Urban heat island in the subsurface

Grant Ferguson[1] and Allan D. Woodbury[2]

Received 11 October 2007; revised 6 November 2007; accepted 12 November 2007; published XX Month 2007.

[1] The urban heat island effect has received significant attention in recent years due to the possible effect on long-term meteorological records. Recent studies of this phenomenon have suggested that this may not be important to estimate of regional climate change once data are properly corrected. However, surface air temperatures within urban environments have significant variation, making correction difficult. In the current study, we examine subsurface temperatures in an urban environment and the surrounding rural area to help characterize the nature of this variability. The results of our study indicate that subsurface temperatures are linked to land-use and supports previous work indicating that the urban heat island effect has significant and complex spatial variability. In most situations, the relationship between subsurface and surface processes cannot be easily determined, indicating that previous studies that relying on such a linkage may require further examination. **Citation:** Ferguson, G., and A. D. Woodbury (2007), Urban heat island in the subsurface, *Geophys. Res. Lett.*, *34*, LXXXXX, doi:10.1029/2007GL032324.

1. Introduction

[2] Differences in climate between urban areas and their rural surroundings have been documented for quite some time [*Landsberg*, 1956]. These differences are of significance due to their effect on energy use [*Taha*, 1997] and human health [*Patz et al.*, 2005]. The effect urbanization may have on meteorological records is of particular interest because of the potential consequences to the study of climate change. There has been a great deal of speculation that urban meteorological records have caused a bias in climate change studies and some of these studies have confirmed that this is an important consideration and is worthy of additional study [*Hansen et al.*, 2001]. However, *Peterson* [2003] demonstrated that there was no significant bias in the United States once raw data has been corrected. *Parker* [2006] demonstrates that this is also the case for the large-scale climate trend for Eurasia. However, the urban heat island effect does have a significant effect on temperatures on a local scale. Several models for estimating the magnitude of this effect as have been proposed [*Oke*, 1973; *Karl et al.*, 1988], many of which rely on city's population or population density. However, *Landsberg* [1981] points out that the urban heat island effect is actually the sum of microclimatic changes in the urban environment, suggesting that a single correction or figure describing the overall effect could be difficult to define, if in fact it has any meaning at all. A large body of more recent research supports this finding. *Bohm* [1998] found that the urban heat island effect was strongly influenced by local surroundings in a study of Vienna, Austria and the surrounding area that examined 6 temperature records. Other studies have found that greenspaces within urban areas are often significantly cooler than the surrounding areas [*Gallo and Owen*, 1999; *Spronken-Smith and Oke*, 1999]. This complexity was underscored by *Oke* [1998], who found that distance from the centre or edge of an urban area insufficient to describe the urban heat island effect.

[3] The urban heat island effect has been studied using subsurface temperatures in several studies [*Taniguchi et al.*, 1999; *Changnon*, 2004; *Ferguson and Woodbury*, 2004; *Taniguchi*, 2006, 2007]. *Taniguchi* [2006] suggested a link between population density and the magnitude of the temperature perturbation in the subsurface in the Bangkok area. This relationship was then used to explain a relationship between the distance from the city centre and the magnitude of the perturbation. In a more recent study, *Taniguchi* [2007] examined subsurface temperatures in several urban areas in Asia and found a link between surface air temperatures (SATs) and the average deviation from steady state heat flow in the subsurface. Considerable variability was present in the temperature profiles in each of the study areas and clearly not all of them agreed with this trend. It unclear how variable SAT may have been in those urban environments and if the approach of averaging temperature profiles is appropriate.

[4] While the application of subsurface temperatures to the study of the urban heat island effect is somewhat novel, this is a well established technique in paleoclimate studies [*Lachenbruch and Marshall*, 1986; *Huang et al.*, 2000]. This technique relies on coupling between SAT and the ground surface temperature (GST) and this has been demonstrated for environments with minimal changes in land cover [*Beltrami et al.*, 2005]. However, in areas with variable or changing land use, GST may not track SAT. Increases in soil temperatures of 2 to 3 K following deforestation have been found in both tropical [*Murtha and Williams*, 1986] and temperate environments [*Nitoiu and Beltrami*, 2005]. *Beltrami and Kellman* [2003] found a similar difference in soil temperatures between forest and grassland environments in a small region. These changes are related to changes in soil biogeochemical processes rather than mesoscale climate [*Covington*, 1981]. Changes in snow cover can also have a noticeable effect on the thermal regime of the subsurface [*Zhang*, 2005]. Additionally, subsurface temperature measurements in urban areas have been found to approach 5 K above those observed in surrounding areas [*Taniguchi et al.*, 1999; *Ferguson and Woodbury*, 2004; *Reiter*, 2006]. This change has been attributed to a combination of mesoscale climate, heat losses from buildings and land use changes, which are similar to

[1] Department of Earth Sciences, St. Francis Xavier University, Antigonish, Nova Scotia, Canada.

[2] Department of Civil Engineering, University of Manitoba, Winnipeg, Manitoba, Canada.

0094-8276/07/2007GL032324$05.00

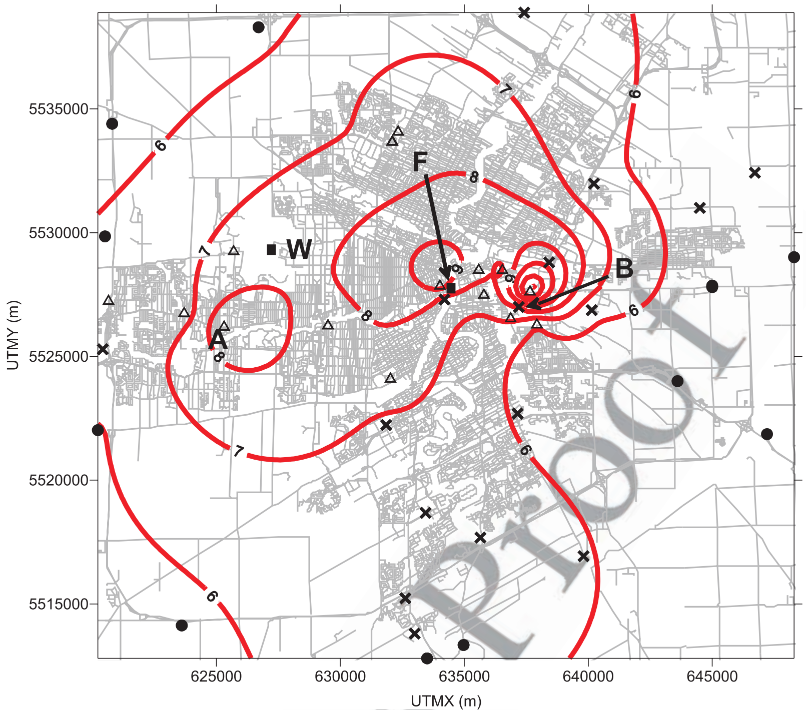

Figure 1. Temperatures in degrees Celsius at 20 m depth beneath Winnipeg, Manitoba, in August 2007. Crosses indicate urban sites, triangles urban greenspaces, and dots agricultural areas. Grey lines in the background are roads. A and B represent locations of temperature profiles shown in Figure 4 and W and F represent locations of SAT records at Winnipeg International Airport and Winnipeg -The Forks, respectively.

the list of factors known to cause the urban heat island effect in SAT measurements. However, heat flow occurs primarily by conduction in the subsurface and advection and radiation are more important in the atmosphere. The importance of landuse changes to subsurface temperature anomalies and the variability in the subsurface heat island will be addressed in this study through an examination of the subsurface heat island effect beneath Winnipeg, Manitoba. This has been previously documented by *Ferguson and Woodbury* [2004]. In the current study we present the results of a more recent temperature survey conducted in August 2007 and compare these results to previously measured temperatures. Comparisons to land uses and meteorological records will be made.

2. Case Study

[5] Temperature measurements were made in 40 monitoring wells in Winnipeg, Manitoba and the surrounding rural area (Figure 1). Measurements were made in August 2002 [*Ferguson and Woodbury*, 2004] and 2007. Additional measurements were made in a subset of these wells in 2000. The measurements were performed using logging equipment with a minimum accuracy of 0.1 K and a minimum resolution of 0.01 K. All wells had a diameters between 0.05 and 0.125 m and free convection should be minimal at the temperature gradients present. The depth of the wells in this study had a range from 20 m to 150 m below ground surface and temperatures were measured at 1 to 2 m intervals in the fluid-filled portion of the well. To maximize the amount of data for this study, temperatures at 20 m below ground surface were used to analyze the spatial distribution of the subsurface urban heat island effect. The temperature at this depth is representative of ground surface temperatures approximately 5 to 10 years ago and corresponds to the time between temperature measurements at these wells. Temperatures at this depth are also insensitive to seasonal temperature variations at the resolution used in this study. These temperatures were contoured using a kriging routine with a search radius of 10000 m.

[6] Measured temperatures indicate that temperatures near the city centre (approximately in the centre of the maps in Figure 1) were generally greater than those in surrounding rural areas. However, there were exceptions to this trend, as demonstrated by the presence the lows between the three highs near the city centre. Land use has a clear effect on subsurface temperatures in the Winnipeg area (Figure 2). Urban areas, classified as those in the immediate vicinity of buildings or areas generally devoid of vegetation, tended to have the highest temperatures, while urban greenspaces tended to be somewhat cooler and agricultural land had the lowest temperatures. Subsurface temperatures in urban areas are also the much more variable than those observed in urban greenspaces or agricultural areas. This variability is likely due to difference in the timing of development of various areas and the spatial variability of land use and heat sources in built up areas. The importance of lateral heat flow originating from buildings, which would be in part responsible for this variability, has previously been demonstrated by *Lachenbruch* [1957] and *Ferguson and Woodbury* [2004]. Urban greenspaces and agricultural areas are much more likely to be less heterogeneous over larger areas than built up areas.

[7] The distribution of SAT throughout the Winnipeg area is not well quantified. The only two continuous records available for the urban area from Environment Canada are

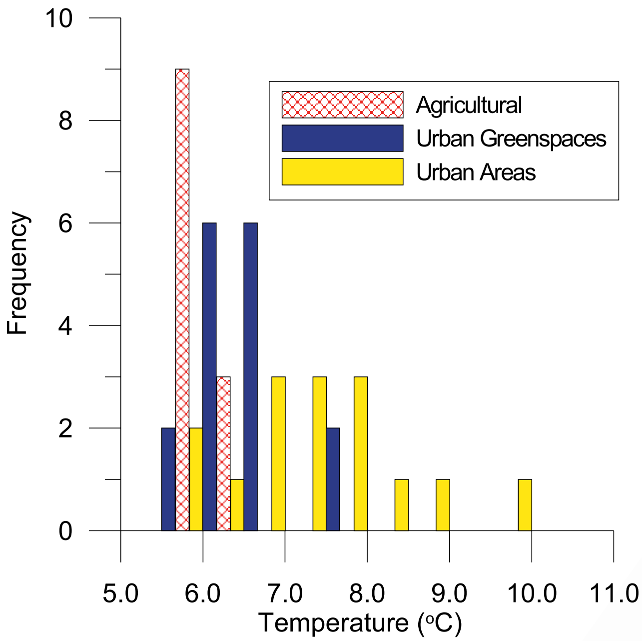

Figure 2. Distribution of temperatures at 20 m depth based on land use.

situated in the northwest area of the city (Winnipeg International Airport) and near the city centre (Winnipeg - The Forks; locations noted in Figure 1). There is a significant difference between these two records, with The Forks being approximately 1.5 K greater than the airport on average. This difference is more pronounced during the winter, possibly because of heat losses from buildings in the downtown area. Differences in snow cover may also cause some of the difference between these two records. However, two continuous records are insufficient to make general comments on the spatial SAT trends within the city.

[8] Changes in SAT over the last five years should affect the temperature at 20 m below ground surface if GST is tracking SAT. There is no strong trend in the SAT over the past five years in either of the continuous temperature records and this correlates with the lack of change in subsurface temperature in many locations (Figure 3). However, there are some locations where subsurface temperatures have changed significantly. These areas can all be explained by forcing other than climate. For the profiles at well A, a strong warming signal is observed (Figure 4). The well where these temperatures were measured is approximately 3 m away from a building, which has been reoccupied in the last 20 years after a period of abandonment. Conversely, one well in the eastern area of the city (well B) exhibits a cooling trend during the past seven years. During this period, buildings on the property were demolished and the site is now covered by grass. At well B there may also be a component of cooling related to changes in groundwater flow patterns in the area due to changes in production and injection. At a location nearby, the largest temperature increase was observed. This can be attributed to a warm water injection well at an industrial site in the area [*Ferguson and Woodbury*, 2005].

3. Discussion and Conclusions

[9] The distribution of excess heat in the subsurface of urban areas follows a similar pattern to the urban heat island effect observed in SATs. Underlying heat flow mechanisms are different in these two environments, with conduction domi-

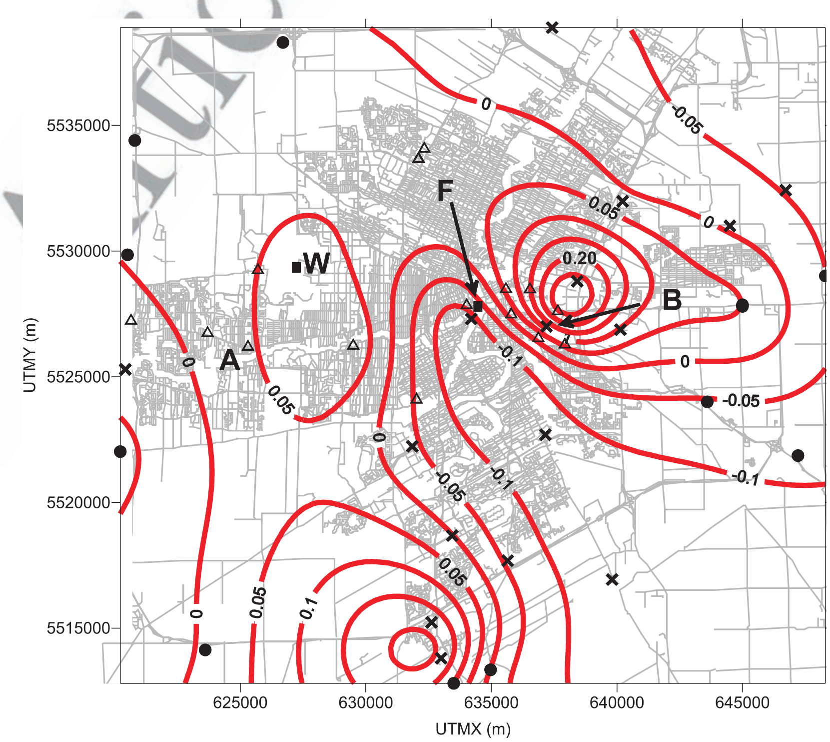

Figure 3. Temperatures changes in K at 20 m depth in Winnipeg, Manitoba, between 2002 and 2007. Note that all wells in this map were logged in 2002 and 2007. Crosses indicate urban sites, triangles urban greenspaces, and dots agricultural areas. Grey lines in the background are roads.

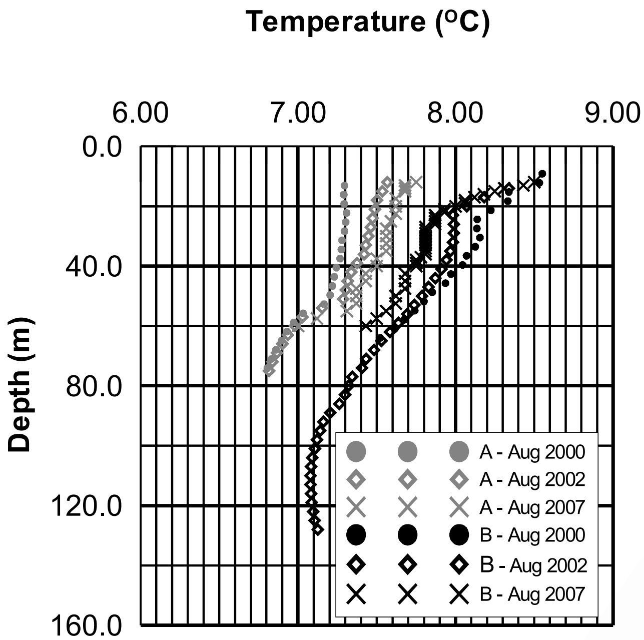

Figure 4. Temperature profiles at wells A and B. Locations shown on Figure 1.

nating in the subsurface and radiation and advection playing a much larger role above the ground surface but the sources and sinks of heat are largely the same. The type of land use is correlated with the temperatures observed in the subsurface of Winnipeg, Manitoba and these various land uses are also accompanied with different amounts of variability.

[10] GST is a potentially useful tool in describing the urban heat island effect and its variability. Subsurface temperature distribution in Winnipeg, Canada supports the concept that there is not a single number or simple mathematical function describing the urban heat island effect [*Oke*, 1998]. GST is linked to changes that humans have made to the landscape, which are quite variable in most urban areas. Some of these changes are the result of changes in microclimate above the ground while others are more closely related to changes in subsurface processes. However, in most situations the subsurface and surface processes cannot be easily separated, indicating that previous studies [*Taniguchi*, 2006, 2007] are flawed because it is uncertain what process is driving the changes in subsurface temperatures and what relationship this process has with SAT. Subsurface temperature measurements are perhaps most useful in assessing the variability in the urban heat island effect until mechanisms responsible for changes in GST are better understood.

[11] **Acknowledgments.** This research was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Manitoba Hydro.

References

Beltrami, H., and L. Kellman (2003), An examination of short- and long-term air-ground temperature coupling, *Global Planet. Change*, *98*, 167–184.
Beltrami, H., G. Ferguson, and R. N. Harris (2005), Long-term tracking of climate change by underground temperatures, *Geophys. Res. Lett.*, *32*, L19707, doi:10.1029/2005GL023714.
Bohm, R. (1998), Urban bias in temperature time series: A case study for the city of Vienna, Austria, *Clim. Change*, *38*, 113–128.
Changnon, S. A. (2004), A rare long record of deep soil temperatures defines temporal temperature changes and an urban heat island, *Clim. Change*, *42*, 531–538.
Covington, W. W. (1981), Changes in forest floor organic matter and nutrient content following clear cutting in northern hardwoods, *Ecology*, *62*, 41–48.
Ferguson, G., and A. D. Woodbury (2004), Subsurface heat flow in an urban environment, *J. Geophys. Res.*, *109*, B02402, doi:10.1029/2003JB002715.
Ferguson, G., and A. D. Woodbury (2005), Sustainability of groundwater as a coolant in Winnipeg, Manitoba, *Can. Geotech. J.*, *42*, 1290–1301.
Gallo, K. P., and T. P. Owen (1999), Satellite-based adjustments for the urban heat island bias, *J. Appl. Meteorol.*, *38*, 806–813.
Hansen, J., R. Ruedy, M. Sato, M. Imhoff, W. Lawrence, D. Easterling, T. Peterson, and T. Karl (2001), A closer look at United States and global surface temperature change, *J. Geophys. Res.*, *106*(D20), 23,947–23,964.
Huang, S., H. N. Pollack, and P.-Y. Shen (2000), Temperature trends over the past five centuries reconstructed from borehole temperatures, *Nature*, *403*, 756–758.
Karl, T. R., H. Diaz, and G. Kukla (1988), Urbanization: Its detection and effect in the United States climate record, *J. Clim.*, *1*, 1099–1123.
Lachenbruch, A. H. (1957), Three-dimensional heat conduction in permafrost beneath heated buildings, *U. S. Geol. Surv. Bull.*, *1052-B*, 51–69.
Lachenbruch, A., and B. V. Marshall (1986), Changing climate: Geothermal evidence from the permafrost in Alaskan Arctic, *Science*, *234*, 689–696.
Landsberg, H. (1956), The climate of towns, in *Man's Role in Changing the Face of the Earth*, edited by W. L. Thomas Jr., pp. 584–603, Univ. of Chicago Press, Chicago, Ill.
Landsberg, H. E. (1981), *The Urban Climate, Int. Geophys. Ser.*, vol. 28, Academic, San Diego, Calif.
Murtha, G. G., and J. Williams (1986), Measurement, prediction and interpolation of soil temperature for use in soil taxonomy: Tropical Australian experience, *Geoderma*, *37*, 189–206.
Nitoiu, D., and H. Beltrami (2005), Subsurface thermal effects of land use changes, *J. Geophys. Res.*, *110*, F01005, doi:10.1029/2004JF000151.
Oke, T. R. (1973), City size and the urban heat island, *Atmos. Environ.*, *7*, 769–779.
Oke, T. R. (1998), Observing urban weather and climate, *Rep. WMO/TD 877*, pp. 1–8, World Meteorol. Organ., Geneva, Switzerland.
Parker, D. E. (2006), A demonstration that large-scale warming is not urban, *J. Clim.*, *19*, 2882–2895.
Patz, J. A., D. Campbell-Lendrum, T. Holloway, and J. A. Foley (2005), Impact of regional climate change on human health, *Nature*, *438*, 310–317, doi:10.1038/nature04188.
Peterson, T. C. (2003), Assessment of urban versus rural in situ surface temperatures in the contiguous United Sates: No difference found, *J. Clim.*, *16*, 2941–2958.
Reiter, M. (2006), Vadose zone temperature measurements at a site in the northern Albuquerque Basin indicate ground-surface warming due to urbanization, *Environ. Eng. Geosci.*, *12*, 353–360.
Spronken-Smith, R. A., and T. R. Oke (1999), The thermal regime of urban parks in two cities with different summer climates, *Int. J. Remote Sens.*, *19*, 2085–2104.
Taha, H. (1997), Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat, *Energy Buildings*, *25*, 99–103, doi:10.1016/S0378-7788 (96)00999-1.
Taniguchi, M. (2006), Anthropogenic effects on subsurface temperature in Bangkok, *Clim. Past*, *2*, 831–846.
Taniguchi, M. (2007), Combined effects of urbanization and global warming on subsurface temperatures in four Asian cities, *Vadose Zone J.*, *6*, 591–596.
Taniguchi, M., J. Shimada, T. Tanaka, I. Kayane, Y. Sakura, Y. Shimano, and S. Kawashima (1999), Disturbances of temperature-depth profiles due to climate change and subsurface water flow: 1. An effect of linear increase in surface temperature caused by global warming and urbanization in the Tokyo metropolitan area, *Water Resour. Res.*, *35*, 137–152.
Zhang, T. (2005), Influence of the seasonal snow cover on the ground thermal regime: An overview, *Rev. Geophys.*, *43*, RG4002, doi:10.1029/2004RG000157.

G. Ferguson, Department of Earth Sciences, St. Francis Xavier University, P.O. Box 5000, Antigonish, N. S., Canada B2G 2W5. (gferguso@stfx.ca)

A. Woodbury, Department of Civil Engineering, University of Manitoba, 15 Gillson Street, Winnipeg, Manit., Canada R3T 4G1. (woodbur@cc.umanitoba.ca)