The Columbia, Missouri, Heat Island Experiment (COHIX) and the Influence of a Small City on the Local Climatology

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Abstract

The heat island effect is a well known feature in the microclimate of urban areas but only a few studies have addressed the effect for smaller urban areas. We examine here the impact of Columbia, Missouri and the University of Missouri campus on the microclimate (temperature and precipitation) of central Missouri. We purchased twenty Radio Shack® digital Max/Min thermometers and ten standard raised-edge rain gauges and these were given to students, staff, and faculty participants who were chosen for their reliability to provide daily data over the course of a year, site the instrument, and their location (in order to provide reasonable coverage locally). We also included information provided by automated and cooperative weather stations, and the weather station at the regional airport located 11 km (7 miles) southeast of Columbia. Our results indicate that the city has no discernable impact on the distribution of monthly precipitation totals. We found a distinct urban influence on the local surface temperatures, and the inner city region and the urbanized area of south Columbia were approximately 2 – 3 ^{o}F (1.0 – 1.5 ^{o}C) warmer in the mean than the surrounding environment. This difference grows to 3 – 6 ^{o}F (1.5 - 3.5 ^{o}C) when comparing the mean of the warmest station in the city to that of coolest station outside Columbia. We also observed a seasonal influence, as the heat island effect was more evident in the mean monthly maximum (minimum) temperatures during the warmest (coldest) months.

Keywords: *Heat island effect, climatology, microclimate, urban influences*

1. Introduction

The effect of urban environments on local temperature and precipitation distributions have been examined often in the past (e.g., Changnon, 1981; Segal and Arritt, 1992; Karl and Knight, 1997; Melhuish and Pedder, 1998; Pinho and Manso-Orgaz, 2000; Baik et al., 2001; Rozoff and Cotton, 2001; Shepherd et al., 2002) and usually for cities that have very large populations. Melhuish and Pedder (1998) and Pinho and Manso-Orgaz (2000), however, examine the heat island effect in smaller urban areas. The "heat-island effect" produced by such cities can have a profound impact, sometimes adverse, on the well-being of its residents (e.g., Karl and Knight, 1997).

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 such effects 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 a large impact on the temperature field (see references above) and the precipitation field (e.g., Shephard et al., 2002). A few studies examined also the climatological (long-term) impact of heat islands including their variance by season (e.g., DeMarrais, 1975; Ackerman, 1985).

Some authors examined the impact of agricultural practices on local environments and they demonstrated that a regional (covering parts of several states) heat island can be produced (e.g., Raymond et al. 1994). The study of local and regional heat islands is a topic that has enjoyed renewed interest lately, especially within the context of global climate change and the impact on human health (e.g., Gaffen and Ross, 1998; NAS 2000; Houghton et al. IPCC, 2001). Additionally, there are many examples of studies in the published literature that explore the impact on local atmospheric phenomena by the unique distribution of regional geography (e.g., Colle and Mass, 1996; Doesken and Weaver, 2000). These also include phenomena such as lake effect snows and the influence of the Great Lakes on larger-scale disturbances (e.g., Sousounis and Fritsch, 1994).

Published work (e.g., Melhuish and Pedder, 1998; Pinho and Manso-Orgaz, 2000) recently demonstrated that medium-sized and small urban areas may also be responsible for heat-island effects. Heat islands associated with medium-sized and smaller urban areas would not be expected to be as pronounced as those of larger cities in general, however, the heat island effect in the latter study was shown to be quite substantial (up to 7.5^{o} C). Thus, Pinho and Manso-Orgaz (2000) concluded that steps should be taken to mitigate the problem, including the implementation of more green-space. Available anecdotal evidence available suggests that Columbia, Missouri, may be responsible for a detectable heat-island effect, in spite of recent attempts to increase the amount of green-space and vegetation in the city limits over the past 15 years. 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.

Our objective in the COlumbia Heat Island eXperiment (COHIX) was to determine the extent to which Columbia, Missouri, and the University of Missouri campus produce a heat-island effect. We deployed several thermometers and rain gauges in and around the city limits to measure the urban impact on the microclimate and the variation in the strength of the heat-island effect with respect to season. Additionally, we measured precipitation in order to determine if the urban area had a discernable impact on precipitation microclimatology in spite of the very short period of record. In order to examine the urban impact on precipitation patterns, at least a few years of data collection would be necessary (e.g., Changnon, 1981). In section two, we discuss the data and methodologies used, and we describe and discuss the heat island study results in section three. In section four, we discuss the effect of cloudiness, wind directions, and wind speeds on the strength of the heat island, and we summarize our work and present the main conclusions in section 5.

2. Data and Methodology

a. Data

Participants in our study provided the temperature and precipitation data. We measured temperature data using a Radio Shack® Indoor/Outdoor Maximum-Minimum thermometer (Item #63 - 1014). Our instruments resided indoors and included a 3 m (10-ft) probe, which was then 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. We also provided participants in this study with a standard clear plastic raised-edge bucket rain gauge (Item RG #6608 – http://www.windandweather.com) to report rainfall information, and which can be purchased from any weather instrumentation vendor. Not every "station" reported every single month or every single day, thus we evaluated the data for suitability and discarded incomplete data in calculating the heat island using monthly means accordingly. Monthly station data was discarded if more than two days temperature readings were missing. Stations with two or less days missing were evaluated subjectively in order to ensure that the missing information would not have skewed the monthly mean substantially. We reported temperatures here in degrees Fahrenheit and precipitation values in inches, since these units are still the standard for surface data in the United States, but these are supplemented with metric units in the text.

b. Methodology

For the purposes of our study, Columbia Missouri (Fig. 1) was considered to be a small urban area. Here, we define 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.

We invited faculty, staff, and students in the Atmospheric Sciences Program (and some outside the program) to participate in our study. A total of 22 participants (17 were observers and 7 analyzed or archived the data) volunteered to take part in the experiment.

Enlisting volunteer participants to measure local variations in climatic parameters has produced successful results in other locations (e.g., Doesken and Weaver, 2000). We selected those who deployed instruments ultimately on the basis of location with respect to their location in the Columbia region, and their ability to accommodate the proper deployment techniques of the instrument(s). We provided students with explicit instructions on how to deploy the instruments. All temperature instruments were deployed in shaded and/or sheltered (but shielded from the sky and precipitation and well ventilated) environments and were deployed close to two meters above the surface. Also we attempted in our site selection 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 value in spite of being subject to the same conditions, we compared the instruments to a standard instrument. During this test, we also calculated the standard deviation among the set thermometers. The temperature range for our instrument set was 1.0 ^{o}F/0.6 ^{o}C (1.3 ^{o}F/0.7 ^{o}C) at room temperature (in an ice bath – occasionally stirred to increase homogeneity), and the standard deviation was 0.35 ^{o}F (0.2 ^{o}C) in our set for both the room temperature and ice bath trials during the test day. Thus, any heat-island effect would have to be significantly larger than the standard deviation after correcting our data to the standard. Also, we tested a Radio-Shack® instrument in real time against an electronic thermometer, the HMP35C, which is 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). We did not perform rigorous statistical testing other than the informal test described above since the small sample precludes producing statistically robust results. In spite of this problem, meaningful results can be obtained (e.g., Nicholls, 2001) here and we can compare to similar studies which found similar results.

The participants collected the maximum and minimum temperature once daily at 10:00 pm local time (0300 UTC – or - 0400 UTC during standard time). These data were recorded (instrument displays temperature to the nearest tenth of a degree) and we then averaged these, with the goal of first determining if the heat island existed in the mean data field. We define the strength of the heat island effect (HI) as:

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

where T_{ic} is the mean temperature recorded by the "inner city" units (9 of these - see enclosed rectangular region which encloses the most intensive development inside Fig. 1 and includes the University of Missouri Campus) and T_{os} is the mean temperature recorded by the instruments more than 1.6 km (1 mile) outside the city limits (four of these). We decided to consider stations (Tos) more than 1.6 km outside the city limits in order to ensure that these regions were much less densely developed than city regions. The remaining instruments (9) were inside the city limits, but outside the inner city domain, and this region can best be described as mixed residential and commercial areas, and is the rectangular shaped area bounded by interstate and main highways. We then compared the mean temperatures and monthly precipitation amounts produced by this instrumentation network in these regions in order to examine the distribution of the heat island effect and measure the effect of the urban area on the precipitation field. Finally, we defined the difference in the mean temperatures between the warmest individual Tic station and the coolest Tos station as the variable HImax.

If we could detect the heat island effect in the mean, then we would stratify individual days first with respect to cloud cover, wind direction, and wind speed. Then we combined the cloud cover and wind speed categories in order to determine under which synoptic conditions the heat island effect was greatest. We also stratified the data in time by month and season in order to determine which time(s) of the year the effect was most influential.

3. Season-by-season results using monthly means

Our analysis of the COHIX project data started with July 2000. Table 1 and Fig. 2 show the results after we examined the data collected from 1 July 2000 to 30 June 2001. Table 2 shows the observed mean monthly temperatures and precipitation values 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). The precipitation amounts for July were close to normal for the month (Table 2), while August experienced several heavy rainfalls that resulted in a total rainfall amount of 9.11 inches (231 mm). This was a new all-time August record for COU. While this might imply cloudier-than-normal conditions prevailing for August, many of these rainfalls were associated with overnight thunderstorms in the first 21 days. Then, the latter half of the month experienced sunny (mostly clear), hot, and dry days generally.

As shown in Table 1, we found a difference of 2.7 and 2.8 ^{o}F (1.5 ^{o}C) 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 difference between the warmest individual inner city station and the coolest outer city station was 3.3 ^{o}F (1.9 ^{o}C) and 4.7 ^{o}F (2.7 ^{o}C) for the maximum and minimum temperatures, respectively (Table 1, HI_{max}). During August, the heat island effect was stronger for the maximum temperatures than that found for July (3.4 ^{o}F/1.9 ^{o}C), while the minimum temperatures produced a weaker signal (1.9 ^{o}F/1.1 ^{o}C). The largest differences between individual stations were 4.8 ^{o}F (2.7 ^{o}C) for maximum temperatures and 3.3 ^{o}F (1.9 ^{o}C) for the minimum temperatures. We found that the warmest individual stations were inner city stations, while the coolest stations were outside the city.

Our examination of the precipitation distributions for July across the Columbia, Missouri region (not shown) reveals that there was a general west-to-east increase in the precipitation amounts. The heaviest monthly precipitation amounts were found southeast and northeast of the city and exceeded 4 inches. Our measurements on the western side of the city revealed less than 2.4 inches (61 mm) of rain fell during July (including one measurement of 1.92 inches/49mm). In our study, the variance was defined as the ratio of the highest monthly precipitation reading divided by the lowest in the region of study. For July, that value was 2.13 in / 54 mm, or the highest value was more than twice the value of the lowest amount (the maximum exceeded the minimum by 113%). The pattern for precipitation measurements taken during July and described above reflected the statewide (Missouri) distribution of precipitation, in which the heaviest amounts were found across north-central Missouri and decreased to the south and west.

For the month of August, our precipitation amounts across the Columbia, Missouri, region were more uniformly distributed than July precipitation amounts. Precipitation amounts ranged from a minimum of 8.62 inches (219 mm) to a maximum of 10.01 inches (254 mm). This represents a variation of 16% across the region, which was remarkably low considering the high precipitation amounts. This reflects the fact that for the first part of the month we observed that a stationary front lay across north central Missouri. Thus, even in the summertime (July and August), we found that the precipitation distributions across the Columbia, Missouri region tended to be strongly influenced by larger-scale and storm-scale features and there is little evidence of a distinct urban-scale influence on the precipitation field. This does not preclude the possibility that other regional features (e.g., the Ozark Mountains, or other topographical features) may be influential in regional precipitation distributions.

b. September - November 2000 results

In general, the fall season of 2000 was cooler and drier than normal, with the exception of October, a month that was warmer than normal for temperature and fairly close to the climatological average for precipitation. A large-scale ridge dominated the midwestern United States during the first part of September resulting in warm conditions during the first half of the month for Columbia. This flow regime broke down during the second part of the month and the net result was a month with close to average temperatures (Table 2). Precipitation was fairly evenly distributed across the state with 2 - 3 inches (51 mm – 76 mm) falling in most locations and isolated pockets of 4 inches or more (> 102 mm) in the northern and southern parts of the state. During October, temperatures remained consistently above normal and there were fewer cloudy days than are typically experienced. The synoptic flow regime favored more rain falling across central and southwestern Missouri, while the rest of the state received less than normal precipitation. Finally, November was quite cold across the state as large-scale troughing prevailed over the mid-western US (Table 2). This resulted in Columbia experiencing the 8th coldest November on record dating back to 1871. Rainfall generally increased from north to south across Missouri, with lower amounts in the northeast part of the state and the heaviest amounts in the southernmost corner of the state.

Our HI values for the fall months were smaller for the maximum temperatures than for the minimum temperatures across all months (Table 1). For September and October, we found that the maximum temperatures were slightly less than 1 ^{o}F (0.5 ^{o}C) in the city of Columbia as compared to the outside, while the minimum temperatures were nearly 2.5 ^{o}F

(1.4 ^{o}C) warmer in the city. These values are smaller than the comparable values for the July and August period. During November, however, we found that the heat island effect was comparable to that of August in spite of the cloudier conditions, with the minimum temperatures showing the stronger signal. Our examination of the differences between the warmest and coldest individual stations (Table 1) revealed 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 in addition to weakening during the cooler months, and examining contour plots of August (Fig. 3) versus October (Fig. 4) supports this hypothesis.

Our precipitation distributions for September and October (Fig. 4) both show a maximum over the southeastern part of the urban area, while the November precipitation in Columbia, Missouri does not show a maximum that is discernable above the synoptic distribution for precipitation described above. During both September and October, we found that the precipitation amounts and distribution were similar to that of the synoptic-scale distribution, except for the distinct maximum that prevails centered over southeastern Columbia. The September maximum was smaller in scale but greater than the background values measured by the volunteer network than was the October maximum, and this is made clearer when examining the variability in precipitation amounts. Our precipitation amounts were more variable across the Columbia region during September (93%) versus those of October (27%) or November (23%). However, it is not speculated here that the September and October maxima are necessarily evidence of an urban influence.

c. December 2000 - February 2001 results

December 2000 was the second coldest December (12 ^{o}F/6.7 ^{o}C less than the 30 year mean - see Tables 1 and 2) on record for the Columbia, Missouri, region (Table 1) as a large-scale trough was responsible for very cold weather throughout the entire midwest. We found that December precipitation was also below normal throughout the state as amounts generally increased from north to south. However, the most pertinent feature for the discussion below was the persistent snow cover that became established in the Columbia region around 12 December and persisted through the rest of the month. January and February were characterized by a more zonal flow regime over the midwest and the result was slightly warmer than normal temperatures throughout Missouri, including Columbia (Table 1). The temperatures were more variable across the state during February with below (above) normal temperatures across the northern (southern) part of the state. The gradient of monthly precipitation values was oriented such that during January, there was above (below) normal precipitation in the northwest (southeastern) part of the state. The gradient reversed itself for February and statewide maximum and minimum values were located in the opposite corners of Missouri. Central Missouri received about 2.5 to 3.5 in/64 – 89 mm (3.5 - 4.5 inches/89 – 115 mm) of precipitation in January (February).

We found that the heat island effect for December was as strong as the heat island effect in the summer months (Table 2), 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 2) and distribution (not shown) of the heat island effect was more typical of the values for the fall season.

In spite of the low precipitation totals for December, we found that the precipitation amounts varied from a maximum of 1.23 inches (31 mm) in Columbia to a minimum of 0.51 inches (13 mm) outside the city, which represents a variance of 141%. Amounts across the city were fairly uniform throughout the winter season and the amounts were consistent with the statewide distribution described above. The precipitation amounts for January and February were less variable across the city, 38% and 22% for January and February, respectively. We then found a small scale, but discernable, maximum in the precipitation field over the southeast part of Columbia, Missouri. The February maximum is more prominent and larger in area than the January maximum (not shown).

d. March - June 2001 results

A northwesterly upper-air flow pattern persisted over Missouri for much of the month of March resulting in below normal temperatures for most of the state, including Columbia (Table 2). This flow regime deprived storms of moisture from the Gulf of Mexico as they crossed the state, and precipitation values were below normal for most of Missouri. Nonetheless, precipitation amounts increased from northwest to southeast across Missouri. For April and the first part of May, ridging persisted over the midwestern states in the large-scale flow pattern. This resulted in warmer than normal conditions for the state and Columbia (Table 2) in spite of the fact that a strong trough and cold conditions persisted over the midwest during the latter part of May and into June. This cool period was associated with an unusual blocking event that persisted over the eastern part of the North American continent and adjacent Atlantic region (e.g., Lupo and Smith, 1995; Lupo and Bosart 1999). April precipitation amounts were close to normal around the state, but during May, the northern (southern) part of the state was wetter (drier) than normal, and the precipitation amounts decreased significantly going southward. During much of June, however, daytime conditions were mostly sunny with intermittent bouts of rain associated with the passage of synoptic systems.

Here we found that 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). There was a difference in our area coverage of the heat island, however, 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 our 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 our assertion of an expanded heat island 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.

Examining the precipitation distributions across the Columbia region reveals that during the spring months and June, our precipitation amounts were not as variable as they were during other months. The precipitation variability in the region as defined by our study was 54%, 32%, 40%, and 42% for March, April, May, and June, respectively. Our precipitation distributions were also similar to that of the synoptic variations described above, and the precipitation maximum found during other seasons was found only for the month of April.

e. Discussion

Our examination of the data reveals that when the monthly average of inner city stations is compared to those outside the city (Fig. 2), we found a discernable urban influence in the local temperature fields on the order of 2 - 3 ^{o}F (1.0 – 1.5 ^{o}C). The difference grows to 3 - 6 ^{o}F (1.5 – 3.5 ^{o}C) when comparing the monthly means of the warmest inner city station versus the coldest station outside the city. Our values are consistent with those found by Pinho and Manso - Orgaz (2000) for a city half the size of Columbia, and are a little less than those which might be expected for a city of Columbia's size (about 7^{o} C or 12 – 13^{o} F, e.g., Aguado and Burt, 2001). However, the values shown for Columbia reflect monthly averages rather than daily values of maximum or minimum temperatures as were reported in the two references above. We found individual days in which the difference in temperature between the warmest inner city station and the coolest station outside the city was on the order of 10^{o} F (> 5.5 ^{o}C) or more. Thus, we are confident that our result is robust even though no rigorous statistical testing was performed due to the small sample size. We also note 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 our 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. Our values of Ts are generally more similar to Tic than those of Tb or Tos. Another possible reason for our results found here, however, may be that we did not deploy instruments in the center of town where there are more buildings and more concrete and asphalt covered surfaces. We did not deploy instruments in this area since we could not guarantee proper instrumentation techniques, data collection, and instrument integrity.

The heat island itself did vary with the seasons as we show in Table 1, Figs. 3 and 4, and the discussion above. The heat island effect did expand in area extent during the warmer months and contracts during the colder months. While our result contradicts the commonly held belief that the heat island expands during the cooler months (e.g, Aguado and Burt, 2001), the contraction of our heat island found here may be due to several factors, including increased cloudiness during the cold season or the low sun angle during the winter months. Also, the Columbia region does not have the construction density of larger cities, thus we propose that it is equally likely that the regional surface may be of more uniform character in terms of the surface albedoes after the vegetation dies off in the fall and before it grows again in the spring. The heat island seemed to be stronger again after April, when regional vegetation grew out.

Our 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) station from the former (latter) group is compared. The heat island effect found here is stronger also in the maximum (minimum) temperatures during the summer (winter) months. This is likely due to the stronger absorption of solar radiation during the warmer months, and more excessive long wave cooling during the cooler months outside the city. For example, December 2000 stands out as a month in which our heat island effect was strongest. We propose that this may be due to this month being the second coldest December in the history of Columbia, and being associated with an unusually persistent snow cover. 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 could 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 in the city 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 in order to absorb more sunlight. Also, the dirty snow would not be as effective of a longwave emitter at night, which possibly accounts for the large difference in the December minima

Our examination the precipitation fields demonstrated that there was not a persistent feature present that can be attributed to the urban area specifically and which stood apart from the synoptic-scale precipitation distribution. A precipitation maximum is present in our monthly precipitation field totals during six of the 12 months in this study, and for only one month (Sept 2000) was this maximum nearly double the value found at the Columbia Regional Airport. Additionally, the precipitation during that month was associated primarily with thunderstorms. Larger cities have been shown clearly to have a more persistent impact on convective-type or convectively driven precipitation events (e.g., Biak et al., 2001; Shepherd et al. 2002). Changnon et al. (1991) showed this impact to primarily be a warm season effect for a city like St. Louis, MO.

4. Stratification by synoptic variables

The purpose of this part of our study was to examine which variable; cloud cover, wind direction, or wind speed, made the greatest impact on the strength and distribution of the heat island effect. We divided the city into four quadrants and the one station which recorded both temperature and precipitation information the most consistently in each quadrant was chosen to represent each quadrant (not shown). In order to keep the impact of larger scales to a minimum, we only included days where there was no precipitation or wind shifts. Our classification of cloud cover and wind speeds are shown in Table 3. We classified cloud cover as in Lupo and Market (2002), where clear (cloudy) skies represent less than 20% (more than 80%) coverage. We partitioned wind speeds to represent light winds, light breeze, moderate winds, and strong winds. We then correlated wind directions versus the quadrant of maximum temperature in order to determine if the wind direction had any impact on the distribution of the heat island effect.

Table 4 shows the correlations between the quadrant of maximum temperature and wind direction under all combinations of cloud cover and wind speeds and the number of time periods (days) which satisfied the combined criterion. While only the clear skies and light wind and light breeze category contained a large enough sample and showed statistically significant negative correlations (greater than the 95% confidence level), the outcome of this exercise are consistent with what should be expected based on the results of studies using larger cities (e.g., Oke, 1982 and later studies referenced above). The negative correlation between the quadrant of maximum temperature and wind direction under most combinations of cloud cover and wind speed indicates that the heat island effect for this city was advected down wind. Finally, as expected, the heat island was least noticeable under conditions of cloudy skies and strong winds, since cloudy skies would block out incoming solar radiation and strong winds promote increased mixing of air close to the ground. This accounts for the weak correlations as well. We also found the strongest heat island effect under the conditions of clear skies and light winds. These days provided for the maximum insolation and least amount of mixing. A sample of this type of day is shown in Fig. 5.

5. 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 comparatively few studies examining this effect for smaller urban areas. For our study, we bought 20 thermometers and 10 rain gauges and distributed 17 of the thermometers throughout the Columbia, MO, region to examine the impact of the city and the University of Missouri campus on the surface temperature fields. Participants gathered daily data points from 1 July 2000 to 30 June 2001. Our experiment provided University of Missouri undergraduate students with an opportunity to participate in meteorological research. Students helped to gather the data, check the data for quality, and process it. Some students also participated in lecture sessions, as this experiment served as the template for the recent development of an instrumentation and experimentation course in the atmospheric science program at the University of Missouri.

The first step in our experiment was to examine mean monthly data in order to determine if the heat island effect is detectable in the region's microclimate. 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. This was true for every individual site as well. 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. Our results suggest that the Columbia, MO, heat island effect is a significant feature in the local microclimate. We also found that 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. We also suggest that fundamentally altering the surface type, such as the persistence of winter snow cover, could have influenced the strength of the heat island. This possibly lead to a stronger heat-island island signal being reflected in the minimum temperature for December 2000 as opposed to the stronger signal in the summer season maxima. Additionally, we detected no discernable or persistent urban effect during this period on the precipitation distributions. Finally, our examination the strength of the heat island as calculated as the difference between the means of the warmest individual station inside the city and the coolest station outside the city revealed temperature differences of 3 - 6 ^{o}F (1.5 – 3.5 ^{o}C).

6. ACKNOWLEDGEMENTS

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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 (^{o}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

Table 3. Variables used in heat island correlations to prevailing synoptic conditions and their characterization.

Cloudiness Classification	Percent coverage	Wind Speed Characterization	Speed (Kts)
Clear	< 20%	Light Winds	< 5 kts
Partly Cloudy	20% - 50%	Light Breeze	5 – 10 kts
Mostly Cloudy	50% - 80%	Moderate Winds	10 – 20 kts
Overcast	> 80%	Strong Winds	> 20 kts

Table 4. The number of samples and correlation coefficients for cloud cover and windspeeds versus the heat island strength (* indicates statistical significance at the 95% confidence level or greater).

Cloud Cover	Wind Speeds	Number of Days	Correlation Coefficient
Overcast	Moderate and Strong	13	0.179
Overcast	Light Winds and Light Breeze	13	-0.30
Clear	Moderate and Strong	16	-0.273
Clear	Light Winds and Light Breeze	38	-0.391*

Figure Captions

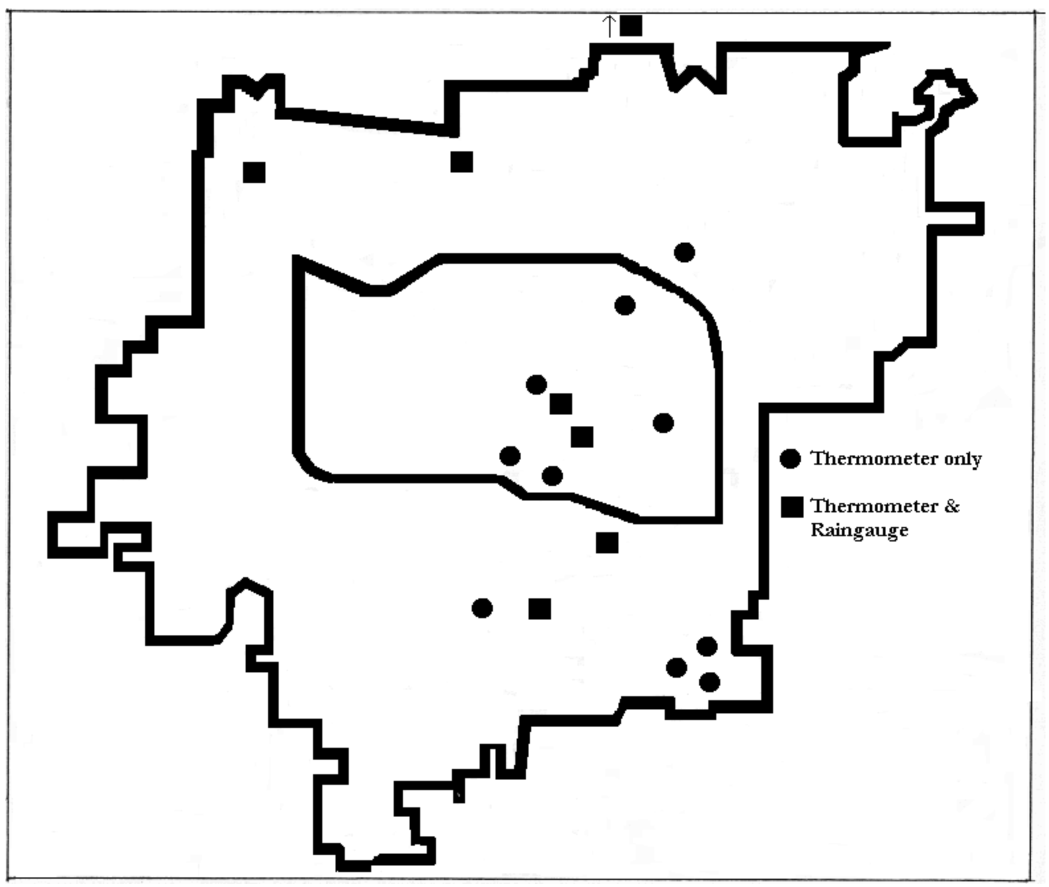
Figure 1. The station location and distribution of the temperature and rain gauge network. Closed squares represent the deployment of both thermometers and rain gauges, while closed circles represent the deployment of only one instrument (see legend).

Figure 2. 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 3. A contour map of monthly mean maximum (solid) and minimum (dashed) temperatures (^{o}F) for August 2000.

Figure 4. As in Fig. 3, except for October 2000.

Figure 5. As in Fig. 3, except for 1 September 2000.



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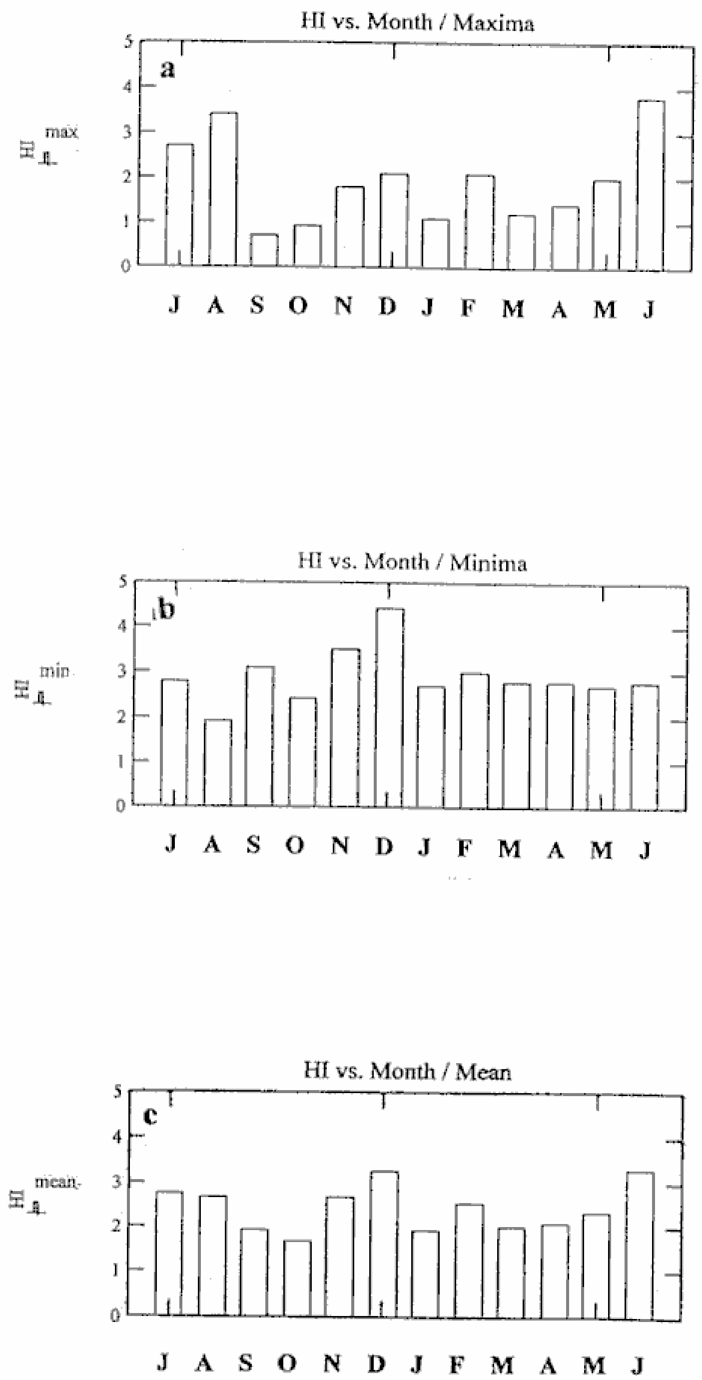

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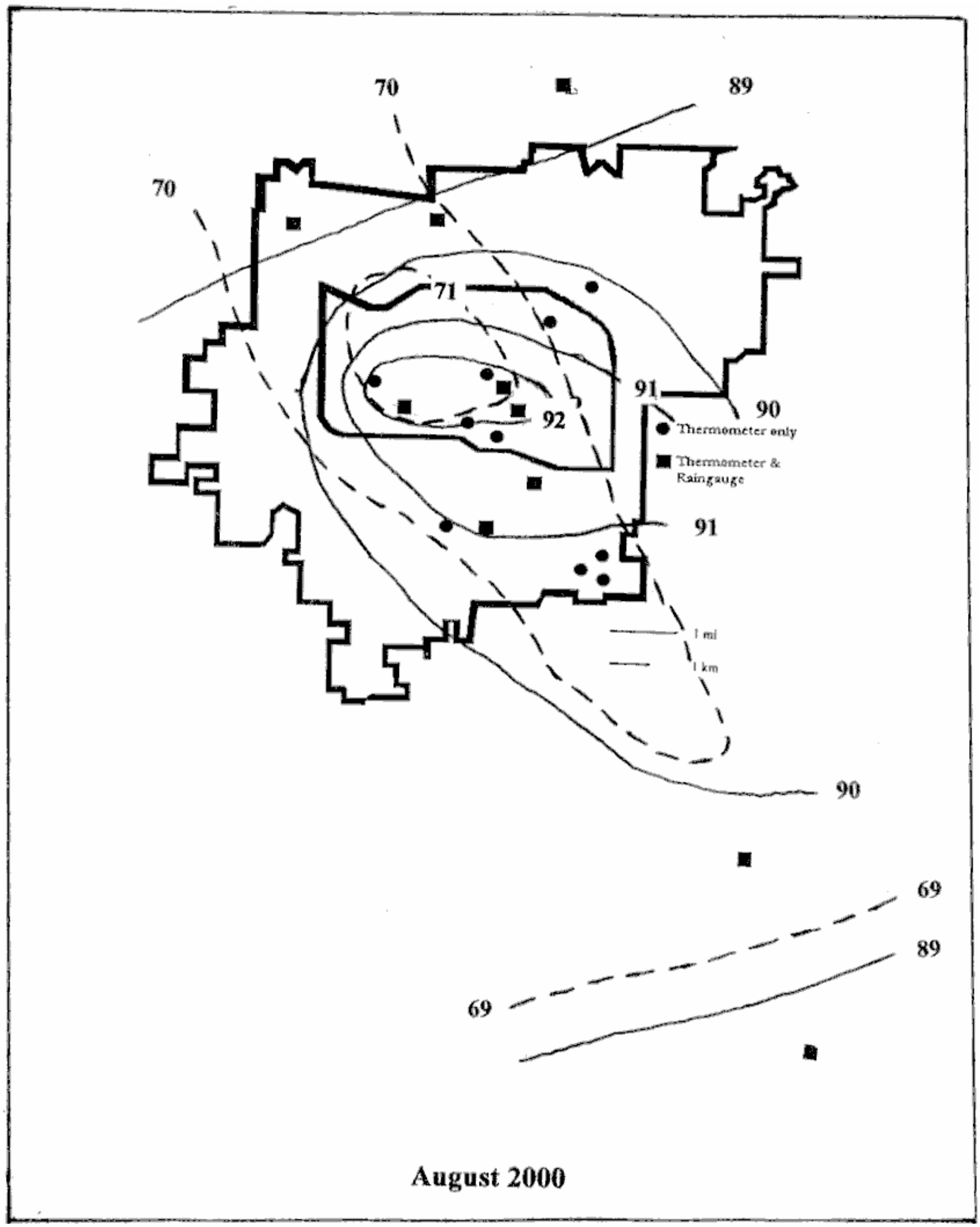

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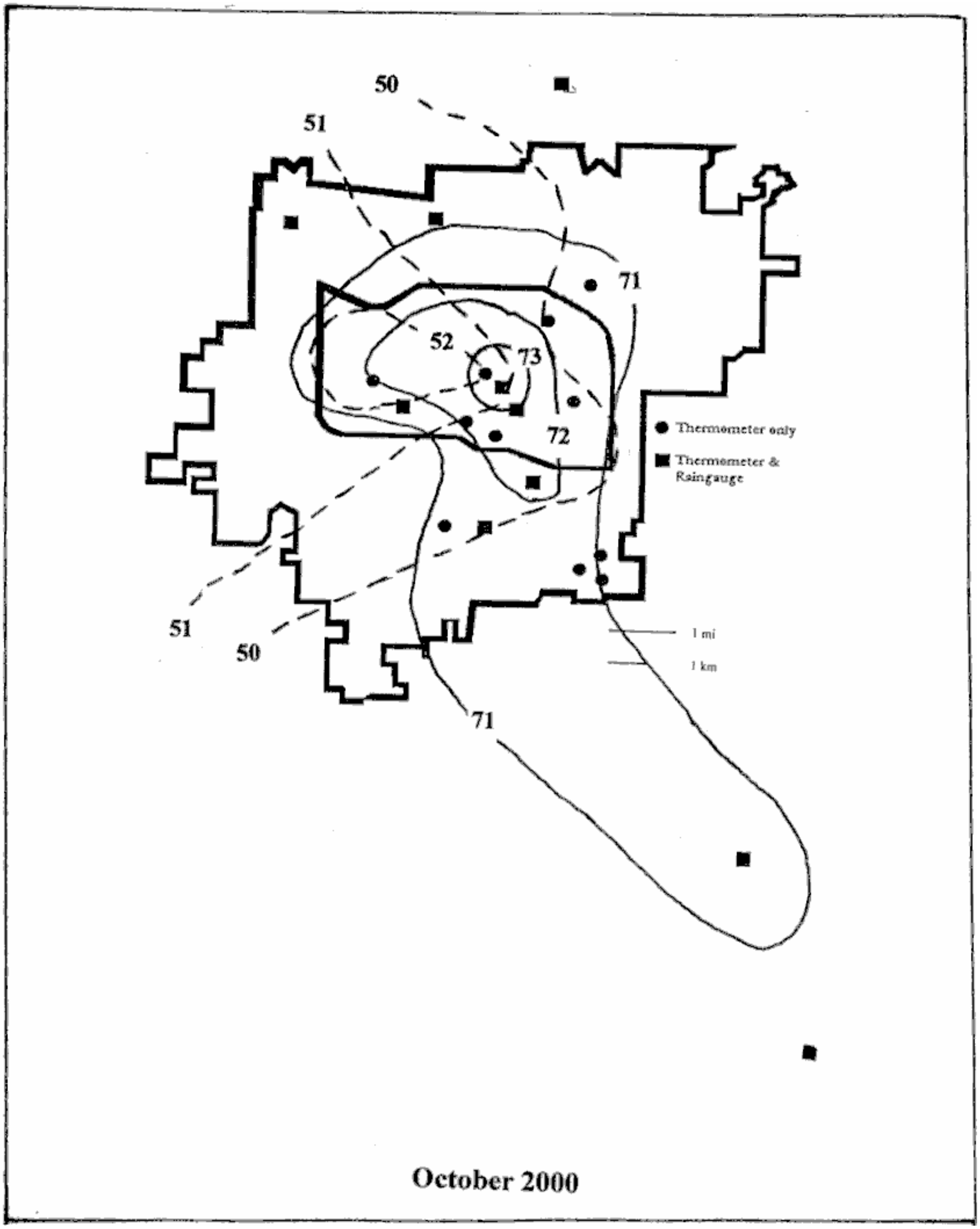

Figure 4. As in Fig. 3, except for October 2000.

Figure 5. As in Fig. 3, except for 1 September 2000.