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 micrometeorological expectations as the surface is approached. In essence, turbulence (and eddy fluxes) are comparatively conservative quantities; characteristics of the mean flow are not.

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 obstacles.
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.

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

<table>
<thead>
<tr>
<th>Washington, DC</th>
<th>Lat (N)</th>
<th>Long (W)</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dept. Commerce (DOC)</td>
<td>38.894</td>
<td>77.033</td>
<td>40 m</td>
</tr>
<tr>
<td>Nat. Acad. Sci. (NAS)</td>
<td>38.893</td>
<td>77.048</td>
<td>25 m</td>
</tr>
<tr>
<td>DC Municipal Ctr. (WMC)</td>
<td>38.917</td>
<td>77.033</td>
<td>40 m</td>
</tr>
<tr>
<td>Dept. of Energy (DOE)</td>
<td>38.887</td>
<td>77.025</td>
<td>40 m</td>
</tr>
<tr>
<td>Naval Res. Labs. (NRL)</td>
<td>38.821</td>
<td>77.025</td>
<td>30 m</td>
</tr>
<tr>
<td>Navy Annex (NAX)</td>
<td>38.868</td>
<td>77.068</td>
<td>30 m</td>
</tr>
<tr>
<td>NOAA, Silver Spg. (SSG)</td>
<td>38.992</td>
<td>77.030</td>
<td>60 m</td>
</tr>
<tr>
<td>DC Arboretum (ARB)</td>
<td>38.916</td>
<td>76.964</td>
<td>10 m</td>
</tr>
<tr>
<td>DC Emerg. Mgt. (EMA)</td>
<td>38.854</td>
<td>76.995</td>
<td>20 m</td>
</tr>
<tr>
<td>R.F.Kennedy Std. (RFK)</td>
<td>38.889</td>
<td>76.973</td>
<td>45 m</td>
</tr>
<tr>
<td>Fort A. P. Hill (APH)</td>
<td>38.072</td>
<td>77.327</td>
<td>35 m</td>
</tr>
<tr>
<td>Nat. Educ. Assn. (NEA)</td>
<td>38.906</td>
<td>77.036</td>
<td>35 m</td>
</tr>
<tr>
<td>WTOP Television (WTO)</td>
<td>38.936</td>
<td>77.074</td>
<td>40 m</td>
</tr>
<tr>
<td>Howard University (HU)</td>
<td>38.922</td>
<td>77.021</td>
<td>25 m</td>
</tr>
<tr>
<td>Amer. Geophys. (AGU)</td>
<td>38.915</td>
<td>77.045</td>
<td>28 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>New York City</th>
</tr>
</thead>
<tbody>
<tr>
<td>Env. Meas. Lab. (EML)</td>
</tr>
<tr>
<td>Times Square (TSQ)</td>
</tr>
</tbody>
</table>

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 \(u^* = \sqrt{<u'w'>/\rho}\). 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; \(L \equiv \sqrt{-<u'w'>^2/(\rho g\langle w'T'\rangle)}\).

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 (f). 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) for 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. 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 –

- 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  
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 cooling. 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  
datset 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 
arounding 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 °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.
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 \( \langle w'T' \rangle \) 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

The support of NOAA management is greatly appreciated.

REFERENCES


