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CHARACTERISTICS OF THE URBAN HEAT ISLAND AT GEORGETOWN, ONTARIO

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Preface

This report is based on a thesis submitted to the University of Toronto, Department of Geography for the Honours B.A. degree. The research was supported in part by the Atmospheric Environment Service through a contractual agreement.

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CHARACTERISTICS OF THE URBAN HEAT ISLAND AT GEORGETOWN, ONTARIO.

1. Introduction

Climatologists have recognized for over a century that urban places are capable of modifying the temperature of the air above them. Since this modification is almost always an increase, the phenomenon is referred to as the urban "heat island". The foremost contributors to our present knowledge of urban climates include Sundborg (1951), Kratzer (1956), Landsberg (1956), Mitchell (1961), Chandler (1962, 1965) and Woollum (1964). Some of the basic findings about the urban heat island, as reported by Sekiguti [1], include:

(a) Heat islands are an almost universal phenomenon of urban places. They occur under most weather conditions, but are especially strong at night under clear skies and light winds.

(b) Urban heat islands correspond in areal extent to the built-up areas of towns and cities, and temperature gradients are steepest at the urban-rural boundary.

(c) Near the centre of large urban areas, there are cells of higher temperature than elsewhere in the urban heat island. As noted by Chandler, there are also 'cold islands' within urban areas. These cold islands are large open spaces (e.g. parks) which resemble the surrounding rural landscape, and which often have lower temperatures than the urban areas, although not as cold as external rural areas.

Clark [2], in his study of vertical temperature distributions in Cincinatti, discovered that the usual phenomenon of aerial drainage (the tendency of cold air to settle in valleys on clear, relatively calm nights) was either muted or reversed in the urban area.

It is not surprising that most studies of the urban heat island have taken place in larger cities (population 50,000 or more) Most researchers and research institutions, as well as the majority of the population, are located in larger cities. The urban heat island has the greatest magnitude in such cities, and there are more thorough climatological records available. However, attention is beginning to shift to the question of urbanization of rural landscapes, as climatologists wish to discover the characteristics of temperature increases in newly-constructed urban areas. This research is considered important because of its relevance to building design, air pollution control, and city planning.[3]

Studies of the urban heat island in larger cities have demonstrated the results of the urbanization process upon temperatures. However, studies of smaller urban areas and of urban places under construction are necessary in order to understand the characteristics of urban temperature increase through time.

Several studies of the urban heat island of small cities are now available. Duckworth and Sandberg reported on their findings in Palo Alto, California[4]

(1) T. Sekiguti, "Urban Temperature Fields", in W.M.O. Symposium on Urban Climates, *Technical Note* 108, Geneva, 1970. p. 137.

(2) J. Clark, "Nocturnal Boundary Layer over Cincinnati, Ohio", *Monthly Weather Review*, Vol. 97:8, 1969.

(3) M. E. Landsberg, "Micro-meteorological Temperature Differentiation through Urbanization", in *W.M.O. Tech. Note* 108, p. 130.

(4) F. Duckworth and J. Sandberg, "The Effect of Cities upon Horizontal and Vertical Temperature Gradient", *Bulletin of the American Meteorological Society*, May 1954.

They found evidence of temperature increases of up to 7 C° on clear nights in the colder half-year. Temperature gradients were similar to those observed in nearby San Francisco. Hutcheon et al.[5] discovered that on clear, calm nights, there were temperature differences of 5 to 7 C° at the university town of Corvallis, Oregon. Sekiguti and others reported in the *Tokyo Journal of Climatology*[6] that urban heat islands had been observed in a large sample of Japanese towns of 10,000 to 50,000 population in various weather conditions. The results displayed similar characteristics to urban temperature fields in North America and Europe. Kopec[7] studied the temperature distribution in the twin city of Chapel Hill and Carrboro, North Carolina (pop. 24,900). Excluding the lower temperatures recorded in nearby stream valleys, the maximum values of the urban heat island at this location were about 5 to 6 C°.

Unfortunately, our knowledge of the urban heat island in small cities is largely confined to extreme cases. In this study, the author has calculated the average magnitude of the urban heat island at Georgetown, Ontario, Canada (pop. 17,000). The study of the urban heat island at Georgetown is of special interest because of three factors: the irregular configuration of the urban area, the predominance of new housing estates ('subdivisions'), and the existence of well-defined stream valleys within and around the urban area. These, and other problems of site, will be discussed in the following section (2). In section 3, the characteristics of the urban heat island will be tabulated and discussed. Section 4 is devoted to a discussion of temperature distribution at the urban-rural boundary at Georgetown, with special reference to the role of site differences. Section 5 is concerned with the magnitude of the urban heat island for cities of various size, with special reference to the urban heat island of towns with less than 5,000 population. Finally, in section 6, the author presents some conclusions about the characteristics of urban heat islands, especially those of relatively small urban places.

Following the text is a section of figures (maps, photographs, and graphs).

2. Site Descriptions and Methods of Research

Figure 1 shows that Georgetown is located about 50 km. west of Toronto (population 2.1 million) and 30 km. north-west of Lake Ontario. Figure 2 shows that the urban area occupies a plateau between the Credit River and a small tributary, the West Credit Creek. The latter has a tributary, Silver Creek, running through the town. These streams all occupy valleys of 25 to 50 metres which are remnants of glacial meltwater erosion. The original town was located west of Silver Creek, and was typical of small Ontario towns in that it had a roughly circular shape and a rectangular road grid. Between 1955 and 1969, the farmland to the east of the town was transformed (in three stages) into a large housing estate for 12,000 people. Another 1,000 were settled in a development in the west end, bringing the population to about 17,000. The central business district is very small (c.5000 m.^{2}) for such a large town. There is virtually no development in the floodplain of Silver Creek, although four town roads cross it. There are about 50 industries in Georgetown, but most of these are modern secondary industries. The only important source of air pollution is a pulp-and-paper mill in the north-west part of town. The north-eastern part of the urban area is an industrial estate where almost 90% of the land is vacant at the time of this study. The surrounding countryside is predominantly agricultural, with very little of the original forest cover (Great Lakes mixed forest). In the valleys of the rivers and streams are three small communities of 500 to 1,000 population (see figure 2).

(5) R. Hutcheon, "Obervations of the Urban Heat Island in a Small City", Bull. Am. Met. Soc., January, 1967.
(6) T. Sekiguti et al., see the 1964 and 1965 volumes of *The Tokyo Journal of Climatology*, Tokyo Univ.
(7) Richard J. Kopec, "Further Observations of the Urban Heat Island in a Small City", *Bull. Am. Met. Soc.*, July 1970.

The map in figure 2 shows the locations of thermometers used in the research. The author's interest in the local climate dates back to 1964, when he established a weather station at location 2. Since 1967, the observations have been taken at the home of A. McAuley at the south end of town. However, there was a period of nine months in 1968–69 when the observations were taken at site 3, which, unlike all the others, is tree-shaded. More will be said about these observations when site differences are discussed.

There was a climatological station operated by the Canadian Meteorological Service about 2 km. west of the town in an agricultural area. This station was roughly 15 metres higher in elevation than site 2. Unfortunately, it was discontinued at the end of 1966, but this gives three years (1964–66) of records for comparative purposes. Based on the three years' data, the author calculated the average values of the urban heat island for maximum and minimum temperatures in each month of the year. These results are found in section three.

The author wished to discover more about the distribution of temperatures than could be derived from this comparison. Six thermometers, registering maximum and minimum temperatures, were purchased from the Taylor Instrument Company. They were placed in portable Stevenson screens, and calibrated against the thermometer at the McAuley site. This thermometer, in turn, has been calibrated against official instruments and has given good results for over seven years. The calibrations were completed on May 10, 1970.

The thermometers were placed in the indicated locations around Georgetown, at distances of 20 to 40 metres from the nearest buildings. The photographs in figures 3–6 show the sites fof locations 4, 5, 6 and 7.(8). During the periods that the thermometers were used, they were not shaded from direct sunlight (except by their screens). Some or all of the thermometers were read on 114 days in 1970 and 1971. The comparisons were studied for various weather situations and seasons. The results are discussed in section three.

Through the co-operation of the Canadian Meteorological Service, an electric automobile traverse thermometer was obtained for use during the Christmas period in 1970. The instrument works on the principle that the amount of electricity conducted by a wire depends on the temperature of the wire. A current is conducted through a sensor mounted at a height of one metre in a shield attached to the front of the automobile. The current, and by calculation the temperature of the air, is recorded on a clock-motor-operated graph. On one typical run, the author drove for 105 minutes at a steady speed of near 40 km. per hour around the Georgetown region, along a course which crossed itself several times. The temperature was noted at 124 places, and corrected when necessary for the change in temperature during the 105-minute run.

Reference will be made in section four to an experiment conducted at the McAuley residence. This house is on a wooded lot (see figure 7) at the south end of town. To the north-west of the house is a large open field of short wild grass, which is an extension of the rural landscape surrounding Georgetown. The thermometer numbered 2 in the diagram (figure 7) is the one used as the weather station instrument, and is read at least twice a day by A. McAuley, a keen amateur weatherman.(9)

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(8) In some cases, the thermometers were removed before the pictures were taken. The position of the instrument is then shown by a metre stick in the snow.

(9) Young Mr. McAuley can be seen reading the thermometer in one of four photographs (fig. 8, 9) of the site of the weather station.

Another instrument was placed about 40 metres further into the field (no. 1). Three other instruments were placed in various positions beneath the profuse tree and shrub population surrounding the house. Thermometer three was beneath a tangle of lilac, maple and fir branches (see fig. 10). Thermometers four and five were on the lawn about 12 metres from the house. Instrument four (figure 11) was underneath a clearing in the trees, and thus was in partial shade. Five (figure 12) was near the base of two large maples, and continuously in their shade.

Comparative data were obtained on 22 different dates in 1970–71 at these sites, and the results are discussed in section four.

Unless otherwise specified, units of measurement used in this report are those of the metric system.

3. Measurements of the Urban Heat Island at Georgetown

(a) *Average and Extreme Monthly Values*

The comparative data for 1964–66 gave the following measurements of the urban heat island effect on daily maximum and minimum temperatures in each month of the year:

TABLE 1: Average and Extreme Daily Values of the Urban Heat Island at Georgetown, °C

MONTH	AVERAGE TEMPERATURES			EXTREME VALUES	
	Maximum	Mean	Minimum	Maximum	Minimum
January	0.2	0.9	1.6	1.0	6.0
February	0.3	1.1	1.9	1.5	6.0
March	0.5	1.0	1.4	2.0	5.5
April	0.7	0.8	0.9	2.5	4.0
May	0.8	1.0	1.2	2.0	3.0
June	0.8	1.0	1.3	2.5	3.5
July	0.6	1.0	1.4	2.5	3.0
August	0.4	0.8	1.2	2.0	3.5
September	0.4	0.8	1.2	2.5	4.0
October	0.5	0.7	0.9	2.0	4.5
November	0.5	0.7	0.8	2.0	5.5
December	0.2	0.7	1.2	1.5	6.5
Annual	0.6	0.9	1.2	2.5	6.5

The magnitude of the urban heat island is explained by several meteorological factors.

Solar radiation represents the input of heat energy during the daylight hours. The urban area, for reasons that will be discussed in section 4, is more efficient at storing this heat energy than the rural landscape. Moreover, the urban surface contains confined spaces where some of the solar radiation, having been reflected once, is re-directed towards the surface. Thus, the urban effect during the daylight hours is greatly influenced by the magnitude of solar radiation. This would be higher in early summer than at other times of year if other factors (cloudiness, wind speed) were invariant, but in fact is much higher because the season of strongest solar radiation co-incides with the season of least cloud cover and lowest wind speed (May, June and July). Therefore, the average magnitude of the urban heat island by day is much greater in summer than in winter. Extreme values, however, are more uniform, since there can be clear, relatively calm days in all months of the year.

Wind speed is a critical factor in the development of the urban heat island. When the speed exceeds a critical value, the formation of the urban heat island will be prevented by advection of cooler air from rural areas. Oke and Hannell[10] have developed a relationship between this critical wind speed and the population of the urban area. The predicted critical wind speed for Georgetown is 2.6 m.sec.⁻¹. However, the relationship was based on data from cities with more regular dimensions than Georgetown[11], and therefore, the critical wind speed may increase to 5 m.sec.⁻¹ or more when the wind is from the west. Since afternoon wind speeds range from 4 m. sec.⁻¹ on average in July to 8 m.sec.⁻¹ in January and February, the urban heat island is more frequent in the summer for maximum temperatures. Wind speed at night is below critical values about 50% of cases in winter, but up to 80% in summer.

Cloud cover has already been mentioned as a factor in the distribution of solar radiation. Cloudiness at night reduces the urban heat island effect, because escaping heat in the form of long-wave radiation is reflected back to the surface. Since average cloudiness ranges from .35 in summer to .72 in early winter, one would expect a peak in the urban effect on minimum temperatures in summer. This peak is evident in column 3 of the data in Table 1. However, the more pronounced maximum for the urban heat island in winter has yet to be explained.

The temperature contrasts of winter are less frequent than in summer, but considerably more intense. They occur during periods of anticyclonic weather. Anticyclones, or high pressure areas, produce ideal conditions for the urban-rural temperature contrast indicated in column 5 of the data in Table 1. They are clear and contain large areas of light or calm winds near their centres. Because of the subsidence of air, there is usually a strong temperature inversion near the surface. In rural areas, and especially in valleys where the coldest, most dense air settles, temperatures drop to very low readings. In urban areas, the inversion traps warm air near the surface, and intensifies the heat island by holding smoke and other particles at roof-top where they prevent heat from escaping in the form of long-wave radiation. Anticyclones are as frequent in summer, but they are less intense and contain more moisture. Especially in autumn, this moisture results in radiation fogs when the temperature falls to the saturation point of the air mass: when this occurs, the temperature stops falling and the contrast is not so intense.

Finally, *snow cover* is an important variable. The temperatures of snow surfaces become relatively low when conditions favour long-wave radiation (heat loss from the surface). Therefore, the presence of snow intensifies the urban heat island. Snow cover at Georgetown usually lasts from December 1 to March 20.

(b) *Temperature Distributions During a Cloudy Period in May*

With the network of thermometers newly installed in May, 1970, the author had an opportunity to study the urban heat island under cloudy conditions. A stationary frontal system between arctic and polar air masses settled over southern Ontario on May 13, and remained for five days. Temperatures remained near the average for the time of year (12°C), but exhibited small daily range. There was a total rainfall of 22.2 mm. on May 15 and 16. Winds were light from the SE direction except for strong SW winds during thundershowers. Cloud was mainly of the stratus variety, and was observed throughout the period. The map in Figure 14 shows that temperatures were uniform around the

(10) T.R. Oke and F. G. Hannell, "The Form of the Urban Heat Island in Hamilton, Canada" in W.M.O. Tech. Note 108, p. 126.

(11) Whereas most of the cities studied were circular, Georgetown has the following dimensions: 6 km. east-west, but only 2 km. north-south.

Georgetown area during this cloudy period. The reason for lower maximum temperatures at Hornby is the existence of a lake-breeze from Lake Ontario, which sometimes reaches Hornby but not Georgetown during periods of SE winds. The map in figure 16 shows a recent case of a strong lake breeze which extended 20 km. inland.

(c) Temperature Distributions During a Dry Spell in June

The month of June, 1970, began with two weeks of very warm, dry weather (rainfall was less than 0.5 mm.) during which the sky was clear almost continuously. There were a few afternoons with cumulus clouds, and one cold frontal passage which produced a light thundershower at night. Observations were taken from June 5 to 14, and the average temperatures during that period (figure 15) exhibited the urban heat island for both daytime and overnight temperatures. It will be noted that the McAuley site has both higher maxima and minima than the rural station at Hornby. The higher maximum average is due to the lake-breeze which was noted at Hornby on June 6 and 14. The higher minimum average appears to have been caused by the advection of warmer air from the town. A heat wave, which lasted from June 8 to 11, was accompanied by light winds for the first three days, and as residents of the town know from the smell of the paper mills, the circulation becomes light northerly during periods of warm, still weather. Minimum temperatures on June 10, for example, ranged from 13° in the Credit Valley to 15.5° at Hornby and 17.5° at the McAuley site. The values observed in the urban area were between 17° and 18°. Winds were north at 1 m.sec.$^{-1}$.

During a spell of arctic air-mass weather, minimum temperatures dropped to 5.5° at McAuley and 5° in the Credit Valley; in the urban area they remained above 8°. (June 6, see figure 17 for a map of temperature distribution). On another occasion (June 14), temperatures ranged from 2° at McAuley to 4.5° at urban sites 2 and 4.

The four-day heat wave, although produced by a maritime tropical air mass, was not particularly humid and skies remained clear except for a few afternoon cumulus. Winds, light for the first three days, strengthened to 8 m.sec.$^{-1}$ from the WSW on June 11. On this date, the maximum temperature increased in the urban area from 31° in the west end to 33° in the east end. (map, figure 18). This is an example of a wind speed which was much higher than the predicted critical wind speed of 2.6 m.sec.$^{-1}$, but which merely displaced the area of highest temperature rather than eliminating it altogether.

Another interesting observation was that, on occasion, minimum temperatures at site 6 would fall to values between those in the rural and urban areas. This occurred on June 6 and 13, nights when the wind was north at about 2 m.sec.$^{-1}$ Since the largely vacant industrial park lies to the north of site 6, one may attribute the cooling to advection of cooler air from this area. Minimum temperatures were 2.0° lower than at sites 1,2 and 4. This phenomenon was observed by Chandler at both London (1962)[12] and Leicester (1965)[13]. He names it the "country wind" and explains that when the temperature gradient becomes too strong to continue in stable equilibrium, cooler air flows into the urban area, at least near the margin. The temperature difference on June 6, as already discussed, was about 3.5° outside the valleys, and on June 13, it was 3.0°. Since both these values are near the maximum difference encountered at Georgetown in June, one suspects that the "country wind" is only generated under optimum conditions. No other suggestions of it were found in the data.

The thermometer at site 1 in the urban area, located near the western boundary of the urban area, recorded higher maxima than the rural stations on only three days, all with

(12) T. J. Chandler, *The Climate of London*, Hutchinson and Co. Ltd., London. 1965.

(13) T. J. Chandler, "Night-time Temperatures in Relation to Leicester's Urban Form", *Meteorological Magazine*, Vol. 96, 1967. p. 1141.

east or south-east winds. During the predominant west-wind circulations, the heat island was displaced at least 250 metres to the east (site 1 is 250 metres east of the boundary). However, the displacement was never more than 800 metres, the distance to site 2 from the boundary. Site 2 was occasionally cooler than site 4 or site 6, but always warmer than site 1.

(d) Temperature Differences in Summer

Temperatures were observed at site 4 for all of July and the first three weeks of Ausut, 1970. Both months were warmer than average at Georgetown, with two heat waves lasting from July 25 to August 1, and from August 7 to 16.

During July, 1970, the average maximum temperature at site 4 was 0.5° higher than at McAuley, while the average minimum temperature was 1.0° higher. The mean temperature for the month was 22.0° in the urban area, and 21.3° at McAuley. Maximum temperatures showed the greatest contrasts during a spell of hazy, humid weather with light winds (July 8 11); temperatures on one date were 2.0° apart (26.0, 28.0). On the other hand, over one-third of the maximum temperatures were not significantly different. For example, on July 19 and 20, which were cool, overcast and rainy, there was no difference. Minimum temperatures were usually lower at the McAuley site, but not during the first heat wave (July 25 August 1) when humidity was very high. Although skies were clear at night, the humidity acted to reduce the long-wave radiation greatly. In fact, on two of the warmest nights, temperatures were higher at the rural site: July 28 (23.0° compared with 21.5°) and August 1 (21.0°, 20.0°). Of course, during a heat wave, there is no heating of buildings in the urban area, and factories are operating at reduced capacity in late July.

During the second heat wave (August 7–16), conditions were not so humid, and minimum temperatures were 2 to 3 degrees different on several nights. August 14 was the warmest day of 1970 at both locations; the maximum was 33.0° at McAuley, and 34.5° at site 4. Another calibration check was carried out by placing a thermometer about 5 km. from Georgetown in a similar site to the McAuley instrument. During a four-week period in July and August, the two instruments displayed no significant differences in temperature.

An automobile traverse was carried out around midnight on July 22/23. Results, mapped in figure 19, show the existence of a weak heat island over the town. The weather was clear with light winds, and a bank of stratus cloud visible to the south-east. The region was under the influence of a sprawling high pressure centre of the polar air mass.

(e) Temperature Distributions in Winter

A series of comparative observations was made for 28 days, beginning on December 7, 1970. After a very mild and pleasant November, temperatures reached record high values of 16.0° on December 1. However, on December 4, there was a fall of 51 mm. of snow, and for the next three weeks, there was a constant progression of snowstorms which dropped a total of 684 mm. The period began with an arctic outbreak, and on the 8th, with clear skies and calm conditions prevailing, minimum temperatures fell to -16° at sites 2 and 4, and -20.5° at McAuley. However, the next 18 days were mainly overcast, and the average urban temperature was only 0.4° higher than the rural. After a storm on December 25, a sprawling high pressure area from the Arctic slowly settled over Ontario, lasting for almost a week. This event was accompanied by clear skies and nearly calm conditions, so that very intense urban heat islands were observed overnight.

During this spell of anticyclonic weather, the author was able to make extensive use of the automobile traverse thermometer. On December 21, with clear skies and a temperature of about -15.0, a traverse was carried out; however, winds were gusting up to 10 m.sec.$^{-1}$ from the NE, and stratus cloud from an approaching storm covered the sky soon after the start of the run. No heat island was observed at that time. On the afternoon of December 24, with overcast skies and a NW wind of 4 m.sec.$^{-1}$, there was a faint heat island effect in the more sheltered western part of Georgetown (see map, figure 20).

Under ideal conditions, a traverse was carried out on December 29/30, beginning at 23:40 EST. The temperature distribution was so complex that a large-scale map had to be employed to show the results (see map, figure 21). There is ample evidence of aerial drainage, as temperatures in the valleys are at least 4° colder than in nearby upland areas. This valley effect at first tends to confuse the picture of the urban heat island. However, it is instructive to note that temperatures in the Silver Creek valley are in the range -24 to -25 outside the urban area, but rise to -20. at two points within the town. On flat terrain, there were several instances of sharp temperature differences of 3 or 4 degrees in a span of 50 metres; these gradients were observed at the urban-rural boundary. From figure 21, it is obvious that there was no warm cell at the location of the central business district. However, in Brampton, a nearby city of 37,000 people, a distinct warm cell was measured around this central core on the previous night, December 28. The results of that traverse, shown in figure 22, suggest that the business district of Brampton is sufficiently large to generate a warm cell, whereas that of Georgetown is not. In the Brampton traverse, the temperature gradient in flat terrain at the north-west boundary of the urban area was 1.0° C every 20 metres.

At Georgetown, the urban-rural temperature contrasts were quite large for a seven-day period ending on January 1. The data are shown in Table 2:

TABLE 2: Temperature Differences During an Anticyclonic Spell in Winter, Georgetown, °C

Date	Minimum Temperatures		Difference
	Urban	Rural	
26 Dec.	-15.0	-16.5	1.5
27 Dec.	11.5	-14.0	2.5
28 Dec.	-16.0	-18.0	2.0
29 Dec.	-18.5	-23.5	5.0
30 Dec.	-23.0	-27.0	4.0
31 Dec.	20.5	-24.5	4.0
1 Jan.	-16.5	20.5	4.0

Maximum temperatures during this period showed little difference from urban to rural areas. They ranged from -6° to -3° through the period. On December 30, the different rates of cooling in urban and rural areas were demonstrated. Temperatures were read every hour at both urban and rural sites, with the following results:

TABLE 3: Different Rates of Cooling, Georgetown, Dec. 30, 1970.

Hour (E.S.T.)	Temperature		Difference
	Urban	Rural	
14	- 5.5	-5.5	0.0
15	- 5.5	9.0	3.5
16	- 8.5	-9.5	1.0
17	11.5	-12.5	1.0
18	15.0	-17.0	2.0
19	-16.0	20.0	4.0
20	-18.0	-22.0	4.0
21	-18.5	-23.0	4.5
22	-19.0	-24.0	5.0
23	19.0	-23.5	4.5
24	19.5	-24.5	5.0

It will be noted from Table 3 that temperatures began to drop about one hour earlier in the rural area, and at both locations, there was a rapid decrease after sunset, which was at 17:06 E.S.T. The decrease in the next three hours amounte to 9.5° at the rural site, but only 6.5° at the urban site. By this time, temperatures had reached to within 1.0 degree of the minimum for the night.

For the month of December, the average difference in maximum (urban-rural) was only 0.2°, but for minimum temperatures it was 1.9°. The mean temperatures for the month were - 6.3° at the urban site, 7.4° at the rural site.

In January, 1971, the average difference in minimum temperature was 1.7°. On January 9, the difference was 5.0°. However, in the latter part of January, there were several periods of windy, cold weather when temperatures dropped below - 20°; during these windy arctic conditions, the difference in temperature did not exceed 2.0°.

In February, 1971, temperatures during an 8-day period averaged 0.2° higher in the urban area by day, and 1.4° higher by night. On February 16, the contrast in minimum temperatures was 4.5° (- 15.0 and - 19.5). Again on March 2, the contrast was 4.5° (- 12.0 and - 16.5).

(f) Snow Depths in Urban and Rural Areas

The winter of 1970 71 was a rather severe one at Georgetown, especially in terms of snow drifting. Local roads were blocked by snow drifts on several occasions. Total snofall to the middle of February was 20 cm. above average, and it was the windiest winter since 1942. Consequently, along the western boundary of the urban area, there were numerous large snow drifts, such as the one in the photograph in figure 13. These drifts are of interest because they occur at, and as a result of, the urban-rural boundary.

Lindqvist[15] suggests that snow depths may provide an indirect measurement of the urban heat island. There is considerable uncertainty about the reasons, but snow depths are usually lower in urban areas than in surrounding rural areas. One possible cause is the combined effect of higher temperatures and more effective use of solar radiation upon snow-melt rates. However, it may be true that less snow falls in urban areas. Changnon[16] believes that cities of medium size may enhance snowfall within their boundaries (by creating more atmospheric particles to act as precipitation nuclei), but larger cities reverse this effect by transforming potential snow into rain. Hare[17], pointing to the fact that the urban heat island is relatively shallow, and noting that freezing rain falls as rain from about 1500 metres, concludes that the transformation involves wet snow falling at temperatures at the surface of 0 to 5 degrees. Changnon feels that present climatological station measurements of snowfall are not accurate enough to compare. The author, having had 7 years' experience in measuring snowfall, strongly agrees. The climatological station observer is confronted with numerous problems in snowfall measurement. Usually, he has a full-time occupation which prevents him from making measurements at the best times. Some snowfalls can be read from his rain gauge, but others, having come down more horizontally than vertically, are almost impossible to measure accurately. Sometimes, snowfall is mized with rain or freezing rain. Without a snow gauge, the volunteer observer has a real problem in measuring these mixed falls. Here in Canada, there are occasional blizzards which may produce over 50 cm. of snow and whip it into huge drifts with gale force winds. Measuring the snow depth with a metre stick then becomes very arbitrary indeed. Therefore, the author decided that the snowfall measurements made by

(15) S. Lindqvist, "Studies on the Local Climate in Lund and its Environs", *Geogr. Annaler*, Vol. 50, February, 1968.

(16) S. A. Changnon, Jr., "Recent Studies of the Urban Effect on Precipitation in the United States", in *W.M.O.* Tech. Note 108, p. 332.

(17) Dr. F. Kenneth Hare, personal communication

himself and the volunteer observers at nearby climatological stations were not accurate enought to compare with any reliability.

On February 16, 1971, snow depths were measured in and around Georgetown. At each location, ten separate measurements were made and the average depth recorded. In Georgetown, these averages were all between 34 to 38 cm. Because of the presence of buildings, snow drifts were mixed with bare spots in most locations. In the open country, snow depths were more uniform. Drifting in the fields and vacant land tends to have the same effect at all points, and there is no net snow-drifting, except onto places that have been cleared (e.g., roads). Measurements were in the range 44 to 55 cm. The difference between urban and rural snow depth was significant at the .01 level, and the magnitude of the difference suggests that different rates of snow-melt are at least partly responsible.

4. Site Differences and the Urban Heat Island

Landsberg[18], in a paper entitled "Micro-meteorological Temperature Differentiation Through Urbanization", discusses the causes of the urban heat island phenomenon. His conclusion is that the major cause is the alteration of the radiation balance in the urban environments. For example, building surfaces and other artificial surfaces retain more heat for nocturnal emission than natural surfaces. Urban regions have systems of drainage which rapidly remove most rainfall, while vegetation retains a much larger proportion of the moisture at the surface: this moisture requires heat energy for evaporation and therefore less heat is available to warm rural air. Profuse vegetation reduces the wind speed but also screens solar radiation. However, the urban environment presents obstacles which reduce the wind speed *and* store heat from solar radiation. The lower wind speeds tend to reinforce the heat island, since turbulence is decreased and the dome of warmer air over the city suffers less disruption.

The sites of the five thermometers at the McAuley residence have already been discussed (p. 7) (figure 7). Temperatures were measured in standard screens at these sites to determine what relation there was between meteorological conditions, presence of vegetation and shade, and temperature distribution.

On the morning of May 28, temperatures fell to - 1.0° at site 1 in the field, but remained above 2.0° at sites 3, 4 and 5. Maximum temperatures of 12.0° were recorded at all sites; skies were mainly overcast and winds were NW (from field to house) at about 7 m.sec. $^{-1}$. On May 29, a clear afternoon with light SE winds, the maximum temperature in the field was 2.0° higher than at site 3, and 1.0° higher than at site 5.

Temperatures were recorded at each site on the McAuley property for 13 consecutive days (August 28 September 9) in late summer, 1970. The following table gives a summary of the results:

TABLE 4: Site Differences and Temperature Distribution

Sites:	1. field	2. lawn	3. in bushes	4. partial shade	5. shade
Average maximum	23.9	23.4	21.8	22.9	21.9
Average Minimum	10.8	11.5	12.7	11.7	12.5
Mean Temperature	17.4	17.5	17.2	17.3	17.2
Highest Temperature	28.0	27.5	25.5	27.0	25.5
Lowest Temperature	3.0	4.0	7.0	5.5	6.5
Temperature Range	25.0	23.5	18.5	22.5	19.0

Range of maximum temperatures on individual dates: 1.5° to 3.5°
Range of minimum temperatures on individual dates: 0.5° to 4.0°

(18) H.E. Landsberg, "Micro-meteorological Temperature Differentiation through Urbanization", in W.M.O. *Technical Note* 108, 1970, p. 130.

On cloudy nights, there was no significant range in minimum temperatures, whether or not winds were light. The afternoon maximum temperatures varied least on days when winds were moderate or strong. All days during the period enjoyed afternoon sunshine, so that it was not possible to observe temperature distributions on cloudy afternoons. However, on other occasions, no temperature difference was observed on overcast afternoons. The temperature difference in the shade was greatest on days with high solar radiation and light winds.

It is evident that, during the period of the experiment at least, site differences have no net effect on mean temperature. The average daily range is reduced by about 25%, but the increase in minimun temperature is balanced by a decrease in maximum temperature. During the same period, both maximum and minimum temperatures at urban location 2 were significantly higher than at the weather station thermometer at the McAuley site. The daily range was over 95% of the rural value. However, when the weather station was at urban location 3, which is similar to sites 4 and 5 in this experiment, there was a similar decline in average daily range, based on a comparison with regional averages all taken in exposed locations.

Under the conditions of late summer, then, the site differences are not capable of producing the urban heat island effect. The distribution of minimum temperatures has the same characteristics as the urban heat island, but the distribution of maximum temperatures has the reverse form.

The deciduous trees at the sites lost their leaves between October 15 and 22, and thereafter, temperature contrasts were much reduced until the appearance of a snow cover (December 4). During the late autumn, despite ideal conditions for strong micro-climatological contrasts in temperature – light winds and clear skies, there was no night when temperature differences exceeded 2.0°. Even in mid-winter, under strong anti-cyclonic inversion conditions, the temperature contrast was no greater than 3.0° on December 30 and January 16. And, as already mentioned, strong temperature gradients were observed on December 30 near the urban-rural boundary, which runs through the McAuley sites. However, the full effect of the urban heat island was not observed at the sites. For example, on January 16, the temperature in the field was -28.5°, while at site 5 at the McAuley property, it was -25.5°. However, at urban site 2, it was -23.5°. On several other occasions, the highest temperature at the McAuley sites was about mid-way between the urban and rural temperatures.

Observations in winter near the urban boundary point out the problem of assessing the role of site difference in accounting for the temperature gradients of the heat island, which sometimes exceed 1.0° per 20 metres.

5. Urban Heat Islands at Small Urban Places

In figure 23, the relationship between city population (P) and the critical wind speed (u_{crit}) is graphed. This relation, based on data for cities of more than 25,000 population, is

$$u_{crit} = 3.4 \log P - 11.6$$

The average value of u_{crit} for Georgetown agrees very closely with the prediction, as do the other data (r=0.97). However, the author feels that the relation is not valid for smaller urban places. The relation predicts that there will be no urban heat island for towns of less than 5,000 population. This is not consistent with data available in the "Monthly Record of Meteorological Observations in Canada", which lists temperatures for over 500 stations in Canada. The author found about 60 cases of urban-rural temperature contrast in Canada for towns and cities of various sizes. Some of the comparisons were not considered reliable because of the presence of deep valleys, large bodies of water or differences in times of observations. Nevertheless, the author found 33 cases of the urban heat island in Canada.

In section 3, it was demonstrated that the urban heat island has different magnitudes in different months at Georgetown, and was greater for minimum temperatures than for maxima. Therefore, it is reasonable to suppose that any relationship between population and magnitude of the urban heat island will depend upon the month and time of day. The author selected minimum temperatures in July, and plotted the values of urban heat islands against population for the 33 urban areas in Canada. The result is graphed in figure 24.

The relationship between urban heat island (dT) and population (P) for minimum temperatures in July is

$$dT = 1.0 \log P - 3.0$$

This relation predicts that there will be an urban heat island for urban places with populations of 1,000 to 5,000. In the data of the Canadian "Monthly Record", the following towns had urban heat islands of 0.5° to 1.5° for July minima: Lloydminster (6,000), Camrose (6,500) and Vegreville (3,000), Alberta; Portage la Prairie (12,000) and Flin Flon (14,000), Manitoba; Leamington (9,000) and Grimsby (8,000), Ontario; and Coaticook (7,000) and Roberval (9,000), Quebec. At Wetaskiwin, Alberta, there has been evidence of an urban heat island since comparison became possible in 1931. The population has risen from 3,000 to 5,500 in the intervening period. Furthermore, the author noticed during automobile traverses that temperatures in the Credit River valley community of Glen Williams (pop. 1,000) were 1.5° or 2.0° higher than in the surrounding fields in the valley (under ideal conditions for the heat island). However, there is no evidence that such differences are due to the existence of a heat island.

The most popular method of demonstrating the existence of the urban heat island is displaying isotherms for a clear, calm night in winter. Spectacular differences of 10 to 15 degrees are found in large cities, and even in towns of smaller rank such as Georgetown (pop. 17,000), the results (5° difference or more) are convincing.

However, for the smallest places exhibiting the urban heat island, the extreme values might reasonably be expected to remain below 2.0°. However, such temperature contrasts are common in homogeneous terrain in winter inversion conditions, so that the measurement of a few extreme cases will not suffice.

At least 12 months of comparative data should be obtained in order to measure the urban heat island at a small urban place. It would be wise to select a small town in relatively flat terrain, located at a suitable distance from any major body of water or larger urban area. In Southern Ontario, two examples of suitable locations for a small-town urban heat island study are Arthur (pop. 1,100) and Stayner (pop. 2,200).

There are several questions which ought to be investigated for small-town urban heat island conditions. These include:

(a) If an urban heat island condition developes during the most favourable time (after sunset), will it continue throughout the night, or will the country wind set in to overcome it? (That is, can the heat island condition exist in stable equilibrium for small urban places?)

(b) What is the smallest urban size for which the heat island, and not site difference, best explains the temperature field?

(c) What degree of conformity will the urban heat island show with respect to the spatial characteristics of the built-up area?

(d) How valid would it be to generalize the results of one small-town heat island study?

(e) How large a body of observational data is required in order to demonstrate the existence of the heat island?

The most promising idea in this field is the method of placing thermometers in locations slated for immediate urbanization. In this case, however, the results would have to be considered with this qualification in mind: by construction, does the urban area remain separate from other larger urban places, or does it in fact become part of the temperature field of some much larger population? Observations are being studied at the planned city of Columbia, Maryland(19). By 1968, when the population had reached 1,600, there were measurable increases relative to nearby stations; however, the role of site difference had not been clarified.

6. Conclusions

In this study of the urban heat island at Georgetown, Ontario, the author has been concerned with the following problems:

- calculation of the magnitude of the heat island on the basis of average monthly temperatures.
- characteristics of the urban temperature distribution in various seasons, times of day, and weather conditions.
- the relationship between site differences and the urban heat island phenomenon.
- special questions raised by the existence of sharp temperature gradients near the urban-rural boundary.
- the magnitude of urban heat islands at urban places of various populations.
- the methods of research required to investigate the heat island at relatively small urban places.

The average values of the urban temperature increase at Georgetown are listed in Table 1 on page 4.

Observations made during 1970–71 at Georgetown indicated that the heat island has the following characteristics:

It is eliminated when the wind speed exceeds a critical value. Because of the non-circular configuration of the urban area, this critical speed varies with wind direction, but the average value (2.6 m/sec) agrees with the predicted value from Oke and Hannell (figure 23). It is also eliminated in overcast weather, in all seasons of the year.

Maximum values of the urban heat island at night approach 3.5° in summer, and 6.0° in winter. They occur during the passage of anti-cyclones of the arctic or polar air masses, and are associated with light winds or calm, and temperature inversions. Temperatures in nearby valleys are often 2 to 4 degrees colder than in nearby rural areas at higher elevations. The aerial drainage phenomenon which causes these low readings may also be responsibile in part for the apparent failure of the country wind to influence temperatures near the edge of the urban area. That is, the cold air near the urban boundary, instead of flowing into the urban area when the temperature gradient becomes too strong to remain in stable equilibrium, may flow towards the valleys which almost encircle the urban area. The surprising paucity of observations suggesting a

(19) H.E. Landsberg, "Climates and Urban Planning" in *W.M.O.* Tech. Note 108, p. 369.

country wind lends support to this theory, which would imply that the presence of the valleys reinforces the heat island. Strong temperature gradients of about 1 C° per 20 metres were found during winter night-time automobile traverses. There was no suggestion of a warm core surrounding the central business district, but there was evidence of one in Brampton, a town with about twice the population (but a central business district four times larger). Other observations revealed the different rates of cooling that produce the urban heat island, and showed that the difference in temperature is established on clear nights by the time of sunset.

It was found that site differences associated with vegetation and a few small buildings were responsible for considerable modification of temperatures. However, although the temperature changes were similar to urban heat island effects at night, they were balanced by reduction of day-time temperatures, so that there was no net change in mean temperature. Site difference alone, then, is not responsible for the temperature changes observed in urban areas. Furthermore, it was found that the temperature gradient near the urban-rural boundary was intensified in the summer, when vegetation was most profuse. In all seasons, however, the site charcteristics of the boundary may influence the temperature gradient found there.

The author studied data from 33 urban areas in Canada, and found that there was a relationship between the magnitude of the urban heat island (u.h.i.) and the population of the urban area (P) for average minimum temperatures in July. This relation can be written:

$$(\text{u.h.i.})_{\substack{\text{July}\\ \text{min.}}} = 1.0 \log P - 3.0$$

For average values of other readings (e.g., maximum temperatures) or for other months, different relationships might be expected to exist, and further research into these relationships would be of value to those interested in understanding the characteristics of the urban heat island. The relationship found by the author suggests that urban heat islands exist for towns of populations of less than 5,000; indeed, they might occur in towns of only 1,000 population.

To investigate the possible urban heat islands of such small urban places, more intensive research is required. The traditional method of studying extreme cases (clear nights in winter) will not suffice, because the temperature differences might be reasonably expected to remain below 2.0°. Such variations are frequently encountered in open countryside during strong temperature inversions. The author believes that useful results will only be obtained after a long series of comparative maximum and minimum temperatures is completed, supplemented with automobile traverses. Some of the characteristics of small-town urban heat islands that ought to be investigated pertain to their frequency, their stability, and their magnitude. The author believes that general characteristics of small-town urban heat islands may be severely disrupted by particular characteristics of small towns; however, a systematic study of deviations from general theory will ultimately increase our understanding of the spatial characteristics of urban heat islands.

ACKNOWLEDGEMENTS

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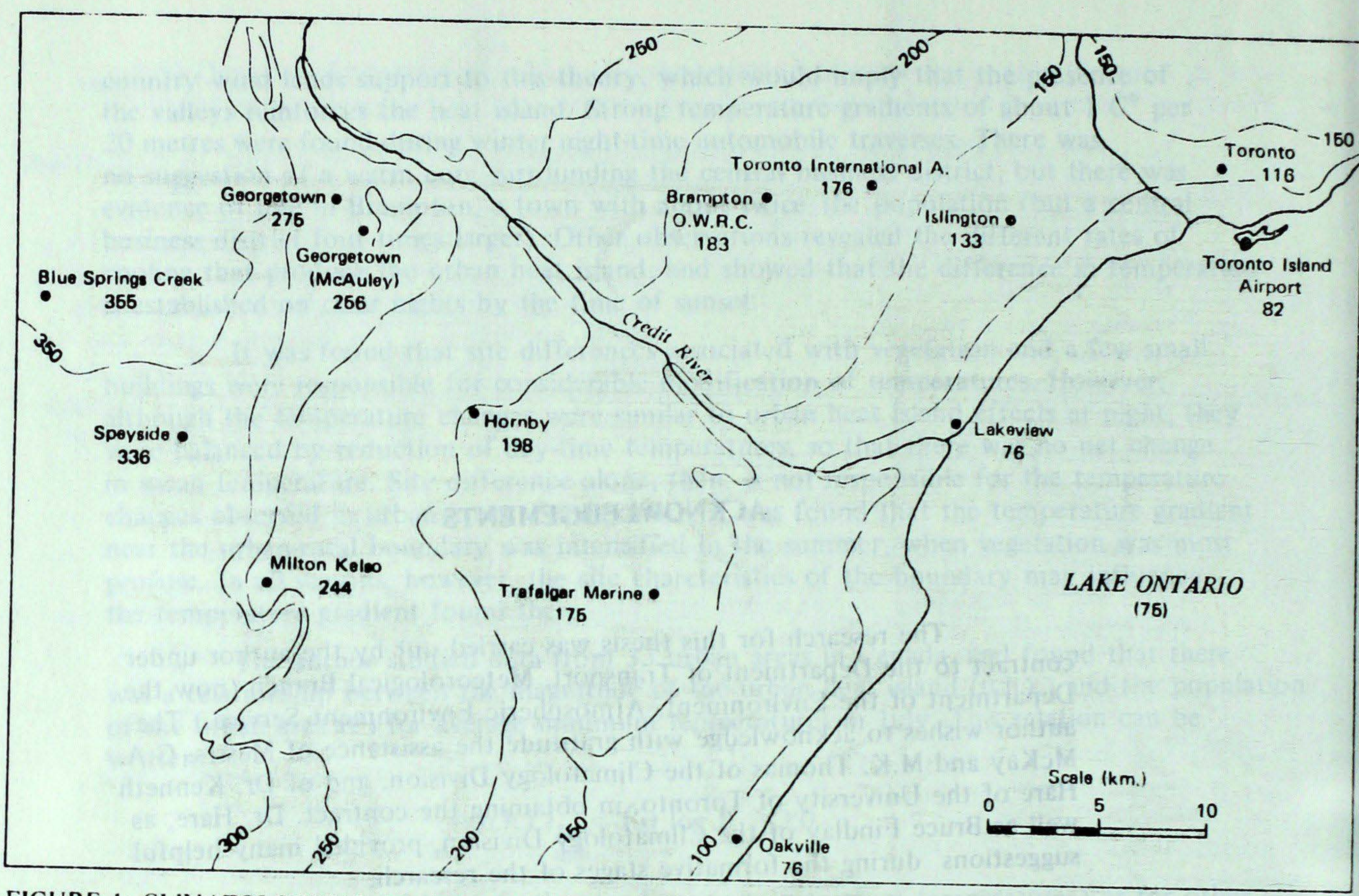

FIGURE 1: CLIMATOLOGICAL STATIONS IN THE TORONTO REGION (Elevations in metres).

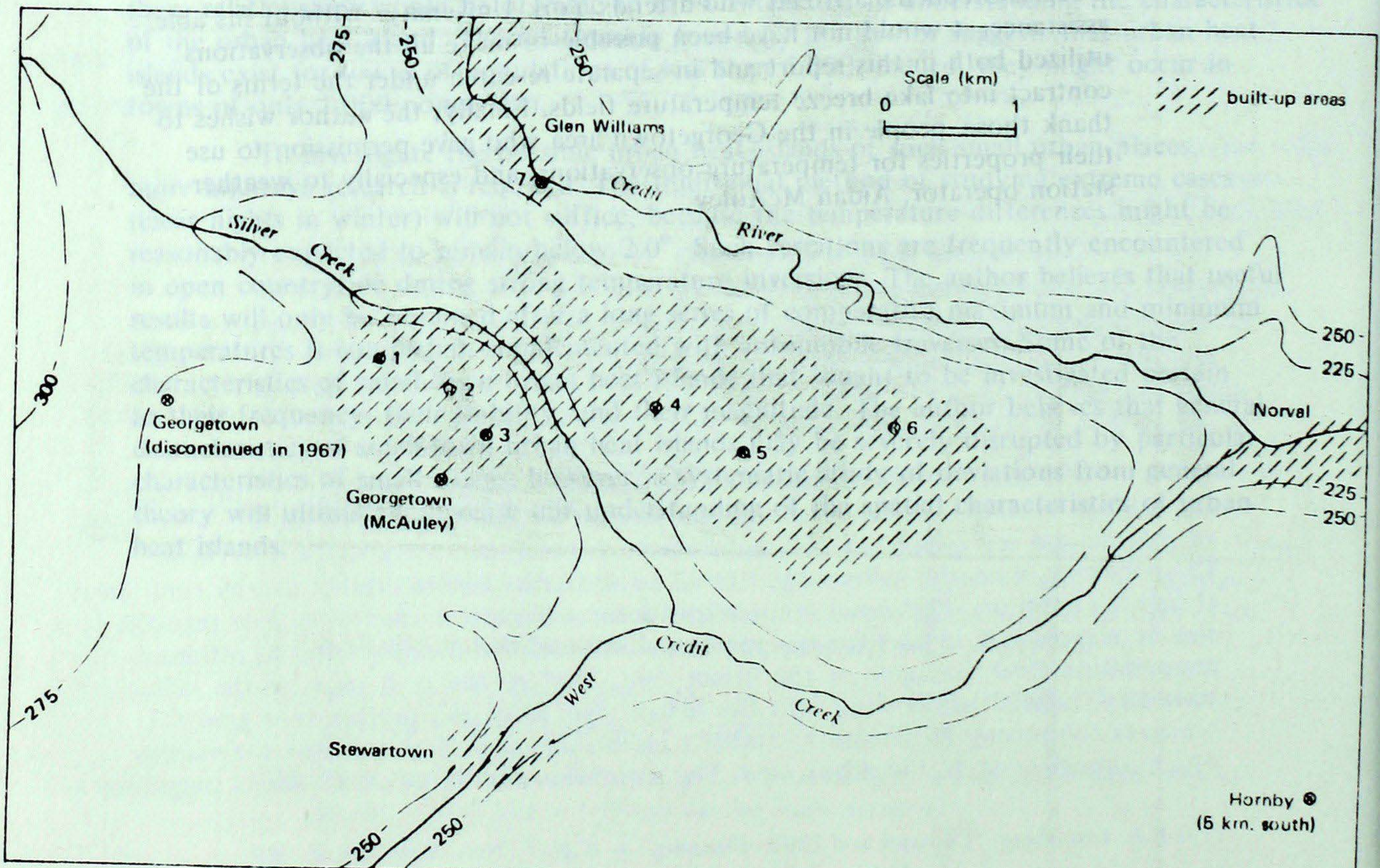

FIGURE 2: LOCATION OF THERMOMETERS IN THE GEORGETOWN URBAN REGION (Elevations in metres)

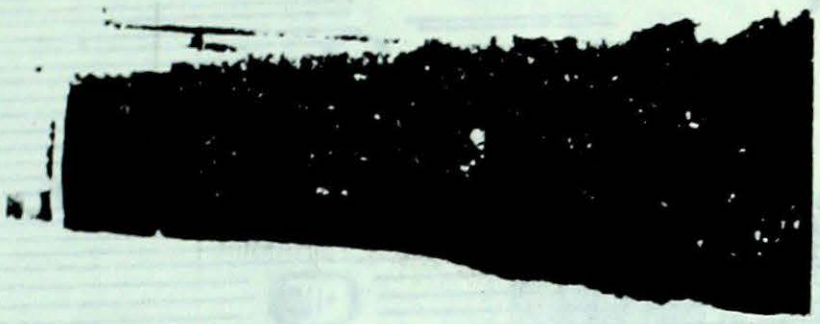

FIGURE 3:
SITE 4, GEORGETOWN URBAN HEAT ISLAND STUDY, FACING N. E.

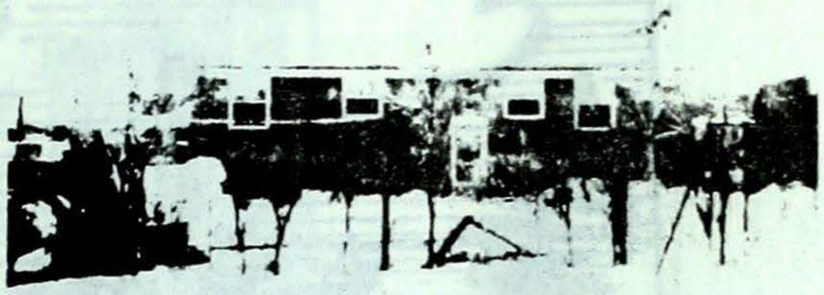

FIGURE 4:
SITE 5, GEORGETOWN URBAN HEAT ISLAND STUDY, FACING EAST. THERMOMETER WAS LOCATED AT THE POSITION OF THE METRE STICK.

FIGURE 5:
SITE 6, GEORGETOWN URBAN HEAT ISLAND STUDY, FACING N. E. THERMOMETER WAS LOCATED AT THE POSITION OF THE METRE STICK, FOREGROUND.

FIGURE 6:
SITE 7, GEORGETOWN URBAN HEAT ISLAND STUDY, FACING N. E. THIS SITE IS AT GLEN WILLIAMS, IN THE CREDIT RIVER VALLEY.

FIGURE 7:
LOCATION OF THERMOMETERS AT McAULEY SITE, GEORGETOWN, ONTATIO

FIGURE 8:
THE SITE OF THE WEATHER STATION
THERMOMETER AT THE McAULEY RESIDENCE,
FACING N.E.

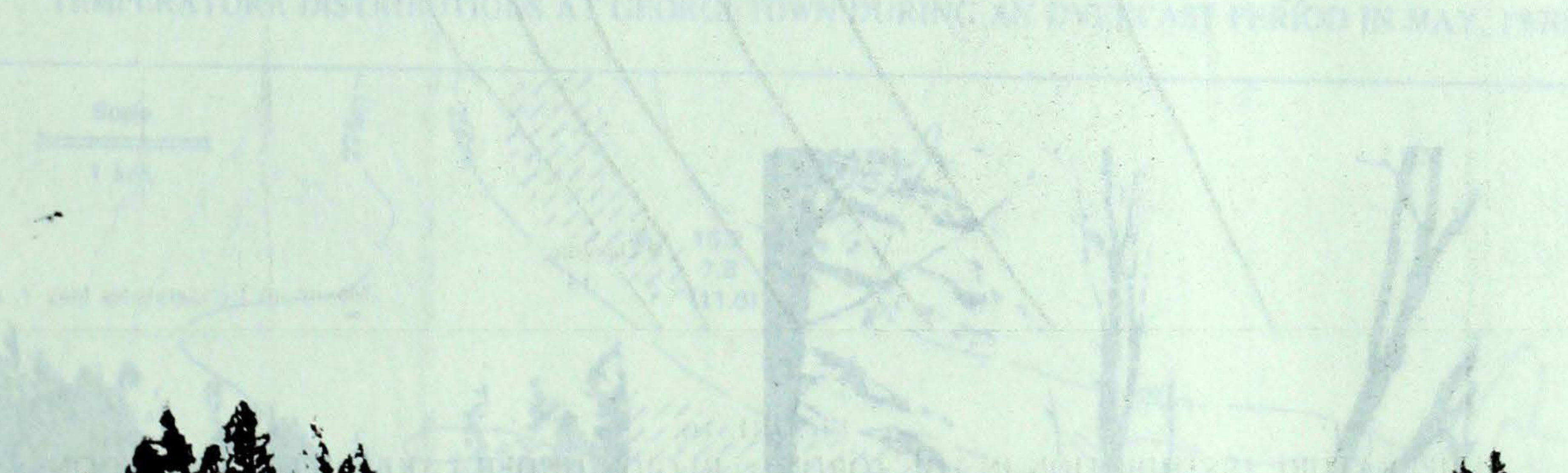

FIGURE 9:
THE McAULEY SITE, FACING SOUTH (left) AND WEST (right)

FIGURE 10:
LOCATION #3 IN THE SITE DIFFERENCE EXPERIMENT. POSITION MARKED BY METRE STICK.

FIGURE 11:
LOCATION #4 IN THE SITE DIFFERENCE EXPERIMENT. POSITION MARKED BY METRE STICK, CENTRE.

FIGURE 12:
LOCATION #5 IN THE SITE DIFFERENCE EXPERIMENT.

FIGURE 13:
LOCATION OF SNOW DRIFTS ALONG WESTERN BOUNDARY OF URBAN AREA, 16/2/71.

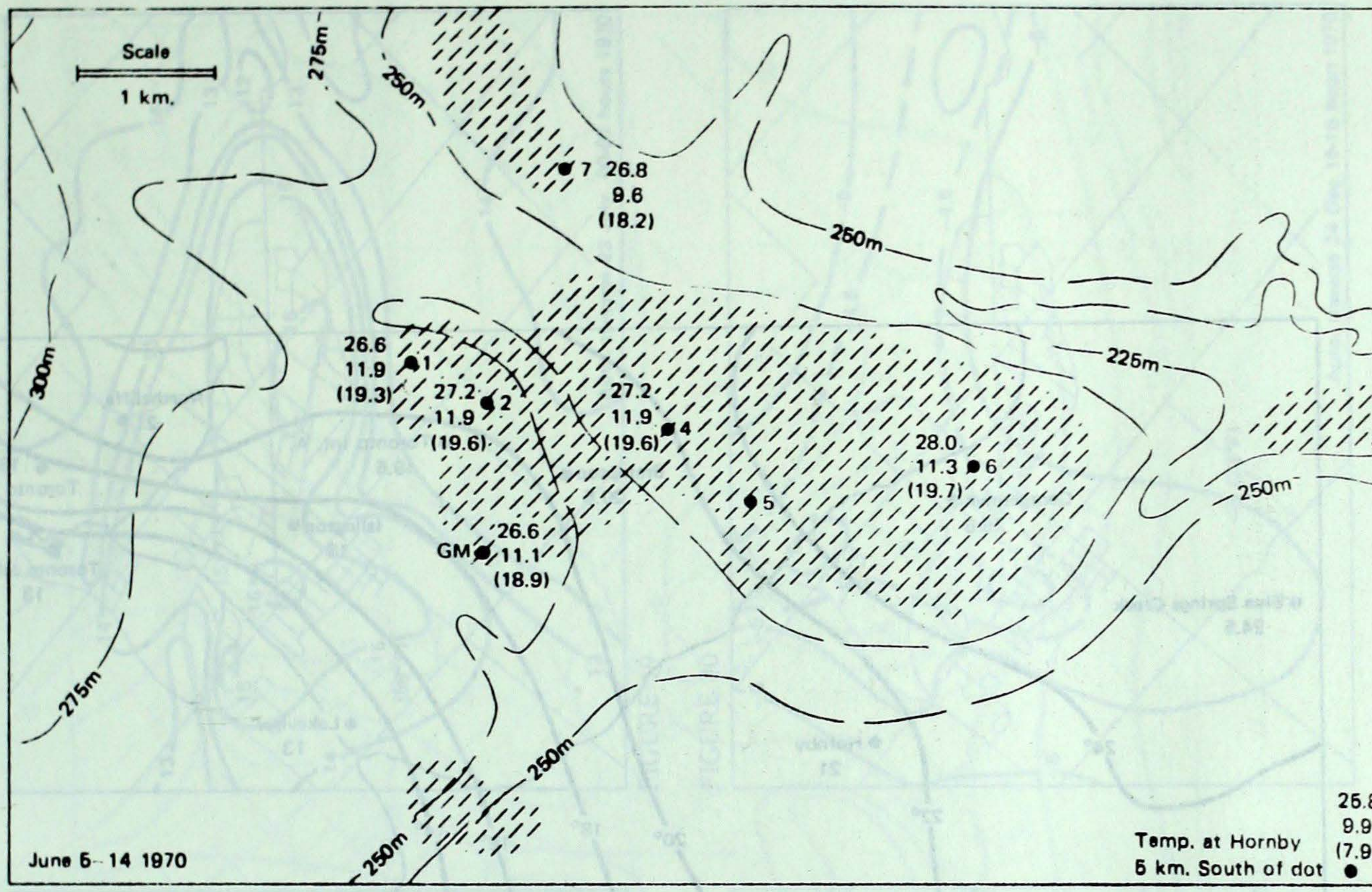

FIGURE 14:
TEMPERATURE DISTRIBUTIONS AT GEORGETOWN DURING AN OVERCAST PERIOD IN MAY, 1970

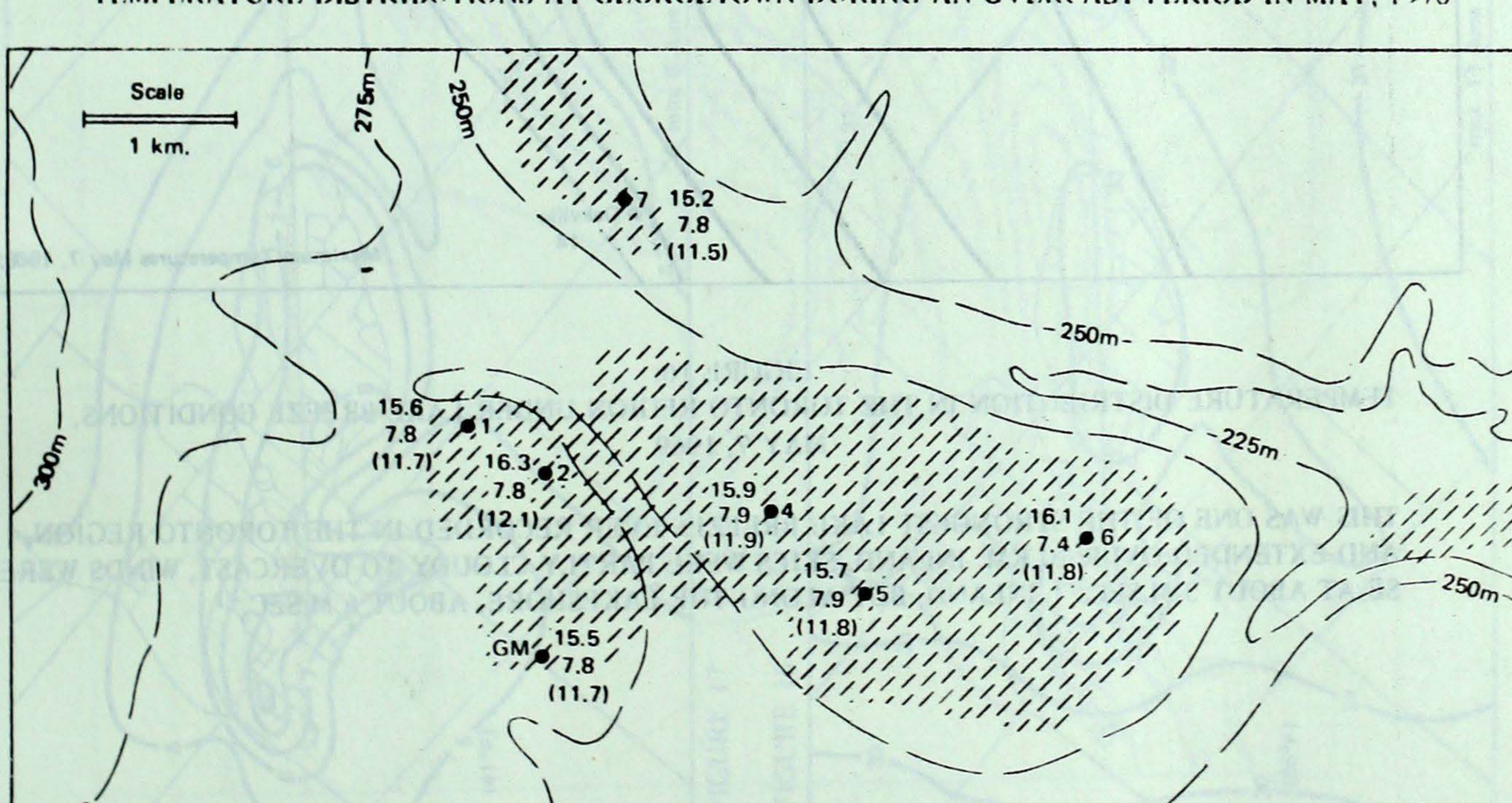

FIGURE 15: TEMPERATURE DISTRIBUTIONS AT GEORGETOWN, JUNE 5–14, 1970

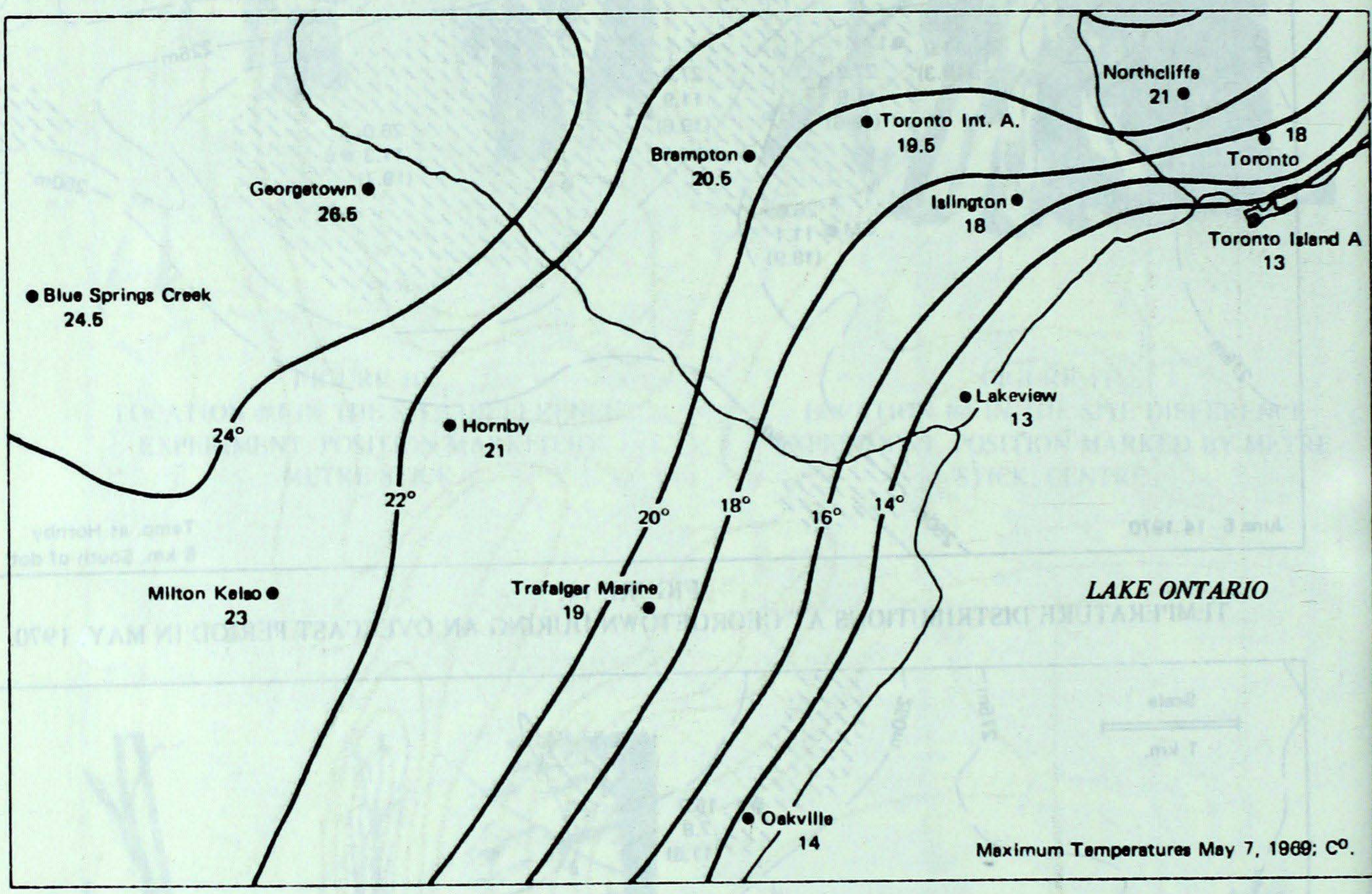

FIGURE 16:
TEMPERATURE DISTRIBUTION IN THE TORONTO REGION UNDER LAKE-BREEZE CONDITIONS, MAY 7, 1969

THIS WAS ONE OF THE STRONGEST LAKE BREEZES EVER RECORDED IN THE TORONTO REGION, AND EXTENDED OVER 20 KM. INLAND. SKIES WERE PARTLY CLOUDY TO OVERCAST, WINDS WERE SE AT ABOUT 3 M.SEC.$^{-1}$ INLAND, BUT ALONG THE LAKESHORE, ABOUT 6 M.SEC.$^{-1}$

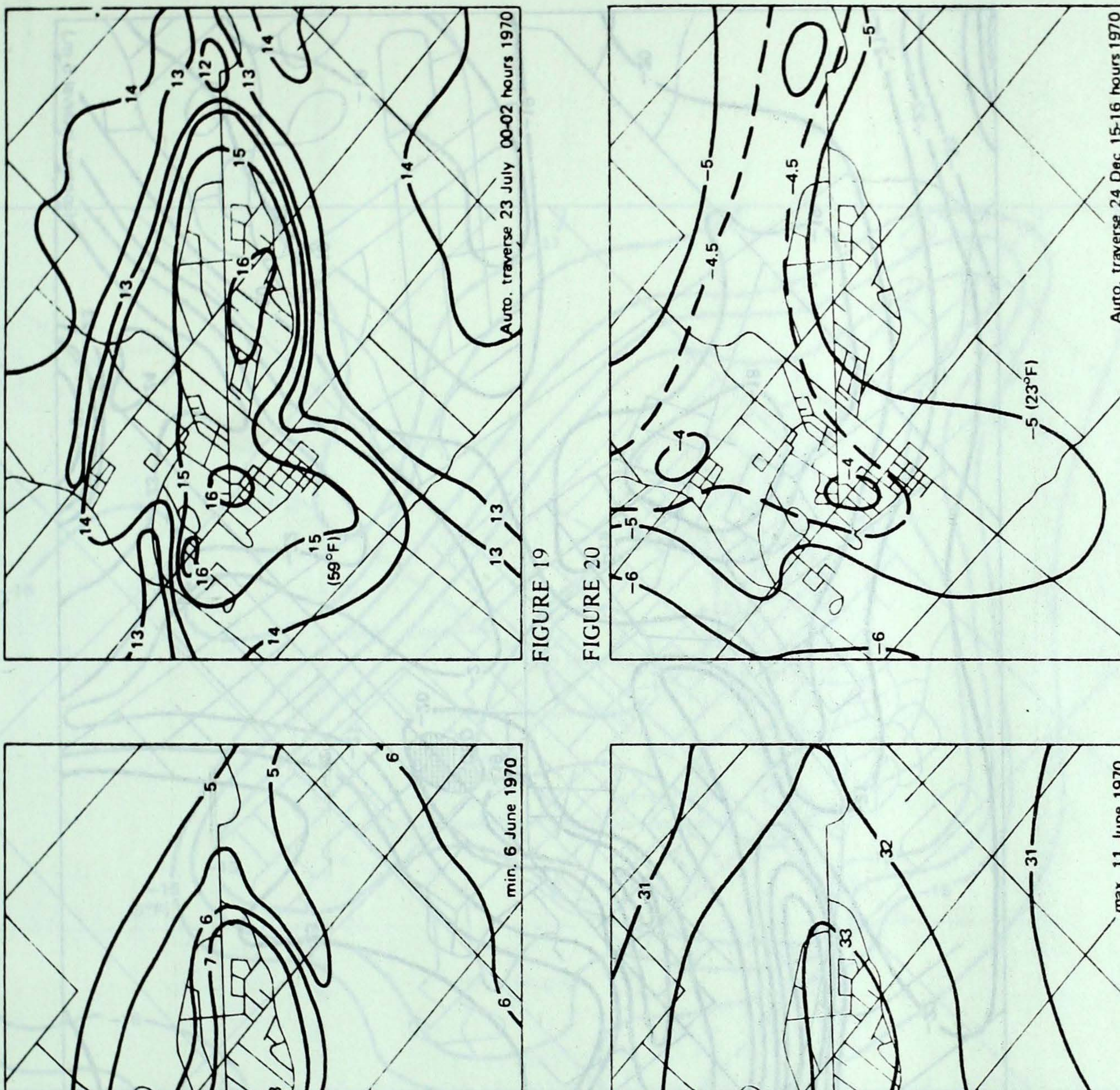

FIGURE 17–20:

TEMPERATURE ISOTHERMS IN THE GEORGETOWN URBAN AREA

17: minimum temperatures, June 6 — 19: automobile traverse, July 23

18: maximum temperatures, June 11 — 20: automobile traverse, Dec 24

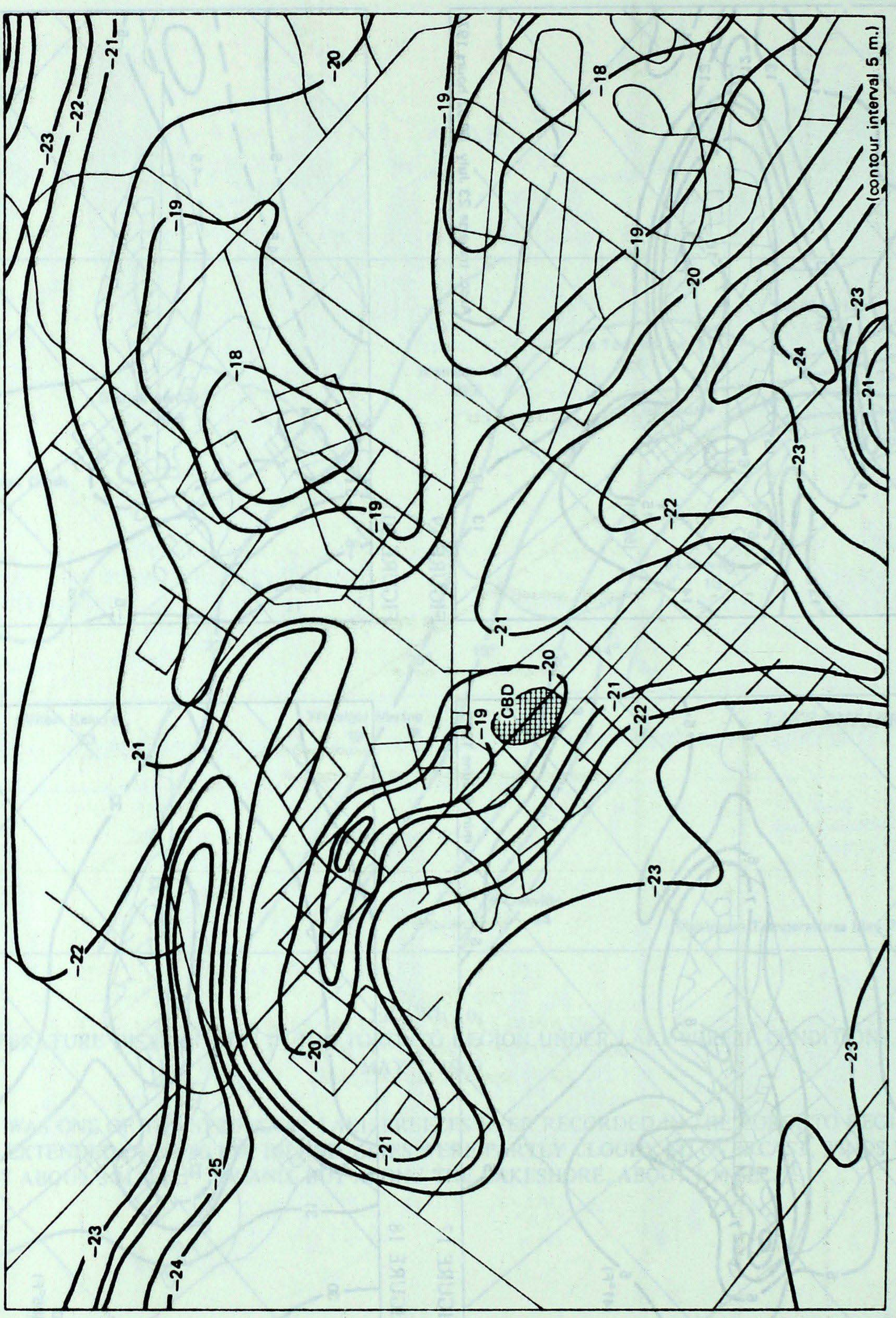

FIGURE 21:
URBAN HEAT ISLAND AT GEORGETOWN, DECEMBER 29 at 2400 h, 1970

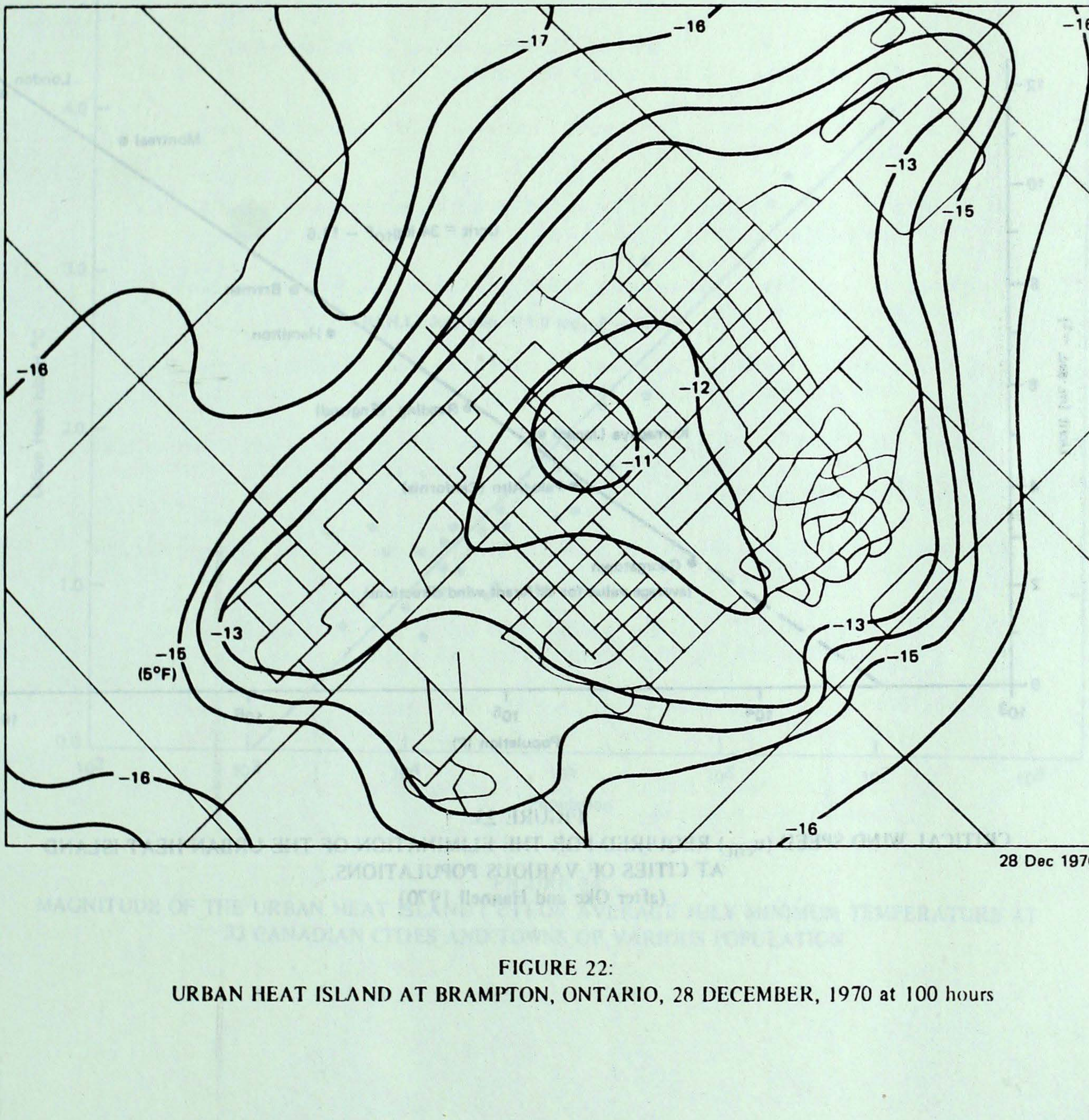

FIGURE 22:
URBAN HEAT ISLAND AT BRAMPTON, ONTARIO, 28 DECEMBER, 1970 at 100 hours

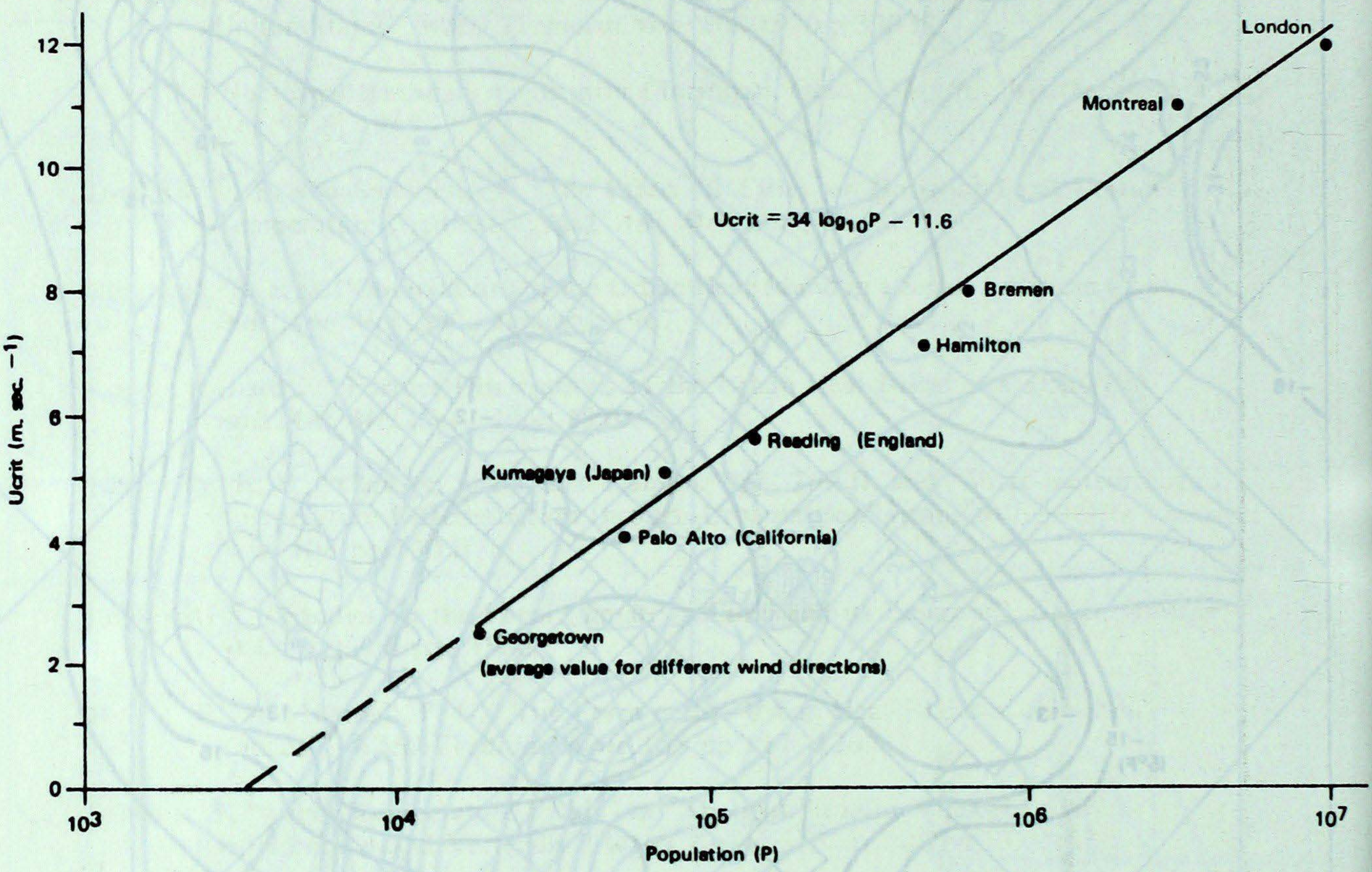

FIGURE 23:
CRITICAL WIND SPEED (u_{crit}) REQUIRED FOR THE ELIMINATION OF THE URBAN HEAT ISLAND AT CITIES OF VARIOUS POPULATIONS.
(after Oke and Hannell 1970)

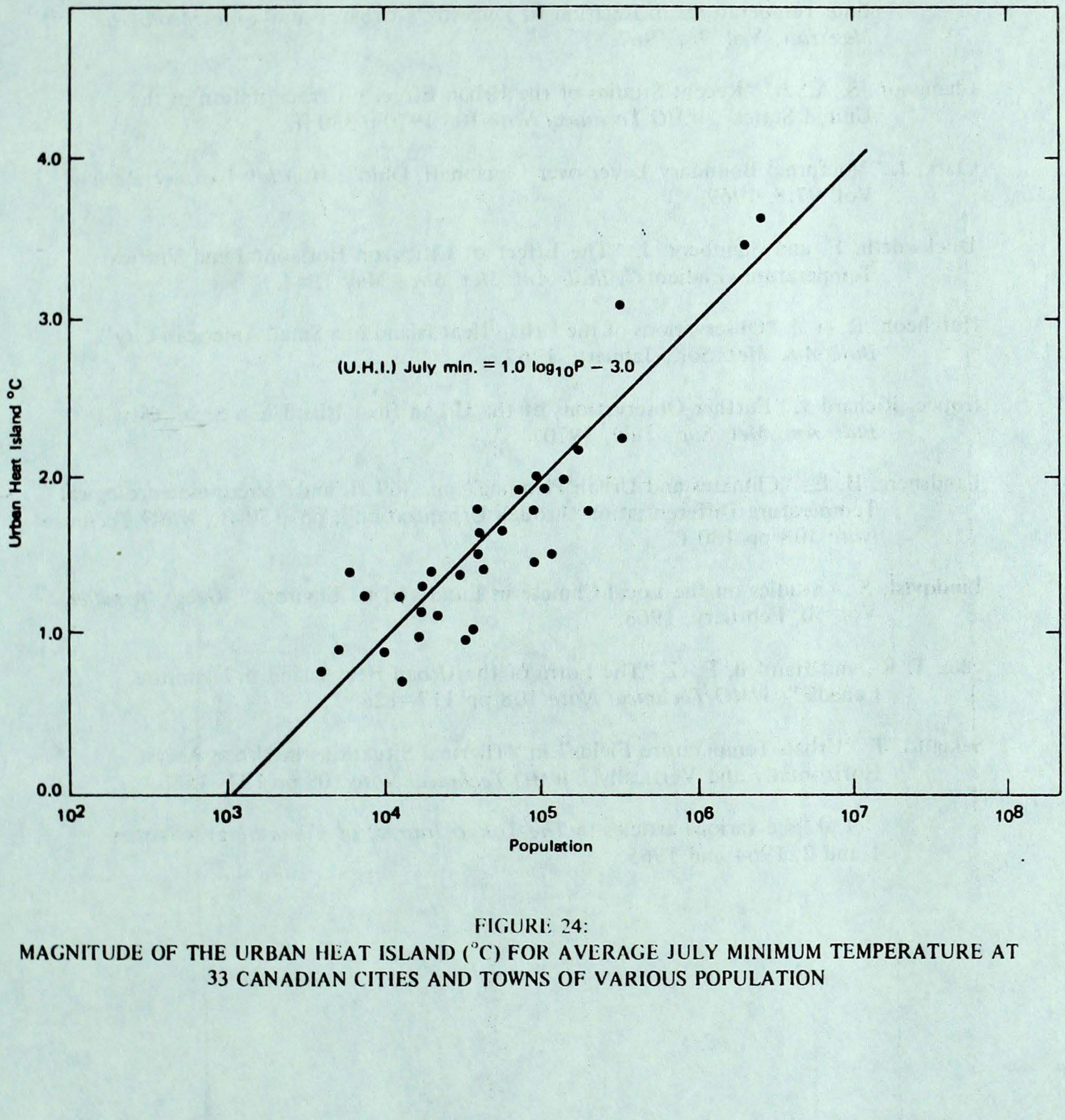

FIGURE 24:
MAGNITUDE OF THE URBAN HEAT ISLAND (°C) FOR AVERAGE JULY MINIMUM TEMPERATURE AT 33 CANADIAN CITIES AND TOWNS OF VARIOUS POPULATION

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