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Urbanization increased annual precipitation in temperate climate zone: A case in Beijing-Tianjin-Hebei region of North China

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ABSTRACT

Rapid urbanization plays important roles in modifying regional climate. The effects of urbanization on annual precipitation in temperate climate zone were complicated and have not been fully investigated. In this study, Beijing-Tianjin-Hebei (BTH) region of North China was selected as research area and field observations of inter-annual precipitation from 1980 to 2015 were utilized to conduct the spatiotemporal analysis and to extract the urbanization effects. Combined statistical methods were applied and the urbanization effects indicator (UE) was created to quantify the roles of urban development on annual precipitation by combining the land cover change of cities and urban–rural precipitation differences. The paper found following main results: (1) In 2000 s, annual precipitation increased faster in urban areas (slope = 7.165 mm/yr) than in rural areas (slope = 4.954 mm/yr). The urbanization effects on the increasing of precipitation have been implied by comparisons of urban–rural difference between 2000 s (slope = 2.211 mm/yr) and 1980 s (slope = 0.165 mm/yr). (2) Rapid urbanization led to increasing of annual precipitation. Built-up areas correlated higher with urban precipitation than with rural precipitation in 9 of 13 cities, and were used as weights to improve the urbanization effects indicator (UE). (3) As the largest and the most developed city, Beijing presented the highest urbanization effects (UE = 44.5) on the increasing inter-annual precipitation, which was 51% higher than the secondary city of Chengde (UE = 21.71). The coastal cities such as Tianjin, Qinhuangdao and Tangshan presented negative UE values probably due to the strong sea-land energy interactions. This study contributes new findings to the effects of urbanization on annual precipitation in temperate climate zone and could help understand the feedback of land surface changes to variations of atmospheric circulation.

1. Introduction

Land cover change due to rapid urbanization significantly modified regional climate (Sun et al., 2016; Zhang et al., 2018a, 2018b). Large scale land transformations potentially affect the patterns of regional meteorological elements (Guo et al., 2019; Paul et al., 2018; Zhu et al., 2019). Variations of precipitation affect the regional hydrological balance (Mavromatis and Stathis, 2011), the phenology of terrestrial vegetation (Yun et al., 2018) and the agricultural yield (Yan et al., 2015). The clear relationship between urban expansion and the inter-annual precipitation is helpful to understand the roles of anthropogenic activities in modifying climate.

Currently, more works focused on the short-term precipitation in various climate and geographical conditions than inter-annual precipitation. Among these studies, more works thought urban expansion increased short-term heavy precipitation (Bornstein and Lin, 2000; Niyogi et al., 2011; Zhang et al., 2019). In China, the enhanced convective activities by urban heat island (UHI) effect and the thermal and dynamic modifications of the tropospheric boundary layer in highly developed urban area were thought probable reasons (Wai et al., 2017; Liang and Ding, 2017; Zhu et al., 2019). Several other increasing trends of heavy precipitation have also been concluded based on researches in urban areas in India and North America (Burian and Shepherd, 2005; Kishtawal et al., 2010; Niyogi et al., 2017). Fewer studies reported decreased precipitation, which were thought caused by aerosols and decreased latent flux in urban areas (Zhong et al., 2015; Guo et al., 2006; Khain et al., 2005).

As for variations of long term inter-annual precipitation, however, much fewer works have described the urbanization roles in inter-annual precipitation, and disputes about the urbanization effects also existed.

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Comparing with short-term precipitation, the urbanization effects on annual precipitation varied with different climate zones, time periods and model configurations. Some field observations reported the decreasing trends of inter-annual precipitation due to the reduced humidity and increased vapor pressure deficit (VPD) in cities of tropical monsoon climate zone (Luo and Lau, 2019; Guo et al., 2006; Han et al., 2014) while the inter-annual precipitation was observed increasing in a city with tropical climate (Mitra et al., 2012). Several simulation studies thought that urbanization reduced annual precipitation because the decreases of latent heat flux and the lower conversion efficiency of atmospheric moisture to rainfall in Beijing with temperate climate (Feng et al., 2015; Wang et al., 2018). However, simulation also reported the increase of the annual precipitation in Beijing due to combined effects of urbanization and anthropogenic heat release (Feng et al., 2012). In North China Plain, two studies indicated increasing (Zhang et al., 2015) and decreasing (Yu et al., 2014) inter-annual precipitation based on the different time periods.

In addition to that, insignificant effects of urbanization on inter-annual precipitation were also presented. In urban areas, increasing air temperature will not definitely lead to the significant precipitation change in megacities (Yang et al., 2015; Ajaaj et al., 2018). Several studies confirmed the urban effects on extreme rainfall but noted the insignificant effects on annual precipitation (Gu et al., 2019; Chaouche et al., 2010; Shastri et al., 2015).

It is difficult to connect the inter-annual precipitation with the urbanization effects (Zhang et al., 2018a, 2018b; Shepherd, 2006) because (1) the variations of climate and terrestrial surface in temperate zone are more complicated than in boreal and tropical zones (Perugini et al., 2017). (2) In urban agglomeration area, for precipitation of longer time scale, the development of urban areas (land cover change), large scale atmosphere circulations (Chen and Frauenfeld, 2016) and locations of cities (Sayemuzzaman and Jha, 2014) were potential factors which may affect the long term precipitation.

So far, the urbanization effects on inter-annual precipitation in temperate climate zones have not been fully understood. Therefore, this study tried to identify the urbanization effects on inter-annual precipitation variations in a temperate zone of China. This study tried to understand (1) how annual precipitation changed with city development in the long term time period and (2) the roles of rapid city development on precipitation. This study conducted spatiotemporal analysis of long-term precipitation data (1980–2015) by combination of statistical methods, and then compared the ‘urban-rural’ differences of annual precipitation. The urbanization effects indicator (UE) was improved and land cover change of urban area has been considered as weights to connect with inter-annual precipitation. Finally, the urbanization effects on inter-annual precipitation were identified and other potential impact factors were discussed.

2. Materials and methods

2.1. Research area

The Beijing-Tianjing-Hebei (BTH) urban agglomeration was set as the research area (Fig. 1). As one of the most important economic zones in China, the BTH region is an appropriate area to explore the urbanization effects because of different populations, unbalanced

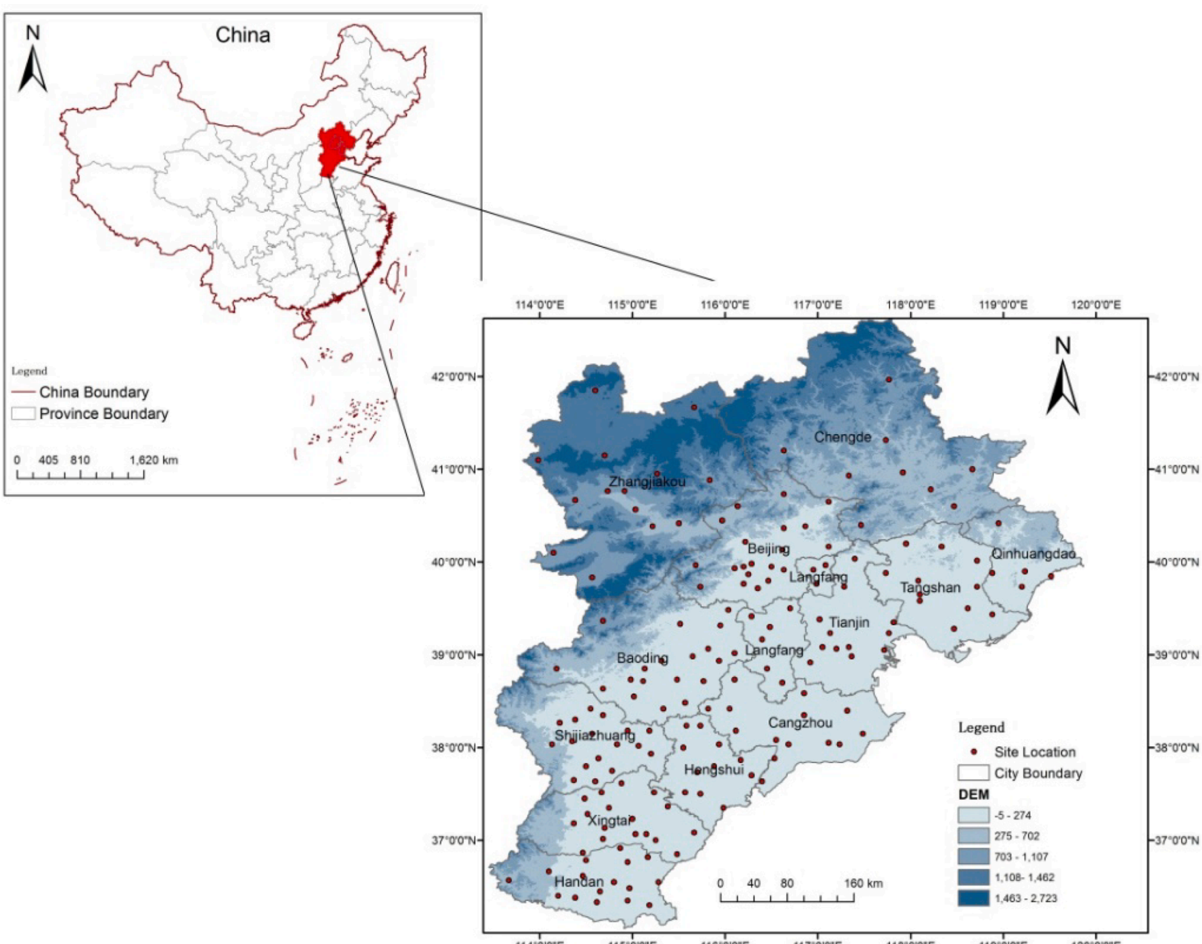

Fig. 1. Location of the Beijing-Tianjin-Hebei urban agglomeration and meteorological site locations.

developments levels among cities and the varied land cover changes (Table 1). The BTH region belongs to a temperate continental monsoon climate, with rainy, hot summers and cold dry winters. Highlands, mountains and hills are distributed in the north and in part of the west, and plains are extensively distributed across the central and south-eastern areas. Tangshan, Tianjin and Qinhuangdao are coastal cities by the Bohai Bay.

2.2. Data and methods

A total of 173 sites of precipitation data from 1980 to 2015 were provided by the National Satellite Meteorological Center (NSMC) of China (Fig. 1). The quality control of data has been handled by the data provider. The raw data were smoothed by the five-year moving average method to reduce the temporal fluctuations (Adamowski et al., 2012). Five sites were excluded because the obvious location changes (identified by the latitude and longitude positions) in the research period and 168 sites were kept. Among available sites, 15 city sites and 153 rural sites were identified (Beijing and Tianjin have two urban sites, respectively). The built-up data used in this study were collected from statistical agencies of each city in the BTH region such as http://tjj.beijing.gov.cn/EnglishSite/.

2.2.1. Spatiotemporal analysis

A combined statistical analysis including linear fittings, significance test, change point detection and anomaly were conducted to present the spatiotemporal variations of precipitation data. The linear fittings and significance (p value) were calculated to show temporal trends from region, city and sites scales. After that, the sequential Mann-Kendall (SQMK) test was used to detect the temporal change points (Ullah et al., 2019), which were mainly caused by the drought period since late 1990s. According to the change point detection, two periods of 1980–1996 and 1999–2015 were identified to compare the temporal trends between city and rural sites.

2.2.2. Identification of urbanization effects

We used the differences of precipitation between urban and rural sites to indicate the potential urbanization effects (Manoli et al., 2019). We assumed precipitation at rural sites have not been affected by the urbanized area, and then derived a precipitation difference (PD) indicator from precipitation of urban and rural sites as following:

$$PD = P_{urban} - P_{rural} \tag{1}$$

As the actual condition, the time of 2000s was the rapid urbanization period while the time of 1980s was nearly the non-urbanization period in BTH region. The PD indicator can be used to show the discrepancies of urban–rural difference in 1980s and 2000s from the regional scale. At the city scale, the PD values were averaged in 1980s and 2000s and the potential urbanization effect (PUE) indicator was derived as the differences between PD in 2000s and PD in 1980s (Luo and Lau, 2019):

$$PUE = PD_{2000s} - PD_{1980s} \tag{2}$$

Signals of urbanization effects were in the decadal averaged PUE values but still cannot be extracted by only the attributes of precipitation. Land cover change within the city was an important factor to impact the land–atmosphere interactions. Hence, it is necessary to build linkage between built-up surface and local precipitation. Generally, the larger built-up area will play more effects when interacting with atmosphere. Therefore, we used the correlation coefficients between urban precipitation and built-up area data as weights to connect the urban precipitation with terrestrial surface:

$$UE = \alpha \times PUE \tag{3}$$

In above equation, α was the correlate coefficient (R^2) between built-up area and urban precipitation in 2000s. The UE was the indicator that peels off the effects of temporal variations of precipitation especially in the non-urbanized period and we finally quantified and sorted the urbanization effects on each city in BTH region.

3. Results

3.1. Spatiotemporal analysis

First, to consider all sites of each city (not showed), the temporal slope from 1980 to 2015 was 0.084 mm/yr with significance test of 0.428. To get the trend clearer, we separated the urban and rural sites and presented the differences of precipitation in non-urbanized time in 1980s and rapid urbanized period in 2000s (Fig. 2). In 1980s, temporal slopes of urban and rural areas were similarly 6.672 mm/yr and 6.838 mm/yr. In 2000s, the obvious faster precipitation slope of 7.165 mm/yr in urban area was showed than the slope of 4.954 mm/yr in rural area. Therefore, for the regional inter-annual precipitation in BTH, after the drought period in late 1990s (Liu, 2005; Qin et al., 2015), we observed the faster reviving of precipitation in urbanized area than in the rural area.

At the site scale, we explored and counted the relationships between fitting significance, change points and temporal trends (Fig. 3). We denoted sites with clear change points with a ‘+1’ multiplicative factor and denoted sites with no clear changes with a ‘−1’ factor. Hence, Fig. 3 relates the change points, fitting slopes and p values. All the 168 sites were separated by slopes and significant values, and the shaded area denotes the scope of significant fitting ($p < 0.05$). The increasing sites with clear inter-annual change points are in the first quadrant (I), the increasing sites with unclear change points are in the second quadrant (II), the decreasing sites with unclear change points are in the third quadrant (III), and the decreasing sites with clear change points are in the fourth quadrant (IV).

Table 1
General social and economy characteristics of BTH cities.

City name	Population (10^4)		Urbanization rates (%)		Built-up Area (km^2)	
	1980	2015	1980	2015	1980	2015
Beijing	904.3	2170.5	0.58	0.87	257.12	1455
Tianjin	748.91	1546.95	0.52	0.83	175	870.2
Shijiazhuang	656.69	1070.16	0.15	0.59	68.14	278.05
Baoding	816	1158	0.09	0.47	52.44	185.7
Langfang	276	456.32	0.09	0.55	26.5	66.28
Chengde	304.8	353.01	0.1	0.47	16.94	116.97
Zhangjiakou	385.4	469	0.09	0.52	24.51	86
Hengshui	336.8	443.54	0.09	0.47	20.79	46.4
Xingtai	491.7	729.44	0.06	0.48	35.5	90.12
Handan	610.23	943.3	0.13	0.51	60.76	127.03
Cangzhou	504.3	773	0.05	0.49	36.82	70.54
Qinhuangdao	212.1	307.32	0.12	0.54	20.27	131.45
Tangshan	573.1	780.12	0.2	0.58	57.73	249

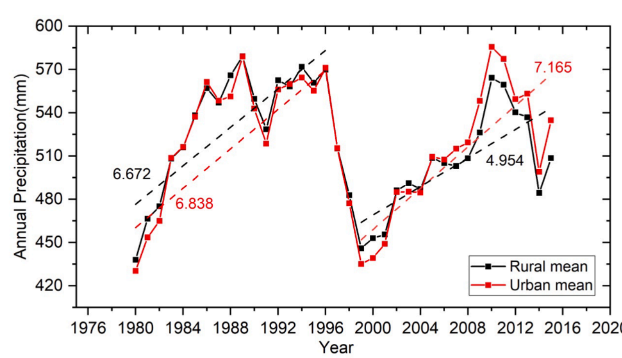

Fig. 2. Temporal trends of separated urban and rural mean values at the regional scale of BTH area.

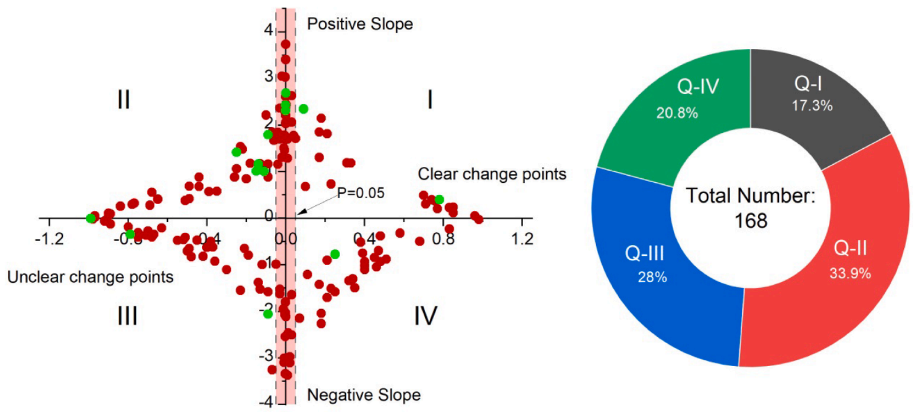

Fig. 3. Distribution of inter-annual change points, fitting significance and slopes (green dots denote urban sites). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In Fig. 3, there were 86 sites presented increasing trend and 82 sites showed decreasing trend. There were 64 sites showed clear change points and 104 sites showed no clear change points. A total of 29 sites (17.3%) were increasing with clear change points (quadrant I), 35 sites (20.8%) with decreasing with clear change points (quadrant IV). A number of 57 sites (33.9%) presented increasing trend and unclear change points (quadrant II) and 47 sites (28%) presented decreasing trend with unclear change points (quadrant III).

3.2. Urbanization effects

3.2.1. Trend difference at regional scale

To obtain the signal of urbanization effects, at the regional scale, we illustrate the annual precipitation differences (PD) (Fig. 4). Both of PD trends in 1980s and 2000s were increasing, with the slope of 0.165 mm/yr in 1980s and slope of 2.211 mm/yr in 2000s. The obvious discrepancy of PD between 1980s and 2000s implied the potential urbanization effects by the rapid increasing of urban–rural differences.

3.2.2. Urban-rural differences in 1980s and 2000s

At the city scale, based on the PD, the potential urbanization effects (PUE) were calculated from mean values of PD in 1980s and 2000s (Fig. 5). The drought period in late 1990s were excluded. Except Qinhuangdao, Tangshan and Baoding, other cities showed higher PD (positive PUE) values in 2000s than in 1980s. According to the precipitation differences in previous sections, we assume that the urbanization increased the annual precipitation. Hence, the urbanization signals have been embedded in the cities of positive PUE values, but have to be extracted further. For these cities, Beijing showed the highest PUE value (70.646), then were Xingtai (51.101), Chengde (44.313) and Shijiazhuang (39.875) and etc. Cangzhou recorded the lowest PUE value of 4.219.

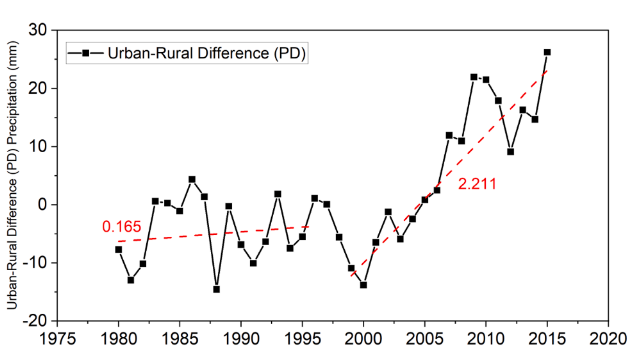

Fig. 4. The regional temporal trends of urban–rural difference of precipitation.

3.2.3. Linkage with land urbanization

Based on PUE results, we further extract the urbanization effects by connecting built-up areas with precipitation. First, the correlations (R^2) of 'built-up area vs urban precipitation' and 'built-up area vs rural precipitation' were compared in Fig. 6. Higher correlations with urban precipitation were observed in 9 cities while the left 4 cities recorded higher R^2 with rural precipitation, which indicates the closer relationships of built-up area with urban precipitation than with rural precipitation. Therefore, it is reasonable to link urbanization effects with precipitation by using built-up areas.

Finally, we used urbanization effects indicator (UE) to present and to quantify the urbanization effects to local and regional precipitation (Fig. 7). Beijing was the most significant affected city by the rapid urbanization process (UE = 44.50). The secondary affected city was Chengde, the urbanization effects (UE = 21.71) was only half of that in Beijing. Tianjin (16.04), Langfang (13.64), Zhangjiakou (13.27) and Shijiazhuang (11.56) were calculated as the similar urbanization effects. Hengshui (5.71) and Handan (3.15) were lower as the same level of urbanization effects, then were Cangzhou (1.81) and Xingtai (1.53). Qinhuangdao (−0.26), Tangshan (−9.16) and Baoding (−10.74) were not observed the assumed urbanization effects due to the higher precipitation differences in 1980s than in 2000s.

4. Discussion

This study quantified the urbanization effects on inter-annual precipitation variations in temperate zone of China. We improved current urbanization effects indicator (Luo and Lau, 2019) and built linkage between urbanization and inter-annual precipitation. The R^2 between built-up area and PUE was 0.24 while the R^2 between built-up area and UE has increased to 0.51 (not showed in this study), which proved the effects of built-up surface on precipitation. Based on field observations, this study provided some new information of urbanization effects on inter-annual precipitation in temperate zone.

Several potential impact factors have to be discussed. First, climate zones may be an effective factor which modified the roles of urbanization effects. From simulations and field observations, several studies have reported that the urban dry land effect and the precipitation deficit occurred in East China (Chen et al., 2015; Luo and Lau, 2019; Ma et al., 2018), which were opposite with our results in temperate zone. In addition to that, a simulation work has reported that under the rapid urbanization process, annual precipitation will be increase in North and decrease in East of China (Feng et al., 2012), which supported our results and enhanced the roles of climate zones in identify urbanization effects. Second, the less number of sites and the different research time periods (Paul et al., 2018; Cong et al., 2010; Han et al., 2014) will also lead to different results. Third, the results could be vary due to flexible

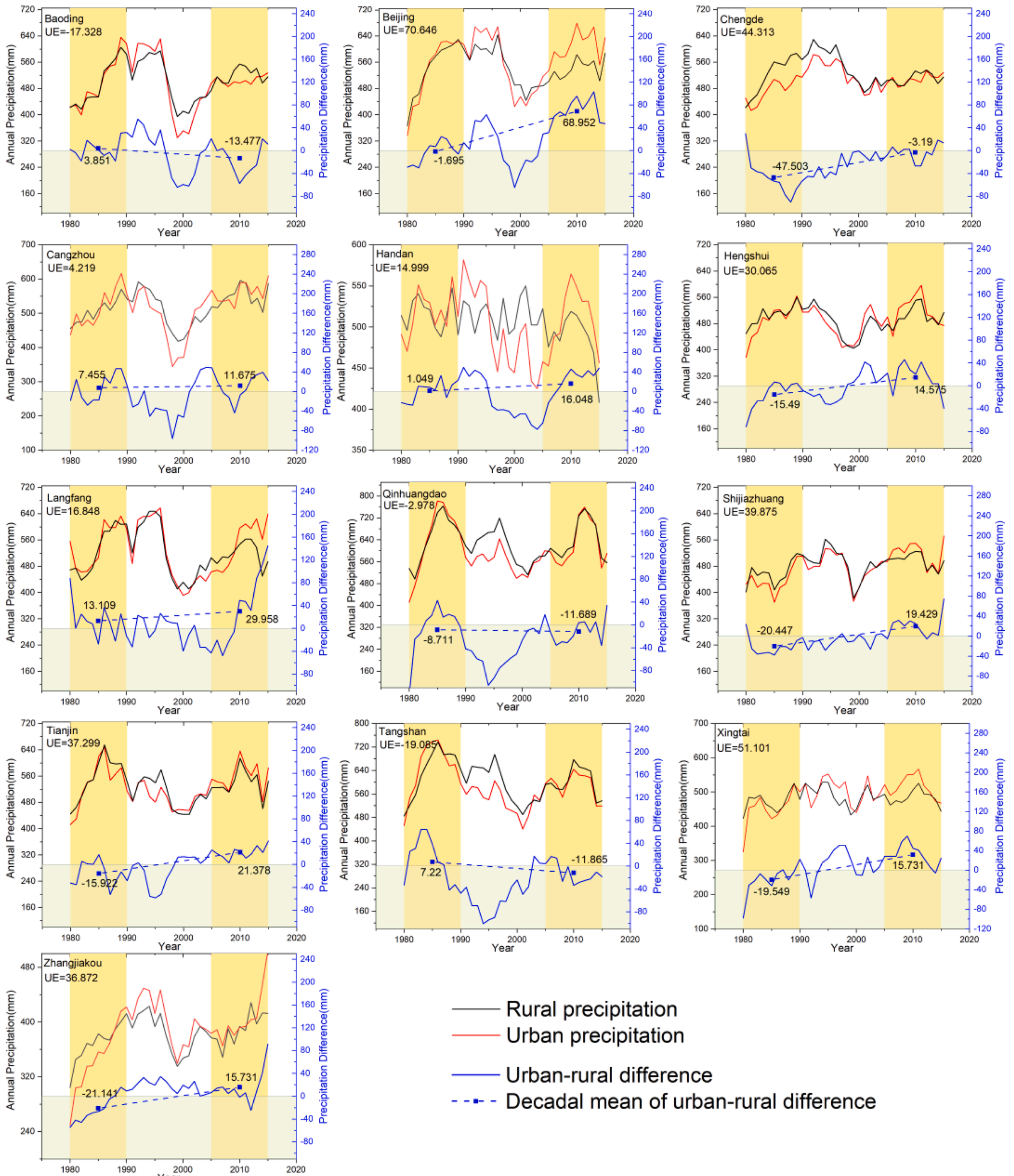

Fig. 5. Annual and decadal urban–rural differences which indicate the potential urbanization effects (PUE) from each city.

parameter configurations and various model components (Feng et al., 2015; Li et al., 2011; Luo et al., 2017; Miao et al., 2011). It was argued that the differences of precipitation over urban and rural areas are highly related to model modifications (Shem and Shepherd, 2009).

Given the complicate 'Earth-Atmosphere' interactions, we have to admit that the factors of atmosphere circulation and locations of cities cannot be fully excluded. In this study, as the second largest coastal city, Tianjin showed far less urbanization effects than Beijing. As previous works pointed out, the coastal wind and topography could play important roles in shaping local precipitation and will suppress the urbanization contributions and lead to higher variability of local precipitation (Shepherd et al., 2010). Therefore, more field observations in urban area

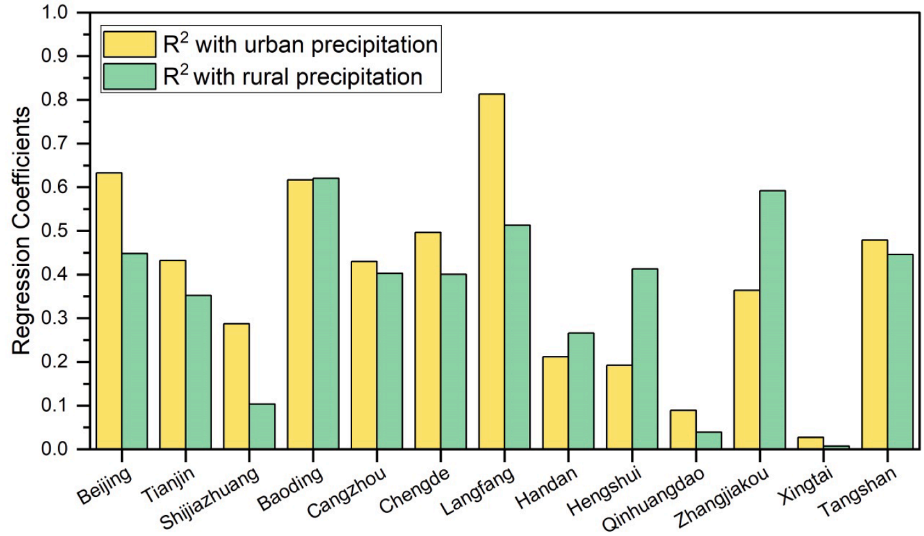

Fig. 6. The coefficients between built-up area and precipitation of each city.

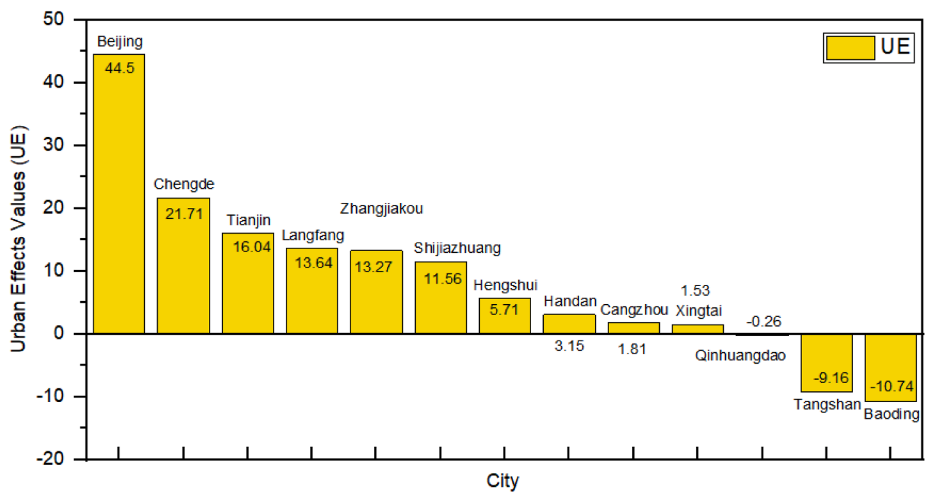

Fig. 7. The sorted urbanization effects (UE) of all cities.

and simulations of climate model which consider the characteristics of coastal cities and various terrains are necessary for further works.

5. Conclusion

This study focused on assessing the urbanization effects on inter-annual precipitation in temperate climate zone, which has not been fully investigated. The urbanization effects on precipitation were assessed by differences of urban–rural precipitation in 2000s and 1980s. In addition, urbanization effects and precipitation was linked with built-up areas and the urbanization effects indicator (UE) has been improved.

This study found that: (1) The urbanization led to the increasing of annual precipitation especially after 2000. The urban precipitation revived faster than rural precipitation after the drought period (late 1990s). Higher urban precipitation increasing slope of 7.165 mm/yr was observed than that in rural areas with slope of 4.954 mm/yr in 2000s. The urbanization effects have been implied by urban–rural difference comparisons between slope of 2.211 mm/yr in 2000s and 0.165 mm/yr in 1980 s. (2) As a whole, built-up areas showed higher correlation with urban precipitation than with rural precipitation in 9 of 13 cities. (3) The urbanization effects have been quantified through UE indicator. Beijing presented the highest urbanization effects with UE of 44.5, which was obvious higher than the secondary cities of Chengde (21.71), Tianjin (16.04) and Langfang (13.64). Cities of Qinhuangdao, Tangshan and Baoding were not observed urbanization effects (UE < 0) probably due to the complicate impacts of 'Earth-Atmosphere' interactions in coastal cities.

This manuscript provides new information about roles of urbanization on annual precipitation in temperate climate zone, which will help understand the contributions of land surface change to long term climate system.

CRediT authorship contribution statement

Tao Sun: Conceptualization, Methodology, Writing - review & editing. **Ranhao Sun:** Methodology, Writing - review & editing. **Muhammad Sadiq Khan:** Data curation. **Liding Chen:** Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The authors declare no conflict of interests.

References

Adamowski, J., Chan, H.F., Prasher, S., Ozga-ZieljDski, B., Sliusarieva, A., 2012. Comparison of multiple linear and nonlinear regression, autoregressive integrated moving average, artificial neural network, and wavelet artificial neural network methods for urban water demand forecasting in Montreal, Canada. Water Resourc. Res. 48.

Ajaaj, A.A., Mishra, A.K., Khan, A.A., 2018. Urban and peri-urban precipitation and air temperature trends in mega cities of the world using multiple trend analysis methods. Theor. Appl. Climatol. 132 (1–2), 403–418.

Bornstein, R., Lin, Q., 2000. Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies. Atmos. Environ. 34 (3), 507–516.

Burian, S.J., Shepherd, J.M., 2005. Effect of urbanization on the diurnal rainfall pattern in Houston. Hydrol. Process. 19 (5), 1089–1103.

Chaouche, K., et al., 2010. Analyses of precipitation, temperature and evapotranspiration in a French Mediterranean region in the context of climate change. C.R. Geosci. 342 (3), 234–243.

Chen, L., Frauenfeld, O.W., 2016. Impacts of urbanization on future climate in China. Clim. Dyn. 47 (1–2), 345–357.

Chen, S., Li, W., Du, Y., Mao, C., Zhang, L., 2015. Urbanization effect on precipitation over the Pearl River Delta based on CMORPH data. Adv. Clim. Change Res. 6 (1), 16–22.

Cong, Z., Zhao, J., Yang, D., Ni, G., 2010. Understanding the hydrological trends of river basins in China. J. Hydrol. 388 (3–4), 350–356.

Feng, J., Wang, Y., Ma, Z., Liu, Y., 2012. Simulating the regional impacts of urbanization and anthropogenic heat release on climate across China. J. Clim. 25 (20), 7187–7203.

Feng, J., Wang, Y., Ma, Z., 2015. Long-term simulation of large-scale urbanization effect on the East Asian monsoon. Clim. Change 129 (3–4), 511–523.

Gu, X., Zhang, Q., Li, J., Singh, V.P., Sun, P., 2019. Impact of urbanization on nonstationarity of annual and seasonal precipitation extremes in China. J. Hydrol. 575, 638–655.

Guo, R., Deser, C., Terray, L., Lehner, F., 2019. Human influence on winter precipitation trends (1921–2015) over North America and Eurasia revealed by dynamical adjustment. Geophys. Res. Lett.

Guo, X., Fu, D., Wang, J., 2006. Mesoscale convective precipitation system modified by urbanization in Beijing City. Atmos. Res. 82 (1–2), 112–126.

Han, Z., Yan, Z., Li, Z., Liu, W., Wang, Y., 2014. Impact of urbanization on low-temperature precipitation in Beijing during 1960–2008. Adv. Atmos. Sci. 31 (1), 48–56.

Khain, A., Rosenfeld, D., Pokrovsky, A., 2005. Aerosol impact on the dynamics and microphysics of deep convective clouds. Q. J. R. Meteorolog. Soc. 131 (611), 2639–2663.

Kishtawal, C.M., Niyogi, D., Tewari, M., Pielke, R.A., Shepherd, J.M., 2010. Urbanization signature in the observed heavy rainfall climatology over India. Int. J. Climatol. 30 (13), 1908–1916.

Li, W., et al., 2011. Urbanization signatures in strong versus weak precipitation over the Pearl River Delta metropolitan regions of China. Environ. Res. Lett. 6 (3), 034020.

Liang, P., Ding, Y., 2017. The long-term variation of extreme heavy precipitation and its link to urbanization effects in Shanghai during 1916–2014. Adv. Atmos. Sci. 34 (3), 321–334.

Liu, B., 2005. Observed trends of precipitation amount, frequency, and intensity in China, 1960–2000. J. Geophys. Res. 110 (D8).

Luo, N., et al., 2017. Simulation of the impacts of urbanization on winter meteorological fields over the Pearl River Delta Region. Adv. Meteorol. 2017, 1–10.

Luo, M., Lau, N.C., 2019. Urban expansion and drying climate in an urban agglomeration of east China. Geophys. Res. Lett.

Ma, H., Li, T., Jiang, Z., Gu, P., 2018. Unexpected large-scale atmospheric response to urbanization in East China. Clim. Dyn.

Manoli, G., et al., 2019. Magnitude of urban heat islands largely explained by climate and population. Nature 573 (7772), 55–60.

Mavromatis, T., Stathis, D., 2011. Response of the water balance in Greece to temperature and precipitation trends. Theor. Appl. Climatol. 104 (1), 13–24.

Miao, S., Chen, F., Li, Q., Fan, S., 2011. Impacts of urban processes and urbanization on summer precipitation: a case study of heavy rainfall in Beijing on 1 August 2006. J. Appl. Meteorol. Climatol. 50 (4), 806–825.

Mitra, C., Shepherd, J.M., Jordan, T., 2012. On the relationship between the premonsoonal rainfall climatology and urban land cover dynamics in Kolkata city, India. Int. J. Climatol. 32 (9), 1443–1454.

Niyogi, D., et al., 2011. Urban modification of thunderstorms: an observational storm climatology and model case study for the Indianapolis urban region. J. Appl. Meteorol. Climatol. 50 (5), 1129–1144.

Niyogi, D., Lei, M., Kishtawal, C., Schmid, P., Shepherd, M., 2017. Urbanization impacts on the summer heavy rainfall climatology over the Eastern United States. Earth Interact 21 (5), 1–17.

Paul, S., et al., 2018. Increased spatial variability and intensification of extreme monsoon rainfall due to urbanization. Sci. Rep. 8 (1).

Perugini, L., et al., 2017. Biophysical effects on temperature and precipitation due to land cover change. Environ. Res. Lett. 12 (5), 053002.

Qin, Y., Yang, D., Lei, H., Xu, K., Xu, X., 2015. Comparative analysis of drought based on precipitation and soil moisture indices in Haihe basin of North China during the period of 1960–2010. J. Hydrol. 526, 55–67.

Sayemuzzaman, M., Jha, M.K., 2014. Seasonal and annual precipitation time series trend analysis in North Carolina, United States. Atmos. Res. 137, 183–194.

Shastri, H., Paul, S., Ghosh, S., Karmakar, S., 2015. Impacts of urbanization on Indian summer monsoon rainfall extremes. J. Geophys. Res.: Atmos. 120 (2), 496–516.

Shem, W., Shepherd, M., 2009. On the impact of urbanization on summertime thunderstorms in Atlanta: two numerical model case studies. Atmos. Res. 92 (2), 172–189.

Shepherd, J.M., 2006. Evidence of urban-induced precipitation variability in arid climate regimes. J. Arid Environ. 67 (4), 607–628.

Shepherd, J.M., Carter, M., Manyin, M., Messen, D., Burian, S., 2010. The impact of urbanization on current and future coastal precipitation: a case study for Houston. Environ. Plann. B: Plann. Des. 37 (2), 284–304.

Sun, Y., Zhang, X., Ren, G., Zwiers, F.W., Hu, T., 2016. Contribution of urbanization to warming in China. Nat. Clim. Change 6 (7), 706–709.

Ullah, S., et al., 2019. Observed changes in maximum and minimum temperatures over China- Pakistan economic corridor during 1980–2016. Atmos. Res. 216, 37–51.

Wai, K.M., et al., 2017. Observational evidence of a long-term increase in precipitation due to urbanization effects and its implications for sustainable urban living. Sci. Total Environ. 599–600, 647–654.

Wang, J., Feng, J., Yan, Z., 2018. Impact of extensive urbanization on summertime rainfall in the Beijing region and the role of local precipitation recycling. J. Geophys. Res.: Atmos. 123 (7), 3323–3340.

Yan, T., Wang, J., Huang, J., 2015. Urbanization, agricultural water use, and regional and national crop production in China. Ecol. Model. 318, 226–235.

Yang, H., Yang, D., Hu, Q., Lv, H., 2015. Spatial variability of the trends in climatic variables across China during 1961–2010. Theor. Appl. Climatol. 120 (3–4), 773–783.

Yu, M., Li, Q., Hayes, M.J., Svoboda, M.D., Heim, R.R., 2014. Are droughts becoming more frequent or severe in China based on the standardized precipitation evapotranspiration index: 1951–2010? Int. J. Climatol. 34 (3), 545–558.

Yun, J., et al., 2018. Influence of winter precipitation on spring phenology in boreal forests. Glob. Change Biol.

Zhang, H., et al., 2015. Challenges and adaptations of farming to climate change in the North China Plain. Clim. Change 129 (1–2), 213–224.

Zhang, S., Huang, G., Qi, Y., Jia, G., 2018a. Impact of urbanization on summer rainfall in Beijing–Tianjin–Hebei metropolis under different climate backgrounds. Theor. Appl. Climatol. 133 (3–4), 1093–1106.

Zhang, W., Villarini, G., Vecchi, G.A., Smith, J.A., 2018b. Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston. Nature 563 (7731), 384–388.

Zhang, H., Wu, C., Chen, W., Huang, G., 2019. Effect of urban expansion on summer rainfall in the Pearl River Delta, South China. J. Hydrol. 568, 747–757.

Zhong, S., Qian, Y., Zhao, C., Leung, R., Yang, X., 2015. A case study of urbanization impact on summer precipitation in the Greater Beijing Metropolitan Area: urban heat island versus aerosol effects. J. Geophys. Res.: Atmos. 120 (20), 10903–10914.

Zhu, X., et al., 2019. Impact of urbanization on hourly precipitation in Beijing, China: spatiotemporal patterns and causes. Global Planet. Change 172, 307–324.