Use of high-resolution precipitation observations in quantifying the effect of urban extent on precipitation characteristics for different climate conditions over the Pearl River Delta, China

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1 INTRODUCTION

Gauges are considered to provide the most accurate precipitation measurement, while the representativeness of uneven or sparse distribution of gauges is worthy of consideration (Li and Shao, 2010). Different from gauge observations, satellite-based products provide gridded-based area-averaged precipitation information, and offer us opportunities to measure precipitation at contiguous spatiotemporal ranges (Huffman et al., 2015). With the help of remote sensing techniques, many products have been rapidly developed and widely used at their high spatial and temporal resolutions in the water resources management and hydrologic prediction researches (e.g., Su et al., 2008; Rhee et al., 2010). Precipitation data at the 3-hr and 0.25° resolution are commonly used. Results from these studies demonstrated that precipitation can be better characterized with the higher resolution data (Haylock et al., 2008). In recent years, precipitation products with finer resolution (hourly and 0.1°) are released, such as the IMERG (Integrated Multi-satelliteE Retrievals for GPM; Huffman et al., 2015) and CMPA (China hourly Merged Precipitation Analysis product; Shen et al., 2014).

Urban expansion plays an important role in shaping regional climate, and the effect of urban extent on climate has become a research focus (Shepherd, 2005). The effect of urban extent on precipitation characteristics can be studied via three different pathways, namely, Urban heat island (UHI), large surface roughness and higher aerosol concentration (Han et al., 2014). Han and Baik (2008) found that...
UHI caused an upward motion downwind of the urban area using a three-dimensional model, which partially explains the increased precipitation over these areas. With the rough surface in urban areas, moist air bifurcates when approaching the urban core, and then gather together downwind of urban areas, which causes more precipitation over there (Cotton and Pielke, 2007). Anthropogenic high aerosol concentration may either inhibit or enhance precipitation, depending on the cloud type, environmental condition, and concentration of aerosol (Rosenfeld et al., 2008). Recent research has demonstrated that urban impacts on regional climate are of a similar order of magnitude as that due to large-scale climate change (Georgescu et al., 2014).

Limited studies have quantitatively investigated the observed relationship between urban extent and precipitation characteristics. The Pearl River Delta (PRD) region (Figure 1) has experienced a rapid urbanization in the past 30 years, which results in an evident contrast between urbanized areas and their surrounding areas (Lin et al., 2009). Wang et al. (2015) found that urban extent is strongly correlated with the maximum precipitation amount and that the correlation coefficient increases with the temporal resolution of precipitation amount over PRD. In this work, we further examine whether the precipitation intensity and frequency are also spatially correlated with urban extent and how the correlations vary with climate condition by using a blended satellite-gauge precipitation data at a high spatiotemporal resolution.

### 2 | DATA AND METHODS

To capture precipitation features at the high spatiotemporal resolution, we use the CMPA data (http://data.cma.cn/) from 2008 to 2013 in this study. Hourly gauge observations of more than 30,000 automatic weather stations over mainland China are merged into the CMORPH (Climate Prediction Center Morphing Technique) estimate by employing an improved probability density function optimal interpolation method. The final product is in $0.1^\circ \times 0.1^\circ$ spatial resolution.
The land use dataset at the 100 m resolution for 2010 (Figure 1c) is derived from Landsat TM/ETM+ (Thematic Mapper and Enhanced Thematic Mapper Plus) images using the methods proposed by Liu et al. (2005). The type of each pixel is categorized by use of the five land use types (i.e., farmland, forest, grassland, water body, and urban). We keep only grid cells with a homogeneous (i.e., 100%) land cover class in the following analysis, in order to maximize the statistical significance of the resulting correlations, which generates 653 0.1 x 0.1° land-only grid cells in the study area (Figure 1d). In each land-only grid, the urban extent is defined as the ratio of the number of urban pixels to the total number of pixels.

The Global Land Data Assimilation System (GLDAS; Rodell et al., 2004) version 1 on a 0.25 × 0.25° resolution from 2008 to 2013 is used to obtain the multi-year average of surface temperature. The Ozone Monitoring Instrument (OMI)/Aura Aerosol Extinction Optical Depth and Aerosol Types (OMAERO) Level 3 product (OMI Team, 2012) from 2008 to 2013 is used to derive the temporal averages of the aerosol optical thickness (AOT) map on a resolution of 0.25 × 0.25°. The Japanese 55-year Reanalysis (JRA-55) data (Kobayashi et al., 2015) at the 6-hr and approximately 0.56° resolution for 2008–2013 is used to derive the temporal mean wind direction, the moisture flux convergence (MFC), and the surface relative humidity (RH) during the precipitation periods. The wind direction is derived based on the zonal and meridional wind at 700 hPa, and the MFC within a grid cell is calculated as follows:

$$MFC = \frac{1,000}{g} \int_{p_b}^{p_t} (\nabla \cdot \mathbf{q}_u + \mathbf{v} \cdot \nabla \mathbf{q}_v) \, dp,$$

where $g$ is the gravitational acceleration, $p_t$ and $p_b$ are the pressures at the top and bottom of the atmosphere, $u$ and $v$ are the zonal and meridional wind vector, respectively, and $q_u$ and $q_v$ are the zonal and meridional specific humidity, respectively. An overbar denotes the difference between the grid and its zonal/meridional two grids. The vertical integrated MFC is calculated by integrating the moisture convergence over 60 pressure levels from surface to the top of atmosphere.

We focus the wet season (April–September) only in this study, as precipitation during the wet season accounts for approximately 80% of the total annual precipitation in the PRD region. The mechanisms of precipitation are different for different climate conditions. The Southwest monsoon dominates in PRD during the early wet season (April–May–June, AMJ), which helps in generating a weather front when the cold air intrudes from the northern areas. Since the subtropical high belt moves northward during the late wet season (July–August–September, JAS), tropical weather systems generally control the PRD region. Typhoon-related heavy rain events largely affect the PRD and occur in JAS and even do occasionally in June and October (Wang et al., 2016). The wet season is further divided into three types of climate conditions: southwest monsoon (during AMJ without typhoon events), tropical convection (during JAS without typhoon events), and typhoon (during the precipitation periods of typhoon events).

To distinguish wet and dry hours, the threshold of 0.1 mm/h is adopted in this study. Following the precipitation extreme indices based on the daily precipitation data (Zhang et al., 2011), we define six indices based on the hourly precipitation data as follows:

- RX1h: monthly maximum 1-hr precipitation amount;
- RX3h: monthly maximum consecutive 3-hr precipitation amount;
- RX24h: monthly maximum consecutive 24-hr precipitation amount;
- TotP: annual total wet-hour precipitation amount during the study period;
- TWH: annual total wet hours during the study period;
- SHII: simple hourly intensity index, calculated as the ratio of TotP to TWH.

Precipitation indices are found to be better correlated with the logarithm of the urban extent, which is supported by several studies on the relationship between population and climate (Wang et al., 2015). Therefore, the spatial correlation coefficient $R$ is calculated as follows:

$$R = \frac{\sum_{i=1}^{N} \left( \ln(P_{u,i}) - \ln(P_{u}) \right) (\text{EPI}_i - \text{EPI})}{\sqrt{\sum_{i=1}^{N} \left( \ln(P_{u,i}) - \ln(P_{u}) \right)^2 \sum_{i=1}^{N} (\text{EPI}_i - \text{EPI})^2}},$$

where $N$ is the number of grid points, $\ln(P_{u,i})$ is the natural logarithm of urban percentage at grid cell $i$, EPI is the extreme precipitation index at grid cell $i$, the overbar denotes a domain average.

## RESULTS

The TotP is greatest in southwestern Jiangmen and the boundary of Guangzhou, Huizhou and Shaoquan, whereas the maximum of the TWH occurs in southwestern Jiangmen and northern PRD (Figure 2). Different from TotP and TWH, SHII shows a spatial pattern with an evident contrast between highly urbanized areas and surrounding areas. Spatially, RX24h is similar to TotP in that the largest values for both indices occur in similar areas. For RX24h, RX3h, and RX1h, when the temporal scale becomes shorter, the high value area extends to the highly urbanized areas, such as Foshan, Zhongshan, Guangzhou, Dongguan and Shenzhen.

Consistent with the spatial patterns in Figure 2, TotP is not correlated with urban extent and the correlation is insignificant (Table 1). A significant negative correlation coefficient ($-0.58$) between TWH and urban extent indicates that rain hours decrease with the increase in urban extent.
Rainfall intensity is enhanced by urban extent based on a positive correlation coefficient between SHII and urban extent. A comparison of RX24h, RX3h, and RX1h versus urban extent indicates that extreme precipitation amount is more tightly correlated to urban extent with the finer temporal scale of extreme indices, which is consistent with the findings of Wang et al. (2015).

TotP under the Southwest monsoon (tropical convection/typhoon) are negatively (positively) correlated to urban extent, while the $R$ values are relative small (Table 1). The magnitudes of TWH under the Southwest monsoon ($R = -0.65$) are larger than those under other climate conditions, indicating that the correlation between precipitation frequency and urban extent during the wet season is largely determined by the correlation under the Southwest monsoon. The correlation coefficients between four intensity indices (i.e., SHII, RX24h, RX3h and RX1h) and urban extent under the Southwest monsoon are similar to those during the entire wet season. Moreover, those correlation coefficients under the tropical convection are larger than the values during the entire wet season and the values under other two climate conditions. In contrast, precipitation

**TABLE 1** $R$ values between natural logarithm of urban extent ($\ln[P_{\text{u}}]$, urban extent in %) versus six precipitation indices derived from hourly precipitation observations under different climate conditions at 0.1 × 0.1° resolution based on 653 100% homogeneous land type grid cells

|               | TotP | TWH | SHII | RX24h | RX3h | RX1h |
|---------------|------|-----|------|-------|------|------|
| Wet season (Apr–Sep) | 0.03 | -0.58 | 0.56 | 0.15 | 0.31 | 0.45 |
| The Southwest monsoon | -0.24 | -0.65 | 0.53 | -0.01 | 0.25 | 0.40 |
| The tropical convection | 0.20 | -0.21 | 0.59 | 0.26 | 0.35 | 0.46 |
| The typhoon events | 0.21 | -0.10 | 0.33 | 0.28 | 0.30 | 0.35 |

*Note.* Value in bold represents a statistically significant correlation at the 99% confidence level.
characteristics of typhoon events have the poorest relationship with urban extent.

Besides urban extent, the large-scale atmospheric forcing (e.g., MFC and wind direction) and topography may also influence regional precipitation characteristics. Under the Southwest monsoon, the large-scale atmospheric forcing together with topography controls the spatial pattern of total precipitation amount. Southwesterly moist wind dominates over PRD, leading to the high RH over the PRD region (Figure 3b). The horn mouth-shaped topography in southwest PRD and the windward slope in the mountain areas of central PRD lead to the large rainfall amount over these areas when moist air passes from southwest to northeast (Figure 3c). A quite low TotP which mainly due to the low frequency of precipitation exists over the urbanized area (Figure 3c). Under the tropical convection, the southeasterly wind becomes dominant (Figure 3e). Higher TotP mainly occurs over the coastal areas, which is similar to the location of moisture convergence (Figure 3g). The atmospheric moisture convergence seems to play the key role in determining precipitation amount and precipitation maxima during typhoon events. The anticlockwise southeasterly wind becomes dominant, and atmosphere moisture converges along the costal line (Figure 3i). The spatial pattern of the moisture convergence consistent with that of TotP, as well as that of RX1h (Figures 3k–l).

Different from total precipitation, the short-duration heavy storm precipitation is often determined by the contrast between different land covers/land uses during the wet season except for typhoon events. The intensity of precipitation extremes are relative high under the Southwest monsoon (Figure 3d). The wind force and RH under the tropical convection are much lower than that of other climate conditions (Figures 3e-f). The high values of precipitation maxima extend to the highly urbanized areas (Figure 3h), probably because local convection is enhanced by urban
environments. It is evident that precipitation concentrates in highly urbanized areas, which is different from the concentrated area of the moisture convergence. In the conceptual model of Rosenfeld et al. (2008), clouds usually develop to greater height and droplets could be lifted to the freezing level when the higher aerosol concentrated, and the latent heat released, resulting in deep convection therefore enhanced precipitation. The spatial pattern of surface temperature (AOT) is consistent with that of RX1h (Figures 4a–c), and spatial correlation coefficients between them are high (Figures 4d,e). Our results are consistent with this theory.

4 DISCUSSION AND CONCLUSIONS

In this study, we use high-resolution precipitation data and satellite-based land cover data to qualitatively and quantitatively investigate the correlation between urban extent and precipitation extremes for different climate conditions. Positive correlations are found between extreme precipitation amount and urban extent. The correlation coefficients between urban extent and extreme precipitation indices are stronger at shorter temporal scales (increase from 0.15 of RX24h to 0.45 of RX1h). Urban heat island and increased land surface roughness may intensify local moisture convergence and convection. In addition, higher aerosol concentration in urban areas may also enhance deep convection. The stronger relationship at smaller temporal resolution reflects the process-level response of extreme precipitation to urban environments, as convective precipitation events usually are of shorter duration. The high relationship between precipitation intensity and urban extent are attributed primarily to the tropical convection, with secondary contribution from the Southwest monsoon, while the distribution of precipitation extremes is similar to total precipitation for typhoon events (Table 1 and Figures 3d, h, l).

Besides examining the relationship between extreme precipitation amount and urban extent, we further reveal that precipitation intensity is also enhanced by urban extent and that rain hours decrease with the increase in urban extent. The negative relationship of TWH is dominated by precipitation frequency under southwest monsoon (Table 1 & Figure 3c). Light rain is suppressed in highly urbanized areas because of high aerosol concentrations as a larger number of smaller cloud droplets are generated in such an environment (Lynn et al., 2007), whereas urban areas can enhance the short-duration heavy precipitation through deep convections induced by higher surface temperature and elevated aerosol loading in the urban environments. The decrease in light rain hours dominates compared with the increase in heavy rain hours, which leads to the
decrease in total wet hours in urbanized areas. Besides, topography together with the large-scale atmospheric forcing exerts the dominant influence on total precipitation mainly through its impact on the frequency of light or moderate precipitation (Sanchez-Moreno et al., 2014). Since total precipitation amount does not change much with urban extent, the intensity is positively correlated with urban extent.

The urban effect on precipitation can be verified by modeling methods in which the impact factors can be isolated through well-designed experiments. An enhancement (suppression) in heavy (light) rain in urban areas over PRD is found by two modeling studies. Wang et al. (2011) focused the effect of aerosol concentrations on precipitation, whereas Wang et al. (2014) investigated the effect of urban induced-land use/land cover change on precipitation. Although factors considered are different in these two different modeling studies, the role of urban environments in determining precipitation characteristics is similar (enhancing heavy rain and suppressing light rain). Our results are consistent with their findings. It should be noted that the rainfall enhancement hypothesis does not always hold over urbanized regions. Georgescu et al. (2009) found that the assumed dynamical and thermodynamical processes have added the moisture at lower atmosphere on a diurnal basis, but it did not lead to rainfall enhancement of the Greater Phoenix region.

At the seasonal scale, precipitation characteristics are mainly determined by topography and the synoptic background. The spatial pattern of the moisture convergence generally matches that of the total precipitation, while it is not well consistent with that of extreme precipitation. By contrast, for the short-duration heavy precipitation events, precipitation characteristics are considerably influenced by the land covers (except during typhoon events). Urban environments probably play a positive role in generating the short-duration heavy precipitation through enhanced deep convections induced by higher surface temperature and higher aerosol concentration; however, mechanisms responsible for urban-precipitation relationship has not been fully understood. A further modeling research is needed to understand the processes and the effect of urban extent on the timing of precipitation events. We are currently working on this problem.

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