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Environmental indices for the Twin Cities Metropolitan Area (Minnesota, USA) urban heat island — 1989

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ABSTRACT: A homogeneous, high-density, daily maximum and minimum air temperature dataset was assembled for the Twin Cities Metropolitan Area (TCMA), Minnesota, USA, to conduct basic urban climatological investigations on the spatial structure and temporal-scale dependence of the urban heat island, and to quantify the urban heat island effect upon several derived environmental indices. By combining data from National Weather Service cooperative stations, the University of Minnesota-St. Paul field station, and the previously unused KSTP-TV cooperative weather station network, a merged dataset of 26 stations was assembled for the TCMA for the year 1989. Extensive quality control was conducted to identify suspect data values, estimate missing data, and adjust for time-of-observation bias. Eight environmental indices were examined to overview the impact of the TCMA urban heat island upon a range of physical and biological activities. These included 2 growing degree-day indices, melting degree-days, cooling and heating degree-days, freezing degree-days, number of frost change-days, and the freeze-free season length. Results illustrate the magnitude and spatial pattern of the urban heat island and derived thermal indices which might be typical of a large midlatitude midcontinental metropolitan area. The mean annual air temperature urban heat island is approximately 2.1°C, and resembles the classic spatial pattern consisting of a peripheral zone of rapid temperature increase, a large plateau of elevated air temperatures, and a small central core of peak temperatures. The impact of the urban heat island upon the magnitude and spatial pattern of the 8 environmental indices was highly index-specific. In many cases, the urban heat island effects are so profound that the response and adaptation of selected environmental systems to the historical urban warming should be evident. Urban environments would appear to offer a suitable laboratory for selected climate change impact studies.

KEY WORDS: Urban heat island · Environmental indices · Urban physical enviroment · Climate change · Twin Cities Metropolitan Area

INTRODUCTION

Urban climates are one of the most frequently studied examples of inadvertent climate change, possessing an extensive and long-established literature (Howard 1833, Oke 1974, 1979, 1983, 1990). The best known urban climate feature, the urban heat island, has been examined using a variety of methodological approaches including the examination of temperature records between urban-rural station pairs over a variable duration time-period (Unwin 1980), direct measurements from automobile traverses on 1 or more days (Oke & East 1971), and comparison of temperature records among a low-density network of climate stations for 1 or more years (Adebayo 1987). A small number of studies employing a high-density climate station network have been conducted (Chandler 1961, Munn et al. 1969, Jauregui 1973, Nkemdirim 1976, Viterito 1989, Unkasevic 1991), but are of limited value in providing information on the spatial pattern and temporal-scale dependence of the urban heat island because of methodological limitations, including the

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lack of continuous observations for a complete annual cycle and insufficient network density to adequately resolve the urban heat island spatial pattern. Only the examination of the Calgary (Alberta, Canada) urban heat island by Nkemdirim & Truch (1978) appears to provide both spatial and temporal detail. Their results, however, cannot be generalized to other locations due to the strong local topographic control upon the Calgary urban climate. Furthermore, with the exception of Winkler et al. (1981), nearly all such studies fail to address the issue of the homogeneity of network data.

Nearly all empirical urban heat island studies have also analyzed direct air temperature measurements, rather than temperature-derived quantities based upon the direct observations, despite the fact that climatologists have long known of the environmental impacts associated with the urban heat island (Landsberg 1981), and that such effects have been quantitatively demonstrated for a number of environmental indices (Baker et al. 1985a). The few urban climatological investigations that have examined temperature-derived quantities have generally focused upon the development of empirical human comfort indices (Bründl & Höppe 1984, Balling & Brazel 1986, Barradas 1991), with only a limited number of studies examining a broader range of environmental impacts (Nkemdirim & Ventkatesan 1985, Schmidlin 1989).

The purpose of this paper is to describe the development of a homogeneous, high-density network of maximum and minimum air temperature observations within the Twin Cities Metropolitan Area (TCMA), Minnesota, USA, and to provide a brief overview of the magnitude and spatial distribution of selected environmental impacts of the TCMA urban heat island.

The development of such an urban heat island network is relevant to urban climatology for 3 reasons.

First, it provides a suitable data set for analyzing the spatial distribution of direct air temperature measurements and temperature-derived environmental indices for use in basic urban climatological research. Current research trends in urban climatology largely focus upon surface energy exchanges, which form the energetic basis of the urban heat island, and employ microclimatological instrumentation (Schmid et al. 1991), or radiative surface temperature patterns obtained from remote sensing platforms (Gallo et al. 1993). Although both approaches provide considerable information on the spatial variability of urban climates, costs constraints and/or inclement weather restrict their suitability for resolving the temporal dimensions of urban climates.

Second, it contributes to our general knowledge of the physical environment of cities (Douglas 1983). Hough (1989) has stated that a new form of urban design is needed which incorporates environmental goals into the urban landscape, and which exhibits an understanding of and concern for the role that the urban physical environment plays in issues of energy use, environmental quality, and natural resource management.

Third, Changnon (1992) has argued that the study of inadvertent climate modification in urban areas over the past century can serve as a useful (though imperfect) analog for the climate impacts of potential global warming. Global climate impact studies share numerous methodological limitations, including uncertainty regarding the rate and magnitude of climate change, omission of linkages between related environmental systems, neglect of the direct effects of CO_2 fertilization, lack of consideration of human adaptation and technological change, and inadequate local-scale climate change information. Urban heat islands exhibit several features which make them suitable analogs for climate impact studies. These include: (1) the rate and magnitude of urban climate change approximate those being simulated by current global climate models, (2) the pattern of urban warming, being concentrated at night and during winter in midlatitude midcontinental locations, is similar to the pattern of historical warming over the past century, (3) urban areas provide a natural model of how environmental systems respond to climate change, (4) urban ecosystems have adjusted to the direct effects of a 25% increase in the CO_2 concentration over the past century, and (5) urban areas provide an example of how climate change may be mitigated by human and technological adjustment. Given the limitations of climate impact methodologies at present and in the foreseeable future, the study of urban climate impact analogs would appear to be an appropriate research avenue to investigate.

DATA AND METHODS

TCMA study site. The Twin Cities of Minneapolis and St. Paul (45° 0' N, 93° 15' W) lie in central North America, and originated in the mid-1800s as an industrial, and transportation and distribution center, respectively (Borchert 1987). The urban population was concentrated in the old central city core until the 1950s, when slow suburban growth began. Completion of the metropolitan freeway system in the late 1970s led to the development of the current TCMA pattern, consisting of an inner metropolis (Hennepin and Ramsey counties), and an outer metropolis comprised of a commuting area of 5 surrounding counties (Carver, Scott, Dakota, Washington and Anoka) (see Fig. 1). In 1950, Hennepin and Ramsey counties accounted for 87% of the 7 county total population, but only 66% of the 2.3 million residents by 1990 (Bureau of Census 1992).

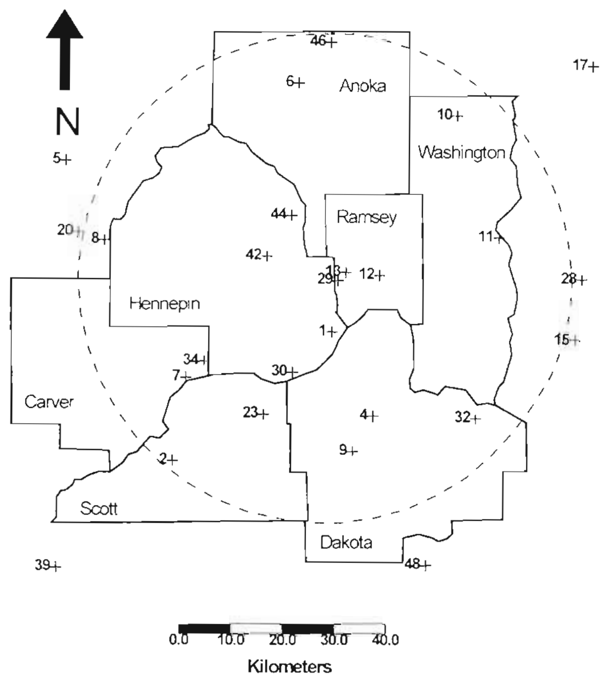

Fig. 1. Twin Cities Metropolitan Area (Minnesota, USA). Base map of temperature station locations. Station numbers as in Table 1. The circle is drawn at a 48.3 km (30 mile) radius from downtown Minneapolis

Topographically, the TCMA offers an advantageous site for urban climate investigations because of its modest local relief (<90 m), and absence of local-scale climate influences due to mountains, oceans or large lakes. The Mississippi River and the numerous small lakes throughout the region have only a localized impact upon the microclimate, and have no influence upon the regional climate.

Climate data network. The 26 stations within the climate data network for 1989 are shown in Fig. 1. These include the National Weather Service Forecast Office at the Minneapolis-St. Paul Airport, and 11 sites which are part of the cooperative NWS station network. Both sets were extracted from an extensive digital climate dataset maintained by the Minnesota State Climatology Office as part of their research support and service mission to the State of Minnesota. The Minnesota State Climatology Office also made available records from a field station operated at the University of Minnesota-St. Paul campus, which has been the focus of considerable climatological research (Baker et al. 1992). The dataset also includes 13 cooperative weather stations organized and maintained by a local television station (KSTP-TV). Archives of the KSTP-TV network were made available by the Minnesota State Climatology Office, and have never previously been used in climatological research.

All of the stations listed in Table 1 include a continuous 365 d record of daily maximum and minimum temperature manually measured using National Weather Service standard maximum/minimum thermometers housed in a meteorological shelter. All subsequent mean daily, mean monthly, mean annual and related environmental indices were derived from these primary maximum/minimum air temperature data. Data are analyzed for the year 1989, a relatively cool, dry year which ranked 23rd for both mean annual temperature and annual precipitation for the 30 yr normal period of 1961–90.

Table 1. Climate data stations, Twin Cities Metropolitan Area, 1989. 'Time' is time-of-observation

Station	No.	Elevation (m)	Time (h LST)
Minneapolis-St. Paul WSFO AP, MN	1	254	24:00
Jordan 1 S, MN	2	284	18:00[a]
Rosemount Agr. Exp. Stn, MN	4	290	17:00
Buffalo, MN	5	305	17:00
Cedar 4 SW, MN	6	277	17:00
Chaska, MN	7	220	16:00
Delano, MN	8	291	24:00[b]
Farmington 3 NW, MN	9	299	19:00
Forest Lake 4 SE, MN	10	276	17:00
Stillwater 1 SE, MN	11	216	19:00
St. Paul, MN	12	279	17:00
Univ. of Minn.-St. Paul, MN	13	295	17:00
River Falls, WI	15	274	18:00
KSTP - Osceola, WI	17	335[c]	22:00
KSTP - Delano, MN	20	284[c]	23:30
KSTP - Prior Lake, MN	23	274[c]	23:30
KSTP - Roberts, WI	28	305[c]	22:00
KSTP - Minneapolis, MN	29	274[c]	17:00
KSTP - Bloomington, MN	30	253[c]	17:00
KSTP - Hastings, MN	32	210[c]	17:00
KSTP - Chaska, MN	34	277[c]	17:00
KSTP - Le Sueur, MN	39	253[c]	17:00
KSTP - New Hope, MN	42	274[c]	24:00
KSTP - Fridley, MN	44	259[c]	24:00
KSTP - East Bethel, MN	46	277[c]	17:00
KSTP - Dennison, MN	48	290[c]	17:00

[a]07:00 h for December
[b]08:00 h for September–December
[c]KSTP elevations estimated from township-range-section information

Data quality control. The 3 data sources which comprise the maximum and minimum air temperature network are examples of secondary data sources, which Guttman (1991) defines as '...data that have been compiled, adjusted or summarized by anyone other than the researcher using the data.' Although guidelines for scrutinizing secondary data are available, strict adherence to these principles are normally relaxed since the vast majority of empirical climatological research involves secondary source data, the time and resource commitment required for strict adherence would be prohibitive, and the principles can be relaxed somewhat without compromising basic scientific integrity (Guttman 1991).

Quality control of the Univ. of Minnesota-St. Paul station data was unnecessary since there was no missing data, and the observational procedures employed at that station are representative of the highest standards. The quality of the 12 cooperative NWS stations was also not examined since the data had already been scrutinized as part of standard NCDC procedures (Robinson 1990). Adjustments were only necessary in the case of missing data, which accounted for less than 1% of the data. The missing NCDC daily maximum and minimum air temperature data were estimated by simple linear regression using corresponding data values for the nearest NCDC station with the same time-of-observation. Pearson correlation coefficients for the various NCDC station pairs used in estimating missing data ranged between 0.972 and 0.997 for daily maximum air temperatures, and between 0.950 and 0.993 for daily minimum air temperatures.

The KSTP station data required a greater level of quality control because of the less consistent observational procedures practiced by some of their observers. The quality of their records ranged from excellent to unacceptable. Stations with consistently low quality data were easily spotted because of a large number of missing days, an inconsistently reported time-of-observation, a high number of erroneous data entries, or an incomplete station-year of data. Stations with such deficiencies were eliminated from the network and not analyzed. The remaining KSTP stations, listed in Table 1, were then subjected to a careful quality control screening. All KSTP daily data were manually keyed from original archival records, and then manually double-checked against the original archives for keying errors. Keyed data were then subjected to an automated quality control using a data entry program developed by the Minnesota State Climatology Office (J. A. Zandlo pers. comm.), which flagged observations in which the current day minimum was greater than the current day maximum, the current day minimum was greater than the previous day maximum, or the previous day minimum was greater than the current day maximum, as well as unusually high daily maximum and low daily minimum temperatures. All flagged KSTP data were changed to missing values and then estimated by simple linear regression against corresponding values for the Farmington 3 NW NCDC station, a homogeneous station of unusually high quality (Baker et al. 1985b). Pearson correlation coefficients for the various KSTP-Farmington 3 NW pairs ranged between 0.981 and 0.994 for daily maximum air temperatures, and between 0.969 and 0.993 for daily minimum air temperatures. A total of 6.7% of the KSTP station data were estimated in this manner, in comparison to the 1% of estimated data for the NCDC stations, and the 2.9% of estimated data among the Minnesota stations within the Historical Climatology Network, probably the most homogeneous multi-station long-term air temperature network in the world (Karl et al. 1990).

The mean daily temperature for a given day is actually the mid-range of the extreme maximum and minimum temperatures observed at a station over a 24 h period, endpoints inclusive, terminating at a fixed observation time on that given day. The ending time defines the time-of-observation. This time varies among cooperative NWS stations, and is selected at the convenience of the local observer, subject to the constraint that the observation time remain constant over time. This lack of agreement between the observation times among cooperative weather stations can result in different temperature extremes over non-contiguous 24 h observation periods terminating on the same calendar day. Thus the time that daily observations are taken influences the mean daily air temperature.

The departure of the mean daily temperature observed at various observation times from the true mean daily temperature for a 24 h period ending at midnight results in a time-of-observation error for mean monthly temperatures which is systematic and cumulative in nature. The magnitude of the time-of-observation error depends upon the timing of the observations with respect to the daily heating cycle, which varies with daylength and continentality, and is also influenced by the frequency and severity of frontal passages.

Baker (1975) analyzed hourly air temperature measurements for 3 yr at St. Paul and found that average annual air temperatures could depart by as much as 1.4°C for nearby stations having different time-of-observations. This potential error is considerably larger than the 0.6°C global temperature increase noted over the past century (Balling 1992), and of comparable magnitude to the average annual urban heat island intensity reported in Baker et al. (1985a) for the TCMA. Since the error is systematic, significant bias will occur in the calculation of environmental indices derived from the summed unadjusted monthly temperature data. Data from multiple station networks with different time-of-observations must be corrected to a standard observation time to remove the bias. Schaal & Dale (1977) found that time-of-observation errors can distort areal patterns and complicate the interpretation of spatial temperature anomaly patterns. Winkler et al. (1981) showed that the strength, spatial pattern, and extent of the TCMA urban heat island were strongly affected by applying time-of-observation corrections to the unadjusted temperature data.

Corrections for the time-of-observation bias were taken from Baker et al. (1985a) and are based upon the

3 yr observations at the St. Paul field station reported in Baker (1975). Mean monthly air temperatures for all stations were first determined from the original daily maximum and minimum air temperatures, and then adjusted to a common 08:00 h LST (local standard time) time-of-observation using the following equation:

$$T_{adj}(08{:}00, j) = T_{unadj}(i, j) + C(i, j)$$

where T_{adj} is the mean monthly air temperature for month j corrected to an 08:00 h LST time-of-observation, T_{unadj} is the original mean monthly air temperature for month j with a time-of-observation of i = 1,24 h, and C is the time-of-observation correction for month j and original observation time i = 1,24 h. An adjustment for the observation of daylight savings time was also made to all appropriate mean monthly temperatures.

Environmental indices. A series of simple environmental indices are frequently used to examine the impact of the thermal regime upon a wide range of physical and biological activities. These indices include those that accumulate degree-days above/below a threshold temperature, and those that sum the number of days of occurrence of a particular event. Although they do not provide insight into basic biophysical processes, such environmental indices are simple to calculate, have proven to be effective in a wide range of applied research, and can be readily adopted by urban designers.

The first category of indices, degree-day totals, arise from the fact that many physical and environmental systems show a close relationship between the rate of system activity, and the accumulation of temperature above/below a critical threshold temperature. This is especially true for stations located at higher latitudes where the seasonal variation in the thermal regime corresponds closely to seasonal daylength changes (Baker et al. 1985a). Two forms of degree-day equations exist: those that accumulate degrees above a threshold temperature, and those that sum temperature below a threshold. The choice depends upon whether system activity is initiated with either rising or falling temperatures. The 2 general forms for rising and falling degree-day accumulations are:

$$DD = \max[0, \Sigma(T - Tb)]$$
$$DD = \max[0, \Sigma(Tb - T)]$$

where DD is the degree-day total, T is the mean daily temperature, and Tb is the threshold temperature above or below which temperature is accumulated. The decision rule ensures that only positive sums are accumulated.

Six degree-day summation environmental indices were examined:

(1) growing degree-days (GDD0) above Tb = 0°C;
(2) growing degree-days (GDD10) above Tb = 10°C;
(3) melting degree-days (MDD) above Tb = 0°C;
(4) cooling degree-days (CDD) above Tb = 18.3°C;
(5) heating degree-days (HDD) below Tb = 18.3°C;
(6) freezing degree-days (FDD) below Tb = 0°C.

Growing degree-days are often used to relate the development and growth stage timing of native plants, agricultural crops, and agricultural pests to environmental conditions. GDD0 would be representative of native vegetation, while GDD10 would be applicable to field corn and selected vegetable crops. Since growing degree-day totals above other threshold temperatures are used for other crops (Baker et al. 1985a), the choice of 0°C and 10°C are only representative of the broad range of possible applications. Melting degree-days are related to the rate of urban snowmelt production, as well as the rate of spring soil thawing. MDD was only accumulated for the snowmelt months of January through April, since MDD is identical to GDD0 when calculated over a complete year. Cooling degree-days and heating degree-days are routinely used by power companies to estimate industrial and domestic space cooling and heating demands. Freezing degree-days correlate with the timing, rate, and depth of soil freezing beneath snow-free surfaces in the fall and winter, as well as the timing, rate, and thickness of lake ice accumulation in winter.

Two count or day summation environmental indices were examined:

(7) number of frost change-days (FCD);
(8) freeze-free season length (FFSL).

The frost change-day total is the number of times the temperature passes through 0°C, regardless of whether the temperature is rising or falling (Geiger et al. 1995), and is a measure of the rate of physical weathering, and the intensity of frost heave action. The freeze-free season length is the number of days between the last freezing temperature in the spring, and the first freezing temperature in the fall, and is important in defining the growing season length for selected ornamental and agricultural plants.

Determination of the last 2 environmental indices were made directly from inspection of the daily maximum and minimum air temperatures. Summation of the degree-day indices from daily station data, however, was not possible because of the bias introduced by the different station observation times. Since time-of-observation bias adjustments are only available for mean monthly temperatures (Baker 1975), degree-day totals were estimated from the adjusted monthly temperatures using the method of Wendland (1983).

Mapping procedure. All 8 environmental indices are spatially dependent random variables, and are suitable for mapping using standard geostatistical methods. First- and second-order polynomial trend surfaces were fitted to each data field to determine whether the spatial variation of each variable included a drift component. *F*-tests for the significance of fit for each pair of trend surfaces ($\alpha = 0.95$) indicated no evidence of drift (Davis 1986), and supported the choice of ordinary kriging of block estimates for grid estimation (Oliver et al. 1989). All variogram modeling and grid interpolation were accomplished using the Geostatistical Environmental Assessment Software (Englund & Sparks 1988). Final contour maps were produced using the Surfer for Windows Software (Golden Software 1994).

RESULTS AND DISCUSSION

A summary of the TCMA urban heat island and derived environmental indices for 1989 is presented in Table 2. Maximum and minimum values for the 26 stations comprising the network are presented, as well as the range and percent difference between the maximum and minimum values. Also given are comparable totals for the kriged grid points located within a 48.3 km (30 mile) radius of downtown Minneapolis. The range and percent difference between the maximum and minimum values for the kriged grid points are generally smaller than the corresponding results for the 26 station network because of the weighting associated with the interpolation process, and the smaller geographical area encompassed by the kriged grid. The kriged surface results are probably more representative of the regional urban heat island because they encompass an area more uniformly urban in character, and are less sensitive to individual station microclimatic anomalies, and will be the basis for all subsequent analysis and discussion.

The TCMA mean annual shelter-height air temperature pattern is given in Fig. 2. Individual values from the kriged grid vary from 6.5°C in the urban core, to

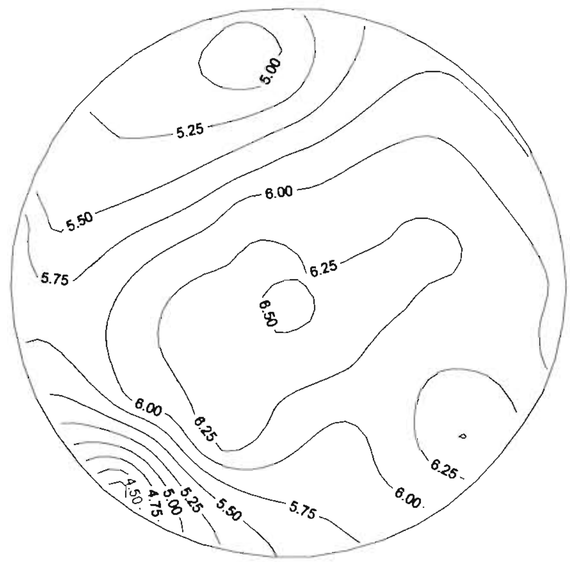

Fig. 2. Mean annual shelter-height air temperature (°C) for the TCMA, 1989

4.4°C along the urban periphery, for a range of 2.1°C. These values are slightly greater than the approximately 1.1°C mean annual air temperature range reported in Baker et al. (1985a) and Winkler et al. (1981). Baker et al. (1985a) based their results upon 10 stations averaged over a 30 yr period ending in 1980, while Winkler et al. (1981) examined 21 stations for a 10 yr period ending in 1976. The use of a greater number of stations, a single annual period, and a later study date all help explain the larger urban-rural air temperature range noted in this study.

Results from studies of intraurban variations in the mean annual temperature for other metropolitan areas by Jauregui (1973), Viterito (1989) and Unkasevic (1991) show urban heat islands of comparable magnitude, although such comparisons are complicated by the different population, areal extent and urban form of each metropolitan area. Nkemdirim & Truch (1978)

Table 2. Summary of 1989 TCMA urban heat island environmental indices. Kriged grid is based upon 181 grid points. %: percent difference between maximum and minimum values

Parameter	26 station dataset			Kriged grid		
	Maximum	Minimum	Range (%)	Maximum	Minimum	Range (%)
Mean temperature (°C)	6.62	4.06	2.6	6.5	4.4	2.1
Growing degree-days (0°C)	3651	2923	728 (25)	3551	3022	529 (18)
Growing degree-days (10°C)	1616	1018	598 (59)	1529	1097	432 (39)
Melting degree-days	228	153	75 (49)	228	164	64 (39)
Heating degree-days	5341	4654	687 (15)	5235	4690	545 (12)
Cooling degree-days	516	173	343 (198)	474	207	267 (129)
Freezing degree-days	1404	1126	278 (25)	1369	1136	233 (21)
No. of frost change-days	238	154	84 (55)	230	157	73 (47)
Freeze-free season length (d)	151	135	16 (12)	151	135	16 (12)

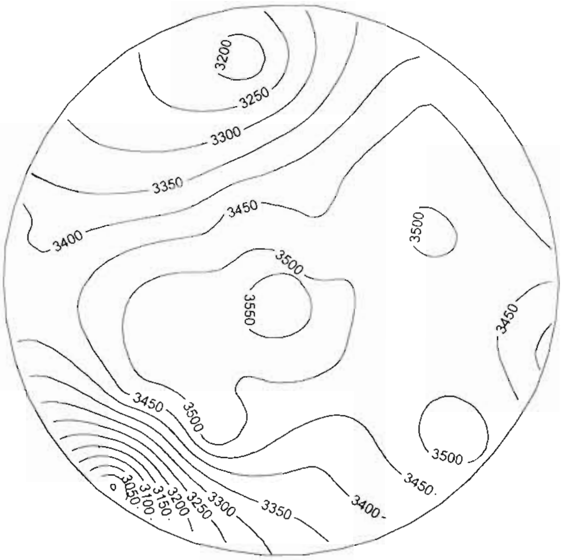

Fig. 3. Growing degree-days above a threshold temperature of 0°C for the TCMA, 1989

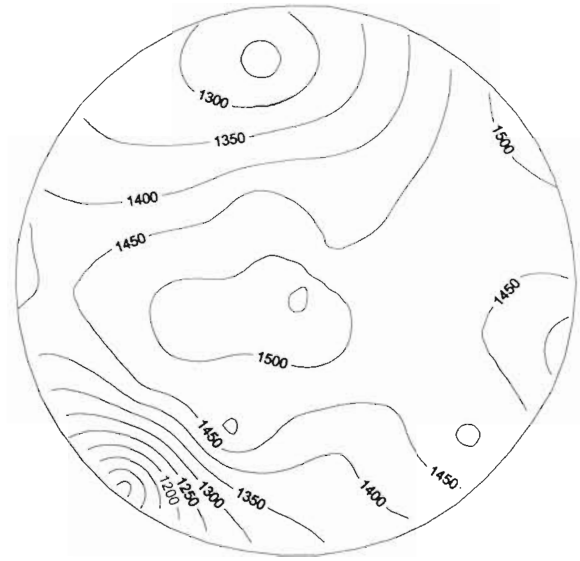

Fig. 4. Growing degree-days above a threshold temperature of 10°C for the TCMA, 1989

found a much larger mean annual temperature urban heat island for Calgary which is probably a unique feature of that city's high latitude, high altitude, and strong topographical control on the local climate. The largest urban heat island magnitudes are normally associated with urban-rural differences in the minimum (night) temperature (Landsberg 1981), and specific synoptic weather conditions (Unwin 1980). Urban heat island magnitudes defined by the mean annual temperature will, therefore, be more conservative than other urban heat island magnitudes reported in the literature. Schmidlin (1989), for example, in his study of the Toledo (Ohio, USA) urban climate, observed an urban heat island of 2.9°C based upon the mean annual minimum temperature, but only 2.0°C when based upon the mean annual temperature.

The urban heat island spatial pattern shows a small maximum over the central city, a broad region of elevated temperatures around the inner core, and a zone of rapid transition along the city periphery that is broadly similar to the 'peak', 'plateau' and 'cliff' patterns identified by Oke (1976). These patterns show a general correspondence to intraurban variations in urban geometry, vegetation cover, and surface materials. There is a slight E-W orientation to the isotherms along the major axis of the metropolitan area, with slight bulges in the isotherms along the WSW and S, the 2 directions of more recent urban development. The isotherms are also stretched toward the SE, due to downwind advection of the urban heat island along the prevailing wind direction.

The nature of the urban environment exposes plants to physical conditions far different from the surrounding landscape (Graves & Dana 1987). The presence of the urban heat island produces higher mean root-zone soil temperatures, a longer growing season, a higher frequency of extreme high temperatures, and a lower frequency of extreme low temperatures. Maps of annual growing degree-day totals based upon threshold temperatures of 0°C and 10°C are shown in Figs. 3 & 4, respectively. Both indices share many of the same general spatial patterns found for the mean annual air temperature. Intraurban degree-day totals range by 529 degree-days (18% variation) for GDD0, and 432 degree-days (39% variation) for GDD10 (Table 2). The fact that the percent difference between maximum and minimum values is nearly 2-fold greater for GDD10 as compared to GDD0 suggests that ornamental plants may be more impacted by the effects of the urban heat island than native vegetation.

Snowmelt begins at an earlier date, and proceeds at a faster rate in urban areas as compared to rural environments. Bengtsson & Westerström (1992) summarize the physical mechanisms responsible for the enhancement of snowmelt production in urban environments. The presence of the urban heat island has been suggested as a minor, though unquantified, contributing factor. MDD totals were accumulated through the end of April, the month during which the rapid transition of average daily albedo from high winter to low growing season values is completed (Ruschy et al. 1991). Melting degree-day totals above a base temperature of 0°C are shown in Fig. 5. The isolines display a concentric ringed pattern, with peak totals displaced slightly to the southwest of the central city. The small magnitude and relatively low range of values indicate that the

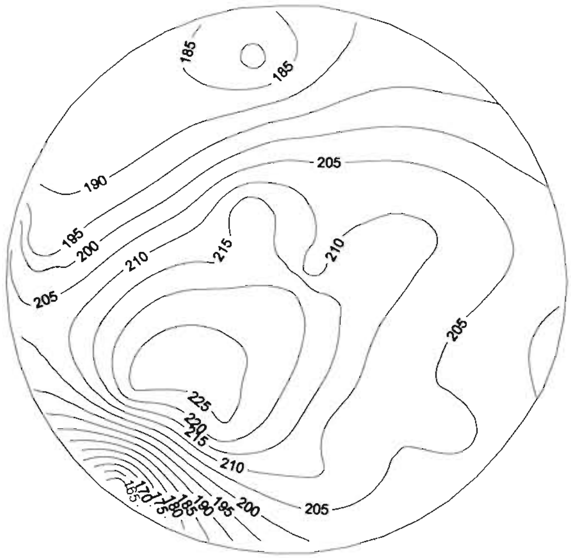

Fig. 5. Melting degree-days above a threshold temperature of 0°C for the TCMA, 1989

urban heat island plays a relatively minor role in explaining urban-rural variations in snowmelt production.

In cold weather climates the urban heat island can have a net positive effect upon urban energy demand since the substantial heating degree-day reduction overcompensates for the minor increase in cooling degree-days (Akbari et al. 1992). Bründl & Höppe (1984) in their study of the Munich (Germany) climate, for example, reported a 17% decrease in the annual number of heating degree-days when comparing urban-rural sites, with no significant change in the cooling degree-day totals. The HDD totals shown in Fig. 6 differ by 545 heating degree-days across the kriged surface, for a 12% urban-rural variation. The minimum number is centered over the urban core, with a downwind plume to the SE reflecting the dominant cold season wind direction between N and NW. HDD isolines indicate a steep gradient on the upwind side of the prevailing cold season wind direction, and a more gradual rate of change along the downwind side. The cooling degree-day totals shown in Fig. 7 exhibit a much greater degree of relative variation over the metropolitan area, with an urban-rural difference of 129%. Because of their much shorter period of accumulation, however, the absolute magnitude of the range, 267 degree-days, is only one-half the magnitude of the HDD urban-rural range. Maximum CDD totals also occur over the city center; however the isolines show a plume which is stretched eastward because of the dominant SW direction of the warm season winds.

The spatial distribution of freezing degree-day totals shown in Fig. 8 displays a close resemblance to the GDD0 and HDD patterns. Basic features include steep isoline gradients to the NW and SW, a central city maximum, and an isoline ridge extending to the SE created by cold season advection. The broad similarities in the spatial patterns of the 3 indices and their relatively modest intraurban variations (≤21%) result from the fact that in a high latitude climate each index will accumulate over the greater part of the annual period.

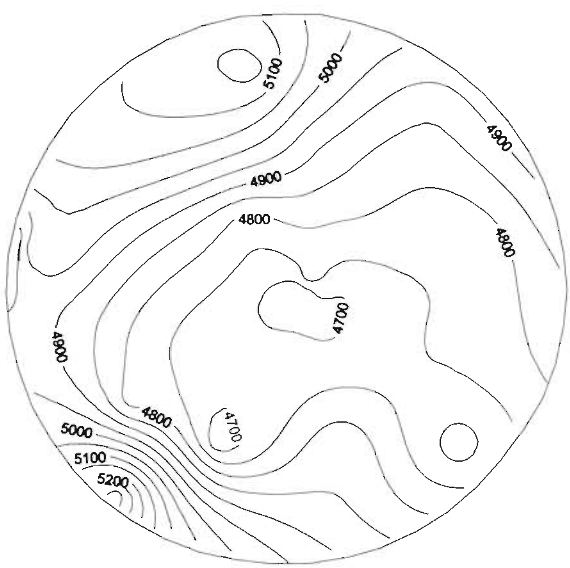

Fig. 6. Heating degree-days below a threshold temperature of 18.3°C for the TCMA, 1989

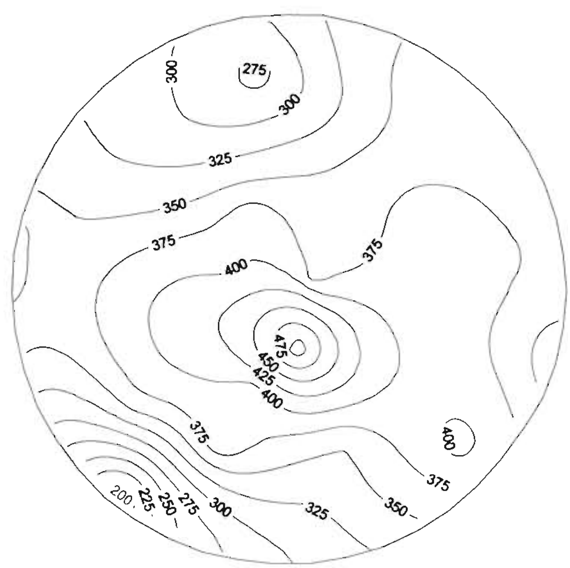

Fig. 7. Cooling degree-days above a threshold temperature of 18.3°C for the TCMA, 1989

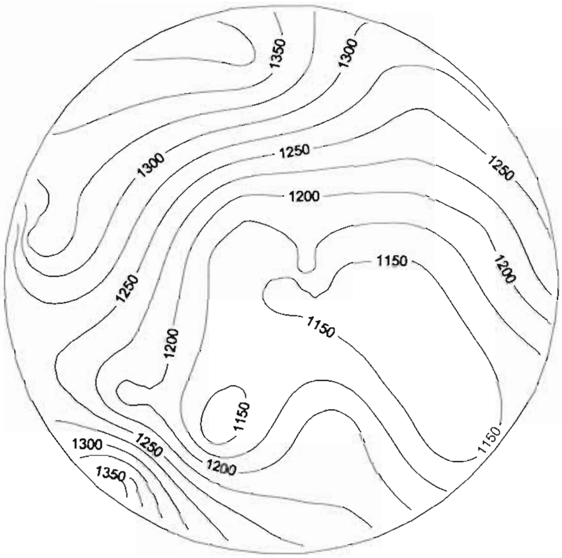

Fig. 8. Freezing degree-days below a threshold temperature of 0°C for the TCMA, 1989

The long duration of the degree-day accumulation period leads to a convergence in the spatial pattern and relative magnitude of the intraurban values. Degree-day totals which only accumulate during the shorter warm season, such as GDD10 and CDD, show more unique spatial patterns and a greater degree of intraurban variation. Presumably the opposite pattern might be expected to occur in the urban climate of cities located at lower latitudes.

The determination of the urban heat island effect upon the 2 count indices shown in Figs. 9 & 10 is more uncertain. The frequency, timing and duration of freezing temperatures is primarily controlled by synoptic weather patterns, with strong secondary influences due to wind speed, cloud cover and local topography (Geiger et al. 1995). The effects of urbanization are superimposed upon these dominant climatological and physical controls. The frost change-day totals in Fig. 9 exhibit an unusual pattern, with lower values in the NE half of the metropolitan area, and higher values in the SW half. Fig. 9 indicates some degree of reduction in the number of frost change-days near the urban core, although further research in needed to separate the individual effects of urbanization and local topography.

Fig. 10 indicates some degree of urban influence upon the length of the freeze-free season, a conclusion supported by the work of Nkemdirim & Venkatesan (1985) and Schmidlin (1989). A general pattern exists of maximum totals in the central city, with values decreasing toward the city periphery, although a secondary minimum occurs in the SSE which may be due to local topography. The maximum and minimum FFSL values range by 16 d, suggesting that urbanization can significantly modify the length of the growing season. These results are comparable to those obtained for the Toledo metropolitan area by Schmidlin (1989), who reported a maximum 23 d increase in the FFSL due to urban heat island effects.

CONCLUSIONS

A high-density, homogeneous, daily maximum and minimum air temperature dataset was developed to

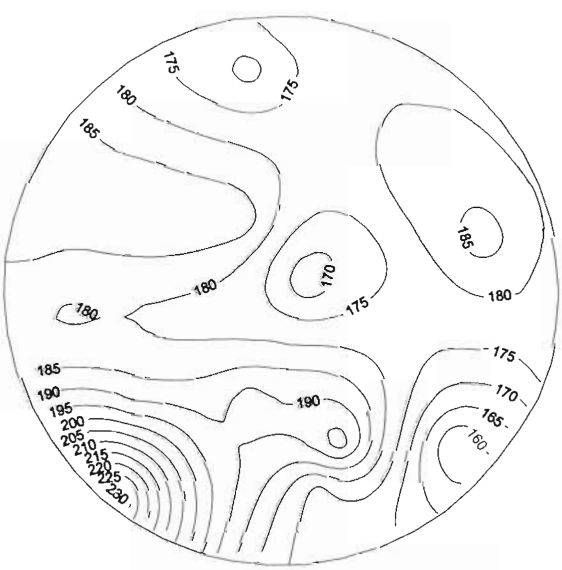

Fig. 9. Frost change days for the TCMA, 1989

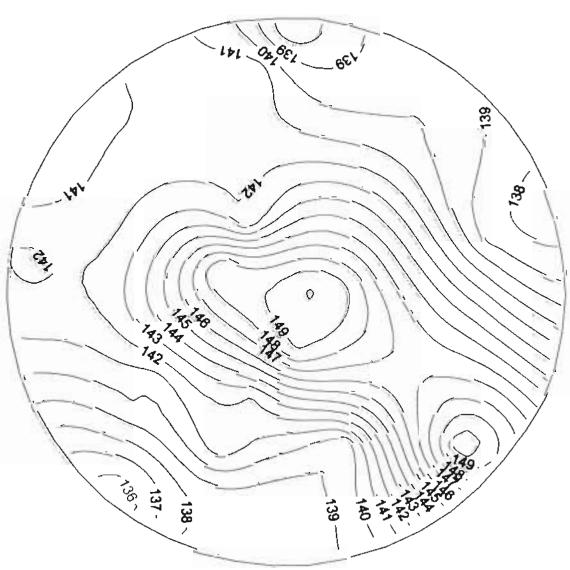

Fig. 10. Freeze-free season length for the TCMA, 1989

examine the magnitude and spatial distribution of the urban heat island and derived environmental index fields for the TCMA. The analysis documents the magnitude and spatial variation of measured and derived temperature-related variables which might be typical of a large midlatitude midcontinental metropolitan area.

The spatial distribution of the mean annual air temperature urban heat island includes a peripheral zone of rapid temperature increase, a large plateau of elevated air temperatures, and a small central core of peak temperatures, a spatial model which has often been proposed, but infrequently documented by climatologists. The approximate magnitude of the mean annual air temperature urban heat island (2.1°C) is sufficiently large and persistent to affect a broad array of physical and environmental systems within the TCMA. The urban heat island results in increased growing degree-day totals for native and ornamental plant species, reduced heating requirements, increased cooling demand, increased snowmelt production, reduced ground freezing, reduced physical weathering rates, and an increased growing season duration. The magnitude and spatial pattern of these temperature-related indices are index-specific, demonstrating that the urban heat island produces variable impacts within the urban environment. The effect of the urban heat island upon some thermal indices are so significant that environmental response and adaptation to the historical urban warming should now be evident. Urban environments, therefore, would appear to offer a suitable laboratory for selected climate change impact research.

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