J16.2 **ON THE ROOFTOP MICROMETEOROLOGY AND HEAT ISLANDS OF WASHINGTON AND NEW YORK CITY**

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1. INTRODUCTION

There have been several recent urban field studies aimed at studying the meteorology and the dispersion of pollutants in urban areas. In the USA, intensive studies have been conducted recently in Salt Lake City, Oklahoma City, and New York City (see Allwine et al., 2002; Hanna et al., 2003). These studies have revealed the complexity of the urban environment in considerable detail. It is now appreciated that the movement of pollutants in street canyons is not directly coupled to the winds aloft with street orientation the major controlling factor. None of this is surprising, but it leads to a suite of difficulties confronting the provision of forecasts where people are actually exposed – at the lowest level of the urban boundary layer.

The heat island of Washington is a well-accepted feature of the area, having been the focus of research for many decades (for early work, see Woolum, 1964). In the case of New York City, the heat island issue has also been the subject of considerable research, culminating in studies to assess potential mitigation strategies (Rosenzweig, et al., 2006).

It is tempting to use conventional micrometeorology, overlooking the constraints associated with flux-gradient relationships and with various schemes for non-dimensionalizing variables. However, given the lack of any other suitable conceptual approach, and using appropriate caution, standard techniques provide a reasonable framework for evaluating experimental data.

There is no doubt that measurements of eddy fluxes can be made at any convenient height above the level of surrounding obstacles, but the region-of-influence for the turbulence measurement footprint is likely to be site-specific. In the current case, the footprint related to sensible heat is likely to be different from that for the momentum flux, because the former is controlled by buoyancy whereas the latter is not. Nevertheless, the higher the measurements, the more likely it is to derive a spatially representative value. The extent of this spatial representativeness is a focus of the DCNet program. It is the state variables (temperature, humidity, velocity) that deviate greatly from the micrometerorological expectations as the surface is approached. In essence, turbulence (and eddy fluxes) are comparatively conservative quantities; characteristics of the mean flow are not.

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DCNet was started in 2002, in recognition that urban areas pose a challenge to dispersion meteorologists. Because of (a) its long history of meteorological and especially dispersion investigation (Draxler, 1987a, b), (b) its spatial uniformity, and (c) its potential attraction as a target for terrorist attack, Washington DC was selected as the first of what was then anticipated to be a series of urban area testbeds for dispersion studies. Micrometeorological towers were erected at various times over the following five years, typically on the roofs of buildings in and around the central business district of Washington. From the meteorological perspective, the "center" of the city is taken to be the area known as the Federal Triangle, this being the location of some of the oldest and most power-demanding buildings of Washington.

2. INSTRUMENTATION & DATA ACQUISITION

Three-dimensional sonic anemometer systems have been deployed, all at the top of 10 m towers usually set up on the roofs of large buildings and located to minimize possible effects of roof edges and nearby

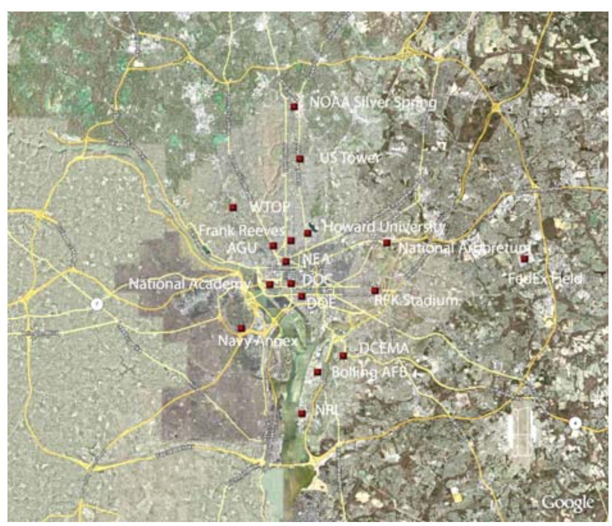

Figure 1. DCNet sites in and around the District of Columbia, as at November, 2008.

Figure 2. An example of a DCNet tower, showing a sonic anemometer at the top of a roof-mounted 10 m tower, with a standard meteorological instrumentation set mounted slightly below.

structures. Figure 1 shows the array of towers now in place and Figure 2 is a close-up of a typical tower. Data from the sonic anemometer are accessed at 10Hz by a local data acquisition system that computes all averages, variances and covariances over 15 minute periods. Every fifteen minutes, computed results are transmitted via cellular modem to a central archive located at the NOAA research facility at Oak Ridge, Tennessee. All archived data are available, upon prior arrangement, via the internet. The archive is updated every fifteen minutes.

Table 1 lists details of the DCNet stations. In the analysis that follows, all available data collected after 1 January 2004 have been used, up until the date of analysis – 15 September 2008. Data have been sorted according to wind direction, in recognition of the fact that the surroundings of the stations vary considerably. For example, the NAS site is located on the roof of the National Academy of Sciences, on Constitution Avenue near the Vietnam Memorial. To the North is the complex of the Department of State. To the South is the verdant expanse of the mall. To the east and west are buildings and gardens similar to the surroundings of the National Academy building itself. Such variations are common among the DCNet sites.

The data used here were extracted from the DCNet archive, and post-processed to correct for sensor tilt. This procedure yields quantifications of the three-dimensional wind components relative to the plane of the streamlines. Two criteria have been used to construct the analysis database. First, it is required that the data record be complete. Second, records yielding a <w'T'> covariance absolute value exceeding 1 C.m/s or a <w'u'> covariance absolute value exceeding 1 $(m/s)^2$ have been rejected. No constraints have been applied on wind speed. It is accepted that wind speed uncertainties will be greatest for light winds, correlating with stability extremes. However, much of the following analysis is based on near-neutral condition, and such light wind concerns should not be critical. Here, angle brackets will be used to indicate time averages. Otherwise, notation is conventional.

TABLE 1

Site details of current DCNet installations. H is the height above ground level. All towers are 10 m tall.

Washington, DC	Lat (N)	Long (W)	H
Dept. Commerce (DOC)	38.894	77.033	40 m
Nat. Acad. Sci. (NAS)	38.893	77.048	25 m
DC Municipal Ctr. (WMC)	38.917	77.033	40 m
Dept. of Energy (DOE)	38.887	77.025	40 m
Naval Res. Labs. (NRL)	38.821	77.025	30 m
Navy Annex (NAX)	38.868	77.068	30 m
NOAA, Silver Spg. (SSG)	38.992	77.030	60 m
DC Arboretum (ARB)	38.916	76.964	10 m
DC Emerg. Mgt. (EMA)	38.854	76.995	20 m
R.F.Kennedy Stad. (RFK)	38.889	76.973	45 m
Fort A. P. Hill (APH)	38.072	77.327	35 m
Nat. Educ. Assn. (NEA)	38.906	77.036	35 m
WTOP Television (WTO)	38.936	77.074	40 m
Howard University (HU)	38.922	77.021	25 m
Amer. Geophys. (AGU)	38.915	77.045	28 m
New York City			
Env. Meas. Lab. (EML)	40.726	74.008	36 m
Times Square (TSQ)	40.760	73.984	125 m

The situation is one that violates standard micrometeorological practice. In particular, the conventional micrometeorological model based on Monin-Obhukov similarity is clearly inappropriate, because data have been obtained within the surface roughness layer. However, as stated above, the M-O construct provides a reasonable analytical framework. While observations are certainly affected to some extent by upwind surface features, all possible efforts were made to minimize the consequences. The variable that is most affected by surface imperfections is the <u’w’> covariance, from which the friction velocity is derived as $u^* = \langle -u'w' \rangle^{1/2}$. The intent of the present analysis is twofold – (a) to investigate the variation of surface roughness with season and (b) to explore flux details of the Washington heat island.

3. SURFACE ROUGHNESS.

A conventional analytical approach would be to plot, for each site and each month, the quantity k/C_f as a function of (z-d)/L, where k is the von Karman constant (0.41), C_f is the friction coefficient (u*/U, where U is the mean velocity reported by the sonic anemometry), z is the height above the ground, d is the height of the zero plane, and L is the Monin-Obhukov scale length; $L \equiv -\langle -u'w' \rangle^{3/2}/(kg\langle w'T' \rangle)$. Note that the quantity k/C_f equals $\ln((z-d)/z_0)$ at neutral, where z_0 is the roughness length. The difficulty that then arises is that u* is a shared variable, and hence a plot of one of these variables against the other will likely indicate a dependence that is a function of the statistics rather than of the physics. For this reason, near-neutral estimates of the property k/C_f have been selected on the basis of the <w’T’> covariance alone.

Figure 3a shows the average annual cycles of k/C_f for the DCNet AGU location. For this purpose, “near neutral” values of k/C_f have been derived by averaging values for which the absolute value of <w’T’> is less than 0.005 C.m/s. Figure 3b shows the corresponding changes in the roughness length, computed on the assumption that the displacement height is 80% of the height of the building on which the sensors are mounted. Further examination of the data shows that the annual cycle in roughness length is not greatly affected by the assumption regarding the value of d. In Figure 3b, two bounds are shown around the data representing flow from the North. These bounds correspond to two alternative assumptions about d: 70% of h or 90% of h. In reality, winds from the north encounter a large office structure upwind of the DCNet location, considerably higher than the sensors. The large roughness lengths of Figure 3b for northerly flow may therefore be considered somewhat of an anomaly (although not rejected, since such anomalies will frequently be encountered and need to be considered). It is reassuring that the other three sectors yield similar behavior, as must be expected on the basis of a visual inspection of the location.

The seasonality of the roughness lengths, evident in Figure 3b, is reproduced for other DCNet locations. Figure 4 shows the overall results for downtown Washington, assembled (as geometric means) using data from those sites within 5 km from the Capitol. Figure 4a, shows the variability with wind direction of the roughness length, computed on the assumption that d = 0.8h. Figure 4b tests the sensitivity to the assumption about d (the displacement height). The

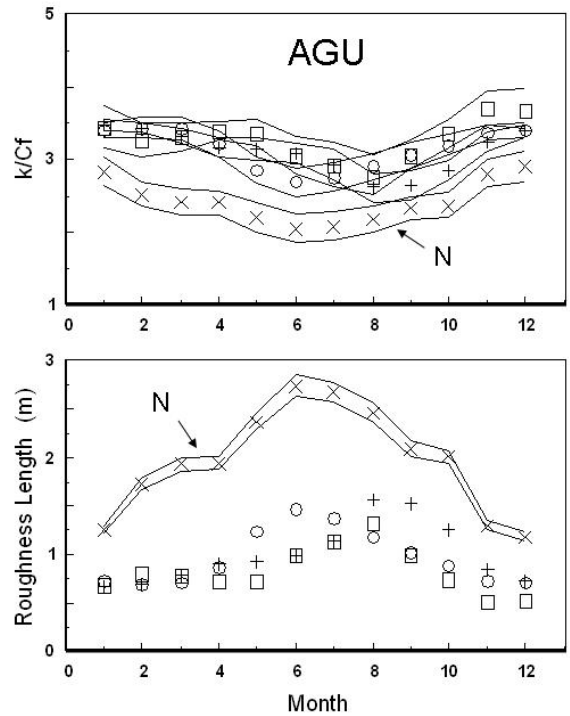

Figure 3. Upper diagram (a) -- average annual cycles of k/C_f for the DCNet AGU location (see Table 1). Averages for the four wind quadrants are shown: North (+), East (o), South (x) and West (⊞). Lower diagram (b) – the corresponding average annual cycles of roughness length, assuming the displacement height is 80% of the height of the building (h). For the northerly winds, the bounds plotted correspond to alternative assumptions: d = 70% and d = 90% of h.

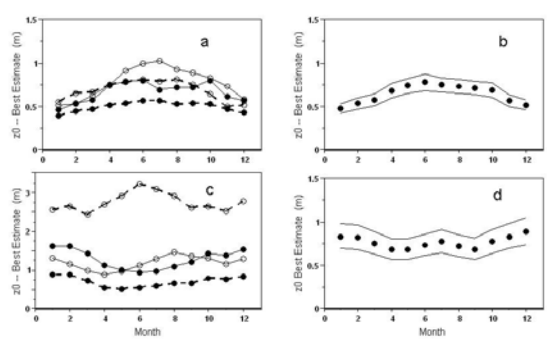

Figure 4. Roughness results for all stations, combined, (a) and (b) for Washington, DC, and (c) and (d) fpor New York City. Wind direction sectors are as in Figure 3. The bounds indicated in (b) and (d) correspond to the assumptions about the displacement height, either d = 0.7h or d = 0.9h, around the average assumption: d = 0.8h.

overall averages are shown, for all wind directions for d = 0.8h. The consequences of alternatives d = 0.7h and d = 0.9h are represented by the bounding lines around the sequence of points. Figure 4c presents results for the two New York City measurement sites, paralleling the analysis in Figure 4a. There is no evidence of seasonality in the New York estimates of z_0. Figure 4d provides an equivalent analysis for New York as in Figure 5b for Washington. Note that the high roughness lengths evident in Figure 4c for easterly winds are likely due to the exceedingly rough fetch experienced at the TSQ site,

4. HEAT FLUXES AND THE HEAT ISLAND

Figure 5 shows monthly average diurnal cycles of <w'T'> for the Silver Spring location. Data are separated into the four calendar seasons (Winter = January, February and March; etc). Figure 6 presents monthly average diurnal cycles <w'T'> for the New York City Times Square location (TSQ). These data display features that are common among many locations –

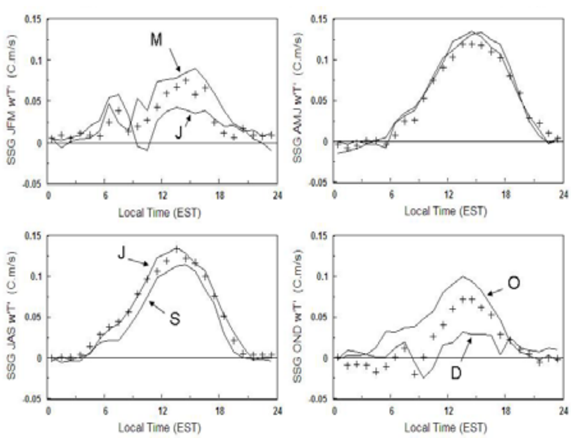

Figure 5. The average diurnal cycles of the <w'T'> covariance, for Silver Spring (SSG), and for the four calendar seasons (Jan, Feb, Mar; Apr, May, Jun; etc).

■ Nighttime sensible heat fluxes are typically close to zero. For some months, the averages at night remain positive. For some other sites (e.g. those closer to the downtown areas) the heat fluxes remain strongly positive throughout the entire diurnal cycle.

■ The months of November, December, January, February and March show short-term increases in the w'T' covariance in the hours immediately before dawn. One explanation for this increase is the time-dependent ramping up of heating systems in winter, in advance of the start of the working day.

Figure 7 presents the annual nighttime averages of <w'T'> for a number of DCNet locations. Data are nighttime averages covering the period from 2200 to

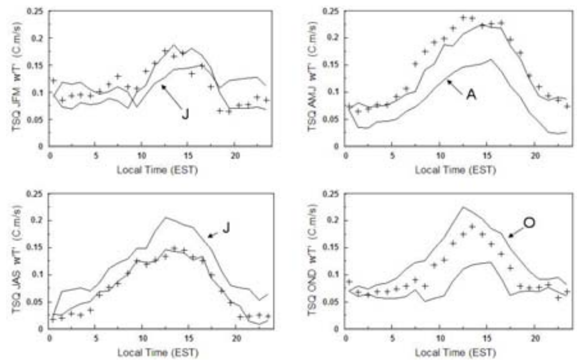

Figure 6. As in Figure 5, but for the Times Square location in New York City (TSQ).

0500. Also shown are average temperatures, evaluated over the same period. As expected, the various temperature cycles are almost identical, however some of the <w'T'> averages show no variation while others display a negative correlation with temperature. For the Washington case, the sites with the strongest negative correlation are the ones located in the older part of the city, where large granite buildings dominate, constructed about a century ago before the awareness of the need for insulation. In the colder weather, there is a greater need for heating of such buildings, and indeed the consequences are evident in many of the cases illustrated.

Figure 8 presents the monthly average cycles derived from the data used to generate Figure 7. For the Washington, DC data, the DOC building shows the consistently highest values of nocturnal <w'T'>, with some evidence of a small upward excursion corresponding to summer air conditioning. The nearby DOE monitoring station (about 1 km away) is above a much more recent structure (the Forrestal Building). It yields a more constrained set of <w'T'> values, although with the expected excursions due to summer cooling and winter heating. The NAS data set is similarly revealing, although difficult to interpret because wind direction effects are not considered here. The Naval Annex data (NAX) are from a site near the Pentagon, where there is a strong influence of surrounding parkland (e.g. the Arlington Cemetery). The NAX data in Figure 8 show little evidence of the summer and winter variations observed elsewhere; the nighttime <w'T'> covariances are systematically negative. Note that the vertical scale is expanded for NAX.

The two New York City data sets shown in Figure 8 are quite different from their Washington counterparts. First, note that the <w'T'> scale of the TSQ diagram is different; the midwinter value of <w'T'> for TSQ is about 0.15 ^{o}C.m/s, about three times the maximum value for the Washington area. The EML location (in midtown Manhattan, near the World Trade Center) displays a winter maximum similar to that of DOC.

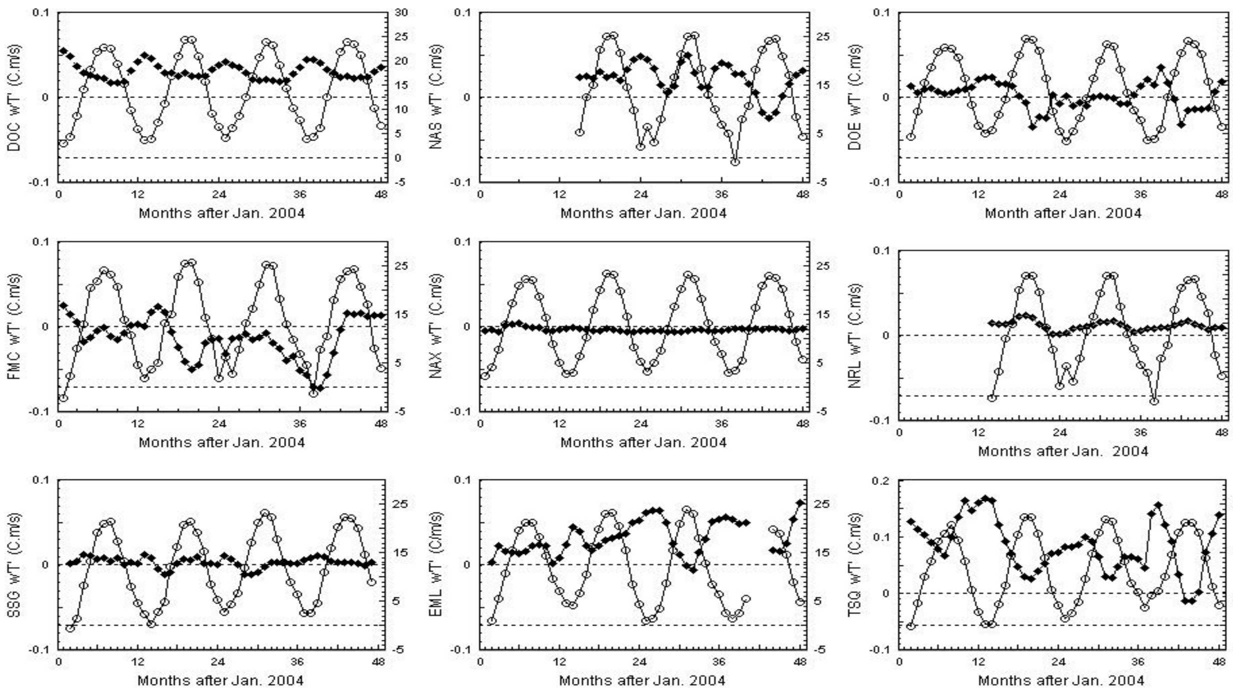

Figure 7. The time sequence of nighttime (2200 to 0500 hrs) average covariances <w'T'> for different DCNet sites, including two in New York City (EML and TSQ). For this presentation, three-month running means are plotted. The right hand axes refer to the corresponding air temperatures, shown as open circles.

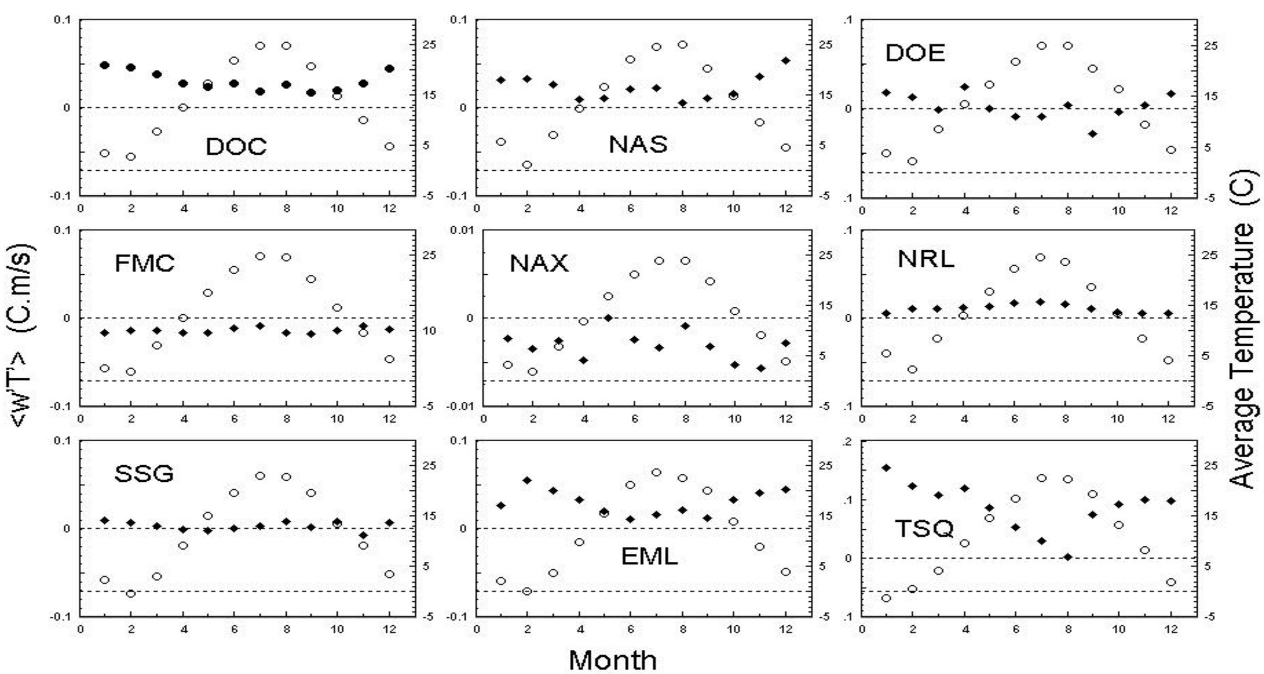

Figure 8. The average annual cycles derived from the data of Figure 7.

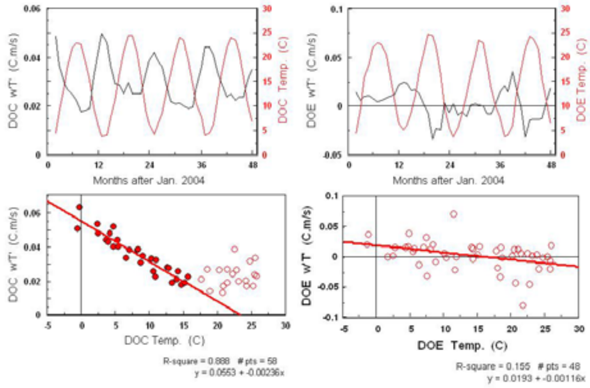

Figure 9. Data for two sites in Washington: DOC and DOE. The upper plots are as in Figure 8. The lower diagrams show the relationship between nighttime <w'T'> and temperature.

Figures 9 and 10 show some additional detail, for two Washington and New York sites. The upper plots present monthly nighttime averages of temperature and heat flux. The lower plots are of <w'T'> versus temperature averaged over the full dataset. The regression lines shown are all highly significant (but note that for the DOC case the regression scope is confined to T < 25 C.) These results suggest benefit from comparison against power consumption data in the vicinities of the sites, but such a study has not yet been attempted.

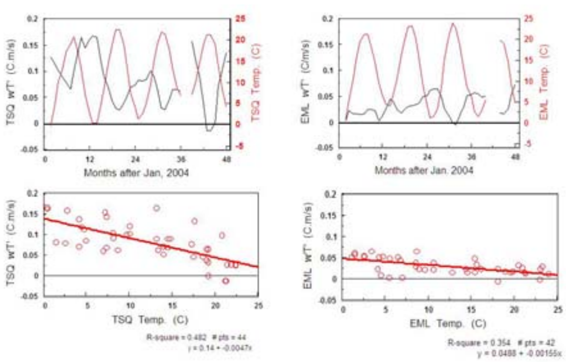

Figure 10. As in Figure 9, but for two sites in New York City: TSQ and EML.

5. CONCLUSIONS.

Assumptions that the Washington DC urban area can be characterized by a single time-invariant roughness length and a single displacement height are wrong. However, the variations appear to depend strongly on wind direction for many locations, and such directional variations tend to average out as a spatial average is constructed. For many locations, there is a marked effect of the seasonal change in vegetation. Trees in the area are largely deciduous, and the present results reflect the leafing of the trees in the early Spring and the loss of leaves in Autumn.

Comparison of data for Washington and New York City reveals a strong seasonal signal for the former that is lacking for the latter, in accord with the expectation that the "greening" of Washington would be evident in the roughness data. Washington is richly endowed with trees, almost all deciduous, with budbreak typically in April/May. The present analysis suggests a best overall estimate of the (spatially averaged) roughness length as about 0.7 m for Washington and about 1.3 m for New York City.

The nighttime sensible heat covariance <w'T'> data show strong differences from site to site, with data obtained in areas of older construction yielding more convincing evidence of effects related to winter heating and summer cooling of the buildings. Discussion of the heat island effect usually draws attention to the many causative factors, such as the urban changes in albedo and vegetation, but the present data suggest strongly that a major factor is the direct generation of heat by building climate controls: the older the buildings, the more striking is this effect. Moreover, comparison between the Washington and New York data supports the expectation that the nocturnal heat island effect is certainly greater for the more massive structures of New York than for the height-constrained buildings of Washington.

ACKNOWLEDGEMENTS

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