Climatic effects of urbanization in Istanbul: a statistical and modeling analysis

Yasemin Ezber,a Omer Lutfi Sen,a,* Tayfun Kindapa and Mehmet Karacaab

a Istanbul Technical University, Eurasia Institute of Earth Sciences, Maslak 34469 Istanbul, Turkey
b Istanbul Technical University, Faculty of Mining, Department of Geology, Maslak 34469 Istanbul, Turkey

Abstract:

Statistical and numerical modeling tools were used to investigate the climatic effects of urbanization in Istanbul, the largest city in Turkey. Mann–Kendall trend test was applied to minimum temperature data from stations located in urban, suburban and rural areas in Istanbul to determine the existence and significance of trends, and the approximate years in which changes in the trends started. In addition, using a mesoscale atmospheric model, a sensitivity experiment was carried out to explore the atmospheric effects of urbanization in the city. Both statistical and modeling analyses indicated significant warming in the atmosphere over the urbanized areas. Mann–Kendall tests indicated statistically significant positive trends in the time series of the differences in minimum temperatures between urban and rural stations. Seasonal analyses showed that the urbanization effect on climate was most pronounced in summer. In most cases, the changes in the trends occurred in the 1970s and 1980s when the population growth rate in Istanbul increased dramatically. The model results exhibited a significant expansion of the urban heat island in Istanbul from 1951 to 2004, fairly consistent with the expansion of the city in this period. A two-cell structure for the urban heat island emerged at the reference level from the difference of the July simulations with current and past landscapes: one on the European side and the other on the Asian side of the city. The maximum reference-level temperature difference between the past and present simulations was found to be around 1°C. The modeling experiment also indicated that the velocity of the prevailing northeasterly wind and the water vapor mixing ratio were both reduced over the city. The heating effect due to urbanization was found to penetrate about 600–800 m height in the atmosphere over the city, and the two surface heat island cells were found to combine aloft. Copyright © 2006 Royal Meteorological Society

KEY WORDS Istanbul; urbanization; Mann–Kendall test; MM5 and urban climate

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INTRODUCTION

Significant anthropogenic changes have occurred in the landscape of the terrestrial earth during the last century. Cultivation, deforestation and desertification are the most important factors causing these changes in terms of the area they affect and their impacts on the atmosphere (Ramankutty and Foley, 1999; Wang and Jenkins, 2002; Sen et al., 2004a,b). Although not in comparable extent to them, urbanization has become another important factor in reshaping the land surface of the earth. Because urbanization makes significant changes in the surface parameters, hence in the surface–atmosphere interaction processes, it has the potential to alter the local climate in cities (Oke et al., 1992).

Approximately 47% of the world’s population are currently living in cities, and this number is expected to increase as more people are moving from the countryside to the cities, especially in the less developed countries, where the percentage of the population that live in cities (41% in 2005) is much less than that of the more developed countries (76% in 2005) (Population Reference Bureau, 2005). Urbanization is therefore important in that it alters the climate of the areas where such a high fraction of the world’s population lives. For this reason, numerous studies have been conducted to investigate and understand the urban climatology. Two recent papers provide excellent reviews of these studies: Arnfield (2003) presents the progress in urban climatology during the two decades after 1980, and Voogt and Oke (2003) review the use of thermal remote sensing in the study of urban climate.

Urbanization comes with three major changes that may have impact on the urban atmosphere; replacement of the natural surfaces with buildings and impermeable pavements, heat of anthropogenic origin and air pollution (Yagüe et al., 1991). The changes in the surface properties affect the surface radiation, energy and water balance. An increase of impermeable surfaces results in a decrease in evapotranspiration and loss of latent heat from the ground, thus causing a warming of the urban area (Kalande and Oke, 1980). Impermeable materials also do have greater specific heat capacity that delay the loss of energy absorbed by the ground (Yagüe et al., 1991). City
geometric effects, such as ‘canyon effect’ or blocking of the wind by tall buildings, work toward the heating of the urban areas or inhibiting the cooling of the urban areas. Heat generation and pollution as a result of human activity are other sources of the increase in temperature of the urban areas. All these make the urban atmosphere warmer than its surroundings. This phenomenon is commonly called ‘urban heat island’ (UHI). UHI is best observed on clear and calm nights because radiative cooling differences are maximized between urban and surrounding rural areas (Voogt and Oke, 2003).

UHI is the most commonly studied feature of the urban climatology. Different methods have been used to demonstrate the existence and characteristics of UHI in many cities around the world (Arnfield, 2003). Analyzing the longterm temperature records from urban and nearby rural stations was perhaps the most commonly used method in studying UHI (e.g. Colacino and Rovelli, 1983; Yagüe et al., 1991; Karaca et al., 1995a,b; Philander et al., 1999; Montavez et al., 2000; Tereshchenko and Filonov, 2001; Zhou et al., 2004). Establishing a network of stations within and around a city or taking measurements along transects across an urban area are other common methods to study the characteristics of UHI (e.g. Landsberg, 1981; Oke, 1982; Park, 1986; Montavez et al., 2000; Kim and Baik, 2005).

UHI was also studied via remotely sensed measurements and surface–atmosphere models (e.g. Gallo et al., 1993; Kinouchi and Yoshitani, 2001; Streutker, 2003; Kusaka and Kimura, 2004; Dandou et al., 2005; Jin et al., 2005; Lamptey et al., 2005).

UHI in Istanbul was previously studied by Karaca et al. (1995a,b) using longterm temperature data (up to the year 1992) from stations within and around the city. According to the results of the common statistical tests applied to yearly data, they reported warming trends in the urban temperatures of southern Istanbul, which was the most densely populated part of the city. As the city expanded further and more data became available during the last decade or so, we decided to reevaluate the UHI in Istanbul. In addition to reevaluating the UHI using longterm yearly data from stations, similar to what Karaca et al. (1995a,b) did, the present study specifically addresses the following questions: What is the seasonal behavior of UHI in Istanbul? In which season is it most pronounced? What is the distribution of UHI in this season, and how did it change from 1951 to 2004? How does it affect the overlying atmosphere in terms of temperature, humidity and wind fields? In the present study, in addition to the common statistical tests, similar to those used in the earlier studies, we used a mesoscale atmospheric model to seek answers to the above questions.

DESCRIPTION OF THE STUDY AREA AND CLIMATE

The city of Istanbul, which is located at 41.01°N, 28.58°E, is the largest city of Turkey with a population of over 10 million. The Bosphorus, a 30-km strait that connects the Black Sea with the Sea of Marmara, is considered to be the boundary between Europe and Asia, and the urban Istanbul is located on both sides of the southern half of the strait (Figure 1). The city has historically expanded in east–west direction along the Marmara shore, but in recent years a northerly expansion has also occurred, especially after the 1999 earthquakes in Turkey, to move away from the North Anatolia Fault, which passes along just the south of Istanbul. The north of the city toward the Black Sea is mostly covered by protected forest patches, and the expansion of the city in that direction is mostly confined to the cliffs along the Bosphorus. The settlement areas along the Bosphorus and at the cliffs looking over the strait are somewhat greener than the rest of the city. The most densely populated parts of the city lie in the south, along the Sea of Marmara. Figure 1 also illustrates the expansion of the urbanization with respect to the years 1949, 1968, 1988 and 2000. These data were taken from Çelikoyan (2004), who defined the city boundaries in these years based on airborne and spaceborne measurements. He obtained the 1949 image by combining three different aerial photographs taken in 1940, 1942 and 1949, assuming that the city expanded little in the 1940s.

The population change in Istanbul between 1935 and 2000 is shown in Figure 2. The city’s population nearly doubled in the 20 years between 1980 and 2000, the fastest growth period for the population. For the period between 1990 and 2000, the population growth rate of Istanbul was 29.64% for urban parts and 81% for rural parts of the city. Total population growth rate was 33.1% for the same period. To compare, these figures are 26.8, 4.2 and 18.3%, respectively, for the whole of Turkey. The ratio of urban population to total population in Turkey increased from 59 to 65% from 1990 to 2000, however, this figure is still smaller than that in more developed countries.

The southern parts of provincial Istanbul, where urban areas mostly lie, show the general characteristics of the Mediterranean climate. However, as one goes northward, the Mediterranean type climate is somewhat modified by the cooler Black Sea and northerly colder air masses of maritime and continental origins. This type is locally called ‘the Black Sea Climate’ and described as having cooler temperatures in both winter and summer, and usually experiences more rains compared to the climate of the Mediterranean coasts of Turkey. The northern parts of Istanbul, thus, have slightly cooler temperatures compared to the south. While the south receives about 650 mm precipitation per year, the inland parts receive about 1050 mm and the northern (the Black Sea) coasts about 850 mm annual precipitation. Istanbul, based on station averages, has average air temperatures of 28°C in summer and 8°C in winter. Average annual total precipitation is around 800 mm. The city is subject to moisture laden mid-latitude cyclones during winter months (Karaca et al., 2000); thus most of the precipitation falls in winter. Summer months have the lowest
rainfall amounts. The prevailing wind in Istanbul is northeasterly; but southwesterly winds are also effective during a considerable part of the year. On the basis of the station measurements during the last 30 years, average annual wind speed is 2.72 ms\(^{-1}\). Average seasonal wind speed is highest in winter (2.97 ms\(^{-1}\)) and lowest in summer (2.39 ms\(^{-1}\)).

**STATISTICAL ANALYSIS**

**Data**

Meteorological data used in the statistical analysis of this study have been obtained from the State Meteorological Service of Turkey. The dataset contains time series of ‘monthly minimum temperature’ for the stations located...
in Istanbul (Figure 1). The term ‘monthly minimum temperature’ refers to the average of daily minimums in that month. From this dataset, we calculated the time series of the ‘yearly minimum temperature’, which refers to the average of monthly minimum temperatures in that year, and the time series of ‘seasonal minimum temperature’, which refers to the average of monthly minimum temperatures in that season.

The stations have varying periods of monthly minimum temperature records with Kandilli having the longest (1912–2004) and Kumköy the shortest (1951–2004). Because the methodology used in this study required taking the difference between stations, we used 1951–2004 as the base period for the analysis.

The stations are broadly classified into three groups as urban, suburban and rural, based on population density and our knowledge of these areas (Tayanç et al., 1997). Göztepe is an urban station, completely engulfed by dense city buildings and structures. Florya is also an urban station, but it is open to direct sea effect from the south. Kandilli and Kireçburnu are suburban stations and both are located on the hills overlooking the Bosphorus. Kandilli, however, is closer to the densely urbanized areas compared to Kireçburnu. Bağçeköy is an inland rural station surrounded by forest areas, and Kumköy is a rural station in an area on the Black Sea coast that has only been recently subject to urbanization. The elevations of the stations are within 150 m from the mean sea level and the differences between the elevations of these stations are not more than 100 m.

The urban and suburban stations were, when they were first established, usually out of the city urban boundaries, and they were not certainly meant to observe the urbanization effects on climate. However, the expansion of the city due to urbanization, which was usually erratic and not consistent in all directions as a result of the waterways, water bodies and protected forest areas, left the stations engulfed by the city’s residential and industrial areas. This reduced the representivity of the stations of that initial landscape. For this reason, there is an ongoing debate on whether to terminate the meteorological operations in Göztepe station.

Mann–Kendall trend test

The nonparametric test of Mann–Kendall is used to determine the existence and significance of a trend in the station data. This method also gives the approximate starting point of a trend and abrupt changes in climate (e.g. Goossens and Berger, 1986; Karaca et al., 1995a; Tayanç et al., 1997).

In Mann–Kendall method, climate data is enumerated in the time series. For each element $y_j$, the number $n_i$ of elements $y_j$ preceding it ($i > j$) is calculated in such a way that $y_i > y_j$. The $t$ test statistics is then given by the equation:

$$ t = \sum_i n_i $$

and under null hypothesis, $t$ is distributed nearly normal with an expected value and variance:

$$ E(t) = \frac{n(n-1)}{4} \quad \text{and} \quad \text{var} (t) = \frac{n(n-1)(2n+5)}{72} $$

When a trend exists, the null hypothesis is rejected for high values of $|u(t)|$ with:

$$ u(t) = \frac{|t - E(t)|}{\sqrt{\text{var}(t)}} $$

If $u_t > 0$ the trend is positive and if $u_t < 0$ the trend is negative and the significance level is taken to be 95% ($\pm 1.96$).

The same principle can be applied to the backward series. In this case, we calculate the number $n'_i$ of $y_j$ terms for each $y_i$ term. The values of $u'_t$ for the backward series are given by the equation:

$$ u'_t = -u(t) $$

The intersection of $u_t$ and $u'(t)$ curves shows the starting point of the changing trend. This approach is known as the ‘Sequential Mann–Kendall Test’ (Goossens and Berger, 1986).

Results

The studies that investigate urbanization effect on climate or urban heat island phenomenon, usually employ minimum temperatures that most clearly illustrate the difference between the city and its outskirts (Landsberg, 1981) because the thermal properties of a city are different from those of its surrounding areas, and urban areas have higher thermal inertia, which delays the cooling of the cities at nights compared to their outskirts (Yagüe et al., 1991). Figure 3 shows the differences of average monthly minimum temperatures between the urban stations (Göztepe (a) and Florya (b)) and the other four stations (Kandilli (a1 and b1), Kireçburnu (a2 and b2), Bağçeköy (a3 and b3) and Kumköy (a4 and b4)). The average monthly minimum temperatures are for two 24-year periods before and after 1980, which approximately marks the beginning of a sharp rise in the population increase in Istanbul. There are three important results that can be inferred from this figure. The first one is that the minimum temperature difference between an urban and a suburban/rural stations increase for the period 1981–2004 compared to the period 1957–1980. For instance, the annual average difference for Göztepe–Kumköy (a4) increases from 0.17 C for the period 1957–1980 to 0.81 C for the period 1981–2004, and similarly, it increases from 0.39 to 0.82 C for Florya–Kumköy (b4). The second is that the minimum temperature disparity between the period after 1980 and that before 1980 increases as we go from suburban to rural stations while taking the difference from urban stations. It increases, for instance, from 0.23 C for Göztepe–Kandilli (a1)
Figure 3. Differences of average monthly minimum temperatures between urban and suburban/rural stations. The averages are taken for two consecutive 24-year periods. The solid lines show the differences for the 1957–1980 period, and the dashed ones show those for the 1981–2004 period.

to 0.41 °C for Göztepe–Kireçburnu (a_2) to 0.57 °C for Göztepe–Bahçeköy (a_3) to 0.64 °C for Göztepe–Kumköy (a_4). Another important result is that the disparity usually occurs in all months, but it is usually larger and most emphasized during the summer and fall months.

Table I summarizes the results of the Mann–Kendall test applied to the yearly minimum temperature time series for all stations (last column). All stations except Kumköy exhibit positive trends. Both Göztepe and Florya, which are urban stations, have high Mann–Kendall values (4.19 and 3.13 respectively), which indicate significant trends at 95% (1.96) confidence level. Significant positive trend is also found for Kandilli (2.31). Bahçeköy and Kireçburnu have positive but statistically insignificant trends. Kumköy has a negative trend but it is not significant at 95% confidence level.

Table I. Mann–Kendall statistics from the analysis of time series of seasonal and annual minimum temperature data from meteorological stations in Istanbul for the period between 1951 and 2004 (Statistically significant numbers are marked bold).

<table>
<thead>
<tr>
<th>Stations</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Göztepe</td>
<td>4.13</td>
<td>4.89</td>
<td>1.70</td>
<td>0.84</td>
<td>4.19</td>
</tr>
<tr>
<td>Florya</td>
<td>2.93</td>
<td>4.26</td>
<td>1.04</td>
<td>−0.49</td>
<td>3.13</td>
</tr>
<tr>
<td>Kandilli</td>
<td>2.84</td>
<td>4.07</td>
<td>0.41</td>
<td>−0.31</td>
<td>2.31</td>
</tr>
<tr>
<td>Kireçburnu</td>
<td>2.65</td>
<td>2.84</td>
<td>−0.49</td>
<td>−0.34</td>
<td>1.35</td>
</tr>
<tr>
<td>Bahçeköy</td>
<td>3.01</td>
<td>2.56</td>
<td>−0.80</td>
<td>−0.80</td>
<td>1.20</td>
</tr>
<tr>
<td>Kumköy</td>
<td>1.29</td>
<td>1.23</td>
<td>−1.56</td>
<td>−0.98</td>
<td>−0.75</td>
</tr>
</tbody>
</table>

Table I also provides seasonal Mann–Kendall statistics for all stations. Spring (March, April and May) and summer (June, July and August) emerge to be the
seasons when the urbanization effect on climate is most pronounced. In these seasons, Mann–Kendall values are positive and significant for all stations except for Kumköy, which has a positive but insignificant trend. No significant trend is found for fall (September, October and November) or winter (December, January and February) in any station.

The Mann–Kendall trend test has so far been applied to the minimum temperature time series of individual stations. This type of analysis alone is usually deemed inadequate to detect the sole urbanization effects on climate because the trends may contain other climate change signals as well. To avoid such complications, Mann–Kendall trend test is usually applied to the time series of temperature difference between an urban/suburban station and a nearby rural station (Karaca et al., 1995a,b). In this way, it is expected to reduce the proportion of the climate change signals due to factors other than urbanization.

Figure 4 shows the results of sequential Mann–Kendall method applied to the time series of annual minimum temperature differences between the four urban/suburban stations and Bahçeköy station. Bahçeköy is an inland station, and it is located in a village in the middle of a forest patch. The village has become popular in recent years; therefore, it has begun to grow, though slowly. The Sequential Mann–Kendall analysis indicates that the time series of annual minimum temperature differences taken between Göztepe/Florya/Kandilli and Bahçeköy (a, b and c) have significant positive trends. For Kireçburnu (d), the positive trend became significant for a few years around 2000, but it fell under 95% confidence level in 2004. The changes in the trends of these time series began around early 1980s for Göztepe and Florya, and late 1980s for Kandilli and Kireçburnu. A similar analysis was carried out using Kumköy as the reference station instead of Bahçeköy (Figure 5). Kumköy, as mentioned earlier, is a village station on the Black Sea coast, thus, being open to sea effect. This area, too, has been subject to urbanization in recent years. The analysis demonstrates that all four time series of differences obtained from subtracting urban and suburban annual minimum temperatures from Kumköy annual minimum temperatures have positive and significant trends at 95% confidence level. The analysis also indicates that the change points in the trends of these time series were in the early 1970s for Göztepe (a), Florya (b), and early 1980s for Kandilli (c) and Kireçburnu (d). The Mann–Kendall statistics for these analyses are summarized in Table II. Table II also provides seasonal Mann–Kendall statistics for corresponding time series obtained by the subtraction of urban/suburban station data from rural station data. Summer appears to have the highest values for all pairs except for Kireçburnu–Bahçeköy and Kireçburnu–Kumköy. Both have the highest values in winter. But Kireçburnu–Bahçeköy does not have a significant value as Kireçburnu–Kumköy does. It can be inferred from this table that fall has higher values than spring does, whereas, the analysis based on individual station data showed that spring had higher Mann–Kendall values than fall did.

Figure 4. Results of sequential Mann–Kendall test applied to annual minimum temperature differences between urban/suburban stations (Göztepe, Florya, Kandilli, Kireçburnu) and a rural station (Bahçeköy). The value ±1.96 (the 95% confidence level) is represented with horizontal dashed lines.
CLIMATIC EFFECTS OF URBANIZATION IN ISTANBUL

Figure 5. Results of sequential Mann–Kendall test applied to annual minimum temperature differences between urban/suburban stations (Göztepe, Florya, Kandilli, Kireçburnu) and a rural station (Kumköy). The value ±1.96 (the 95% confidence level) is represented with horizontal dashed lines.

Table II. Annual and seasonal Mann–Kendall statistics from the analysis of time series of minimum temperature differences between urban and rural stations for the period between 1951 and 2004 (statistically significant numbers are marked bold and highest seasonal values are underlined).

<table>
<thead>
<tr>
<th>Station pairs</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Göztepe–Bahçeköy</td>
<td>4.26</td>
<td>6.31</td>
<td>5.00</td>
<td>3.42</td>
<td>5.60</td>
</tr>
<tr>
<td>Göztepe–Kumköy</td>
<td>5.51</td>
<td>6.96</td>
<td>5.78</td>
<td>4.89</td>
<td>6.84</td>
</tr>
<tr>
<td>Florya–Bahçeköy</td>
<td>0.18</td>
<td>4.33</td>
<td>3.48</td>
<td>0.35</td>
<td>3.22</td>
</tr>
<tr>
<td>Florya–Kumköy</td>
<td>3.48</td>
<td>5.25</td>
<td>4.62</td>
<td>3.05</td>
<td>5.93</td>
</tr>
<tr>
<td>Kandilli–Bahçeköy</td>
<td>0.64</td>
<td>3.27</td>
<td>2.59</td>
<td>0.29</td>
<td>2.07</td>
</tr>
<tr>
<td>Kandilli–Kumköy</td>
<td>2.98</td>
<td>4.08</td>
<td>3.76</td>
<td>2.62</td>
<td>4.35</td>
</tr>
<tr>
<td>Kireçburnu–Bahçeköy</td>
<td>0.09</td>
<td>0.55</td>
<td>0.89</td>
<td>1.30</td>
<td>1.68</td>
</tr>
<tr>
<td>Kireçburnu–Kumköy</td>
<td>3.39</td>
<td>1.87</td>
<td>3.10</td>
<td>4.46</td>
<td>4.39</td>
</tr>
</tbody>
</table>

We further extended our analysis on the minimum temperature difference series between urban/suburban and rural stations by applying linear regression to see how the UHI intensity changed from 1951 to 2004. The UHI intensity is defined by Oke (1987) as the temperature difference between the ‘city peak’ and the rural background temperature of the night, cloudless skies and light wind conditions. Because we do not have all the information that complies with this definition, we assume that the linear fit, which eliminates the year-to-year variability, is a measure of the change of average UHI intensity over time. Table III gives the UHI intensity changes between 1951 and 2004 for the station pairs. These values are calculated based on linear fit to the time series of the minimum temperature differences between urban/suburban and rural stations, and they express the differences of linear regression values between 2004 and 1951. The differences are usually larger when the reference rural station is Kumköy. Maximum differences are observed in the urban–rural pairs. For instance, annual UHI intensity increases 1.43 °C for Göztepe–Kumköy pair and 0.94 °C for Florya–Kumköy pair over the 54-year period. The UHI intensity changes are usually the largest in the summer and lowest in the winter. In general, the values of the UHI intensity changes are smaller than those reported in the literature, and this could be related to the fact that the city of Istanbul lies along large water bodies and waterways. In fact, there are studies (e.g. Kim and Baik, 2004)

Table III. Annual and seasonal warming values (in °C) from 1951 to 2004 based on linear regression analysis of time series of minimum temperature differences between urban and rural stations for the period between 1951 and 2004.

<table>
<thead>
<tr>
<th>Station pairs</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Göztepe–Bahçeköy</td>
<td>0.75</td>
<td>1.40</td>
<td>1.24</td>
<td>0.66</td>
<td>1.00</td>
</tr>
<tr>
<td>Göztepe–Kumköy</td>
<td>1.25</td>
<td>1.75</td>
<td>1.68</td>
<td>1.19</td>
<td>1.43</td>
</tr>
<tr>
<td>Florya–Bahçeköy</td>
<td>0.10</td>
<td>0.87</td>
<td>1.21</td>
<td>0.10</td>
<td>0.52</td>
</tr>
<tr>
<td>Florya–Kumköy</td>
<td>0.67</td>
<td>1.17</td>
<td>1.65</td>
<td>0.63</td>
<td>0.94</td>
</tr>
<tr>
<td>Kandilli–Bahçeköy</td>
<td>0.10</td>
<td>0.65</td>
<td>0.55</td>
<td>0.02</td>
<td>0.31</td>
</tr>
<tr>
<td>Kandilli–Kumköy</td>
<td>0.61</td>
<td>1.00</td>
<td>0.98</td>
<td>0.54</td>
<td>0.73</td>
</tr>
<tr>
<td>Kireçburnu–Bahçeköy</td>
<td>0.04</td>
<td>0.16</td>
<td>0.19</td>
<td>0.22</td>
<td>0.18</td>
</tr>
<tr>
<td>Kireçburnu–Kumköy</td>
<td>0.54</td>
<td>0.50</td>
<td>0.63</td>
<td>0.75</td>
<td>0.60</td>
</tr>
</tbody>
</table>
that report that the UHI intensity tends to be smaller in coastal cities than in inland cities.

The statistical analysis of station data yields important results for climatic effects of urbanization in Istanbul. From this analysis, it is clear that urbanization is the reason behind the increases in the minimum temperatures in Istanbul. Despite this result, it is difficult to depict a complete picture of the urban heat island of Istanbul as there are not enough stations uniformly distributed across the city. Moreover, the surface data do not give any information about how high the urbanization affects the overlying atmosphere. To seek answers to these issues, we decided to carry out a mesoscale atmospheric modeling experiment whose details are given in the next section.

NUMERICAL MODELING EXPERIMENT

Model

For the modeling experiment, we employed the widely used MM5 model, which was jointly developed by the Penn State University (PSU) and National Center for Atmospheric Research (NCAR). The MM5 model is a limited area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation. It is a community mesoscale modeling system that includes several physical options for radiation, cumulus, planetary boundary layer, surface and explicit moisture parameterizations. The MM5 model is commonly used for numerical weather prediction, air quality and hydrological studies (e.g. Mass and Kuo, 1998; Kindap et al., 2006; Warner et al., 1991).

Experimental design

The MM5 model allows nested modeling. We took advantage of this feature and used nested grids with spatial resolutions of 27, 9 and 3 km, respectively, and 23 vertical layers. The outermost domain covered an area (33–48°N and 15–35°E) including western half of Turkey, Balkans and eastern half of Italy. The innermost domain spanned 111 km east–west direction and 111 km north–south direction covering the city of Istanbul and surrounding land and water masses. Our computing facilities allow us to go as high as 3 km spatial resolution for the innermost domain, which was, unfortunately, not high enough to fully resolve the Bosporus strait and some of the detailed features of the city.

United States Geological Survey land use (25 category) and terrain data with 30-s resolution were used in the simulations. Initial and boundary conditions were provided by the NCEP/NCAR reanalysis data (at 2.5 × 2.5 degrees and 17 vertical levels). Among several physical options in the MM5 model, rapid radiative transfer model (RRTM) atmospheric radiation scheme, Grell (for the two outermost domains) and Kain–Fritsch (for the innermost domain) cumulus parameterization schemes, MRF (NCEP Medium Range Forecast) planetary boundary layer scheme, 5-layer soil scheme and mixed-phase microphysical scheme were selected for the simulations in this study.

Because the statistical analysis showed that the largest impact of urbanization on the local climate is in summer, we selected a summer month (July, 2004) with typical climatic conditions for the numerical experiment. The experiment is designed to reflect the difference in the UHI between scenarios with ‘recent’ and ‘past’ landscapes. The two different landscape maps for the MM5 model are prepared based on the data given in Çelikoyan (2004). To conduct a comparable modeling study with the station statistics, we aimed to conduct the ‘past’ simulation with 1951 and ‘recent’ simulation with 2004 landscape maps, but Çelikoyan (2004) provides urbanization maps for only certain years. For this reason, we had to choose the closest years to 1951 and 2004 for which Çelikoyan (2004) provides a landscape map. For the ‘past’ simulation this is 1949, and for the ‘recent’ simulation it is 2000. Thus, the model’s surface maps for 1951 and 2004 were prepared using the city urban boundaries provided in Çelikoyan (2004). It turned out that the model uses a very old land cover/vegetation map that does not reflect the current urban boundaries in Istanbul at all; therefore, we had to make a substantial change, especially for 2000 (102 model grids), to incorporate approximately the current urban landscape into the model. In this practice, these model grids, most of which were ‘dryland crop’ class (a small number of them were ‘crop/grass mosaic’, ‘grassland’, ‘shrubland’ and ‘deciduous broadleaf’ classes), were assigned ‘urban’ class. Table IV, whose information is derived from the MM5 manual, provides the values of some parameters for these classes. When the landscape is changed from ‘dryland crop’ to ‘urban’, the albedo changes from 17% to a slightly larger value (18%), moisture availability from 30% to a much smaller value (10%), emissivity from 92% to a smaller value (88%), roughness length from 15 cm to a much bigger value (50 cm), and thermal inertia from 0.04 cal cm−2 k−1 s−1/2 to a smaller value (0.03 cal cm−2 k−1 s−1/2). Strictly speaking, the modeling experiment is designed to simulate the urbanization effects within the context of the changes in the above parameters as a result of landscape change and it does not include any changes in the city’s structural and geometrical features that are difficult to resolve and incorporate in the model at a 3-km resolution. For both 1951 and 2004 simulations the model is forced by the same initial and boundary conditions to observe the response of the urban atmosphere to the urbanization in Istanbul.

Results

Figure 6 exhibits the difference between 2004 and 1951 surface temperatures (reference level) averaged from the simulated 6 A.M. values for July. It is clear from Figure 6 that two urban heat island cells emerge in Istanbul: one on the European side and the other on the Asian side of the city. Note that this figure only shows the expansion of the UHI after 1951. The complete UHI in Istanbul is expected
Table IV. Land use type features in MM5.

<table>
<thead>
<tr>
<th>Land use type</th>
<th>Dryland crop</th>
<th>Crop/Grass mosaic</th>
<th>Grassland</th>
<th>Shrubland</th>
<th>Deciduous broadleaf</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albedo(%)</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>22</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>Moisture availability (%)</td>
<td>30</td>
<td>25</td>
<td>15</td>
<td>10</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>Emissivity (% at 9 µm)</td>
<td>92</td>
<td>92</td>
<td>92</td>
<td>88</td>
<td>93</td>
<td>88</td>
</tr>
<tr>
<td>Roughness length (cm)</td>
<td>15</td>
<td>14</td>
<td>12</td>
<td>10</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Thermal inertia (cal cm⁻² k⁻¹ s⁻¹/²)</td>
<td>0.04</td>
<td>0.04</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Figure 6. Surface temperature (reference level) difference (in °C) between 2004 and 1951 July simulations. The difference is calculated from monthly averaged 6 A.M. surface temperature outputs of model simulations.

to cover the urbanized parts of the city before 1951 too. Given the fact that the MM5 model cannot completely resolve the Bosporus strait, it can be realized that the two-cell structure occurs primarily as a result of pre-1951 urban areas (mostly situated along the Bosporus) that are treated identically in both simulations. The maximum difference between 2004 and 1951 surface temperatures at 6 A.M. for July is around 1°C. Figure 7 shows the corresponding water vapor mixing ratio difference. It is clear that the urbanization decreases the mixing ratio in the overlying atmosphere as a result of reduced moisture availability (see Table IV). The maximum decrease in mixing ratio is around −0.15 g kg⁻¹. Figure 7 also shows that the surface mixing ratio is increased over a region to the west of urbanized areas in Istanbul. Figure 8 illustrates surface wind (10 m) anomalies between 2004 and 1951 because of urbanization in Istanbul. It seems that the urbanization decreases the wind magnitude over the city and surrounding areas. The wind vectors show a southwesterly anomaly. The changes in wind magnitude and wind vectors together imply that the velocity of the northeasterly winds (prevailing winds in July) is reduced over Istanbul. This should primarily be a response to the increased roughness length when the landscape is changed from past landscape to urban, which usually has larger roughness length. In addition to the changes in the surface air, we looked into the changes at higher levels in the atmosphere over the city. We examined the temperature differences at different heights to see how the UHI developed at these heights, and longitudinal cross sections of air temperature differences on the European and Asian sides to see how high the urbanization effect penetrates into the overlying atmosphere. Figure 9 shows 6 A.M.-temperature differences between 2004 and 1951 at two levels, about 36 m (a) and about 200 m (b) above the ground, and cross sections of the temperature differences along 28.75E on the European side (c) and 29.16E on the Asian side (d). It seems that the two UHI cells apparent in the surface air temperature difference are combined at higher atmospheric levels over the Bosporus (Figure 9a and b), and the combined cell extends southward over the Sea of Marmara most likely because of the prevailing
northeasterly flow in July, but still the largest temperature differences are over the urban areas. The heating effect of urbanization could easily reach up to 600–800 m heights (Figure 9c and d). A slightly cooled region appears in a layer between 600 and 800 m above the ground, just north of the urbanized areas in the European side, (c) and in a layer between 800 and 1200 m above the ground, over the urban areas on the Asian side (d).

SUMMARY AND CONCLUSIONS
This study investigates the climatic effects of urbanization in the city of Istanbul. The thermal behavior of the
urban stations (Göztepe and Florya) with reference to suburban (Kandilli and Kireçburnu) and rural stations (Bahçeköy and Kumköy) before 1980 is compared to that after 1980 on a monthly basis. To determine the existence and significance of a trend, nonparametric Mann–Kendall tests are applied to minimum temperature data that are taken between 1951 and 2004 at the stations in the city and those in the close proximity of the city. The same method is applied to the time series of the minimum temperature differences between urban/suburban and rural stations for the same purpose as taking such differences is thought to eliminate the climate change signals caused by factors other than urbanization. Sequential Mann–Kendall test is used to identify the approximate starting point (year) of the change in the trends of these time series. In addition to statistical analysis, a mesoscale atmospheric model is deployed to investigate the change in the urban heat island of Istanbul from 1951 to 2004. The results from both the statistical analysis and the modeling experiment are summarized as follows:

1) Statistically significant positive trends are found in Göztepe, Florya and Kandilli annual minimum temperature data for the period between 1951 and 2004. Kireçburnu and Bahçeköy exhibit positive trends too, but they are not significant. Kumköy shows negative but insignificant trend. Seasonal Mann–Kendall trend analysis of individual station data indicates that statistically significant positive trends occur only in spring and summer for all stations except for Kumköy, which has no significant seasonal trend at all. Another analysis that takes into account the time series of annual minimum temperature differences between urban/suburban and rural stations shows significant positive trends for all pairs in case the reference station is Kumköy. In case Bahçeköy is taken as the reference station, all pairs except Kireçburnu–Bahçeköy show significant positive trends. The sequential Mann–Kendall analysis of these data series reveals that all of the trend changes started after 1980 when Bahçeköy
The modeling experiment, which is performed for the European and Asian sides of Istanbul. This may imply that the urban heat island intensity calculated for Göztepe and Florya are most likely smaller than those expected to occur at the centers of urban areas because the expansion of the city has somewhat left these stations closer to the edges rather than the centers. Putting these together, it could be said that the modeling experiment somewhat underestimated the maximum warming in Istanbul over the 54-year period between 1951 and 2004. However, one should bear in mind that the modeling experiment does not include all the aspects of urbanization, let alone the limitations due to the model and experimental design. Still, it reveals some important features related to the urban heat island of Istanbul. The experiment shows that the two-cell surface heat island combines and makes a single-cell one at higher atmospheric levels. The experiment also reveals that the urban heating effects could penetrate as high as 600–800 m in the atmosphere, and that a cooling layer occurs aloft. Tapper (1990) reported a similar phenomenon to the latter. The model results also indicate a drier and calmer surface air, which together with the excess warming due to the urbanization increase the depth of the planetary boundary layer over the city (not shown). Although the modeling experiment is very limited in several aspects, the modeled changes in the atmosphere may imply that the UHI of Istanbul may enhance convection over the city and make its boundary layer relatively unstable. Several studies (e.g. Shepherd et al., 2002; Changnon and Westcott, 2002) suggest that local dynamics and thermodynamics associated with an UHI-induced convergence zone and a destabilized boundary layer may enhance rainfall in and around cities.

The present study addresses some UHI questions for Istanbul that were not answered in the previous studies, and the statistical and modeling tools used in this study were satisfactory in this regard. However, there are more questions related to the climatic effects of urbanization in Istanbul that require further research involving higher resolution data and models to better resolve and represent the landscape of Istanbul. For instance, water resources of the city mostly lie in the central and northern parts of the provincial Istanbul, and given the delicate environment and location of the city, it is very important to investigate how the urbanized Istanbul environment interacts with the atmospheric systems to impact rainfall and its distribution and hence the city’s water resources. Furthermore, the model results indicate a warmer, drier and calmer environment for Istanbul that may have important implications for this crowded historical city. The modified environment would definitely have impacts on human health, historical site/building conservation and energy consumption in Istanbul. The present study was not planned to address such issues, but they may well be the topic of another study.

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