

Combined Effects of Urbanization and Global Warming on Subsurface Temperature in Four Asian Cities

Makoto Taniguchi,* Takeshi Uemura, and Karen Jago-on

Subsurface temperature profiles measured in boreholes can be analyzed to infer depths of thermal disturbance and associated surface warming due to combined global warming and urbanization (heat island effects). Asian cities are extremely vulnerable because of rapid increases in population. Average subsurface temperature profiles in four Asian cities (Tokyo, Osaka, Seoul, and Bangkok) were compared and analyzed to evaluate the effects of surface warming. The magnitude of surface warming is largest in Tokyo (2.8°C), followed by Seoul (2.5°C), Osaka (2.2°C), and Bangkok (1.8°C). Comparisons between analytical solutions and observations show that the mean depth of deviation from the regional geothermal gradient in each urban area may be one of the indicators of the history of urbanization in each city. The mean depth of deviation from the steady thermal gradient, which is approximately 140 m in Tokyo, 80 m in Osaka, and 50 m in Seoul and Bangkok, indicates the time from the start of the additional heat from urbanization. These results agree qualitatively with air temperature records in the cities during the last 100 yr. The heat island effect on subsurface temperature is an important global groundwater quality issue because it may alter the groundwater systems chemically and microbiologically. Measurement of subsurface temperature data provides important information for understanding the joint effects of urbanization and global warming on groundwater systems.

While global warming is considered a serious environmental issue, discussion of the phenomena has been limited primarily to issues above the ground or near the ground surface. However, subsurface temperatures are also affected by surface warming (Huang et al., 2000). In addition, the “heat island effect” due to urbanization creates subsurface thermal anomalies in many cities (Taniguchi et al., 2003). The combined effects of urbanization and global warming may reach more than 100 m below the surface and can have potential consequences on groundwater systems. The effect of heat islands on subsurface temperature is a global groundwater quality issue because increased subsurface temperature alters groundwater systems chemically and microbiologically through geochemical and geobiological reactions (Knorr et al., 2005) that are temperature sensitive, which may increase degradation of groundwater resources. This has been identified by the UNESCO-GRAPHIC (Groundwater Resources under the Pressures of

Humanity and Climate Change) project as an important groundwater quality issue.

Subsurface temperature is used to reconstruct past climate change because the signature of changes in ground surface temperature is preserved in the subsurface thermal regime (Birch, 1948; Lachenbruch and Marshall, 1986; Beck, 1982; Chapman and Harris, 1993; Beltrami et al., 1995; Bodri and Cermak, 1998; Harris and Chapman, 1997; Pollack et al., 1998; Huang et al., 2000; Taniguchi et al., 2003). Recent air temperature in cities has increased from global warming and heat island effects due to urbanization. Studies on the effects of heat from urban areas on subsurface temperature are limited but have been done in some urbanized areas in Europe (Bodri and Cermak, 1999) and in Asia (Okubo et al., 2003). Other studies on the effects of surface warming due to urbanization are limited to studies within local areas (Ferguson and Woodbury, 2004). No comparison has been undertaken on the regional level, such as in the Asian region, to evaluate the magnitude of urban warming (heat island) using subsurface temperatures. Analyses of the timing of the start of urbanization using subsurface temperature data are also limited.

The objectives of this study are to evaluate the combined effects of urbanization and global warming on subsurface temperature in four cities in Asia and to describe the development of heat islands due to urbanization using subsurface temperature data. This paper illustrates the concept of relating groundwater temperatures to surface warming by averaging borehole profile temperatures within each city, thereby avoiding more detailed

M. Taniguchi and K. Jago-on, Research Institute for Humanity and Nature, Kyoto 603-8047, Japan; T. Uemura, The Graduate Univ. for Advanced Studies, Kanagawa 240-0193, Japan. Received 5 July 2006. *Corresponding author (makoto@chikyu.ac.jp).

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analyses of individual temperature profiles resulting from localized recharge and discharge zones.

Study Areas and Methods

The study areas are four cities in Asia: Tokyo, Osaka, Bangkok, and Seoul (Fig. 1). The topography in Asian coastal cities is characterized by alluvial plain, terraces, and hills. Surface geology at coastal cities (Tokyo, Osaka, and Bangkok) consists of an alluvium underlain by marine formation comprising the main unconfined and confined aquifers. Only Seoul has a different aquifer geology, composed mainly of basement of the Precambrian gneisses, Jurassic granitoids intrusions, and overlying thin alluvium and soils. The hydrogeology of the basin underlying these cities is detailed in Taniguchi et al. (1999) for Tokyo, Taniguchi and Uemura (2005) for Osaka, Sanford and Buapeng (1996) for Bangkok, and Okubo et al. (2003) for Seoul.

Borehole temperatures were measured at 1-m depth intervals in 29 boreholes in Tokyo from November to December 1992 (Dapaah-Siakwan and Kayane, 1995), in 37 boreholes in Osaka from August to November 2003 (Taniguchi and Uemura, 2005), in 13 boreholes in Bangkok in June 2006 (this study), and in 15 boreholes in Seoul from July 1991 to July 2002 (H.C. Kim, personal communication, 2006). Thermistor thermometers, which can read temperature at 0.01°C resolution with an accuracy of 0.05°C, were used for these measurements. The boreholes are located throughout each basin, which includes groundwater recharge and discharge areas. The diameter and depth of the boreholes in Tokyo are 8 to 20 cm (mostly 15 cm) and 126 to 450 m (mostly 200–300 m), respectively. Well diameters in Osaka are 10 to 40 cm (mostly 20 cm), and the depths range from 47 to 465 m (mostly 60 to 200 m). The depths of the boreholes in Bangkok and Seoul are 55 to 437 m and 498 to 968 m, respectively. The diameter of these boreholes is mostly between 10 and 30 cm. Therefore, no thermal free convection is expected (Taniguchi et al., 1999). The logged boreholes were drilled and cased mostly before the 1980s. Thus, the water temperatures in boreholes represent the temperature of groundwater surrounding the boreholes.

To infer the effects of global warming and urbanization in the temperature-depth profiles for each city, a presumably representative linear temperature depth profile was estimated. We refer to this profile as the geothermal gradient but acknowledge that the geothermal gradient at each city may be disturbed. The geothermal gradient was constructed by closely fitting (approaching) the temperature–depth trend obtained by averaging of the temperature–depth logs available for each city at a relatively large depth, where the trend becomes essentially linear. The extrapolated surface temperatures for the inferred geothermal

gradients all are higher than “old” air temperatures in the cities, which is largely consistent with the general observation that ground surface temperatures tend to be somewhat higher than air temperature.

To analyze the temperature–depth profiles, subsurface temperatures have been calculated using a heat advection due to groundwater flow and heat conduction equation. Carslaw and Jaeger (1959) obtained the analytical solution for subsurface temperature using a one-dimensional heat conduction–advection equation under the condition of a linear increase in surface temperature with time as

$$T(z,t) = T_0 + a(z - Ut) + \left(\frac{b + aU}{2U} \right) \left[(z + Ut)e^{Uz/k} \operatorname{erfc} \left(\frac{z + Ut}{2\sqrt{kt}} \right) + (Ut - z) \operatorname{erfc} \left(\frac{z - Ut}{2\sqrt{kt}} \right) \right] \quad [1]$$

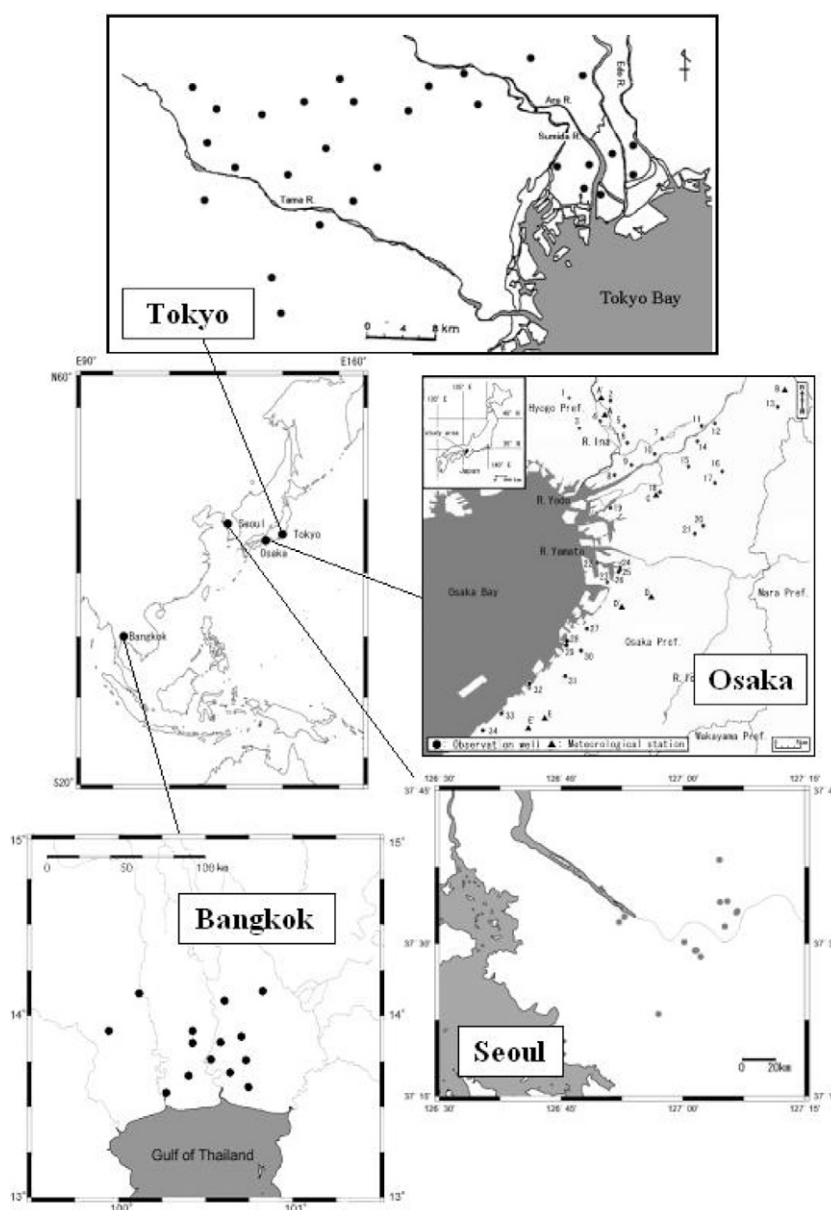


FIG. 1. Locations of the urban study areas and boreholes for subsurface temperature measurements.

where b is the rate of increase in surface temperature, t is the time after semi-equilibrium condition (Taniguchi et al., 1999), T_0 is the surface temperature, a is the mean geothermal gradient, and $U = \nu c_0 \rho_0 / c\phi$ in which ν is the vertical groundwater flux (Darcy's velocity), $c_0 \rho_0$ is the heat capacity of the water, and $c\phi$ is the heat capacity of the aquifer. The modeling is limited to semi-infinite layers with only vertical conduction and convection, and vertical groundwater flux is assumed to be constant with depth. This assumption may be a bit too simplistic, but the first-order effect of surface warming on the average subsurface temperature can be discussed semiquantitatively. Setting parameters as $T_0 = 13^\circ\text{C}$, $k = 6.0 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$, $a = 0.022^\circ\text{C m}^{-1}$, and $U = 0.0001 \text{ m yr}^{-1}$ (negligible groundwater flow), temperature–depth profiles are computed using Eq. [1]. Sensitivities of the analytical Eq. [1] are discussed in Taniguchi et al. (1999).

Results

Subsurface Temperature in Asian Cities

All temperature–depth profiles observed in the four cities are shown in Fig. 2–5. There is huge variability among individual temperature profiles in each city. Some are affected by groundwater pumping (Taniguchi et al., 1999). The effect of regional groundwater flow is another cause for the huge variability between the temperature profiles. In the absence of surface temperature change, vertical groundwater flow modifies the linearity of the geothermal gradient, where a convex upward temperature depth profile tends to reflect downward and a concave upward profile upward groundwater flow, respectively (Domenico and Palciauskas, 1973). Subsurface temperatures are cooler in recharge areas and warmer in discharge areas (Taniguchi et al., 1999; Taniguchi and Uemura, 2005). Previous studies (Taniguchi et al., 1999) showed the difference in temperature–depth profiles between recharge and discharge areas. Although the temperature–depth profiles varied over a wide range in each city, synthesizing these data, including recharge and discharge areas, can tell us the average subsurface temperature profiles in each city, which may be representative of the effect of surface warming as a first-order assumption.

We averaged the profiles to demonstrate the general idea more qualitatively. The averages of whole temperature–depth profiles observed in the four cities, with standard deviations and regional geothermal gradients, are shown in Fig. 2–5. Mean geothermal gradients are estimated to be $0.022^\circ\text{C m}^{-1}$ in Tokyo (Taniguchi et al., 1999), $0.028^\circ\text{C m}^{-1}$ in Osaka (Taniguchi and Uemura, 2005), $0.040^\circ\text{C m}^{-1}$ in Bangkok (M. Yamano, personal communication, 2006), and $0.024^\circ\text{C m}^{-1}$ in Seoul (H.C. Kim, personal communication, 2006). Subsurface temperature shifts higher at 100 to 200 m depths in Osaka because many boreholes at that maximum depth range are located in the discharge area (concave profiles). Nevertheless, the averaged temperature–depth profiles in all cities show strong evidence of surface warming. The differences between (old) surface temperature extrapolated from geothermal gradients and (new) surface temperature extrapolated from the average of observed subsurface temperature are estimated to be 2.8°C in Tokyo (Fig. 2), 2.2°C in Osaka (Fig. 3), 2.5°C in Seoul (Fig. 4), and 1.8°C in Bangkok (Fig. 5).

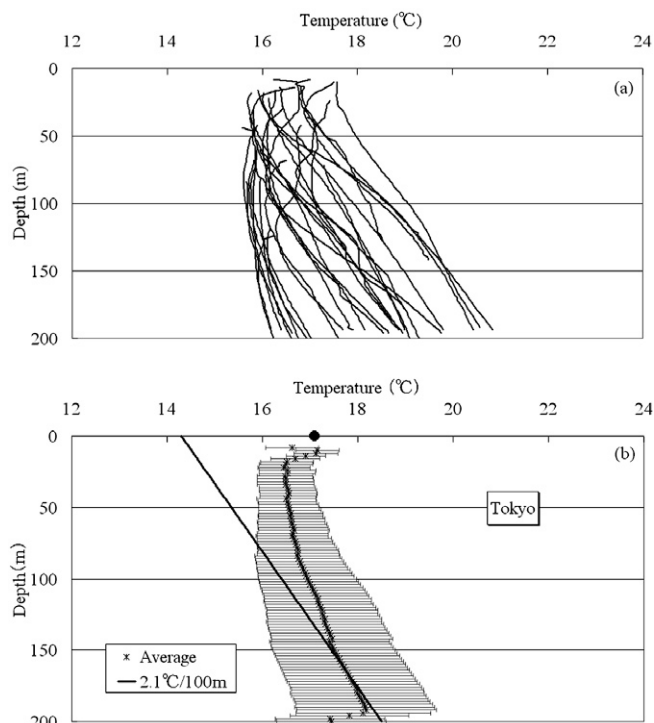


Fig. 2. (a) Observed temperature–depth profiles and (b) average and standard deviation of profiles with estimated "new" surface temperature shown by solid circle and estimated geothermal gradient in Tokyo.

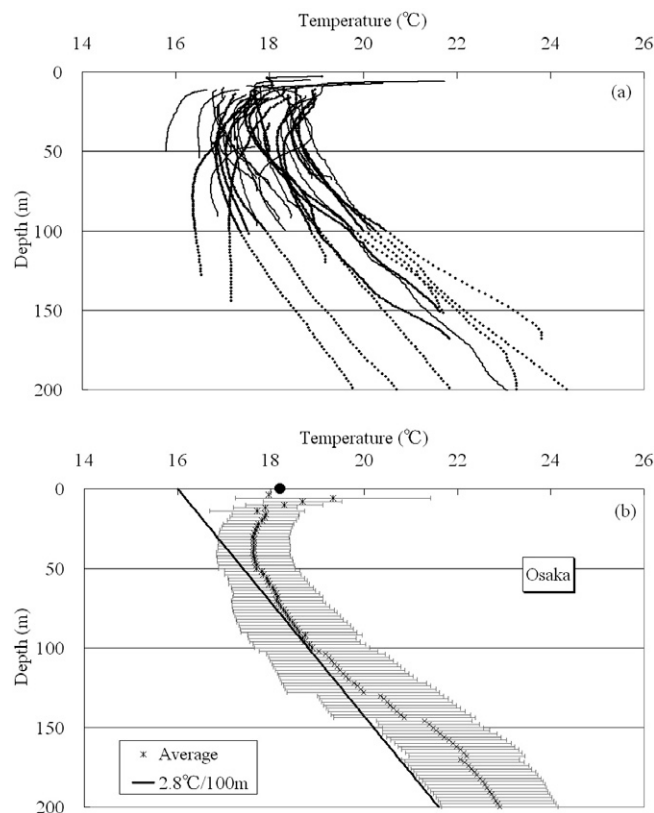


Fig. 3. (a) Observed temperature–depth profiles and (b) average and standard deviation of profiles with estimated "new" surface temperature shown by solid circle and estimated geothermal gradient in Osaka.

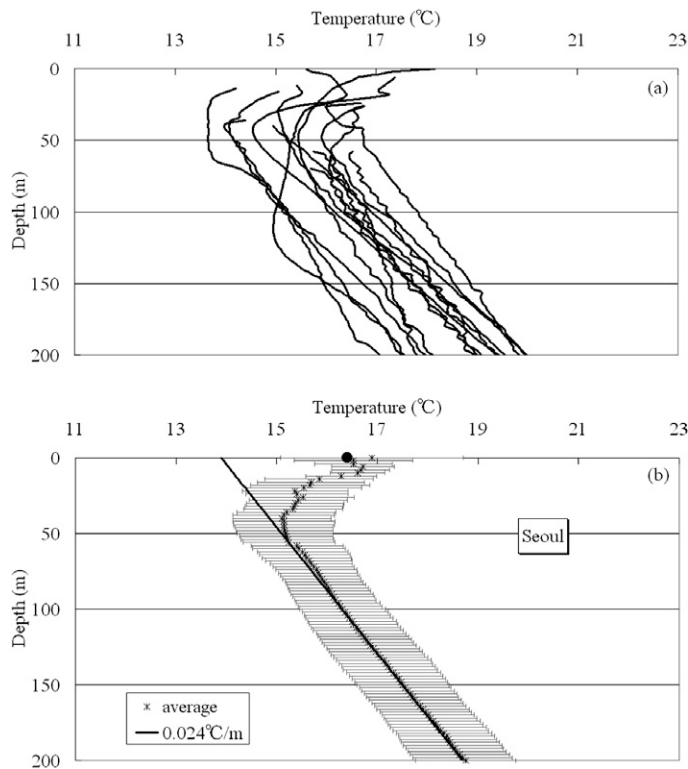


FIG. 4. (a) Observed temperature–depth profiles and (b) average and standard deviation of profiles with estimated “new” surface temperature shown by solid circle and estimated geothermal gradient in Seoul.

Air temperature records in the four cities are shown in Fig. 6. To evaluate the nonlinearity of the air temperature change, regression analyses of air temperature change have been made with different periods linking a starting time in the past with the present. The R^2 values of the regression line by the least squares method with different starting years (i.e., different periods) are shown in Table 1. The best correlations were found using 100, 70, 50, and 30 yr for Tokyo, Osaka, Seoul, and Bangkok, respectively. Therefore, the air temperature in Tokyo, Osaka, Seoul, and Bangkok appears to have accelerated 100, 70, 50, and 30 yr ago, respectively. As can be seen in Fig. 6, the estimated air temperature increased by $2.96^{\circ}\text{C } 100 \text{ yr}^{-1}$ ($R^2 = 0.814$) in Tokyo, $2.22^{\circ}\text{C } 70 \text{ yr}^{-1}$ ($R^2 = 0.687$) in Osaka, $2.39^{\circ}\text{C } 50 \text{ yr}^{-1}$ ($R^2 = 0.557$) in Seoul, and $1.64^{\circ}\text{C } 30 \text{ yr}^{-1}$ ($R^2 = 0.734$) in Bangkok.

According to the analyses of global trends of air temperature change by Hansen and Lebedeff (1987), the magnitude of average global warming is about $0.5^{\circ}\text{C } 100 \text{ yr}^{-1}$. There is a range of subregional warming rates within the Asian study domain from 0.2 to $1.0^{\circ}\text{C } 100 \text{ yr}^{-1}$, but the average of global warming is approximately $0.5^{\circ}\text{C } 100 \text{ yr}^{-1}$. The estimated increase in surface temperature from borehole temperature by Huang et al. (2000) is also about $0.5^{\circ}\text{C } 100 \text{ yr}^{-1}$. Thus, increased air temperatures in these four cities include not only average global warming but also other factors. These four cities were developed and urbanized rapidly during the last century, particularly after World War II. Therefore, the most reasonable explanation for the increase in air temperature above the global warming rate is heat islands caused by urbanization.

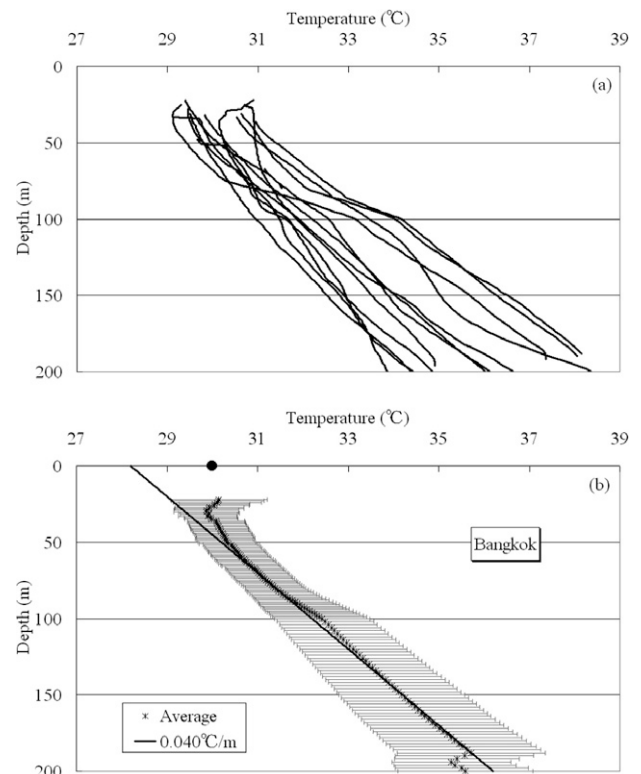


FIG. 5. (a) Observed temperature–depth profiles and (b) average and standard deviation of profiles with estimated “new” surface temperature shown by solid circle and estimated geothermal gradient in Bangkok.

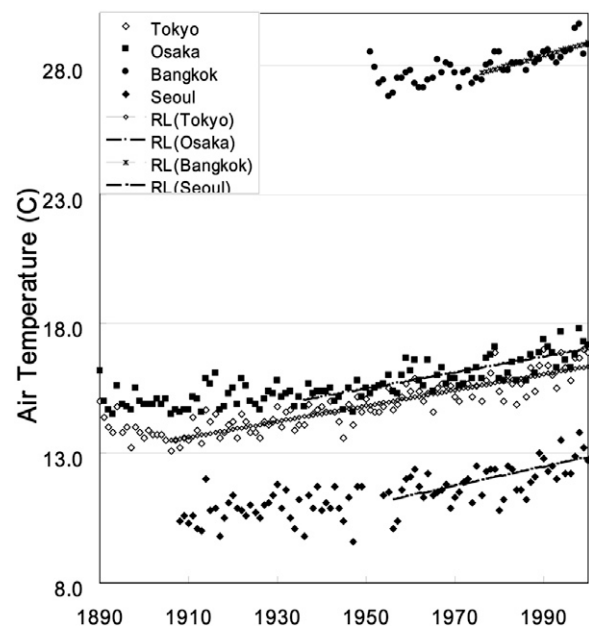


FIG. 6. Historical records of air temperature in Asian cities and best fits of linear trends (RL = regression line; see Table 1 for R^2 values). The location of the meteorological station is almost the center of each city.

Aside from the magnitude of surface warming due to urbanization, the depth of deviation from the thermal gradient differs among these four Asian cities. To demonstrate the effect of surface warming, we used here the depth at the point where the average temperature profile deviated 0.1°C from the geo-

TABLE 1. Coefficients of determination (R^2) of the linear regression lines with the different starting years (before present) of surface warming.

Years	Tokyo	Osaka	Seoul	Bangkok
120	0.778			
110	0.761	0.657		
100	0.814	0.675		
90	0.775	0.655	0.551	
80	0.759	0.682	0.538	
70	0.699	0.687	0.535	
60	0.645	0.669	0.549	
50	0.557	0.573	0.557	0.631
40	0.438	0.496	0.468	0.706
30	0.406	0.512	0.454	0.734
20	0.408	0.501	0.518	0.644

thermal gradient. The depth at which deviation starts is somewhat ambiguous because it is rather sensitive to the choice of undisturbed geothermal gradient. However, it does at least seem to reveal systematic differences in the depth to which surface temperature changes have propagated for the various cities. The inferred penetration depth is deepest in Tokyo (140 m, Fig. 2), followed by Osaka (80 m, Fig. 3), Seoul (50 m, Fig. 4), and Bangkok (50 m, Fig. 5).

Developmental Stages of the Cities and Subsurface Temperatures

To evaluate the effect of the starting time of urbanization on subsurface temperature, calculations of Eq. [1] with different bt values were performed and shown as subsurface temperature–depth profiles in Fig. 7. As can be seen in Fig. 7, the depth of deviation from the constant gradient becomes deeper with increased elapsed time from the start of surface warming due to urbanization and with the rate of surface warming. To evaluate the history of urbanization (i.e., time of the start of surface warming), comparisons between the observed and calculated depths that deviated by 0.1°C from the constant thermal gradient in each city (Fig. 2–5) and the elapsed time from the start of surface warming were made and are shown with the different magnitudes of surface warming ($+1$, $+2$, or $+3^\circ\text{C}$) in Fig. 8.

Based on the information in Fig. 6 and Table 1, it was estimated that air temperature started to increase first in Tokyo in the first decade of the 1900s (100 yr ago), followed by Osaka in the 1930s (70 yr ago), then Seoul in the 1950s (50 yr ago), and Bangkok in the 1970s (30 yr ago). Incorporating the magnitude of increased air temperature, which is 2.96°C in Tokyo, 2.22°C in Osaka, 2.39°C in Seoul, and 1.64°C in Bangkok, into Fig. 8, we can obtain independent estimates the depths of deviation from the thermal gradient. As can be seen in Fig. 8, the depth increases in the same order as the elapsed time from start of surface warming. The estimated depth of deviation from the constant gradient using air temperature is 97 m in Tokyo, 76 m in Osaka, 65 m in Seoul, and 45 m in Bangkok. Those depths agree reasonably well with the observed depths of deviation from the constant thermal gradient in Osaka (80 m), Seoul (50 m), and Bangkok (50 m). In Tokyo, the difference between the estimated depth (100 m) and observed depth (140 m) may be due to strong fluid flow effects (Taniguchi et al., 1999; Taniguchi et al., 2005). Thus, the depth of

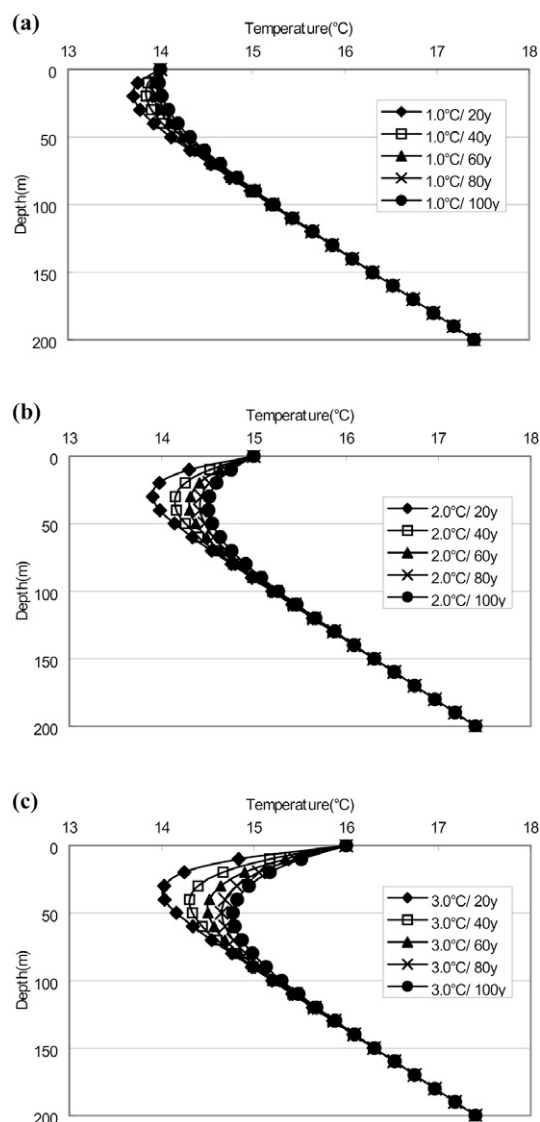


FIG. 7. Temperature–depth profiles calculated using Eq. [1] with surface warming (bt) values of (a) 1.0°C , (b) 2.0°C , and (c) 3.0°C .

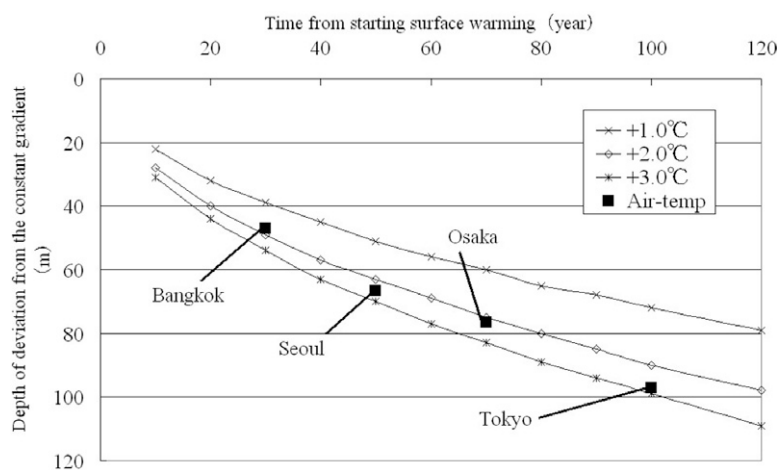


FIG. 8. Relationships between elapsed time from the start of surface warming due to urbanization and the depth of deviation from the constant thermal gradient. The lines show the theoretical results using Eq. [1], solid squares show the predicted values based on Eq. [1] using bt values estimated from air temperature in each city, and where t along the horizontal axis is the estimated time of onset of accelerated air temperature increase from Table 1.

deviation from the thermal gradient is an indicator of both the magnitude of surface warming and the timing of surface warming, so it may be used to investigate differences in the history of urbanization between cities.

In this study, we used “forward” calculations by using air temperature to evaluate the effects on subsurface temperature (Fig. 8). Although the “inverse” calculations using subsurface temperature to reconstruct the changes in surface temperature may be possible, comparisons between forward and inverse methods are left for future work. One may be able to separate urbanization and global warming effects by comparing the results with global meteorological studies (Kalnay and Cai, 2003; Kalnay et al., 2006; Lim et al., 2005). However, incorporating the effects of fluid flow on estimated surface warming and its causation requires additional detailed hydraulic data and analyses.

Conclusions

Subsurface temperatures in four Asian cities have been evaluated to estimate the effects of surface warming due to urbanization and global warming, as well as the developmental stage of each city. Mean surface warming in each city ranged from 1.8 to 2.8°C. The depth of deviation from the regional geothermal gradient was deepest in Tokyo (140 m), followed by Osaka (80 m), Seoul (50 m), and Bangkok (50 m). The analysis of the timing of the start of surface warming showed that the depth of 0.1°C deviation from a constant geothermal gradient in subsurface temperature was deeper when the elapsed time from the start of surface warming due to urbanization was larger. This trend was confirmed by air temperature records in the study areas from the last 100 yr. The heat island effect due to urbanization on subsurface temperature is an important global groundwater quality issue because it may alter groundwater systems geochemically and microbiologically. Many cities in the world have the same problem, particularly in Asia, where population is increasing rapidly.

The present screening study demonstrates the overall value of measuring temperature–depth profiles in boreholes to estimate regional surface warming. More detailed analyses of the spatial data have been left for future work. Analyses of individual profiles are complicated by localized vertical groundwater flow and heat transport in recharge and discharge areas. Localized surface warming is also expected in urban areas, and borehole temperature profiles may be useful for identifying such spatial variability within urban and peri-urban areas.

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