1.2 USING URBANET DATA TO QUANTIFY THE NOCTURNAL HEAT ISLANDS OF US CITIES

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1. INTRODUCTION

The urban heat island is a well recognized example of man's modification of the environment. The causes are well known – the modification of surface albedo, the removal of vegetation, and heat generated by heating/cooling and traffic. Washington, DC, has been a long-time target for related studies (e.g. Woolum, 1964). Most recent attention has resulted from the availability of satellite infrared imagery (e.g. Baumann, 2001) which actually depicts temperatures of the surface itself rather than of the air that people breathe. Such studies give a remarkable view of the magnitude and extent of the heat island effect. Other studies have made use of aircraft transects, which have led to an understanding of the temperature deviations of air well above the surface roughness layer. People are actually exposed to air that lies between the two extremes revealed by the satellite and aircraft studies.

Here, surface data generated by the "WeatherBug" network of AWS Convergence Technologies, Inc. (see http://weather.weatherbug.com) are used to explore the spatial extent and magnitude of two heat islands – those of Washington, DC, and New York City. One year of data is used – CY 2007. These cities are selected because of the availability of direct measurements of surface sensible heat fluxes from the companion DCNet program operated by NOAA (see http://www.atdd.noaa.gov/dcnet.htm). Details of the thermodynamics of these two urban heat islands derived from DCNet data are presented elsewhere in this series of presentations based on the collective data base of the two networks (Callahan et al., 2008; Hicks et al., 2008; Pendergrass et al., 2008).

The present focus is on the air alone, and is not to be confused with satellite surveys which address the temperatures of actual elements of the surface. Figure 1 shows the national distribution of sites from which the data considered here have been derived. It should be noted that while DCNet is limited to operation in Washington and New York, the WeatherBug network is nationwide. The methods developed here could readily be extended to address the major cities of the USA. The analysis that follows will consider both nighttime and daytime situations. The nighttime analysis will consider all measurements made during the period from 2200 to 0500 local time. The daytime window will be from 1100 to 1700. No data screening has been imposed.

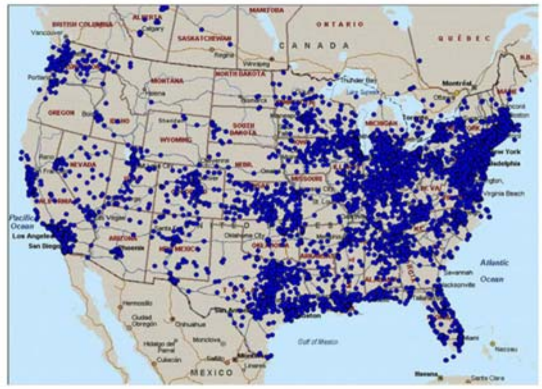

Figure 1. The array of "WeatherBug" sites, operated by AWS Convergence Technologies, Inc., from which sites for the present analysis were selected.

2. THE WASHINGTON CASE

To explore the spatial extent of the Washington heat island, data have analyzed according to their distance from the assumed center of the island – taken to be the Federal Triangle area of downtown Washington. This area contains some of the oldest government buildings, including the headquarters of the Department of Commerce (DOC; 38.894°N, 77.033°W) which occupies a complete city block. There is a DCNet micrometeorological station on the roof of this building.

The method of analysis used here smoothes through a lot of the local complexity of the urban air temperature distribution (see Figure 8.14 of Oke, 1978, for an example of the detail involved). Figure 2 is a satellite image of the Washington area, showing the high degree of variability in surface temperatures. It remains to be seen how this variability translates into variability in the temperature of air near the surface. For each month, data have been ordered according to their distance from DOC, and average temperatures and standard deviations have been computed for each 3 km ring. In the first analysis, no

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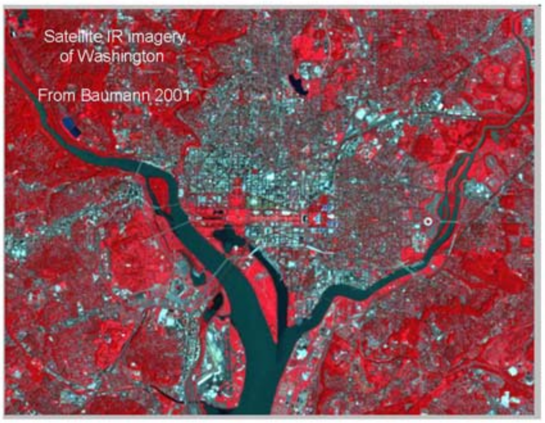

Figure 2. Infrared satellite view of Washington, DC, showing the thermal complexity of the surface. Reproduced with permission from Baumann (2001).

wind direction effects have been considered; a strong wind speed dependence is expected (see Oke, 1973). Figure 3 shows the nighttime results, by month, with data grouped according to the 3 km radial bands out to a distance of 60 km. Figure 4 shows the results for the daytime case. Not surprisingly, the nighttime data are far more revealing – the January and March data show large heat islands, with temperatures falling consistently as far as the present analysis extends. The February data are more difficult to interpret, but it seems likely that they indicate a far more extensive heat island effect than for the adjacent months. This cannot be easily tested, because of the influence of other metropolitan areas (e.g. Baltimore) at the extremities of the current analysis. Less extensive heat island effects are evident for many of the other months, with most extending to as far as about 20 km from the downtown centroid.

Several rings yield data that appear anomalous. Whether this is due to some atmospheric behavior or to an undetected error in the data remains to be discovered. It is tempting to attribute some of the averages that initially appear anomalous (unexpectedly cooler than their neighbors) to the influence of the large unpopulated areas that are characteristic of the District of Columbia and its surroundings. For example, the Potomac River could drive temperatures lower than would be the case for adjacent populated areas. There are many such areas of anomalous surface temperatures apparent in infrared imagery, and there are definite features of the Washington metropolis that would need to be considered in a more detailed examination of these data (e.g. the beltway, at a distance of about 10 km from DOC).

Scrutiny of the data of Figures 3 and 4 makes it clear that DOC might not the best choice for a center of the DC heat island. Satellite imagery (Figure 2) indicates that a better choice could be Mount Vernon Square (38.902°N, 77.031°W), about 1.5 km distant from DOC. However, a re-analysis using this new center does not improve the overall picture. Additional examination of this aspect leads to the conclusion that there is no single point that can be assumed to be a center of the Washington heat island. Instead there is a large complex area across which the heat island effect is distributed, but not uniformly.

3. NEW YORK CITY

Figures 5 and 6 are the New York equivalents of Figures 3 and 4. For the New York City case, the center is assumed to be Times Square (40.760°N, 74.008°W), where once again DCNet flux data are available. The matter of spatial variability is again tantamount; the obvious fact that Manhattan is an island generates an over-riding level of uncertainty. As in the case of Washington, New York City has an impressive legacy of heat island studies, culminating with recent research on methods to reduce the magnitude of the heat island effect (Rosenthal et al., 2003).

The monthly diagrams presented in Figure 5 appear more convincing than those of Figure 3. For the nighttime case, the months of May through September display a consistent and uniform heat island effect, with the city center being at least 3°C warmer than its distant surroundings (i.e. more than 60 km distant). This consistency is not evident in the daytime results of Figure 6. Inspection of the diagrams of Figure 6 reveals, however, that there is a repeated heat island effect at a distance of about 30 km, which is not as apparent in the nighttime data of Figure 5. Clearly, the reason is not associated with sensor limitations, but with some specific locations (that remain to be identified) with elevated daytime temperatures. The winter months (Jan, Feb and Mar) appear to be evidence of a much larger heat island than for other months. The January and February data seem to indicate an effect stretching beyond the 60 km limitation of the present analysis.

Note that there appears to be an anomaly in the October, November and December data, for the 57 to 60 km band. The reason has not yet been identified. All other apparent anomalies appear to be valid interpretations of actual air temperatures, although perhaps influenced by exposure shortcomings.

4. DISCUSSION AND CONCLUSIONS

A common feature of Figures 4, 5, 6 and 7 is that the standard deviations plotted appear to be minimal for the colder months, and are greatest for the hotter months. The evidence for this is striking, but the causes are not clearly evident.

Other workers have confirmed a wind speed effect that can be strong (see Oke, 1978). The present data

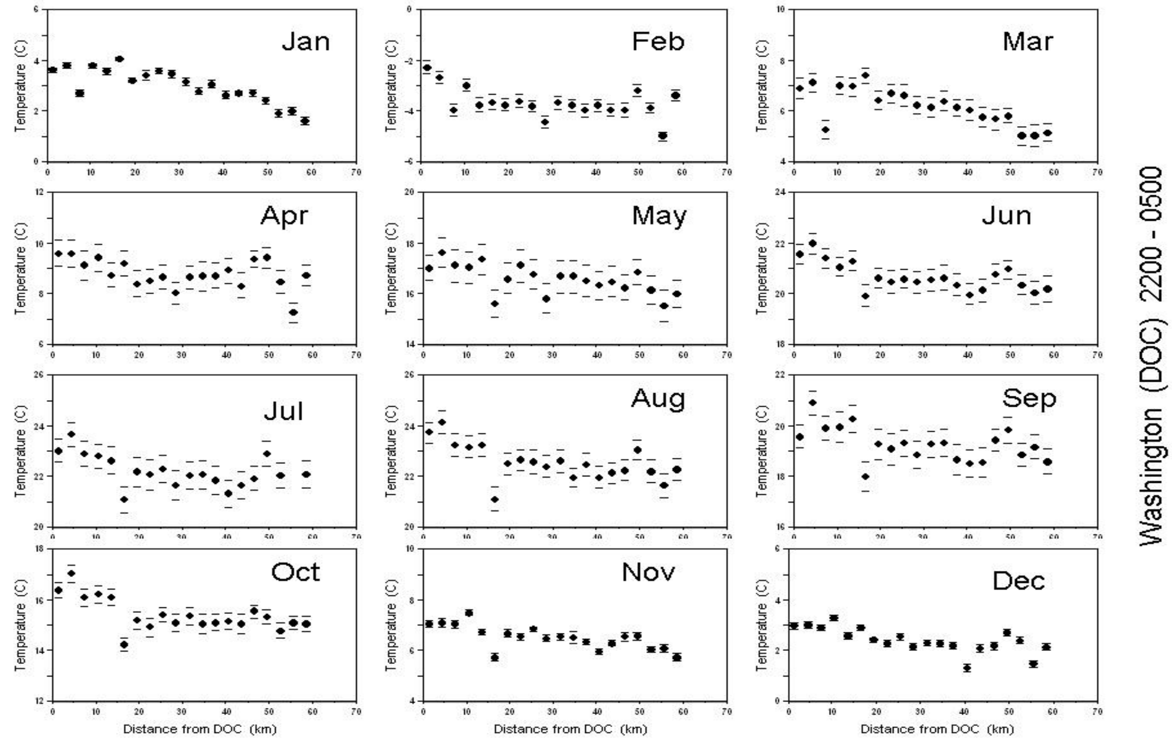

Figure 3. The Washington DC nighttime (2200 – 0500 hrs) surface air heat island assuming circular and centered on the Federal Triangle district. Data are for the year 2007. Points correspond to averages within bands 3 km wide. Standard error bounds are shown.

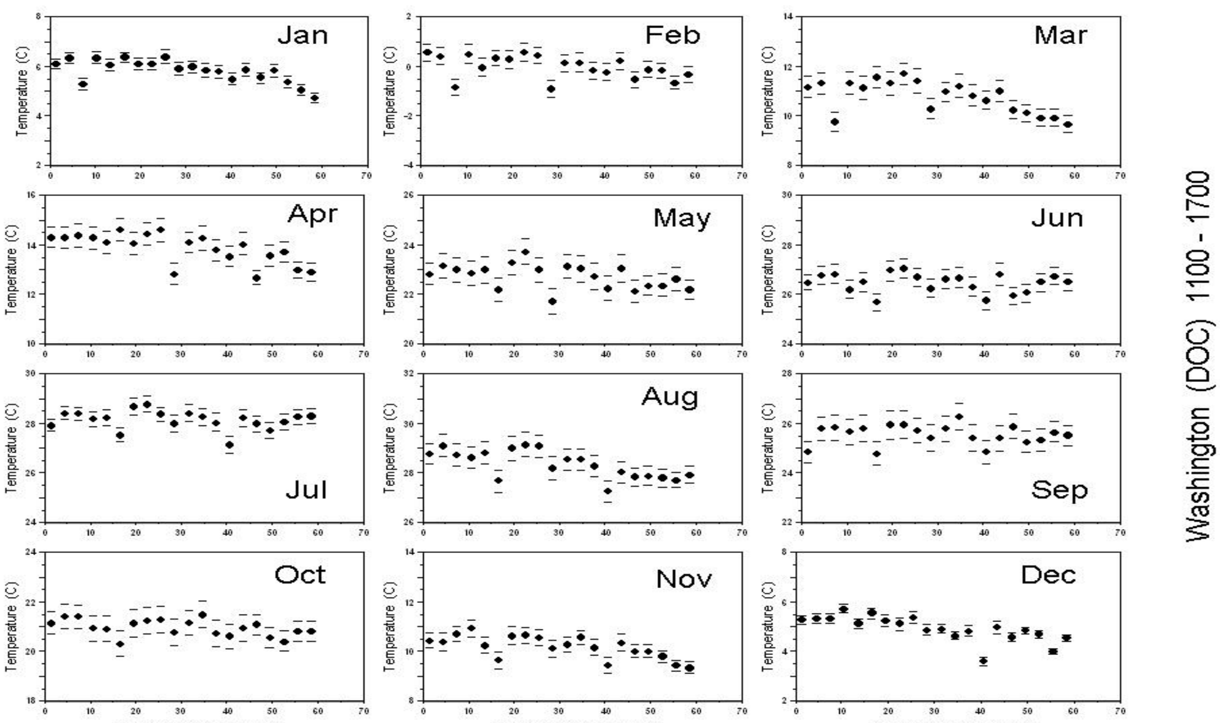

Figure 4. As in Figure 3, but for daytime (1100 – 1700 hrs).

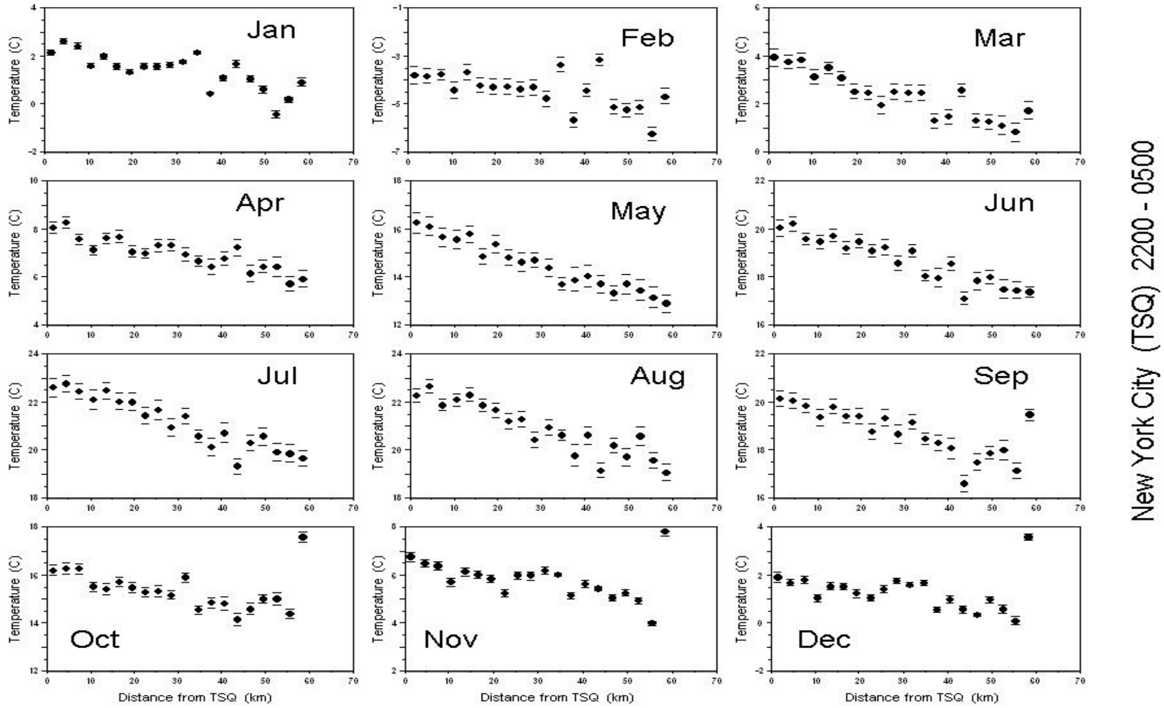

Figure 5. As in Figure 3, but for New York City, centered on Times Square.

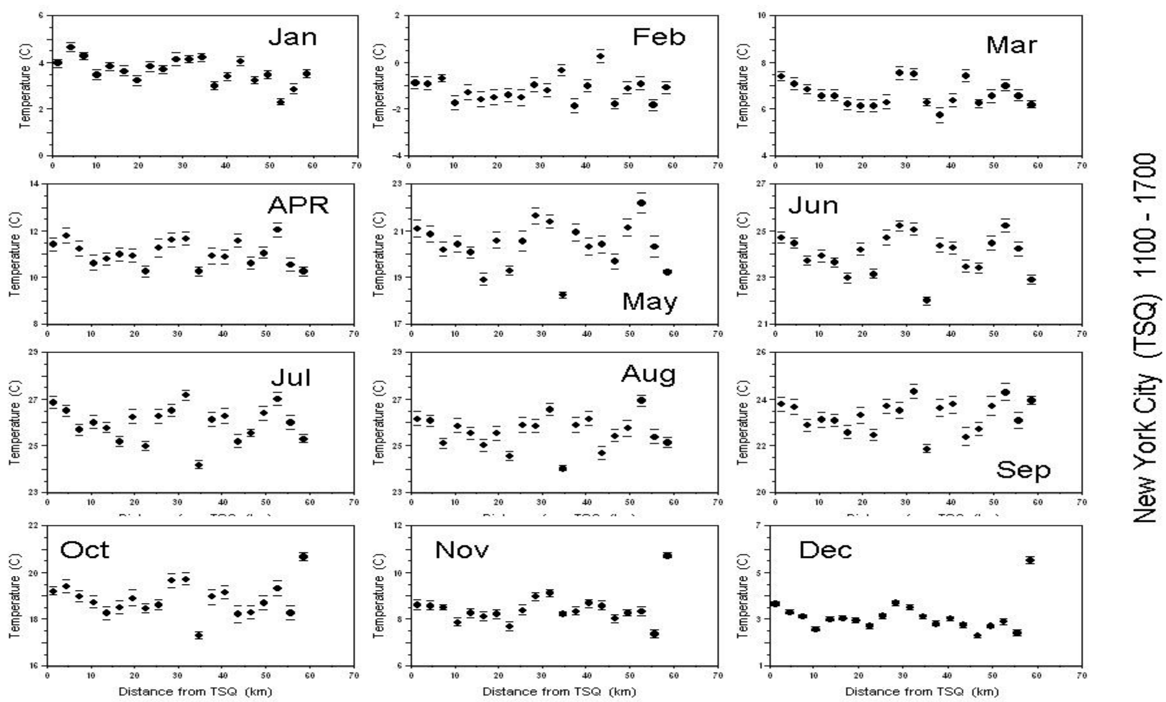

Figure 6. As in Figure 5, but for daytime (1100 – 1700 hrs).

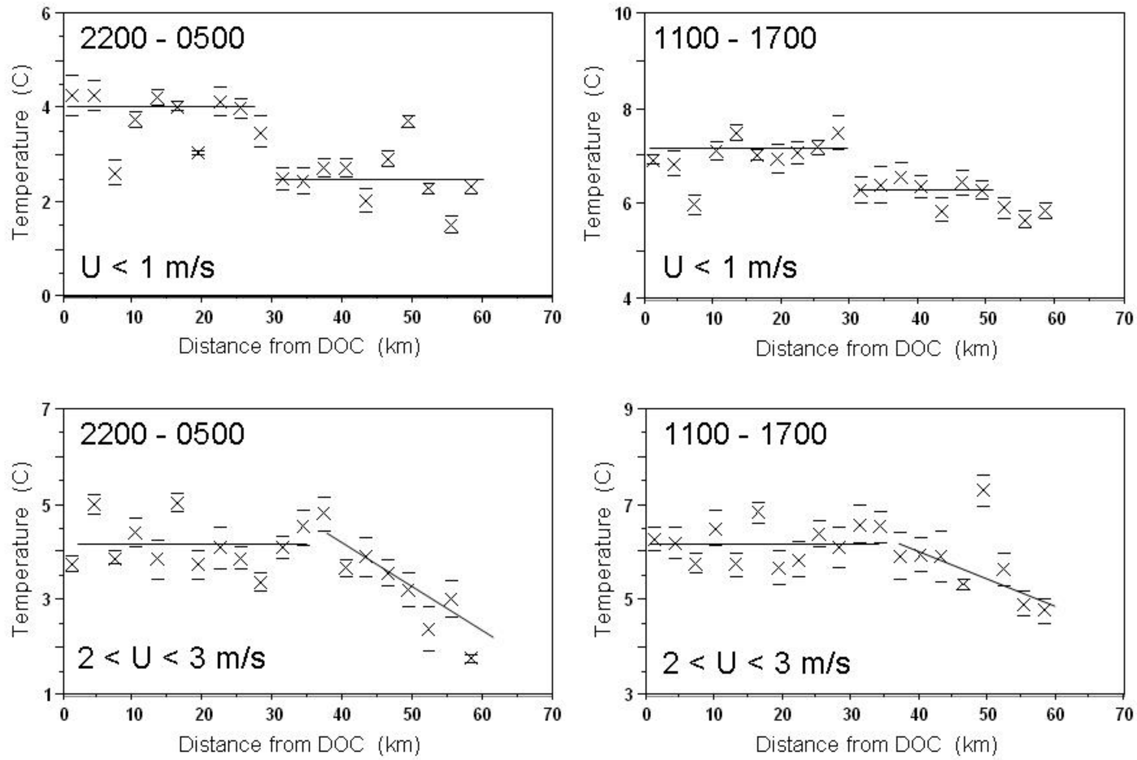

Figure 7. Detailed behavior for Washington, for January, showing the effects of increasing wind speed.

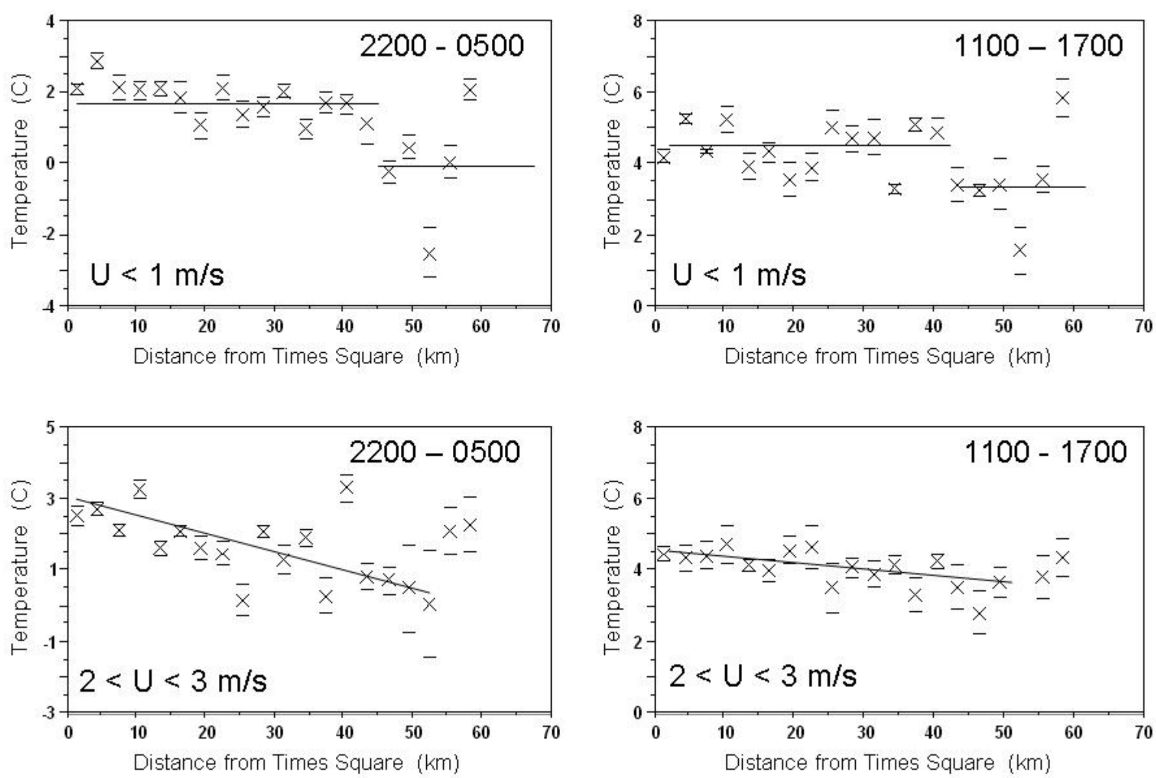

Figure 8. As for Figure 7, but for New York City (centered on Times Square).

permit a crude examination of this effect. Figure 7 gives four plots of Washington DC data, grouped according to wind speed (one pair for U < 1 m/s, the other for 2 < U < 3 m/s), for both of the daytime and nighttime situations. January data are selected for display. The plots indicate some support for the wind speed expectation, but the dependence does not appear to be strong. The lines drawn by eye indicate an interpretation of the results that is certainly open for discussion. For the light wind case, the horizontal scale of the heat island area appears to be about 25 to 30 km. For the higher wind speed case, the area is larger – about 35 km in radius. This applies for both the nighttime and daytime cases.

Figure 8 is comparable to Figure 7, although it appears less clear-cut. The lines drawn are by eye, and should not be interpreted as more than a possible description of the average behavior. The spatial extent of the New York heat island in January seems to be greater for the 2 to 3 m/s case than for the 0 to 1 m/s case – 50 to 55 km *versus* 40 to 45 km respectively, although clearly this is open to other interpretations.

Figure 9 presents some relevant information derived from the DCNet flux sites centering the Washington and New York analyses above. The nighttime situation is illustrated. There is an obvious anticorrelation between the w'T' covariances and temperature, for both locations. However, the magnitude of the w'T' covariance for New York maximizes (in mid winter, as expected due to the need for heating of buildings) at a magnitude about triple that for Washington. However, there is no obvious local spike in the magnitude of the heat island that would correspond to this elevated level of local heating. Clearly, the atmosphere serves to smooth out the consequences of the high local sensible heat flux. (Note that a covariance of 1.0 C.m/s corresponds to a sensible heat flux of about 1220 W/m^2 in nominal conditions.)

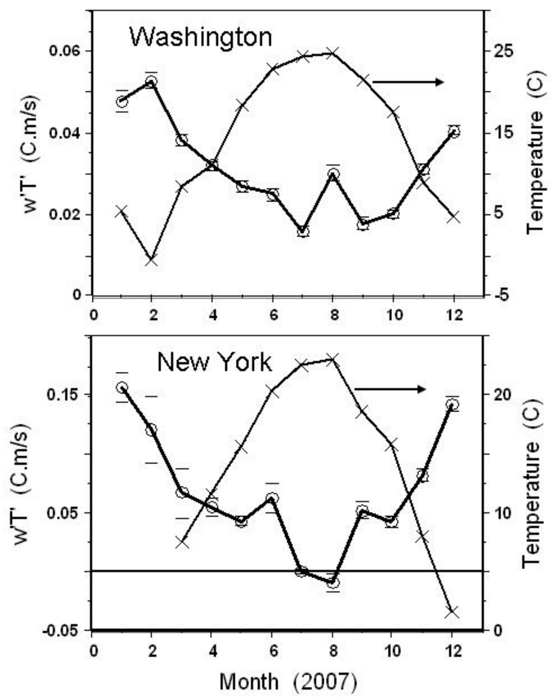

Figure 9. Annual cycles of the w'T' covariance for the sites selected as centers for the analyses presented here, together with air temperature data from the same locations. Note that these data were collected above the level of measurement of the AWS stations considered elsewhere in this report, and so a direct relationship between the temperatures plotted here and those indicated in Figures 3 to 8 is not expected.

Consider the nighttime case. Figure 9 shows that the average condition is of instability, except for the midsummer months for New York. This is not to say that the nighttime atmosphere is always unstable for the other cases, but in the present consideration of average behavior, convective conditions will often prevail. New York City is decidedly rougher than Washington, where building heights are constrained by regulation. For New York, therefore, not only are the winter heat fluxes greater than for Washington, but mechanical mixing will also be more energetic. The depth of the convectively well mixed layer will be greater for New York than for Washington. Hence, the effects of locally elevated sensible heat fluxes will be distributed through a deeper mixed layer than for Washington. Quantifying the difference presents a problem that is beyond the present capabilities, since the area in question is obviously highly complex and the familiar relationships that might otherwise be utilized are therefore inappropriate. At present, heurism appears unavoidable. The magnitude of the temperature difference associated with the New York heat island is expected, therefore, to be less than would be anticipated on the basis of a linear scaling of the Washington results according to the sensible heat flux. The spatial extent of the New York heat island is greater than that for Washington, again not surprisingly.

For the present, it can be concluded that the effects of the urban heat island on people, as revealed by the present data set for within the surface roughness layer, will be less than might be expected if data from greater heights were employed. Not surprisingly, the surface data indicate that the spatial extent of the New York heat island is greater than that of

Washington. Identifying a center for the heat islands presents difficulties that have not yet been overcome, but related exploration suggests that a search for such a center might be pointless. Finally, it is clear that the surface data provided by the AWS network provide a useful tool for examining the local atmospheric environments that are most related to human exposure. As weather forecasting increasingly addresses predictions as they directly impact people, such network data could provide a valuable and currently untapped resource.

ACKNOWLEDGEMENTS

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