further observations of the urban heat island in a small city

Richard J. Kopec
University of North Carolina
Chapel Hill, N. C.

Abstract

Studies of the heat island effect produced by urban centers have focused almost exclusively on large cities. Knowledge concerning the extent to which small places, i.e., towns with less than 50,000 people, exert a similar effect on their atmospheric environment is limited in this country. Only at Palo Alto, Calif., and Corvallis, Oreg., have such studies been conducted. This paper reports the results of temperature measurements and their spatial patterns taken by mobile traverses during the course of three seasons at Chapel Hill, N. C., and compares the heat island effect identified in this small university town with previous studies. The comparison shows a similarity among derived data which lends support to the ranking of urban places by population size as a climatic parameter.

1. Introduction

The "heat island" phenomenon associated with urban places has received increasing attention from meteorologists and climatologists during the past twenty-five years. That cities of significant population numbers generate, under specific atmospheric conditions, a dome of warmer air above the more densely populated and structured areas within their regional boundaries has been observed and documented since the early nineteenth century. The air temperature differences between city centers and their outskirts were recognized and understood for many years, but it was not until the relationships between the cities' heat island and the pathogenic and pernicious effects of air pollution were made evident that the study of this urban phenomenon was stimulated and accelerated.

In the years following World War II, a number of studies dealing with the urban heat island have been produced. Among these are included the notable works of Sundborg (1951), Duckworth and Sandberg (1954), Kratzer (1956), Landsberg (1956), Mitchell (1961), Chandler (1962) and Woollum (1964). In these works, the cities under study were generally industrial centers having relatively large populations. The urban heat island is most pronounced and therefore best studied in such places. The only exceptions to this pattern of urban climate study in the United States were those conducted at Palo Alto, Calif. (Duckworth and Sandberg, 1954), and Corvallis, Oreg. (Hutcheon *et al.,* 1967). Both cities are comparatively small university centers and both exhibited temperature patterns peculiar to their population size and service function, which contrasted significantly with larger cities similarly studied. Aside from these studies, no others have been conducted or reported relating to small urban places. This report is a further contribution to the sparse literature dealing with the horizontal thermal aspect of the atmosphere over small urban centers. It is the first report on this subject from the southeastern United States.

This study shows that 1) the nocturnal heat island is evident not only in association with small cities but more explicitly with small, non-industrial cities having low population densities and low-profiled, linearly arranged central business district (CBD); 2) only under critical limits of cloud cover and wind velocity will a heat island develop over such towns; 3) significant local relief tends to exaggerate the heat island effect where CBD's and other causal factors are situated at high elevations, and tends to obscure the effect when located at lower elevations; and 4) mobile temperature observations made over a 1-1/2 hour period during the night will not necessarily invalidate the study of small, dispersed urban centers by incorporating a temporal factor.

2. Site description and study method

The towns of Chapel Hill and Carrboro comprise one small urban place. Chapel Hill, the larger of the two, is a university town whereas Carrboro, appended to Chapel Hill's west side, is primarily a market town. Located in the piedmont of North Carolina, the combined communities exist in a rural setting with the city of Durham (98,000), their nearest neighbor, about ten miles to the northeast. An estimated population of 24,900 citizens and students reside within the corporate boundaries of the twin communities. The density averages 2650 people per square mile and the growth rate index of Chapel Hill is 1.34 (Mitchell, 1961). No manufacturing industries exist within or proximal to the towns, and allowing for some contamination from the coal-fired university heating plant and the usual high percentage of automobiles attendant with university towns, the atmosphere above Chapel Hill–Carrboro has a relatively low pollution count.

The main business district for both towns is strung along one street for one mile. Aside from church spires, isolated high-rise dormitories and three-to-five storied academic buildings, business and residential structures are generally three levels or less in height. Only along the CBD is spacing between buildings "tight." Otherwise, distances among university and residential structures are relatively large and vegetation within these spaces is profuse. Local relief is prominent, about 400 ft in the study area, from approximately 250′ to 650′ above sea level. The topography is analogous to three spurs or fingers spread apart and pointing due eastward separating the higher western half of the study area from the lower eastern section. The towns' built-up region and the university proper occupy the middle spur from which private residences spill outward (see figures).

To study the pattern of horizontal temperatures in and around the Chapel Hill–Carrboro area, a SAAB automobile was equipped with a Westemp resistance thermometer placed inside a Climet radiation shield and mounted to the right-front bumper 1-1/2 meters above the road. The indicator within the auto was read by a student having a map with the 51-mile itinerary inked in. The student kept a running log of temperature observations while the author, very seldom hampered by traffic since the traverses were conducted between the hours of 2200 and 2330, moved along at an average speed of 33 mph. The quick response sensor provided readings representative within 48 ft of their occurrence when the automobile moved at average speed. This distance was acceptable and commensurate with the scale of the map used. About 580 recordings were taken per each traverse.

The traverse was designed to obtain both urban and rural horizontal temperatures. The path of the itinerary crossed over itself at several points as a check on temperature change due to time. A further check on the time parameter was gained when the traverse ended where it began allowing for a comparison of temperature at 2200 and 2330. Parenthetically it can be stated that temporal temperature change during the traverse never amounted to more than one degree at check points along the route or two degrees between starting and ending times, and even these contrasts were seldom experienced.[1] The time for the study was selected in accordance with the literature which reports the urban-rural temperature contrast to be most pronounced between the hours of 2200 and 2400.*

Daytime temperature observations were attempted but discontinued. The author found that, aside from the dampening effect imposed on urban-rural temperature contrasts by critical limits of wind velocity and cloud cover, daytime attempts to record temperature patterns were frustrated by constant sun-shade changes along the roads traveled. The effect of sun-shade changes brought about by trees, buildings and other roadside obstructions resulted in continuous fluctuation of the indicator needle and made daytime temperature differences between Chapel Hill–Carrboro and their environs obscure and impossible to interpret.

A dozen traverses were made over a nine-month period during the winter, spring, and summer seasons. Of these traverses, the February 10th, May 28th, and September 15th, 1969, samplings are given here to represent their respective seasons. Several traverses were begun and then aborted when recordings indicated an insignificant contrast between town and suburban temperatures. On such occasions, temperatures ranged less than 3° along 50% of the traverse and indicated no definite spatial pattern. It was found that the heat island effect was evident at those times when sky cover was less than 2/10ths and wind velocities were under five knots.** Tolerances beyond these values may permit the heat island phenomenon to exist over the study area but the range between those conditions which permitted or did not permit its existence was not fully or precisely explored. Optimum atmospheric conditions were estimated to be attendant for all twelve observations.

For the examples illustrated, the study area was under the influence of cP air masses. On February 10th, the nearby weather station at Raleigh–Durham reported a relatively low dew point, a sky cover of 2/10ths, and zero wind velocity.[2] On May 28th and September 15th, the station reported completely clear skies with wind velocities of 4–5 knots and high dew point recordings. Ground fog was observed in several places on the 15th. Conditions at Chapel Hill–Carrboro were visually estimated as calm and clear when measurements began.

3. Results

Examination of Figs. 1, 2 and 3 shows that the isothermal pattern is both similar and consistent through time. Since nocturnal inversions existed in each case, temperatures higher than the mean are associated with higher elevations, and lower temperatures with low elevations.[3] However, the effect of Chapel Hill–Carrboro on air temperature is evident in that the highest temperatures recorded in every case have been inside the corporate boundaries of Chapel Hill, and the region of high temperatures is largest and encompasses the towns in a pattern approximate with highest population densities. Because the towns and the university are located

[1] All temperatures are given in degrees Fahrenheit unless otherwise specified.

* See, for example, Duckworth, F. S., and J. S. Sandberg, 1954: The effect of cities upon horizontal and vertical temperature gradients, *Bull. Amer. Meteor. Soc.*, **35**, 198–207; and Chandler, T. J., 1962: London's urban climate, *Geogr. J.*, **128**, 279–298.

** Visual estimates were made of prevailing atmospheric conditions and then checked against local climatological data as recorded by the Raleigh–Durham Airport Weather Station (20 miles to the southeast) for comparison and verification.

[2] These data are those reported at 2200 hours.

[3] Two types of isolines are given on the maps. The solid line represents temperatures above the mean. The dotted line represents temperatures lower than the mean.

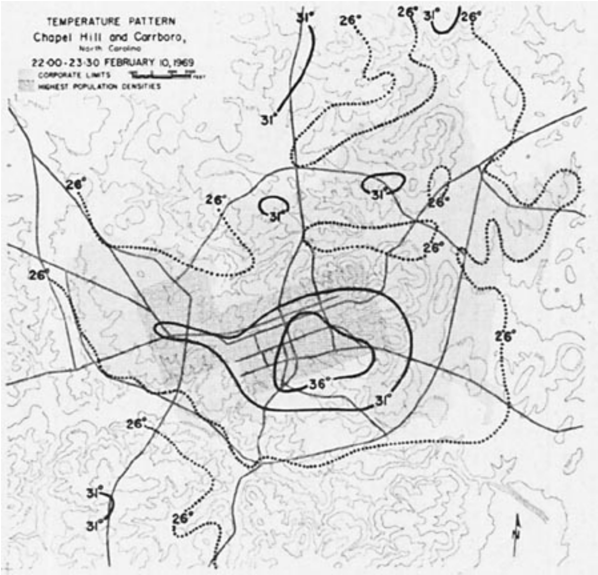

Figure # 1

FIG. 1.

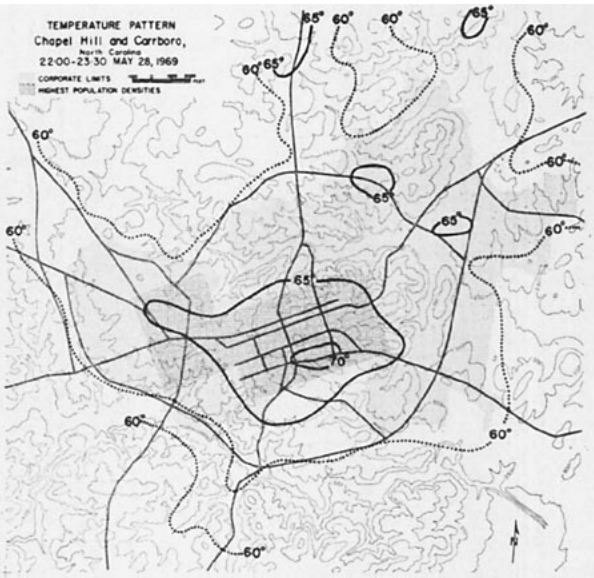

Figure # 2

FIG. 2.

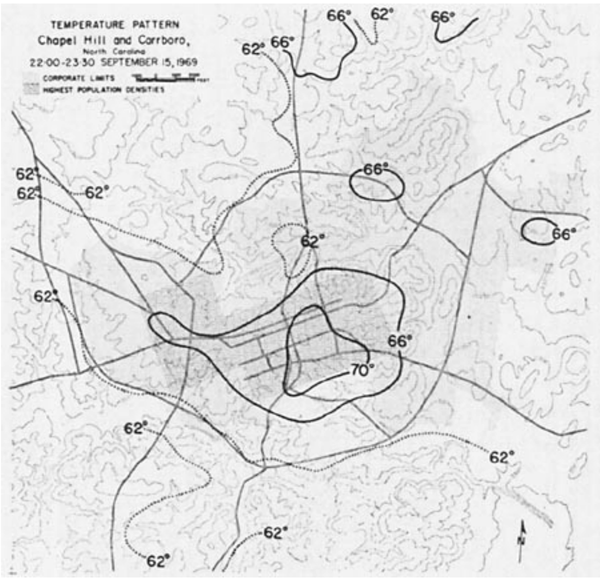

Figure # 3

FIG. 3.

on higher elevations, the heat island effect is best seen in contrast with the western half of the map. Here elevations are as high as those within the heat island yet temperatures are roughly 8°–10° lower.

Nowhere do the regions of higher temperatures induced solely by altitude approach the temperature maxima generated by the CBD and the large university buildings. There is at least a 5° difference between the two. In fact, the highest temperature recorded for all the completed traverses was found on the UNC campus in the vicinity of the hospital complex. At times, equally high values were recorded along the CBD or adjacent to dormitories, but the hospital site was consistently the location of maximum temperatures.[4]

Table 1 collates data derived for Figs. 1–3. Both average values and value ranges are provided to allow comparison of representative data with data obtained from all observations made during the study period.

TABLE 1.*

	10 February	28 May	15 September	Mean for all observations	Range of values
D_t	14°	14°	11°	13.5°	11°–16°
$R/\Delta T$	0.095	0.076	0.099	0.086	0.070–0.099
A, mi^2	1.36	1.50	1.66	1.52	1.31 –1.76

* *Definition of Symbols:*

D_t —Difference between the highest and lowest temperatures observed along the traverse.

$R/\Delta T$ —The minimum distance (in miles) that a 1F change in temperature is recorded, measured from the center of the heat island outward.

A, mi^2—That area measured around the urban center bounded by the isotherm two degrees (F) higher than the mean determined by the D_t.

The urban temperature differential (D_t) and the differential intensity values ($R/\Delta T$) derived for Chapel Hill–Carrboro are consistent with the values presented in the Palo Alto and Corvallis studies. For Palo Alto (33,000 in 1954) comparable values (under ideal atmospheric conditions) were 12.6° for D_t and 0.054 for $R/\Delta T$. Similarly, Corvallis provided temperature ranges

[4] Temperatures were not recorded in the immediate vicinity of the heating plant.

of 10° for the two nights observed and differential intensity values of 0.150 and 0.075. 'A' values averaged 1.02 mi² for Palo Alto.[5] Since the populations are similar in numbers, the generalization that cities of similar population size exhibit similar thermal characteristics appears valid.

The values for Palo Alto are comparable to those for Corvallis and Chapel Hill–Carrboro only when the figures recorded under equally optimum meteorological conditions are used. Those figures listed by Duckworth and Sandberg as representative provide indicative rather than precise values, and identify mean rather than optimum conditions. Accordingly, in contrast with the figures given for Palo Alto, the values for Chapel Hill–Carrboro, although analogous, are greater in all categories. Based on the premise that cities having larger built-up areas and larger populations show greater D_t, $R/\Delta T$, and 'A' values, it is apparent that since Palo Alto is the larger city in both population and dimension some other factor(s) should be considered here to explain these small but significant differences. One or more of the following factors may be applicable: 1) study area size; 2) amount of local relief; 3) compactness of the business district; 4) macroclimate; 5) degree of aerodynamic "roughness"; and 6) vegetation type, height, and density.

The size of the study area for Chapel Hill–Carrboro included about thirteen square miles of which 9.38 mi² represented the area within the towns' boundaries. For Palo Alto, measurements were obtained from a study area of six mi². This difference in study area size enhances the probability that the larger study area will provide lower temperature minima thereby increasing the urban temperature differential. With a nighttime inversion in effect, the farther temperature observations are conducted from the heat island center, the more likely extreme temperature minima will be encountered. An increased D_t will also affect the size of that region having temperatures at least 2° higher than the mean established by the D_t, viz, the 'A' measurement. Larger D_t values will translate into larger 'A' values.[6] This is true not only in this instance but when comparing values among cities of conspicuously dissimilar sizes.[7]

Since the measurements being compared for Palo Alto and Chapel Hill–Carrboro were obtained under stable conditions, significant variation in local relief will affect D_t values and horizontal temperature gradients. This fact will be evident especially where a town's business district is located on an area of considerable relief. At such a place, $R/\Delta T$ figures will be low indicating a relatively rapid change in temperature over horizontal distance. Also, the compactness of the business district undoubtedly affects the horizontal temperature gradient. Greater homogeneity of air temperature will be apparent where business districts are circular, rectangular or square rather than linear. This is evident where large urban centers have been studied. Chapel Hill–Carrboro with its lenticular business district showed relatively rapid change in temperature away from its CBD which resulted in comparatively low $R/\Delta T$ values.

While cities of all sizes create their own specific climate apart from the regional macroclimate in which they exist, nevertheless, the specificity of an urban microclimate is dependent, in the first instance, upon the larger climate. It has been shown that among cities of like size, those located in lower latitudes exhibit a smaller urban temperature differential than cities located in the middle latitudes. Where winters are mild or virtually non-existent, temperature minima are seldom very low and do not provide the milieu for large urban-suburban temperature contrasts.[8] Similarly, a region's annual and diurnal temperature ranges will be determined by its degree of continentality. Middle latitude cities existing where continentality is a significant control on the macroclimate must balance more severe winters by producing more artificial heat.[9] The escape of this heat (and its concomitant pollutants) to the atmosphere will result in greater temperature contrasts between these cities and their cold suburbs. Therefore, Chapel Hill–Carrboro, located in a continentally-controlled climatic region (Cfa) should show slightly greater D_t and 'A' values than Palo Alto and Corvallis where milder, maritime climates exist (Csb and Cfb).

Another consideration is aerodynamic roughness which is defined as the resistance offered to wind velocity by surface obstacles such as hills, buildings, trees, etc. The height and density of buildings in a city primarily determine its degree of roughness which commonly increases with city size. For cities having a low roughness factor, the existence of a heat island requires low wind velocities. Conversely, a high roughness factor contributes to a reduction of surface wind velocities thereby inducing greater urban temperature differentials.[10] Because Palo Alto had a higher roughness index in 1954 than Chapel Hill–Carrboro has now, it is expected that its D_t values should be larger. This is not the case.

However, the primary importance of urban structures in promoting aerodynamic roughness can be abetted, offset, or nullified by another significant consideration, namely, vegetation type, height, and density. It is reported that vegetation serves similarly as urban structures in reducing wind flow in and about the city.[11]

[5] 'A' values were not reported for Corvallis.

[6] The efficacy of D_t and 'A' values as yardstick measurements will require some agreement on the limits of study area size.

[7] Duckworth and Sandberg, 1954, *op. cit.*, p. 203.

[8] Kratzer, P. A., 1956: The climate of cities. Translated by the American Meteorological Society, Boston, Mass., p. 66.

[9] It is estimated that up to 50% of the energy in the winter atmosphere over cities is derived from artificial sources. Geiger, R., 1966: *The Climate Near the Ground.* Harvard University Press, Cambridge, Mass., p. 489.

[10] It is reported that large cities reduce prevailing wind velocities from 12% to 50%. Landsberg, H. E., 1956: *The Climate of Towns. Man's Role in Changing the Face of the Earth.* Chicago University Press, Chicago, Ill., pp. 602–603.

[11] Munn, R. E., 1966: *Descriptive Micrometeorology.* Academic Press, New York, p. 205.

Thick, towering vegetation has the capacity to substitute for a city's lack of tall buildings and provide a resultant effect on wind velocity and turbulence comparable to that produced by a city having a high roughness index. Chapel Hill–Carrboro has abundant vegetation within its boundaries, and equally important, most of this vegetation is coniferous (see Fig. 4). Consequently, the influence of vegetation on wind speed is quite consistent here unlike those urban places where deciduous trees exert a seasonal control.

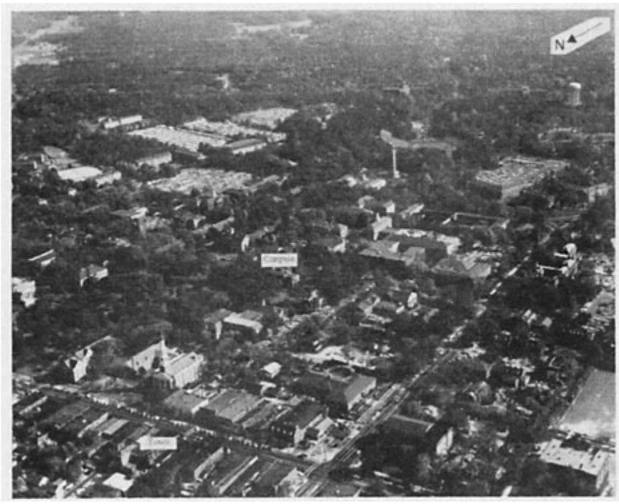

FIG. 4.

4. Conclusion

The need for more and better data on the temperature fields over cities has been recorded and declared urgent throughout the literature. However, the term "city" should not always be construed to mean large urban center. It is recognized that the need for temperature studies is more important for cities of higher rank since their problems with air circulation and pollution are greater. But small urban places should not be altogether ignored. They, too, have their atmospheric problems. And, although they are analogous in many ways to their larger cousins, the temperature fields they produce are peculiar to their own unique characteristics and for that reason must be studied. Therefore, better design and planning of our cities must include the temperature profiles of small as well as large urban places.

Even though studies such as this one are two-dimensional and represent a single facet of the complex budget of energy and mass associated with cities of any size, nevertheless, where monies for instrumentation and assistance are limited, they provide a positive contribution, however slight, to our knowledge of the small city's influence on its atmospheric environment.

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correction

The date of the Conference on Cloud Physics at Ft. Collins, Colo., was printed incorrectly in the boxed heading on page 557 of the June BULLETIN. It should be August 24–27, 1970.

announcements

New film

Magnetosphere, a 30-minute, color film, defines this region of the upper atmosphere by location and behavior and describes the efforts of scientists to establish more accurate concepts about it and its relation to other phenomena. Following a delineation of the best theoretical pattern of the magnetosphere according to present knowledge, viewers learn how scientists became aware of the presence of this region. A variety of instruments and techniques being used to study the magnetosphere are mentioned. The film then explains how the magnetosphere differs from the rest of the atmosphere and explains its significance to space probes. The film may be purchased for $220 or rented at $16.00 from McGraw-Hill Films, 327 W. 41st St., New York, N. Y. 10036. It is a part of the Earth and Sky Series, produced by the National Academy of Sciences.

(More **announcements** on page 634)