The Effect of Clouds and Wind on the Difference in Nocturnal Cooling Rates between Urban and Rural Areas

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ABSTRACT

The urban warming effect is interesting in its own right and is important for understanding global warming. The aim of this study is to determine how the urban warming effect changes with cloud conditions and with wind speed. Studies of the urban warming effect have mostly concentrated on the urban–rural difference in daily maximum or minimum temperatures. The problem was approached using a new technique. Instead of comparing a city, represented by a first-order weather station, with the surrounding rural area, represented by data collected by cooperative observers; pairs of cities, each with a first-order weather station, were studied. One city was large. The other city was small enough to have a minimal warming effect and was close enough to the larger city to approximately represent the rural area. In this way, hourly temperatures, cloud cover, and wind data could be studied rather than only the differences between the daily maxima or minima. Results show that wind disrupts the normal nocturnal cooling pattern in which the smaller city, with lower thermal inertia, cools more quickly than the larger city. Clouds also disrupt this pattern, at least to the extent that one must be careful about extrapolating either magnitudes or patterns of urban–rural temperature difference observed by satellites under clear sky conditions to partly cloudy or cloudy conditions.

1. Introduction

For many years it has been known that urban areas are warmer than the surrounding countryside (Kratzer 1937; Woolum 1964; Landsberg 1981). Interest in this phenomenon has increased recently because it is related to the global warming problem as follows. To determine whether the temperature of the globe is changing, one needs to examine long-term temperature records from surface weather stations. Many of these stations are located in urban areas. The difficulty is that as a city grows, its urban warming effect causes a warming signal in the weather records that has nothing to do with the global temperature. For global warming studies, it is important to quantify and remove the urban warming effect from long-term temperature records (Karl and Jones 1989).

Developing an accurate urban warming correction, however, is not an easy task. Typically, urban areas have a single weather station, usually at the airport. These first-order stations make accurate, detailed observations that nicely characterize the urban area. The rural area surrounding the station is not as well observed. Usually one must rely on cooperative observers who normally record only daily maximum and minimum temperatures and rainfall. Because there are few cooperative observers, the rural area is poorly sampled both spatially and temporally. With few exceptions (such as major field studies like METROMEX; Changnon 1981) studies of the urban warming effect have mostly concentrated on the urban–rural difference in daily maximum or minimum temperatures because little else is available.

Rao (1972) first noticed that weather satellites could be used to measure the urban warming effect with high spatial resolution (now on the order of 1 km). Many studies have used satellite data for this purpose (e.g., Matson et al. 1978; Price 1979; Vukovitch 1983; Kidder and Wu 1987; Roth et al. 1989; Gallo et al. 1993; Johnson et al. 1994). While the satellite studies have added significantly to our knowledge of the magnitude of the urban warming effect, there is a possible bias in their data: infrared channels can sense the surface only under clear sky conditions. If one is to understand the urban warming effect, one must have information about it under overcast and partly cloudy conditions as well.

2. Approach

The aim of this study is to determine how the urban warming effect changes with cloud conditions and with wind speed. However, as outlined above, the data necessary for this study are not readily available; in particular, the rural cooperative stations do not observe wind speed or cloud conditions. Instead, the problem

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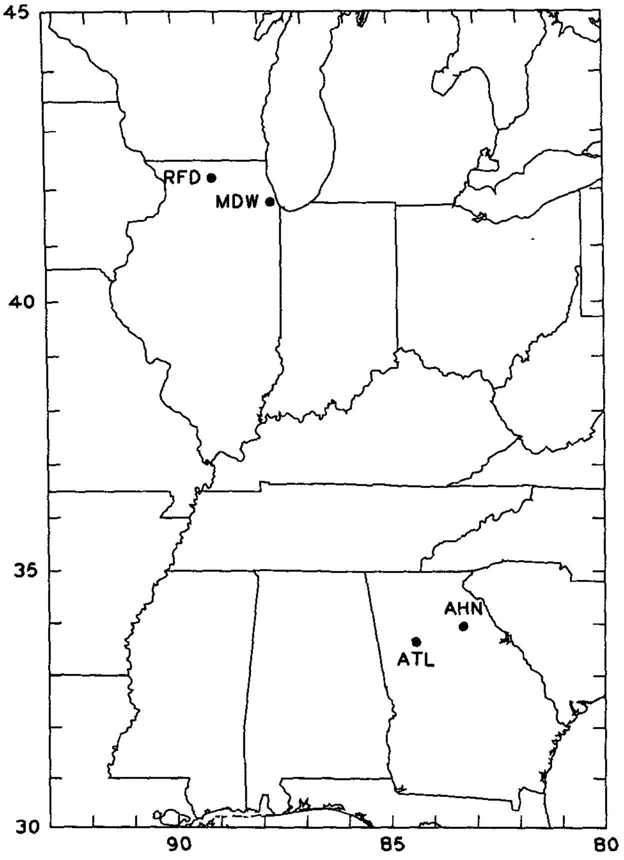

FIG. 1. Location of large–small city pairs.

was approached by studying city pairs, one city being large, and the other being small, but close enough to represent the area surrounding the large city. Two pairs of cities were chosen: Chicago–Rockford and Atlanta–Athens. Figure 1 shows the locations of these stations, and Table 1 has information about them. The advantage of this paired-city scheme is that hourly data from first-order weather stations can be used for both the large and small cities. The disadvantage is that the small cities have an urban warming effect of their own (Karl et al. 1988); therefore, large–small city differences that appear in the data may be underestimates of the true urban–rural differences. Oke (1976) gives the following formula for maximum urban–rural temperature differences:

$$\Delta T = 3.06 \log_{10}(P) - 6.79, \qquad (1)$$

where P is the city population and ΔT is in kelvins. Based on this formula, with the populations given in Table 1, one would expect approximately a 5-K maximum difference between Chicago and Rockford and between Atlanta and Athens, whereas the maximum difference between these cities and the unpopulated rural area would be about 14, 9, 13, and 8 K for Chicago, Rockford, Atlanta, and Athens, respectively.

TABLE 1. Station characteristics.

	Atlanta	Athens	Chicago	Rockford
Station ID	ATL	AHN	MDW	RFD
Latitude (°N)	33.65	33.95	41.78	42.20
Longitude (°W)	84.43	83.32	87.75	89.10
Elevation (m)	315	244	190	221
1980 population	2 138 136	42 549	6 060 383	139 712
1990 population	2 833 511	45 734	6 069 974	139 943
Sunrise, 15 Feb	0724 EST	0720 EST	0650 CST	0654 CST
Sunrise, 15 Jul	0538 EST	0532 EST	0429 CST	0433 CST
Sunset, 15 Feb	1823 EST	1817 EST	1725 CST	1729 CST
Sunset, 15 Jul	1951 EST	1948 EST	1928 CST	1932 CST

The urban warming problem was approached by studying nocturnal cooling rates rather than the urban–rural difference in maximum or minimum temperatures. This choice was made for three reasons. First, studies using extrema can be misleading because they represent a single instant during the day at an unknown time. Second, it is difficult to determine cloud or wind conditions associated with the maximum or minimum. Third, as shown in Fig. 2 and explained in the appendix, cities with different heat capacities should display a simple difference in their change of temperature with time: at night the larger city cools more slowly than its smaller companion. If this pattern is disrupted by clouds or wind, there is reason to conclude that the urban warming effect itself is similarly disrupted. Finally, the nocturnal period was chosen for study rather than the entire day for two reasons: (1) albedo differences are unimportant at night, and (2) there are fewer cases when cloud and wind conditions persist for an entire day than for only the nighttime period.

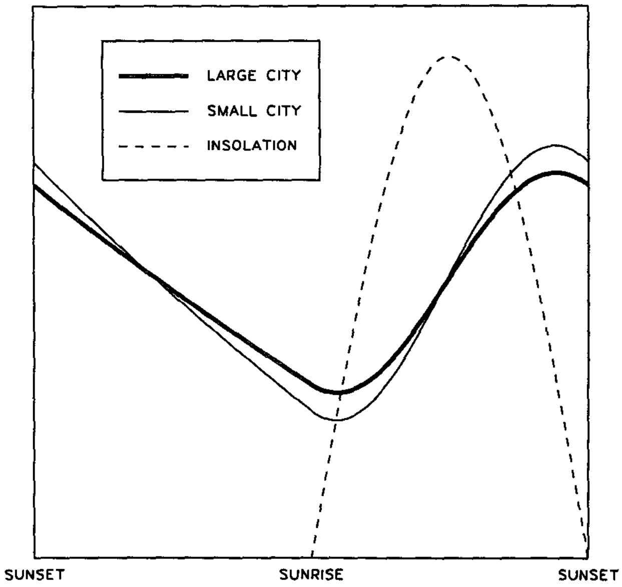

FIG. 2. Schematic of the diurnal variation under clear sky conditions of two "cities" with different heat capacities (thermal inertia).

3. Data and analysis

The primary data employed in this study are from the CD-ROM titled "Solar and Meteorological Observation Network" (SAMSON) compiled by the Department of Energy's National Renewable Energy Laboratory (NREL) in Golden, Colorado, and the Department of Commerce's National Climatic Data Center (NCDC) in Asheville, North Carolina. The data, which may be ordered from NCDC, consist of hourly observations for the years 1961–90 for 239 U.S. stations.

To study the nocturnal cooling rates, temperatures at each hour from sunset to sunrise were averaged to form a cooling curve. Because the cooling is likely to be different in different seasons, two months were chosen for study: February was chosen to represent the winter season (due to a parallel study using satellite data in which February data were required), and July was chosen to represent the summer season. Though not exactly six months apart, these two months seem adequate to represent their respective seasons, at least in this initial study.

The data were further categorized into three cloud-cover types and two wind speed classifications. The average sky cover in tenths was calculated between the hours of 2100 LST[1] and 0700 LST. The data for a particular night were classified as "clear" for mean sky cover less than 2.9 tenths, "cloudy" for mean sky cover greater than 7.9 tenths, and "partly cloudy" otherwise. The data were also stratified into wind categories: "light wind" when the wind speed at 0000 LST was 5 $\mathrm{m\ s^{-1}}$ or less; "strong wind," otherwise.

Thirty years of temperature data were used to compile 48 average cooling curves (4 cities × 3 cloud categories × 2 wind categories × 2 months). However, the data were excluded if the wind and cloud conditions were not the same in each city pair. For example, for a particular night, if the wind category in Chicago was different than in Rockford, or if the cloud category in Chicago was different than in Rockford, the data were excluded.

To check the results, minimum and maximum temperatures (acquired from NCDC) in Atlanta were compared with those at three cooperative stations near Atlanta (Fig. 3) for Februarys during the period 1988–92. Cloud conditions in Atlanta were assumed to represent the cloud conditions at the cooperative stations, and the maximum and minimum were assumed to occur near the "normal" times. These data were not stratified by wind speed. These assumptions are necessary because cooperative stations do not record cloud cover, wind speed, or time of minimum and maximum. We note, however, that in the case of Atlanta and Athens (which is further from Atlanta than any of the three cooperative stations) the cloud categories matched more than 85% of the time in February.

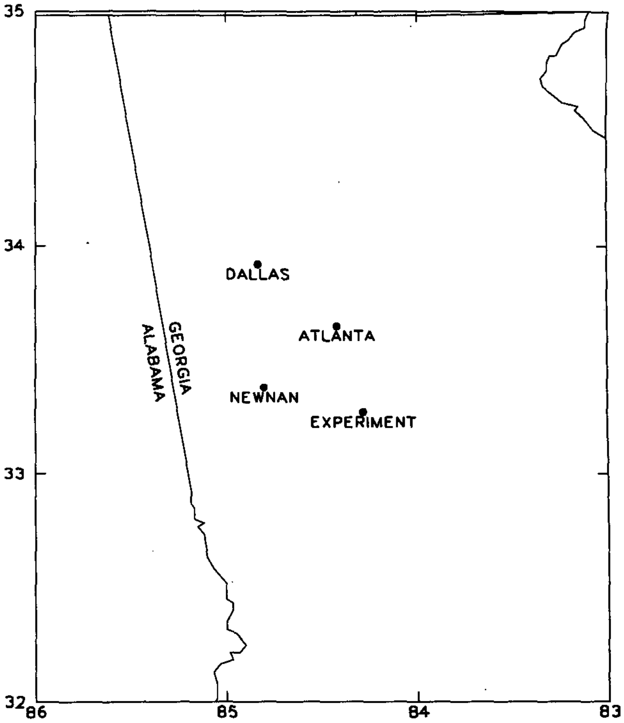

FIG. 3. Locations of the three cooperative stations used in this study.

4. Results

Figure 4 shows the hourly mean temperatures for Atlanta–Athens categorized by season, wind speed, and cloud cover; Fig. 5 shows the results for Chicago–Rockford. It is noted that the curves are rather smooth, much smoother than cooling curves based on only a few nights' observations (c.f. Landsberg 1981, 1986). Averaging over 30 years considerably reduces noise. However, the curves are still not easy to explain. Consider first the light wind situation (Figs. 4a, 4c, 5a, and 5c). Many of the curves look qualitatively like Fig. 2, at least in the sense that the smaller city starts the night warmer than the larger city and ends colder than the larger city. This indicates that thermal inertia differences are important. Not all of the curves follow this pattern, however. Chicago is always warmer than Rockford at night in February, which cannot be explained as a thermal inertia difference. A plausible explanation is that there is increased heat input in Chicago during the winter. During the summer, the explanation of the cooling curves is more difficult. Under cloudy, light-wind conditions in July, Chicago is consistently warmer than Rockford at night, but under clear or partly cloudy conditions, the Chicago–Rockford cool-

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[1] Local standard time. Central standard time was used for Chicago and Rockford; eastern standard time for Atlanta and Athens.

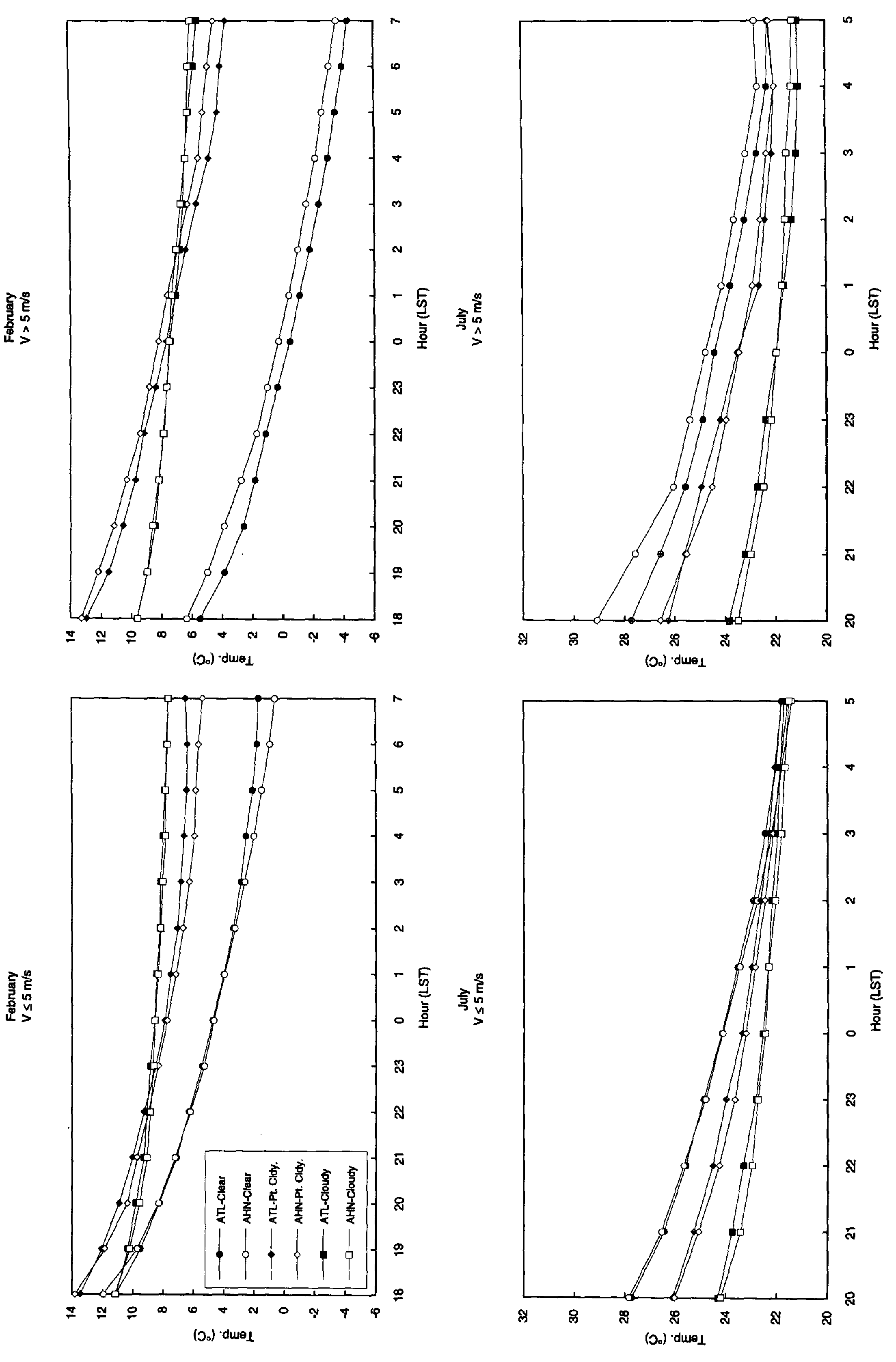

FIG. 4. Mean hourly temperatures for Atlanta and Athens, Georgia, for the indicated wind and cloudiness conditions.

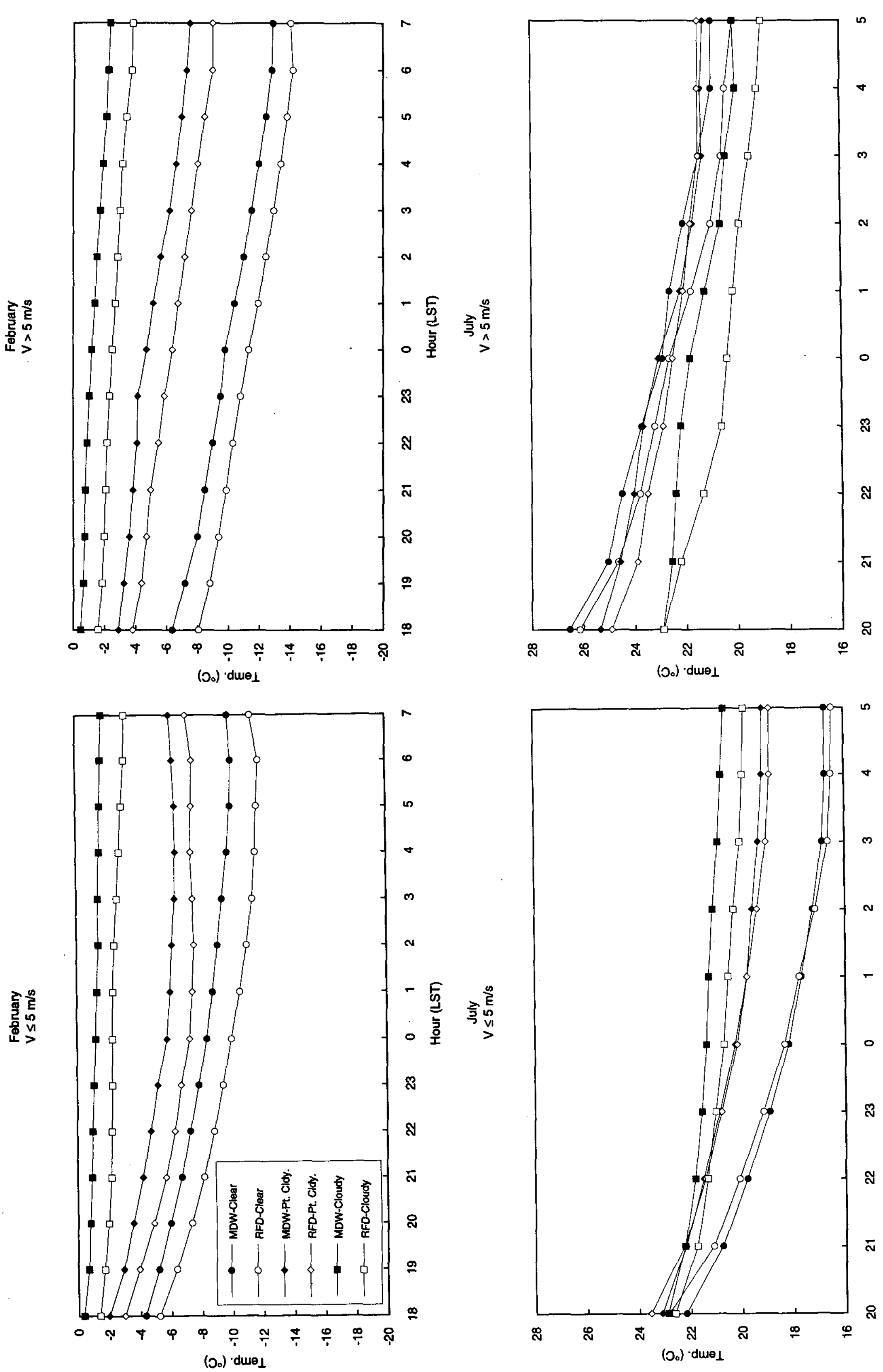

FIG. 5. Mean hourly temperatures for Chicago and Rockford, Illinois, for the indicated wind and cloudiness conditions.

TABLE 2. Mean cooling rates for Atlanta and Athens (1961–90). The cooling rates are presented as mean temperature differences (K) between the hours indicated. For example, ATL cools an average of 6.39 K between 1800 LST and 2400 (midnight) when the sky is clear and the winds are light in February. Here α is the statistical significance for the difference in the two means to its left. It indicates whether or not the two cities cool at a different rate (see text). Here N is the number of nights in the 30-yr period when the same cloud and wind conditions were observed in both cities.

	Clear						Partly cloudy						Cloudy					
	$V \leq 5$			$V > 5$			$V \leq 5$			$V > 5$			$V \leq 5$			$V > 5$ m^{-1} s		
Hour	ATL	AHN	α	ATL	AHN	α	ATL	AHN	α	ATL	AHN	α	ATL	AHN	α	ATL	AHN	α
February																		
N		87			51			35			21			63			85	
1800–2400	6.39	7.28	0.001	5.90	6.05	—	5.24	5.07	—	5.56	6.05	—	2.59	2.60	—	2.16	2.07	—
0000–0700	2.66	3.18	0.02	3.50	3.41	—	1.46	1.92	—	3.63	3.33	—	0.93	0.92	—	1.90	1.48	—
1800–0700	9.05	10.45	0.001	9.39	9.46	—	7.02	7.97	—	8.37	8.40	—	3.46	3.53	—	4.06	3.55	—
July																		
N		109			51			84			9			62			22	
2000–2400	6.18	7.24	0.001	5.45	6.64	—	4.77	5.55	0.05	4.26	4.59	—	3.93	3.86	—	3.55	2.88	—
0000–0500	2.60	3.06	0.01	2.02	1.87	—	1.72	1.84	—	1.06	1.00	—	0.85	1.08	—	0.98	0.67	—
2000–0500	8.78	10.30	0.001	7.47	8.51	—	6.49	7.39	0.05	5.31	5.59	—	4.78	4.94	—	4.53	3.55	—

ing curves look like Fig. 2. Because it is warmer under cloudy conditions, increased air conditioning in Chicago could be the explanation of this difference, but cloudy conditions are only slightly warmer than partly cloudy conditions.

Under light-wind conditions, there is a general tendency for cities, large or small, to cool less over night under cloudy conditions than under clear conditions, but the relative temperatures can be different. In most cases, it is cooler under clear conditions than under cloudy conditions, at least by sunrise, but the reverse is true in Georgia in the summer. It is interesting that during the summer, in the Southeast, temperatures fall to near the dewpoint in the early morning regardless of cloud conditions, which indicates the importance of water vapor as a greenhouse gas. It is also interesting that the population-based estimate of the temperature difference between the cities is about 5 K for both city pairs, yet only the Chicago–Rockford pair comes close to this value. The mean difference between Atlanta and Athens at night is nearly zero.

Now, consider the strong-wind situation (Figs. 4b, 4d, 5b, and 5d). The cooling curves are less smooth than in the light-wind case, in part because of smaller sample size (see below). The general pattern of the curves is not unlike the light-wind situation, but there are some interesting reversals. For example, in July in northern Illinois, it is warmer under cloudy conditions for light winds but colder under cloudy conditions for strong winds. This probably has to do with differing synoptic situations causing cloudiness during winter and summer. Another interesting reversal is that in Georgia under strong-wind conditions there is a tendency for Athens to be warmer than Atlanta.

As explained in the appendix and illustrated in Fig. 2, a city with smaller thermal inertia should cool faster at night than one with larger thermal inertia. This should be true regardless of the temperature at sunset. Three temperature differences were used to estimate the cooling rates. One difference represented the cooling during the whole night. It is the difference in temperature near sunset (1800 LST in winter, 2000 in summer) and near sunrise (0700 in winter, 0500 in summer). Because the temperatures fall more rapidly before midnight than afterward, the temperature differences between sunset and midnight and between midnight and sunrise were also calculated. Table 2 shows the average temperature differences for these three time periods for Atlanta–Athens; Table 3 is for Chicago–Rockford. (Note that the number of cases N during the 30 Februarys or 30 Julys when the cloud and wind condition were the same in each city are indicated in Tables 2 and 3.)

Student's t-test for a difference in means (see Essenwanger 1986, 271) was used to determine whether the differences in nocturnal cooling rates between the larger city and the smaller city are statistically significant. A two-sided test was applied. The null hypothesis was that the small city and the large city have the same cooling rate. The significance level α (also shown in Tables 2 and 3) is the probability that a difference in cooling rates could have occurred randomly. It is customary to accept statistical significance when $\alpha \leq 0.05$. In Tables 2 and 3 the α value is listed when it meets this criterion; otherwise a dash is placed in the α column. In other words, when a number appears in the α column, the two cities appear to cool at different rates and, therefore, appear to have different thermal

TABLE 3. Mean cooling rates for Chicago and Rockford (1961–90). Same as Table 2 except MDW—Chicago and RFD—Rockford.

	Clear						Partly cloudy						Cloudy					
	$V \leqslant 5$			$V > 5$			$V \leqslant 5$			$V > 5$			$V \leqslant 5$			$V > 5$ m^{-1} s		
Hour	MDW	RFD	α	MDW	RFD	α	MDW	RFD	α	MDW	RFD	α	MDW	RFD	α	MDW	RFD	α
February																		
N	115			43			67			28			133			121		
1800–2400	4.05	4.73	0.01	3.43	3.27	—	3.83	4.29	—	1.84	2.58	—	0.87	0.90	—	0.72	0.93	—
0000–0700	1.45	1.34	—	3.10	2.74	—	0.25	−0.15	—	2.79	2.58	—	0.47	0.87	—	1.18	1.29	—
1800–0700	5.50	6.07	—	6.54	6.00	—	4.08	4.14	—	4.63	5.15	—	1.35	1.77	—	1.90	2.23	—
July																		
N	285			10			133			7			107			14		
2000–2400	4.01	4.52	0.001	3.62	3.50	—	2.87	3.37	0.01	2.29	2.40	—	1.53	1.94	0.03	1.07	2.49	—
0000–0500	1.45	1.89	0.001	1.95	2.52	—	1.12	1.33	—	1.79	1.03	—	0.74	0.84	—	1.71	1.39	—
2000–0500	5.46	6.41	0.001	5.57	6.02	—	3.99	4.70	0.01	4.07	3.43	—	2.27	2.77	—	2.78	3.88	—

inertias. Conversely, when a dash appears in the α column, the two cities appear to have the same thermal inertia.

When the sky was clear and the wind was light, at least one of the time periods (sunset–sunrise, sunset–midnight, or midnight–sunrise) shows a statistically significant difference in the cooling rate between the small city and the large city. This indicates that thermal inertia is an important parameter in nocturnal cooling rates.

When the wind was stronger than 5 m s^{-1}, no statistical significance was found in the large–small city cooling rate differences. Wind, therefore, "disrupts" the normal nocturnal cooling by eliminating or lessening the normal urban–rural or large city–small city differences. This result makes physical sense, because strong winds advect rural characteristics into the city, thus mitigating urban influences. Strong winds also promote vertical mixing, thus lessening the surface cooling.

Clouds also modify the urban warming effect, as indicated by the large city–small city cooling rates. For light winds, all four of the clear cases (2 city pairs × 2 months) showed significant differences in the cooling rates of the two cities. Only two of the four partly cloudy cases showed significance, and only one of the four cloudy cases showed significance. It is also noted that all of the significant cloudy and partly cloud cases occurred in July, not February. Clouds tend to disrupt nocturnal cooling by emitting infrared radiation downward where it is absorbed by the surface, thus partially compensating for surface radiative loss, slowing nocturnal cooling, and therefore lessening the difference between large and small city cooling rates.

To check these results, a more traditional analysis was performed. Maximum, minimum, and the difference between maximum and minimum temperature in Atlanta were compared with those at three rural cooperative stations (Fig. 3) for Februarys in the years 1988–92. The data were classified by the cloud cover in Atlanta; the identical cloud cover was assumed to apply to all of the cooperative stations. The data were not classified by wind speed. It was assumed that the maximum and minimum occurred at the "normal" times around 1400 and 0700 LST, respectively. The results of this analysis are shown in Table 4. Briefly, no significance was found in the February urban–rural maximum temperature differences. The minimum temperatures showed substantial significance, which increased as cloudiness decreased. This finding reinforces the results of the paired-city study above.

5. Conclusions

The new "city pair" technique presented in this paper is a substantial improvement over previous techniques, which use only daily maximum and minimum temperatures for studying the thermal characteristics of large urban areas. It is also easily applied using newly available datasets on CD-ROM.

Using the technique, it has been shown statistically that strong winds and clouds disrupt the normal thermal-inertia-driven nocturnal cooling pattern in which small cities (or rural areas) cool more rapidly than larger cities (or urban areas). This does not mean that cloudiness destroys urban–rural temperature differences. It means that one must be careful about extrapolating either magnitudes or patterns of urban–rural temperature difference observed by satellites under clear sky conditions to partly cloudy or cloudy conditions. Readers may want to compare the results presented here with the results of the METROMEX study around St. Louis (Changnon 1981) and with Landsberg (1981).

TABLE 4. Comparison of Atlanta with rural stations in February (1988–92). MAX—maximum temperature (°C), MIN—minimum temperature, DIFF—the difference between maximum and minimum temperatures, which is an index of the overnight cooling. ATL—Atlanta, DAL—Dallas, NEW—Newnan, EXP—Experiment. Skycover (in tenths) is the average from 1800 to 0700 LST for Atlanta: clear < 2.9, cloudy > 7.9, partly cloudy between. Here α is the statistical significance of the difference in the mean values for Atlanta and the rural station to its left (see text).

	ATL	DAL	α	NEW	α	EXP	α
Clear ($N = 47$)							
MAX	12.83	12.42	—	13.81	—	13.07	—
MIN	0.01	−3.99	0.001	−2.37	0.01	−1.90	0.03
DIFF	12.82	16.41	0.001	16.18	0.001	14.97	0.01
Partly cloudy ($N = 31$)							
MAX	16.05	14.82	—	17.44	—	16.09	—
MIN	5.79	1.51	0.005	3.94	—	3.32	0.03
DIFF	10.25	13.31	0.01	13.50	0.001	12.77	0.04
Cloudy ($N = 62$)							
MAX	15.79	15.39	—	16.98	—	16.13	—
MIN	6.27	3.74	0.02	6.43	—	5.18	—
DIFF	9.51	11.65	0.03	10.55	0.05	10.94	—

The sample size in this study, two city pairs, is too small to draw firm conclusions about the effect of clouds on the urban warming effect. Because of its importance in the global warming debate, however, the authors suggest that more research on this subject is warranted. Specifically, additional city pairs should be studied, and additional, cloud-classified urban–rural studies should be done. Finally, modeling studies in which controlled experiments with different cloud cover can be performed appear useful.

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APPENDIX

Schematic of the Variation of Urban–Rural Temperatures Due to Different Thermal Inertias

To create the schematic diagram (Fig. 2) of urban–rural (or large city–small city) temperature variation due to thermal inertia differences, the simplest possible radiative model was constructed. The time rate of change of temperature was assumed to be due to an imbalance between the outgoing longwave radiation from a blackbody and absorbed solar radiation:

$$C\frac{dT}{dt} = -\sigma T^4 + S(t), \tag{A1}$$

where C is the thermal inertia (heat capacity), σ is the Stefan–Boltzmann constant, T is the absolute temperature, and $S(t)$ is the absorbed solar radiation. Here $S(t)$ was modeled as a cosine function during the day, peaking at 1200 local time and decreasing to zero at 0600 and 1800 local time; at night $S(t)$ was zero. This approximates spring or fall conditions. Equation (A1) was numerically integrated for many days until equilibrium was reached. The large city (or urban area) was modeled as having a thermal inertia C of 1.0 MJ $\mathrm{m}^{-2}\ \mathrm{K}^{-1}$, and the small city (or rural area) was modeled as having 0.8 MJ $\mathrm{m}^{-2}\ \mathrm{K}^{-1}$.

Figure 2 shows the results of this simple model. *Note that Fig. 2 is* not *to be interpreted quantitatively; thus, there is no vertical scale in the figure.* The model demonstrates schematically what has been known for many years: other effects being equal, cities (areas of higher thermal inertia) cool more slowly at night and warm more slowly during the day than rural areas (with lower thermal inertia).

Note that in this simulation in which the sky has been cloud-free for many days and in which there is no wind or other disturbing influences, the mean temperature is essentially the same in both cities, which means that the smaller one has a higher maximum and a lower minimum than the larger city. In real situations where clouds come and go, the two cities can have higher or lower daily mean temperatures (or maximum or minimum temperatures), but the smaller city (or the rural area) should always cool faster at night because the cooling rate is inversely proportional to the thermal inertia. In other words, if one wants to study thermal inertial differences, one should examine cooling rates rather than temperature differences.

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