

1 **Asymmetrical shift toward less light and more heavy precipitation in an urban**
2 **agglomeration of East China: Intensification by urbanization**

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37 **Abstract:** Under global warming, projected changes in precipitation have shown an asymmetrical
38 shift from light to heavy precipitation over China. However, the role of urbanization in this shift
39 remains unknown. Here we show that increases in total rainy season (May-September) precipitation
40 over the Yangtze River Delta (YRD) urban agglomeration of East China are characterized by
41 decreasing light precipitation and increasing heavy precipitation during 1961-2019. This
42 asymmetrical shift toward heavier precipitation is even more prominent in urban than rural areas.
43 Areas with faster urban expansion rates exhibit stronger negative (positive) trends in light (heavy)
44 precipitation. Urbanization contributes to 44.4% (26.4%) of the decreasing (increasing) light (heavy)

45 precipitation in the urban areas of the YRD. We suggest that urban managers should consider
46 potential adverse impacts of this asymmetrical shift, which may favor increases in both the
47 frequency of heatwaves and waterlogging.

48

49 **Plain Language Summary**

50 China has experienced rapid urbanization in recent decades, alongside decreases in light
51 precipitation and increases in heavy precipitation. This shift in precipitation patterns is also observed
52 in the Yangtze River Delta (YRD), a typical densely populated region of China. Over the period
53 1961–2019, urban areas of the YRD have witnessed intensifying precipitation characterized by
54 sharper decreases in light precipitation as well as sharper increases in heavy precipitation than rural
55 areas. We estimate that 44.4% of the decrease in light precipitation and 26.4% of the increase in
56 heavy precipitation in urbanized areas can be attributed to urbanization.

57

58 **Key Words:** Asymmetrical shift; Light precipitation; Heavy precipitation; Urbanization; Yangtze
59 River Delta

60

61 **Key Points:**

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

67

68 **1. Introduction**

69 Precipitation-temperature relations are regulated by the Clausius-Clapeyron (C-C) equation
70 (Wang et al., 2017; Westra et al., 2014), whereby the water vapor holding capacity of the atmosphere
71 increases by 6–7% for each degree of warming. This scaling relationship theoretically explains
72 increasing precipitation intensity in a warming climate (Donat et al., 2016; Giorgi et al., 2011; Gu
73 et al., 2017; Ingram, 2016). For example, Donat et al. (2016) found that both wet and dry regions of
74 the world have witnessed increasing heavy precipitation using *in-situ* and model data. Conversely,
75 most areas of the globe have also observed a decreasing trend in light precipitation in recent decades,
76 such as North America (Dai et al., 2020), Europe (Qian et al., 2010), and Asia (Ren et al., 2015; Ma
77 et al., 2015; Wu et al., 2017; Zhou et al., 2020). Ma et al. (2015) found that China witnessed more
78 heavy precipitation (≥ 50 mm/day) and less light and moderate precipitation (< 10 mm/day and 10–
79 25 mm/day, respectively) during 1960–2013, which shows an asymmetrical change for different
80 categories of precipitation intensity. Both lower-tropospheric warming and decreasing water vapor
81 content are responsible for this reduction in light precipitation (Dai et al., 2020; Giorgi et al., 2011;
82 Wu et al., 2015). Additionally, greater changes per unit warming are found in light and heavy
83 precipitation than in medium intensity precipitation (Ma et al., 2015).

84 Since atmospheric temperature warming drives this asymmetrical change in light and heavy
85 precipitation, local urbanization, which leads to a higher temperature in urban than surrounding rural
86 areas (known as the urban heat island [UHI] effect; (Kong et al., 2020; Ren et al., 2008; Ren &
87 Zhou, 2014; Sun et al., 2016), may further affect this asymmetry. Previous studies have widely
88 investigated UHI effects on heavy precipitation (Gu et al., 2019a, 2019b; Li et al., 2020; Singh et

89 al., 2016; Wang et al., 2018; Yang et al., 2017b). For example, Li et al. (2020) found that extreme
90 precipitation increased 3 times more in urban than rural areas in Kuala Lumpur, Malaysia using
91 observed and modeled evidence. Additionally, several studies have detected an urban dry island
92 (UDI) effect (Li et al., 2021; Liu et al., 2009; Luo & Lau, 2019; Yang et al., 2017a), where
93 urbanization may lead to reductions in relative humidity and amplification of vapor pressure deficit
94 (VPD). This drying atmospheric moisture and enhanced VPD make it harder for light precipitation
95 to occur in urban areas (Dai et al., 2018, 2020; Ren et al., 2016; Yang et al., 2021). Yang et al. (2021)
96 showed that the frequency of light precipitation (hourly 0.1–0.3 mm) is significantly smaller in the
97 central urban area of Beijing relative to the surrounding rural areas, and they attributed this spatial
98 pattern to the remarkable decrease in relative humidity, the increase of cloud base height and a
99 denser aerosol concentration in the urban areas. From the above-mentioned researches, we
100 hypothesize here that the asymmetrical change in different categories of precipitation intensity may
101 therefore be caused or intensified by urbanization. Whether or not this hypothesis is confirmed by
102 observed evidence should be investigated, because other processes associated with urbanization
103 (such as surface roughness, anthropogenic aerosols, and evapotranspiration) may also alter
104 precipitation occurrence and distribution (Freitag et al., 2018; Han et al., 2014; Li et al., 2020; Zipper
105 et al., 2017).

106 The Yangtze River Delta (YRD) is densely populated, economically developed, and represents
107 a typical highly urbanized region in eastern China. Given that the YRD contributes 11% of the
108 population and 25% of Gross Domestic Product (GDP) of China (Zhu et al., 2016) for just 2.2% of
109 the land surface area, it is frequently chosen as a typical region to investigate strong urbanization
110 effects (Jiang et al., 2020; Lu et al., 2019; Luo & Lau, 2019; Wang et al., 2021; Yang et al., 2017).

111 Here, we assess the potential effect of urbanization on the asymmetrical change in light and heavy
112 precipitation within the urban agglomeration. Because this asymmetry may be causing increases in
113 extreme hydro-climatic events, our results could provide a valuable reference for understanding
114 large-scale changes in extreme precipitation patterns and for improving urban planning and design
115 in other regions of the globe beyond eastern China.

116

117 **2. Study region and data**

118 The YRD region includes 27 cities (total areas: 301,700 km²) within the Shanghai, Jiangsu,
119 Zhejiang, and Anhui provinces (Fig. 1a; Luo & Lau, 2019). It has experienced rapid urbanization
120 since the 1980s, with urban areas expanding at a rate of 973 km²/yr during 1980–2015 (Fig. 1a).
121 Previous studies have found enhanced extreme precipitation and prominent reductions in humidity
122 in the summer due to strong urban effects in YRD (Jiang et al., 2020; Lu et al., 2019; Luo & Lau,
123 2019; Wang et al., 2021).

124 We obtained a quality-controlled and homogenized daily dataset for 2481 weather stations from
125 the National Meteorological Science Data Center. This dataset includes observations since the 1950s
126 for eight variables, including precipitation, surface air temperature, and relative humidity. The
127 locations of the stations are provided for each year, so any effects of site migration on the
128 identification of urban stations can be considered. A station is retained for the following analyses if
129 it has observations over 1961–2019 and a missing rate during the rainy season (May–September) of
130 no more than 5%. After filtering, 126 stations remain in the YRD region (Fig. 1a).

131 The actual evapotranspiration during 2000–2019 is estimated using a coupled diagnostic
132 biophysical model (i.e. PML_V2). The performance of PML_V2 has been evaluated and validated

133 with other estimated evapotranspiration datasets and *in-situ* observations (Zhang et al., 2016, 2019).
134 The spatial and temporal resolutions of PML_V2 are 500 m and 8 days, respectively. This PML_V2
135 dataset has been widely used in previous studies (Elnashar et al., 2021; Huang et al., 2020; Zhang
136 et al., 2020), and more details on the model can be found in Zhang et al. (2019). Hourly K-index
137 data, indicating atmospheric instability and thunderstorm potential are obtained for 1961–2019 from
138 the ERA5 reanalysis data with 0.25° spatial resolution.

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

144

145 **3. Methods**

146 3.1 Definition of different categories of precipitation intensity

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

155

156 3.2 Dynamic identification of urban and rural stations

157 We identify urban stations by considering both site migration and dynamic urbanization, using
158 the annual locations of weather stations and annual LULC data. For each station, a 7-km circular
159 buffer is established in each year of 1980–2015 (see Fig. S2a for an example), and the percentage
160 of urban area in this buffer is calculated. For each station, the annual change in urban area (unit:
161 km²/yr) within the 7-km circle is taken as the urban expansion rate. The radius is set to 7 km because
162 previous studies have suggested that this radius is the optimal radius to identify urban stations in the
163 YRD region (Luo & Lau, 2019; Yang et al., 2017). Similar to these two previous studies, we test
164 the correlations between urban expansion rates estimated in buffers with a radius of 1–10 km and
165 changes in different categories of precipitation intensity (Fig. S1 and Text S1). We find that the
166 correlations tend to be stable for a radius ≥ 7 km.

167 For each year, a station is identified as an urban station if the percentage of urban area within
168 the 7-km buffer is more than 20%. This percentage is consistent with previous studies (Luo & Lau,
169 2019; Yang et al., 2017). However, several studies chose other percentages to identify urban stations,
170 such as 33% (Liao et al., 2018; Ren & Zhou, 2014), so we also test whether our results are sensitive
171 to urban station identification using other percentages (20%, 25%, ..., 50%). We identify 26
172 urbanized stations (in all years from 1980), 82 urbanizing (where the station became urbanized
173 during 1980–2015), and 18 rural stations (in all years from 1980) (Fig. 1b, Fig. S2b-i and Fig. S3
174 and Text S1).

175

176 3.3 Quantification of urbanization effects

177 By dynamically classifying stations as urban and rural, changes in total precipitation are
178 estimated in urban and rural stations over the period 1961–2019, i.e. P_U and P_R , respectively, for
179 different categories of precipitation intensity. The urban effect is quantified by $|P_U - P_R|$, and the
180 contribution of urbanization is estimated by $\left| \frac{P_U - P_R}{P_U} \right| \times 100\%$, as in previous studies quantifying
181 the urbanization effect on and contribution to surface air temperature (Luo & Lau, 2019; Ren &
182 Zhou, 2014).

183

184 3.4 Model experiments

185 The Weather Research and Forecasting (WRF) modeling system (version 3.6) is employed to
186 simulate urban impacts on precipitation over the YRD region. LULC data for the year 1988
187 (Urb1988), 2000 (Urb2000), and 2010 (Urb2010) are utilized as surface boundary conditions,
188 respectively. The June-August precipitation is simulated over the YRD region in 2001, 2003, and
189 2005 under the two surface boundary conditions. The three years are chosen for their consistent
190 summertime temperature with the climatological mean temperature. Detailed information on the
191 WRF physical parameterizations, experiment designs, and model evaluations can be found in Cao
192 et al. (2016).

193

194 **4. Results and discussion**

195 During 1961–2019, the YRD urban agglomeration has undergone rapid urbanization especially
196 since the 2000s (671 km²/yr during 1980–2000 and 1712 km²/yr during 2001–2015; Fig. 1a and b).
197 Over the same period, the YRD is dominated by increasing trends in total rainy season precipitation
198 (Fig. S4 and Text S2). These increases in total precipitation are most prominent in the stations with

199 higher urban expansion rates (e.g., stations in Shanghai and surrounding areas). The significant
200 positive regression relation ($p < 0.01$) between increasing total precipitation trends and urban
201 expansion rates (see scatterplot in Fig. S4d) suggests that the faster the urban expansion, the greater
202 the rise in total precipitation. The increase in total precipitation is confirmed by positive trends in
203 all quantile ranks (i.e. 10th, 20th, ..., 90th, 95th, 100th values of each year), but the increasing rates are
204 uneven and rise exponentially for higher percentiles (Fig. 2a). This exponentially rising feature in
205 the increasing rates of all quantile ranks is most obvious in urbanized areas, followed by urbanizing
206 areas, and rural areas (Fig. 2b, Fig. S5a, and Text S2). For each of the 82 urbanizing stations, the
207 year when the station turned from rural to urban is used to divide the whole period (i.e. 1961–2019)
208 at a given station into two sub-periods (i.e. rural and urban). The exponential rise is more obvious
209 during the urban period than during the rural period (Fig. S6a and Text S2). The above results
210 demonstrate that total precipitation over the YRD shows an asymmetrical increase in heavy
211 precipitation and urbanization plays an important role in this asymmetrical increase.

212 We further investigate how this asymmetrical increase affects the precipitation amounts for
213 different intensities. The 10th, 20th, ..., 90th, and 95th percentiles of rainy days during 1961–1990 are
214 calculated and then the precipitation amounts of $\leq 10^{\text{th}}$, 10th–20th, ..., and $\geq 95^{\text{th}}$ in each year are
215 counted. We find that precipitation totals below low quantiles exhibit distinctly negative trends,
216 especially for the two categories of $\leq 10^{\text{th}}$ and 10th–20th percentiles (mean rates are -6.3% per
217 decade and -7.3% per decade, respectively; Fig. 2c). Precipitation trends in the medium categories
218 (i.e. 20th–30th, ..., 60th–70th) are slightly negative (with a mean rate of -1.3% per decade), and then
219 switch to increases in the 70th–80th percentile category. A sharp increase is found in the precipitation
220 amounts above high quantiles (i.e. the 90th–95th and $\geq 95^{\text{th}}$ percentiles exhibit mean rates of +1.6%

221 per decade and +7.1% per decade, respectively). This clearly indicates an asymmetrical shift toward
222 heavier precipitation over the YRD in the rainy season, in line with previous studies (Ma et al., 2015;
223 Wu et al., 2015).

224 It is worth noting that this asymmetrical shift is more evident for urbanized and urbanizing
225 stations than that for rural stations (Fig. 2d and Fig. S5b). Specifically, the precipitation totals in low
226 quantiles ($\leq 10^{\text{th}}$ and $10^{\text{th}}-20^{\text{th}}$) decrease faster at urban stations, while the totals in high quantiles
227 ($90^{\text{th}}-95^{\text{th}}$ and $\geq 95^{\text{th}}$) increase faster at urban stations. For the 82 urbanizing stations, precipitation
228 totals also decrease below low quantiles and increase above high quantiles during the urban period
229 relative to the rural period (Fig. S6b), demonstrating that the difference in precipitation trends (seen
230 for low and high quantiles) between rural and urbanized stations is not due to other spatial
231 differences such as elevation (FigS3b). For the medium-intensity precipitation totals, we observe
232 smaller differences in their changes between urban and rural stations and between urban and rural
233 periods (Fig. 2d, Fig. S5b, and Fig. S6b). These results imply that urbanization effects mainly occur
234 in the low and high tails of the probability distribution of precipitation, in other words, urbanization
235 tends to suppress light precipitation and enhance heavy precipitation.

236 We now exclusively examine the changes in light ($\leq 20^{\text{th}}$) and heavy ($\geq 90^{\text{th}}$) precipitation
237 during the rainy seasons (Fig. 1c and d). A widespread reduction in light precipitation is observed
238 over the YRD, and this reduction is particularly pronounced in the northeastern YRD (Fig. 1c).
239 Almost all stations, show increasing trends in heavy precipitation, and the most prominent increases
240 are seen in the eastern YRD (Fig. 1d). The spatial patterns of changes in both light and heavy
241 precipitation are very similar to the spatial distributions of urban areas and urban expansion rates
242 (see Fig. 1a and b). These similarities in spatial patterns are further confirmed by significantly

243 negative (positive) regression relations between the trends in light (heavy) precipitation and urban
244 expansion rates (see scatterplots in Fig. 1c and d). When taking values $\leq 10^{\text{th}}$ ($\geq 95^{\text{th}}$) and $\leq 25^{\text{th}}$
245 ($\geq 85^{\text{th}}$) percentiles as quantiles to define light (heavy) precipitation (Figs. S7-S8), the spatial
246 patterns of the changes in light and heavy precipitation are not altered.

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

253 We plot time series of regionally-averaged light/heavy precipitation for urbanized, urbanizing,
254 and rural stations in the YRD to assess their consistency (Fig. 3 and Fig. S9). Regionally, light
255 precipitation ($\leq 20^{\text{th}}$ percentile) at rural stations exhibits a statistically significant decrease at a rate
256 of 0.12 mm per decade. The negative rate at urbanized and urbanizing stations is almost twice as
257 high (0.21 and 0.23 mm per decade, respectively) than at rural stations. In contrast, heavy
258 precipitation ($\geq 90^{\text{th}}$ percentile) significantly increases at a rate of 14.8, 20.2, and 21.8 mm per
259 decade at rural, urbanizing, and urbanized stations, respectively.

260 In our study, we identified urban stations if the percentage of urban areas in the 7-km buffer is
261 more than 20%. This percentage is relatively conservative in comparison with previous studies (e.g.
262 Liao et al., 2018; Ren & Zhou, 2014) where the percentage is set as 33% or larger. We try to set the
263 percentage as 35% and identified 46 rural stations. The samples of urban and rural stations are
264 changed, while results of urban impacts on light and heavy precipitation are not altered (Fig. S10).

265 The difference in sample size between 82 urbanizing, 26 urbanized, and 18 rural stations may also
266 affect the results. We employ a bootstrap approach to sample an equal number of 18 stations
267 (equivalent to the number of rural stations) from the 82 urbanizing and 26 urbanized stations,
268 respectively, and estimate the precipitation trend from each group of 18 stations. We repeat this
269 process 1000 times, and find there is a significant difference between rural/urban/urbanizing
270 categories, irrespective of the sample size (Fig. S11 and Text S2).

271 To reduce the impact of any regional confounding factors, we pair rural and urban stations by
272 selecting urban stations that are located within a 100-km buffer of rural stations (Gu et al., 2019b;
273 Luo & Lau, 2018). The above analyses are repeated based on the paired rural-urban stations (Figs.
274 S12-S14 and Text S3). We test the results when choosing 75 and 125 km as the radius, respectively,
275 and obtain consistent results. Because the LULC data used in this study only cover the period 1980–
276 2015, we also test our results during this period (Figs. S15-S16 and Text S4). The finding that
277 urbanization enhances the asymmetrical shift toward heavier precipitation can be still observed.

278 We finally quantify the contribution of urbanization to the decrease in light precipitation (\leq
279 20th percentile) and increase in heavy precipitation (\geq 90th) in urban areas (Fig. 3b and d).
280 Urbanization (combining urbanized and urbanizing stations into one group) contributes to 44.4% of
281 the decline in light precipitation and 26.4% of the increase in heavy precipitation over the YRD. We
282 also evaluate these contributions and obtain consistent results, when taking \leq 10th (\geq 95th) and \leq
283 25th (\geq 85th) as quantiles to define light (heavy) precipitation (Fig. S17). Moreover, there is little
284 sensitivity to the buffer radius and percentage of urban to total areas (Fig. S17 and Text S5).

285 As suggested by previous studies, this asymmetrical shift in precipitation can be linked to
286 temperature warming (Dai et al., 2018, 2020; Giorgi et al., 2011; Ma et al., 2015). Therefore, we

287 assess the mechanisms driving UHI impacts on light precipitation changes in the YRD (Fig. 4a and
288 Figs. S18–S19 and Text S6). During light-precipitation days ($\leq 20^{\text{th}}$), we find the surface air
289 temperature increases by +0.24 and +0.10 °C per decade in the urban and rural areas of the YRD,
290 respectively. The faster increase in surface air temperature enlarges the atmospheric moisture
291 demand in urban areas. This enlarged water demand is reflected by the increase in potential
292 evapotranspiration (estimated by using the Penman-Monteith equation (Nyolei et al., 2021) in the
293 urban areas (+0.4 mm per decade)), while the trend in rural areas is negative (-7.89 mm per decade).
294 However, impervious surface expansion inhibits actual evapotranspiration from soils and plants
295 (Zipper et al., 2017), resulting in a greater decrease of actual evapotranspiration (-23.02 vs -15.46
296 mm per decade for urban vs. rural areas, respectively). On the one hand, the greater reduction of
297 local evapotranspiration leads to faster decreasing relative humidity (-1.3 vs -0.43 % per decade)
298 and increasing vapor pressure deficit (+0.59 vs +0.23 hPa per decade) in urban areas relative to rural
299 areas. This leads to the formation and development of an UDI effect in urban areas (Unkasevic et
300 al., 2001; Yang et al., 2017a). Luo and Lau (2019) discussed other factors such as urban roughness
301 and vegetation degradation linked with this UDI effect. The drier moisture and stronger vapor
302 pressure deficit lead to a lower probability of precipitation occurrence (Dai et al., 2020; Giorgi et
303 al., 2011; Ren et al., 2016) and thus a faster decline in light precipitation in urban areas. On the other
304 hand, the reduction in urban evapotranspiration decreases local precipitation recycling (i.e. the
305 percentage of precipitation sourced from local evapotranspiration) and then constrains the
306 transformation of water vapor to precipitation (Wang et al., 2018).

307 During heavy-precipitation days ($\geq 90^{\text{th}}$ percentile; Fig. 4b and Figs. S20–S21), although there
308 is no obvious difference in trend magnitudes of surface air temperature between urban and rural

309 stations (+0.16 vs +0.14°C per decade), the atmospheric water holding capacity increases faster in
310 urban than rural areas (+0.33 vs +0.22 hPa per decade in saturated vapor pressure). An enlarged
311 atmospheric water holding capacity could result in stronger heavy precipitation in urban areas, when
312 the condition for large-scale moisture transport and moisture convergence is met in the rainy season.
313 Besides this thermal and moisture effect, the thermodynamic effects of the UHI and land surface
314 roughness may further drive instability in the lower atmosphere, enhancing horizontal convergence
315 and intensifying convective systems in urban areas (Freitag et al., 2018; Gao et al., 2021; Li et al.,
316 2020; Lorenz et al., 2019). Gao et al. (2021) found high sensitivity of heavy precipitation to the land
317 surface alteration. We show that the K-index (an index used for indicating atmospheric instability)
318 is growing more than twice as fast in the urban areas of the YRD as in the rural areas (0.25 vs 0.11
319 K per decade).

320 We finally compared surface air temperature, relative humidity, and vapor pressure deficit
321 (surface air temperature and saturated vapor pressure) during light (heavy) precipitation days
322 between the Urb2010 and Urb1988 experiments (Figs. S22-S25 and Text S7). Changes in these
323 variables under Urb2010 relative to Urb1988 confirm the above results based on observations.

324 Previous studies pointed out that light and heavy precipitation in the urban areas show different
325 responses to the same factor, such as surface heat fluxes and tropospheric aerosols (Holst et al.,
326 2016; Li et al., 2019). Urbanization contributes to increased urban surface sensible heat fluxes,
327 which results in a stronger UHI effect and heavier precipitation but has less impact on light
328 precipitation (Holst et al., 2016). The heavy air pollution from aerosol particles in urban areas of the
329 YRD has become a primary environmental concern in recent decades (Zhu et al., 2021), and the
330 light (heavy) precipitation in urban areas tends to be suppressed (enhanced) under the same cloud

331 thickness condition (Li et al., 2019).

332

333 **5. Conclusions**

334 In recent decades, China has witnessed decreases in light precipitation and increases in heavy
335 precipitation under global warming and regional urbanization. In this study, we investigate the
336 impacts of urbanization on this shift from light to heavy precipitation over the YRD urban
337 agglomerations of East China. During 1961–2019, the YRD witnessed increasing total precipitation
338 in the rainy season (May–September). However, the increases are disproportionately larger for
339 higher precipitation quantiles, and this phenomenon is more obvious in urban than rural areas. This
340 pattern is confirmed by the decreases in light precipitation and increases in heavy precipitation over
341 the YRD. The asymmetrical shift toward higher precipitation is stronger in urban than in rural areas,
342 and is verified by a significant negative (positive) regression relation between the trends in light
343 (heavy) precipitation and urban expansion rates. By comparing the changes in regional averages of
344 light (heavy) precipitation between urban and rural stations, we estimate that about 44.4% (26.4%)
345 of these changes can be attributed to urbanization.

346 Our results have wide-reaching impacts for the YRD, and may also be investigated elsewhere.
347 The decrease in low quantiles of rainy-season precipitation may contribute to more frequent
348 heatwaves in urban areas (Kong et al., 2020; Liao et al., 2018; Luo & Lau, 2018; Yang et al., 2017).
349 The YRD region is frequently assaulted by heatwaves in the rainy season, and less light precipitation
350 could mean more hot and dry days (Luo & Lau, 2019; Yang et al., 2017). Conversely, greater heavy
351 precipitation increases the risk of urban flooding and waterlogging (Jiang et al., 2018; Song et al.,
352 2020). As urbanization amplifies this asymmetrical shift in precipitation in the rainy season, we

353 suggest that measures should be taken considered to mitigate the adverse effects associated with this
354 asymmetrical shift in a warming climate.

355

356 **Open Research**

357 The *in-situ* meteorological observation data were collected from the National Meteorological
358 Science Data Center available at <http://www.nmic.cn/en>. This dataset is now unavailable for public
359 download. However, based on this dataset, the processed values associated with the results in this
360 study can be assessed at <https://doi.org/10.5281/zenodo.5533152>. The actual evapotranspiration
361 data (PML_V2; doi: 10.11888/Geogra.tpdc.270251) were collected from National Tibetan Plateau
362 Scientific Data Center available at [https://data.tpdc.ac.cn/en/data/48c16a8d-d307-4973-abab-
363 972e9449627c/](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
364 at <https://doi.org/10.5281/zenodo.3923728>. The ERA5 reanalysis data are available at
365 <https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>.

366

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582

583 **Figure captions:**

584 Fig. 1 Spatial distributions of (a) urban areas, (b) urban expansion rate, (c–d) precipitation trend,
585 and (e–f) difference in light and heavy precipitation over the Yangtze River Delta (YRD). Panel
586 a shows annual urban area from 1980 to 2015. Panel b shows urban expansion rates within a 7-
587 km radius in rural and urban (including both urbanized and urbanizing) stations. Panels c and
588 d show trends in total precipitation below and above the 20th and 90th quantiles during the rainy
589 season of 1961–2019 at all stations, respectively. Inset scatterplots in c and d show linear
590 regressions between the precipitation trends and urban expansion rates. In the scatterplots, blue
591 (orange) dots indicate values from rural (urban) stations. In panels e and f, light/heavy
592 precipitation is the daily value ≤ 5 mm/ ≥ 50 mm, and the difference is calculated as
593 $((\text{Urb2010 values} - \text{Urb1988}) / \text{Urb1988})$ from the WRF experiment. The areas enclosed by
594 black lines in e and f are the main urban areas, and the stipples indicate the difference of light

595 (heavy) precipitation between the two WRF experiments is significant at the 0.05 level in the
596 urban areas.

597 Fig. 2 Distribution of trends in precipitation quantiles and total precipitation for different categories
598 of precipitation intensity during the rainy seasons of 1961–2019 over the YRD. In a and b,
599 taking the 10th quantile as an example, we calculate the 10th quantile of rainy days in each year
600 for each individual station, and obtain a time series of this quantile. The trend (units: mm/yr)
601 in this time series is estimated using the modified Mann-Kendall method. In c and d, we
602 calculate the 10th, 20th, ..., 90th, and 95th quantiles of rainy days during 1961–1990 for each
603 station, and then compute total precipitation $\leq 10^{\text{th}}$, $10^{\text{th}}\sim 20^{\text{th}}$, ..., and $\geq 95^{\text{th}}$ quantile in each
604 year. Trends (units: %/yr) in total precipitation for different categories of precipitation intensity
605 are estimated for all stations. In b and d, urban stations include urbanizing and urbanized
606 stations.

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

615 Fig. 4 Schematic diagrams showing impacts of urbanization on light (a) and heavy (b) precipitation
616 during the rainy season of 1961–2019 over the YRD.