Estimating the Urban Heat Island Contribution to Urban and Rural Air Temperature Differences over Complex Terrain: Application to an Arid City

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ABSTRACT

This study proposes a method for estimating the canopy-layer net urban heat island (UHI) in regions with complex terrain that lack preurban observations. The approach is based on a linear relationship between the urban–rural temperature difference \( \Delta T_{\text{u} \rightarrow \text{r}} \), measured via screen-level air temperature, and the population of the city, which was found to have the highest correlation with observations. The linear relation is extrapolated to zero population to yield the desired preurban value. The difference between the zero population \( \Delta T_{\text{u} \rightarrow \text{r}} \) and the current one is proposed to represent the net UHI. Given the uncertainties of the population method, the relatively short time period of the temperature record, and possible inhomogeneity in the data, the results should be regarded as a first-order approximation of the net UHI contribution. The UHI was evaluated for an arid city, Beer Sheba, Israel, for the minimum and maximum air temperatures for the summer and the winter. The study region resembles the combined effect of complex terrain (i.e., the concave topography of the city in contrast with the plateau landscape surrounding it), the UHI, and the regional warming trend. The study assumes that the regional warming does not affect the \( \Delta T_{\text{u} \rightarrow \text{r}} \). The concave topography of the city dominates over the UHI contribution during nighttime, resulting in an average lower minimum temperature in the city relative to the rural area. This difference has decreased considerably during the study period and has even reversed for the summer nights toward the end of the period. The estimated net UHI contribution in Beer Sheba varies between 0.8°C and 3.1°C, with the highest values during the night hours. The high positive UHI during the night is in line with previous studies. The positive UHI in the summer implies further aggravation of heat stress beyond that occurring, and that predicted to increase, over the region.

1. Introduction

The urban heat island (UHI) has been studied mostly through the temperature differences between urban and neighboring rural stations \( \Delta T_{\text{u} \rightarrow \text{r}} \). These studies refer to the “canopy-layer heat island” (Oke 1976, 1987, 252–302) via screen-level air temperatures (~2 m AGL). Such an approach may be found to be problematic because \( \Delta T_{\text{u} \rightarrow \text{r}} \) may be influenced by differences in topographic posting between the urban and the rural regions and by spatial and temporal variations in the characteristics of the rural region itself. “In selecting station pairs it is particularly important to try to eliminate extraneous effects due to topography, water bodies and the downwind effects of the urban area itself” (Oke 1987, p. 273). According to Lowry (1977), Oke (1987, 252–302), and Stewart and Oke (2009b), the ideal database needed for evaluating the UHI is an extensive series of preurban measurements that can be compared with present-day observations. However, only in rare cases are such data available, and \( \Delta T_{\text{u} \rightarrow \text{r}} \) is commonly used to represent the magnitude of the UHI. Stewart and Oke (2009b) claim that “one-third of empirical UHI literature gives no quantitative or qualitative description of the measurement sites defining UHI magnitude…”.

The intensity of UHI depends on several factors. It is most intense under stable weather, calm air, and cloudless skies, defined by Oke (1982) as ideal conditions for the development of UHI. Clouds and strong winds have been shown to suppress it (e.g., Morris et al. 2001; Unger

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et al. 2001). UHI magnitude reaches nighttime maxima because of differential radiative cooling above urban and rural surfaces, which in turn is a response to surface geometry (urban canyon vs open rural) and heat storage [urban concrete vs rural soils; e.g., Oke (1981, 1982)]. Thus, the UHI is most clearly seen in daily minimum temperatures (e.g., Martinez et al. 1991; Unger 1996). Several studies have demonstrated the intensification of the UHI in time together with the increase of the urbanization, for example, in Madrid, Spain (Martinez et al. 1991); Tucson, Arizona (Comrie 2000); Seoul, Korea (Kim and Baik 2002); and Prague, Czech Republic (Brazdil and Budkova 1999).

Most studies of the UHI have focused on mid- and high latitudes. UHI intensity in subtropical regions is regarded as lower relative to that in temperate cities with similar population and shows a seasonal variation, with higher intensity during the dry season (Roth 2007). Arid cities, such as Tucson and Phoenix, Arizona (Comrie 2000; Hawkins et al. 2004), showed significant UHI, on the order of 3°C. On the contrary, in Kuwait City, Kuwait, the UHI is negligible because of the similarities in the urban and rural landscapes and because the city is in close proximity to a large water body (Nasrallah et al. 1990). Saaroni et al. (2000) found significant UHI in Tel Aviv, Israel (subjected to Mediterranean climate), reaching 5°C in the canopy layer of a stable winter night. For desert cities in Israel, Sofer and Potchter (2006) studied the UHI of the superarid city of Eilat for several case studies in the summer and winter seasons. Their measurements indicate the development of moderate UHI, 0.5°–1.5°C in magnitude, that is more significant at midday, during the summer. Potchter et al. (2006) studied the magnitude of the UHI in Beer Sheba, Israel, through several case studies and found a maximum magnitude, of 6.9°C, in the early-morning hours.

The time evolution of the UHI can be measured by comparing the long-term temperature trend in the urban and rural regions. Nasrallah et al. (1990) showed that the long-term temperature trend in Kuwait City was 0.12°C (10 yr)−1, larger than the 0.07°C (10 yr)−1 of the near desert area. Comrie (2000), using a similar method, showed that in Tucson the UHI increased by 3°C over the twentieth century, with >2°C of this warming within the last 30 yr. Because the eastern Mediterranean region is subjected to a more intense warming trend during the summer season relative to the global rate (Saaroni et al. 2003; Ziv et al. 2005), any signal of positive UHI implies further aggravation of summer heat conditions within urban regions there.

The complexity of the factors affecting the ΔT_{u−r} implies that the UHI cannot be deduced directly from the temperature difference. This study proposes a method according to which the time variation of ΔT_{u−r} against population is used to estimate the net contribution of the UHI. The method is applied for the arid city of Beer Sheba.

2. Geographical and climatological background

The city of Beer Sheba (31°14’N, 34°47’E, 260 m MSL) is the largest city in the Negev Desert of Israel (Figs. 1a and 1b). The city covers 54 km², and its population in 2005 was 185 000 [from the Statistical Abstract of Israel 2008 (No. 59) of the Central Bureau of Statistics; obtained online at http://www1.cbs.gov.il/reader/shnatonenew.htm (URL displays current version)], as compared with 70 000 in 1967, the beginning of the study period. The meteorological station (the urban station, hereinafter, belonging to the Israeli Meteorological Service) is located in one of the residential neighborhoods, in the commercial center of the city (Fig. 1b). The city of Beer Sheba is dominated by a “block”-type landscape [according to Oke (2004) and Stewart and Oke (2009a)] with 47% built area, a typical building height of four floors, and a sky-view factor (SVF) of ~0.8 due to relatively large roads.

The rural station [World Meteorological Organization (WMO) Climate Station 401910] is located 10 km west of Beer Sheba, at an elevation of 195 m MSL, 65 m lower than the urban station (Fig. 1b). The topographic posting of this station is a plateau, unlike the urban area, which has a concave landscape (Fig. 1c). The area is a “hot desert” [according to Stewart and Oke (2009a)], dominated by loess soil. The rural station is surrounded by isolated low buildings of one–two floors with spacing of ~100 m between them and an SVF of >0.95. These features have not been changed along the study period.

Beer Sheba is located near the border between the semiarid (BS) and the arid (BW) climate regions according to the Köppen classification (Goldreich 2003, 12–14), having an average annual rainfall of 200 mm, confined to the winter season (Bitan and Rubin 1994). Table 1 presents the average daily minimum and maximum temperatures for the summer and the winter in the urban and the rural stations. The diurnal range is 13.2°C in the summer and 10.6°C in the winter, and the seasonal range is 12.8°C.

According to Lowry (1977) the temperature differences between urban and neighboring rural locations are affected by three factors: the regional “background” climate, the local landscape, and the effects of urbanization. For our study region, the regional factor is the arid climatic conditions described above. The regional effect is subjected to the warming trend, mainly in the
summer (Saaroni et al. 2010), but we assume that it is equal for both stations and so does not affect $\Delta T_{u-r}$. The landscape factor is composed of two elements. One is the higher elevation of the urban station with respect to the rural, implying lower temperatures in the former, on the order of 0.5°C, especially in the day hours, when the planetary boundary layer is well mixed. The second is the concave topography of the city, in contrast to the flat landscape of the rural region (Fig. 1c), implying enhanced nocturnal cooling (and daytime warming) in the urban location. These two topographic effects are expected to be constant during the study period. The cooling imparted by the concave topography of the city opposes the heating imparted by the urban effect during the night hours, and both intensify when the winds are weak.

3. Materials and method

The study period starts in 1967, when the rural station began to perform measurements, and ends in 2004. The location of the urban station has not been changed during the study period. The rural station was moved about 500 m southeast in 1977 but remained at the same location.
altitude and posting. Both stations have been operated according to the WMO regulations for climatological stations (although they shifted from manual to automatic instrumentation in 2000) and are controlled by the Israeli Meteorological Service.

The analysis is divided into the two main seasons: the summer, June–August (JJA), and the winter, December–March [DJFM, as defined by Alpert et al. (2004)]. The observational data for the two stations include the daily minimum and maximum temperatures and the wind at 0000 and 1200 UTC, corresponding to 0200 and 1400 LST, which represent the approximate times of minimum and maximum temperature, respectively.

Because the magnitude of the UHI cannot be resolved directly from the $\Delta T_{u-r}$, because of topographical differences between the two stations, we used the temporal variation of $\Delta T_{u-r}$ ($\Delta TT$, hereinafter) for deriving the evolution rate of the UHI and for reconstructing its magnitude. The $\Delta TT$ was derived separately for the minimum and maximum temperatures and for the summer and winter seasons. The population of cities is commonly used as a measure for the magnitude of UHI (Oke 1987, 252–302), although UHI has no direct physical relationship with the number of inhabitants in a city. Nevertheless, the population serves as a substitute for urban form [e.g., SVF and city geometry; Oke (1981)] and magnitude of anthropogenic activity. Following the above arguments, the $\Delta TT$ is analyzed here with respect to the population growth. To reconstruct the preurban temperature difference between the urban and the rural locations, we extrapolated the dependence of $\Delta T_{u-r}$ back to zero population ($\Delta T_{p=0}$, hereinafter). Then, the difference between the present day and $\Delta T_{p=0}$ yields the estimated net UHI. Our approach for estimating the UHI is based on the assumption that the regional climate changes do not alter $\Delta T_{u-r}$ for any population size (and, therefore, $\Delta TT$) and therefore it depends on the urban features alone.

4. Results

The interannual variation of $\Delta T_{u-r}$, calculated for the minimum and maximum temperature, is shown in Figs. 2a and 2b for the summer and the winter, respectively. In both seasons an increasing trend was found for the minimum and the maximum temperatures, with the largest $\Delta TT$ for the minimum temperatures in the summer and the winter, 0.46°C and 0.26°C (10 yr)$^{-1}$, respectively. For the maximum temperatures the values are also positive but lower, 0.17° and 0.20°C (10 yr)$^{-1}$ for the summer and the winter, respectively. The interannual variations show several irregularities, especially in the early 1990s, when $\Delta T_{u-r}$ for the minimum temperature rose sharply in both seasons and dropped for the maximum temperature, especially in the summer. This could be explained by a change in the location or immediate surrounding of one of the stations, but such a change did not occur in any of the stations during that period. We, therefore, suggest that these changes result from a considerable population growth in the city of Beer Sheba of 35% within 5 yr (1990–95) due to the emigration wave from Russia [from the Statistical Abstract of Israel 2008 (No. 59) of the Central Bureau of Statistics; obtained online at http://www1.cbs.gov.il/reader/shnatonenew.htm (URL displays current version)], accompanied by intensive construction activity there. The construction activity most likely caused increased dust loading over the city (no evidence is available for that), producing a “blanket effect,” that is, blocking of both solar and terrestrial radiation, which decreases the maximum temperatures and increases the minimum temperatures in the urban station. The larger decrease in $\Delta T_{u-r}$ for the maximum temperature in the summer supports this hypothesis because in the summer the solar radiation is stronger and more persistent than in the winter as a result of the absence of cloudiness in the daytime during that season.

The use of $\Delta TT$ as a function of time does not allow reconstruction of $\Delta T_{u-r}$ in the preurban period because the rural station records do not go farther back than 1967. Moreover, the urbanization rate may vary irregularly with time, making simple functional dependence on time problematic. This problem is circumvented by the use of population as a surrogate for urbanity and as an argument for the UHI magnitude. Oke (1987, 252–302) proposed a logarithmic dependence for calm conditions and a quadruple dependence (population$^{0.25}$) when the wind appears as an additional independent variable. We plotted $\Delta T_{u-r}$ as a function of population and examined various functional relationships between them (quadruple, logarithmic, linear, polynomial, and exponential). The highest correlation between observed and calculated $\Delta T_{u-r}$ was found for the linear relationship and thus is used for our analysis. Note that convex functional relationships (such as logarithmic and quadruple) yield a considerable UHI even for small populations, in agreement with Landsberg (1970) and Oke.
Therefore, our linear assumption may underestimate this effect.

The UHI is best exhibited under calm conditions (Oke 1987, 252–302). Therefore, the analysis was done separately for reduced samples that exclude observations in which the wind speed was $>3$ and $>2$ m s$^{-1}$. For a $3$ m s$^{-1}$ threshold, the smallest size was obtained for the daytime in the summer (271; 8% of the full sample), but for the $2$ m s$^{-1}$ threshold only 91 observations ($<3\%$) remained for the summer days. Nevertheless, no considerable change was found in the derived parameters while lowering the thresholds. The results for the full sample and the reduced sample of $\leq3$ m s$^{-1}$ are specified in Table 2. The $\Delta T_{TT}$ was found to be positive for both times of the day and seasons. It is considerably higher during the nighttime hours: about 4 times that in the day hours in the summer and 1.4 times in the winter. The smallest rate (for the reduced sample) is 0.42$^\circ$C per 100 000 population for the summer maximum, and the largest rate is 1.66$^\circ$C per 100 000 population for the summer minimum. The results for the full sample are similar (Table 2). The pronounced positive UHI in the night hours is consistent with previous studies, but the significant positive UHI in the day hours in both seasons is not trivial. Daytime “cool islands” have been found in several cities, resulting from the urban geometry, that is, street canyons or vegetation (i.e., parks and green space effects; e.g., Hafner and Kidder 1999; Shigeta et al. 2009; Mendonca 2009). Moreover, settlements in arid regions tend to develop “oasis effects” expressed in cooling during daytime (Saaroni et al. 2004), which has also been noted in several arid cities, such as in Botswana (Jonsson 2004).

The temperature difference for zero population, $\Delta T_{p=0}$, when subtracted from the present-day $\Delta T_{u-r}$, is considered here as the estimated net UHI. It is demonstrated in Fig. 3 by the temperature difference (seen on the $y$ axis) between the intersections of the straight line approximating $\Delta T_{u-r}$ with population = 0 and with population = 185 000 (x axis). The values (reduced sample) for the nights are $+3.07^\circ$C for the summer and $+2.11^\circ$C for the winter, and for the days they are

![Fig. 2. Interannual variation of $\Delta T_{u-r}$ ($^\circ$C) for the period 1967–2004 and the long-term linear trend for the minimum and maximum temperatures during the (a) summer and (b) winter.](http://journals.ametsoc.org/doi/pdf/10.1175/2010JAMC2473.1)

Table 2. Measures of the UHI in Beer Sheba (as a function of population) for the minimum and maximum temperature for summer and winter seasons: the slope of $\Delta T_{u-r}$ (degrees Celsius per 100 000 residents) calculated by linear regression, the correlation between the observed and calculated $\Delta T_{u-r}$, the extrapolated $\Delta T_{u-r}$ to zero population $p$, and the calculated net UHI. The measures and the number of days included are shown separately for the full sample and for the days with wind speed $\leq3$ m s$^{-1}$ (boldface).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min temperature</td>
<td>Max temperature</td>
</tr>
<tr>
<td>No. of days</td>
<td>Full sample</td>
<td>3462</td>
</tr>
<tr>
<td></td>
<td>Wind speed $\leq3$ m s$^{-1}$</td>
<td>3304</td>
</tr>
<tr>
<td>Slope of $\Delta T_{u-r}$ ($\Delta T_{TT}$)</td>
<td>Full sample</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>Wind speed $\leq3$ m s$^{-1}$</td>
<td>1.66</td>
</tr>
<tr>
<td>Correlation R</td>
<td>Full sample</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Wind speed $\leq3$ m s$^{-1}$</td>
<td>0.91</td>
</tr>
<tr>
<td>$\Delta T_{p=0}$</td>
<td>Full sample</td>
<td>-2.82</td>
</tr>
<tr>
<td></td>
<td>Wind speed $\leq3$ m s$^{-1}$</td>
<td>-2.84</td>
</tr>
<tr>
<td>Net UHI</td>
<td>Full sample</td>
<td>3.03</td>
</tr>
<tr>
<td></td>
<td>Wind speed $\leq3$ m s$^{-1}$</td>
<td>3.07</td>
</tr>
</tbody>
</table>
Table 2. The values of \( \Delta T_p \), \( \Delta T_r \), \( \Delta T_u \), and \( \Delta T_{u-r} \) for the minimum and maximum temperatures, for the (a) summer and (b) winter. The dashed extensions of the linear lines are extrapolated to zero population.

\[
\begin{array}{|c|c|c|c|}
\hline
 \text{Season} & \text{Temperature} & \text{Value} \\
\hline
 \text{Summer} & \Delta T_p & 0.78 \degree C & 0.29 \degree C \\
 & \Delta T_r & 0.80 \degree C & 0.91 \degree C \\
 & \Delta T_u & 1.54 \degree C & 1.00 \degree C \\
 & \Delta T_{u-r} & 0.29 \degree C & 0.91 \degree C \\
\hline
 \text{Winter} & \Delta T_p & 1.54 \degree C & 1.00 \degree C \\
 & \Delta T_r & 1.54 \degree C & 1.00 \degree C \\
 & \Delta T_u & 1.54 \degree C & 1.00 \degree C \\
 & \Delta T_{u-r} & 0.29 \degree C & 0.91 \degree C \\
\hline
\end{array}
\]

5. Summary and conclusions

This study proposes a method for estimating the canopy-layer net UHI in a region with complex terrain in which observations from the “preurban” period are not available. The approach is based on a linear relationship between \( \Delta T_{u-r} \) and city population, which was found to have the highest correlation with the observations. First, the linear relationship is extracted for the study period for which observations are available. Then, it is extrapolated to zero population to yield the desired preurban value, \( \Delta T_{p=0} \). The difference between \( \Delta T_{p=0} \) and the current \( \Delta T_{u-r} \) is proposed to reflect the net UHI.

The UHI was evaluated for an arid city (Beer Sheba) for 1967–2004, during which period the population grew from 70,000 to 185,000. It was derived for the minimum and the maximum temperatures for the summer and the winter months separately. Because the UHI is best exhibited under calm conditions (Oke 1987, 252–302), the analysis was done also for reduced samples, excluding observations for which the wind speed was >3 and >2 m s\(^{-1}\). The net UHI found for the minimum temperature are on the order of +3\(^\circ\) and +2\(^\circ\) C for the summer and the winter, respectively. These values are comparable with those found by Comrie (2000) and Hawkins et al. (2004) for the arid cities of Arizona. The high positive UHI in the night hours is in line with previous studies. The large values in the summer nights relative to those in the winter can be attributed to the stable conditions that prevail in Israel during that season, when a marine inversion predominates (Dayan and Rodnizki 1999; Dayan et al. 2002; Ziv et al. 2004). For the maximum temperatures, the values are also positive: +0.8\(^\circ\) for the summer and +1.5\(^\circ\) for the winter. The positive UHI in the day hours is suggested to express the growth of the urban area and the increase in anthropogenic activity (e.g., energy consumption, transportation,
and air conditioning), which sets off daytime cooling effects such as the oasis effect imparted by municipal parks (Oke 1987, 252–302; Saaroni et al. 2004) or the cool islands often found in large cities (e.g., Saaroni et al. 2000).

Given the uncertainties of the population method, the relatively short time period of the temperature record, and the possible inhomogeneity in the data, the results should be regarded as a first-order approximation of the net UHI contribution and as the best estimates that can be offered in view of the data and method restrictions. Note also that the method proposed here cannot capture abrupt changes (e.g., massive construction projects) in the cities' development, such as that which happened in the early 1990s when a wave of immigrants came to Beer Sheba.

The positive UHI in the summer implies further aggravation of heat stress in this arid, hot region beyond that occurring, and that expected to proceed, over the region. The linear temperature trends in the summer season are significantly positive. For the maximum temperature, it is +0.31°C (10 yr)\(^{-1}\) at the rural station and +0.48°C (10 yr)\(^{-1}\) at the urban station. For the minimum temperature the warming trends are even higher, +0.33°C (10 yr)\(^{-1}\) and +0.80°C (10 yr)\(^{-1}\) for the rural and the urban stations, respectively. Further rapid increase in the minimum temperature of the summer in the urban area will bring about heat-stress conditions even during the nighttime hours and will increase the probability for continuous periods with warm nights. Meehl and Tebaldi (2004) incorporated in their heat-wave definition the nighttime temperatures, indicating its crucial contribution for uncomfortable conditions. In addition, Karl and Knight (1997) stated that sequences of consecutive nights with no relief that result from very warm nighttime minimum temperatures may be most important in terms of health impacts. It is imperative that any discussion of global warming and its regional and environmental implications should not discard the further warming imparted by the urban heat island.

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