Effect of Temperature Adjustments on the Minneapolis-St. Paul Urban Heat Island[1]

JULIE A. WINKLER[2] AND RICHARD H. SKAGGS
Department of Geography, University of Minnesota, Minneapolis 55455

DONALD G. BAKER
Department of Soil Science, University of Minnesota, St. Paul 55101

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ABSTRACT

In order to better estimate urban influence on local climate, mean temperature series were corrected for biases and heterogeneities. Annual, January and July mean temperatures for 21 stations in and around Minneapolis-St. Paul, Minnesota were adjusted for background climate, differences in observation time, and changes in station location. The effect of the adjustments on the spatial structure of the urban heat island was judged by comparing isopleth analyses of the adjusted and unadjusted temperatures for each of the three time periods. Adjusted temperature data depict a larger heat island that conforms more closely to the urban structure. The influence of the adjustments on the strength of the heat island was estimated by comparing urban-rural temperature differences calculated from both data sets for the three time periods. The mean urban minus mean rural temperature differences calculated from the adjusted data are as much as 50% larger than the differences calculated from the unadjusted data.

1. Introduction

The urban effect on local climate usually has been estimated by the difference between instantaneous values or mean values of a weather element at "urban" and "rural" stations. Three important problems are associated with this approach. First, observations at individual stations are affected not only by the urban area but also by the local landscape and the regional or background climate (Lowry, 1977). The estimate of the urban effect on local climate is biased when the background climate and landscape effects at the urban and rural stations are different. Second, heterogeneities in weather records can also distort the estimate of the urban effect when comparing urban-rural differences. Schaal and Dale (1977) have shown the importance of the difference in observation time when comparing mean temperatures. They concluded that the time of observation bias is of the same order of magnitude as the urban-rural difference. Fukui (1964) stated that variation in weather elements in Japanese cities can be partially attributed to the location changes of the stations. Third, stations outside the urban boundary, usually considered rural, may actually be affected by the urban area. Lowry (1977) proposed that the region including an urban area be divided into three subareas: *u* the urbanized area, *e* the area outside the urban boundaries where the urban area has an effect on the weather element, and *r* the area outside the urban boundaries and unaffected by the urban area.

The objectives of this paper are to illustrate the importance of adjusting temperature observations for biases and heterogeneities and to classify as urban only those stations where the urban area has an effect on local temperature (subareas *u* and *e* in Lowry's model) and as rural only those stations outside the area affected by local urbanization. Mean annual, January and July temperature data from the Minneapolis-St. Paul urban area and the surrounding rural environs are used as an example in the following discussion.

2. Data

Mean monthly temperatures for the 10-year period 1967–76 were collected for the Minneapolis-St. Paul National Weather Service station and for 20 cooperative weather stations in an ~18 000 km² area surrounding Minneapolis-St. Paul (Table 1 and Fig. 1). Less than 1% of the monthly averages were missing. Missing observations were estimated by linear regression. The temperature values for a station with a missing value were regressed on the temperature values of a base station, Farmington 3NW. The base station met the following criteria:

[1] Scientific Journal Series No. 11,127, Minnesota Agricultural Experiment Station.

[2] Present affiliation: Department of Geography, San Diego State University, San Diego, CA 92182.

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TABLE 1. Station adjustments.

Station	No. on Fig. 1	Adjustments
Buffalo	1	A, B, C
Cedar	2	A, B
Chaska	3	A, B, C
Ellsworth	4	A, B
Fairbault	5	A, B, C
Farmington	6	A, B
Forest Lake	7	A, B
Gaylord	8	A, B
Jordan	9	A, B, C
Maple Plain	10	A, B, C
Minneapolis-St. Paul	11	B
North St. Paul	12	B
River Falls	13	A, B
Rosemount	14	A, B
St. Anthony	15	A, B
St. Croix Falls	16	B
St. Paul	17	A, B
St. Peter	18	A, B
Stillwater	19	A, B
University of Minnesota-St. Paul	20	A, B
Zumbrota	21	A, B, C

A: adjusted to midnight to midnight observation.
B: background climate adjustment.
C: adjustment for change in station location.

1) no missing values, 2) no changes in observation time other than Daylight Savings Time, 3) no changes in the location of the station, and 4) little change in the physical setting of the station. Simple linear regression is an inadequate estimator of missing values if a time trend exists in the data. The temperature series of the base station and the temperature series for the stations with missing values were regressed on time, polynomial time and log time to check for a time trend. None of the time regressions was significant.

3. Adjustment of the temperature series

Mean monthly temperatures were adjusted for background climate, time of observation bias, and change in station location. Adjustments were not made for changes in instrumentation and local landscape. The adjusted and unadjusted mean temperatures for each station are given in Table 2. The methods by which the temperature series were adjusted are detailed below.

a. Time of observation bias

Mean daily temperatures, defined as the average of the minimum and maximum temperatures for the 24 h period ending at observation time, are influenced by the time of observation. First-order National Weather Service stations compute mean temperatures for the period midnight to midnight. Cooperative weather stations take observations at times convenient to the observer, and the means are calculated for the 24 h period ending with the observation. The mean temperatures for stations taking observations at different times are not comparable. The effect is greatest when the observation time is near sunrise or in late afternoon, corresponding to the approximate minimum and maximum points of the diurnal heating cycle (Baker, 1975; Mitchell, 1958). Changes of even 1 h at these critical times can have a large effect on mean temperatures; thus the switch to Daylight Savings Time can introduce a bias into the temperature series (Mitchell, 1958).

Mean temperature can be adjusted to a standard observation time by using

$$T = c + T_0, \tag{1}$$

where T is the adjusted mean, T_0 the mean value for the actual observation period, and c a correction factor (Conrad and Pollak, 1950). Baker (1975) has calculated values of c for the University of Minnesota-St. Paul station for adjusting to a midnight observation. The mean temperatures for the cooperative stations were corrected to a midnight observation using these c values. Adjustments were also made for Daylight Savings Time.

b. Changes in station location

Changes in location have introduced heterogeneity into the temperature series for several stations (Table 1). The means for stations with location changes were adjusted by the method suggested by Thom (1966):

$$\bar{Y} = A + \bar{X}, \tag{2}$$

where $\bar{X}$ is the mean for the homogeneous period at

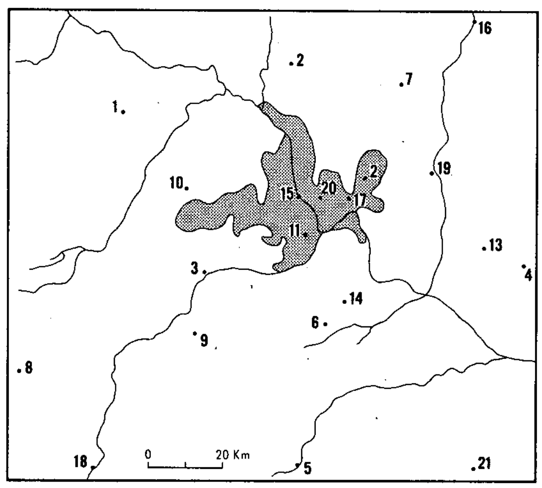

FIG. 1. Location of temperature recording stations. 45°N is just north of the long axis of the urban area.

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TABLE 2. Adjusted and unadjusted mean annual, January and July tempertures (°C).

Station	Annual			January			July		
	Adjusted	Unadjusted	Classification	Adjusted	Unadjusted	Classification	Adjusted	Unadjusted	Classification
Buffalo	5.6	6.7	R*	−13.2	−12.0	R	21.3	21.8	R
Cedar	6.0	6.4	R	−12.4	−11.9	R	21.4	21.9	R
Chaska	6.2	6.9	U**	−12.6	−12.1	R	22.3	22.8	U
Ellsworth	5.7	6.8	R	−12.4	−11.4	R	21.3	22.3	R
Fairbault	5.4	6.8	R	−12.6	−11.3	R	20.7	21.9	R
Farmington 3NW	5.6	6.4	R	−12.9	−11.9	R	21.0	21.7	R
Forest Lake	5.6	6.1	R	−12.7	−12.2	R	20.7	21.2	R
Gaylord	5.9	7.2	R	−12.6	−11.3	R	21.6	22.7	R
Jordan	5.4	6.3	R	−12.7	−11.6	R	20.6	21.3	R
Maple Plain	7.0	6.3	U	−11.4	−12.0	U	22.3	21.8	U
Minneapolis-St. Paul WSFO	6.7	6.9	U	−11.7	−11.6	U	22.5	22.7	U
North St. Paul	6.5	6.5	U	−11.7	−11.7	U	21.8	21.9	U
River Falls	5.9	6.7	R	−12.2	−11.4	R	21.2	21.9	R
Rosemount	5.4	6.6	R	−13.1	−12.1	R	21.2	22.0	R
St. Anthony	8.1	8.6	U	−10.9	−10.2	U	24.3	24.8	U
St. Croix Falls	5.6	6.0	R	−12.2	−12.6	R	21.7	21.5	R
St. Paul	6.4	7.3	U	−11.5	−10.6	U	21.7	22.4	U
St. Peter	6.3	6.8	R	−12.0	−11.9	R	21.8	22.5	R
Stillwater	6.6	7.1	U	−12.1	−11.4	R	22.2	22.7	R
Univ. of Minnesota-St. Paul	6.3	7.2	U	−12.0	−11.2	U	21.8	22.7	U
Zumbrota	5.2	6.6	R	−12.7	−11.4	R	20.3	21.8	R

* R: rural station.
** U: urban station.

the base station corresponding to the heterogeneous period at the station with a location change, and $\bar{Y}$ the adjusted mean. The adjustment factor A is estimated from

$$A = \bar{U} - \bar{V}, \qquad (3)$$

where $\bar{U}$ and $\bar{V}$ are the means from concurrent periods of homogeneous record at the station needing adjustment and at the base station, respectively. Farmington 3NW was used as the base station. The means were adjusted to the location of the longest homogeneous record and not necessarily to the most recent location.

c. *Background climate*

The major difference in the background climate that affects the estimate of the urban heat island when comparing long-term mean values for Minnesota is the decrease of temperature with latitude. Between-station variations in parameters such as cloud cover influence temperature observations on an hour-to-hour and day-to-day basis but can be ignored when using monthly and annual means.

The background climate can be broken into two parts, T and ΔT, where T is the temperature at a specified base latitude, and ΔT the change of temperature with latitude. The base latitude is 45°N for this study, and all temperatures were adjusted to this latitude. Values of ΔT were estimated from 30-year annual, January and July averages for 12 pairs of stations outside the metropolitan area. The means of the 12 ratios of temperature decrease with latitude were used as the ΔT values. The values are 0.96, 1.06 and 0.75°C per degree of latitude for the annual, January and July adjustments, respectively.

4. Effect of the adjustments

The areal extent and strength of the mean annual, January and July heat island for Minneapolis-St. Paul were estimated from both the adjusted and unadjusted temperature values to illustrate the effect of the adjustments. The areal extent was estimated by isopleth mapping of the temperature values. The strength was measured by the difference between the mean temperature of the urban stations and the mean temperature of the rural stations. The stations were classified as urban or rural according to their location with respect to the closed isotherms around Minneapolis-St. Paul on the adjusted mean temperature maps. Stations located outside the closed isotherms on the adjusted mean annual, January and July temperature maps were considered outside the area affected by urbanization and were classified as rural stations. The remaining stations were classified as urban (Table 2). For comparative purposes, the same urban-rural classification was used when

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estimating the unadjusted urban-rural differences, even though several of the stations classified as urban from the adjusted data were outside the closed isotherms on the unadjusted temperature maps.

Statistical tests were applied to the temperature data to determine 1) whether mean urban temperatures remain significantly different from mean rural temperatures after the temperature values have been

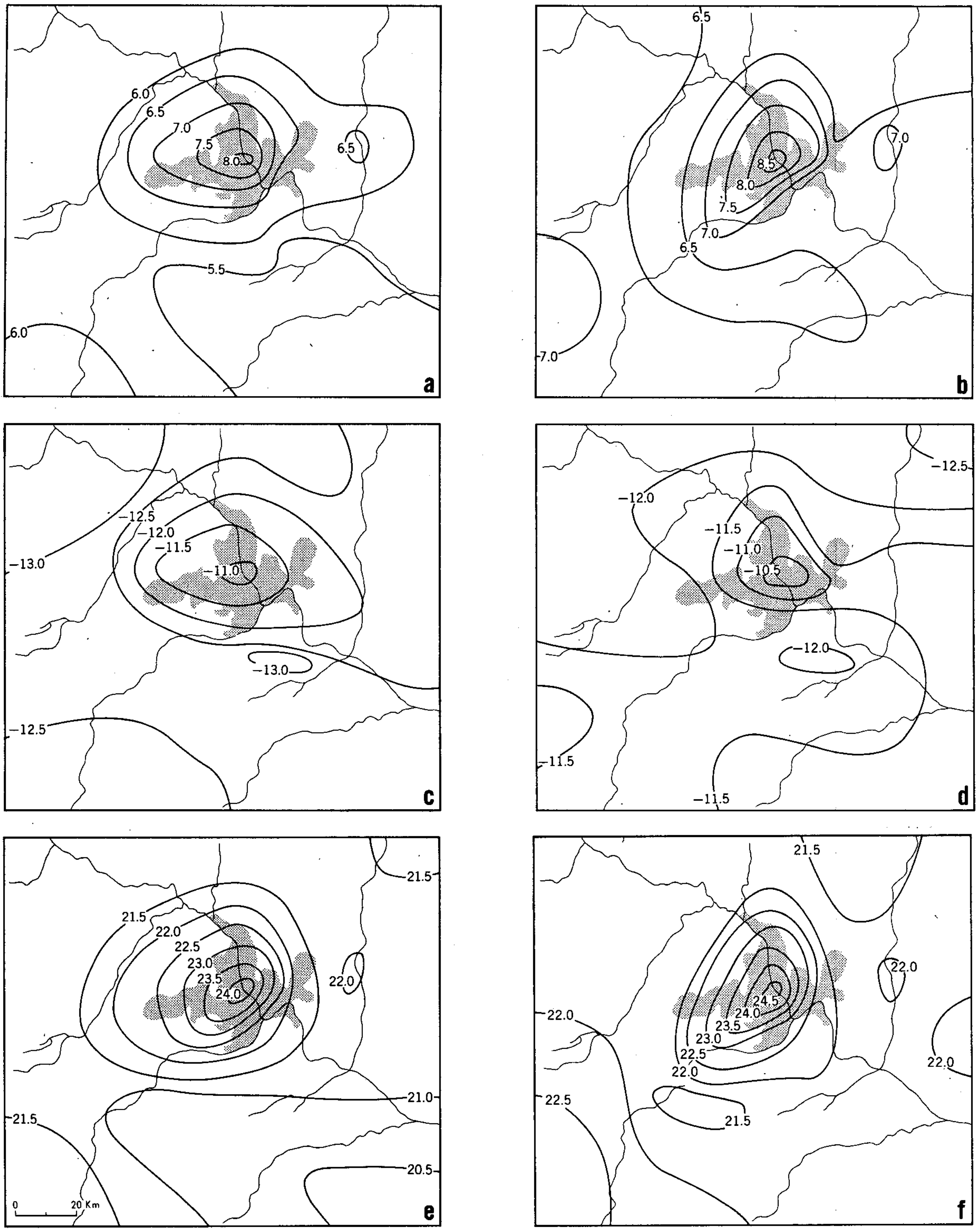

FIG. 2. Mean temperature (°C): (a) annual adjusted, (b) annual unadjusted, (c) January adjusted, (d) January unadjusted, (e) July adjusted and (f) July unadjusted.

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adjusted for biases and heterogeneities, and 2) whether adjusted temperatures are significantly different than unadjusted temperatures. The two-sample t-test and the Mann-Whitney U-test (Mendenhall, 1967) were used to test the statistical significance of the urban-rural and adjusted-unadjusted temperature differences. The Mann-Whitney U-test, a non-parametric test, was used because of uncertainty about the normality of several of the temperature distributions. A 5% probability of Type I error was used as the test criterion in a two-tailed test. This is the same as a 2.5% criterion in a one-tailed test that mean urban temperatures are greater than mean rural temperatures. The normal deviate was calculated to determine the statistical significance for the Mann-Whitney U-test even though the sample size frequently was too small.

The spatial structure of the mean annual, January and July heat islands is greatly affected by the adjustments applied to the temperature series (Fig. 2). Compared to the unadjusted temperatures, the adjusted temperatures show a larger and stronger urban heat island, particularly in January. The configuration of the heat island also is affected by the adjustments.

The isothermal maps based on the adjusted temperatures are more reasonable than those based on the unadjusted temperatures. The major axis of the Minneapolis-St. Paul urban area is east–west. The heat islands as depicted by the adjusted mean temperatures also are oriented east–west, unlike the unadjusted heat islands which are oriented southwest–northeast. The adjusted January mean map shows a flat temperature gradient across the built-up area, while the unadjusted January mean temperature map shows a much steeper temperature gradient across the metropolitan area. A flat gradient is expected at this time of year as the snow-covered urban area has a more uniform surface. The unadjusted mean temperature maps poorly classify stations as urban and rural. In fact, several stations within the urban boundary are outside the closed isotherms on the unadjusted mean temperature maps. For the adjusted data, all stations within the urban boundary are inside closed isotherms.

TABLE 3. Adjusted and unadjusted urban-rural temperature differences (°C).

	Urban-rural difference	t-statistic	Mann-Whitney U-statistic	z-score
Annual				
Adjusted	1.0	5.39*	103	3.69*
Unadjusted	0.5	2.39*	83	2.24*
January				
Adjusted	1.1	5.93*	90	3.50*
Unadjusted	0.6	2.31*	67	1.71
July				
Adjusted	1.2	3.76*	94	3.36*
Unadjusted	0.8	2.49*	82	2.46*

* Significant at the 95% confidence level.

TABLE 4. Tests for significance of adjusted versus unadjusted mean temperatures.

	t-statistic	Mann-Whitney U-statistic	z-score
Annual			
All data	−3.93*	373	3.84*
Urban	−1.15	47	1.58
Rural	−7.41*	167	4.23*
January			
All data	−3.76*	366	3.66*
Urban	−0.98	24	0.96
Rural	−5.80*	215	4.25*
July			
All data	−2.39*	346	3.16*
Urban	−0.68	36	1.47
Rural	−3.89*	172	3.40*

* Significant at the 95% confidence level.

The strength of the heat island as measured by the adjusted urban-rural temperature differences is substantially larger than the strength as measured by the unadjusted differences. The magnitude of the urban-rural temperature difference is doubled for the annual period (1.0°C compared to 0.5°C) and is nearly doubled for January (1.1°C compared to 0.6°C). The adjusted July difference is two-thirds larger than the unadjusted difference (1.2°C compared to 0.8°C).

The adjusted and unadjusted urban-rural temperature differences are statistically significant at the 95% confidence level for all time periods, except January (Table 3). The unadjusted January urban-rural difference is significant when the t-test is used to check for significance but not significant by the Mann-Whitney test. The probability of a Type I error is smaller for the adjusted urban-rural differences than for the unadjusted urban-rural differences.

The unadjusted and adjusted data were compared for annual, January and July time periods and for rural, urban and all data groupings (Table 4). The urban adjusted mean temperatures are not statistically different from the urban unadjusted temperatures, but the rural adjusted values are statistically different than rural unadjusted temperatures. Two factors explain this finding. First, the latitudinal or background climate correction is larger for the rural stations than for the urban stations because of the greater areal distribution of the rural stations. The urban stations required only a small background climate correction due to the east–west orientation of the urban area. Most of the urban stations are at nearly the same latitude. Second, many of the rural stations take temperature observations between 1700 and 1800 CST. The correction factor for adjusting to a midnight observation is greatest for late afternoon observation times.

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5. Summary

The findings of this study suggest that previous heat island studies in midlatitude, continental locations have underestimated the areal extent and strength of the mean urban heat island by neglecting to adjust temperature observations for biases and heterogeneities. Adjusted mean temperatures depict a larger, better defined heat island that conforms more closely with urban structure. Adjusted urban-rural temperature differences are considerably larger than unadjusted temperature differences. Finally, the isothermal maps based on adjusted temperatures better divide stations into urban and rural classes.

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REFERENCES

Baker, D., 1975: Effect of observation time on mean temperature estimation. *J. Appl. Meteor.*, **14**, 471–475.

Conrad, V., and L. Pollak, 1950: *Methods in Climatology*. Harvard University Press, 459 pp.

Fukui, E., 1964: Increasing temperature due to the expansion of urban areas in Japan. *Tokyo J. Climat.*, **1**, 53–59.

Lowry, W., 1977: Empirical estimation of urban effects on A problem analysis. *J. Appl. Meteor.*, **16**, 129–135.

Mendenhall, W., 1967: *Introduction to Probability and Statistics*. Wadsworth, 393 pp.

Mitchell, J., Jr., 1958: Effect of changing observation time on mean temperature. *Bull. Amer. Meteor. Soc.*, **39**, 83–89.

Schaal, L., and R. Dale, 1977: Time of observation temperature bias and "climate change." *J. Appl. Meteor.*, **16**, 215–222.

Thom, H., 1966: Some methods of climatological analysis. Tech. Note No. 81, World Meteorological Organization, Geneva, 53 pp.

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