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Urbanization signatures in strong versus weak precipitation over the Pearl River Delta metropolitan regions of China

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Abstract

We assess the issues of urban effects on the precipitation over the Pearl River Delta (PRD) metropolitan regions of China. The spatial and temporal variations of strong versus weak precipitation over the PRD and surrounding nonurban areas are investigated. The results show that the urbanization signatures in strong precipitation are significantly different from those in weak precipitation over the urban areas. The PRD experiences more strong precipitation but less weak precipitation compared to surrounding nonurban regions. In addition, the strong precipitation over the PRD displays a pronounced seasonal variation. The seasonality of weak precipitation, however, is much weaker over the PRD compared to the surrounding nonurban regions. Moreover, a strengthening in the precipitation intensity, a reduction in the rainfall frequency and an increase in the convective precipitation as well as the afternoon precipitation are found over the urban areas, which are probably associated with the abundance in strong precipitation and the deficit in weak precipitation over the PRD.

Keywords: urbanization effects, precipitation, Pearl River Delta of China

1. Introduction

The Pearl River Delta (PRD), Zhu Jiang Delta or Zhusanjiao, in Guangdong province of China, is the low-lying area surrounding the Pearl River estuary where the Pearl River flows into the South China Sea. It is one the largest metropolitan regions in the world containing a total area of about 11 300 square kilometers and having a population over 52 million (Guangdong Statistical Bureau 2006, 2009). During the past three decades, as one of the major engines in propelling the rapid economic development of China, the PRD has experienced a rapid expansion of urban areas. Accompanying the urbanization is the rapid change in land surfaces. Satellite remote sensing has shown that there has been much more urban or built-up land and much less agricultural land over the PRD than in the surrounding areas for the last decade (Weng 2002, Seto et al 2002, Seto and Fragkias 2005).

The differences in land surfaces properties between the urban and surrounding rural areas have been proved to have significant effects on the local climate. A well-recognized phenomenon of the urban climate is the urban heat island (UHI; see the review by Collier 2006), characterized by a temperature contrast between a city and its surrounding rural areas. Recently, the influences of urbanization on the local precipitation are causing increasing concern. An
Intergovernmental Panel on Climate Change report (Trenberth et al. 2007) highlighted the growing body of research linking urban-related processes and regional precipitation. Increases in precipitation due to urban effects are typically observed at distances between 30 and 75 km from the city center (Landsberg 1970, Sanderson and Gorski 1978, Bornstein and Lin 2000, Shepherd et al. 2002, Shepherd 2006, Mote et al. 2007, Hand and Shepherd 2009, Halfon et al. 2009). Moreover, a number of recent studies (Hand and Shepherd 2009, Kishtawal et al. 2010, Tomohiko et al. 2011) have reported a significantly increasing trend in the frequency of heavy rainfall climatology over the urban regions. Compared with those for other metropolitan regions in the world, the urbanization effects of the PRD on precipitation are seldom investigated. On the basis of the observatory data for 1988–96, Kaufmann et al. (2007) suggested that urbanization in the Pearl River Delta of China has reduced local precipitation because of the changes in surface hydrology. Seto and Kaufmann (2009) further indicated that the reduction in precipitation induced by the urban land cover change over the PRD occurs mainly during the winter months. This finding differs from previous results concerning the enhancement of precipitation by the urbanization. Some other recent studies reported an increase in precipitation and severe thunderstorms over the Pearl River Delta (Meng et al. 2007, Zhang et al. 2009).

Despite the above-mentioned results providing evidence that convection and precipitation can be enhanced or initiated by urban regions, the urbanization effects of the PRD on the local precipitation still remain elusive.

It has become known from the synoptic theory that the mechanisms of strong precipitation are different from those of weak precipitation. For example, the strong (weak) precipitation is sensitive (insensitive) to the temperature lapse rate (Takemi 2010). Therefore, the urban effects on strong precipitation should be different from those on weak precipitation. However, the assessment of the urban effects on the extreme (strong or weak) precipitation has been lacking until now. Here we divide the precipitation into strong precipitation and weak precipitation to examine the urban effects on the local extreme precipitation.

The remainder of the paper is organized as follows. The data employed in this study and the background of the PRD are presented in section 2. Section 3 presents the results on the urbanization signatures in strong versus weak precipitation over the PRD. A summary is provided in section 4.

2. Data and the background of the Pearl River Delta

Given the historical scarcity and uneven distributions of in situ measurements over the PRD, data from the Tropical
Rainfall Measuring Mission (TRMM) satellite observations were employed to identify the urbanization signature in precipitation. The satellite rainfall estimates have been used to provide more uniform and continuous data for investigating the urbanization effects on precipitation (e.g., Shepherd et al. 2002). The major data sets used in this study are described as follows.


TRMM 3B42 version 6 provides high spatial (0.25° × 0.25°) and high temporal (3 h) precipitation data. These data are created by blending passive microwave data collected by the TRMM Microwave Imager (TMI), the Special Sensor Microwave Imager (SSM/I), the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E), the Advanced Microwave Sounding Unit B (AMSU-B), and the IR data collected by the International Constellation of Geosynchronous Earth Orbit (GEO), based on calibration with the precipitation estimate of the TMI–PR combined algorithm (Huffman et al. 1995, Huffman 1997). Although TRMM precipitation radar (PR) provides the most directly measured surface rainfall estimates for many application, the swath width of the PR is around 1/3 of the TMI swath width, resulting in significantly poorer sampling for many climate applications. Therefore, we choose 3B42 rather than the PR related data set in this study.

2.2. TRMM 3A12 monthly convective and stratiform precipitation (1998–2009)

In order to understand the convective and stratiform rainfall situations, TRMM TMI level-3 data set 3A12 is also used.
in this study. The 3A12 data set is an accumulation of the TRMM 2A12 TMI retrieval algorithm. This data set contains monthly mean values of the convective rainfall rate as well as the stratiform rainfall rate. The 2A12 algorithm used for this product is based on the technique of Kummerow et al. (2001).

Our study region is the Pearl River Delta (PRD), which is located in the southern Chinese province of Guangdong. The PRD is anchored by the cities of Guangzhou, Foshan, Jiangmen, Zhaoqing, Dongguan, Huizhou, Zhongshan, Zhuhai, Macao, Shenzhen and Hong Kong. The Pearl River Delta Region occupies the low-lying areas alongside the Pearl River estuary where the river flows into the South China Sea. It can be defined in geographic terms as a triangle with the eastward leg extending about 120 km from Guangzhou to Hong Kong and with a westward leg of about the same length from Guangzhou to Macao. The main metropolitan region of the PRD is located in (22.25°N–23.5°N, 112.25°E–114.5°E). Features of urbanization over the PRD are shown in figure 1.

The PRD has a dry season during a temperate winter and two rainy seasons (Ding and Wang 2008), the first rainy season (or pre-summer rainy season) occurring in April–June dominated by the mid-latitude weather systems, and the second rainy season (or post-flooding season) occurring in July–September dominated by the tropical weather systems. The dual-peak pattern of precipitation over South China is one of the most unique climate features over the sub-tropical East Asia monsoon regions (Ding 1994).

3. Results

In this study, ‘strong precipitation’ (‘weak precipitation’) refers to the precipitation with rain rates above (below) average in TRMM 3B42. Figure 2 shows the spatial distributions of strong precipitation and weak precipitation averaging from 1998 to 2009 based on TRMM 3B42. It is interesting to note that the spatial distributions of the strong precipitation are totally different from those of weak precipitation over the PRD. In cases of the strong precipitation (figure 2(a)), the high-value areas are located over the PRD, indicating that the PRD experiences much more strong precipitation compared to surrounding nonurban regions. In cases of the weak precipitation (figure 2(b)), however, the low-value areas are located in the PRD, suggesting that the PRD experiences much less weak precipitation compared to surrounding nonurban regions.

To see the long term variations of the strong and weak precipitation associated with the rapid urbanization over the
Figure 4. Time–longitude cross-section of the monthly mean strong precipitation (rain rates above average) (a) and weak precipitation (rain rates below average) (b) along the center longitude (23°N) of the PRD. The PRD metropolitan regions are located between 112.25°E and 114.5°E. Units: mm h⁻¹.

PRD, we do further investigation based on the rain gage data for Guangdong Province from 1968 to 2007. Figure 3 shows spatial distributions of heavy rainfall (≥50 mm day⁻¹) based on rain gage data for four periods: 1968–77, 1978–87, 1988–97, 1998–2007. Rapid urbanization has occurred over the PRD since the 1990s (figure not shown). It is seen from figure 3 that the heavy rainfall center of mid-northern Guangdong Province is getting closer to the PRD with the urban growth in this region. In cases of weak precipitation, there is a low-value center of light rainfall (≤10 mm day⁻¹) over the PRD during 1998–2007 (figure not shown). Analysis of the heavy rainfall cases also shows that the precipitation is significantly enhanced while the rain belts move to the PRD (figure not shown). Both the results based on TRMM and the rain gage data suggest that the urbanization effects of the PRD may result in an increase in strong precipitation and a decrease in weak precipitation over urban areas. This is in good agreement with results obtained from investigation of the urban areas over India by Kishtawal et al (2010). Many previous studies (Landsberg 1970, Sanderson and Gorski 1978, Bornstein and Lin 2000, Shepherd et al 2002, Shepherd 2006, Mote et al 2007, Hand and Shepherd 2009, Halfon et al 2009) have revealed that the increases in precipitation due to urban effects are typically observed in the downwind area at distances between 30 and 75 km from the city center. Dividing precipitation into two types, ‘strong’ and ‘weak’ precipitation, our results suggest that the maximum effects of urbanization on the strong and weak precipitation are felt on the central urban areas of the PRD. This finding differs from previous results based on the total precipitation.

To investigate the seasonal variations of strong and weak precipitation, we plot the time–longitude cross-section (figure 4) of monthly mean strong precipitation and weak precipitation along the center latitude (23°N) of the PRD.
Figure 5. Annual precipitation frequency (a) and precipitation intensity (b) averaging from 1998 to 2009 based on TRMM 3B42 data. The inset box shows the locations of the PRD metropolitan regions (22.25°N–23.5°N, 112.25°E–114.5°E). Units: times yr\(^{-1}\) for (a) and mm h\(^{-1}\) for (b).

It is of note in figure 4(a) that the strong precipitation displays a much more pronounced seasonal variation over the PRD compared to surrounding nonurban regions, with a strong maximum in April–June and a weak minimum in January–February. It is suggested that the urbanization effects on the strong precipitation of the PRD are most efficient during the pre-summer rainy season (April–June) which is dominated by the mid-latitude weather systems. During the post-flooding season which is dominated by the tropical weather systems, however, the urbanization signature in the strong precipitation is negligible. In cases of weak precipitation, the seasonal variation is much weaker over the PRD compared to the surrounding nonurban regions (figure 4(b)). The mechanism involved needs further investigation.

Precipitation frequency and intensity are important factors related to the strong and weak precipitation. Figure 5 shows the annual precipitation frequency and precipitation intensity averaging from 1998 to 2009 based on TRMM 3B42 data. Here, the annual precipitation frequency is defined as the annual number of precipitation times in TRMM 3B42; the precipitation intensity is obtained through dividing the annual total precipitation by the precipitation times in TRMM 3B42. It is noted in figure 5(a) that the annual precipitation frequency over the PRD is substantially lower than for the surrounding nonurban area, suggesting that the urbanization effects of the PRD may lead to less frequent precipitation occurrence over the urban areas. On the other hand, the precipitation intensity is much stronger over the PRD compared to the surrounding nonurban areas (figure 5(b)). Therefore, the abundance in strong precipitation and the deficit in weak precipitation over the PRD are probably associated with the reduction in rainfall frequency and the strengthening in precipitation intensity over the urban areas.
As revealed by the basic synoptic theory, the strong precipitation generally originates from convective clouds, while the weak precipitation is usually related to stratiform clouds. To see whether there are any differences between the convective and stratiform precipitations over the PRD, we plotted the spatial distributions of convective precipitation and stratiform precipitation on the basis of TRMM 3A12 (figure 6). It is noted in figure 6 that there are high-value areas of convective precipitation over the PRD (figure 6(a)). Another significant area of convective precipitation west of the PRD box is associated with the Yunkai Mountains (1274 m). However, the stratiform precipitation (figure 6(b)) over the PRD is almost the same as for the surrounding nonurban areas. It is suggested that the urbanization effect of the PRD seems to significantly enhance the convective rainfall rather than the stratiform rainfall, which is also associated with the increase in strong precipitation over the PRD. A number of previous studies (e.g., Stallins and Bentley 2006, Rose et al 2008, Shem and Shepherd 2009) were conducted and emphasized the urban effects on lightning or thunderstorms. They concluded that urbanization may result in an enhancement of lightning or thunderstorms. Lightning or thunderstorms and convective precipitation originate from the same initial convective and microphysical processes. Therefore, our results concerning the increase in the convective precipitation over the PRD are reasonable.

Recent studies have shown that the diurnal rainfall pattern is strongly modulated by the effects of urbanization (Burian and Shepherd 2005, Mote et al 2007). To see more aspects of the precipitation variability related to the increase in strong precipitation and decrease in weak precipitation over the PRD, we investigated the diurnal variations of the precipitation over these regions. Figure 7 shows the diurnal variations of precipitation along center longitude (113.0°E) and center latitude (23°N) of the PRD based on the TRMM 3B42 data for 1998–2009. It is noted in figure 7 that there are substantial

![Figure 6. Spatial distributions of convective rainfall (a) and stratiform rainfall (b) from TRMM 3A12 for 1998–2009. Units: mm h⁻¹. The inset box shows the locations of the PRD metropolitan regions (22.25°–23.5°N, 112.25°–114.5°E). Units: mm h⁻¹.](image-url)
Figure 7. Diurnal variations of precipitation along the center longitude (113.0°E) (a) and latitude (23°N) (b) of the PRD during 1998–2009 based on TRMM 3B42 data. The PRD metropolitan regions are located in (22.25°N–23.5°N, 112.25°E–114.5°E). Units: mm h⁻¹.

differences in the precipitation diurnal variations between the PRD and surrounding nonurban areas. The afternoon precipitation is much more pronounced over the PRD than the surrounding nonurban areas, which is conducive to the increase in strong precipitation over the urban areas.

4. Summary

Taking into account the differences of the mechanisms between strong and weak precipitation, we assess the issue of the urbanization effects of the PRD on the local precipitation by dividing the precipitation into two types: strong precipitation and weak precipitation. Interestingly, the spatial and temporal variations of strong precipitation are significantly different from those of weak precipitation over the PRD. The PRD experiences more strong precipitation and less weak precipitation compared to the surrounding nonurban regions. The strong precipitation over the PRD displays a pronounced seasonal variation, with a strong maximum in April–June and a weak minimum in January–February. The seasonality of weak precipitation is much weaker over the PRD compared to the surrounding nonurban regions.

The abundance in strong precipitation and the deficit in weak precipitation over the PRD are associated with the other precipitation features over the urban areas. The precipitation frequency over the PRD is substantially lower than for the surrounding nonurban area, suggesting that the urbanization effects of the PRD may lead to less frequent precipitation occurrence over the urban areas. On the other hand, the precipitation intensity is much stronger over the
PRD compared to the surrounding nonurban areas. Moreover, there are substantial differences in the precipitation diurnal variations between the PRD and surrounding nonurban areas. The afternoon precipitation and the convective precipitation are much more pronounced over the PRD than the surrounding nonurban areas.

As shown in other studies, the urbanization not only modifies the exchange of heat, water and momentum between the land surface and overlying atmosphere (Crutzen 2004) but also changes the composition of the atmosphere over urban areas (Pataki et al. 2003). Which are the dominant factors causing the local precipitation anomalies over urban areas? The evidence provided in this paper concerning the abundance in strong precipitation and the deficit in weak precipitation over the urban areas may highlight the studies of the related mechanisms as regards the urban environment’s impact (land use, aerosols, thermal properties) on precipitation.

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