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Variations in New York city's urban heat island strength over time and space

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With 8 Figures

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Summary

We analyse historical (1900 – present) and recent (year 2002) data on New York city's urban heat island (UHI) effect, to characterize changes over time and spatially within the city. The historical annual data show that UHI intensification is responsible for $\sim 1/3$ of the total warming the city has experienced since 1900. The intensification correlates with a significant drop in windspeed over the century, likely due to an increase in the urban boundary layer as Manhattan's extensive skyline development unfolded. For the current-day, using 2002 data, we calculate the hourly and seasonal strength of the city's UHI for five different case study areas, including sites in Manhattan, Bronx, Queens and Brooklyn. We find substantial intra-city variation (~2 °C) in the strength of the hourly UHI, with some locations showing daytime cool islands – i.e., temperatures lower than the average of the distant non-urban stations, while others, at the same time, show daytime heat islands. The variations are not easily explained in terms of land surface characteristics such as building stock, population, vegetation fraction or radiometric surface temperatures from remote sensing. Although it has been suggested that stations within urban parks will underestimate UHI, the Central Park station does not show a significant underestimate, except marginally during summer nights. The intra-city heat island variations in the residential areas broadly correlate with summertime electricity demand and sensitivity to temperature increases. This relationship will have practical value for energy demand management policy, as it will help prioritize areas for UHI mitigation.

1. Introduction

Urban heat islands are portrayed in a number of different ways, but most commonly by comparing urban air temperatures with non-urban (rural, suburban) temperatures (Oke 1987). This comparison can be done over different spatial and time scales, as no general rule for what constitutes the optimal scales exists. Another method is to show maps of surface (radiometric) temperatures from remote sensing, which directly reveal the high temperatures produced by low-albedo, impervious urban surfaces in comparison to ex-urban vegetated areas. However, with such maps the distinction between radiometric and near-surface air temperatures needs to be borne in mind.

Given the complexity of the UHI phenomena and the multitude of urban environments, it is

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challenging to try and illustrate all aspects in a single portrayal. A popular drawing on heat island websites, for example, depicts the effect with a hypothetical ‘‘late afternoon’’ air temperature curve, rising from rural to suburban areas, peaking over skyscrapers and dipping within parks. While late afternoon urban temperatures may be higher than rural temperatures in many cases, there is also data suggesting (Karl et al. 1988; Peterson 2003) that many urban mid-afternoon air temperatures are *cooler* than surrounding rural areas. Moreover the predominant nocturnal strength of UHI is not conveyed with such illustrations.

The issue of the park temperature effect is important to UHI analysis as urban vegetation is one of the key strategies available to mitigate excess urban heat. Also it has been suggested that park cool islands may be partially offsetting the UHI bias for weather stations located in urban parks (Peterson 2003). One goal of this paper is therefore to look at the effect of Central Park on its station’s UHI signal, as compared to other non-park city stations.

New York city is a large, densely populated urban area that is approximately 309 square miles (800 km^2). It is composed of five boroughs (Manhattan, Bronx, Brooklyn, Queens and Staten Island) with extensive shorelines on the Atlantic Ocean, the New York Bay, the Hudson River, the East River, or Long Island Sound. The land use of New York city is very heterogeneous, with a complex assemblage of business districts with office buildings that have high daytime energy use as well as densely populated residential areas with high evening energy use, less dense residential areas with one and two-family detached homes, vegetated open spaces, industrial areas, and many mixed residential/commercial areas.

Recent prior studies of New York’s heat island effect include Gedzelman et al. (2003), Childs and Raman (2005), Kirkpatrick and Shulman (1987), Rosenzweig et al. (2006) and Sastre (2003).

2. New York city’s historical heat Island variations

Comparing annually averaged temperatures between urban and non-urban areas provides a computationally straightforward UHI signal for New York. For this estimate we use the 1900-to-present historical record from Central Park and compare it to the average of 23 non-urban stations, over the same period, that were included in the regional climate assessment of Rosenzweig and Solecki (2001). The 23 stations surround the city geographically, with distances ranging from 50 to 150 km from its centre. The data were obtained from the NOAA/NCDC U.S. Historical climate network and include an adjustment for local ‘urbanization,’ using a population surrogate for UHI strength (Karl et al. 1988). We assume that this suburban UHI population correction largely removes the urbanization trends over time for the non-city stations. The Central Park record is not adjusted in any way, of course, since the goal is to reveal its UHI strength.

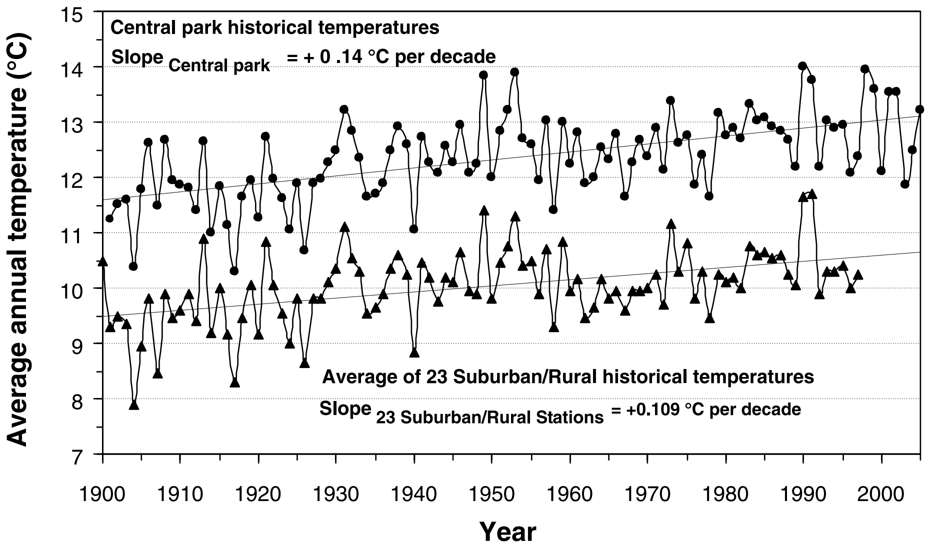

Fig. 1a. (upper line) Central Park’s annually averaged temperature from 1900 to the present compared to (lower line) the average of 23 surrounding rural and suburban stations well removed from the city (Rosenzweig and Solecki 2001). The urban heat island is revealed by the vertical offset between the two lines

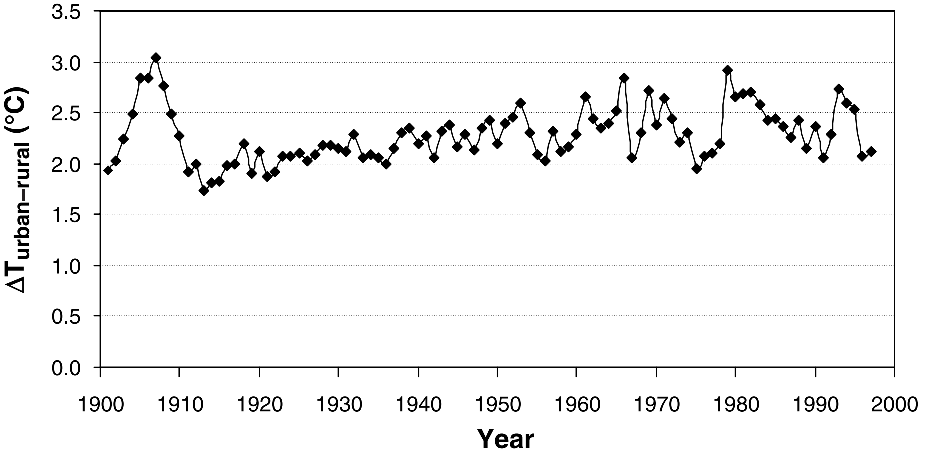

Fig. 1b. The annually average strength of New York city's urban heat island computed from the difference between the two historical records shown in Fig. 1

The upper curve in Fig. 1a is the Central Park record, while the lower curve is the average of the 23 non-urban stations. Figure 1b explicitly shows the temperature offset, $\Delta T_{\mathrm{urban-rural}}$ (year) between these two historical records. It reveals a growth of the Central Park UHI strength from ~2.0 °C in 1900 to ~2.5 °C today.

The relative strength of New York's UHI in 1900, and subsequent modest growth of ~0.5 °C, is interesting given the intensive increase in urban infrastructure since that time and continuing today. Historical photographs show that the building heights around Central Park were quite low in 1900, compared to the tall structures today, with a much greater skyview then (Black 1973). The resulting reduction in skyview over time should lead to UHI enhancement through reduced net longwave cooling (Oke 1986). Given the vast scale of New York's skyline development since 1900, one might *a priori* expect a larger increase than 0.5 °C. It is possible though that the Central Park station, located ~300 m from the nearest streets, was less impacted by skyview loss over time. Additionally, although New York's urban landscape and building heights were different, the Manhattan island population in 1900 was even larger (~1.85 million persons in 1900) than today (~1.54 million in 2000), due to turn-of-century immigration. So to the extent that population is an indicator of UHI strength, the relative 1900 UHI magnitude may be partially understandable.

The data in Fig. 1 thus suggest that of the total ~1.5 °C warming Central Park has experienced over the century, roughly 33% of it was due to an increase in the UHI strength and 66% was due to regional/global climate change. This contribution of UHI to local warming is much lower than that observed in some rapidly growing cities in developing countries, like Beijing, where up to 80% of the local warming since 1961 may be due to UHI intensification (Ren et al. 2007). The Fig. 1a data also indicate that the combination of UHI and regional/global warming has elevated the city's annual average temperature by almost 3.5 °C above what it would be without these two effects – a considerable local climate alteration by any measure.

2.1 New York city UHI and windspeed changes over time

A monthly analysis of the historical UHI growth shown in Fig. 1 by Sastre (2003) indicates that it is mostly due to an increase during the Winter and early Spring months, especially March. March tends to be the windiest month in New York City, so one hypothesis explaining the increase could be there has been a drop in windspeed, correlating with the urban canyon build-up surrounding the park. Tall buildings, whose presence has dramatically increased over the century surrounding Central Park, will increase the roughness length scale of turbulence and also the urban boundary layer thickness (Oke 1986). This will lower windspeeds within the urban canopy level, including those experienced near the ground. Lower windspeeds reduce sensible heat cooling of the ground.

Figure 2 shows available historical windspeed data for Central Park, from 1929 to 2006, for the two months of March and September. Windspeed

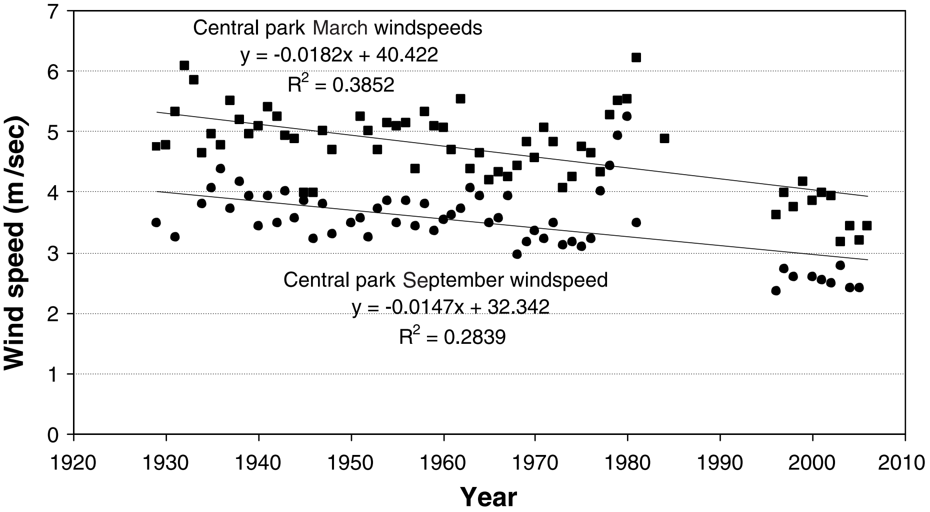

Fig. 2. The annually average windspeed (m/s) for the Central Park weather station, 1930 to the present. The upper data is for the month of March and the lower is for September, which tend generally to be the highest and lowest windspeed months for New York City, respectively

data from 1900 to 1928 was not available. These two months tend to be the highest and lowest windspeed months of the year, respectively, for the area. The relative monthly UHI strength is consistent with these relative windspeed differences – with March tending to have the weakest UHI strength while September has the strongest. The drop in windspeed over the century is quite large, with current March speeds almost half of the average in 1930, and presumably even less compared to 1900. Thus windspeed is a likely factor contributing to the increasing March and annual UHI over time.

On the other hand, the same monthly UHI analysis (Sastre 2003) also shows that the September UHI has hardly increased since 1900, even though windspeeds during September have also dropped (Fig. 2a). One explanation could be there is a windspeed threshold, below which UHI intensity is not as strongly affected, and September winds, the lowest windspeed month, were already near or below this threshold earlier in the century.

3. Data sources for hourly UHI calculations

To obtain a better spatial and time characterization of New York city's current UHI, we performed hourly calculations. Due to the more intensive data requirements for this, we restricted the non-urban data to a smaller set than the 23 stations used in the annual estimates. We also use city station data outside of Central Park to investigate the park cool island effect and other questions.

For the non-urban stations, we use data from the Techniques Development Laboratory, U.S. and Canada Surface Hourly Observations dataset, originally prepared by the National Centre for Atmospheric Research (NCAR) (http://gcmd.nasa.gov/records/GCMD_ds472.0.html). The data is available nationally, has a temporal resolution of 1 hour and spans years 1988 to 2004. We acquired a regional subset of the national data and selected 8 stations from this set that lie approximately 100 km from Central Park, and ring the city geographically.

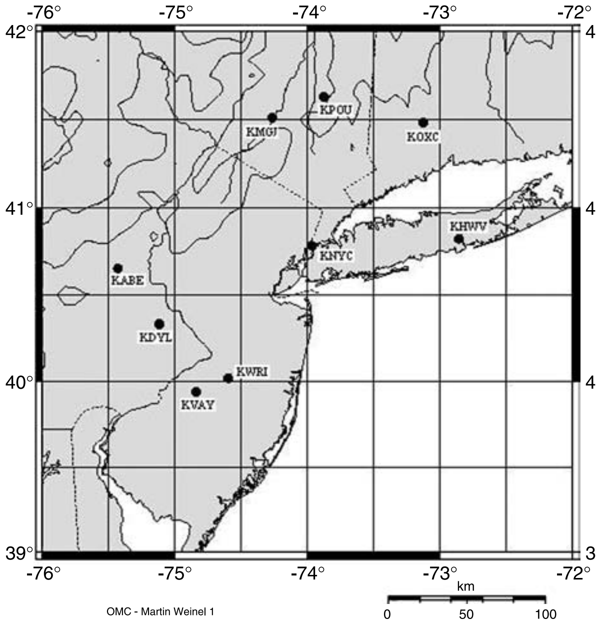

Fig. 3. Location map for the 8 suburban stations used for hourly UHI calculations for the year 2002. The central dot is located in Central Park. The stations average 100 km from the Central Park station

Table 1. Suburban stations used for the hourly UHI calculations, with station identifier information

	Station code	Station name	State	Kms to NYC	Long	Lat	Population
East	KHWV	Shirley	NY	93.8	−72.86	40.82	25,395
	KOXC	Oxford	CT	104.9	−73.13	41.48	9,821
North	KPOU	Poughkeepsie	NY	94.6	−73.88	41.63	29,871
	KMGJ	Montgomery	NY	84.7	−74.27	41.51	20,891
West	KABE	Allentown	PA	124.2	−75.43	40.65	106,632
	KDYL	Doylestown	PA	109.4	−75.12	40.33	8,227
South	KWRI	McGuire AFB	NJ	99.9	−74.6	40.02	9,744
	KVAY	Mount Holly	NJ	118.9	−74.84	39.94	10,728

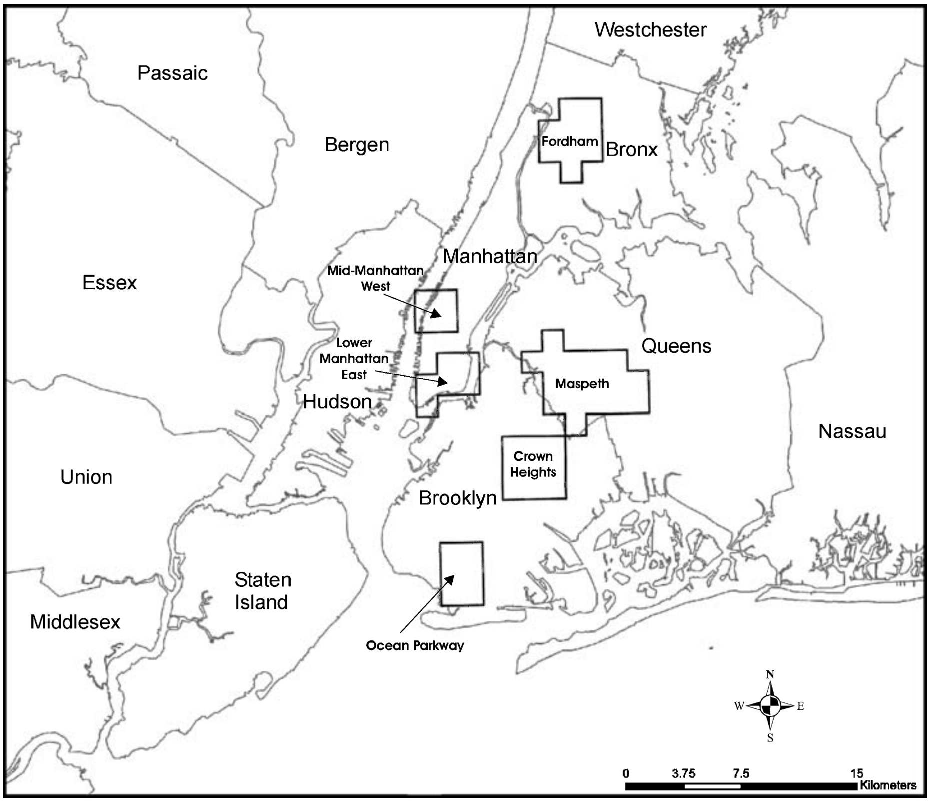

Fig. 4. Location map for the 5 urban case study areas and weather stations used for the hourly UHI calculations for the year 2002

A map of the 8 surrounding stations is shown in Fig. 3 and Table 2 provides station identifier information. We do not make any corrections for rural/suburban station elevation or non-urban UHI increases, based on population. We estimate that the average elevation difference between the non-urban and the urban stations is only ~60 m. With regard to rural UHI increases, Karl et al. (1988) recommend against using their population surrogate for small sample sizes, as is our case.

For the urban stations we used an array of "WeatherBug" (www.aws.com) sites primarily located on school rooftops in Manhattan, Brooklyn, Bronx and Queens boroughs. Figure 4 shows the urban station locations. Socio-economic and land use characteristics for these urban station areas are given in the Appendix.

4. New York city case study area hourly UHI curves

Figures 5 and 6 show the 2002 hourly UHI signals for Central Park and each of the other urban case study areas. Figure 5 shows the hourly UHI during each of the four seasons. Figure 6 shows the hourly UHI for the Summer season only, at all the case study areas. The predominant nocturnal nature of the city's UHI is evident, as

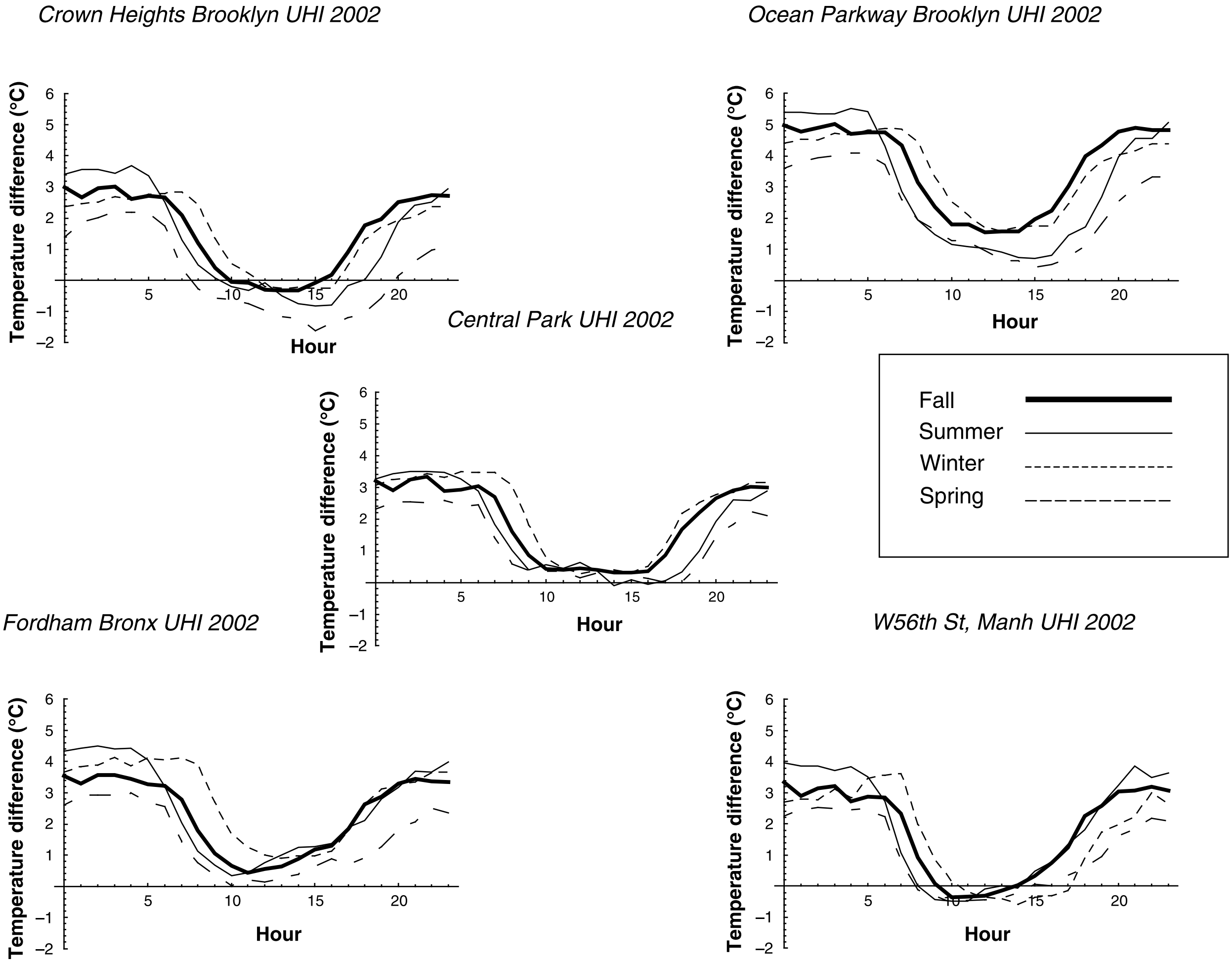

Fig. 5. Hourly urban heat island temperature difference, by season, between each of the urban case study areas (Fig. 4) and the average of the 8 suburban stations (Fig. 3) (Queens station is not included because of insufficient data other than for the summer season)

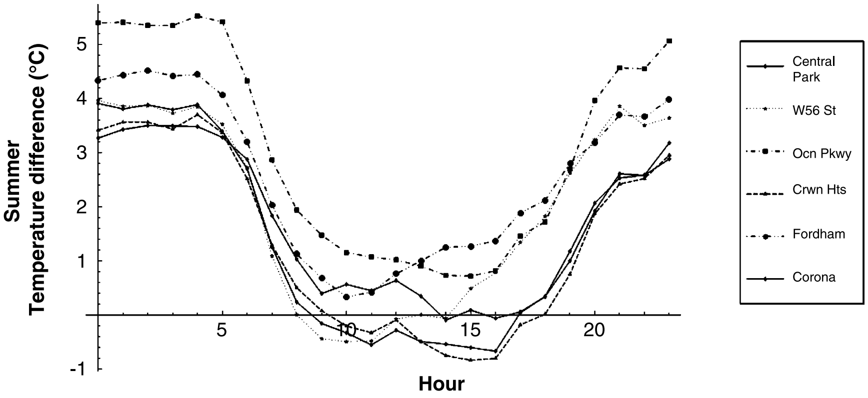

Fig. 6. Summer season hourly urban heat island temperature difference for each of the urban stations. The Central Park station is marginally the coolest nocturnal urban heat island station, which is an indicator of the park cool island effect. However during other times of the day and during other seasons it has an average UHI signal

has been seen in prior studies (Gedzelman et al. 2003; Childs and Raman 2005). The magnitude of the Central Park hourly curve is broadly consistent with, albeit a little weaker than, the annual average UHI estimates shown in figure 1b. Inspecting the mid-night to 5 am portion of the hourly curves shows that the Summer and Fall seasons are generally the strongest UHI times

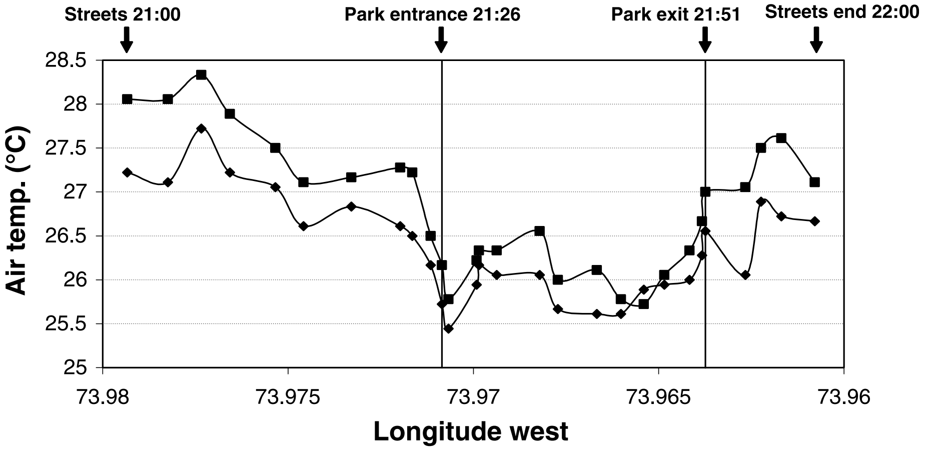

Fig. 7. Air temperature readings taken during a nocturnal traverse through Central Park in July 2006. The readings began in the west urban street areas and entered and exited the park as indicated. Nocturnal cycle cooling complicates interpretation of the data during the entrance to the park and the extent to which the park cool island contributes is unknown. However, the warming during the exit from the park, in opposition to temporal nocturnal cooling, is a clear indication of the park cool island effect

of year, and Spring the weakest, consistent with the different average windspeeds in NYC for those seasons (Fig. 2).

The Central Park station does not stand out as unusually cool compared to the other stations, especially considering the Crown Heights, Brooklyn station, which is a fully urbanized area. Thus, the Central Park station would require a substantial UHI correction if it were to be used in a study of the area's regional warming due to global change. This is in contrast to a statistical study of many U.S. city stations by Peterson (2003), who found no UHI – indeed that report found urban *cool* islands – for large cities including Boston, Massachusetts; Dallas Texas; Detroit, Michigan and Seattle, Washington. Our study differs from that of Peterson (2003) in that we did not make latitudinal and elevation corrections for our non-urban stations. As seen in Fig. 3, our stations have good latitudinal and longitudinal placement around the city centre and the elevation differences are not considered large enough (average rural elevation 60 m higher than the Central Park station) to significantly create a false UHI signal of the magnitude we find.

The one positive indicator for the park's cool island may be summer nights, in which the Central Park station is marginally cooler compared to some of the other stations (Fig. 6). The authors made a night-time summer traverse through Central Park in 2006, passing near the official park weather station, measuring air temperatures with 2 air probes.

Approaching the park entrance from the west, we were moving through dense urban streets. The temperatures were declining because of the nocturnal cycle. This nocturnal cooling continued into the park until we began to approach the eastern edge where a warming trend in opposition to the nocturnal cooling is apparent. Exiting the park clearly showed that the neighbouring urban streets were significantly warmer than the park itself, demonstrating the nighttime park cooling effect. No traverse data for other seasons has been taken yet by the authors.

4.1 Intra-city UHI variations

Figures 5 and 6 also illustrate significant intra-city variations in UHI strength, as shown in particular by the two Brooklyn sites. The Crown Heights station stands out as relative cool-island, with Spring mid-afternoon temperatures up to 2 °C cooler than the average non-urban stations. By contrast, the Ocean Parkway station stands out as a hotspot within the city's urban heat island. Summertime temperatures are often close to 2 °C warmer than other city sites. These variations reveal the potential for large temperature changes over small scales, as the two stations are only separated by ~5 km.

The two Brooklyn stations and the Manhattan stations are all located on school rooftops and we made site visits. The Ocean Parkway station school rooftop, which is the hottest nighttime station, has a dark gravel ballast on the roof.

However we do not believe this dark ballast is necessarily biasing the UHI signal for the following reasons: (1) the weather station is sited around 5 m above the roof surface; (2) the area of the roof is completely unobstructed and experiencing good canopy level winds; (3) the station's UHI strength is predominantly nocturnal. So many hours after sunset (Fig. 5), when albedo should not be a temperature factor, we would not expect a darker roof, in a well-ventilated and well-elevated station, to cause 2 °C temperature biases. Rooftops are also unlikely to store thermal energy for long because they are generally low mass building facades for structural reasons.

On the other hand, the UHI variability is not easily explained in terms of land surface characteristics like building stock, vegetation fraction and surface temperatures, as the two Brooklyn sites, for example, do not have dramatically different building stock and vegetation fractions. With regard to surface temperatures, Rosenzweig et al. (2006) estimated that the Crown Heights site had the hottest surface temperatures for the case study areas, while Fig. 5 shows it to be the weakest urban heat island area with respect to air temperatures. Also there is no correlation between the local UHI intensity and the population of each case study area. A site visit to the individual weather stations indicated stronger tree cover in the cool island area of the Crown Heights, Brooklyn site, compared to the other weather stations. Thus the effects of urban forestry in the area may be having a positive impact on temperatures. It is also possible that sea breezes are helping this particular area, and a future analysis might include more site-specific wind information.

4.2 Heat wave electric load and UHI intensity

Variations in electric load are due to many factors such as ambient weather, building occupancy (time of day, day of week), and load distribution amongst users. While these are not the only factors that influence electric load, they are commonly accepted as the most significant factors. Because of this, it is reasonable to expect a correlation between local UHI intensity and load demand for individual case study areas.

Electricity load data during a July 2002 heat wave was available for these case study areas (Rosenzweig et al. 2006). Figure 8a, b plot the July 3, 2002 heat wave peak day electricity load, in total and *per capita* units respectively, against the average 2002 summer UHI intensity, calculated from the data in Fig. 6. The *per capita* datum is used to correct for demand differences due simply to population size differences. We use peak day load as a practical energy metric to relate to UHI because peak demand is when the electric utility serving New York is most severely constrained. Seasonal demand could be another interesting metric to compare with local UHI, however such data were not readily available.

We excluded the Manhattan study site from these plots because of the predominate influence

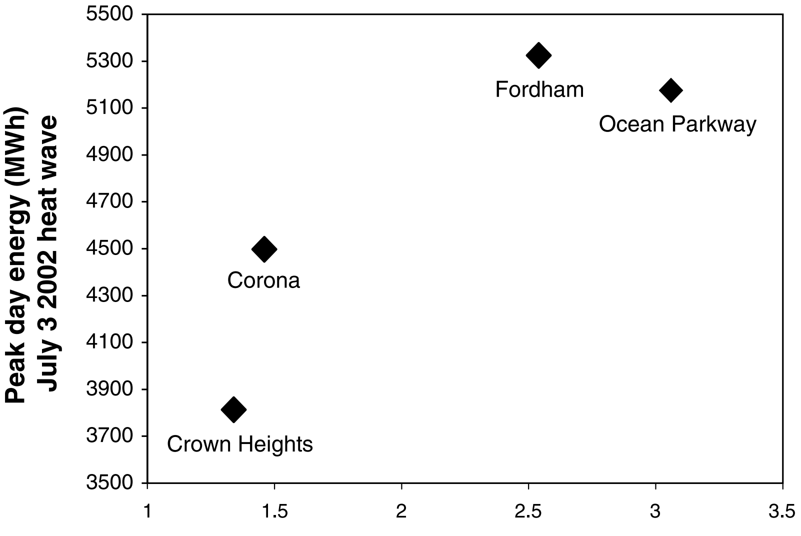

Fig. 8a. Scatter plot of average summertime UHI temperature effect for the four residential case study areas, against the total electricity consumed (MWh) in each area during a 24 h peak period of a July 2002 heat wave. The relationship of peak demand to UHI locally is of practical interest because that is the time when the electric utility serving New York is most constrained

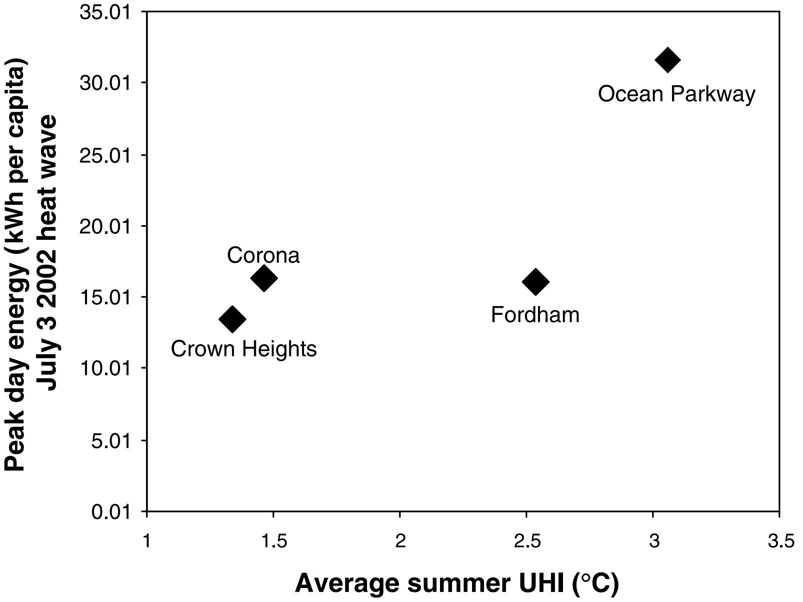

Fig. 8b. Same as figure 8a, except the electricity consumption is *per capita* for each case study area, to remove differential total population size effects on total demand. A land area adjustment was not made because the electric load pocket land area data were unavailable

of commercial and business energy usage in this area, compared to the other more residential sites. Although the sample size is small, there is a suggestion of a correlation between the local UHI intensities and peak load data. In addition, regression lines between ambient temperature and electric load for these areas (Rosenzweig et al. 2006) show that the strongest and weakest regression line slopes correlate with the hottest and coolest UHI areas.

Using a regional climate model, the authors recently completed a study of mitigating UHI in these case study areas, by considering a number of scenarios for urban forestry, living green roofs and bright surfaces, including bright pavement (Rosenzweig et al. 2006). In general, substantial reductions in surface and near surface 3 pm daily temperatures were suggested by the modeling. One recommendation of the study was to "implement urban heat island mitigation strategies appropriate to conditions in individual neighborhoods and communities···" The present paper illustrates how a spatial analysis of UHI could help achieve that recommendation by identifying local hotspots and cool islands and their daily timing.

5. Conclusions

One of the main findings in this paper is that the Central Park weather station has recorded a strong heat island effect from early in the century, despite it being located in a heavily vegetated park environment of ∼341 hectares area. Moreover, the park UHI signal is a good representation of the general features (timing, magnitude, seasonality) of New York city's urban heat island effect. These findings are in contrast to a recent analysis of other large U.S. cities (Peterson 2005), including Boston, Dallas, Salt Lake City and Seattle which suggested that a significant UHI may not exist for those cities, after corrections are made for rural elevations and other station "inhomegeneities," and taking into account the possibility that many city weather stations may be located in parks.

Secondly, the historical growth of city's UHI strength can be contrasted to the much higher rates reported in developing country urban areas (Ren et al. 2007). The Central Park UHI signal has only grown from 2.0 to 2.5 °C over the century and this increase is likely due to a number of energetic effects from the ever-increasing skyline development in Manhattan and surrounding the park. Foremost would be the reduction in skyview and windspeed as building heights have increased over time. Windspeed data show a stong decline over the century consistent with these effects. The historical data also reveal that UHI intensity is responsible for 33% of the overall warming the city has experienced over the century.

Our spatial analysis included five case areas in surrounding boroughs of New York and also in a station nearby Central Park, but outside its perimeter. A maximum nocturnal and minimum daytime UHI signal was found in all cases and Summer and Fall were generally the strongest UHI seasons, consistent with seasonal windspeed changes for the area. No simple pattern was found, however, with respect to the park station versus the other non-park stations. Non-park stations could be cooler or warmer than Central Park. Nor were these differences easily related to observed surface temperatures, building stock, or populations for the respective areas. The one positive indicator for a Central Park cool island was Summer night-time temperatures, which seem to be cooler than the non-park stations.

Using electric load data for a heat wave that occurred during the summer of 2002, we find a suggestion of a correlation between the local average UHI strength of an area an its electricity consumption. However the sample size is small. Future work should seek to increase sample sizes for this correlation, because such relationships clearly will have practical value for urban energy demand management policy.

The analyses presented in this paper indicate the importance of studying UHI as a variable condition over space and time, using networks of urban weather stations, rather than simply averaging urban stations for a signal (Gedzelman 2001). This approach will assist UHI mitigation strategies by revealing high priority areas for remediation. It can be complimented by remote sensing maps of surface temperature, which are very effective at pinpointing local sources of high sensible heat flux, such as dark rooftops and other low-albedo, impervious surfaces. However, future research should look more closely into meteorological variables, such as sea breezes and winds, that might help explain UHI variability, because standard remotely-sensed indicators do not definitively clarify UHI causality for New York city.

Appendix

Urban station area characteristics

Mid-Manhattan West

The Mid-Manhattan West case study area, located in western Manhattan from 35th street to the southern end of Central Park at 59th, is approximately 2.5 square miles (7 square kilometres) running along the coast of the Hudson River. Mid-Manhattan West has a population density of ~45,000 people per square mile. The central portion of the Mid-Manhattan West case study area is a commercial and business district with high-rise buildings and street-level commercial space with a daytime population that is much higher than the night time residential population. The northern and southern areas have a high residential population density. There is a gridded street pattern with very few vegetated areas and many industrial areas.

We used weather station data from two sites within this case study area: (i) the Central Park weather station, located well within the park boundaries; and (ii) a weather station on a public school outside and south of Central Park, but near the park's south west boundary.

Fordham Bronx

The Fordham case study area, located in the west-central part of the Bronx, is approximately 6 square miles (15 square kilometres). Fordham is a heterogeneous site and a mixed-use neighbourhood of one-to-four family homes, high rises, commercial spaces, transportation hubs and some industry. Fordham has a population density of ~55,000 people per square mile, is predominantly low-income (average median household income is $22,770), and is high-minority and dense population.

Maspeth Queens

The Maspeth Queens case study area, located in west-central Queens, is approximately 11 square miles (29 square kilometres) and has relatively low surface temperatures. It contains Forest Park, many cemeteries, a large industrial area, and several residential areas with a mix of detached homes and high-rise apartment buildings. The population density in the Maspeth case study is the lowest of all areas (~25,000 people per square mile), although it ranges from relatively low in the industrial areas to relatively high in the residential areas. The industrial areas and the large parks and cemeteries are characterized by large tracts and few roads, while the residential areas have a fairly gridded street pattern.

Crown Heights Brooklyn

This community is located in central Brooklyn and is approximately 6 square miles (15 square kilometres). The housing is predominantly mixed residential and commercial with two-to three-story attached homes and multi-story prewar apartment buildings. The vegetation varies significantly across the study area, with some residential areas having a large number of street trees, while other areas have very little vegetation. The average population density is ~47,000 people per square mile, but much lower in the industrial areas. There are several large industrial areas and few open spaces. Crown Heights has a predominantly low-income population, with an average median household income of $28,371.

Ocean Parkway Brooklyn

The Ocean Parkway Brooklyn case study area, located on and near the coast in southern Brooklyn, is approximately 4 square miles (10 square kilometres). It is a predominantly two-story post-WWII residential community characterized by wide boulevards and tree-lined sidewalks. The average population density is ~41,000 people per square mile, with the highest population density in the western portion of the area. Although there is some high-rise housing, the average building height is just 1.5 floors. There are few open spaces and few industrial areas.

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