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Observational evidence of a long-term increase in precipitation due to urbanization effects and its implications for sustainable urban living

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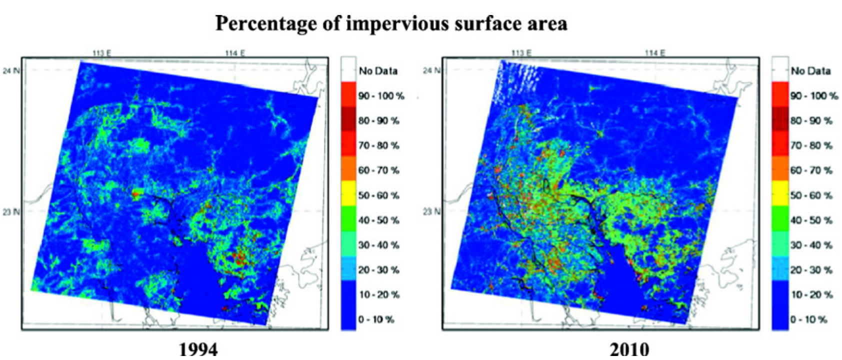
HIGHLIGHTS

- Analysed a ten-year precipitation dataset for a megacity and nearby stations
- Remote sensing techniques revealed rapid urbanization at the megacity.
- Significant increasing trend of precipitation existed only at the megacity station.
- Urbanization-induced increase is higher than that from the future climate change.
- Findings have implication to coastal defenses, disease spread and heat stress.

GRAPHICAL ABSTRACT



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ABSTRACT

Although projected precipitation increases in East Asia due to future climate change have aroused concern, less attention has been paid by the scientific community and public to the potential long-term increase in precipitation due to rapid urbanization. A ten-year precipitation dataset was analysed for both a rapidly urbanized megacity and nearby suburban/rural stations in southern China. Rapid urbanization in the megacity was evident from satellite observations. A statistically significant, long-term, increasing trend of precipitation existed only at the megacity station (45.6 mm per decade) and not at the other stations. The increase was attributed to thermal and dynamical modifications of the tropospheric boundary layer related to urbanization, which was confirmed by the results of our WRF-SLUCM simulations. The results also suggested that a long-term regional increase in precipitation, caused by greenhouse gas-induced climate change, for instance, was not evident within the study period. The urbanization-induced increase was found to be higher than the precipitation increase (18.3 mm per decade) expected from future climate change. The direct climate impacts due to rapid urbanization is highlighted with strong implications for urban sustainable development and the planning of effective adaptation strategies for issues such as coastal defenses, mosquito-borne disease spread and heat stress mortality.

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1. Introduction

A median increase of precipitation of 9% in East Asia by the end of the 21st century is projected under the A1B scenario due to greenhouse gas-induced climate change (IPCC, 2007). Although this has aroused many discussions among the scientific community and the public, much less attention has been paid to changes in precipitation due to urbanization effects, and there has been little quantification of these effects. Globally, 54% of the population lived in urban areas in 2014, compared with 30% in 1950, and this population is projected to increase to 66% in 2050 (UN, 2015). Developing countries, such as those in Latin America and Africa, have undergone the process of rapid urban growth or are on the path towards it. A better understanding of the urbanization effects on the environment is required (van Ginkel, 2008). Urbanization replaces forests with buildings and roads and reduces the evaporation (and thus cooling) at the surface. Tall buildings reduce the ventilation rate and trap the heat within urban areas (Arnfield, 2003). These factors, as well as anthropogenic heating (Quah and Roth, 2012), cause urban heat island (UHI) effects in many mega-cities in the world. In China, land use/cover change and human activities were attributed to be the primary reason for the rising temperatures in Jiangsu Province (Huang et al., 2015). Since the 1970s, the enhancement of precipitation intensity has been linked to urbanization effects (METROMEX, 1974; Changnon, 1979). City (i) acts as the warm center to increase unstable air masses and (ii) increases the surface roughness to enhance surface convergence, which both mechanisms enhance the convection over and downwind of the city center (Hjelmfelt, 1982; Lin et al., 2008a). By analysis of six precipitation events, Bornstein and Lin (2000) showed that the UHI induced a convergence zone that initiated convective activities over and immediately downwind of Atlanta, Georgia, U.S.A. The findings were further supported by a study based on 5-year data on land-use, radar reflectivity, surface meteorological data and upper-air soundings (Dixon and Mote, 2003). The impacts on strong vertical convection were also reflected by lightning activities. Naccarato et al. (2003) reported an enhancement of 60–100% in the cloud-to-ground lightning flash density over Brazilian urban areas compared to their surroundings. Numerical model simulations (Hjelmfelt, 1982; Lin et al., 2008a; Zhong and Yang, 2015) are consistent with the anomalies found from observational studies. For example, sensitivity tests of the MM5 meso-scale model suggested that UHI perturbed thermal and dynamic processes at the atmospheric boundary layer and affected the location of precipitation over the western plain of Taiwan. Precipitation over the upwind area was also enhanced (Lin et al., 2008a) by the increasing size of the urban area. However, the above-mentioned studies mainly focused on short-term events.

The Pearl River Delta (PRD) is one of the rapidly developing areas in southern China. Urban area in the PRD was expanded from 0.5% to 12.9% from 1993 to 2004. Guangzhou, located in the PRD, is one of the largest megacities in China, along with Beijing and Shanghai, and has a population of approximately 25 M. The relationships between UHIs and land-use/land-cover changes in the PRD have been studied (Chen et al., 2006). They reported the percent of built-up area increased from 6.09% in 1990 to 13.08% in 2000, while the percent of cropland decreased from 42.23% to 21.48% for the same time span. Based on our simulations, precipitation increased 15% over urban and leeward areas in summer due to the urbanization of the Yangtze River Delta in eastern China (Zhang et al., 2010). In this study we attempted to provide, for the first time, observational evidence of long-term urbanization-induced enhancement of precipitation (UIEP). We first compared satellite products of surface temperatures between 1994 and 2010 to provide support for the existence of a UHI and urbanization over the Guangzhou megacity. Then, a 10-year daily precipitation dataset (1997–2006, covering a period of high urbanization rate in the Guangzhou megacity) of rain gauge measurements in and near the PRD was analysed to study the long-term urbanization effects on precipitation. The Weather Research and Forecasting (WRF) model, detailed later, was used to perform numerical experiments to confirm the UIEP by simulations of typical precipitation events in summer. Finally, because the effects could become more significant in the future (Pielke et al., 2007), implications of the effects on sustainable urban planning were discussed.

2. Data and methodology

2.1. Satellite products

The large spatial coverage of satellite images makes them advantageous for detecting UHIs, which are city-scale phenomena. Land surface temperature (T_s) derived from the satellite images has been used in many urbanization and UHI studies (Balling and Brazel, 1988; Dousset and Gourmelon, 2003; Nichol et al., 2009). Two Landsat images were acquired at 10:30 am (local time) on October 24, 1994 and October 28, 2010. The land surface temperature products at 30 m resolution were derived using the emissivity modulation method (Nichol, 2009) with correction of the emissivity of the original thermal channel using land use and land cover data.

The trend of urbanization in terms of the impervious surface area (ISA) was also evaluated to understand the land use change during the urban development. The impervious surface is the built environments, such as building, road and infrastructure, which can be an indicator of urbanization and related to urban heat island effects and regional energy balances (Sawaya, 2003). The ISA products currently presented were those being post-processed from the mentioned Landsat images. Following the study of Wu and Murray (2003), the ISA was calculated based on the result of land use classification (i.e., building, bare land, vegetation and water categories) within a specific area. The spatial distribution of ISA is generated from 5 by 5 pixels of window size all over the study area.

2.2. Surface precipitation measurements

The 10-year (1997–2006) surface daily precipitation measurements at various locations at and near the PRD were used to study if the urbanization had long-term effects on the precipitation amount. Rain-gauge measurements at Guangzhou (GZ; 23.1°N, 113.3°E), Fogang (FG; 23.8°N, 113.5°E), Lianpin (LP; 24.4°N, 114.5°E), Naxiong (NX; 24.9°N, 114.2°E) and Shaogua (SG; 24.7°N, 113.5°E) (Supplementary information Fig. S1) were used. The ISA is >80% for station GZ and are in the range of 0–30% for the rest of the stations. Guangzhou is a typical megacity in China, and the GZ urban station located near the Guangzhou metropolis is suitable for studying urbanization effects. Other stations near the Guangzhou metropolis are suburban or rural in nature and acted as controls to detect if any long-term, regional effects on precipitation occurred. To the south of the Guangzhou metropolis is the coastal line facing towards the South China Sea and the PRD (Fig. 1).

2.3. Trend analysis

The precipitation data at each selected station were first tested for trend significance by the well-known Mann-Kendall (M-K) test, which has been employed in trend investigations of precipitation and other environmental variables (Brunetti et al., 2001; Joshi and Pandey, 2011; Ziv et al., 2013). Details of the test have been described, for example, in Gilbert (1987) and the quoted references, and thus are not repeated here. Briefly, the M-K test computes the S- and Z-statistics to test a null hypothesis of no trend and an alternative hypothesis of the existence of a trend. We tested the null hypothesis at the 95% confidence level. Linear least-square regression was then used to quantify the trend magnitude when the trend at a station was determined to be statistically significant. Linear regression is a popular method for trend-magnitude studies (Liebmann et al., 2004; Groisman et al., 2005; Knowles et al., 2006 and refer to the three references mentioned above).