The Columbia, Missouri, Heat Island Experiment (COHIX): The Influence of a Small City on Local Surface Temperature Distributions and Implications for Local Forecasts

Anthony R. Lupo[1] Patrick S. Market[1] F. Adnan Akyüz[1,2] Patrick E. Guinan[1,2]

Janelle E. Lam[1] Angela M. Oravetz[1] William C. Maune[1]

[1]Department of Atmospheric Sciences
389 Mc ReynoldsHall
University of Missouri – Columbia
Columbia, MO 65211

[2] Missouri Climate Center
365 Mc Reynolds Hall
University of Missouri-Columbia
Columbia, MO 65211

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**Corresponding author address: Anthony R. Lupo, LupoA@missouri.edu.*

Abstract

The heat island effect is a well known feature in the microclimate of large urban areas, but only a few studies have addressed the heat island effect for smaller cities. Here we examined the combined impact of Columbia, Missouri, and the University of Missouri campus on the microclimate of central Missouri; temperature was the primary variable examined here. Students, staff, and faculty at the University of Missouri volunteered to provide readings over a one-year period of study. Twenty Radio Shack® digital Max/Min thermometers were purchased and given to participants who were chosen for their reliability to provide data, site the instrument, and their location (in order to provide reasonable coverage locally). Also included in the data set was information provided by area automated weather stations, cooperative weather stations, and the station at the Columbia Regional Airport located 11 km (7 miles) southeast of Columbia. When examining the monthly mean temperatures, there is a distinct urban influence on the local surface temperatures. In particular, the inner city region and the urbanized area of south Columbia were approximately 2 – 3 ^{o}F warmer in the mean than the surrounding environment. This difference grows to 3 – 6 ^{o}F when comparing the mean of the warmest station in the city to the mean of coolest station outside Columbia. There is also a seasonal influence observed, as the heat island effect is more evident in the mean monthly maximum (minimum) temperatures during the warmest (coldest) months. This kind of information could be helpful in augmenting forecasts using the latest technology available to weather forecasters.

1. Introduction

The effect of urban environments on local temperature and precipitation distributions have been examined in the past (e.g., Changnon, 1981; Segal and Arritt, 1992; Karl and Knight, 1997; Melhuish and Pedder, 1998; Pinho and Manso-Orgaz, 2000; Rozoff and Cotton, 2001; Changnon, 2003). These studies have usually focused on cities that have large populations, however, Melhuish and Pedder (1998) and Pinho and Manso-Orgaz (2000) examine the heat island effect in smaller urban areas. The "heat-island effect" produced by cities can have a profound impact, sometimes adverse, on the well-being of its residents (e.g., Karl and Knight, 1997). Weather elements that impact on human health and comfort are routinely included in local forecasts and/or forecast discussions or are accounted for by forecasters in their county warning areas.

The heat island effect is produced by many factors which result in a change in the underlying energy budgets in the boundary layer due to urbanization. These include effects such as (e.g., Oke, 1982); an increase in sensible heating (e.g., due to changes in surface albedoes), an increase in thermal storage capacity of the underlying surface, decreased evapo-transpiration, and heat given off (generated) by urban structures. These processes then can have an impact on the temperature field (see references above) and the precipitation field (e.g., Shephard et al., 2002; Rozoff et al. 2003; Changnon, 2003). A few studies examined also the climatological (long-term) impact of heat islands including their variance by season (e.g., DeMarrais, 1975; Ackerman, 1985).

There is published work (e.g., Melhuish and Pedder, 1998; Pinho and Manso-Orgaz, 2000) demonstrating that medium-sized and small urban areas may also be responsible for heat-island effects. While the heat islands associated with these smaller urban areas would not be expected to be as pronounced as those of larger cities, the heat island effect in the latter study was shown to be quite substantial (up to 7.5^{o} C for individual days). Columbia would be at the smaller end of the spectrum of what is considered to be an urban area in the United States and is composed of a downtown area and the University of Missouri campus. Intensive residential and retail development flanks these two core regions.

The main objective for this work was to demonstrate the temporal and spatial extent to which Columbia, Missouri (a smaller urban area), and the University of Missouri campus produce a heat-island effect that could be incorporated into forecasts using the latest technology and made available to the public (e.g., the National Digital Forecast Database or NDFD, see Glahn and Ruth (2003) and references therein).

2. Data and Methodology

a. Data

Volunteer participants provided the temperature data, which were measured using a Radio Shack® Indoor/Outdoor Maximum-Minimum thermometer (Item #63 - 1014). These instruments resided indoors and included a 10-ft probe, which was deployed outdoors. The Missouri Climate Center, the Columbia Regional Airport, two cooperative weather stations, and two automated weather stations in the Columbia area provided additional temperature data. The Columbia Regional Airport (COU) is located approximately 11 km south-southeast of the city. Not every "station" reported every single month or every single day, thus these data were evaluated for suitability and discarded in calculating the heat island using monthly means accordingly. Degrees Fahrenheit are used here since that is still the standard for surface observations in the United States.

b. Methodology

For our purposes, Columbia, Missouri (Fig. 1) was considered to be a small urban area. We defined a small city as one that has a population of more than 75,000 (but less than 200,000) residents and covers an area of roughly 40 km^2 (25 $mi.^2$) or more. Excluding the transient student population, Columbia, Missouri has roughly 80,000 residents. This number is greater than 120,000 if the residential areas near the city limits are included; 140,000 when the student population is in residence. This is smaller than the urban area studied by Meluish and Pedder (1998), but considerably larger than that in the Pinho and Manso-Orgaz (2000) study.

The terrain surrounding the Columbia region (Fig. 2) varies from about 183 m (600 ft) in some low-lying creek beds to approximately 244 m (800 ft) south of the city. In Fig. 2, these creek beds, which eventually lead into the Missouri River, are highlighted in green. The terrain becomes gently rolling hills, especially to the south and east of the city. All the instruments were cited to avoid creek bed areas and as such the readings should be less subject to micro-scale effects such as cool air drainage. The elevation of the instruments in Fig. 1 ranged from about 220 – 235 m.

Faculty, staff, and students (22 volunteer participants in all - 17 were observers and 7 analyzed or archived the data) in the Atmospheric Sciences Program (and some outside the program) were invited to participate in this project. Enlisting volunteer participants to measure local variations in climatic parameters has produced successful results in other locations (e.g., Doeskin and Weaver, 2000). Those who deployed instruments were ultimately selected on the basis of their location in the Columbia region, and their ability to accommodate the proper deployment techniques of the instrument(s). Students were given explicit instructions on how to deploy the instrument. Also included in the site selection was an attempt to concentrate some instruments in the south-central part of Columbia, which has less green-space in comparison to other regions of the city due to recent development.

In order to determine if the heat island effect was detectable given the fact that each Radio Shack® instrument did not read the same values despite being subject to the same conditions, the instruments were compared to a standard instrument. The standard deviation among the set thermometers was calculated. The range in the set was 1.0 ^oF (1.3 ^oF) at room temperature (in an ice bath), and the standard deviation was 0.35 ^oF in the set for both trials. Thus, any heat-island effect would have to be significantly larger than the standard deviation after correcting the data to the standard. Also, a Radio-Shack® instrument was tested in real time against an electronic thermometer, HMP35C, used by the automated weather stations, and there was remarkable agreement between the two instruments (this automated instrument would fall somewhere in the middle of our max/min. instrument sample). Rigorous statistical testing other than the informal test described above was not performed since the small sample precludes producing statistically robust results. In spite of this problem, meaningful results can be obtained (e.g., Nicholls, 2001) and compared to studies which found similar results.

The participants collected the maximum and minimum temperature once daily at 0400 UTC (10:00 pm LST). These data were recorded and then averaged, with the goal of determining if the heat island existed in the mean data field. The strength of the heat island effect is defined as:

$$HI = T_{ic} - T_{os} \quad (1)$$

where T_{ic} is the mean temperature recorded by the "inner city" units (defined as the square area on Fig. 1) and T_{os} is the mean temperature recorded by the instruments more than 1 mile outside the city limits. The mean temperatures produced by this instrumentation network in these regions are compared in order to examine the distribution of the heat island effect.

3. Season-by-season results using monthly means

The analysis of the COHIX project data started with July 2000. Table 1 and Fig. 3 show the results after examining the data from 1 July 2000 to 30 June 2001. Table 2 shows the observed mean monthly temperatures and their departures from the 1961 - 1990 means (since part of the experiment took place in 2000).

a. July and August 2000 results

The monthly mean temperature for July (August) was below (above) normal when comparing the mean at the COU airport with the 30-year normals (Table 2). As shown in Table 1, there was a difference of 2.7 and 2.8 ^{o}F between the mean of the inner city and outside city stations (HI) for the maximum and minimum temperatures for July, respectively. All the inner city stations, in general, recorded monthly mean temperatures that were higher than the highest means recorded outside the city for maximum or minimum temperatures. The largest difference between the warmest individual inner city station and the coolest outer city station was 3.3 ^{o}F and 4.7 ^{o}F for the maximum and minimum temperatures, respectively (Table 1, HI_{max}). During August (Fig. 4), the heat island effect was stronger for the maximum temperatures than that found for July (3.4 ^{o}F), while the minimum temperatures produced a weaker signal (1.9 ^{o}F). The largest differences between individual stations were 4.8 ^{o}F for maximum temperatures and 3.3 ^{o}F for the minimum temperatures. The warmest individual stations were inner city stations, while the coolest stations were outside the city.

b. September - November 2000 results

The HI values for the each of the fall months were smaller for the maximum temperatures than for the minimum temperatures (Table 1). For September and October, the maximum temperatures were slightly less than 1 ^{o}F in the city of Columbia as compared to the outside, while the minimum temperatures were nearly 2.5 ^{o}F warmer in the city. These values are smaller than the comparable values for the July and August period. During November, however, the heat island effect was comparable to that of August despite cloudier conditions, with the minimum temperatures showing the stronger signal. An examination of the differences between the warmest and coldest individual stations (Table 1) reveal that these values are comparable to those of the warmer months. This suggests that the coverage of the heat island effect may have shrunk in area coverage and weakened during the cooler months, and examining contour plots of August (Fig. 4) versus October (Fig. 5) supports this hypothesis.

c. December 2000 - February 2001 results

The heat island effect for December was as strong as that for the summer months (Table 1), but like the fall season, the region of Columbia affected was smaller in area and effect was greater for the minimum temperature. However, December showed the greatest difference of any month between the warmest inner city station and the coolest station outside the city. This may be related to the persistent snow cover that remained in place for much of the month fundamentally altering characteristics of the underlying surface and, thus, the radiation balance at the earth's surface. During January and February, the strength (Table 1) and distribution (not shown) of the heat island effect was more typical of the values for the fall season.

d. March - June 2001 results

The strength of the heat island for the spring months was similar to that of the other months when examining HI or taking the difference between the warmest inner city station and the coldest station outside the city (Table 1). However, there was a difference in the area coverage of the heat island as the effect expanded during these months and by May and June the area coverage was similar to that of July and August of 2000 (not shown). Also, the strength of the heat island effect was quite large during June, and the effect was larger for the maximum temperatures than for the minimum temperatures. Table 1 supports the assertion of an expanding heat island during the spring season when comparing the values of Tb (temperatures at stations inside the city limits but not in the inner domain) to those of the inner (Tic) and outer (Tos) city stations. During the latter part of the fall and throughout the winter months, the values of Tb were closer to those of Tos. Then during the spring season, these two values were closer to Tic as they were during July and August of 2000.

e. Discussion

An examination of the data reveals that when the monthly average of inner city stations are compared to those outside the city (Fig. 3), there is a discernable urban influence in the local temperature fields on the order of 2 - 3 ^{o}F. This difference grows to 3 - 6 ^{o}F when comparing the monthly means of the warmest inner city station versus the coldest station outside the city. These values are consistent with those found by Pinho and Manso - Orgaz (2000) for a smaller city, and are a little less than those which might be expected for a city of Columbia's size (see Aguado and Burt, 2001, ch. 14). Thus, the investigators are confident that their result is robust even though no rigorous statistical testing was performed due to the small sample size. It should also be noted that the heat island effect found here is larger than the spread in the instrument sample, the standard deviation of the sample, and even the precision of the instruments used (+/- 1^{o} C or 1.8 ^{o}F for the Radio-Shack® instrument).

That the heat island effect is not of the magnitude expected for a city of Columbia's size may be partially due to the fact that Columbia has made an effort to increase the amount of green-space within city limits over the last 15 years. The assertion that green-space can reduce the heat island effect is supported by Table 1 when comparing the values of Ts (stations in the southern part of the city where there has been more intensive development and decreasing green-space) to those of Tic, Tos, and Tb. The values of Ts are generally more similar to Tic than those of Tb or Tos. However, another possible reason for the results found here may be that no instruments were deployed in the center of town where there are more buildings and more concrete and asphalt covered surfaces. No instruments were deployed in this area since proper instrument deployment, data collection, and instrument integrity could not be guaranteed.

The heat island itself does vary with the seasons as is shown by Table 1, Figs. 4,5 and the discussion above. The heat island effect does expand in area extent during the warmer months and contracts during the colder months. This contradicts the commonly held belief that heat islands expand during the cold season. The contraction of the heat island here may be due to several factors including, increased cloudiness during the cold season, or the low sun angle. Also, the Columbia region does not have the construction density of larger cities, thus it is likely that the regional surface may be of more uniform character in terms of surface albedoes after vegetation dies off in the fall and grows again in the spring.

The HI values are similar for all months whether the means of all the inner city and stations outside the city are used, or the warmest (coldest) stations from the former (latter) group are compared. It also appears that the heat island effect is stronger in the maximum (minimum) temperatures during the summer (winter) months. Finally, December 2000 stands out as a month in which the heat island effect was strongest. This may be due, at least partially, to the fact that this month was the second coldest December in the history of Columbia, and was associated with an unusually persistent snow cover during that month. The persistent snow cover would fundamentally alter the regional surface radiation balance as snow cover is well known to be a strong reflector (emitter) of shortwave (longwave) radiation. Also, snow cover in the regions outside the city would be expected to stay fresher for a longer period of time, while snow is removed from large portions of Columbia's surface area. What snow remains becomes dirtier more quickly in Columbia since the city maintenance department liberally spreads black cinders on the roads to improve vehicle traction on snow covered roads and absorb more sunlight. However, we acknowledge that the December heat island may also be partially due to the increased need for heating in the city as suggested by Oke (1982) and others. Nonetheless, since the areal coverage of the strong heat island was similar to that of the other fall months, and did not expand as other studies have shown, the former explanation regarding the change in albedo due to snow cover is plausible.

An examination of individual days shows that for 54 (31) of the daily maxima (mininma), the temperatures were 5 – 10 ^{o}F greater inside the city than outside the city. Most of these were associated with mostly clear skies and winds of less than 10 kts. Most of these daily maxima (minima) occurred during the warm (cold) season, which reflects the seasonal changes in monthly means described above. While these represent a small percentage of the days during the year, this kind of information, for example, could make a difference in the urban area forecasts on a digital map for extremely warm days, or during, for example, freezing rain events (Changnon, 2003).

4. Summary and Conclusions

Many publications have shown the impact on small-scale regional surface temperatures as caused by urbanization or agricultural activities. The heat island effect has been studied extensively for larger cities, but there are fewer studies examining this effect for smaller urban areas. For this study, 17 thermometers were distributed throughout the Columbia, MO, region to examine the impact of the city and the University of Missouri campus on the surface temperature fields. Daily data was gathered from 1 July 2000 to 30 June 2001.

We examined mean monthly data in order to determine if the heat island effect is detectable in the region's microclimate, and all 12 months exhibited a clear "heat island effect" as the mean temperature of the inner city sites exceeded those of the sites outside the city. The heat island effect was much larger than both the standard deviation of the 20 individually purchased (and deployed) instruments or their range when they were tested under "uniform" conditions. This suggests that the Columbia, MO, heat island effect is a significant feature in the local microclimate. The heat island effect was larger in area during the warm season with a stronger effect shown in the maximum temperatures during the summer months and in minimum temperatures during the winter months. Also, fundamentally altering the surface type such as adding green-space or a persistent snow cover is shown to influence the strength of the heat island. When examining the strength of the heat island as calculated by the difference between the monthly means of the warmest individual station inside the city and the coolest station outside the city revealed temperature differences of 3 - 6 ^{o}F.

With this type of knowledge about urban areas in a forecaster's CWA, this kind of temperature information could be included in routine forecasts which utilize new technologies for displaying temperature forecast information.

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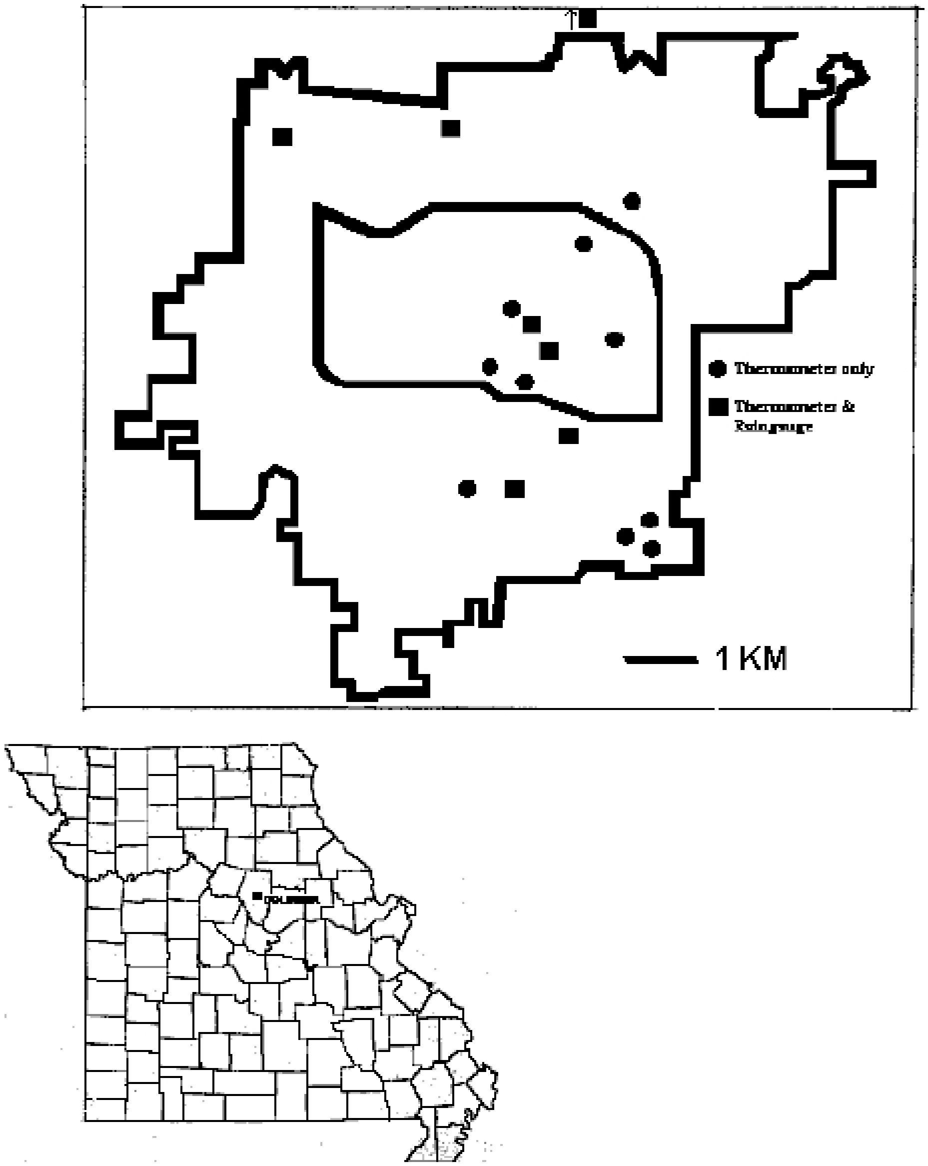

Figure 1. The station location and distribution of the temperature and rain gauge network. Closed squares represent the deployment of both thermometers and rain gauges, while closed circles represent the deployment of only one instrument (see legend). The Missouri map shows the location of Columbia.

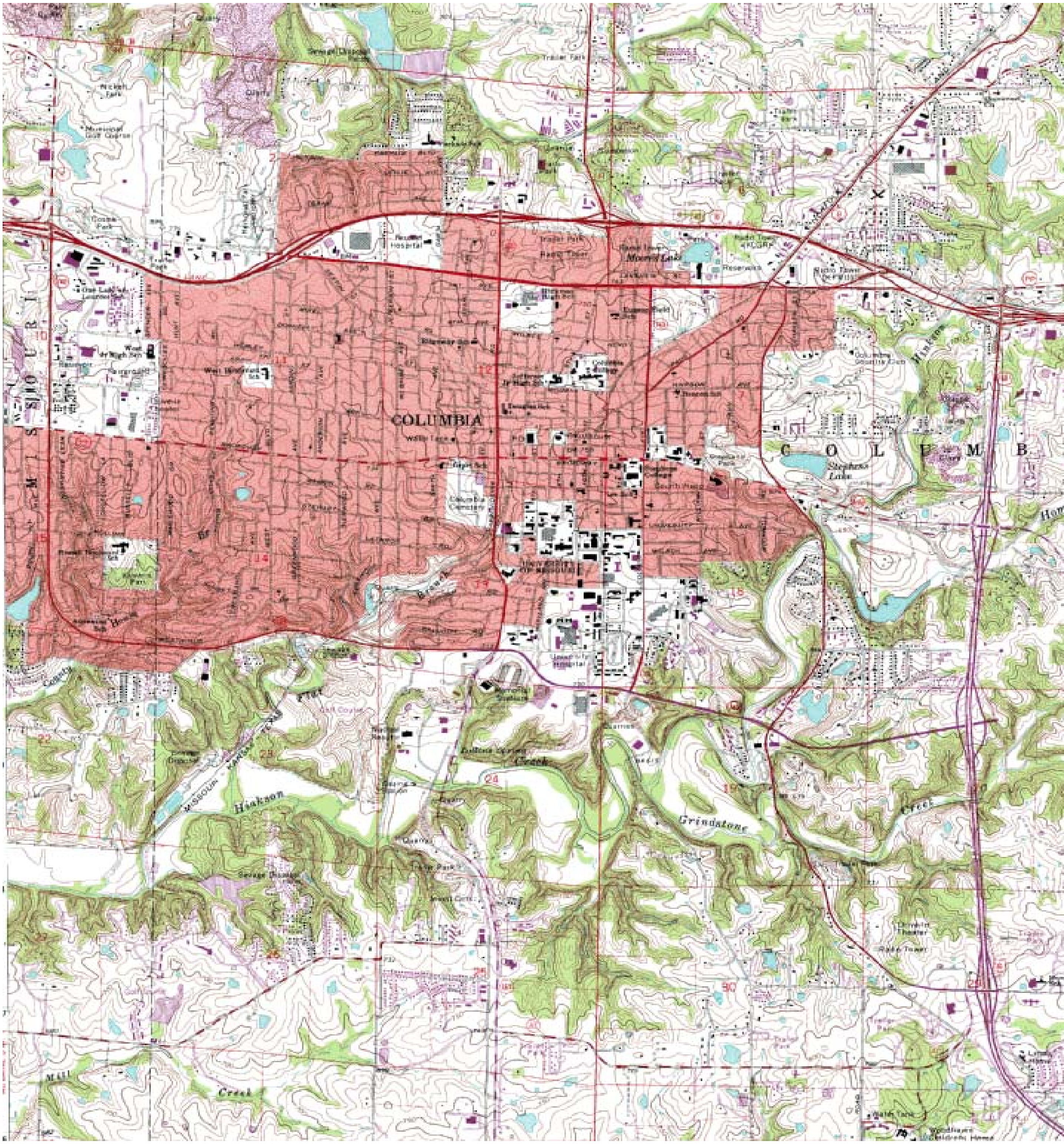

Figure 2. A topographical map of the Columbia, MO, region, courtesy of the United States Geological Survey (USGS). Orange describes the city area, green denotes river basins, and pink defines wetlands; the latter two generally define lower-lying areas. This map can also be viewed online.

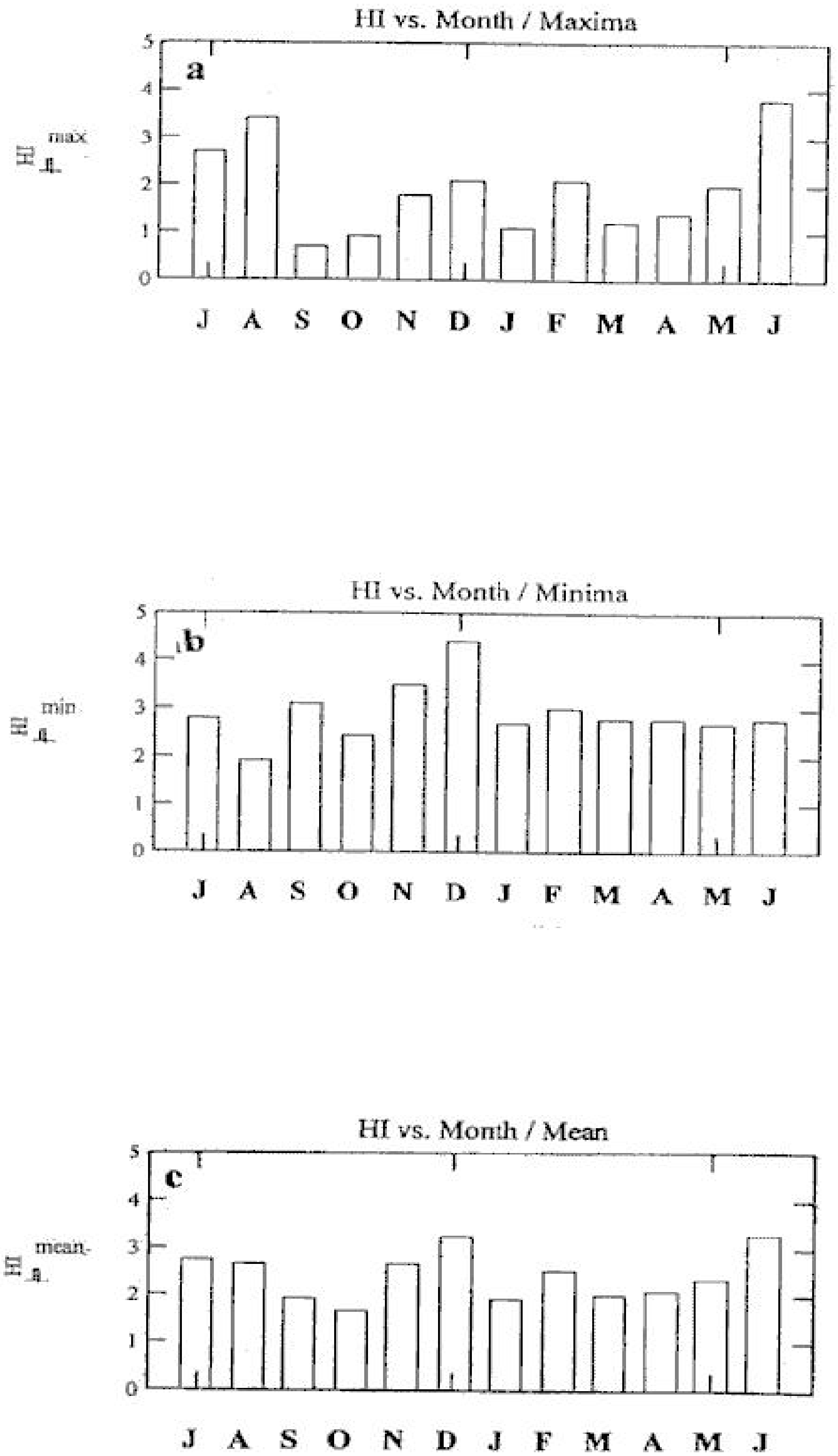

Figure 3. The monthly mean strength of HI (^{o}F) as defined by Eq. (1) for the a) maximum, b) minimum, and c) monthly average temperatures.

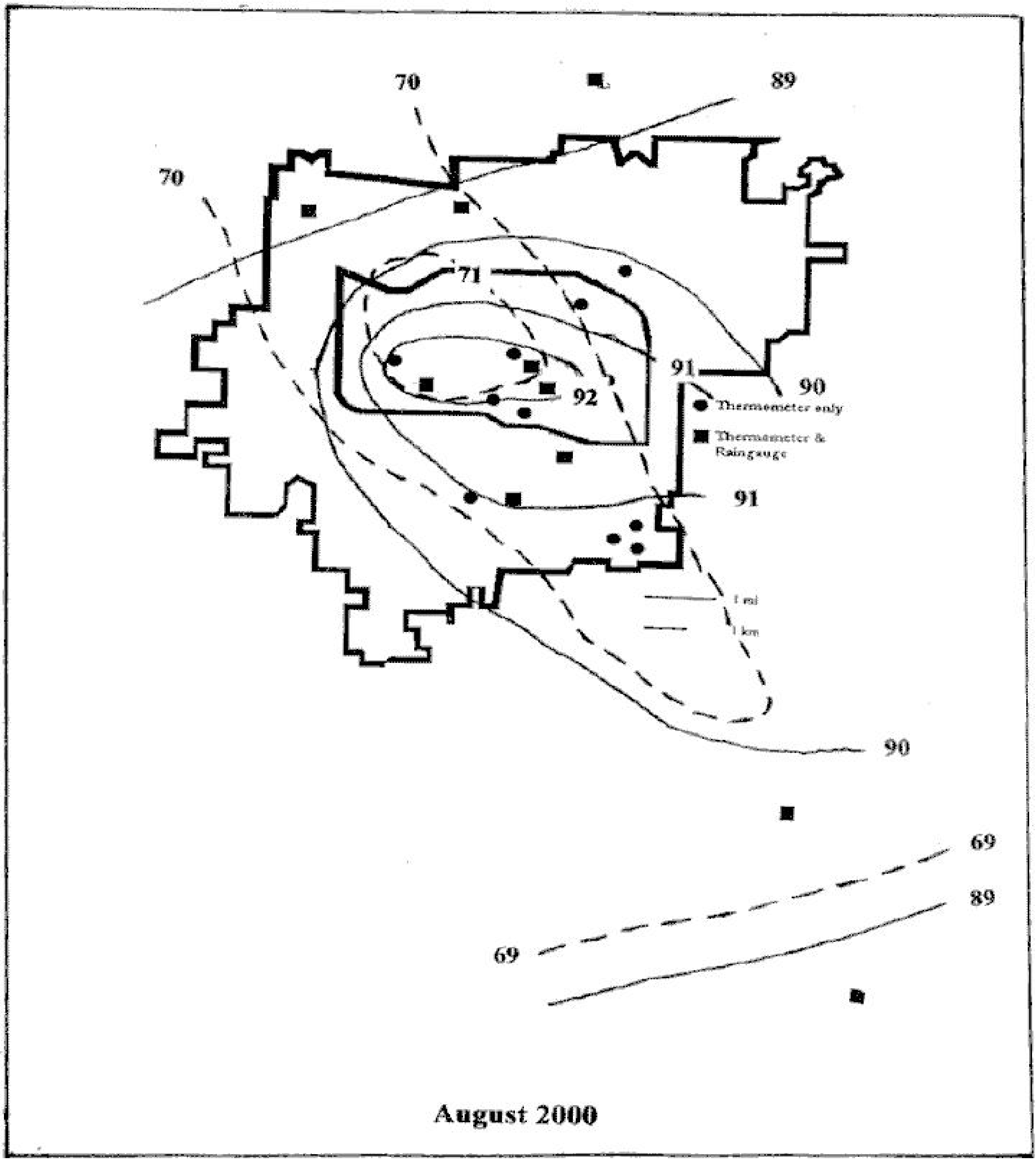

Figure 4. A contour map of monthly mean maximum (solid) and minimum (dashed) temperatures (^{o}F) for August 2000.

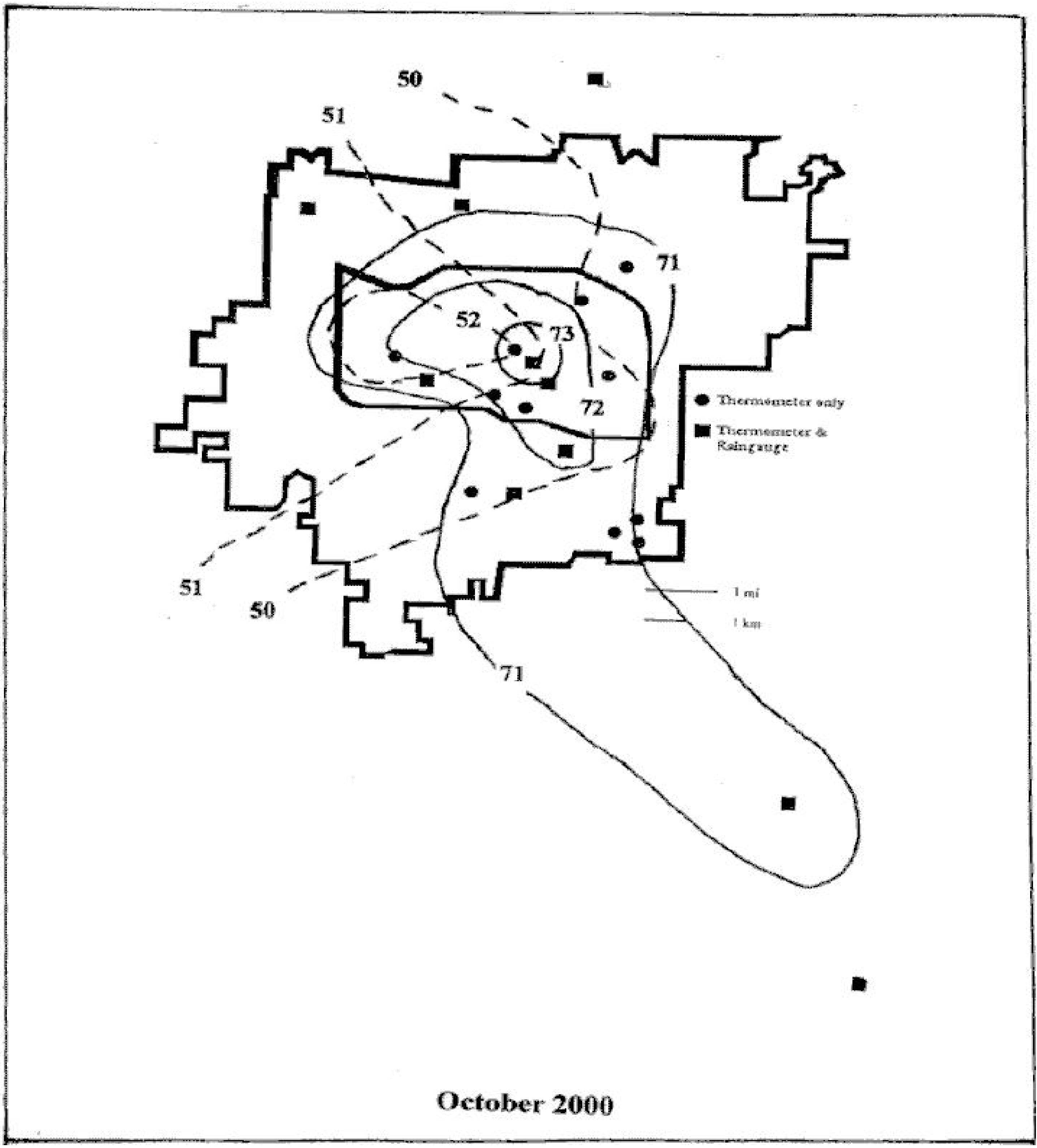

Figure 5. As in Fig. 4, except for October 2000.

Table 1. The mean maximum and minimum temperatures (°F) for various regions in the Columbia, MO region for July 2000 - June 2001, where the mean temperature of the instruments is represented by (Tic) for the inner city domain (see Fig. 1), (Tos) for the domain outside the city limits, (Tb) represents the mean temperature of instruments between Tic and Tos, and Ts is the temperatures of instruments inside the city, but south of the University of Missouri campus (located inside the Tic domain).

Month Max/Min	Tic	Tos	Tb	Ts	HI	HI_{max}
July 2000	88.1 / 68.8	85.4 / 66.0	85.7 / 68.6	88.0 / 68.4	2.7 / 2.8	3.3 / 4.7
August 2000	92.2 / 70.9	88.8 / 69.0	88.8 / 70.8	91.6 / 70.3	3.4 / 1.9	4.8 / 3.3
September 2000	81.8 / 58.0	80.5 / 54.9	81.0 / 56.0	81.4 / 55.9	0.7 / 3.1	3.6 / 6.0
October 2000	72.0 / 51.5	71.1 / 49.1	71.2 / 50.3	71.5 / 50.1	0.9 / 2.4	3.1 / 3.5
November 2000	50.3 / 33.4	48.5 / 29.9	49.6 / 32.3	50.3 / 32.2	1.8 / 3.5	2.3 / 5.5
December 2000	31.5 / 14.9	29.4 / 10.5	30.4 / 13.2	30.7 / 12.9	2.1 / 4.4	5.6 / 6.4
January 2001	39.5 / 24.0	38.4 / 21.3	38.7 / 22.0	39.8 / 23.2	1.1 / 2.7	3.4 / 3.3
February 2001	46.2 / 26.2	44.1 / 23.2	45.4 / 24.7	47.3 / 25.1	2.1 / 3.0	3.4 / 3.1
March 2001	52.6 / 32.0	51.4 / 29.2	53.1 / 30.9	54.4 / 31.2	1.2 / 2.8	3.0 / 3.6
April 2001	74.2 / 52.9	72.8 / 50.1	74.6 / 50.0	75.1 / 48.7	1.4 / 2.8	4.0 / 2.4
May 2001	77.8 / 58.2	75.8 / 55.5	76.9 / 57.0	77.1 / 56.7	2.0 / 2.7	3.8 / 4.1
June 2001	85.4 / 64.3	81.6 / 61.5	83.6 / 63.0	85.3 / 62.9	3.8 / 2.8	6.8 / 5.0

Table 2. The observed monthly mean temperatures (°F) and precipitation (inches) and their departures from the mean (1961 - 1990) for the 1 July 2000 to 30 June 2001 period for the Columbia Regional Airport (COU).

Month	Temperature / Departure	Precipitation / Departure
July 2000	75.8 / -1.6	4.09 / +0.42
August 2000	78.5 / +3.3	9.11 / +5.83
September 2000	67.8 / -0.1	1.75 / -2.11
October 2000	59.9 / +3.4	3.60 / +0.38
November 2000	38.7 / -5.4	1.74 / -1.19
December 2000	19.8 / -12.0	0.87 / -1.60
January 2001	29.3 / +1.8	2.69 / +1.24
February 2001	33.2 / +1.1	4.41 / +2.57
March 2001	39.9 / -3.2	1.09 / -2.08
April 2001	61.3 / +6.6	3.39 / -0.44
May 2001	65.1 / +1.5	6.37 / +1.36
June 2001	71.2 / -0.8	5.24 / +0.92