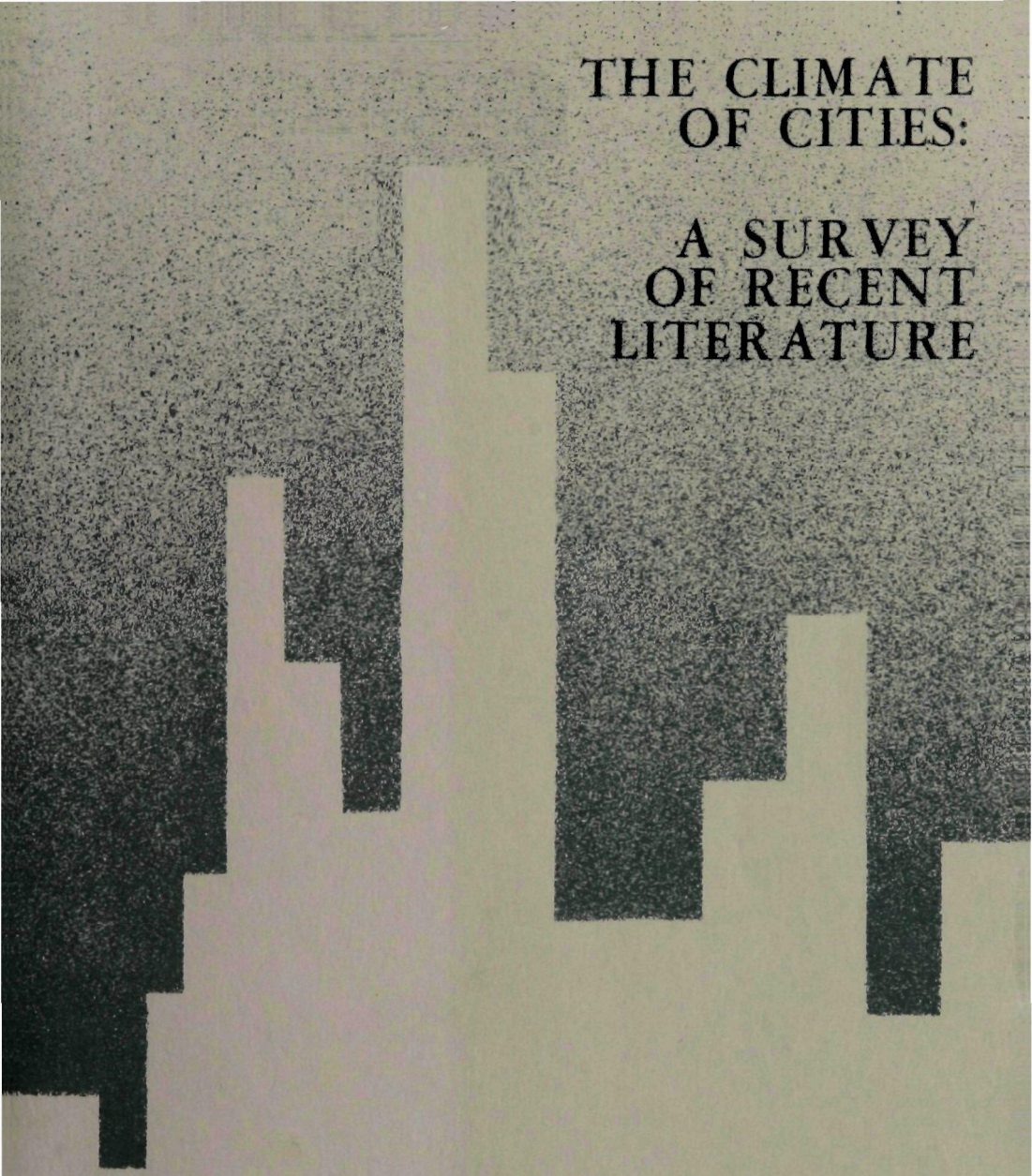
THE CLIMATE OF CITIES:

A SURVEY OF RECENT LITERATURE



U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Consumer Protection and Environmental Health Service

THE CLIMATE OF CITIES: A SURVEY OF RECENT LITERATURE

by

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U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
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ABSTRACT

The climate of a city differs from that of the rural areas surrounding it, and an increasing amount of scientific research is devoted to comparative studies of urban and rural climates. This report is a survey of the literature on city climatology, with emphasis on that written since the series of articles published by Dr. H. Landsberg, from 1956 to 1962. Those meteorological aspects of urban climate that have been most frequently investigated are discussed herein; they are temperature, humidity, visibility, radiation, wind, and precipitation.

KEY WORDS: urban climatology, climate of cities, urban-rural climate differences, literature survey, temperature, precipitation, humidity, visibility, solar radiation, wind speed and direction.

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THE CLIMATE OF CITIES: A SURVEY OF RECENT LITERATURE

SUMMARY

This review of urban-rural comparative studies discusses many aspects in which the climate of a city differs from that of the "natural" rural areas surrounding it. The several papers by Landsberg, which have served as the standard review of urban climate, provide the basis for this summary of city-country meteorological differences; his results, which were presented in tabular form in his articles of 1960 and 1962, are summarized in Table 1. Research in the decade since Landsberg's work has concurred with almost all the values in his table; however, additional aspects of urban climatology have been studied, and more detailed knowledge is now available.

Table 1. CLIMATIC CHANGES PRODUCED BY CITIES (AFTER LANDSBERG, 1962)

Element	Comparison with rural environs
Temperature	
Annual mean	1.0 to 1.5 °F higher
Winter minima	2.0 to 3.0 °F higher
Relative humidity	
Annual mean	6 % lower
Winter	2 % lower
Summer	8 % lower
Dust particles	10 times more
Cloudiness	
Clouds	5 to 10 % more
Fog, winter	100 % more
Fog, summer	30 % more
Radiation	
Total on horizontal surface	15 to 20 % less
Ultraviolet, winter	30 % less
Ultraviolet, summer	5 % less
Wind speed	
Annual mean	20 to 30 % lower
Extreme gusts	10 to 20 % lower
Calms	5 to 20 % more
Precipitation	
Amounts	5 to 10 % more
Days with < 0.2 inch	10 % more

Recent studies of urban-rural temperature differences have essentially supported the results of Landsberg's summary. However, the emphasis of these papers has now shifted to such considerations as the effect of city size on heat island magnitude. Small cities and even small building complexes have been shown to create nocturnal heat islands, and urban-rural differences in temperature have been shown to depend strongly on local microclimatic conditions. In studies of the vertical distribution of temperature over a city, such phenomena as multiple elevated inversions and a downwind urban heat plume have been observed. Finally, additional research on the determination of meteorological parameters important for heat island formation has shown that the size of urban-rural temperature differences is highly correlated with the suburban low-level temperature lapse rate.

Although the recent investigations of relative humidity agree with those of Landsberg, such studies now consider absolute humidity as well. Chandler (1965, 1967) adequately summarizes the results of such papers. The relative humidity of towns has been shown to be almost always lower than that of adjacent rural areas, whereas urban-rural differences of absolute humidity show no such clear-cut relationship. Although a weak, general tendency for drier air is apparent within the city, the frequencies of occurrence of urban vapor pressures above and below those of the country are almost equal.

Landsberg's conclusions on dust particle concentrations and the occurrence of fog also are generally valid. However, some recent evidence suggests that the frequency of very dense fog in the city center is less than that in outlying regions, possibly because of warmer urban temperatures. Other studies have shown that visibilities are improving in some cities, probably as a result of local efforts at air pollution abatement.

Recent solar radiation investigations have substantiated Landsberg's results on this subject. Additional papers have been devoted to urban-rural contrasts, and such aspects as vertical variation of the attenuation of solar radiation and hours of bright sunshine over a city have also been studied.

A modification of Landsberg's results for wind speed may be indicated by the results of a recent study by Chandler (1965). His limited data sample showed that when regional wind speeds were relatively low, speeds over London were higher than those over the countryside, and that fewer calms occurred over the city than over the country. The critical value of wind speed (which determined whether urban or rural winds were faster) usually was between 4 and 5 $m \cdot s^{-1}$, though it varied with time of day and season. New work on direction of wind flow has indicated that when conditions are conducive to heat island formation the wind flow converges toward the city.

Precipitation research has been greatly expanded since the publication of Landsberg's articles. Precipitation patterns around several cities with dense rain gauge networks have been studied, and small

increases were usually found downwind of the cities. Changnon's paper (1968) on the La Porte, Indiana, anomaly, which recorded large increases of precipitation and of days with thunderstorms and hail, has indicated the size of the possible precipitation increase that can result from man's activities. A new research effort has been directed at determining the effects of the many dust particles, produced by a city, on the development and growth of clouds. Such studies hope to show whether dust particles, which serve as condensation and ice nuclei, act to inhibit or promote rainfall and in what concentrations they are most effective.

INTRODUCTION

As metropolitan areas expand, they exert a growing influence on their climate. An increasing amount of scientific literature is being devoted to analyses of data on urban climates, often comparing urban data with data from nearby rural areas to show the differences between "natural" conditions and those influenced by man. These studies also contribute to such areas as the effects of urban environment on health, the influence of meteorological parameters on urban diffusion, and the possible global climatological consequences of increased atmospheric pollution.

The standard review of urban climate consists of the paper by Dr. H. Landsberg (1956) and his supplementary articles in 1960 and 1962. The purpose of this report is to review the recent literature in this field, primarily that in English, to note the areas of agreement and difference with Landsberg's earlier summaries and to point out the aspects of urban climatology for which more detailed information is now available. This survey concentrates on the most frequently discussed aspects of city-country climatic differences: temperature, humidity, visibility, radiation, wind, and precipitation. Also included is a discussion on urban particulate concentrations. A review of urban concentrations of various gaseous pollutants has recently been published by Tebbens (1968) and thus will not be discussed in this report.

Previous summaries of literature on urban climates include an extensive article by Kratzer in 1937 (revised in 1956 and translated into English), containing references to 533 works, and a bibliography by Brooks (1952) listing 249 references. Books by Geiger (1965) on microclimatology and Chandler (1965) on the climate of London, from which several examples are included herein, also refer to a number of other urban studies. Chandler is currently compiling a bibliography on urban climate under the auspices of the World Meteorological Organization (WMO); this bibliography will reference well over 1000 articles.

TEMPERATURE

Of all the urban-rural meteorological differences, those of air temperature are probably the most documented. That the center of a city is warmer than its environs, forming a "heat island," has been known for more than a hundred years and continues to receive considerable attention in the literature. Many aspects of a heat island have been studied, such as possible reasons for its occurrence; diurnal, weekly, and seasonal variations; relation to city size; and dependence on topography. This section reviews some of these characteristics of urban-rural air temperature relationships.

NIGHTTIME DIFFERENCES

The fact that a city is warmer than its environs is seen most readily in a comparison of daily minimum temperatures. As Landsberg (1956) pointed out, such comparisons often show temperature differences of 10 °F and occasionally differences as great as 20 °F. However, since nocturnal temperatures are dependent on topography, a fraction of these differences, sometimes a large fraction, can often be ascribed to terrain features.

Numerous measurements of urban heat islands have been made, frequently by use of automobiles to obtain many observations within a short time period. An example of a London temperature survey associated with clear skies, light winds, and anticyclonic conditions is presented in Figure 1 (Chandler, 1965). This figure shows certain features common to most heat islands. The temperature anomalies are generally related to urban morphology. The highest temperatures are associated with the densely built-up area near the city center; moreover, the degree of warming diminishes slowly, outward from the city's heart, through the suburbs and then decreases markedly at the city periphery. The effect of topography is also evident in this example. Urban warming is reduced along the Thames River, in the smaller non-urbanized valleys, and near the city's higher elevations.

Steep temperature gradients at a city's edge have been measured during clear, calm conditions at Hamilton, Ontario (Oke and Hannell, 1968),* and Montreal, Quebec (Oke, 1968). These investigators found temperature changes of 3.8 and 4.0 °C·km^{-1}, respectively, which they regarded as typical values for moderate to large cities.

*Several papers from an international conference on urban climatology at Brussels, Belgium, sponsored by the WMO, in October 1968, are mentioned in this review; although they are not generally available now, their publication as a proceedings is planned.

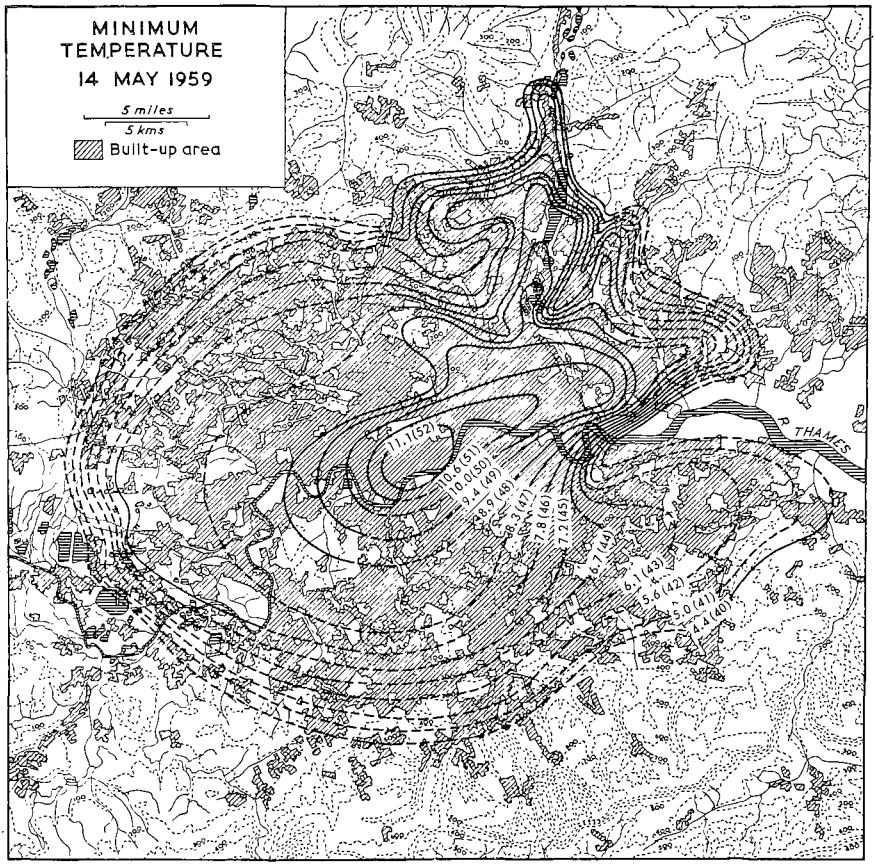

Figure 1. Minimum temperature distribution in London, May 14, 1959, in °C with °F in brackets (from Chandler, 1965).

Some recent studies have indicated that the mean annual minimum temperature of a large city may be as much as 4 °F higher than that of surrounding rural areas. Chandler (1963, 1966) reported on two studies of London, which showed differences of 3.4 and 4.0 °F in mean minimum temperatures at urban and rural sites. The first study was based on data from 1921 to 1950 for several stations in and around London; the second compared 1959 data for one downtown and one rural location and applied a correction for the difference in elevation at the stations. In another study, Woollum (1964) and Woollum and Canfield (1968) presented data for several stations in the vicinity of Washington, D. C., for a 20-year period; mean minimum temperatures for each season were approximately 4 °F higher in downtown areas than in outlying regions.

Although the city heat island as indicated by minimum temperatures can be readily detected year-around, the investigations in London by Chandler (1963, 1966) and in Reading, England, by Parry (1966) indi-

cated that the greatest temperature differences occur in summer or early autumn. Woollum (1964) also found that the mean differences between the warmest and coldest stations of his network were greatest in fall and summer, but that the greatest extreme differences between these stations occurred in winter (see also Landsberg, 1956).

DAYTIME DIFFERENCES

The heat island of a city can be detected during the day, but much less readily than during the evening. The slight daytime temperature differences observed are often difficult to distinguish from those due to the effects of topography. In some instances daytime city temperatures may even be lower than those of the suburbs. For example, Landsberg (1956) presented 1 year of data from city and airport observations in Lincoln, Nebraska, a location essentially free from complicating terrain factors. Daily maxima in the cold season showed little difference between the two sites. During the warm season, however, the airport was more frequently warmer than the downtown site. Such results are not the rule, however, and Landsberg also points out cases of daily maxima that are higher in the city. Similar examples have been given by Chandler (1963, 1966); his data showed that the annual average maximum temperatures of London were 0.6 and 1.1 °C higher than those in the outlying areas. Munn et al. (1969) also readily detected a daytime heat island at Toronto, Canada, using daily maximum temperatures.

A recent report by the Stanford Research Institute (Ludwig, 1967; Ludwig and Kealoha, 1968) presents perhaps the most comprehensive documentation of urban daytime temperatures to date. The authors made about twelve auto traverses each at San Jose, California; Albuquerque, New Mexico; and New Orleans, Louisiana, during daytimes in the summer of 1966. Although the temperature anomalies resulting from topographical influences in these cities were greater than those from the heat island, the downtown areas were approximately 0.5 °C warmer than the suburbs despite the effects of topography.

In the summer of 1967 SRI extended the study to Dallas, Ft. Worth, and Denton, Texas (population 35,000), where they made 20, 4, and 2 surveys, respectively. When the 1966 and 1967 data were combined with data from three surveys each at Minneapolis, Minnesota, and Winnipeg, Canada (Stanford U. Aerosol Laboratory, 1953a, 1953d, 1953e), * and one at London, the investigators found that for these 67 cases the city's warmest part near the downtown area averaged 1.2 °C above the typical areas of its environs, with a standard deviation of about 1.0 °C. This average value is higher than that observed by other studies, and Ludwig and Kealoha pointed out two possible reasons why investigations of the daytime heat island may underestimate its

*These reports are part of a series (1952, 1953a, 1953b, 1953c, 1953d, 1953e) which were recently declassified (1963) and describe a number of detailed observational surveys of urban temperature and diffusion.

magnitude. First, they noted that at ground level the highest temperatures of a city do not occur in the central area of tall buildings but rather near that part of the downtown area with "densely packed three- to five- story buildings and parking lots." Second, they noted that temperatures observed at suburban airports were higher than those of a true rural environment, either grass-covered or forested.

The diurnal and seasonal heat island variations discussed above are illustrated in Figure 2, taken from Mitchell (1962). This figure shows hour-by-hour monthly averages of temperature at an urban and a suburban site in Vienna, Austria. The temperature of the city is higher at night during both February and July, but this urban-rural difference is greater in July. In the daytime, however, the city-rural temperature differences are small during July and consistently small and positive during winter.

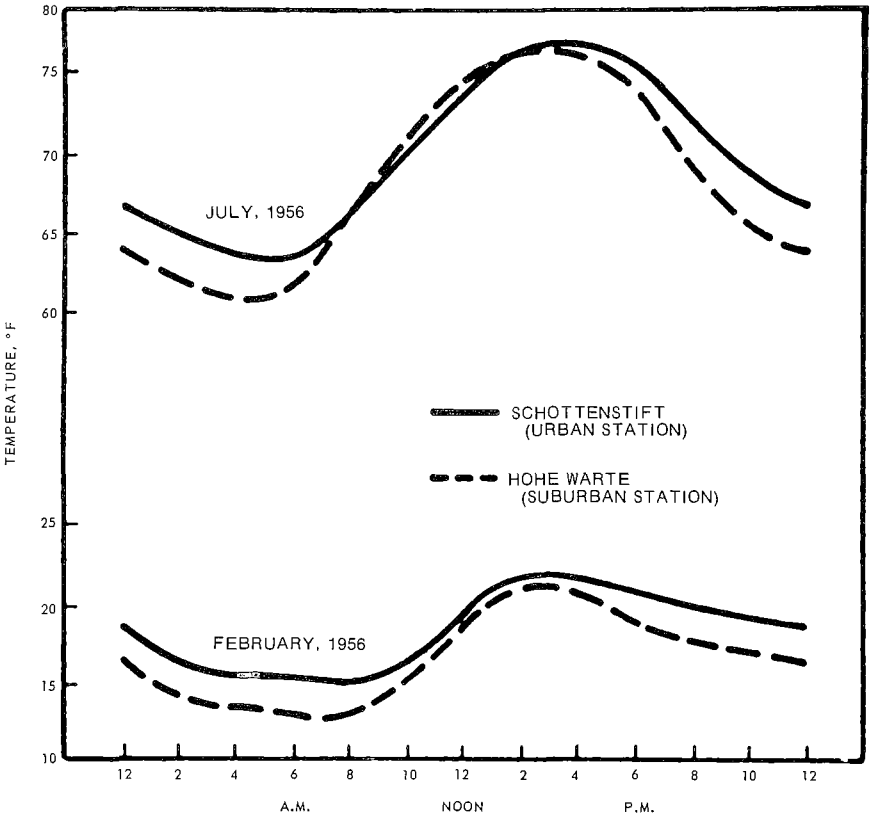

Figure 2. Diurnal variation of temperature in Vienna for February and July for both an urban and suburban station (from Mitchell, 1962).

ANNUAL DIFFERENCES

The average annual temperatures of a city and its environs, calculated from the daily maxima and minima, also reflect the presence of the urban heat island. Table 2 (Landsberg, 1960) lists the average annual urban-rural temperature differences for several large cities. To this can be added the average value for London of 1.3 °C based on the two studies by Chandler (1963, 1966). Although Woollum and Canfield (1968) do not state a specific number for the mean annual urban-rural temperature differences of Washington, D. C., their recent data for that city indicate that it should be at least 1.0 °C, after consideration of the elevation changes of more than 200 feet within the area.

Table 2. ANNUAL MEAN URBAN-RURAL TEMPERATURE DIFFERENCES OF CITIES, °C

Chicago	0.6	Moscow	0.7
Washington	0.6	Philadelphia	0.8
Los Angeles	0.7	Berlin	1.0
Paris	0.7	New York	1.1

EFFECTS OF CITY SIZE

Several urban studies have considered the effect of city size on the magnitude of the heat island. For example, Mitchell (1961, 1962) showed that during this century most major U. S. metropolitan areas have been both expanding and warming. While the temperature increase may be partly due to global climatic conditions, the amount of warming is well correlated with city growth rate. Dronia (1967) compared temperature trends from 67 paired locations around the world, each pair representing an urban and a rural site, usually separated by several hundred kilometers. He found that in the first five decades of this century the urban areas warmed by 0.24 °C more than the rural locations. Similarly, Lawrence (1968) noted that from the late 1940's to early 1960's mean daily minimum temperatures at the Manchester, England, airport increased by about 2.0 °F relative to nearby rural stations as the urban area expanded beyond the airport. Landsberg's paper (1960) gave 30 years of data for Los Angeles and San Diego which showed that as the difference in population between those cities increased so did the difference between their mean temperatures.

The relation between city size and urban-rural temperature difference is not linear, however; sizeable nocturnal temperature contrasts have been measured even in relatively small cities. For example, in more than 20 surveys of Palo Alto, California (population 33,000), Duckworth and Sandberg (1954) found that the maximum temperature difference of the survey area was 4 to 6 °F. Hutcheon et al. (1967) measured the temperature distribution in Corvallis, Oregon (population 21,000), on two occasions and noted a definite heat island, with maximum temperature differences of 13 and 10 °F. Sekiguti (1964) observed a heat island in Ina, Japan (population 12,000). Finally, a heat island

effect resulting even from a small, isolated building complex after sunset has been detected (Landsberg, 1968). In contrast, during the two daytime surveys at Denton, Texas, Ludwig and Kealoha (1968) reported no appreciable difference in the maximum temperatures at the center of town and at its outskirts.

Although general relationships have been developed between heat island magnitude and some parameter representing city size, be it area, population, or building density, Chandler (1964, 1966, 1967b) has emphasized that the heat island magnitude at a given location often depends strongly on the local microclimatic conditions. He noted (1968) that data from several English towns showed that the strength of the local heat island was strongly dependent upon the density of urban development very near the observation point, sometimes within a circle as small as 500 meters radius. During nights with strong heat islands, the correlation between the heat island and building density was usually greater than 0.9.

VERTICAL TEMPERATURE PROFILE DIFFERENCES

Investigators need detailed knowledge about the vertical distribution of temperature near urban areas to accurately determine the dispersion of pollutants. In two recent investigations, one over New York City (Davidson, 1967; Bornstein, 1968) and one over Cincinnati (Clarke, 1969) helicopters have been used to measure the three-dimensional, nocturnal temperature patterns over a city. Besides recording multiple elevated inversions over New York City, Davidson and Bornstein observed that a ground-based inversion was present over the outlying areas, while over the city temperatures were generally higher than those over the countryside from the surface up to about 300 meters. At heights around 400 meters temperatures over the city were generally lower than those of the surrounding area. This finding is similar to those of Duckwork and Sandberg (1954), who noted a "crossover" of the urban and rural temperatures on about half of their wiresonde data.

Clarke has studied vertical temperature distributions in Cincinnati both upwind and downwind of the city. Figure 3 shows an example from one of his surveys. On clear evenings, with light consistent surface winds, he found a strong surface-based inversion upwind of the urban area. Over the build-up region, lapse conditions occurred in the lowest 200 feet, while downwind of the urban area a strong inversion was again observed at the surface. Above this inversion, weak lapse conditions prevailed, which Clarke interpreted as the downwind effect of the city. This "urban heat plume" was detectable by vertical temperature measurements for several miles in the lee of the city.

Other authors have investigated the vertical distribution of nighttime urban temperatures with tower-mounted instruments. DeMarrais (1961) compared lapse rates in Louisville between 60 and 524 feet with typical rural profiles. During the warm half of the year, while surface inversions were regularly encountered in the country, nearly 60 percent of the urban observations showed a weak lapse rate and another

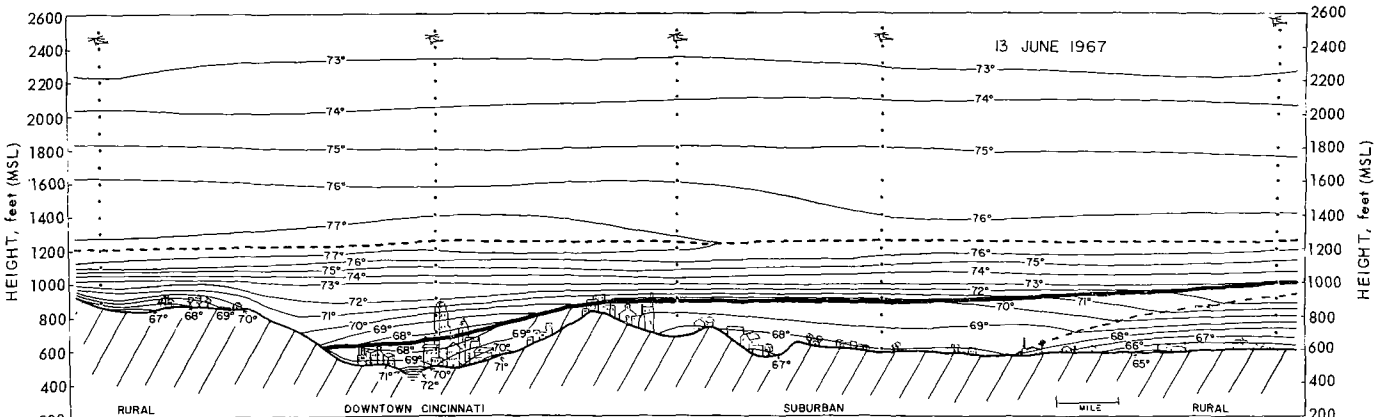

Figure 3. Cross section of temperature (°F) over metropolitan Cincinnati about 1 hour before sunrise on June 13, 1967. The heavy solid line indicates the top of the urban boundary layer and the dashed lines indicate a temperature discontinuity with less stable air above. Wind flow was from left to right (from Clarke, 1969).

15 percent showed weak lapse conditions above a super-adiabatic lapse rate. Munn and Stewart (1967) instrumented towers at 20 and 200 feet in central Montreal, suburban Ottawa, and a rural location near Sarnia, Canada. They noted that inversions occurred more frequently and were stronger over the country than over the city. Both DeMarrais, and Munn and Stewart, however, found little difference between rural and urban daytime temperature profiles.

In another study of the vertical distribution of temperature, Hosler (1961) compiled statistics on the frequency of inversions based below 500 feet above station elevation for selected United States localities and discussed the dependence of these data on season, cloud cover, wind speed, time of day, and geographic location. Since he used radiosonde data, which are usually taken at an airport on the outskirts of a city, his results are generally representative of suburban locations and thus underestimate the inversion frequencies of rural sites and overestimate those of cities.

IMPORTANCE OF METEOROLOGICAL FACTORS

In addition to city size the magnitude of the urban heat island has been shown to depend upon various meteorological parameters. An early study of this type was made by Sundborg (1950), who investigated the relation between the temperature difference between Uppsala, Sweden, and its rural surroundings and meteorological variables measured at the edge of the city. He derived two equations by regression analysis for daytime and nighttime conditions at Uppsala, based on more than 200 sets of data. Correlation coefficients between observed and calculated temperatures were 0.49 and 0.66 for day and night, respectively. At night, wind speed and cloud cover were the most important variables for determining the heat island magnitude.

Chandler (1965) made a similar study based on temperature differences of daily maxima and minima at city and country sites for London and meteorological data observed at London airport. The multiple correlation coefficients for the four equations are 0.608, 0.563, 0.286, and 0.114 for nighttime (summer and winter) and daytime (summer and winter), respectively, an indication that the equations are much better estimators for nocturnal than for daytime conditions. The magnitude of the heat island was shown to depend on wind speed and cloud amount at night, whereas no meteorological variables were found to be particularly significant during the day.

Ludwig and Kealoha (1968) estimated the magnitude of a city's heat island by using the near-surface temperature lapse rate, which was usually measured in the environs of the city or at a radiosonde facility of a nearby city. They found this single variable to be highly correlated with the heat island magnitude and thus provided a simple, accurate method for predicting urban-rural temperature differences. These investigators compiled data from 78 nocturnal heat island surveys from a dozen cities and estimated the heat island magnitude by subtracting a typical rural temperature from the highest temperature in the city's

center. Examples of their results, stratified by city population, are as follows:

$$\Delta T = 1.3 \quad 6.78\gamma \qquad \text{population} < 500,000 \qquad (1)$$

$$\Delta T = 1.7 \quad 7.24\gamma \qquad 500,000 \text{ to } 2 \text{ million} \qquad (2)$$

$$\Delta T = 2.6 \quad 14.8\ \gamma \qquad > 2 \text{ million}, \qquad (3)$$

where the lapse rate, γ, is the temperature change with pressure ($^\circ C \cdot mb^{-1}$), i.e., a surface-based inversion is represented by negative γ. Correlation coefficients between ΔT and γ for the three cases are -0.95, -0.80, and -0.87, and the root mean square errors are ± 0.66, ± 1.0, and $\pm 0.96^\circ$ C, respectively. Thus, the resulting equations of this example will usually predict ΔT to within $\pm 2.0^\circ$ C.

Another meteorological parameter that influences heat island development is wind speed. When the regional wind speed is above a critical value, a heat island cannot be detected. Table 3, taken from Oke and Hannell (1968), summarizes several reports on the relation between city population (P) and this critical wind speed (U). Log P and U are highly correlated (0.97), and their relationship is described by the regression equation:

$$U \quad -11.6 + 3.4 \log P \ . \qquad (4)$$

Table 3. CRITICAL WIND SPEEDS FOR ELIMINATION OF THE HEAT ISLAND EFFECT IN VARIOUS CITIES

City	Author	Year of survey	Population	Critical wind speed, $m \cdot s^{-1}$
London, England	Chandler (1962a)	1959-61	8,500,000	12
Montreal, Canada	Oke, et al.[a]	1967-68	2,000,000	11
Bremen, Germany	Mey	1933	400,000	8
Hamilton, Canada	Oke, et al.[a]	1965-66	300,000	6-8
Reading, England	Parry (1956)	1951-52	120,000	4-7
Kumagaya, Japan	Kawamura	1956-57	50,000	5
Palo Alto, California	Duckworth, et al.	1951-52	33,000	3-5

[a]Unpublished

The authors used this equation to estimate the smallest-sized city that would form a heat island. When U O, equation (4) yields a population of about 2500. Although they had no data to test this estimate, they recognized that the scatter of their data points increased at the smaller populations and that sometimes even small building complexes produced measurable heat island effects.

The location of the highest city temperatures also depends on local meteorology. Munn et al. (1969) noted that at Toronto, Canada, the position of the daytime heat island was strongly influenced by the

regional and lake breeze windflow patterns of the area and was often displaced downwind of the city center.

CAUSES OF THE HEAT ISLAND

It is generally accepted that two primary processes are involved in the formation of an urban heat island, both of which are seasonally dependent (see, for example, Mitchell, 1962). First, in summer the tall buildings, pavement, and concrete of the inner city absorb and store larger amounts of solar radiation (because of their geometry and high thermal admittance) than do the vegetation and soil typical of rural areas. In addition, much less of this energy is used for evaporation in the city than in the country because of the large amount of run-off of precipitation from streets and buildings. At night, while both the city and countryside cool by radiative losses, the urban man-made construction material gradually gives off the additional heat accumulated during the day, keeping urban air warmer than that of the outlying areas.

In winter a different process dominates. Since the sun angle at mid-latitudes is low and lesser amounts of solar radiation reach the earth, man-made energy becomes a significant addition to the solar energy naturally received. Artificial heat results from: combustion for home heating, power generation, industry, transportation, and human and animal metabolism. This energy reaches and warms the urban atmosphere directly or indirectly, by passing through imperfectly insulated homes and buildings. This process is most effective when light winds and poor dispersion prevail.

Many authors have investigated the magnitude of man-made energy in metropolitan areas. In two often-cited older studies for Berlin and Vienna (see Kratzer, 1956), the annual heat produced artificially in the built-up area equalled 1/3 (for Berlin) and 1/6 to 1/4 (for Vienna) of that received from solar radiation. More recently, Garnett and Bach (1965) estimated the annual average man-made heat from Sheffield, England (population 500,000), to be approximately 1/3 of the net all-wave radiation available at the ground. Bornstein (1968) reported results from a similar study of densely built-up Manhattan, New York City. During the winter the amount of heat produced from combustion alone was 2-1/2 times greater than that of the solar energy reaching the ground, but during the summer this factor dropped to 1/6.

In addition to the two seasonal primary causes of heat islands, other factors are important year-around. The "blanket" of pollutants over a city, including particulates, water vapor, and carbon dioxide, absorbs part of the upward-directed thermal radiation emitted at the surface. Part of this radiation is re-emitted downward and retained by the ground; another part warms the ambient air, a process that tends to increase the low-level stability over the city, enhancing the probability of higher pollutant concentrations. Thus, airborne pollutants not only cause a more intense heat island but alter the vertical temperature structure in a way that hinders their dispersion.

Reduced wind speed within an urban area, a result of the surface roughness of the city, also affects the heat island. The lower wind speeds decrease the city's ventilation, inhibiting both the movement of cooler outside air over the city center and the evaporation processes within the city.

Tag (1968) used a numerical model of the energy balance at the atmosphere-ground interface to investigate the relative importance of albedo, soil moisture content, soil diffusivity, and soil heat capacity on urban-rural temperature differences. The author found that during the day the lower city values of albedo and soil moisture caused higher urban temperatures, whereas the higher diffusivity and heat capacity of the city surface counteracted this tendency. At night, however, the relative warmth of the city was primarily the result of the higher urban values of soil diffusivity and heat capacity.

HUMIDITY

Even though little research on humidity has been done, the consensus of urban climatologists is that the average relative humidity in towns is several percent lower than that of nearby rural areas whereas the average absolute humidity is only slightly lower in built-up regions. The main reason to expect differences in the humidity of urban and rural areas is that the evaporation rate in a city is lower than that in the country because of the markedly different surfaces. The countryside is covered with vegetation, which retains rainfall, whereas the floor of a city is coated with concrete, asphalt, and other impervious materials that cause rapid run-off of precipitation. Although the city's low evaporation rates result from the shortage of available water and the lack of vegetation for evapotranspiration, some moisture is added to urban atmospheres by the many combustion sources.

Variations of relative humidity within metropolitan areas resemble those of temperature, since the spatial temperature changes of a city are significantly greater than those of vapor pressure. Thus, because of the heat island, relative humidities in a city are lower than in the suburbs and outlying districts. The humidity differences are greatest at night and in summer, corresponding to the time of greatest heat island intensity (Chandler, 1967a). Other studies have yielded similar findings. Sasakura (1965) reporting on 1 year of data from Tokyo showed that the mean relative humidity in the city center was 5 percent lower than that in the suburbs, a value that concurs with Landsberg's average figure. Chandler (1965) also found a 5 percent difference in the relative humidity of a downtown and a rural site near London. In other work (1962b, 1967a) he has presented nocturnal relative humidity profiles across London and maps of spatial distribution for Leicester, England. These show the dependence of relative humidity variations on the form of the city's heat island, which in turn depends upon the density of the built-up complex. Typical humidities of 90 to 100 percent were noted in rural areas during conditions favorable to heat island formation, whereas in the heart of the city humidity values were approximately 70 to 80 percent. Because of the temperature dependence, when the magnitude of the heat island was small, the urban-rural humidity differences were also small.

Although Chandler (1965) found that the mean annual vapor pressure in London was slightly lower (0.2 mb) than that at a nearby rural location, he (1962b, 1967a) frequently observed that at night the urban absolute humidity was higher than in the outlying regions. Furthermore, variations of humidity within the city often directly corresponded to building density, especially when the meteorological conditions were conducive to heat island formation. Typically under these conditions

urban vapor pressures were about 1.5 to 2.0 mb higher than those in the country. The corresponding relative humidities were about 80 and 90 percent for the city and country, respectively. Chandler attributed these higher urban absolute humidities to the low rate of diffusion of air near ground level between tall city buildings during nights with light winds. This air with its high daytime moisture was trapped in the city canyons and remained there into the evening, keeping the absolute humidity high.

The summer surveys at Dallas by Ludwig and Kealoha (1968) recorded slightly lower values of absolute humidity within Dallas than outside it, with the greatest differences measured in the afternoon. During the morning hours the observed patterns were not well developed and could not be related to the urban complex.

VISIBILITY

The atmosphere of metropolitan areas is usually characterized by increased concentrations of pollutants, which cause a difference between the visibilities of urban and rural regions. In this section, the effect of cities on atmospheric particulates is discussed first, followed by examples of visibility contrasts between city and country, with emphasis on the effects of fog. Readers interested in further information on these subjects should consult Robinson (1968), who presents a comprehensive review of practical and theoretical aspects of visibility, or the summary by Holzworth (1962), which also discusses visibility trends and their analysis.

ATMOSPHERIC PARTICULATES

A consequence of metropolitan areas is increased concentrations of atmospheric particles, such as smoke and combustion products. Landsberg (1960) stated that on the average the number of particulates present over urban areas is 10 times greater than that over rural environs. A more recent study by Horvath (1967), who measured the number and size distribution of submicron particles over Vienna and a nearby mountainous region, concurred with this figure. Although the particulate concentrations in Vienna varied considerably, often because of differing meteorological conditions, the general shapes of the size distribution curves of both the urban and rural samples were similar.

Summers (1966) also showed that the number of particles in an urban atmosphere depends on industrial activity. In central Montreal the soiling index (Hemeon et al., 1953) was approximately 20 percent lower on Saturday and Sunday than on weekdays. Furthermore, in midwinter, the time of maximum heating requirements, this index was 2 to 3 times that of midsummer. Similar weekly and annual variations were also found by Weisman et al. (1969) for Hamilton, Ontario. In addition to industrial sources, urban particulate concentrations depend on meteorological conditions, particularly ventilation. In a summary of the relation between smoke density over Montreal and various weather factors, Summers (1962) showed that winter snow cover was particularly important in that it produced low-level atmospheric stability and frequent temperature inversions.

As a result of air pollution and the associated high aerosol concentrations, visibilities are lower and occurrences of fog are higher in a city than outside the metropolitan area. Fog is more frequent within urban regions because many atmospheric particulates are hygroscopic (Byers, 1965). Thus water vapor readily condenses on them and forms small water droplets, the ingredients of fog. An analogous example

was described by Buma (1960), who analyzed visibility data at Leeuwarden on the Netherland coast. For similar relative humidities the visibility was much lower when the wind was from the continent (with high concentrations of condensation nuclei) than when the wind was from the sea (with low concentrations of nuclei). An example of the relationship between air pollution and visibility has been given by Georgii and Hoffman (1966), who showed that for two German cities low visibilities and high concentrations of SO_2 were highly correlated when low wind speeds and low-level inversions prevailed. McNulty (1968) pointed out that between 1949 and 1960 the occurrence of haze as an obstruction to visibility at New York City increased markedly as a result of increased air pollution.

URBAN-RURAL VISIBILITY CONTRASTS

As part of his general summary Landsberg (1956) presented visibility data from Detroit Municipal Airport (6 miles from downtown) and the Wayne County Airport (17 miles from town). During conditions conducive to the formation of city smogs (winds of 5 miles per hour or less) visibilities less than 1 mile were observed an average of 149 hours per year at the Municipal Airport but only 89 hours at the rural site. The cause of these low visibilities was listed as smoke in 49 of the observations at the Municipal Airport but in only 5 at the County Airport; most of the occurrences of low visibility were during the late fall and winter. Landsberg (1960) summarized urban-rural fog differences by noting that metropolitan areas had 100 percent more fog in winter and 30 percent more in summer. In another study, Smith (1961) compiled the number of occurrences of visibilities less than 6 1/4 miles for locations throughout England in the afternoon, the time of least likelihood of fog (Figure 4). He found that industrial areas reported low visibilities on two to three times more days than did the rural areas.

Although fog generally occurs more frequently in metropolitan areas, this is not true for very dense fog. Chandler (1965) attributed the high frequencies of fog within a city to atmospheric pollution and relatively low wind speeds, but the extra warmth of a city often prevents the thickest nocturnal fogs from reaching the densities reported in the outlying districts. Table 4, presented by Chandler from data of Shellard (1959), shows the estimated hours per year of various density fogs in the vicinity of London, based on four observations per day. The high frequency of fog and the low frequency of very dense fog in the city center are evident. These same general relationships were also detected by Brazell (1964) using similar London data.

EFFECTS OF AIR POLLUTION CONTROL

A few recent reports indicate that the visibility in many locations has improved during the last two decades. The better visibilities of major U.S. cities have been associated with local efforts at air pollution abatement and substitution of oil and gas for soft coal in production of heat (see Holzworth, 1962; Beebe, 1967). Brazell (1964), Wiggett (1964), and Freeman (1968) have suggested that London's improved visibility may be due to enforcement of the air pollution ordi-

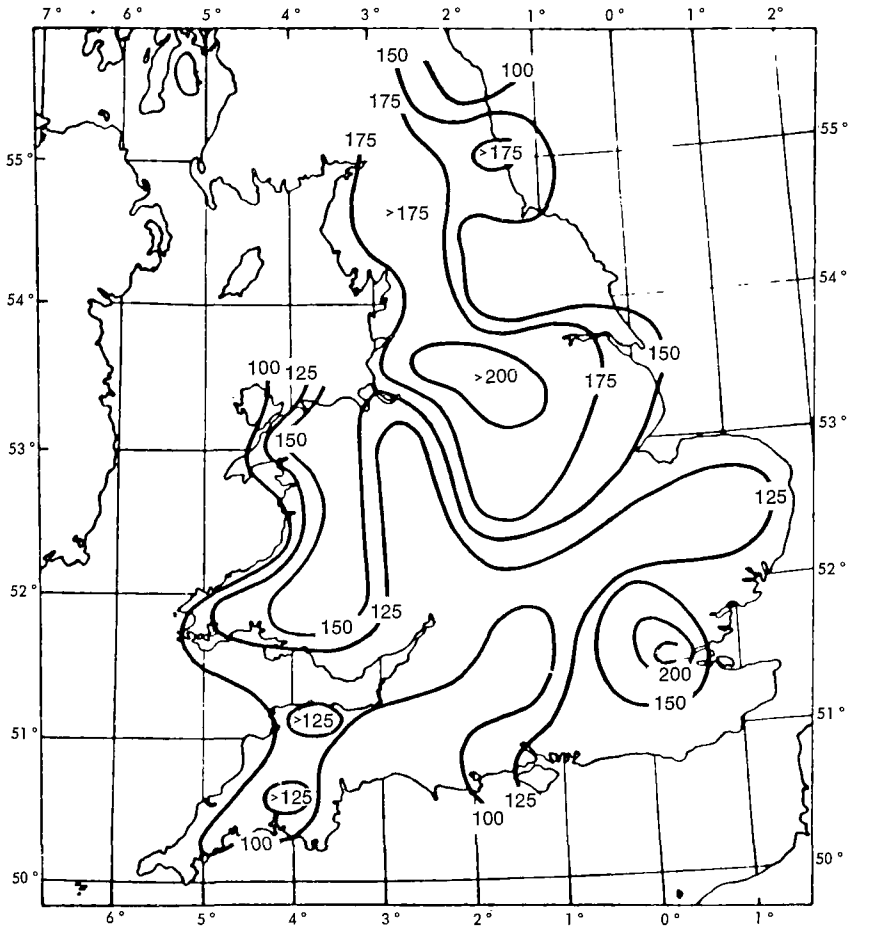

Figure 4. Average number of days per year with afternoon visibilities less than 6¼ miles in England and Wales (from Smith, 1961).

Table 4. FOG FREQUENCIES IN LONDON

	Hours per year with visibility less than			
	40 m	200 m	400 m	1000 m
Kingsway (central)	19	126	230	940
Kew (inner suburbs)	79	213	365	633
London Airport (outer suburbs)	46	209	304	562
Southeast England (mean of 7 stations)	20	177	261	494

nances of 1954 and 1956. Similarly, Atkins (1968) and Corfield and Newton (1968) found that visibility has also improved near other English cities as a result of air pollution legislation. In another study of London, Commins and Waller (1967) compiled data showing that the

particulate content of that city's atmosphere has decreased. Measurements from downtown London showed that the average smoke concentration from 1959 to 1964 was 32 percent lower than that from 1954 to 1959.

Visibility is not improving at all United States cities. A study by Green and Battan (1967) has shown that from 1949 to 1965 the frequency of occurrence of poor visibility at Tucson, Arizonia, definitely increased and was significantly correlated with that city's population.

RADIATION

The blanket of particulates over most large cities causes the solar energy that reaches an urban complex to be significantly less than that observed in rural areas. The particles are most effective as attenuators of radiation when the sun angle is low, since the path length of the radiation passing through the particulate material is dependent on sun elevation. Thus, for a given amount of particulates, solar radiation will be reduced by the largest fraction at high-latitude cities and during winter. Landsberg (1960) summarized the average annual effect of cities on the solar radiation they received as follows: the average annual total (direct plus diffuse) solar radiation received on a horizontal surface is decreased by 15 to 20 percent, and the ultraviolet (short wavelength) radiation is decreased by 30 percent in winter and by 5 percent in summer.

De Boer (1966) based a recent study on this topic on 2 years of global solar radiation measurements at six stations in and around Rotterdam, Netherlands. The study showed that the city center received 3 to 6 percent less radiation than the urban fringe and 13 to 17 percent less than the country. Chandler (1965), also reporting on the solar energy values in the heart of smoky urban areas, observed that from November to March solar radiation at several British cities was 25 to 55 percent less than in nearby rural areas. In addition, the central part of London annually received about 270 hours less of bright sunshine than did the surrounding countryside because of the high concentration of atmospheric particulates.

Further emphasizing the dependence of the transfer of solar radiation on the air's smoke content, the study of Mateer (1961) showed that the average annual energy received in Toronto, Canada, was 2.8 percent greater on Sunday than during the remainder of the week. Moreover, the Sunday increase during the heating season, October through April, was 6.0 percent but was only 0.8 percent in all other months.

The investigations of atmospheric turbidity by McCormick and Baulch (1962) and McCormick and Kurfis (1966), which were based on aircraft measurements of the intensity of solar radiation, provided data on the variation of solar energy with height over Cincinnati. These authors observed that pollutants over the city, which often had a layered structure and were dependent on the vertical temperature profile, significantly reduced the amount of solar energy that reached the city surface. In addition, they discussed changes of the vertical variation of turbidity (or solar radiation) from morning to afternoon, from day to day, and from clean air to polluted air. Roach (1961) and

Sheppard (1958) have also studied attenuation of solar radiation by atmospheric dust particles. They concurred that most radiation scattered by these particles is directed forward and thus attenuation of total solar radiation is primarily due to absorption. Roach estimated that over "heavily polluted areas" absorption of solar energy by the particles was of sufficient magnitude to cause atmospheric heating rates in excess of 10° C per day. A discussion of optical properties of smoke particles is presented in a report by Conner and Hodkinson (1967).

The introduction of smoke controls in London during the mid-1950's has afforded an opportunity to check the radiation-smoke relation. Monteith (1966) summarized data on particulate concentration and solar energy at Kingsway (central London) for the years 1957 to 1963. During this time smoke density decreased by 10 $\mu g \cdot m^{-3}$ while total solar radiation increased by about 1 percent. The average smoke concentration of 80 $\mu g \cdot m^{-3}$ at Kew (inner suburbs) represents an energy decrease of about 8 percent, and in the center of town, where smoke concentrations average 200 to 300 $\mu g \cdot m^{-3}$, the income of solar radiation is about 20 to 30 percent less than that in nearby rural areas. Similarly, Jenkins (1969) reported that the frequency of bright sunshine in London also increased in recent years after implementation of the air pollution laws. During the period 1958 to 1967, the average number of hours of bright sunshine from November through January was 50 percent greater than that observed from 1931 to 1960.

Measurements of ultraviolet radiation in downtown Los Angeles and on Mt. Wilson (Nader, 1967) showed its dependence on the cleanliness of the atmosphere. Attenuation of ultraviolet radiation by the lowest 5350 feet of the atmosphere averaged 14 percent on no-smog days; when smog was present, attenuation increased to a maximum of 58 percent. Reduced values of ultraviolet radiation in Los Angeles were also measured by Stair (1966). He presented an example in which the effect of smog was to decrease the amount of ultraviolet radiation received at the ground by 50 percent, and he also noted that on "extremely smoggy days" the decrease may be 90 percent or more.

WIND

The flow of wind over an urban area differs in several aspects from that over the surrounding countryside. Two features that represent deviations from the regional wind flow patterns are the differences in wind speeds in city and country and the convergence of low-level wind over a city. These differences occur because the surface of a built-up city is much rougher than that of rural terrain--exerting increased frictional drag on air flowing over it--and because the heat island of a city causes horizontal thermal gradients, especially near the city periphery. The excess heat and friction also produce more turbulence over the urban area. These general ideas were discussed by Landsberg (1956, 1960); he stated that the annual mean surface wind speed over a city was 20 to 30 percent lower than that over the nearby countryside, that the speed of extreme gusts was 10 to 20 percent lower, and that calms were 5 to 20 percent more frequent. Since then several investigations have refined and expanded the studies summarized by Landsberg. Readers interested in a comprehensive and detailed review of wind flow over a city are directed to a recent paper by Munn (1968).

A difficulty in estimating urban-rural wind differences is selecting representative sites within the city from which to take measurements. Most observations of urban wind flow have been taken either from the roofs of downtown buildings, usually several stories high, or from parks or open spaces, whereas very few data have been obtained at street level in the city center, that place where most human activity occurs. However, these conventional measurements are generally representative of the gross wind flow patterns over a city, and as long as their limitations are recognized they can be useful for urban-rural comparisons.

WIND SPEED

Although recent reports have concurred that the average wind speed within a city is lower than that over nearby rural areas (Frederick, 1964; Munn and Stewart, 1967; Graham, 1968), the study reported by Chandler (1965) for London shows significant variation from this general rule. Although his analysis is based on only 2 years of data, it indicates that differences in urban and rural wind speeds depend on time of day, season, and wind speed magnitude. Some of these relations are brought out in Table 5 (taken from Chandler, 1965), which summarizes the mean wind speeds at London Airport (on the fringe of the city) and indicates their excess over the values recorded at Kingsway (in central London). The data show that when the regional wind speeds are light (typically at night) the speeds in downtown London are higher than those at the airport, whereas when wind speeds are

relatively high, higher speeds are recorded at the airport. This is evident in comparison of the daytime and nighttime wind speeds given in Table 5.

Table 5. AVERAGE WIND SPEEDS AT LONDON AIRPORT AND DIFFERENCES FROM THOSE AT KINGSWAY, $m \cdot s^{-1}$

	0100 GMT		1300 GMT	
	Mean speed	Excess speed	Mean speed	Excess speed
December - February	2.5	-0.4	3.1	0.4
March - May	2.2	-0.1	3.1	1.2
June - August	2.0	-0.6	2.7	0.7
September - November	2.1	-0.2	2.6	0.6
Year	2.2	-0.3	2.9	0.7

Chandler (1965) attributes this diurnal variation of urban influence to the diurnal differences of regional wind speed and atmospheric stability. At night when surface winds are relatively calm, the stability is much greater in the country, where inversions are common, than in the metropolitan area, where lapse conditions may prevail. This relative instability in the city, combined with the greater surface roughness, enhances turbulence and allows the faster moving winds above the urban area to reach the surface more frequently; thus at night the average city wind speeds tend to be greater than those of the country. During the day, however, with faster regional winds, the frictional effect of the rough city surface dominates the turbulence effect, and lower wind speeds are observed within the built-up area.

The critical value of wind speed that determines whether the urban winds will be faster or slower than those of the country is highest during summer nights and during both day and night in winter (about 5.0 to 5.5 $m \cdot s^{-1}$). These are times of relatively high atmospheric stability. The lowest values of critical speed (about 3.5 $m \cdot s^{-1}$) occur during summer and fall days. Moreover, the magnitude of the decrease in urban wind speeds is greatest during spring days and least during spring nights.

Chandler (1965) summarized the wind speed statistics for London by noting that the annual average urban and suburban speeds were lower than those of the outlying regions but only by about 5 percent. However, the annual differences between wind speeds in the center of London and in the outlying areas were somewhat greater. For these locations, when speeds were more than 1.5 $m \cdot s^{-1}$ the average difference was about 13 percent, whereas for speeds greater than 7.9 $m \cdot s^{-1}$ the mean difference was only 7 percent. In summer, little difference between average city and rural wind speeds was evident. Light regional winds (1.5 $m \cdot s^{-1}$ or less), which increase in speed over the city, occur more frequently in summer and compensate for the occurrences of strong rural winds, which decrease over the city. Finally, in contrast to the earlier figures reported by Landsberg, the London data showed that fewer calms and light winds occurred in the city center than in rural regions.

WIND DIRECTION

Past research on the direction of wind flow over urban areas has been primarily concerned with detecting and measuring a surface flow in toward the urban complex. It has been surmised for some time that if a city is warmer than its environs the warm city air should rise and be displaced by cooler rural air. However, this inflow is weak and occurs only in conjunction with well-developed heat islands, which in turn are dependent on certain meteorological conditions. Since direct measurements of the inflow require a coordinated set of accurate observations, few such investigations have been made.

Pooler (1963) analyzed wind records from the Louisville local air pollution study and determined that there was indeed a surface inflow of air toward the city. This inflow was the dominant feature of the surface wind flow pattern when the regional winds were weak, a situation that could result, for example, from a weak large-scale pressure gradient. Georgii (1968) reported on urban wind measuremens in Frankfort/Main, Germany. During clear, calm nights an inflow toward the city center was detected, with a convergent wind velocity of up to 2 to 4 $m \cdot s^{-1}$. He also noted that when the large-scale surface geostrophic wind speed reached 3 to 4 $m \cdot s^{-1}$ a local city circulation was prevented from becoming established, although the increased roughness of the city was still affecting the wind regime.

Measurements of the wind flow around an oil refinery in the Netherlands have been reported by Schmidt (1963) and by Schmidt and Boer (1963). Although the area involved (4 km^2) was much smaller than that of a moderate-sized city and the heat produced by the refinery per unit area was considerably greater than that of a city, the general relationships are of interest. A cyclonic circulation occurred around the area, with convergence toward the center. Furthermore, ascending air was detected over the center of the area, with descending currents over the surroundings. The greatest vertical velocities measured in the vicinity of the maximum heat production were about 15 $cm \cdot s^{-1}$.

Vertical wind velocities were obtained from low-level tetroon flights over New York City by Hass et al. (1967) and Angell et al. (1968). They observed an upward flow over densely built-up Manhattan Island and downward motion over the adjacent Hudson and East Rivers. They ascribed this flow pattern to the urban heat island, to the barrier effect of the tall buildings, and to the relatively cool river water. Low-level convergence over a city has also been detected by Okita (1960, 1965), who applied two novel techniques. For one study he utilized the fact that rime ice formed on the windward side of tree trunks and the thickness of the ice was proportional to wind speed. For the other, (Figure 5), he observed the smoke plumes from household chimneys. By observing these features around the periphery of Asahikawa, Japan, he deduced the local wind flow patterns and determined that when the large-scale wind flow was weak there was a convergence over the city.

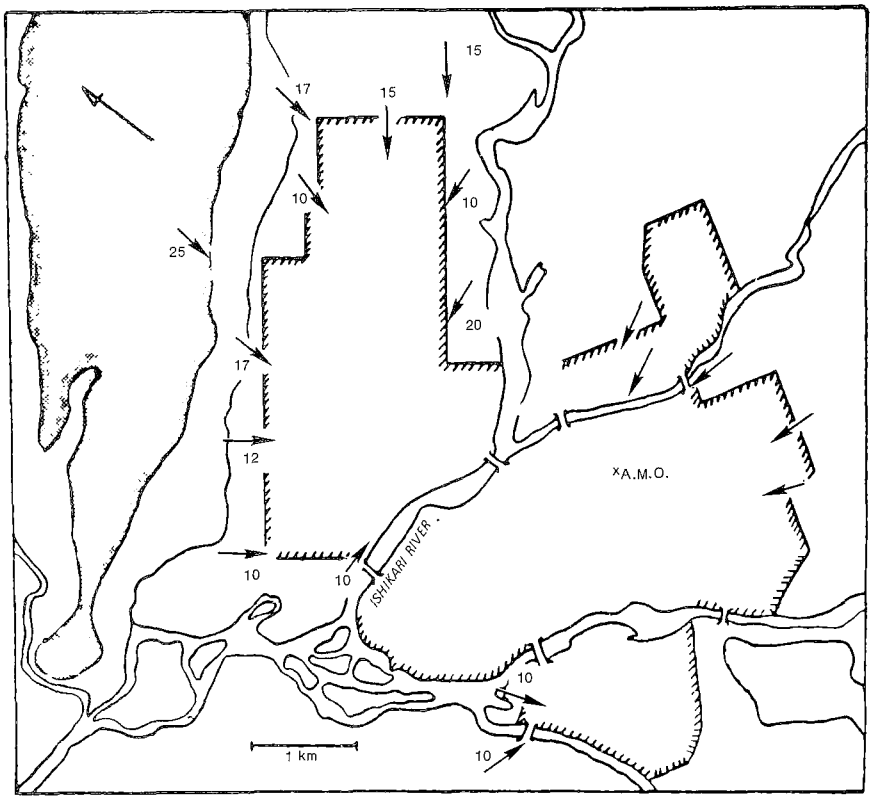

Figure 5. The direction of wind flow around Asahikawa, Japan, February 26, 1956, as deduced from formation of rime ice on tree branches (from Okita, 1960).

As a final consideration of urban wind flow, Chandler's observations (1960, 1961) on the periphery of London and Leicester are of interest. Chandler noted that when a well-developed nocturnal heat island formed with a strong temperature gradient near the edge of the built-up area, winds flowed inward toward the city center, but the flow was not steady. Rather, movement of cold air from the country toward the city occurred as pulsations, the strongest winds occurring when the temperature gradient was strongest.

PRECIPITATION

A city also influences the occurrence and amount of precipitation in its vicinity. For several reasons an urban complex might be expected to increase precipitation. Combustion sources add to the amount of water vapor in the atmosphere, higher temperatures intensify thermal convection, greater surface roughness increases mechanical turbulence, and the urban atmosphere contains greater concentrations of condensation and ice nuclei. Since no continuous, quantitative measurements of these various parameters have been made in conjunction with the few urban precipitation studies, the relative significance of these factors is not easy to establish. Landsberg (1956, 1958) gave several European examples of urban-rural comparisons and concluded that the amount of precipitation over a city is about 10 percent greater than that over nearby country areas. More recent studies have shown that his conclusion may be an oversimplification and that the greatest positive anomalies occur downwind of the city center.

THE EFFECTS OF CITIES

The effects of cities on precipitation are difficult to determine for several reasons. First, very few rural areas remain undistrubed from their natural state. Second, there is a lack of rain gauges in metropolitan areas, especially instruments with long-term records and uniform exposure throughout the record. Third, many cities are associated with bodies of water or hilly terrain, and these also affect the patterns of precipitation. Finally, the natural variability of rainfall, particularly the summer showers of mid-America, further complicates the analysis of urban-rural precipitation differences. An example of the difficulty of rainfall analysis is the study of Spar and Ronberg (1968). They observed that the record from Central Park, New York City, showed a significant decreasing trend of precipitation of 0.3 inch per year from 1927 to 1965. This trend was not substantiated by data from other nearby sites; at Battery Place, the nearest station, a small rainfall increase was observed during the period.

A very striking example of the effect of the Chicago urban region on local precipitation has been documented by Changnon (1968a). He showed that at La Porte, Indiana, some 30 miles downwind of a large industrial complex between Chicago and Gary, Indiana, the amount of precipitation and the number of days with thunderstorms and hail have increased markedly since 1925. Furthermore, the year-to-year variation of precipitation at La Porte agrees generally with data on the production of steel and number of smoke-haze days at Chicago (Figure 6).

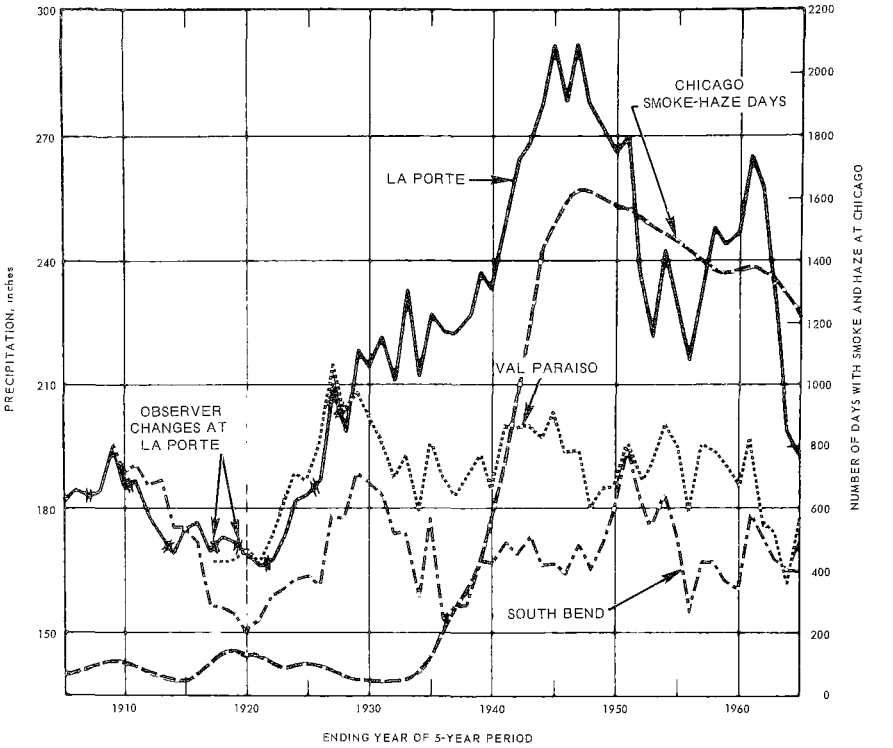

Figure 6. Five-year moving totals of precipitation at several Indiana stations and smoke-haze days at Chicago (from Changnon, 1968a).

During the period from 1951 to 1965, the positive anomalies at La Porte were 31 percent for precipitation, 38 percent for thunderstorm days, 246 percent for hail days, and 34 percent for days with precipitation ≥ 0.25 inch. These results are summarized in Table 6. Changnon concluded that these observed differences were a real effect of the industrial area and that they represent the general size of precipitation increase that is possible as a result of man's activities. However, because of the effect of Lake Michigan and its associated lake breeze in channeling the pollutants around the south end of the lake toward the La Porte area and inhibiting dispersion, the large differences detected in this study probably are not representative of American cities in general.

Changnon (1961, 1962, 1968b, 1969) has summarized precipitation data for several other midwestern cities and detected positive increases, but not nearly as pronounced as those at La Porte. In St. Louis, Chicago, Champaign-Urbana, Illinois, and Tulsa, Oklahoma, the city precipitation was 5 to 8 percent higher than the average of nearby rural stations. At St. Louis and Champaign-Urbana the rainfall maxima were downwind

Table 6. SUMMARY OF URBAN AREA INCREASES IN PRECIPITATION AND RELATED CONDITIONS (EXPRESSED AS A PERCENT OF RURAL VALUES)

	Chicago	La Porte	St. Louis	Tulsa	Champaign-Urbana
Annual precipitation	5	31	7	8	5
Warmer half-year precipitation	4	30	a	5	4
Colder half-year precipitation	6	33	a	11	8
Rain days ≥ 0.01 or 0.1 inch					
Annual	6	0	a	a	7
Warmer half-year	8	0	a	a	3
Colder half-year	4	0	a	a	10
Rain days ≥ 0.25 or 0.5 inch					
Annual	5	34	a	a	5
Warmer half-year	7	54	a	a	9
Colder half-year	0	5	a	a	0
Annual number of thunderstorm days	6	38	11	a	7
Summer number of thunderstorm days	13	63	21	a	17

[a]Data not sufficient for comparison.

of the urban center. The increase of 5 percent at Chicago proper represents a relative maximum over the city and is distinct from the higher precipitation rates downwind of Chicago at La Porte. Spatial data were not available for Tulsa. Table 6 (from Changnon, 1968b) shows that the percentage precipitation increase is greater during the cold season and that increases in the warm season result from more days of moderate rain and thunderstorms.

Authors do not totally agree on the distribution of precipitation over cities. The rainfall minimum over the Missouri half of metropolitan St. Louis detected by Changnon (1968b) was also noted by Feig (1968), who observed that a map of isohyets of annual precipitation over the eastern United States showed that minimum precipitation areas occur around most cities having no obvious geographic influences. The annual precipitation pattern at Washington, D. C. (Woollum and Canfield, 1968), also shows low values downtown along the Potomac River, with the greatest amounts of precipitation on the north to northwest side of town and with relative maxima in both the eastern and western suburbs (Figure 7). On the other hand, Dettwiller (1968) has indicated that the effect of a city is to increase precipitation. He showed that from 1953 to 1967 the average rainfall in Paris was 31 percent greater on weekdays than on Saturdays and Sundays.

Another reason for believing that more precipitation falls over metropolitan districts is that heavy thundershowers sometimes occur over an area that roughly coincides with the urban complex (Staff, 1964; Chandler, 1965; Atkinson, 1968). However, it is always difficult to determine whether a thundershower was a natural event or whether the city actually influenced it in any way.

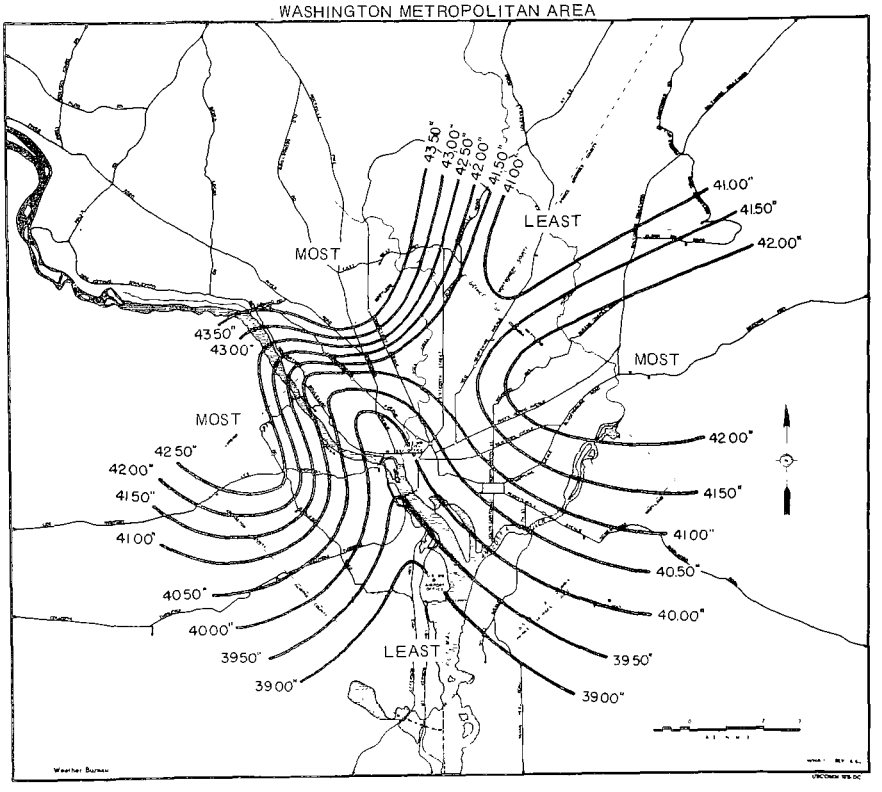

Figure 7. Mean annual precipitation (inches) over the Washington, D. C., metropolitan area (from Woollum and Canfield, 1968).

THE IMPORTANT URBAN FACTORS

Although it is hard to determine the relative importance of the several urban factors that affect precipitation, the extensive studies by Changnon (1968b) led him to the following conclusions about the city-precipitation relationship. Two factors were probably most effective in enhancing precipitation at La Porte — high concentrations of ice nuclei from nearby steel mills and added heat from local industrial sources. Because of the high frequency of nocturnal thunderstorms and hailstorms at La Porte, he concluded that the thermal and frictional effects were probably the most significant. In addition, the precipitation maximum associated with Champaign-Urbana, an area with little industry and a minimum of nuclei sources, also indicated that the thermal and frictional factors could produce significant differences.

Many recent studies have concentrated on measuring condensation and ice nuclei and determining their possible influence on cloud development and precipitation. Measurements showing that cities are an important source of nuclei were reported by Mee (1968). Typical

concentrations of cloud droplets and condensation nuclei at the convective cloud base near Puerto Rico were 50 cm^{-3} in the clean air over the ocean, about 200 cm^{-3} over the unpolluted countryside, and from 1000 to 1500 cm^{-3} immediately downwind of San Juan. Abnormally high concentrations were detected for at least 100 miles downwind of the city. In another study, Squires (1966) pointed out that measurements of condensation nuclei over Denver showed that the concentrations of these nuclei produced by human activities were similar to the natural concentration there. Moreover, Telford (1960), Langer (1968), and Langer et al. (1967) observed that industrial areas, and in particular steel mills, are good sources of ice nuclei. Finally, Schaefer (1966, 1968a) and others (Morgan, 1967; Morgan and Allee, 1968; Hogan, 1967) have shown that lead particles in ordinary auto exhaust form effective ice nuclei when combined with iodine vapor.

Even though cities are generally recognized as good sources of nuclei, the net effect of such nuclei cannot be definitely determined. For example, a few ice nuclei added to supercooled clouds may enhance rainfall, a principle used by commercial cloud seeders. On the other hand, rain that falls from warm clouds is dependent on a number of large drops within a cloud so that coalescence may be effective. If large numbers of condensation nuclei are introduced into a warm cloud, many small drops will form and thus rainfall may be inhibited (Gunn and Phillips, 1957; Squires and Twomey, 1960).

Many examples in the literature show that rainfall can be artificially increased, whereas only a few show decreases. Fleuck (1968) statistically analyzed results of the Missouri seeding experiments by the University of Chicago group and concluded that seeding of clouds in that area suppressed precipitation. In addition, reports of an investigation of the trend of rainfall in eastern Australia (Warner and Twomey, 1967; Warner, 1968) concluded that as the amount of smoke from burning sugar cane in the area increased during the past 50 years, rainfall correspondingly decreased by 25 percent. Therefore, an accurate determination of the effect of a city on precipitation in its neighborhood requires knowledge not only of the number and type of nuclei being introduced by the city but also of such factors as the concentration of natural nuclei and vertical temperature profiles over the city.

Recent findings have further documented Landsberg's statement that it is becoming increasingly difficult to find undisturbed rural areas with which to compare cities to determine urban-rural meteorological differences. Both direct (Schaefer, 1968b) and indirect (Gunn, 1964; McCormick and Ludwig, 1967; Peterson and Bryson, 1968; Volz, 1968) measurements have shown that the particulate content of the atmosphere, even in remote areas, is increasing as a result of greater human activity.

OTHER PRECIPITATION ELEMENTS

Two other precipitation elements of interest are hail and snowfall. Changnon's study (1968b) of the La Porte anomaly found that from 1951

to 1965 the number of hail days was 246 percent greater than that of surrounding stations. Results from similar investigations at other midwestern cities were not definitive. Landsberg (1956) cited a few instances in which snowfall over an urban area was lighter than that at nearby rural locations, presumably because of higher temperatures over the cities. Potter (1961) found similar results for Toronto and Montreal, Canada.

SUGGESTED FUTURE RESEARCH

Although this review indicates that a large volume of research has been conducted in urban climatology, several areas warrant emphasis in the future. Among the following suggestions for further study, many were brought out at the recent international conference on the climate of cities at Brussels.

Few studies have been made of the vertical structure of the urban atmosphere, which includes such features as the variation with height of temperature, wind flow, pollutants, and radiation. More such information is needed for a better understanding of the transport and diffusion of pollutants over metropolitan areas. Likewise, additional urban wind measurements are needed at a variety of sites with different exposures, to delineate the fine structure of wind flow throughout a city.

Several aspects of urban-rural radiation differences should be further investigated. In several studies of the effects of a polluted atmosphere on ultraviolet radiation in Los Angeles, the effects were found to be significant. Observations from other cities are now needed to show the amount of attenuation of ultraviolet radiation at different locations. Similarly, studies should be conducted to determine the net effect of a polluted city atmosphere on the total radiation balance of a city, including visible and thermal infrared wavelengths, since net radiation comprises a major fraction of a city's energy budget. In particular, urban-rural differences of infrared radiation should be measured to determine whether reduced values of solar radiation at the city surface resulting from atmospheric pollution are compensated for by an increase in infrared energy.

A cause-and-effect relationship between a city and precipitation has not yet been found. Although several factors are believed to be important, the role of anthropogenically produced dust particles is of special interest. The influence of these particles on the physics of precipitation and the optimum concentration for modifying precipitation have not yet been determined. Also, investigations should be undertaken to ascertain whether city-induced precipitation anomalies of a size similar to that at La Porte, Indiana, are widespread or whether this example is primarily the result of local influences, such as Lake Michigan.

Further research should be directed toward determing exactly upon which parameters urban-rural temperature differences depend.

For example, the relative importance of the type and density of local buildings and gross city size on the temperature at a given city location has yet to be definitely established. Similarly, the local cooling produced by parks and greenbelts and the extent of this cooling into nearby neighborhoods should be measured. Such information would be useful in city planning and land use studies, for example.

Finally, these two questions should be studied: How far downwind does a city influence climate, and to what extend does a city in the tropics modify its climate? The former question has implications in larger-scale studies of inadvertent weather modification; the latter is important since nearly all research in urban climatology has been done at cities in temperate climates.

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