The Urban Heat Island at Toledo, Ohio[1]

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ABSTRACT. Thirty-one years of daily maximum and minimum temperatures at a rural site and a roof-top urban site were examined to determine the magnitude and seasonal variability of the urban heat island. Mean annual temperature was 2.0°C warmer at the urban site with the greatest urban-rural temperature difference occurring during the summer and the smallest difference during the spring. The urban heat island was more evident in daily minimum temperatures than in daily maxima. The number of days over 32°C (90°F) was more than doubled by the urban heat island and the number of freezing days was reduced by 16%. The freeze-free season was lengthened approximately 24 days by the urban warming, heating degree days were reduced by 10%, and cooling degree days were increased by 70%.

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INTRODUCTION

A city has a climate that differs from the surrounding rural area in many ways. Differences in surface material and structure between a city and the surrounding rural area lead to the differences in climate between the two regions and create the "urban climate." One well-documented urban modification to climate is the warmer temperatures in the urban setting. This feature, called the "urban heat island", has been recognized for at least 150 years (Landsberg 1981). The urban heat island is a result of extensive paved surfaces and the attendant lack of vegetation and surface moisture, a polluted atmosphere, the canyon effects of buildings, and the artificial heating of buildings in the urban areas (Nunez and Oke 1977).

Study of urban heat islands has often been accomplished through the use of a few hours or days of intensive measurements, usually with mobile thermometers (Duckworth and Sandberg 1954; Hutcheon et al. 1967; Kopec 1970; Oke and Maxwell 1975). These short-term studies are useful in determining specific relationships between urban temperature and meteorological conditions or terrain, but they cannot provide the larger view of the urban heat island averaged over all of the seasonal variety in weather conditions that a region offers. Study of urban heat islands through the use of longer periods (30 years) of data at urban and rural sites is difficult because of the changes in observation time and changes in instrument location that are so often encountered when a long climate time series is examined (Kukla et al. 1986). Differences in the landscape position of the urban and rural sites may lead to a different climate that will mask the urban effects or the rural site may not be entirely outside of the region of urban effects (Lowry 1977).

Weather records from relatively stable urban and rural locations at Toledo, Ohio (83.5°W, 41.7°N), present the opportunity to examine the local urban heat island. The sites are in flat terrain, the rural site is well outside of the urban region and usually upwind of the city, and temperature measurement techniques have been reasonably consistent within each station. This paper reports on 31 years of daily maximum and minimum temperatures recorded at two sites to determine the urban effect on temperature at Toledo.

SITE DESCRIPTION

Toledo is in Lucas County at the western end of Lake Erie near the mouth of the Maumee River (Fig. 1). Terrain is flat in the region. The 1980 population of the city was 354,635 and Lucas County had a population of 471,853. The urban site for temperature measurement was at The Blade building in downtown Toledo, near the middle of the central business district (called "downtown" or "urban site"). The Blade is one of about 100 official cooperative observer stations in Ohio with instruments provided and maintained by the National Weather Service. Thermometers were mounted on the roof of the building, 16.8 m above the street and 198 m above sea level (Mike Wyatt, pers. commun.). The roof-top thermometer exposure is likely to lead to warmer temperatures than an exposure over sod, although these urban roof-top temperatures are typical of the outdoor environment of urban residents and structures. In fact, urban street-level temperatures may be warmer than those measured officially by The Blade at the better ventilated 16.8 m roof height. Liquid-in-glass maximum-minimum thermometers in a standard instrument shelter were used until 1983. An electronic remote-reading thermometer was installed at that time. A thermograph was also maintained as a back-up system and was used occasionally when personnel were not available to read thermometers on weekends prior to 1983.

The rural site was the National Weather Service office at Toledo Express Airport where weather records have been kept since January 1955 (called "airport" or "rural site"). This site was 23 km southwest of The Blade site and surrounded by rural homes, small farms, and wooded land. Ground elevation was 204 m and terrain was flat. Daily maximum and minimum temperatures were measured on a roof 9.1 m above the ground until October 1959 when a hygrothermograph was established at 1.2 m height over sod between runways (Mike Wyatt, pers. commun.). Temperatures at the rural and urban

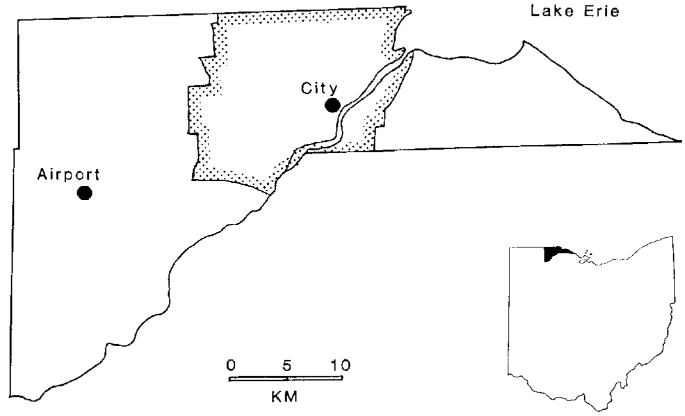

FIGURE 1. Map of Toledo and Lucas County showing the city and airport sites used in the analysis.

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sites were recorded in Fahrenheit units, which have been converted to Celsius in this paper.

Daily maximum and minimum temperatures were recorded at the airport for the 24-hour period ending at midnight so extreme temperatures were recorded on the calendar date that they occurred. Maximum and minimum temperatures downtown were recorded for the 24-hour period ending at 08:00 h and were recorded on that date. Maximum temperatures recorded on a date generally occurred during the previous day. An 08:00 h time of temperature observation causes a bias toward colder means, especially during winter when the daily minimum temperature occurs near 08:00 h. Winkler et al. (1981) have shown that a correction of observation times was necessary when comparing urban and rural sites in urban heat island studies. Monthly means of daily maximum and minimum temperatures downtown were corrected to a midnight observation time by the method of Karl et al. (1986) so that the urban temperature could be compared to the rural airport values. All monthly average temperatures presented for the urban site were corrected to a midnight observation time.

Study of the urban-rural temperature difference at Toledo is complicated by the proximity of Lake Erie and Maumee Bay. The prevailing wind direction is from the land to the lake, but air temperatures over land can be affected during times of on-shore flow when the water temperature is different from prevailing regional air temperatures. The downtown site is affected most often by its proximity to the bay and lake, while the airport is less affected because of its distance from the lake. The effect of the lake on air temperature over land varies hourly and no effort has been made to remove this effect from the average monthly temperature data presented here. The Maumee River flows through downtown Toledo but its width is only 300 m so any impact on the urban climate would be negligible.

RESULTS AND DISCUSSION

The temperature data presented here are averaged over monthly periods and do not indicate that the urban-rural temperature difference is constant. In fact, the temperature difference is highly variable on a daily or hourly basis (Landsberg 1981). The urban heat island generally reaches its greatest intensity in clear, calm weather and is less evident in windy or cloudy conditions. In addition, with only two long-term temperature sites to examine, it is not possible to identify the core of the urban heat island. The downtown site is near the core of the central business district, but the location of the core of the heat island will vary daily with prevailing wind direction and lake temperature (Munn et al. 1969) and will vary over the years as the surface structure of the urban area changes.

The mean annual temperature is 2.0°C warmer downtown than at the airport (Table 1). Toledo's urban heat island is most evident during June, July, and August when the mean monthly temperature is 2.5° to 2.6°C warmer downtown. The heat island is weakest in December and March. December is the cloudiest month and March is the windiest month at Toledo, and these factors may account for the weaker expression of the heat island in those months. Ackerman (1985) found that the urban heat island at Chicago was strongest in summer and weakest in April with an annual average urban-rural difference of 1.9°C. The average intensity of the heat island at Toledo is larger than reported by Ackerman for Chicago because the "urban" site used at Chicago was actually 14 km from the city center, rather than in the core of the central business district. Sanderson et al. (1973) found the urban heat island of Detroit-Windsor was strongest during late summer and weakest in late winter.

TABLE 1

Temperature of downtown (urban) and airport (rural) sites at Toledo, Ohio, for the period 1955–85. Mean temperatures downtown were corrected to a midnight observation time.

	Month												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Mean daily maximum temperature													
Downtown	−0.1	1.9	7.5	15.5	22.3	28.3	30.3	29.1	24.9	17.9	9.9	2.7	15.9
Airport	−1.5	0.9	6.9	15.1	21.4	26.3	28.4	27.6	23.7	17.2	8.9	1.7	14.7
Difference	1.4	1.0	0.6	0.4	0.9	2.0	1.9	1.5	1.2	0.7	1.0	1.0	1.2
Mean daily temperature													
Downtown	−3.6	−1.9	3.4	10.5	16.5	22.3	24.5	23.6	19.4	12.9	6.0	−0.9	11.0
Airport	−5.7	−3.7	1.8	8.8	14.7	19.7	22.0	21.1	17.2	10.9	4.1	−2.4	9.0
Difference	2.1	1.8	1.6	1.7	1.8	2.6	2.5	2.5	2.2	2.0	1.9	1.5	2.0
Mean daily minimum temperature													
Downtown	−7.2	−5.7	−0.8	5.5	10.6	16.2	18.6	18.0	13.8	7.8	2.0	−4.5	6.2
Airport	−10.0	−8.4	−3.4	2.4	8.0	13.0	15.6	14.6	10.6	4.5	−0.7	−6.5	3.3
Difference	2.8	2.7	2.6	3.1	2.6	3.2	3.0	3.4	3.2	3.3	2.7	2.0	2.9
Mean daily range													
Downtown	7.1	7.6	8.3	10.0	11.7	12.1	11.7	11.1	11.1	10.1	7.9	7.2	9.7
Airport	8.5	9.3	10.3	12.7	13.4	13.3	12.8	13.0	13.1	12.7	9.6	8.2	11.4
Difference	1.4	1.7	2.0	2.7	1.7	1.2	1.1	1.9	2.0	2.6	1.7	1.0	1.7
Average number of days with a maximum temperature ≥32°C (90°F)													
Downtown	0	0	0	0.1	1.8	6.5	11.2	8.0	3.3	0.2	0	0	31.1
Airport	0	0	0	0	0.5	3.3	5.0	3.2	1.5	*	0	0	13.5
Average number of days with a minimum temperature ≤0°C (32°F)													
Downtown	28.5	24.3	20.5	5.4	0.4	0	0	0	0	2.0	12.9	25.6	119.6
Airport	29.5	25.8	23.2	11.1	1.6	*	0	0	0.4	6.4	17.8	26.8	142.6

* between 0.00 and 0.05

The urban heat island is more evident in daily minimum temperatures than in daily maximum temperatures (Table 1 and Fig. 2). Average daily minimum temperatures are generally 2.6° to 3.4°C warmer downtown with the greatest differences in summer. The urban heat islands of Chicago (Ackerman 1985) and Detroit-Windsor (Sanderson et al. 1973) were also more evident in daily minimum temperatures than daily maxima.

Average daily maximum temperatures during spring are nearly the same downtown and at the airport. This may be an indication that the cool waters of Lake Erie are depressing the urban temperatures and masking the heat island. A cold lake-breeze circulation on a warm spring day may result in afternoon temperatures that are several degrees cooler downtown than at the airport. Maximum temperatures through the rest of the year average 1° to 2°C warmer downtown, reaching their greatest difference in summer. The urban Toledo weather observing site is among the hottest in Ohio, in spite of its northern location. Hickox (1984) examined the 108 temperature-recording sites in Ohio during 1981 and found that Toledo Blade was ranked tenth in frequency of recording the warmest daily temperature in Ohio.

The length of the freeze-free season indicates the growing season for tender plants. The freeze-free season is 43 days longer downtown than at the airport (Table 2). The last spring freeze occurs 18 days earlier downtown and the first autumn freeze occurs 25 days later downtown. In addition to an urban heat island effect, this difference in the freeze-free season is also caused by the moderating influence of Lake Erie on downtown temperatures. The surface temperature of western Lake Erie is near 10°C at the end of April and 14°C in mid-October (Webb 1974); thus, even non-urban land near the lake has a longer freeze-free season than land farther from the lake. The greater difference in urban-rural freeze dates in autumn than in spring is expected since the lake is warmer in October than in April. The moderating effects of the lake on local minimum temperatures is well-known and allows the cultivation of tender fruits such as grapes and peaches near the shore.

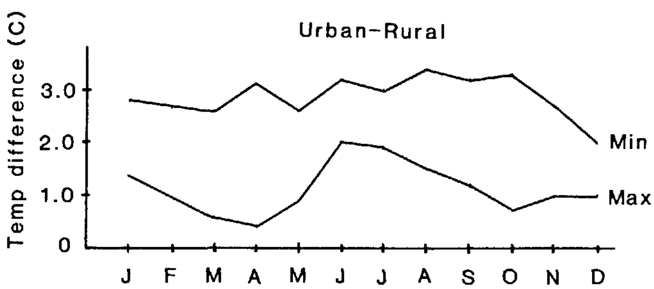

FIGURE 2. Monthly variation between the urban and rural sites in daily minimum and maximum temperatures at Toledo.

In an attempt at removing the lake effect on freeze dates at Toledo, the average freeze dates at Monroe and Adrian, Michigan, were compared. Monroe is on Lake Erie 25 km northeast of Toledo and Adrian is 55 km inland from the lake. The last spring freeze at Monroe is 6 days earlier than at Adrian and the first autumn freeze is 13 days later at Monroe than at Adrian, giving Monroe a freeze-free season that is 19 days longer than at Adrian. If we assume that 19 days of the 43 day freeze-free season extension at downtown Toledo is due to the effect of Lake Erie, then the remaining 24 days of the freeze-free season extension downtown is likely caused by the urban heat island. Based on this estimate from two nearby stations, the Toledo heat island extends the freeze-free season by approximately 12 days in the spring and by approximately 12 days in the autumn.

Kalkstein and Davis (1989) have shown that heat deaths increase significantly with summer daily maximum temperatures over 32°C (90°F) in the lower Great Lakes region. The average annual number of days with a maximum temperature 32°C or above at Toledo is 14 at the airport and 31 downtown, an urban increase of 121%. This indicates that there is a significant additional heat stress to residents of the urban region, especially those who do not have air-conditioning. The average annual extreme maximum temperature was 37.5°C downtown and 35.2°C at the airport. The hottest temperature recorded downtown during the period under examination was 40°C on 28 June 1971, while the extreme maximum at the airport was 38.3°C on 15 July 1977. (The temperature reached 40°C at the airport and 39.4°C downtown on 26 June 1988.)

The average annual number of days with a minimum temperature of −18°C (0°F) or below is 9 at the airport and 4 downtown, an urban decrease of 56%. The average annual extreme minimum temperature was −20.8°C downtown and −24.1°C at the airport. The coldest temperature recorded at the airport was −28.9°C on 21 January 1984. The extreme minimum downtown was −26.7°C on 24 January 1963 and 21 January 1985.

Heating degree days (base 65°F) are published for the period 1951–80 by the National Oceanographic and Atmospheric Administration (1982) and are an indica-

TABLE 2

Summary of last spring and first autumn freeze (≤0°C) dates at urban and rural Toledo locations, not corrected for the effects of Lake Erie.

	Last in spring		First in autumn		Freeze-free season length		
	Average	Latest	Earliest	Average	Shortest	Average	Longest
Downtown	19 Apr	29 May 1966	2 Oct 1974	29 Oct	148 1974	193	224 1985
Airport	7 May	11 Jun 1972	14 Sep 1975	4 Oct	120 1972	150	175 1985

tion of the fuel required for heating buildings. Published data for Toledo Airport and Toledo Blade show an annual average of 6570 heating degree days at the airport and 5926 downtown. The urban heat island at Toledo reduces the heating degree day total by 10% from the rural values. This is a conservative figure since the time of temperature observation correction would reduce the urban heating degree day totals. Cooling degree days (base 65°F), which indicate the fuel needed for summer air-conditioning, are increased at least 70% by the Toledo heat island. The annual average at the airport is 622 cooling degree days and the average downtown is 1049. While temperature plays an important role, the actual cost of heating or cooling a building is also affected by proximity to other buildings, vegetation, and exposure to wind.

CONCLUSIONS

Comparison of 31 years of temperature records from a rural site and a roof-top urban site at Toledo indicated that a heat island existed in mean monthly temperatures throughout the year. Average annual temperature was 2.0°C warmer at the urban site than at the rural site. The heat island was most intense during the summer months and least evident during winter and spring. This seasonal variability in the heat island may be caused by seasonal changes in radiation, cloud cover, wind speed, and effects of Lake Erie on local temperatures. Degree days, extreme temperatures, and days with temperatures above or below common climatic threshold temperatures all showed evidence of warmer temperatures at the urban site. The freeze-free season, when corrected for the local effect of Lake Erie, was approximately 24 days longer at the urban site. These results indicate that there are climatic differences of practical significance within the Toledo metropolitan region. The urban heat island reduces winter heating costs, increases summer cooling costs, lengthens the growing season, and causes increased heat stress on urban residents.

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