Urbanization Impacts on Pearl River Delta Extreme Rainfall Sensitivity to Land Cover Change Versus Anthropogenic Heat

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Abstract Impacts of urban land cover and anthropogenic heat (AH) on extreme local rainfall over the coastal Pearl River Delta (PRD) megacity region during boreal summer are investigated by conducting numerical experiments using the Weather Research and Forecasting model coupled with a single-layer urban canopy model. To examine the relative importance of land cover change versus the presence of AH, three numerical experiments corresponding to different levels of urbanization in the PRD area were designed: one with cropland covering the whole region, one with urban land cover but zero AH, and one with urban land cover and a strong diurnal maximum of 300 W m⁻² of AH in the model simulations. Results show that the increase of rainfall in the urban area is much more sensitive to the intensity of AH than the mere change of surface properties. Urbanization with intense AH can enhance both the intensity and frequency of extreme rainfall, which can be attributed to higher surface temperature (of about 3.5–4°C), higher convective available potential energy, and lower convective inhibition, thus creating an environment more conducive to strong convection over the urban areas. Moreover, enhanced rainfall is supported by moisture supply from the South China Sea and increased water vapor flux convergence over the PRD city area. The amount of moisture flux converging over the coastal megacity area was found to depend on the direction of prevailing background wind.

1. Introduction

The effects of urbanization on the local climate such as extreme precipitation have become a hot research topic since last century, with rapid urbanization be observed over the global scale (Hannah, 2018). It is reported that the urban influence on precipitation tends to be found in downwind area of urban (Changnon, 1968; Huff & Changnon, 1972). After these pioneering works, many researches also reported urban impacts on precipitation, especially over locations downwind of cities. Shepherd and Burian found that the strongest annual mean precipitation is located in the downwind of Houston by analyzing Tropical Rainfall Measuring Mission (TRMM) data from January 1998 to May 2002 (Shepherd & Burian, 2003). Besides, by numerical simulating two extreme precipitation cases in Atlanta, Shem and Shepherd (2009) showed that the center of rainfall increment caused by the urban heat island (UHI) effect was located downwind of the city, by 10%–13%.

However, the influence of urbanization is complex and might depend on the intensity of UHI and geographical locations. Studies focused on Beijing found that strong UHI effect can increase rainfall directly over the downtown area of Beijing, while for weak UHI, rainfall would be bifurcated and avoid the city center (Dou et al., 2015; Zhang et al., 2017). For coastal locations, there are stronger and more frequent extreme rainfall over coastal urban area such as Osaka Kinki and the Tokyo metropolitan region, which can be attributed to stronger sensible heat flux, lower atmospheric stability, stronger vertical convection, and more water vapor supply from the ocean (Kusaka et al., 2014; Shimadera et al., 2015; Xiao et al., 2020). A summary of results on urban influence on rainfall was recently given by Liu and Niyogi (2019). The increase in precipitation intensity induced by urbanization can reach about 11% (14%)–21% (22%) over the urban (downstream) area but weak over other regions.
China has experienced rapid urbanization during recent few decades, and the Pearl River Delta (PRD) megacity is one of the urban clusters with fast urbanization. Based on station data and satellite reanalysis data, it was found that there are stronger and more frequent extreme rainfall induced by urban expansion over PRD in recent years; stronger afternoon rainfall can be observed in urban locations in the region, compared to that in the surrounding rural area (Li et al., 2015; D. Wang, Jiang, et al., 2015). PRD urban locations also tend to see faster increasing trends of extreme rainfall frequency and more extreme rainfall events, characterized by abrupt and shorter duration episodes (Wu and Zhang, 2018; Yan et al., 2020). Besides, it was found that the extreme rainfall intensity, spatial distribution, and frequency are highly sensitive to the urban surface heat flux. Based on numerical model experiments, stronger anthropogenic heat (AH) leads to stronger and more frequent extreme rainfall over the PRD urban area (Fung et al., 2021; C. Holst et al., 2016, 2017).

Overall, extreme urban precipitation—with related hazards such as urban flooding—is becoming more and more common in China and can cause great economic and life losses (Yang et al., 2015). However, deeper understanding of the physical mechanisms of urban impact on precipitation is required, and the relative contribution of urban land cover and AH on extreme rainfall enhancement needs to be ascertained. This study seeks to investigate (1) the sensitivity of extreme rainfall to land cover change versus AH and (2) physical mechanisms of urban impacts on extreme precipitation over the coastal PRD area. This is done by dynamical downscaling cases from general circulation model (GCM) outputs with a high-resolution weather scale model coupled with urban canopy model, under different land cover and AH intensity. Descriptions of the model and experimental settings are given in Section 2; results from the model simulated experiments are described in Section 3; and discussions and conclusions can be found in Section 4.

2. Methodology

2.1. Model Configuration and Case Selection

In this study, the Weather Research and Forecasting (WRF) model with the Advanced Research WRF dynamical core version 3.8.1 was utilized to dynamically downscale GCM outputs, generated by the Geophysical Fluid Dynamical Laboratory Earth System model version 2 (GFDL-ESM2M; Dunne, 2013; Dunne et al., 2012). (In our companion study by Fung et al. (2021), outputs from the same GFDL-ESM2 are downscaled for assessing the relative impacts of climate change and urbanization on PRD extreme rainfall). The atmospheric component of GFDL-ESM2M has a horizontal resolution of 2° × 2.5° in latitude and longitude, and its ocean component is the Modular Ocean Model version 4. The model was adopted by many studies (e.g., McSweeney et al., 2015); it performs reasonably well in simulating the East Asia monsoon circulation. By comparing its simulation with TRMM-V3B42 or ERA-Interim reanalysis data, the model gives reasonable summertime (May–September) rainfall distribution and 850 hPa flow, albeit with slightly underestimated mean precipitation over South China (figures not shown).

For the WRF simulations, three nested domains were used for the dynamical downscaling with one-way nesting adopted. Figure 1(a) shows the WRF nested domains, with domain 1 (at 50 × 50 km resolution), domain 2 (at 10 × 10 km resolution), and domain 3 (2 × 2 km resolution) covering the East Asia/western North Pacific area (2.23°–43.82°N, 70.81°–147.05°E), South China (19.94°–27.09°N, 110.68°–117.60°E), and PRD (21.5°–23.83°N, 112.51°–115.04°E), respectively. In each domain, results from the buffer zones (four grid boxes from the boundary) were not considered in our analyses. There were 39 vertical levels, reaching the height of ~23 km. Physical parameterizations in WRF included the Rapid Radiative Transfer Model for General Circulation Model for the longwave radiation (Iacono et al., 2008), the short wave radiation scheme by Dudhia (1989), the WRF single-moment 6-class microphysics scheme (Hong et al., 2006), the Eta Similarity theory for the surface layer options (Janjic, 1994), the NOAH land surface model, which supports the single-layer urban canopy model (SLUCM) (F. Chen & Dudhia, 2001; Kusaka et al., 2001; Tewari et al., 2008), the Bougeault and Lacarrère planetary boundary layer scheme (Bougeault & Lacarrère, 1989), and the simplified Arakawa–Schubert cumulus parameterization (for the outermost domain only; Han & Pan, ). To ensure that WRF can reproduce the same synoptic-scale circulation from the parent model, spectral nudging is applied in the outmost domain (d01) and strength of 3 × 10−4 s for U, V wind above 500 hPa, at the wavelength of about 1,300 km.
Extreme rainfall cases to be downscaled were identified based on daily rainfall from GFDL-ESM2M. In particular, daily precipitation averaged over the region of 17°–27°N, 105°–117°E from a GFDL-ESM2M run (from 1946 to 2005) was first computed. Days during which the daily mean rainfall is larger than the 99th percentile (based on rainfall in wet days, defined as days with rain rate >0.1 mm/day) were defined as extreme rain days. About 60 cases from May to September were chosen and then dynamically downscaled by WRF in the outermost domain. Downscaling results were then inspected, and only cases giving rainfall patterns consistent with the GFDL-ESM2M outputs were considered. We further stratified cases into those related and not related to TC occurrence (referred to as TC and non-TC cases, respectively). This was achieved by inspecting their rainband organization; cases with anticlockwise spiral rainbands were regarded as TC cases, and the rest as non-TC cases. Twenty-six non-TC cases were dynamically downscaled over the PRD region to a resolution of 2 × 2 km, with each integration starting (ending) 72 h prior to (after) the identified extreme rain day.

2.2. Experimental Design and UCM Setup

After case selection, three sets of parallel numerical experiments were carried out for examining the sensitivity of extreme rainfall to urban land use and AH over the PRD region. In Experiment 1 (referred to as NO-URBAN), the PRD urban area was replaced by “cropland” in the land use categorization in the WRF simulations, since most surrounding areas of the PRD megacity are cropland. For Experiments 2 and 3 (referred to as AH0 and AH300, respectively), WRF coupled with SLUCM were utilized with...
different values of AH (0 W/m² and 300 W/m² for diurnal maximum). 2002 land use categorization based on the Moderate Resolution Imaging Spectro-radiometer (MODIS) data, consisting of 17 types of land cover, was adopted in WRF-SLUCM. Figure 1(b) gives the land use categories within domain 3 such as Water (blue shading in Figure 1(b)), Evergreen Needleleaf Forest, Evergreen Broadleaf Forest, Deciduous Needleleaf Forest, Deciduous Broadleaf Forest, Mixed Forest (green), Closed Shrublands, Open Shrublands, Woody Savannas, Savannas (pink), Grasslands (cyan), Permanent Wetlands, Croplands (yellow), Urban and Built-up (red), Natural Vegetation Mosaic, Snow and Ice (white), and Barren (black), also shown are the locations of major cities in PRD, namely, Hong Kong (HK), Shenzhen (SZ), Dongguan (DG), Guangzhou (GZ), Foshan (FS), Zhongshan (ZS), Zhuhai (ZH), and Macao (MC) (see black dots). SLUCM can incorporate three types of urban categories: “low intensity residence,” “high intensity residence,” and “commercial and industrial.” Due to lack of data in MODIS, all urban grid points were categorized as high intensity residence. Figure 1(c) shows the land use distribution of NO-URBAN experiment, with the urban land cover replaced by cropland in all domains.

Table 1 gives UCM parameters prescribed for MODIS land cover. The mean building height was set to 30 m (based on data from the Hong Kong Lands Department). The standard deviation of building height was 4 m, and the road width was 16 m, based on default values for commercial land use. Satellite measurements indicated that a 289 W m⁻² diurnal peak value in AH in Hong Kong during summer (Wong et al., 2015). For the AH300 experiments, a diurnal AH profile with its maximum at midnight to about 9 a.m., and minimum at 8 p.m. local time was adopted in SLUCM (see C. Holst et al., 2016); AH was set to 0 for the AH0 runs. The former choice thus represents a high urbanization scenario, equivalent to having commercial and industrial land use over every urban location within PRD.

3. Results

3.1. Surface Temperature

Figure 2(a) shows the AH0 minus NO-URBAN surface albedo in the innermost model domain. Compared with natural land cover in NO-URBAN, the surface albedo decreased by about 40%–45% (see Figure S1) over the original urban area in AH0 (or AH300, which gives the same albedo as AH0). Lower surface albedo over the urban area can lead to more absorbed shortwave radiation and therefore stronger sensible heat flux compared with rural areas. Also shown in Figure 2 is the 2-m temperature difference between experiments AH0 and NO-URBAN and also between AH300 and NO-URBAN. It is noteworthy that AH0 experiment gives higher temperature than NO-URBAN over almost the whole urban area in PRD (see Figure 2(b)), meaning that the presence of a megacity itself can lead to a higher temperature, even if there is no AH released within the city. The warming magnitude ranges from 0.5 to 2°C; over more inland/northern PRD urban locations, change of 2-m temperature can reach 1.5°C or more. On the other hand, warming outside the urban area is rather small (<0.5°C), meaning that the influence of surface properties on the temperature is very localized. Overall, surface warming is likely caused by the decrease of surface albedo, which can lead to more shortwave radiation received over the megacity area. In addition, complex building structures can hold more heat, which can also contribute to the warmer temperature within the megacity.

Figure 2(c) gives the 2-m temperature difference between AH300 and NO-URBAN. It can be seen that, with the presence of AH, temperature within the city area can increase by ~2–4°C. More than 3.5°C warming is found in northwestern and northeastern parts of the megacity. The 2-m temperature anomaly pattern in Figure 2(c) is very similar to that in Figure 2(b). Finally, it is noteworthy that warming due to changes in land surface only (i.e., difference between NO-URBAN and AH0) is about 1.2°C averaged over the urban area, while the presence of AH (i.e., between AH300 and AH0) can lead to about 1.65°C increase in temperature of the city. Thus, under such a high urbanization scenario, AH appears to have a stronger effect on the urban surface temperature.

Table 1: Values of UCM Parameters Prescribed for the Urban Land Use Category

| UCM parameter                                      | High intensity residence |
|----------------------------------------------------|--------------------------|
| Anthropogenic heat (diurnal maximum) (W m⁻²)       | 300.0                    |
| Building height (m)                                | 30                       |
| Urban fraction                                     | 0.9                      |
| Standard deviation of roof height (m)              | 4.0                      |
| Roof width (m)                                     | 9.4                      |
| Road width (m)                                     | 16.0                     |
| Surface albedo of road                             | 0.2                      |
| Surface albedo of roof                             | 0.2                      |
| Surface albedo of building wall                    | 0.2                      |
In addition to changes in the surface temperature, we have also examined the vertical temperature profiles (see Figure S2). The temperature difference between NO-URBAN and other two experiments is largest at the surface, with temperature anomaly of $\sim 0.3^\circ \text{C}$ (0.76°C) at 200 m for AH0 (AH300). Such warming due to either changes in surface properties or increased AH decreases with height, with the positive temperature difference between AH0 (AH300) and NO-URBAN vanishing at 0.6 km (1.4 km). It is obvious that the warming effect due to urbanization has limited vertical extent. On the other hand, at 800 m (1,600 m) altitude for AH0 (AH300), temperature is actually lower than that in the NO-URBAN experiment. The cooler temperature might be the result of the enhanced cloud fraction over the urban area, which leads to radiative cooling in the atmosphere. Further analysis revealed that the cloud fraction averaged over all layers increased more than 5% over most urban locations for AH0 (over whole urban area and some downstream locations for AH300) compared with NO-URBAN (see Figure S3).

### 3.2. Precipitation

In order to investigate the impact of urbanization on the occurrence of extreme rainfall characteristics, probability density functions (PDFs) of hourly precipitation rates over all urban grids for all rainfall events were considered. Figure 3(a) shows the rainfall PDF results for NO-URBAN, AH0, and AH300. Comparing AH300 with NO-URBAN, it is seen that the rainfall occurrence increases significantly for rain rates larger than 10 mm/h. AH0 also gives higher probability of heavy rainfall compared to NO-URBAN, but only with a small difference (no more than 20% for 10–100 mm/h). However, for hourly rainfall in the range of 60–110 mm/h, the frequency increases drastically by about 2.5–3 times due to both urban land cover and AH. In general, urbanization can significantly enhance the likelihood of heavy rainfall in the PRD region, mainly due to the AH effect. Also shown in Figure 3 is the ratio of probability of hourly rain rate in the PRD urban area in the range of 1–110 mm/h. It is clear that the impact of urbanization on heavy rainfall (50–110 mm/h) is stronger than that on light rainfall (1–20 mm/h). It can be inferred that, in the range of 1–100 mm/h, the likelihood of rain over urbanized locations, in comparison to cropland, increases as the
rainfall intensity increases, with the ratio between AH0 and NO-URBAN being 1–1.5 and that between AH300 and NO-URBAN being 1.25–3. Based on the Kolmogorov–Smirnov tests (see Figure S4), there are only a few locations in which the AH0 hourly rain rate in PRD is significantly different from that for NO-URBAN. On the other hand, PDFs of AH300 and NO-URBAN are distinct from each other (at the 95% confidence level) over most of the urban locations.

Figure 4 shows the mean precipitation difference between various numerical experiments, computed by averaging over entire integration periods for all selected extreme cases. Compared with NO-URBAN (see Figure 4(a)), accumulated rainfall increases slightly over the city area in the AH0 runs. Daily mean rainfall is enhanced by about 4–6 mm/day over the northeastern corner of the PRD megacity, but otherwise the difference is small (no more than 4 mm/day) over most other urban locations. Moreover, the intensity of rainfall decreases by about 4–12 mm/day in regions such as the eastern part of the urban PRD area. For the AH300 experiment, the averaged rain rate is increased by about 8–12 mm/day over most urban grids compared with NO-URBAN (see Figure 4(b)), with maximum increase of ∼20 mm/day in the northwestern part of the domain (near cities of Guangzhou and Foshan). The more intense precipitation over these city areas appear to be related to the strong warming at the same locations (see Figure 2(c)). In our model environment, stronger surface temperature warming related to urbanization tends to result in more rainfall within the PRD megacity. Indeed the aforementioned precipitation change due to land cover change only (AH0

Figure 3. (a) PDFs of hourly precipitation rates over urban locations within PRD, within the ranges of 1–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, 70–80, 80–90, 90–100, and 100–110 mm/h (denoted by 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110 mm/h, respectively) for the NO-URBAN (black), AH0 (blue), and AH300 (red) experiments. (b) Ratio of the probabilities between AH0 and NO-URBAN (blue) and that between AH300 and NO-URBAN (blue) at different precipitation rates. PDF, probability density function; PRD, Pearl River Delta.

Figure 4. Precipitation rate (units: mm/day) difference between (a) AH0 and NO-URBAN and (b) AH300 and NO-URBAN, averaged over entire integrations for all selected extreme cases.
vs. NO-URBAN) is insignificant, while that due to both urban land cover and AH is found to be statistically significant, passing the 95% significance level (see Figure S5).

The above suggests that urbanization can enhance rainfall intensity due to strong warming over the urban area. To further illustrate such a temperature effect, we have plotted the difference of 2-m temperature versus accumulated rainfall over urban grids between AH0 and NO-URBAN and also those between AH300 and NO-URBAN (see Figure S6). For AH0, surface warming and rainfall difference are weakly related, whereas a much stronger positive relationship between the two variables can be found for AH300 experiments. Very similar relationship can also be found between extreme precipitation and surface warming (with extreme rainfall defined as the 95th percentile of hourly rain rate throughout the integration periods of all cases considered). It also appears that, at some grid points, large increase of rainfall tends to be associated with small surface warming (see blue box in Figure S6(a)); further inspection shows that these grid boxes are located at the boundary of the urban area (see red grids in Figure S6(b)). It seems plausible that enhanced rainfall in these locations is the result of advection of more intense rainfall from the urbanized region in the domain.

3.3. Convective Instability and Moisture Transport

Physically, building materials such as cement and concrete have lower permeability to water vapor, leading to reduced evapotranspiration and less surface evaporation in the urban area compared to cropland (see Figure S7). To ascertain why the rainfall is still increased in the PRD megacity despite suppressed local evaporation, the atmospheric environment and the propensity of convection are further investigated. Figure 5 gives the convective available potential energy (CAPE) and convective inhibition (CIN) difference for parcels lifted at 1,000 m between AH0 and NO-URBAN and also between AH300 and NO-URBAN. For AH0 versus NO-URBAN (see Figure 5(a)), the change of CAPE is small (no more than 10 J/kg) in most locations. However, for the AH300 experiment, there is a strong increase of CAPE over the whole urban area compared to NO-URBAN (see Figure 5(b)), with difference greater than 70 J/kg over the northern part of the megacity. Change of CIN is weak (no more than 1.5 J/kg) when comparing AH0 with NO-URBAN (see Figure 5(c)). For AH300 minus NO-URBAN, CIN gives a strong decrease of more than 5 J/kg over the northeastern part of the urban area (see Figure 5(d)), while for other urban locations the decrease of CIN is about 3–5 J/kg. Stronger CAPE and lower CIN create a more unstable atmosphere and convection can be triggered more easily, both consistent with more intense precipitation over the urban area in AH300, compared with NO-URBAN. It can also be seen that the distribution of both CAPE and CIN difference between AH300 and NO-URBAN corresponds well with the distribution of the mean rainfall (see Figure 4(b)).

The vertical profile of the difference of CAPE and CIN averaged over the urban area was also examined (see Figure S8). Both AH0 and AH300 experiments give lower CAPE than NO-URBAN for parcel starting in low levels (lower than 600 m) in the urban area (see Figure S8(a)). This might be related to reduced water vapor content at these levels (see Figure 6), and the higher lapse rate of the virtual temperature for dry parcels. For the AH300 experiment, it can be inferred that CAPE is larger than NO-URBAN at altitudes higher than 600 m. Moreover, there is a decrease of CIN at all levels for either AH0 or AH300 compared with NO-URBAN (see Figure S8(b)). Therefore, it can be said that convection can be triggered more easily due to the presence of megacity with nonzero AH.

The vertical profile of specific humidity from various experiments and also their differences were also inspected. Figure 6 shows the southwest to northeast cross section of the difference of mean vertical wind vector and specific humidity over the PRD region between AH0 and NO-URBAN and also between AH300 and NO-URBAN. Both AH0 and AH300 still give more water vapor than NO-URBAN at higher altitudes, especially for the AH300 experiment. Specific humidity increases more than 0.3 g/kg from 0.6 km to 2 km in AH300, 0.1 g/kg at 4.2 km, and less than 0.1 g/kg at 15 km (see Figure 6(b)). Integrating over all levels in the urban area, there is more water vapor in the AH300 runs compared with NO-URBAN. Note that stronger vertical motion in the urban area was found in AH300, which can be attributed to higher CAPE and lower CIN. The increase of specific humidity in higher altitude for AH0, on the other hand, is not as significant as AH300, with no more than 0.1 g/kg from 0.2 km to 2.5 km. Also, the difference in the vertical velocity vector is noisier than that in AH300 (see Figure 6(a)).
To understand the increase of rainfall and its relationship with moisture transport, Figure 6 gives the vertically integrated difference of water vapor flux and its divergence between AH0 and NO-URBAN and also between AH300 and NO-URBAN. Difference of both moisture flux vector and divergence is weak between AH0 and NO-URBAN runs: there are even weak northwesterly anomalies over the ocean, which can be attributed to negative temperature difference above 800 m between AH0 and NO-URBAN results. But a southwest to northeast directed vector difference can be found in the AH300 minus NO-URBAN moisture flux, indicating stronger moisture transport from the ocean to the urban area. Moreover, stronger convergence is found almost over the whole urban area for AH300, this is especially in the northwestern and eastern urban locations, where the difference of moisture flux divergence can be more than −0.04 g/m²·s⁻¹ (see Figure 6(d)). According to the moisture budget equation:

\[
\overline{P} - E = -\frac{1}{g} \nabla \cdot \left( \frac{r_s}{r_t} q \overline{V} dp \right)
\]

the mean rainfall (\(P\)) equals the sum of surface evaporation (\(E\)) and vertically integrated moisture flux convergence. Though there is decrease of surface evaporation due to the presence of megacity, increased moisture flux convergence still leads to more rain over in the same region. Finally, we have also examined

Figure 5. Same as Figure 4 except for (a, b) CAPE (units: J/kg) and (c, d) CIN (units: J/kg). CAPE and CIN values are computed by averaging over entire integrations for all selected extreme cases, and for parcels rising at 1,000 m of height. CAPE, convective available potential energy; CIN, convective inhibition.
the relationship between the prevailing background wind direction and moisture transport. Figure S9 shows the low-level prevailing background wind direction, together with the vertically integrated moisture flux divergence between AH300 and NO-URBAN, for each case over the urban area. Here, the 950 hPa prevailing background wind directions are classified into four types (3 with northeasterly wind, 6 with easterly wind, 15 with southeasterly wind, and 2 with southerly wind). It can be seen that cases with a southerly wind component tend to be associated with stronger moisture flux convergence than those with northerly winds. The above suggests that the background prevailing wind also plays a role in determining the magnitude of the moisture flux convergence effect induced by urbanization.

4. Discussions and Summary

By utilizing the WRF-SLUCM, sensitivity of extreme precipitation to the level of urbanization described by land use and AH over PRD megacity region was assessed. Parallel experiments were designed by varying the value of surface AH flux (0 or 300 W m⁻² as diurnal maximum) and land use types (urban or cropland). As a result, under a highly urbanized scenario, the PRD mega city cluster had strong UHI effect, leading to a higher surface temperature, higher CAPE and lower CIN, and stronger vertical convection. Furthermore, both the intensity and frequency of extreme rainfall in the urban area for the AH300 experiment were increased significantly. The accumulated rainfall increased by more than 12 mm/day, and the probability for strong precipitation is enhanced by 20% at 10–20 mm/h⁻¹ to almost 250% at 90–100 mm/h⁻¹, when comparing AH300 with NO-URBAN. The above fits well with observations indicating that both the intensity and frequency of extreme rainfall have increased in the PRD mega city cluster area in recent years (J. Wang, Feng, et al., 2018); here, our results suggest that changes in these extreme rainfall...
characteristics can be rather sensitive to AH released in this region. Enhanced amount of precipitation was also found to be positively related to surface warming. Moreover, the ocean also plays a role in the increased precipitation. Though surface water vapor content was reduced over the urban area due to less surface evaporation, there was more water vapor supply from the South China Sea due to circulation induced by the strong UHI effect in AH300, compared to NO-URBAN, supporting even stronger extreme rainfall over the PRD megacity. On the other hand, though AH300 still have higher urban surface temperature than NO-URBAN, the change of both rainfall intensity and frequency was insignificant; changes in moisture transport and vertical convection in AH300 versus NO-URBAN were also weak. Overall, the comparison between AH300 and NO-URBAN experiment is consistent with results of Fung et al. (2021), who also utilized the WRF-SLUCM for dynamical downscaling and found that high AH can lead to stronger extreme rainfall.

Due to the limitation of SLUCM and lack of land use data when conducting these experiments, only one type of urban land cover was imposed, which gave urban land surface properties that were too homogeneous. With more refined urban use information, more heterogeneous distribution of urban parameters should be incorporated. In the future, we plan to adopt the WRF model coupled with a multiple-layer UCM, with more precise urban parameters in order to better capture the urban physics over the PRD region. We will also focus on urban effect on extreme rainfall under different weather system such as premonsoon period and rainfall induced by tropical cyclones.

Data Availability Statement

All raw data utilized in this study are publicly accessible in the following ways. The GFDL-ESM2M data were from this website-ftp://nomads.gfdl.noaa.gov/CMIP5/output1/NOAA-GFDL/GFDL-ESM2M/. The Weather research and forecasting (WRF) model V3.8.1 coupled with single-layer urban canopy model (SLUCM) was downloaded online (https://www2.mmm.ucar.edu/wrf/users/download/get_sources.html). ERA-Interim was from https://www.ecmwf.int/en/forecasts/datasets/. TRMM-3B42 rainfall estimate products are from https://doi.org/10.5067/TRMM/TMPA/3H/7. Variables from WRF model output are available on Zenodo (http://doi.org/10.5281/zenodo.4274053).

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