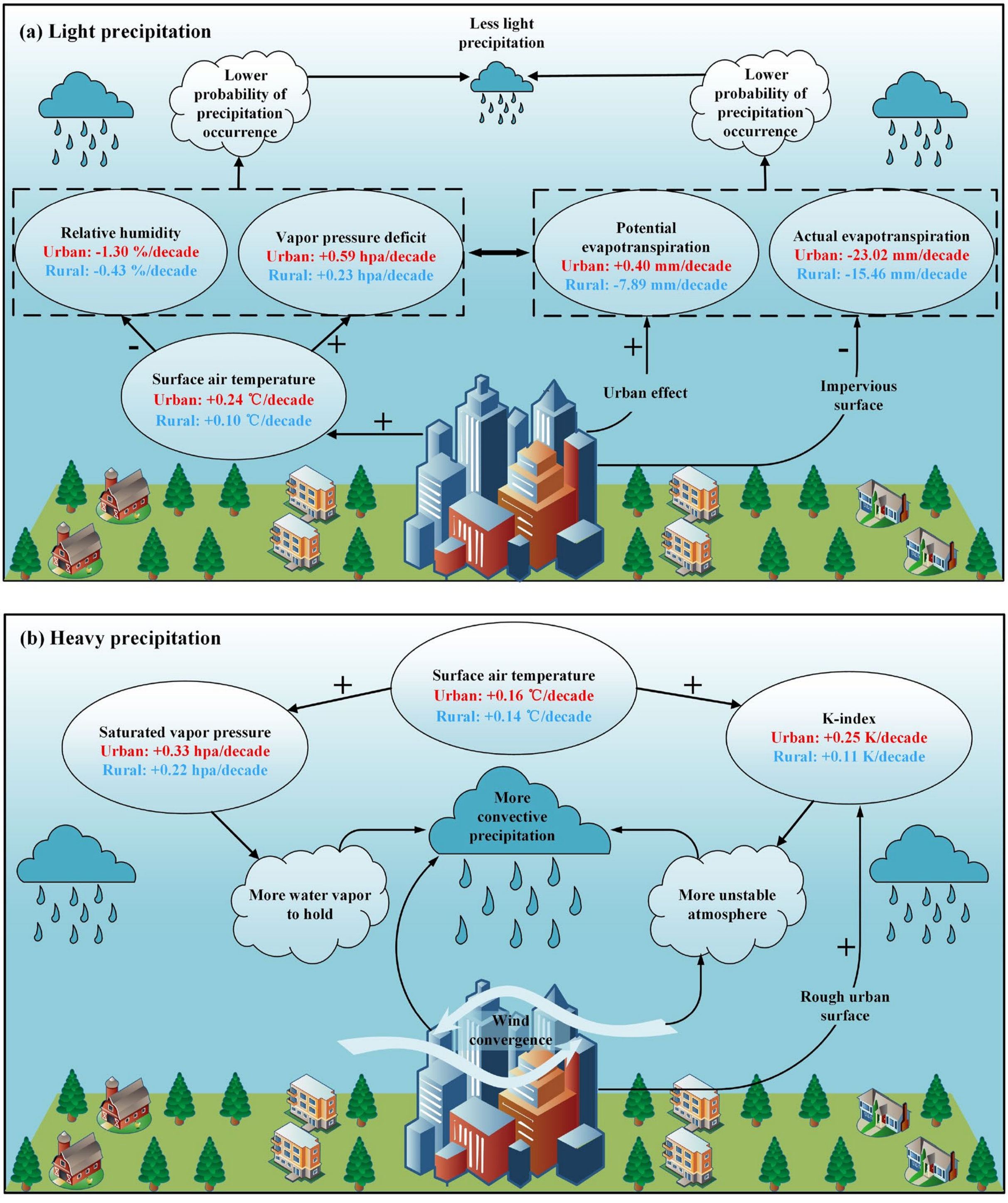

Figure 4. Schematic diagrams showing impacts of urbanization on light (a) and heavy (b) precipitation during the rainy season of 1961–2019 over the Yangtze River Delta (YRD).

5. Conclusions

In recent decades, China has witnessed decreases in light precipitation and increases in heavy precipitation under global warming and regional urbanization. In this study, we investigate the impacts of urbanization on this shift from light to heavy precipitation over the YRD urban agglomerations of East China. During 1961–2019, the

YRD witnessed increasing total precipitation in the rainy season (May-September). However, the increases are disproportionately larger for higher precipitation quantiles, and this phenomenon is more obvious in urban than rural areas. This pattern is confirmed by the decreases in light precipitation and increases in heavy precipitation over the YRD. The asymmetrical shift toward higher precipitation is stronger in urban than in rural areas, and is verified by a significant negative (positive) regression relation between the trends in light (heavy) precipitation and urban expansion rates. By comparing the changes in regional averages of light (heavy) precipitation between urban and rural stations, we estimate that about 44.4% (26.4%) of these changes can be attributed to urbanization.

Our results have wide-reaching impacts for the YRD, and may also be investigated elsewhere. The decrease in low quantiles of rainy-season precipitation may contribute to more frequent heatwaves in urban areas (Kong et al., 2020; Liao et al., 2018; Luo & Lau, 2018; Yang, Leung, et al., 2017). The YRD region is frequently assaulted by heatwaves in the rainy season, and less light precipitation could mean more hot and dry days (Luo & Lau, 2019; Yang, Leung, et al., 2017). Conversely, greater heavy precipitation increases the risk of urban flooding and waterlogging (Jiang et al., 2018; Song et al., 2020). As urbanization amplifies this asymmetrical shift in precipitation in the rainy season, we suggest that measures should be taken considered to mitigate the adverse effects associated with this asymmetrical shift in a warming climate.

Data Availability Statement

The in situ meteorological observation data were collected from the National Meteorological Science Data Center available at http://www.nmic.cn/en. This data set is now unavailable for public download. However, based on this data set, the processed values associated with the results in this study can be assessed at https://doi.org/10.5281/zenodo.5533152. The actual evapotranspiration data (PML_V2; https://doi.org/10.11888/Geogra.tpdc.270251) were collected from National Tibetan Plateau Scientific Data Center available at https://data.tpdc.ac.cn/en/data/48c16a8d-d307-4973-abab-972e9449627c/. The land use/land cover data were developed by Xu et al. (2020) and are available at https://doi.org/10.5281/zenodo.3923728. The ERA5 reanalysis data are available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5.

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