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Modeling the relationship between the urban development and subsurface warming in seven Asian megacities

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ABSTRACT

The authors used a mesoscale climate model, CSU-MM and digital land-use data from seven Asian megacities to simulate ground surface temperature (T_{sfc}) related to urbanization for three discrete years of the 20th century. The variability of T_{sfc} was compared with the measured vertical profiles of subsurface temperature in the targeted megacities, which were expected to record the historical time-series of T_{sfc}. Considering a calm and clear day of the hottest season, results showed that T_{sfc} increased about 1.1 K 100 y^{-1} during the 20th century. Considering the seasonal climate variability, simulations were run for three additional cases (rainy day in the hottest season; clear day and rainy day in the coldest or rainy season) for each year in each megacity. The difference between the rates of change of T_{sfc} in Bangkok (0.9 K 100 y^{-1}) and Tokyo (1.9 K 100 y^{-1}) is considerable, which suggests that the differences of annual climatic variability are important for the analyses of urban subsurface warming. The authors conclude historical digital land-use data are useful to study past urban climate change in numerical simulation, and difference of annual climatic variability brings the difference of subsurface warming in each megacity.

1. Introduction

1.1. Problem presentation

About 120 years have passed since meteorological observations began in Asia; since then, researchers have used a variety of methods to reconstruct the climate of earlier times. One such method has been to use notations about weather in ancient documents and journals. Since the early modern times, the Japanese have left many usable records, and, although these are mostly qualitative accounts, researchers have learned how hot in summer, or how cold in winter, it was in the past. Although the information collected from these documents contains many temporal and spatial gaps, recent advances in computerized meteorological modeling have made it possible to compute local distributions of climatologic parameters; for example, the distribution of surface air temperature (T_a) is determinable if the surface boundary conditions, like the land-use distributions, are known (Ichinose, Shimodozono, & Hanaki, 1999; Kimura and Takahashi, 1991). Ichinose (2003) used numerical simulations with a mesoscale climate model referenced to digital land-use data (2 km grid) covering all of Japan to attempt to isolate the influence on T_a of regional warming related to land-use change during a recent 135-year period. During this period, areas of regional warming related to changes of land use expanded around Tokyo and Osaka. However, validation of the results of this study was difficult because of the limited amount of available data on long-term climate fluctuations.

To validate the results of modeling such as that of Ichinose (2003), observed climatologic data (e.g., air temperature) are needed to provide initial values for the modeling. The network of weather stations and other observation facilities that has been established throughout Japan since 1876 provides long-term temperature fluctuations to the present day. Data for Tokyo in particular have often been used to associate changes in urban climate in conjunction with urbanization (Yoshino, 1990/1991). Many instances of global warming (Jones, 1988) and changes of air temperature due to the regional climate change have been identified over broader areas and longer periods than those caused by local land-use changes (Maejima et al., 1980); comparing these to modeled temporal changes in air temperatures may elucidate the contribution of land-use change to climate change in Japan. Comparisons like this will also help to overcome the problem of temporal and spatial discontinuity in historical climatologic information.

Another reason such research is important in Japan is that

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urbanization in large Japanese cities has increased local air temperatures by about 1 °C during the latest century (Fujibe, 1995). Until now researchers have relied on statistical methods to distinguish between the influence on air temperature of localized warming caused by urbanization, and the influence of global warming and other broader scale changes of air temperature (Kato, 1996). Of course, such methods cannot be applied to regions or time periods for which there are no observed data. Much pioneering research has eliminated the influence of urbanization as noise when estimating temperature changes over large areas (Kukla, Gavin, & Karl, 1986). Use of a mesoscale model with past land-use distributions as surface boundary conditions to simulate past climatologic parameters (e.g., air temperature distributions) might help to distinguish the influence of localized warming due to urbanization from that of global warming and regional-scale (e.g. Far East Region, Eastern Asia, Japan and Chinese Coastal Area etc.) fluctuations of air temperature for regions and time periods lacking observed data (Ichinose, 2003). Certainly, the mesoscale and urban-scale meteorological model have been widely used in other studies, such as Kusaka et al. (2012) and Doan, Kusaka and Ho (2016), which created the Weather Research and Forecasting Model (WRF) to examine the phenomena of urban climate in different scales. This WRF is one of the newest models as so far, powered by the super computer technology. However, Kusaka's model still needs to be improved especially on the respect of human activity affect and urban concentration, which the authors are focusing on.

Case studies of the area around the upper reaches of the Rhine River as it was in 1710 (Lenz, 1996) and of the Edo area (Tokyo was called "Edo" until the middle of the 19th century) during the first half of the 19th century (Ichinose, 2003) are examples of attempts to quantify the influence of urbanization-induced changes in the surface heat budget on surface air temperatures, as opposed to research from a historical climatology perspective. These researchers derived land-use distributions for the periods they studied from historical maps and other historical sources. Because the periods they studied pre-date the keeping of meteorological records, comparisons with observed meteorological data are not possible. The results of a similar study by Kusaka, Kimura, Hirakuchi, & Mizutori (2000) in the Tokyo region (the Kanto Plain) for c. 1985, c. 1950, and c. 1900 agree well with those of Ichinose (2003).

1.2. Research background and purpose

Because subsurface temperatures are affected by surface warming (heat of the ground level is conducted downwardly), the vertical profile of subsurface temperature obtained from boreholes can be used to determine past ground surface temperatures (T_{sfc}) (Huang, Pollack, & Shen, 2000; Lewis, 1992; Pollack, Huang, & Shen, 1998). Such depth profiles preserve past temperature gradients, which can be used in the reconstruction of past climate (Cermak, 1971; Lanchenbruch & Marshall, 1986; Pollack & Chapman, 1993; Pollack & Huang, 2000; Taniguchi, Shimada, & Uemura, 2003; Wang, 1992). Past ground surface temperatures derived from subsurface temperature profiles for four Asian cities over the last 100 years agree with air temperature records in those cities (Taniguchi, Uemura, & Jago-on, 2007). Subsurface temperature profiles can also provide important information for separating the effects of urbanization and global warming on groundwater systems.

Agreement of past values of T_{sfc} computed in the time periods of meteorological observations with T_{sfc} estimated for the same period from vertical profiles of subsurface temperature supports the validity of numerical simulations applied to periods before the start of meteorological observations based on the theory suggested by Huang et al. (2000). Moreover, when T_{sfc} during pre-observation periods is reconstructed from vertical profiles of subsurface temperature, estimation of the past annual average surface air temperature (T_a) is possible, because the main cause of variability of T_a (apart from air mass advection) is variability of T_{sfc} due to heat exchange at the ground surface (Huang et al., 2000). "Vertical profile of borehole temperatures" is the only available (observable) data to evaluate the (effect of) past T_{sfc}. Therefore, observing it is the best way for estimating the behavior of the past T_{sfc}. The authors assume that delta T_{sfc} (i.e. warming) between targeted two stages and the subsurface warming (expected from vertical profile of borehole temperatures) has a proportional relationship. Therefore, the authors regard that T_{sfc} represents the subsurface warming. In this model, computed T_{sfc} is defined at the center depth of the primary subsurface grid (vertical size: 1 cm), so the temperature at 0.5 cm below the ground surface is computed and given as this T_{sfc}. Increases of surface air temperature are not as strong as those of ground surface temperature derived from subsurface temperature profiles, because heat conduction in the subsurface is much slower than heat convection in the air above the ground surface (Huang, Taniguchi, Yamano, & Wang, 2009).

The "heat island effect" due to urbanization has contaminated the subsurface thermal regime in many cities (Miyakoshi, Hayashi, Monyrath, Lubis, & Sakura, 2009; Taniguchi et al., 2003). Safanda, Rajver, Correia and Dedecek (2007) attributed a peculiar increase in subsurface temperature at a monitoring station in Prague to recent surface construction near the station. Taniguchi, Burnett and Ness (2009a) and Taniguchi, Shimada, Fukuda, Yamano, Onodera et al. (2009a) described subsurface temperature anomalies caused by the heat island effect on the basis of measured vertical profiles of subsurface temperature in Asia. Taniguchi and Uemura (2005) analyzed borehole temperature profiles in the Osaka area and inferred from the shape of the profiles that the magnitude of recent surface warming was much larger in the city center than in suburban Osaka. Taniguchi, Shimada, Fukuda, Yamano, Onodera et al. (2009b) showed that the heat island effect on subsurface thermal regimes in urban areas in Asia decreases exponentially with distance from the city center.

Certainly, unlike this study, closely related works on urban subsurface (i.e. ground surface) temperature and groundwater temperature which are not modeled but correlated from remotely sensed maps (e.g. Zhan et al., 2014, Benz, Bayer, Goettsche, Olesen, & Blum, 2016) are present, as well as recent work on long-term evolution of subsurface urban heat islands based on observed data (Menberg, Blum, Schaffitel, & Bayer, 2013). Zhan et al. (2014) and Benz et al. (2016) examined the urban subsurface temperature and groundwater temperature by using the remote sensing approach. However, these studies cannot prove a reference of revealing the historical changing of the urban climate (including urban subsurface temperature), because the previous remote sensing data is impossible to obtain before the launch of satellite. Unlike these studies, the authors are focusing on both the past T_{sfc} of 100 years ago and the current one, in order to clarify the relationship between the urban development and subsurface warming in seven Asian megacities based on the numerical simulation of urban climate, considering the land-use data in these megacities for three discrete years of the 20th century.

In this study, the authors used the Colorado State University Mesoscale Model (CSU-MM) (Pielke, 1974; Ichinose, 2003) and digital land-use data (2 km grid) from seven Asian megacities (Seoul, Tokyo, Osaka, Taipei, Bangkok, Manila, and Jakarta) to simulate T_{sfc} for three discrete years of the 20th century. As mentioned in Section 1.1, this paper used this CSU-MM for the mesoscale urban simulation instead of the WRF model, because using the CSU-MM is enough for the computing of this paper and the purpose has been realized successfully. The land-use data (Fig. 1) were established by Research Institute for Humanity and Nature (RIHN). Moreover, Taniguchi, Burnett and Ness (2009b) used these data for the project of "Human Impacts on Urban Subsurface Environments". Then, same data were used by this paper in numerical simulations of urban subsurface warming related to recent urbanization in the seven cities in a project for which borehole temperatures were logged in the cities and surrounding areas. Taniguchi, Burnett and Ness (2009b) recognized the effects of recent surface warming in the shapes of most of the temperature profiles obtained, and