Observations of the Urban Heat Island Effect in New York City[1]

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ABSTRACT

Differences in the temperature fields through the lowest 700 m of the atmosphere in and around New York City during the hours near sunrise are analyzed. Data were obtained by an instrumented helicopter on 42 predetermined test mornings from July 1964 to December 1966.

Results show urban surface temperature inversions to be less intense, and far less frequent, than those in the surrounding non-urban regions. A high frequency of weak elevated inversion layers at an average height of 310 m was observed over the city.

The average intensity of the urban heat island, i.e., urban temperature excess, was a maximum near the surface and decreased to zero at 300 m. On mornings with relatively strong urban elevated inversion layers the heat island extended to well over 500 m. For more than two-thirds of the test mornings there existed an elevated "cross-over layer" in which rural temperatures were higher than urban temperatures. The magnitude of the cross-over effect was less than that of the heat island effect.

1. Introduction

As part of a larger research project in urban air pollution dynamics, described by Davidson (1967), detailed observations of the temperature structure over the New York City area were obtained by the Sign-X Laboratories of Essex, Conn. An instrumented helicopter was flown on 34 predetermined mornings from July 1964 to December 1966 during the period from 2 hr before to 2 hr after sunrise. In addition, Sign-X made similar observations during eight additional mornings in 1966 as part of a plume rise project for Consolidated Edison (Simon and Proudfit[2]). The purpose of the present paper is to describe the characteristics of the horizontal and vertical temperature distribution in and around New York City.

2. Background

a. *Physical basis of the urban heat island*

A schematic representation [after the manner of Munn (1966)] of the energy balances in rural and urban regions is shown in Fig. 1. In rural regions a net daytime gain of energy through radiation at the earth-atmosphere interface results in a turbulent transfer of heat Q_H to the atmosphere, conduction of heat Q_G into the surface, and evaporation Q_E. During the night a net loss of energy through radiation in rural regions at the interface results in decreased evaporation or condensation, turbulent transfer of heat from the atmosphere, and conduction of heat from the ground.

In a city, modifications of the above energy balance can result from any or all of the following: 1) furnace heating, 2) limited amounts of surface moisture, 3) urban structures, and 4) atmospheric pollution.

The reduced surface moisture decreases the energy Q_E used for evaporation, thus increasing the energy transferred to the atmosphere (Q_H) and to urban surfaces (Q_G). Nevertheless, daytime temperatures of urban surfaces can remain lower than those of rural surfaces, due to the large heat capacity and high heat conductivity of urban building materials. These thermal properties prevent rapid cooling after sunset and rapid warming after sunrise, but allow the storage of large amounts of solar energy Q_G and furnace heat Q_F.

Kratzer (1957) estimated the total energy released by combustion in Berlin as one-third of the energy received from direct solar radiation. As part of the urban air pollution dynamics project, it has been calculated that the annual production of heat by combustion in New York City is 2.8×10^{17} cal. Residential and utility sources account for 77% of the total, with industry, motor vehicles and ships contributing the remainder.

Combustion during winter in Manhattan releases 250% more heat than the 0.114 cal cm^{-2} min^{-1} which London (1957) calculated as reaching the surface from the sun. By comparison, combustion during summer is only one-fifth of the winter value, while insolation increases by a factor of three.

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[2] Some observations of plume rise and plume concentration distribution over New York City. Paper presented at the 60th Annual Meeting of the Air Pollution Control Assoc., Cleveland.

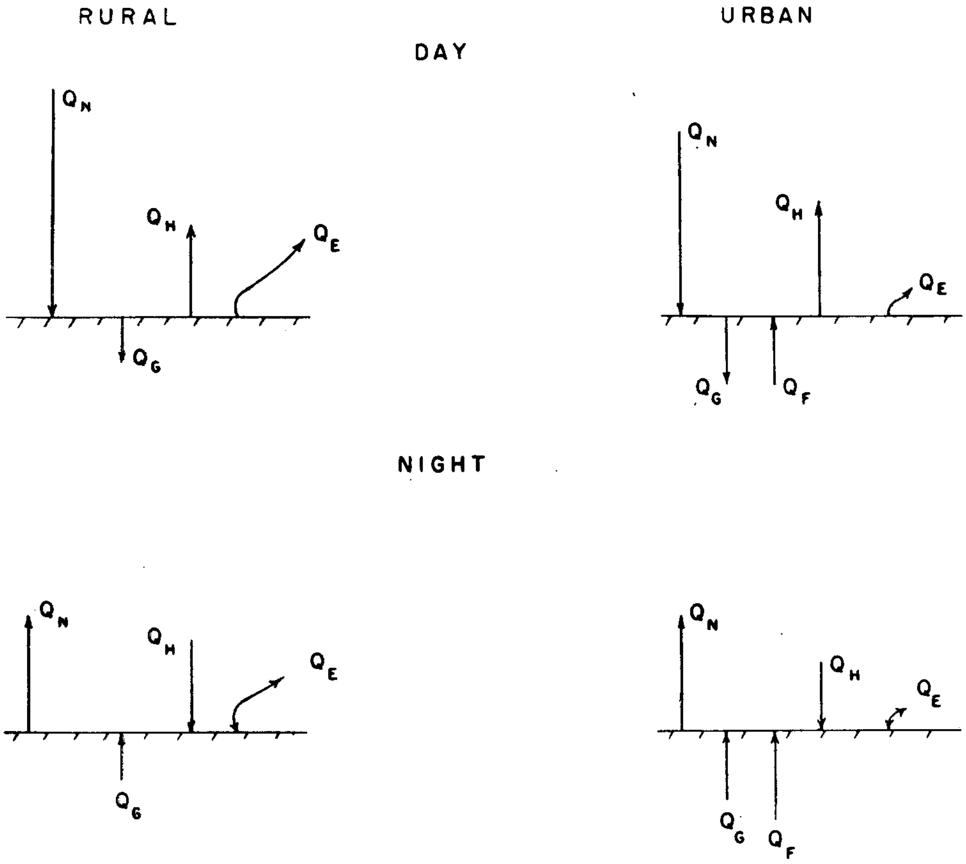

FIG. 1. Schematic representation of the energy balances in rural and urban regions [after the manner of Munn (1966)]. See text for explanation of symbols.

During winter days the normal net flow of energy Q_G into urban surfaces may be reversed due to the large ratio of furnace heating to insolation. The additional energy Q_H thus convected to the atmosphere is spread horizontally and vertically by atmospheric turbulence before significant urban-rural atmospheric temperature differences are established.

In winter, convection of energy Q_H from the atmosphere to urban surfaces during nocturnal hours is reduced, or perhaps reversed, by the conduction of large amounts of furnace heat Q_F to the interface, and in summer by the conduction of large amounts of stored solar energy Q_G to the interface. The air above an urban area thus remains warmer than the air above an adjacent non-urban region, i.e., the nocturnal urban heat island effect.

Elevated layers of smoke, water vapor, carbon dioxide and sulphur dioxide contribute to nocturnal heat island development by absorbing and re-radiating energy from urban surfaces. Sheppard (1958) noted that the nocturnal loss of longwave radiation by an urban haze layer is capable of cooling the air above the layer by several degrees centigrade, thus producing an elevated inversion layer. Shortwave energy received at urban surfaces is reduced by the absorption and scattering of haze layers. Several hours after sunrise the haze layers are destroyed by convective currents associated with insolation.

Meteorological conditions favorable to the nocturnal cooling of rural regions, such as clear skies and low wind speeds, lead to large temperature differences between urban and rural atmospheres. The critical wind speed above which differences become zero is estimated as 22 kt in London (Chandler, 1960) and 13 kt in Palo Alto (Duckworth and Sandberg, 1954). The latter were unable to demonstrate any significant correlation between absolute temperature, dew point or absolute humidity and the urban temperature excess.

The creation of a heat reservoir over an urban area leads to vertical motions, which requires a low level convergence into the area. Pooler (1963), Okita (1960) and Scudder (1965) observed such flows when geostrophic winds were weak.

b. Previous observations of the urban heat island

Differences between urban and rural vertical temperature fields are not known in detail due to a general lack of data. Munn and Stewart (1967) studied distributions of air temperature at towers in urban and rural sites in southern Ontario. Higher percentages of inversion-free nights were observed at the urban sites. DeMarrais (1961) concluded from tower data that daytime vertical atmospheric temperature gradients in Louisville differed only slightly from those in rural regions. At night, however, surface inversions were less frequent in the city. Nocturnal inversions were twice as frequent in the upper level of the tower as in the lower level.

Duckworth and Sandberg (1954) found radiation inversions at the surface in 30 out of 32 rural wiresonde temperature soundings taken during 12 test periods between the hours of 2000–0100 PST. Simultaneous urban temperature soundings exhibited inversions in only seven cases, isothermal conditions in seven and lapse conditions in 18. At some level between 100 and 300 ft the temperatures became identical. This level varied with the size of the urban area, and was approximately three times as high as the roofs over which the soundings were taken. Fifty per cent of these cases showed rural temperatures above this level to be significantly warmer than urban values. This "crossover effect" occurred most frequently with very light winds and strong rural inversions. The following were suggested as possible causes of this effect: vertical mixing over the urban area, an urban convection cell, radiative loss by the smoke pall, and variations in the wind field between 100 and 1000 ft. Duckworth and Sandberg believed the last explanation to be the most probable.

Aircraft measurements of the vertical atmospheric temperature field over Cincinnati, Ohio, during 0900–1000 CST by McCormick and Baulch (1962) exhibited decreasing temperatures from the surface to about 125 m with inversions above.

3. Data used in study

Readings from the airborne temperature and pressure sensors were corrected for dynamic heating and electrical drift. Heights were obtained from the pressure values by use of the standard atmosphere. Temperature and height values were accurate to 0.1C and 15 m, respectively. Sampling flights consisted of horizontal traverses and vertical soundings in the area shown in Fig. 2. U. S. Coast and Geodetic Survey maps show this area to be everywhere below 200 m MSL and rarely above 100 m MSL.

Temperatures were averaged to the nearest 0.1C through 50-m layers in each sounding. These layers were centered at 50 m above sea level and at 50-m intervals above this level to the top of a sounding, usually about 700 m. When a sounding continued to sea level, an average value was obtained for the lowest 25 m. The averaging was performed to smooth turbulent temperature fluctuations but may also screen out shallow, weak inversion layers. While these layers may be of extreme importance to the diffusion of pollutants, they are not the main concern of this study.

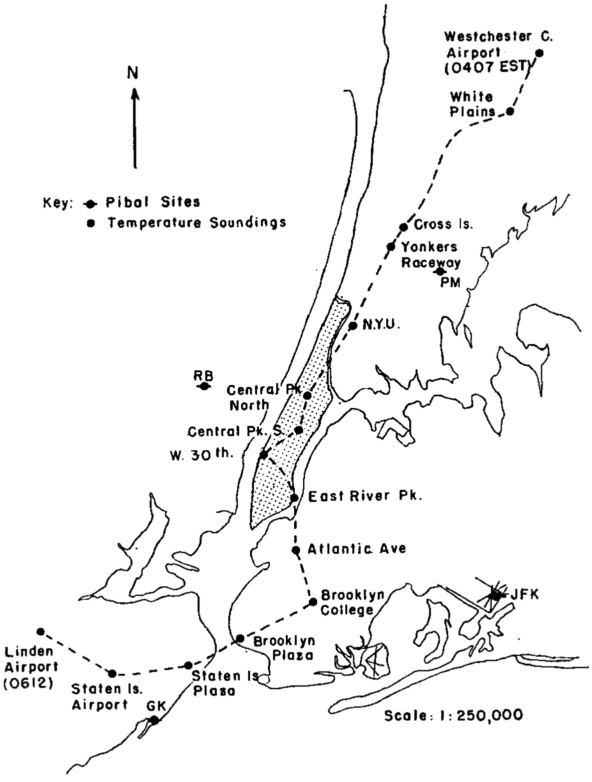

FIG. 2. Area used in study, with typical helicopter flight plan for 16 July 1964.

Sky cover during the hours of the test flights and during the evening hours before the flight, in addition to temperatures and winds at shelter level, were supplied by Weather Bureau stations. Additional shelter-level winds were obtained from Scudder's (1965) mesoscale wind analyses. Eastern Standard Time is used unless otherwise noted.

4. Typical temperature distributions

In terms of the number of soundings taken (Fig. 2), 16 July 1964 was one of the most intensive tests of the program. Clear skies and low wind speeds prevailed from the previous afternoon to the termination of the test period. Shelter-level winds generally were WSW at 5 kt at 0400 and N at 6 kt at 0600.

The distribution of temperatures through the lowest 700 m of the atmosphere on this morning from 0407–0612 is shown in Fig. 3. The vertical cross section was constructed from the average temperature values and follows the route of the aircraft. Geographic distances between soundings are proportional to their separation in the section. Approximate height profiles of the surface are indicated by the hatched areas at the bottom of the section. Vertical lines indicate the range of the soundings, while inversion and isothermal layers are indicated by the shaded regions.

Areas several miles north and south of the city

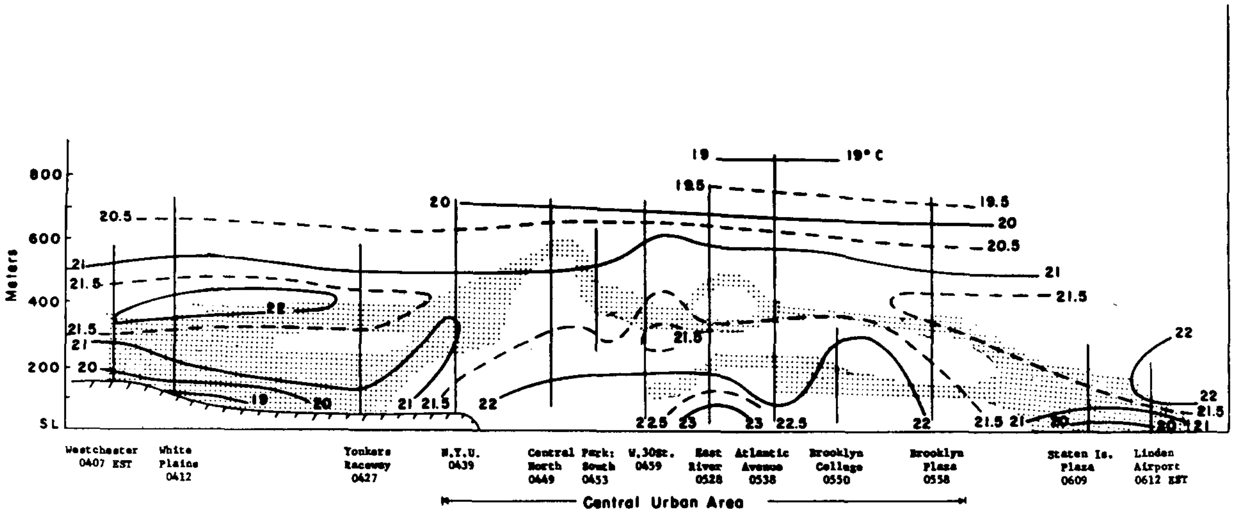

FIG. 3. Vertical and horizontal temperature distribution over the New York City area on 16 July 1964 from 0407–0612 EST.

exhibit surface inversions, while over the city elevated inversions are present. The urban temperature excess is greatest near the surface (4C) and decreases rapidly with height. The temperature excess is near zero at 300 m, which is just below the top of the rural surface inversion, and is negative in the subsequent 100 m. Above 500 m the isotherms are nearly horizontal.

While the depth and intensity of the inversion layer in Fig. 3 increases with increasing distance from the center of the urban heat island, its elevation decreases. The seven urban sites in Manhattan and Brooklyn (North Central Park to Brooklyn Plaza) exhibit from one to three elevated isothermal and/or inversion layers, which are at most 100 m in depth and exhibit a temperature increase not greater than 0.5C. At suburban Yonkers Raceway, both an elevated and weak surface inversion (0.9C through 200 m) were measured, while at rural White Plains only a surface inversion (3.2C through 300 m) was observed. Thus, a weak elevated inversion "dome" existed over the city during this morning.

Lapse rates in the sub-inversion layers over the city varied from nearly adiabatic to nearly isothermal. The lowest 200 m of the East River Park sounding shows nearly adiabatic conditions, while through the same layer at the Heliport nearly isothermal conditions were observed. Lapse rates above rural and urban inversion layers were also close to adiabatic.

Although sunrise was at 0430, the absence of a surface inversion in the city did not result from solar heating. Rural soundings, some of which are shown in Fig. 3 at sites south of the city, exhibited surface inversions at times after sunrise and later than those at urban sites showing only elevated inversion layers.

Temperature soundings 0638–0802 on the same morning revealed the effects of solar heating on surface inversion layers. Rural soundings still exhibited surface inversions until 0646, though significantly weakened. For example, the temperature inversion at Linden Airport decreased from 1.7C through 100 m at 0612 to 0.6C through 50 m at 0638. Urban inversion layers at 600 m were several hundred meters above their levels in the previous section. Similar elevated layers were found at 450 m in the final (rural) soundings. Lapse rates in the sub-inversion layers at all sites were close to dry adiabatic.

The flight path for the morning of 3 March 1965 is similar to that of 16 July 1964. The most significant difference between the two temperature fields is the stronger and better defined main inversion layer over the city on 3 March (Fig. 4). The temperature increase through the inversion layer was 2.4C through 60 m at the center of the heat island.

In summary, the main features of the temperature distribution in the hours around sunrise are the following: 1) intense surface inversions at non-urban sites, 2) absence of surface inversions over the city, 3) one or more relatively weak elevated inversion layers over the city, and 4) an urban temperature excess which decreases rapidly with height.

5. Statistical comparison of urban and rural inversion patterns

The frequency of surface and/or elevated inversions as observed in the lowest 700 m of the averaged soundings from urban and rural sites is presented in Table 1. In addition, the frequency of inversion bases below 700 m during flight mornings was determined from data block A of the WBAN 31A form of the 0615 and 0015 (only during 1966) synoptic soundings at the Weather Bureau station at John F. Kennedy Airport.

The most significant feature of Table 1 is the relatively high frequency of rural surface inversions and

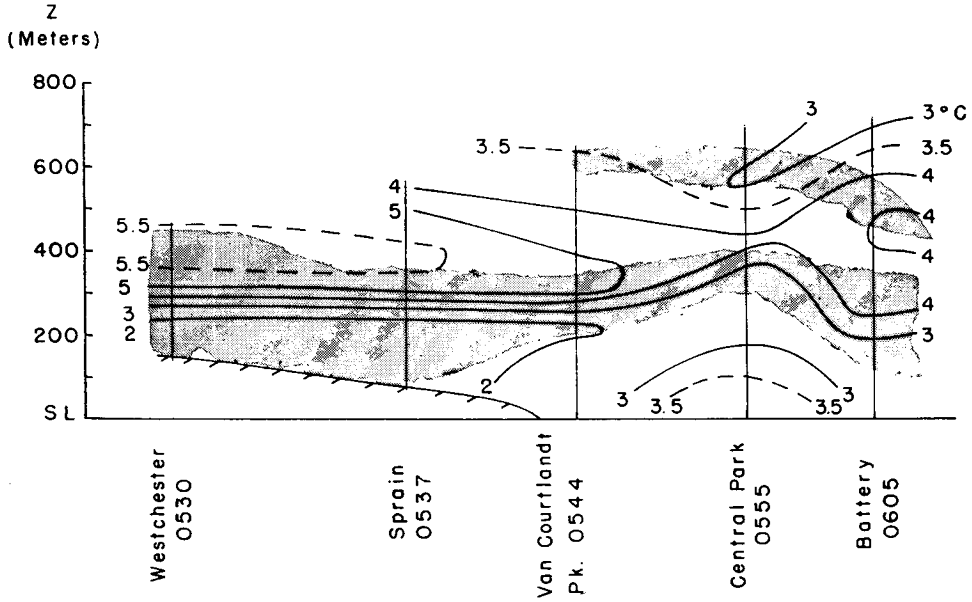

FIG. 4. Vertical and horizontal distribution of temperature over the New York City area during the morning of 3 March 1965. Section is in the direction of surface winds which were N at 8 kt.

urban elevated inversions. Also significant is the non-urban nature of the Kennedy Airport synoptic sounding in that there is a relatively high frequency of surface inversions at 0615. Eleven of the 13 mornings on which surface inversions were observed at the airport also exhibited surface inversions at rural sites. Because of a rapid rate of ascent and large time constant, the synoptic sounding is unable to detect a significant fraction of the weak, elevated inversions layers over the city.

On most of the test mornings when an elevated inversion layer was present over the city, one distinct layer existed (as on 3 March 1965), with at least five mornings revealing two such layers. Weak inversion layers similar to those on 16 July 1964 were often observed in conjunction with the distinct layer, but were sometimes observed alone.

TABLE 1. Number of mornings on which surface and/or elevated inversions below 700 m were observed in the New York City area during the hours near sunrise.

	Number of surface inversions	Total number of mornings	Number of elevated inversions	Total number of mornings
Urban (New York City)	4	42	37	42
Rural	29	40	5	34*
Kennedy Airport (0015)	5	25	3	25
Kennedy Airport (0615)	13	42	7	42

* Temperature data from rural sites were not complete during the eight mornings of the Consolidated Edison project.

On all but three of the 29 mornings the surface inversion appeared at every rural site, but on no days did the surface inversion appear at every urban site. Surface inversions were present at some urban sites on four mornings when the waters around Manhattan Island were cooler than the adjacent land area.

Even the more intense urban surface inversions appear weak when compared with rural surface inversions from sites several miles from the city, as in the upper panel of Fig. 5. Lapse rates through the lowest 200 m of the urban atmosphere were frequently close to adiabatic, while as seen in the lower panel of Fig. 5, intense surface inversions existed several miles from the city. The largest temperature increase through a rural surface inversion was 11.6C, which occurred over the greatest depth of 370 m. Corresponding maxima for urban surface inversions were 1.2C and 100 m, respectively.

For each morning, the center of the heat island was defined as that site at which the base of the most intense elevated inversion layer was highest. The average temperature lapse rates at the center of the heat island were used to identify the main inversions, and if two intense inversions were present, the lower one was used. The non-averaged soundings were then used to determine the elevation of the inversion base, as well as its depth, intensity and temperature increase. Daily maxima of the last three inversion parameters were also determined for the rural surface inversions.

The frequency distribution of the height of the urban elevated inversion base at the center of the heat island is shown in Fig. 6. Heights ranged from 70–550 m, with a mean of 310 m and a standard deviation of 110 m.

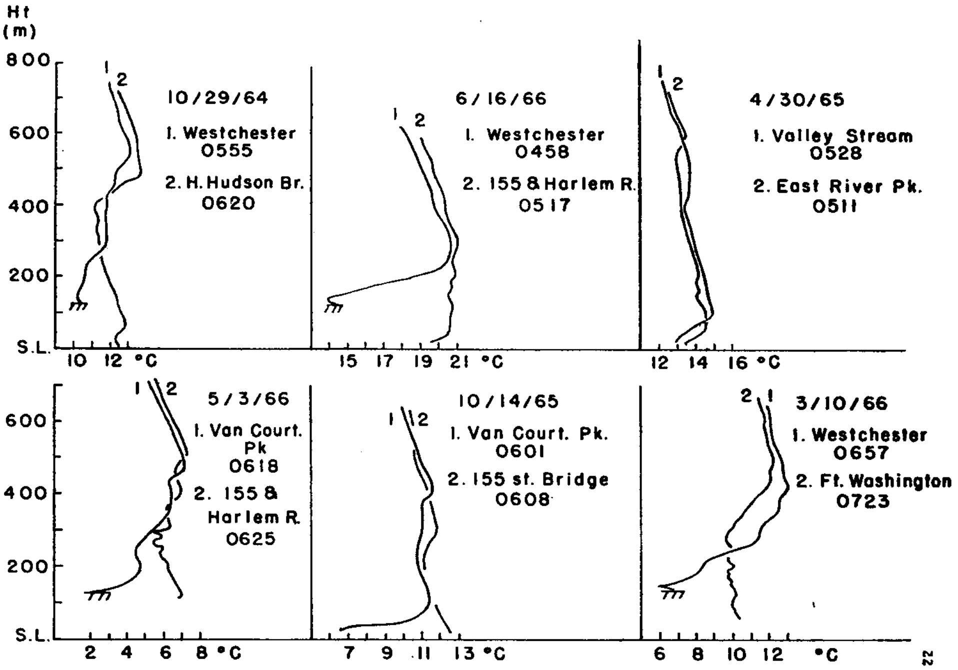

FIG. 5. Examples of temperature soundings from urban and rural regions, labelled 1 and 2, respectively.

Characteristics of inversion depth, temperature increase and intensity for both urban elevated and rural surface inversions are given in Table 2. The data show urban elevated inversions to be more shallow and less intense, as well as less variable, than rural surface inversions.

6. Height variation of urban-rural temperature differences

For each test morning, except those from the plume rise study, the warmest urban sounding through the lowest 150 m and a nearby (in time and space) sea level rural sounding were selected. The height variation of the mean difference between the 50-m averaged temperatures at these sites is shown in Fig. 7.

TABLE 2. Statistics of urban elevated and rural surface inversion characteristics.

	Urban elevated	Rural surface
Depth [m]		
Mean	95	170
Standard deviation	70	90
Range	20–280	40–370
Temperature increase [°C]		
Mean	1.4	3.7
Standard deviation	1.1	2.3
Range	0.1–3.8	0.8–11.6
Intensity [°C(100m)$^{-1}$]		
Mean	1.8	3.3
Standard deviation	1.4	2.3
Range	0.4–6.7	0.9–8.3

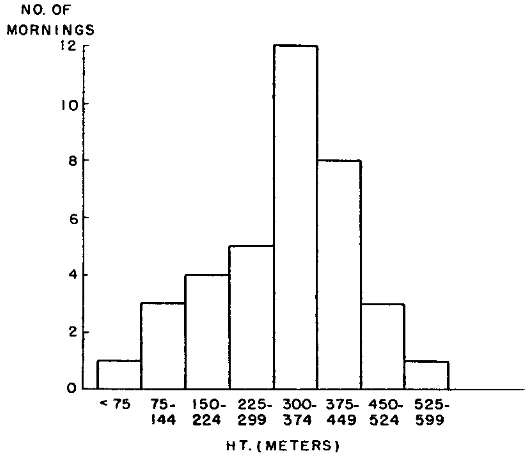

FIG. 6. Frequency distribution of heights of elevated inversions bases.

The curve shows an almost linear decrease in the mean urban temperature excess from 1.7C at 1.25 m to zero at 300 m. Above 300 m the magnitude of the mean difference is less than 0.2C, and is negative from 300 to 500 m.

Differences as large as 4.6C at 50 m in the averaged temperatures of nearby urban and rural sites were observed near the surface on mornings with intense rural surface inversions. Urban excesses >1.0C were found at levels above 500 m on mornings when the temperature increase through the elevated inversion layer over the city was relatively large, i.e., 2–3C.

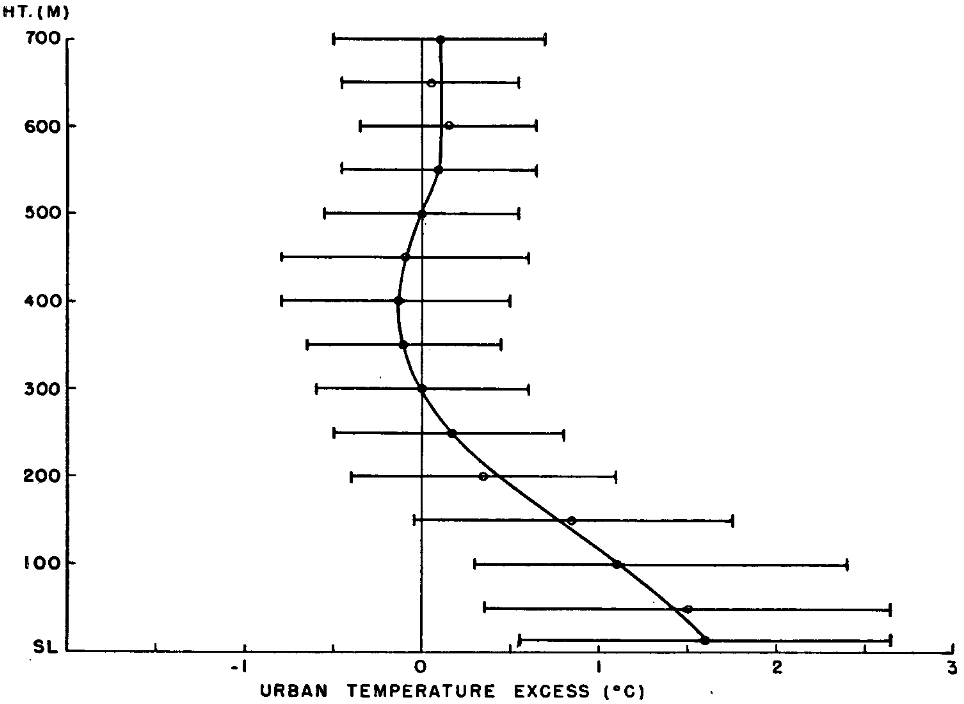

FIG. 7. Height variation of the magnitude of the urban heat island of New York City during the hours near sunrise. Range of plus and minus one standard deviation is also shown.

During more than two-thirds of the test mornings a reverse heat island effect was observed through a layer whose base was always above 150 m. On the average, the cross-over effect dominated the heat island effect through the layer from 300–500 m as seen in Fig. 7.

Characteristics of the base and depth of the cross-over layer, as well as those of the rural temperature excess, are given in Table 3.

The difference between the relatively large value of the maximum rural excess, as given in Table 3, and the small value of the reverse heat island effect in Fig. 7, is explained by the nature of the cross-over layer. Due to the wide range in the base height and the shallowness of the cross-over layer, no more than half of the urban-rural temperature differences at any level were negative, and the cross-over effect was almost averaged out of the curve in Fig. 7. Thus, when a cross-over layer was present, its magnitude was greater than shown in Fig. 7, but less than the magnitude of the urban heat island.

7. Conclusions

In the area of urban influence, surface inversions were less intense and far less frequent than in the surrounding non-urban regions. A high frequency of elevated inversion layers, which were less intense than the nearby rural surface inversions, were observed over the city. Lapse rates below the inversion layers varied from near-isothermal to near-adiabatic, while above the inversion near-adiabatic conditions were observed. The average height of the base of the urban elevated inversion layer (310 m) was almost identical to the average level at which urban-rural temperature differences became zero.

The average intensity of the urban heat island, as measured by the magnitude of the temperature difference between urban and rural sites, was a maximum (1.6C) below 25 m and decreased to zero at 300 m. On mornings with strong urban elevated inversion layers (2–3C), the heat island extended to well over 500 m.

Many test mornings exhibited an elevated cross-over layer of about 200 m in depth, in which rural temperatures were higher than urban temperatures. The magnitude of the cross-over effect was less than that of the heat island effect. Therefore, even with a cross-over layer, the total heat energy in an air column was greater over the city than over a surrounding non-urban region.

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TABLE 3. Statistics of the cross-over layer parameters.

	Mean	Standard deviation	Range
Base of layer (m)	305	100	150–600
Depth of layer (m)	180	90	50–400
Level of maximum rural excess (m)	370	110	200–700
Maximum rural excess (°C)	0.84	0.53	0.2–1.9

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