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Mesoscale aspects of the Urban Heat Island around New York City

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With 19 Figures

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Summary

A mesoscale analysis of the Urban Heat Island (UHI) of New York City (NYC) is performed using a mesoscale network of weather stations. In all seasons the UHI switches on rapidly in late afternoon and shuts down even more rapidly shortly after dawn. It averages about 4 °C in summer and autumn and 3 °C in winter and spring. It is largest on nights with clear skies, low relative humidity through much of the troposphere, and weak northwest winds, when it may exceed 8 °C. The synoptic meteorological situation associated with the largest UHI occurs roughly two to three nights after cold front passages.

During spring and summer, sea breezes commonly reduce and delay the UHI and displace it about 10 km to the west. Backdoor cold fronts, which occur most frequently in spring and early summer, reduce or even reverse the UHI, as cold air from the water to the northeast keeps NYC colder than the western suburbs. Cases documenting the sensitivity and rapidity of changes of the UHI to changes in parameters such as cloud cover, ceiling, and wind speed and direction are presented.

1. Introduction

Ever since Luke Howard discovered that London was warmer than the surrounding countryside, studies of the Urban Heat Island (UHI) have tended to emphasize its climatological aspects (Renou, 1862; Landsberg, 1981). The urban energy budget has usually been evaluated without including the troublesome effects of advection by the wind (Oke, 1995). To predict the magnitude of the UHI under particular weather conditions, regression equations have been developed that relate the UHI to synoptic meteorological parameters such as cloud cover or wind speed (Eliasson, 1996; Runnalls and Oke, 2000) or to generalized synoptic weather regimes (Morris and Simmonds, 2000). The major conclusions that emerge from such studies are as follows: the UHI is most pronounced on calm, dry, clear nights near the center of anticyclones. Under such conditions heat is retained in the city while a pronounced nocturnal inversion forms in the countryside as the ground radiates heat rapidly to space. Conversely, the UHI is reduced on windy, humid, overcast nights with precipitation, often under cyclonic conditions, because the nocturnal inversion cannot form, and urban and rural heat budgets are similar.

In an attempt to produce a more complete picture of the UHI, increased attention has been focused on the impact of horizontal advection and on varying weather conditions. Thus, the UHI is displaced by the prevailing wind (Oke, 1995). The energy balance is affected not only by the prevailing wind but also by the circulation set up by the temperature difference between city and surrounding countryside (Haeger-Eugensson and Holmer, 1999). The impact of mesoscale phenomena such as drainage winds (Hertig, 1995) and the sea breeze (Yoshikado, 1990, 1992) on the UHI are now examined in data and modeling studies.

Many studies that attempt to produce more detailed pictures of the UHI have been conducted as field experiments for limited time periods (Zois, 1986; Montávez et al., 2000). In such studies data from a relatively small number of resident weather stations are enhanced by finer-scale records obtained from instrumented vehicles performing transects of the region during the period of the field experiment. General conclusions must be based on fortuitous cases.

The recent establishment of mesoscale weather networks (Brock et al., 1995) has made it possible to obtain pictures of the mesoscale meteorological aspects of the UHI on a routine basis. In the mid 1990's a mesoscale network of weather stations in the Greater Metropolitan Area around New York City (NYC) was established. In this article the data from this network is used to provide a mesoscale picture of the UHI in and around NYC.

The coastal setting of NYC imparts a strong mesoscale component to the UHI. NYC is located on several islands and one peninsula of the mainland along the East Coast of the United States. Long Island extends to the east of NYC and is bounded on the south by the Atlantic Ocean and on the north by Long Island Sound. New Jersey, situated to the west and mostly south of NYC, is bounded on the east by the Atlantic Ocean. Along the coastal strip, appreciable land-sea temperature contrasts exist in all seasons and impart a strong local signal to a range of meteorological phenomena. During winter storms, the rain-snow line often lies directly over NYC and snow cover increases almost abruptly to the northwest. Sea breezes that cool NYC more than the inland suburbs are common on warm spring and summer days, while the ocean frequently warms coastal locations on cold nights in autumn, winter, and early spring. On many spring days, 'backdoor cold fronts' (Richwien, 1980) followed by cold northeast winds that are channeled along the coast by the hills and mountains to the north and west overwhelm the UHI by chilling NYC more than the western suburbs.

2. Data sources and methodology

The primary data source for this study consists of hourly surface weather observations for the two-year period, 1997–98 from a network of 50 volunteer and about 25 National Weather Service (NWS) stations in the New York – New Jersey Metropolitan area that included several ocean buoys (see Fig. 1). Surface meteorological data at NWS stations includes cloud cover and height, visibility, weather, pressure, temperature, dew point temperature, wind speed and direction, and precipitation. Volunteer stations do not include visibility or cloud measurements. The buoys give water temperature but do not include visibility, cloud cover or precipitation. The surface weather data is augmented by several other

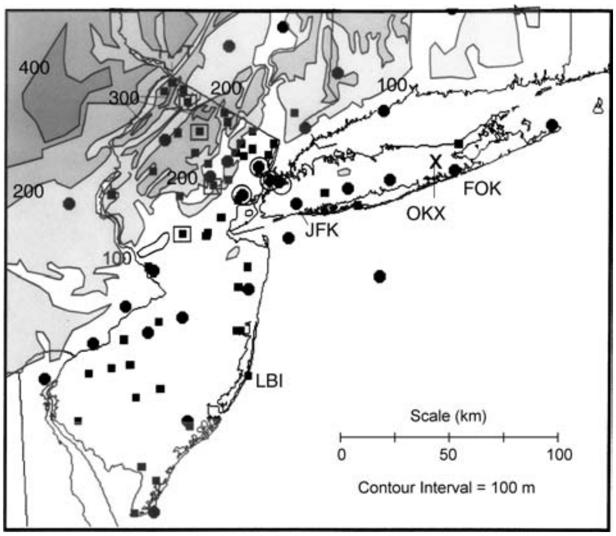

Fig. 1. Weather stations and topography of the Greater New York City Metropolitan Area. Circles indicate NWS stations, squares, private stations. The four stations marked by concentric circles and concentric squares are used as the urban and rural stations respectively. The contour interval is 100 m and the analysis omits fine scale features. The sickle-shaped ridge about 10 km west of NYC represent the Watchung Mountains

sources including soundings, mainly from the NWS station, OKX at Brookhaven, NY (100 km east of NYC), satellite and NEXRAD radar imagery, and analyses and forecasts of various parameters from NWS models.

Stations are several kilometers apart at best, so that only the mesoscale aspects of the UHI are investigated here. The magnitude of the UHI is almost certainly understated because traverses through the urban heartland were not included (Runnalls and Oke, 2000) and because no stations are located in the paved heart of the urban center. For example, station NYC is located atop a small hill in Central Park, Manhattan roughly 300 m from the nearest grid of streets and buildings. Many of the volunteer stations, particularly in northern New Jersey, are located on the grounds of private homes and do not conform to international standards. Local topography plays a significant role in temperature variations, with differences of 3 °C or more commonly occurring in less than 100 m of relief on clear nights. Therefore, using international standards to register variations of surface temperatures in and around cities has been recognized as a significant problem (Voogt and Oke, 1997).

Given these problems regarding the reliability of the setting of stations and the accuracy of the data, hourly surface weather maps of temperature and wind were constructed and inspected to screen data from for obvious errors and inconsistencies. Inconsistent or blatantly erroneous data were deleted and stations whose data was biased were excluded. The final product was a consistent set of hourly surface weather maps for the year 1998.

A major component of this research was to identify illustrative or extreme examples of the UHI for case study. These were identified using two techniques. First, the hourly surface analyses were color-coded for temperature and animated for each day in 1998. In this way a host of phenomena including the UHI, sea breezes, frontal passages, and squall line motions could be visualized in an unmistakable manner. Second, meteorograms and scatter diagrams relating the UHI to standard parameters such as wind speed and direction, cloud cover, and the strength of the rural nocturnal inversion, were prepared to identify anomalous cases. Each of these cases was then analyzed in greater detail to identify causative factors.

Climatological analyses included the two-year period, 1997–98. In the climatological analyses, seasons were defined as three-month periods using the meteorological standard that the period, DJF (December, January and February) constituted winter, MAM, spring, JJA, summer, and SON represented fall.

3. Climatological features of the Urban Heat Island

The UHI is a nocturnal phenomenon in all seasons. A surface plot of temperature at midnight during Autumn (Sep–Nov) across the Greater New York Metropolitan area (Fig. 2) shows the highest values occur in New York City while much lower values occur in the northwest suburbs. Nocturnal temperature also drops substantially below urban values in the rural eastern portions of Long Island.

The magnitude of the urban-rural temperature difference, ΔT_{U-R}, was defined using the average temperature of four urban stations (NYC, LGA, EWR, and TEB) minus the average temperature at four of the reliable and representative inland rural stations (BLM, CHA, OKR, and SSX). The rural stations are centered 50 km west of the urban stations and further inland. This introduces a bias whenever east–west temperature gradients existed, such as during frontal

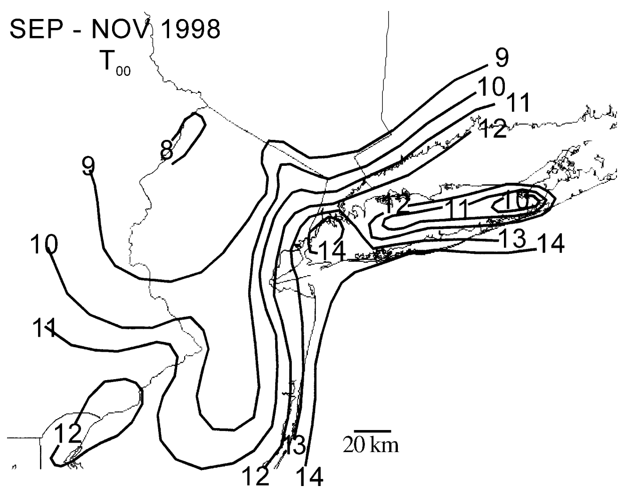

Fig. 2. Map of mean temperature (°C) at midnight during meteorological autumn (Sep–Nov) across the region

passages and sea breezes. This bias was subtracted when appropriate (e.g. as in Fig. 6). After 22 July 1998 station FOK (40.85 N, 72.83 W and 95 km east of the urban stations) – began reporting hourly weather data, which showed that similar nocturnal cooling occurred east of NYC as well.

ΔT_{U-R} has an average magnitude of 3 °C in winter and spring, and 4 °C in summer and autumn, when wind speeds are smaller on average (Fig. 3). It increases rapidly from almost zero in mid afternoon to an almost constant value all night, as Oke and Maxwell (1975) and Hage (1972) have found. In the morning, ΔT_{U-R} decreases even more sharply than it increases in the evening, because the nocturnal inversion tends to steepen more than it deepens over the course of the night. This differs from the more rapid evening cooling found around St. Louis during METROMEX (Hilberg, 1978). Even near the winter solstice, the rising sun can produce extremely rapid temperature increases in the countryside because it only has to heat a very shallow layer of air. In fact, 2-hour increases of ΔT_{U-R} exceeding 6 °C occurred 22 times during the fall and winter months of 1998. This never happens during late spring and summer when the nights are shorter and clear, dry and, almost calm nights near the center of polar high pressure areas are least likely. Two-hour decreases of ΔT_{U-R} exceeding 6 °C occurred only 3 times in 1998, but each of these cases was associated with the passage of a cold front or squall line during mid afternoon, and not by nocturnal cooling.

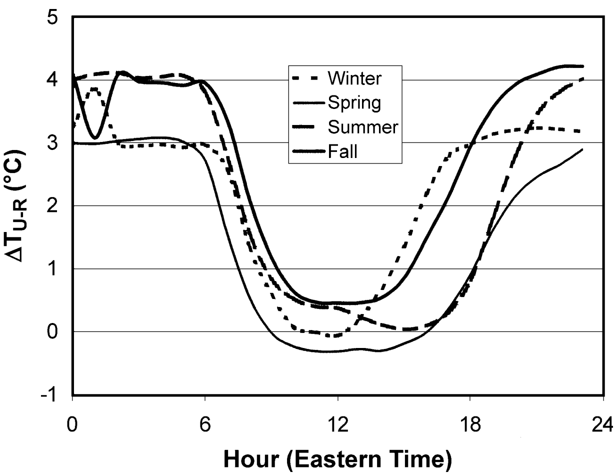

Fig. 3. Hourly values of urban – rural temperature difference, ΔT_{U-R}, for each of the four meteorological seasons (Winter = Dec–Feb)

For 1998, the maximum nightly value of ΔT_{U-R} correlated positively (0.37) with the magnitude of the 1200 UTC surface temperature inversion at OKX (ΔT_{INV}), much as Ludwig (1970) found for a number of cities. However, considerable scatter exists for several reasons. First, the sun rises early enough in the months near the summer solstice to reduce or destroy the nocturnal inversion by sounding time. Second, surface inversions also occur during sea breezes or frontal situations when ΔT_{U-R} tends to be small or negative. To reduce the impact of these cases, Fig. 4 shows ΔT_{U-R} vs ΔT_{INV} only on Year days 1–120 and 240–265 when the inversion height was less than 300 m. Under

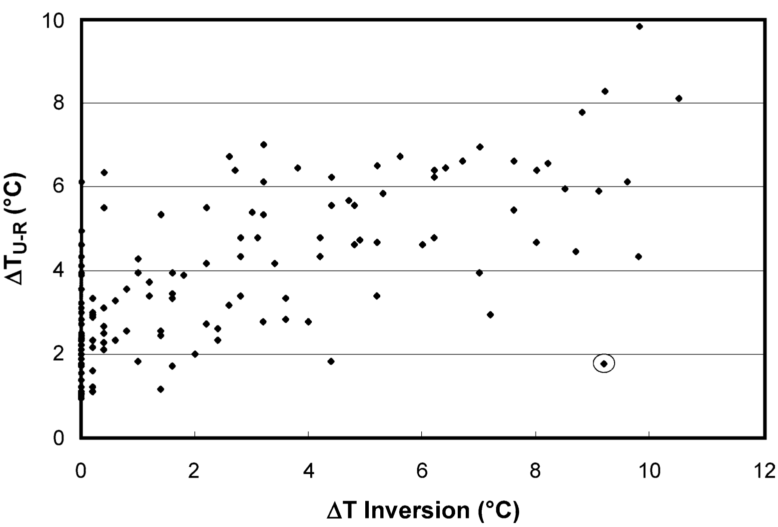

Fig. 4. Relation between the magnitude of the surface temperature inversion at OKX at 1200 UTC and ΔT_{U-R} for Year days 1–120 and 240–365 on nights when the depth of the nocturnal inversion was less than 300 m. Circled point near lower right is the night of 27–28 Oct

these restricted conditions, the correlation between the nightly maximum ΔT_{U-R} and the magnitude of the surface inversion increases to 0.694.

Figure 4 reveals anomalous cases, such as the night of 27–28 October (circled point), when ΔT_{U-R} was only 1.8 °C despite a large $\Delta T_{INV} = 9.2$ °C. On this night, high pressure over New England produced clear skies over NYC and OKX while the northwestern suburbs were covered by a low overcast that kept temperatures in the western suburbs relatively high. Removal of this single case raised the correlation between ΔT_{U-R} and ΔT_{INV} to 0.728.

Cloud cover and height, surface humidity, and wind speed, have the expected large impacts on the magnitude of the UHI (Semonin, 1981). Under clear skies, ΔT_{U-R} averages 4.5 °C. When the sky is overcast the average ΔT_{U-R} falls to 2.3 °C, and large values never occur (Fig. 5). ΔT_{U-R} also increases as the height of the cloud base increases. Opaque clouds radiate like black bodies according to their absolute temperature. Therefore, as the height of cloud base increases less heat is radiated downward, assuming a positive lapse rate above the nocturnal boundary layer. The correlation between the height of cloud base as determined from the sounding at OKX and the maximum ΔT_{U-R} on any night is 0.54. (Clear soundings are assigned a cloud base at 12 km.) ΔT_{U-R} also correlates significantly (0.49) with the depression of the dew point temperature ($T - T_d$) at the

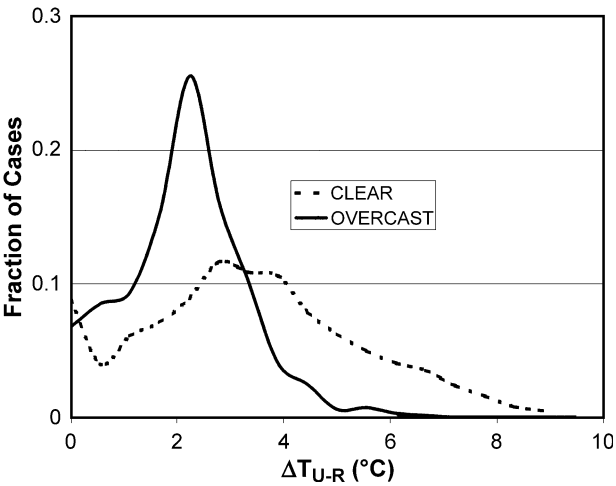

Fig. 5. Histogram of ΔT_{U-R} for clear and overcast conditions

Table 1a. Magnitude of the UHI as a function of wind speed at JFK

Wind speed (kt)	ΔT_{U-R} (°C)
<5	4.9
>10	2.8
>15	2.3
>20	2.1

surface since dry air radiates less heat down to the ground. Average ΔT_{U-R} increases from 2.1 °C when $T - T_d < 3$ °C to 5.6 °C when $T - T_d > 14$ °C.

Wind reduces the magnitude of the UHI in two ways – by mixing cold air at the surface with warmer air aloft and by ventilating the city. At midnight, ΔT_{U-R} averages 4.8 °C when wind speed is less than 5 kt but only 2.1 °C when wind speed is above 15 kt (Table 1a). Wind speed varies with the synoptic setting and is typically larger during cyclonic weather or in the hours following a cold front passage. As winds slow and high pressure with clear skies and drier air approaches, ΔT_{U-R} increases to a maximum value for any synoptic weather condition between two and three nights after a cold front passes (Fig. 6). Because the rural stations are located an average of 50 km west of the urban stations, the bias in the ΔT_{U-R} due to the synoptic scale temperature field was removed from Fig. 6 by subtracting the east–west temperature differences at the 850 hPa level.

Wind direction has a profound influence on the magnitude and location of New York City's urban heat island because of its coastal setting. This makes it informative to group ΔT_{U-R} by wind quadrants (Table 1b) and season. During spring and summer, ΔT_{U-R} is significantly larger when the wind blows from either of the two westerly quadrants, i.e. from the land. The largest average ΔT_{U-R} occurs with winds from the northwest quadrant since skies tend to be clearest and have the lowest relative humidity. When the wind has an easterly component, it comes off the cold waters and tends to cool the city more than stations located further inland. The smallest average ΔT_{U-R} at midnight occurs when the wind of the previous afternoon blows from the southeast quadrant, the direction of the sea breeze in the area. Antecedent winds provide the highest correlation with ΔT_{U-R} because the cooling caused

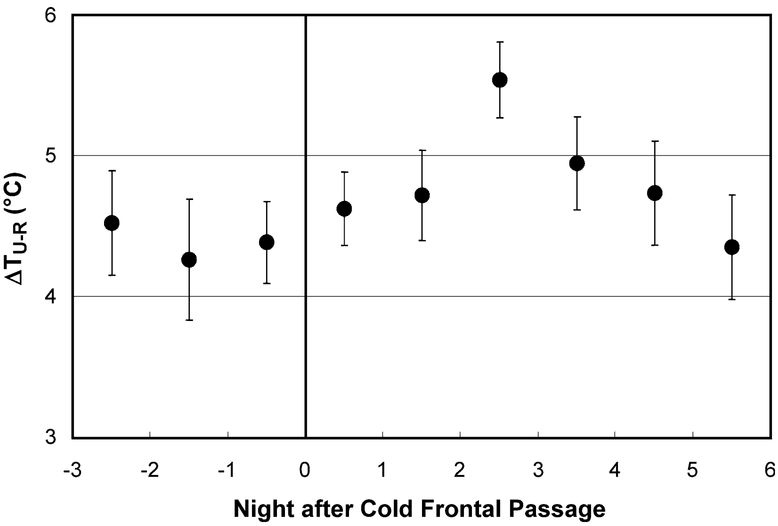

Fig. 6. Average ΔT_{U-R} for each night before and after cold front passage. The largest mean ΔT_{U-R} occurs on the third night after cold front passage. Vertical lines represent error bars for each night

Table 1b. Magnitude of the UHI as a function of wind direction at JFK

Wind direction	ΔT_{U-R} (°C)
0–90	2.9
90–180	2.2
180–270	3.5
270–360	4.2

by the sea breeze tends to persist for several hours after the wind direction has changed.

Even though the sea breeze has a major impact on temperatures, cooling the coastal strip and NYC more than the outlying rural areas to the north and west, its impact on ΔT_{U-R} often disappears shortly after midnight. The sea breeze does, however, delay the UHI for several hours. Figure 7 shows that on nights with a strong sea breeze, the ΔT_{U-R} starts somewhat later and increases more slowly, but both ultimately reach the same magnitude around midnight. The criterion used to define a day with a strong sea breeze is that at 1600 local time, temperature at NYC must be at least 2.2 °C warmer than at JFK, and the southerly component of the wind at JFK must exceed that at NYC by 5 kt.

During the early hours of the night, when the lingering effects of the sea breeze are still felt, the center of the heat island is often displaced to the New Jersey Meadowlands, about 10 km west of Manhattan. Cooling by the sea breeze diminishes with distance inland from the coast at a rate that varies with wind direction and speed and the depth of the chilled layer. Because of the

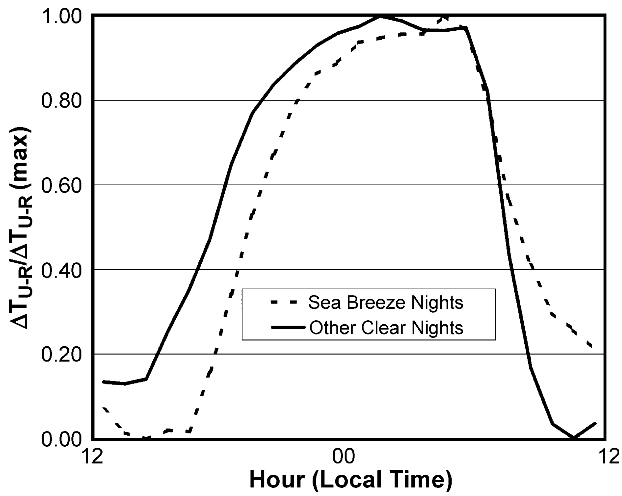

Fig. 7. Normalized mean hourly values of the ratio $\Delta T_{U-R}/\Delta T_{U-R}$ (max) on sea breeze vs. other mostly clear nights

prevailing southerly winds during late spring and summer, the sea breeze often penetrates further inland and is associated with a smaller temperature gradient on the south-facing shores of Long Island, NYC, and Connecticut than on the east facing shore of New Jersey.

Nocturnal cooling, sea breezes and backdoor cold fronts all produce surface temperature inversions. Nocturnal radiation inversions tend to be quite shallow (<100 m), which accounts for the occasional rapid decrease of ΔT_{U-R} in the morning. Inversions associated with the sea breeze at OKX (determined from the 0000 UTC soundings) average just above 400 m deep. This is shallow enough to allow rapid warming and produce a large temperature gradient inland from the coast in most cases during spring and summer days. More elevated inversions are associated with backdoor cold fronts, enabling the cold air to penetrate much further inland.

Backdoor cold fronts are anomalous situations in which cold air invades the NYC Metropolitan Area from the northeast. They are most common in late winter and spring, and tend to produce the smallest UHI in the Greater New York Metropolitan Area. During intense backdoor cold fronts, ΔT_{U-R} may even be negative. At such times, chilling, damp NE winds, from polar high pressure areas centered over southeastern Canada, blow down the length of Long Island Sound and into NYC. The Appalachian Mountains to the west simultaneously block the advance of warmer air from the southwest and dam the surface layer of cold air against the eastern slopes. This both thickens the cold air mass and deflects it down the Eastern Seaboard as far south as the Carolinas (Richwien, 1980). As a result, the cold air layer associated with pronounced backdoor cold fronts is often more than 1500 m deep. Backdoor situations occur much less often than the sea breeze so that some years have few good cases. In 1998, there were only a few relatively weak backdoor cold fronts. These seldom passed far south of NYC, and had a mean inversion height on 804 m for the 0000 UTC sounding at OKX.

The inland penetration of cold air following backdoor cold fronts is often increased by a blanket of low clouds and fog that is thickened further by frictional convergence along the coast. At such times temperatures on the foggy coast can be 25 °C colder than inland temperatures in the sunny western and northern suburbs.

4. Meteorological features of the UHI

To illustrate how meteorological factors affect the UHI we analyze exemplary cases of the UHI for a number of different weather situations in 1998 revealed by the mesoscale network of stations shown in Fig. 1.

4.1 Classical UHI

A classical case of a large UHI occurred on the night of 9–10 December 1998, two days after

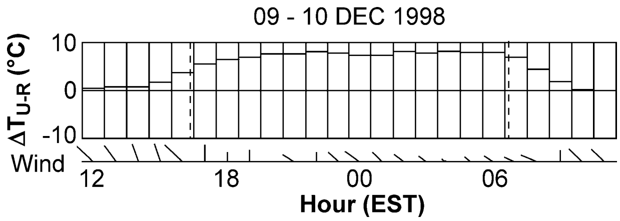

Fig. 8. Meteorogram of ΔT_{U-R} and wind at JFK for the classical UHI of 9–10 December 1998. Dashed lines indicate times of sunrise and sunset. Length of the wind shafts is proportional to wind speed

record warmth in the Northeast United States. The meteorogram (Fig. 8) shows that ΔT_{U-R} began to increase rapidly about two hours before sunset and approached its maximum value of 8 °C by 2000 EST. Thereafter, ΔT_{U-R} remained almost constant until dawn, after which it rapidly decreased and disappeared by 1000 EST.

The synoptic situation provided optimal conditions for a large UHI. On the previous night, a low pressure area moved up the coast and skies were mostly overcast. Because no precipitation occurred the ground remained dry. After the low passed by to the northeast, sinking air prevailed and high pressure approached from the west. Skies cleared by dawn on the 9th and winds backed to northwest. Wind speed diminished to 5 kt or less by late afternoon, everywhere except at LGA, where winds remained brisk until almost midnight. The sounding at OKX for 1200 UTC of 10 December contains a sharp nocturnal inversion only 70 m deep, and dry, clear air to the top of the troposphere (Fig. 9). However, the appearance of a broken layer of high clouds shortly after dawn on the 10th slowed the morning warming and the disappearance of the UHI.

The ΔT_{U-R} for this case had one of the largest magnitudes of 1998. Most cases of large UHI occur under the same general synoptic conditions, namely clear skies with gentle northwest winds and dry air from ground up to the tropopause. Such conditions typically occur about two to three nights after the passage of a cold front, when high pressure is centered a relatively short distance to the west of NYC. As is typical of such situations, a map of the 3-h temperature change (from 1500 to 1800 EST on 09 December) shows that the suburbs cool much more quickly than the urban centers in the early evening hours (Fig. 10). Once the rural nocturnal

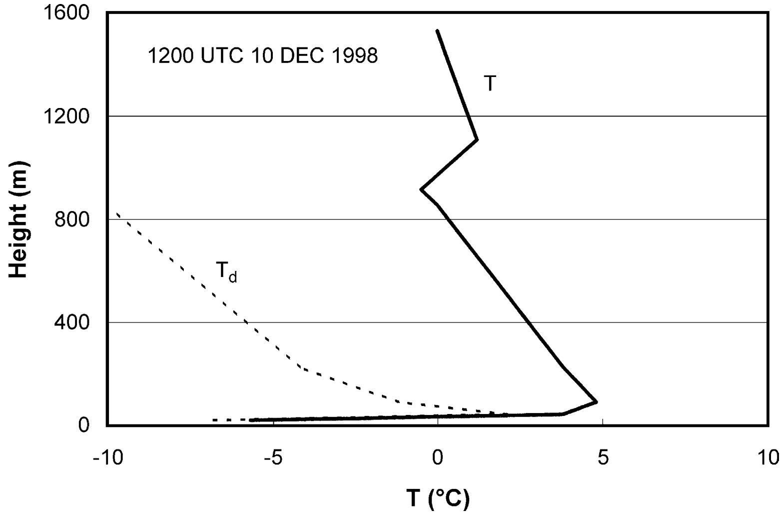

Fig. 9. Vertical sounding of temperature and dew point temperature at OKX for 1200 UTC of 10 Dec 1998 with a sharp nocturnal inversion 70 m above the ground, and dry, clear air above

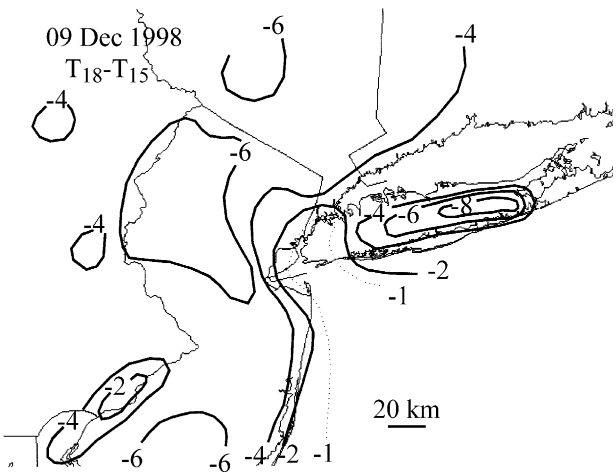

Fig. 10. Surface map of the 3-hour temperature change (from 1500 to 1800 EST on 09 Dec 1998) with much more rapid early evening cooling in the rural suburbs than in the urban centers

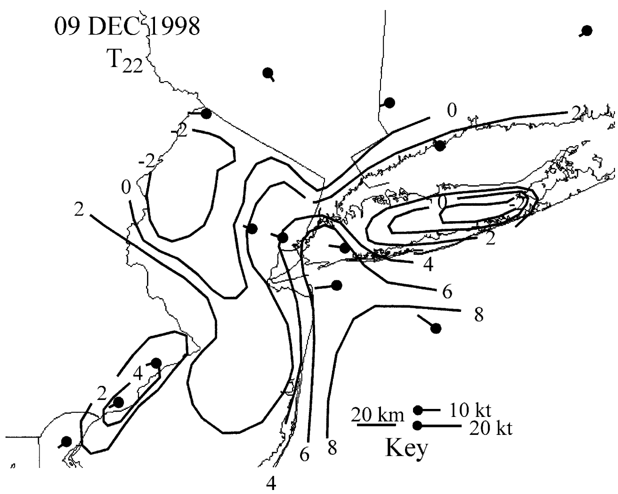

Fig. 11. Surface weather map of temperature and wind at 2200 EST on 9 Dec 1998 with a pronounced UHI centered over NYC. Wind direction and speed are shown for selected stations. Wind speed is proportional to the length of the shaft

inversion is established, city and countryside cool at almost the same rate. Cooling rates are also highly influenced by topography and hence are more localized than the contour analysis suggests. For example, early evening cooling rates are almost always anomalously small at High Point in extreme northwest New Jersey (elevation 465 m) since this sloped, elevated site invariably reduces the nocturnal inversion.

The map of surface temperatures at 2200 EST on the 9th shows the large UHI centered over NYC (Fig. 11). A smaller and less pronounced UHI is also apparent over Philadelphia. On this night, UHI was compounded by the proximity of a very warm ocean. The map shows a striking temperature contrast between land and water. Air at any station with a trajectory that passed over water was distinctly warmer than inland locations. LBI (Long Beach Island, NJ), which was roughly 6 °C warmer than the mainland to the west, is a case in point. LBI is located on a barrier island and separated from the mainland by Barnegat Bay, which at that point is 7 km wide. The elevated temperature at LBI results largely from the turbulent transfer of sensible heat from the warmer water surface to the thin layer of nocturnally cooled air passed over Barnegat Bay. Using the Austauch equation, the sensible heat flux, F, for air as it first reaches the Bay is roughly,

$$F = C\rho c(T_{SST} - T_{AIR})v \approx 32\,\mathrm{W\,m^{-2}}$$

where the sea surface and air temperatures are respectively $T_{SST} = 10\,°C$, $T_{AIR} = 2\,°C$, $C \approx (10)^{-3}$ is the Austauch coefficient, $\rho = 1.28\,\mathrm{kg\,m^{-3}}$ is the density of the air, $c = 1004\,\mathrm{J\,kg^{-1}\,K^{-1}}$ is the specific heat capacity of air at constant pressure and, $v = 3\,\mathrm{m\,s^{-1}}$ is the wind speed. Since the nocturnal inversion at OKX was only 70 m (9 hPa) thick, the calculated temperature rise in crossing Barnegat Bay is 8 °C, assuming the heating decreased linearly (a) with height to the top of the nocturnal inversion and (b) with distance from the mainland to LBI. This is more than enough to produce the observed temperature at LBI.

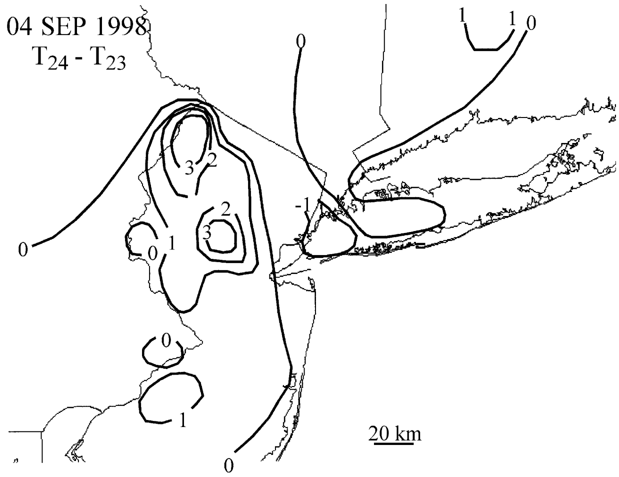

Fig. 12. Surface map of temperature change showing urban cooling and rural warming from 2300 to 2400 EDT on 04 Sept 1998. At the time, wind speed increased and a band of altocumulus crossed the region

4.2 Quick response UHI

Hour-by-hour comparison of rural and urban stations reveals that during the night, ΔT_{U-R} can respond rapidly to changes of larger scale meteorological parameters such as wind speed and cloud cover. Increased surface wind speed causes mixing that warms the countryside by reducing the shallow nocturnal inversion at the same time it cools the city through ventilation and advection. Onset of a cloud cover dramatically slows or even reverses cooling in the countryside once a marked nocturnal inversion has developed while it has much less impact on urban temperatures.

A good case of a quick response UHI occurred on the night of 4–5 September 1998. ΔT_{U-R} increased to 5.7 °C by 2300 EST under mostly clear skies and gentle winds. Shortly before midnight a broken deck of altocumulus (base 2700 m) passed over the region. At the same time, wind speed at both EWR and LGA increased from near calm to about 10 kt. In response to these changes, ΔT_{U-R} decreased by 1.8 °C as mean urban temperature fell and rural temperature simultaneously rose between 2300 and 2400 EDT (Fig. 12).

Once the sun rises following clear, calm nights, ΔT_{U-R} disappears rapidly because the nocturnal inversion in the countryside tends to be quite shallow and steep. The largest 2-hour decrease of ΔT_{U-R} in 1998 (9.8 °C) took place between 0600 and 0800 EST on the morning of 25 October 1998. While the rural stations warmed by an average of 10.8 °C, the urban stations only warmed by 1.0 °C (Fig. 13). The OKX sounding at this time (Fig. 14) had a steep, shallow inversion ($\Delta T_{INV} = 9.8\,°C$, $\Delta z = 82\,\mathrm{m}$) topped by clear, dry air with the dew point depression exceeding 20 °C through most of the troposphere. Simple heat balance calculations show that such an inversion will be erased in 2 hours with a mean solar irradiance of only $70\,\mathrm{W\,m^{-2}}$.

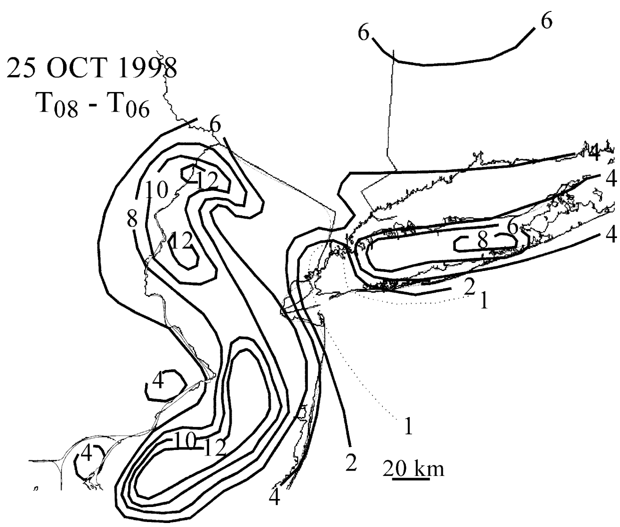

Fig. 13. Surface map two hour temperature change from 0600 to 0800 EST 25 Oct 1998 with much more rapid morning warming in the rural areas than in New York City

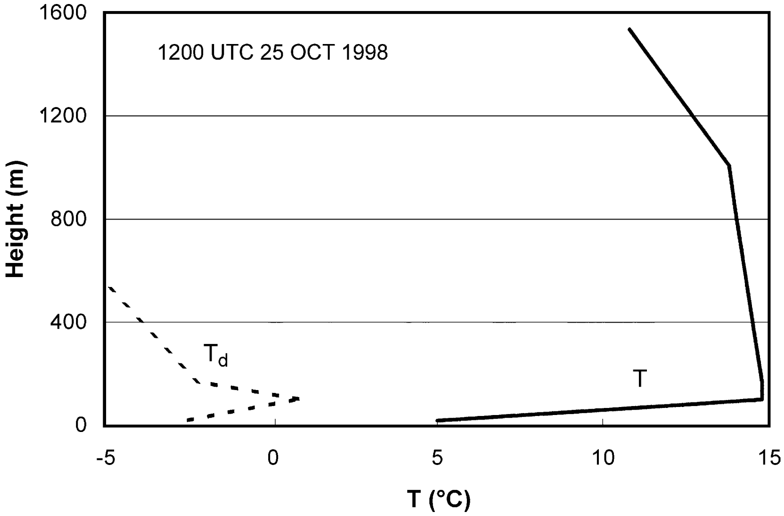

Fig. 14. Sounding of temperature and dew point temperature at OKX for 1200 UTC 25 Oct 1998 with an intense but shallow nocturnal inversion

4.3 UHI during a strong sea breeze

Prevailing southerly winds during the warm season cause the sea breeze to penetrate further inland over the south facing shores of Long Island and Connecticut than over the east facing shore of New Jersey. Because NYC extends into Long Island, the sea breeze cools it more than the urbanized counties of New Jersey immediately to the west. During the peak summer months, the cooling effect of the sea breeze diminishes gradually over the course of the night. This slows the increase of ΔT_{U-R} and displaces the center of the UHI about 10 km to the west for the first few hours of the night so that it is often centered near the New Jersey Meadowlands. On most summer nights the center of the UHI gradually shifts back toward New York City shortly after midnight.

During spring, the sea breeze does not occur as frequently as during summer because it is often suppressed by strong westerly or northerly synoptic scale winds and polar air outbreaks. Nevertheless, the most dramatic sea breezes occur on warm spring days because the largest land-sea temperature contrasts occur at this time of year. From 27 March to 03 April 1998, unseasonably warm air invaded the Eastern Seaboard under mostly south-southwest winds. Temperatures a short distance inland reached values as high as 30 °C while sea surface temperature south of Long Island was only 5.5 °C. This established favorable conditions for extremely strong sea breezes. A comparison of soundings from OKX and ALB (Albany, NY) at 0000 UTC on 29 March (Fig. 15) shows that the sea breeze was

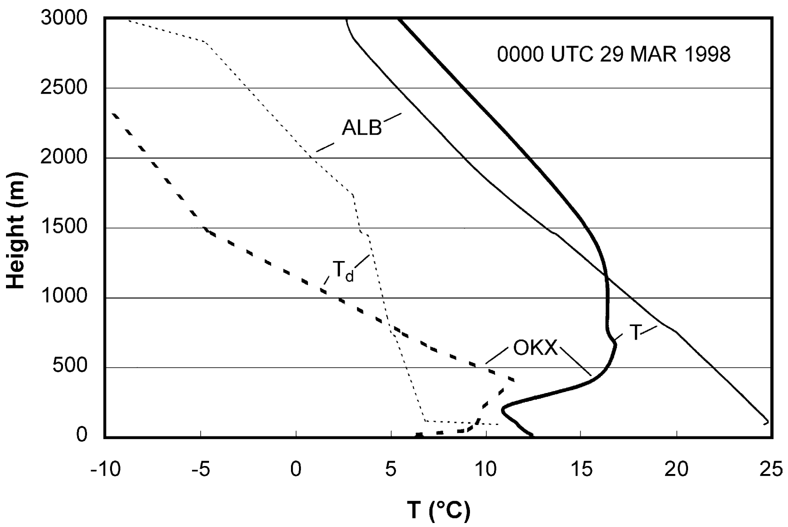

Fig. 15. Comparison of soundings at OKX and ALB for 0000 29 Mar 1998 with warm air aloft at both locations but a sea breeze inversion only at OKX

associated with a pronounced inversion. The sea breeze inversion averaged about 400 m deep during the period from 27 March to 03 April and disappeared only briefly when strong west winds suppressed the sea breeze at 0000 on 30 March.

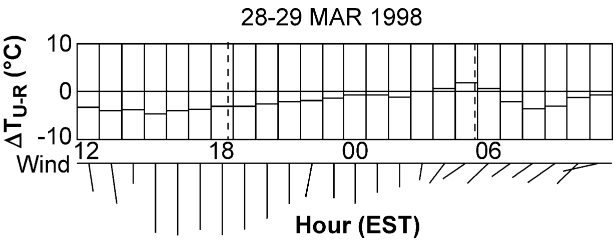

Fig. 16. Meteorogram for 28–29 March 1998. A strong sea breeze delayed UHI and reduced ΔT_{U-R}

On the afternoon of the 29th and again on the 31st, the westerly wind component was strong enough to suppress the sea breeze and NYC recorded its all time high temperature record for March. At the same time, however, the sea breeze reached JFK and cooled it significantly. On the days that the westerly component of the wind weakened, strong sea breezes cooled NYC while record high temperatures were recorded in the western suburbs.

On the night of 28–29 March 1998, the sea breeze not only delayed the UHI and shifted it to the west, it also kept NYC colder than the western suburbs until 2 h before dawn (Fig. 16).

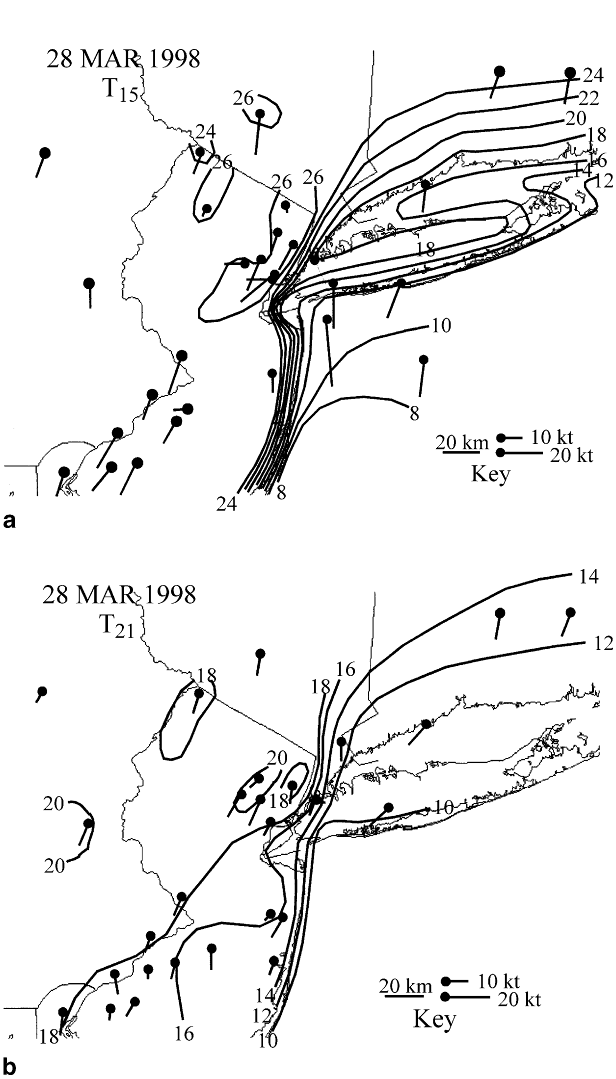

Fig. 17. Surface map for (**a**) 1500 EST 28 Mar 1998 with a sharp sea breeze front and (**b**) 2100 EST 28 Mar 1998 with UHI displaced westward

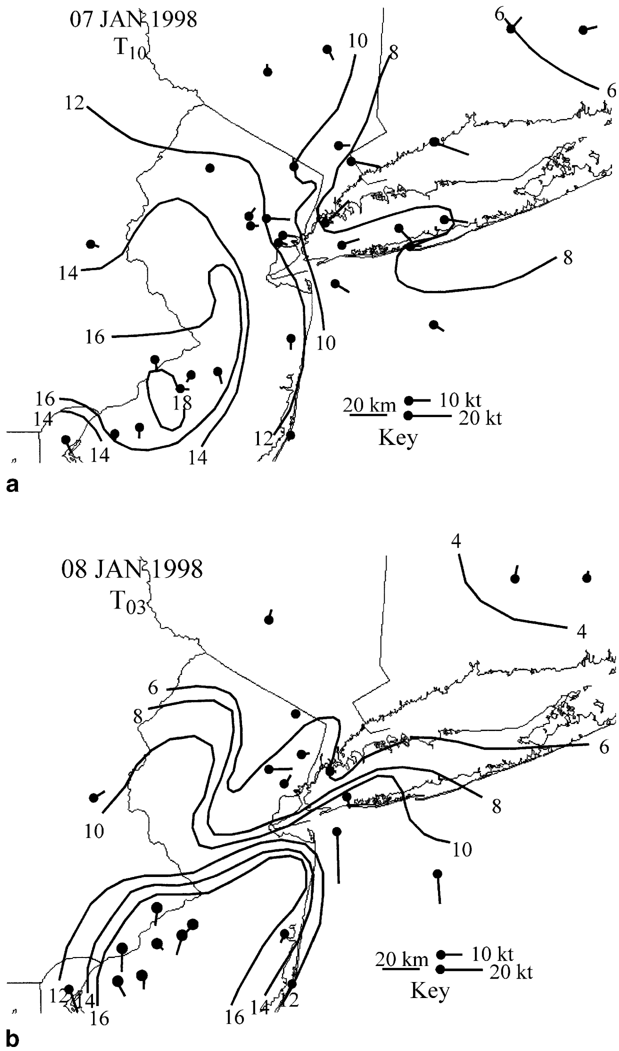

Fig. 18. Surface map showing temperatures at (**a**) 1000 EST 07 Jan 1998 with an advancing backdoor cold air and (**b**) 0300 EST 08 Jan 1998 with the backdoor front retreating as a warm front

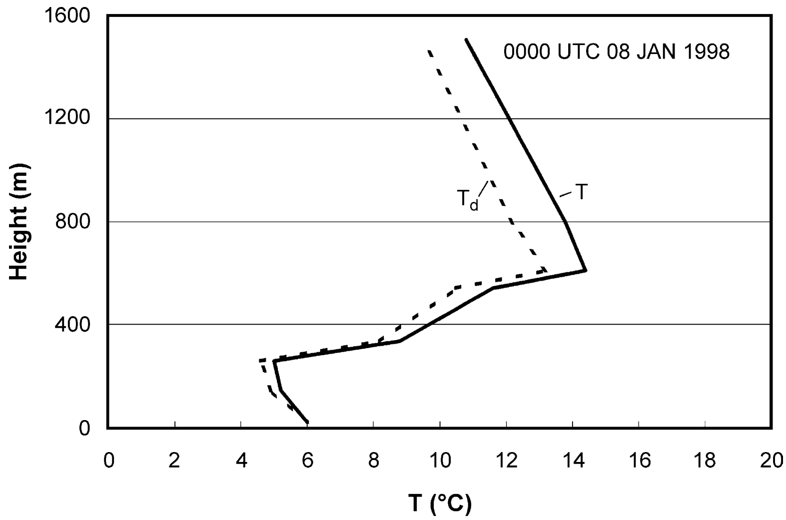

Fig. 19. Sounding for 0000 UTC 08 Jan 1998 with an inversion and low overcast associated with a backdoor cold front. Winds were northeast below the inversion and southwest above it

At that time the south wind at JFK weakened and the winds inland turned north for a few hours. South-southwest winds limited the westward penetration of the sea breeze over Coastal New Jersey and led to the formation of a distinct sea breeze front a few miles inland that extended northward across the New Jersey Meadowlands (Fig. 17a). The temperature gradient associated with the sea breeze front sharpened just west of NYC as the wind veered to almost due west at several stations just south of the Watchung Mountains. This deflection of the winds in this area was observed on several other days when synpotic scale winds were south-southwest and the atmospheric boundary layer was statically stable.

Cold air penetrated much further inland over Long Island and coastal Connecticut where the southerly sea breeze was superimposed on the prevailing south-southwest winds. At 2100 EST the highest temperatures were still centered west of NYC but Manhattan warmed somewhat when the wind veered south-southwest (Fig. 17b).

4.4 UHI following passage of a backdoor cold front

NYC tends to be much colder than the western suburbs under northeast winds and overcast skies when the ocean is relatively cold. Such conditions occur most often in spring and early summer. However, a warm spell in early January 1998 that produced a record-breaking ice storm in Northern New England, Quebec and Ontario also provided the setting for an unusually early season backdoor cold front in New York City. On the morning of 7 January, cold air from eastern New England crossed the New York City Metropolitan Area (Fig. 18a). This cold air mass reached central New Jersey and eastern Pennsylvania. It remained entrenched over the Metropolitan Area until the early morning hours of 08 January, when warm southerly winds reinvaded the region (Fig. 18b).

Because the front was located a short distance south and west of NYC, the cold air mass remained relatively shallow over the Metropolitan Area with an inversion height of 600 m at OKX (Fig. 19). However, because the sun is so feeble in early January, and because skies remained mostly overcast, the air remained cold north of the front. As a result, NYC remained distinctly colder than the suburbs to the southwest, and so, ΔT_{U-R} remained negative through much of the time.

5. Summary and conclusions

A mesoscale analysis of the climatological and meteorological aspects of the Urban Heat Island (UHI) around New York City (NYC) was presented using a mesoscale network of weather stations as the primary data source. On average, UHI increases rapidly in the late afternoon, remains almost constant during the night and then decreases quickly after dawn. The urban – rural temperature difference, ΔT_{U-R} is greatest on clear nights with low humidity throughout the troposphere and gentle northwest winds. This tends to occur two to three nights after a cold front passage. ΔT_{U-R} is strongly reduced by sea breezes and by backdoor cold fronts, which drive cold air into the City during spring and summer from the southeast and northeast respectively.

Case studies showing the impact of particular meteorological situations on the UHI were presented. A classic large magnitude UHI occurred on the night of 9–10 December near the center of a high pressure area under clear skies with gentle northwest winds. In the early evening hours temperatures in the countryside dropped rapidly until they fell almost 10 °C colder than NYC. Thereafter, city and country cooled at the same rate until dawn, when the rural areas warmed rapidly. Rapid warming was due to the shallowness of the nocturnal surface inversion (82 m deep).

The second case involved a brief period of cloud cover with increased wind speed in an otherwise clear, calm night (25 October 1998). During this time, ΔT_{U-R} decreased in response. Rural temperatures rose as faster winds increased vertical mixing in and above the nocturnal inversion and downward radiation increased because of the cloud layer. At the same time, temperature dropped in NYC as faster winds increased ventilation and advection from the colder suburbs.

In the third case several days of unusually strong southerly sea breezes at the end of March 1998 during a record breaking heat wave caused advection of cold air over Long Island and the eastern portions of NYC. A sharp sea breeze front formed a short distance to the west of the New Jersey Coastline and extended northward along a line about 10 km west of NYC. The temperature gradient was enhanced just west of NYC, where winds veered to skirt the Watchung Mountains. The deflection of the winds by the modest topography will be examined further in a future study. The net result of the sea breeze was to displace the core of the UHI to the west during the early part of the night and suppress it in NYC until after midnight.

The final case involved an unusual, midwinter backdoor cold front on 7–8 January 1998. A midwinter heat wave was interrupted when cold air invaded the region from the northeast. The backdoor cold front only passed a short distance south and west of NYC, where it stayed for less than 24 hours. This rendered Long Island and NYC much colder than the western suburbs and completely squelched the UHI.

Our future studies have two goals. The mesoscale weather network has been augmented to include more stations inside New York City. This will make it possible to obtain a finer scale view of the UHI. We will also employ the mesoscale weather model MM5 to assess the role of the various geographical and meteorological features revealed by the mesonet and that contribute to the UHI.

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