Urban Warming*

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ABSTRACT

Meteorological stations located in an urban environment in North America warmed between 1941 and 1980, compared to the countryside, at an average rate of about 0.12°C per decade. Secular trends of surface air temperature computed predominately from such station data are likely to have a serious warm bias.

1. Introduction

Secular trends of large-scale, average, surface temperature have special importance in the detection of the climatic impact of increasing CO_2 (Riches and Koomanoff, 1985). Recently published compilations of land surface air temperature of the Northern Hemisphere show the early 1980s to be the warmest in the last 130 years (Jones et al., 1986). In contrast, the nighttime air temperature over the ocean was highest in the 1940s (Folland et al., 1984). Whether the differences between the two records may be the result of inhomogeneities in the marine series (Barnett, 1984) or can be accounted for by the thermal inertia of the ocean is not known. It is also possible that the land record is affected by a progressive urban warming bias. Many stations used in the computation of temperature trends are located in a city environment subject to urban heating (Landsberg, 1981). As cities grow, the temperature difference with respect to the countryside has been shown to increase (Mitchell, 1953).

2. Analysis

In order to quantify the magnitude of this effect we compared the linear surface air temperature trends over the 1941–80 interval for a number of urban/rural station pairs in North America. We also compared the cities to the climate divisions. The divisional averages are based on a number of stations in a defined geographic area.

For the purpose of this study the distinction between urban and rural is based on population size. The majority of selected urban stations are located at airports of cities with recent metropolitan populations well in excess of 100 000. Most of the rural locations have less than 7000 inhabitants with a few between 30 000–40 000 (Table 1). Because heat islands have been detected in small towns with populations of only 1000 (Landsberg, 1981), the urban/rural difference reported here may represent the lower limit of the urban effect.

Although the rural stations used in this study have relatively few documented inhomogeneities, at about one-third of them the observation time for reading and resetting the maximum/minimum thermometer changed from the afternoon to the morning, a source of a potential cooling bias (Mitchell, 1958). At the urban sites numerous inhomogeneities are present, most importantly, relocations from cities and municipal airports to the airports in outlying areas and moving the thermometer from rooftops to ground level.

The climate divisions are geographic regions within a state commonly covering an area of 10^4 to 10^6 km^2. Monthly mean temperatures are arithmetically averaged from a number of stations. Several sources of inhomogeneities and biases are known to affect the data. For example, the number and geographic distribution of the stations changes with time. The degree to which this influences the averages is likely to vary from division to division. The observation time bias described above has also been shown to affect the divisional data (Schaal and Dale, 1977). In order to remove this influence, adjustments were made following the procedure described in Karl et al. (1986). Because the division averages are composed of a varying proportion of urban and rural stations, a residual warm bias may be present.

In the first test, we compared trends of the 34 urban/rural station pairs listed in Table 1. The urban stations show a warming with respect to the countryside throughout most of the year. The average annual difference of the trends is about 0.11°C per decade (Tables 2 and 3, group A1). The same urban sites (with the

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TABLE 1. List of station pairs used in this study. Population rounded to nearest thousand. Distance between urban and rural sites derived from a U.S. Department of Commerce (1973) publication. All listed stations included in group A. Time interval analyzed for group D shown. In each pair, urban station listed first, rural second.

Station pairs	Population (1000s) 1940	1980	Distance (km)	Groups	Remarks*
Augusta, GA	60	346	66		1
Warrenton, GA	1	2			2
Akron, OH	349	773	45		1
Wooster, OH	11	19			
Amarillo, TX	53	149	69	B	
Vega, TX	<1	<1			2
Austin, TX	106	537	77	B, C	
Blanco, TX	4	5			
Baltimore, MD*	1047	2200	26	B, C	
Woodstock, MD	<1	<1		D (1951–69)	
Boise, ID	22	173	119	B	
Cambridge, ID	<1	<1			2
Boston, MA	2351	3972	103	B	
Concord, NH	25	30			
Cincinnati, OH*	789	1660	95	B	
Cambridge City, IN	2	2		D (1952–73)	2
Denver, CO	384	1618	71	B	
Cheesman, CO	<1?	<1?			2
Duluth, MN	157	267	29		1
Cloquet, MN	7	11			
Evansville, IN	142	276	93	B, C	
Harrisburg, IL	12	10			
Ft. Smith, AR	31	71	32		1
Ozark, AR	2	4			
Greensboro, NC	73	852	48	B	
Asheboro, NC	7	15			
Indianapolis, IN	455	1167	92	B	
Cambridge City, IN	2	2			2
Louisville, KY	434	957	40	D (1961–77)	1
Shelbyville 6 NW, KY	4	4			2
Montgomery, AL	66	273	63		1
Clanton, AL	2	6			2
Montreal, QUE*	1145	2828	80		
Bethierville, QUE	1	4			
Newark, NJ	981	1879	31	B, C	
Boonton, NJ	7	9			
New Orleans, LA	540	1256	47		1
Houma, LA	7	33			2
Oklahoma City, OK	221	861	109		1
Ada, OK	11	16			
Omaha, NB	288	585	35	B, C	
Logan, IA	2	2			
Ottawa, ONT	226	718	80		
Brockville, ONT	10	36			
Portland, ME	107	194	51	B	
Lewiston, ME	35	40			2
Raleigh, NC	47	561	93		1
Goldsboro, NC	21	32			2
Reno, NV	18	194	90	B	
Fallon, NV	2	4			2
Sacramento, CA	159	1100	80	B, C	
Colfax, CA	<1	<1		D (1961–80)	
San Antonio, TX	319	1072	64	B, C	
Blanco, TX	4	5			
Shreveport, LA	112	333	47		1
Plain Dealing, LA	1	1			
South Bend, IN	147	242	80	B, C	
South Haven, MI	5	6		D (1953–79)	
Springfield, MO	71	483	55		1
Lockwood, MO	<1	<1			
St. Louis, MO	1370	2380	97	B, C	
La. Starks Nur., MO	4	4		D (1961–80)	

TABLE 1. (*Continued*)

Station pairs	Population (1000s) 1940	Population (1000s) 1980	Distance (km)	Groups	Remarks*
Tampa, FL	210	1614	47		1
St. Leo, FL	<1	<1		D (1953–74)	
Tucson, AZ	33	531	90		1
Wilcox, AZ	<1	3			
Waco, TX	53	101	72		1
Mexia, TX	7	7		D (1954–72)	

* 1 ≡ stations which moved from the city or a municipal airport to a suburban airport after 1942. 2 ≡ rural station with an observation time bias. Urban sites which are located in the city marked with asterisk. The remainder are airport locations.

exception of the two Canadian cities) were also compared with the corresponding climatic divisions. A considerably smaller annual urban heating rate of 0.04°C/decade is found compared to the station pairs (group A2). This is likely to be due both to the elimination of the observation time bias and the inclusion of urban stations in the division averages.

The above results reflect various inhomogeneities including the urban effect. In order to eliminate an apparent cooling trend introduced by stations which relocated from downtown to outlying suburban airports, a subset of 18 urban sites which did not move were compared with the adjusted divisional averages (Tables 2 and 3, group B). An annual decadal urban warming of 0.10°C is indicated.

In order to further test the effect of removing major inhomogeneities, subset C1 was analyzed. This group also includes only those urban stations which did not relocate from the city to the airport. The rural sites had less than 11 000 inhabitants in 1980 with less than a 30% increase in population over the 40-year interval. No observation time bias is present. The nine urban sites warmed with respect to their rural counterpart at an average rate of 0.12°C per decade (Tables 2 and 3, group C1). Comparison of the same urban stations with the adjusted divisional averages results in an annual difference of 0.14°C per decade (group C2).

As the previous comparisons do not eliminate potential inhomogeneities introduced by vertical and horizontal instrument moves other than relocation to the airport, more rigorous criteria were applied and an additional subset of stations (group D) was analysed. These eight urban/rural station pairs had few, if any, changes in instrument location at *either* site. The rural population remained below 7000 and increased less than 20%. Because none of the stations conformed to these criteria throughout the 1941–80 interval, each station pair was compared over a different but shorter time interval between 1951 and 1980 (cf. Table 1). The average difference between trends amounts to an annual mean urban warming rate of 0.34°C/decade. Values from May through August averaged 0.44°C/decade while December showed the smallest difference. The reason the warming rate in subset D is considerably higher than in the other groups is not clear. One possibility is that the rate may have increased after the 1950s, commensurate with the large recent growth in and around airports. Another possibility is that the large difference is due to further reduction of inhomogeneities.

TABLE 2. Monthly urban warming rates. Average rates (*x*) of warming and standard deviations (*sd*) in °C/decade for groups described in text. Urban locations compared separately to rural stations and divisions. Based on the 1941–80 interval for groups A–C and for varying time intervals between 1951–80 for group D (cf. Table 1).

Group	Warming rate (°C/decade)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
A1	*x*	.09	.16	.14	.13	.10	.10	.10	.10	.10	.06	.10	.10
	sd	.27	.31	.27	.22	.21	.20	.21	.20	.20	.22	.22	.26
A2	*x*	0	.04	.03	.03	.05	.06	.05	.07	.09	.05	.03	.03
	sd	.23	.25	.20	.20	.21	.21	.20	.19	.16	.22	.16	.17
B	*x*	.07	.13	.10	.11	.12	.11	.12	.10	.14	.10	.07	.06
	sd	.25	.23	.17	.18	.21	.23	.20	.17	.14	.24	.16	.17
C1	*x*	.11	.14	.10	.14	.12	.14	.12	.13	.13	.06	.12	.12
	sd	.23	.25	.17	.23	.19	.23	.22	.22	.21	.25	.25	.28
C2	*x*	.13	.17	.09	.12	.15	.18	.20	.19	.19	.15	.08	.07
	sd	.31	.30	.17	.19	.18	.21	.16	.14	.15	.30	.19	.18
D	*x*	.41	.26	.25	.34	.45	.42	.43	.46	.34	.37	.23	.09
	sd	.48	.27	.23	.25	.39	.41	.43	.22	.40	.37	.40	.48

TABLE 3. Summary of reported annual urban warming rates. Rates are relative warming at the city stations with respect to the rural sites or to smaller towns as reported by the author or computed by us from the published data.

Rate (°C/10 yrs)	No. cities	Interval	Region	Remarks	References
0.11	34	1941–80	U.S./Canada	Group A1 Urban/rural pairs	This study
0.04	32	1941–80	U.S.	Group A2 Urban/divisions	This study
0.10	18	1941–80	U.S.	Group B Urban/divisions	This study
0.12	9	1941–80	U.S.	Group C1 Urban/rural pairs	This study
0.14	9	1941–80	U.S.	Group C2 Urban/divisions	This study
0.34	8	1951–80	U.S.	Group D Urban/rural pairs varying intervals	This study
0.09	10	1893–1954	E U.S.	Annual rate averaged from seasonal values taking insignificant differences as zero	Mitchell (1961b)
0.30	7	1933–80	SW U.S.	Average of cities vs 5 rural sites	Cayan & Douglas (1984)
0.42	2	1940–80	SW U.S.	Tucson City vs Airport & San Diego vs Scripps	Cayan & Douglas (1984)
0.30	3	1946–80	SW U.S.	Surface/700 mb; x Jan & Jul for Las Vegas, San Diego, Tucson	Cayan & Douglas (1984)
0.32	1	1904–79	Maryland	Baltimore/Woodstock	Landsberg (1981)
0.14	1	1903–47	Illinois	Urbana air/soil difference	Changnon (1964)
0.14	31	1917–83	California	Cities vs 31 rural sites	Goodridge (1985)
0.00	31	1917–40	California	Cities vs 31 rural sites	Goodridge (1985)
0.11	31	1941–60	California	Cities vs 31 rural sites	Goodridge (1985)
0.31	31	1961–83	California	Cities vs 31 rural sites	Goodridge (1985)
0.02	9	1891–1950	Europe	Largest cities/14 rural sites	Callendar (1961)
0.09	17	1891–1960	World	Cities vs selected rural sites (No. of cities from first decade)	Dronia (1967)
0.15	3	1871–1890	Europe	Cities vs selected rural sites (No. of cities from first decade)	Dronia (1967)
0.14	17	1891–1920	World	Cities vs selected rural sites (No. of cities from first decade)	Dronia (1967)
0.01	61	1921–40	World	Cities vs selected rural sites (No. of cities from first decade)	Dronia (1967)
0.13	45	1941–60	World	Cities vs selected rural sites (No. of cities from first decade)	Dronia (1967)
0.09	3	1886–1935	Japan	Average of Tokyo, Kyoto, Osaka vs Wakayama, Koti, Hamamatsu, Numazu, Miyako, Gihu, Sakai, Kanazawa, Husiki	Arakawa (1937)
0.33	1	1920–1950	Argentina	Buenos Aires vs countryside	Prohaska (1954)
0.10	1	1878–1968	England	Kew Observatory, London vs Rothamsted Experimental Stn.	Moffit (1972)
0.12	1	1891–1968	France	Paris vs Lyon, Besancon & Nantes	Dettwiller (1970)

The considerable differences of urban warming rates as well as the high degree of variability shown in Table 2 and Fig. 1 reflect the nonuniform impact of various inhomogeneities. Practically all stations have undergone changes potentially affecting their record to some degree (Mitchell, 1953; Griffiths and Vining, 1984). It is also probable that the urban effect will vary depending on many complex factors including wind direction and speed, cloudiness and topography (Landsberg, 1981; Ackerman, 1985). Although for these reasons an average urban warming rate is difficult to reliably compute, the consensus of our tests suggests a rate of approximately 0.12°C per decade.

3. Comparison with other results

Our results agree with those found for different parts of the world and for different time intervals over the past century (Table 3). It is therefore likely that urban warming affects cities on a global basis. However, the degree to which the bias influences the Northern Hemisphere temperature trends is not reliably known. Attempts have been made to estimate the potential impact of this bias on the temperature curve. Dronia (1967) compared data for 67 urban (population over 100 000) and 67 rural (population under 10 000) sites worldwide. He also separately analyzed urban and rural stations used by Mitchell (1961a) and proposed a reduction of the global secular trend by 0.50°C between 1870–1960 and by 0.20°C from 1900–1960. No correction was required between 1920 and 1940. Because of the small number of stations in Dronia's analysis prior to 1900, his results for the 1871–1900 interval should be viewed with utmost caution. Mitchell (1967) estimated the urban warming bias in his data to be only about 0.07°C between 1901 and 1940 and essentially zero from 1940 to 1960 because of numerous station relocations from cities to airports in outlying

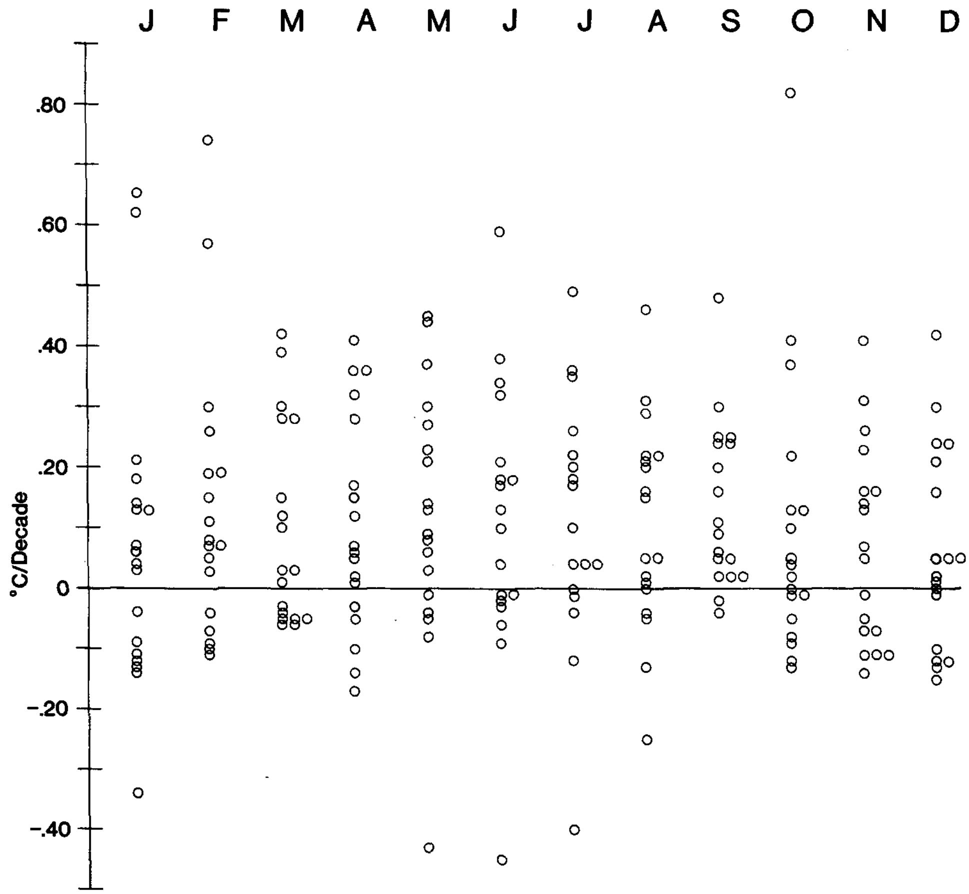

FIG. 1. Urban minus divisional trends in air surface temperature for the 1941–80 interval for group B. Individual values shown for each month from January–December in degrees centigrade per decade.

areas. He based his conclusion on the relation of heat islands to the population growth, reported earlier (Mitchell, 1953).

Recently Jones et al. (1986) discussed the effects of urbanization on their Northern Hemisphere surface air temperature averages. Only 38 stations out of 2666 were identified as having an urban warming bias and omitted from their analysis. The method used to assess homogeneity consisted of comparing annual temperature anomalies at one station with several neighboring stations and plotting the differences as a time series to detect abrupt changes or trends. However, if the stations being compared are similarly affected by urban warming no differences would be found (Jones et al., 1985). More rigorous testing will be needed to ascertain the degree to which this bias is still present in large scale temperature averages. Records of free atmosphere temperature which are not affected by urban warming and are available for the last few decades may be useful in this respect.

4. Conclusion

The large differences of our individual station pairs demonstrate that isolation of the urban warming effect from other inhomogeneities is a complicated task. Estimates of urban effects on hemispheric and global temperature trends (Dronia, 1967; Mitchell, 1967; Jones et al., 1986) can only be considered very approximate. As most stations used in the computation of large scale temperature trends have probably relocated to the airports prior to 1960, compensation for the urban bias in the most recent decades is unlikely. Although it would be unrealistic to attribute the entire 0.4 to 0.5°C hemispheric warming since 1900 to urban growth, the warming trends through 1940 and since the mid 1970s are likely to be less expressed than previously reported. Our results and those of others show that the urban growth inhomogeneity is serious and must be taken into account when assessing the reliability of temperature trends.

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