# Urban Turbulence in Space and in Time

BRUCE B. HICKS

*Metcorps, Norris, Tennessee*

WILLIAM J. CALLAHAN

*Earth Networks, Inc., Germantown, Maryland*

WILLIAM R. PENDERGRASS III AND RONALD J. DOBOSY

*Atmospheric Turbulence and Diffusion Division, Air Resources Laboratory, NOAA, Oak Ridge, Tennessee*

ELENA NOVAKOVSKAIA

*Earth Networks, Inc., Germantown, Maryland*

(Manuscript received 5 January 2011, in final form 8 September 2011)

ABSTRACT

The utility of aggregating data from near-surface meteorological networks for initiating dispersion models is examined by using data from the ''WeatherBug'' network that is operated by Earth Networks, Inc. WeatherBug instruments are typically mounted 2–3 m above the eaves of buildings and thus are more representative of the immediate surroundings than of conditions over the broader area. This study focuses on subnetworks of WeatherBug sites that are within circles of varying radius about selected stations of the DCNet program. DCNet is a Washington, D.C., research program of the NOAA Air Resources Laboratory. The aggregation of data within varying-sized circles of 3–10-km radius yields average velocities and velocity-component standard deviations that are largely independent of the number of stations reporting—provided that number exceeds about 10. Given this finding, variances of wind components are aggregated from arrays of WeatherBug stations within a 5-km radius of selected central DCNet locations, with on average 11 WeatherBug stations per array. The total variance of wind components from the surface (WeatherBug) subnetworks is taken to be the sum of two parts: the *temporal* variance is the average of the conventional wind-component variances at each site and the *spatial* variance is based on the velocity-component averages of the individual sites. These two variances (and the standard deviations derived from them) are found to be similar. Moreover, the total wind-component variance is comparable to that observed at the DCNet reference stations. The near-surface rooftop wind velocities are about 35% of the magnitudes of the DCNet measurements. Limited additional data indicate that these results can be extended to New York City.

## 1. Introduction

There is no clear indication of how to select surface observations to drive dispersion models for the lowest levels of the urban/suburban environment, where pedestrians and others will be exposed. In the United States, data from the nearest Automated Surface Observing System (ASOS) weather station operated by the National Weather Service are conventionally used as input, but the ASOS sites are generally far from the location of specific interest and, hence, provide only limited information on relevant wind statistics. In many cities, the nearest ASOS station is located at a major airport, where conditions are likely to be considerably different from downtown.

There are several different paths that researchers on urban dispersion are following. One path concentrates on using detailed knowledge of the area in question to help to drive computational fluid dynamics models or large-eddy simulations, from which wind fields are derived with sufficient detail to drive a dispersion code (Baik et al. 2003; Xie and Castro 2009). Another path

*Corresponding author address:* Bruce B. Hicks, Metcorps, P.O. Box 1510, Norris, TN 37828-1510.
E-mail: hicks.metcorps@gmail.com

DOI: 10.1175/JAMC-D-11-015.1

focuses on applying more-conventional dispersion codes, but applying them in situations in which there are no (or very few) local data (e.g., Sykes and Gabruk 1997). The basic requirement is then for an adequate understanding of the processes that control velocity and turbulence within the surface roughness layer, such that whatever few data are available can be used. To these ends, there have been many intensive (but short term) field studies involving the release of tracer materials and dense networks of meteorological instrumentation (e.g., Allwine et al. 2002; Arnold et al. 2004; DePaul and Sheih 1985, 1986; Hanna et al. 2006; Rotach et al. 2005). A longer-term multitracer study of dispersion in and around Washington, D.C., was performed in the 1970s and constitutes one of the reasons for the choice of Washington as an experimental focus in this paper (see Draxler 1987a,b). Yet another path might address the situation that is more common in North America and is increasingly common elsewhere: there are many observations available, but their utility is often questioned for modeling applications because the network stations are not individually representative of the model's coarser grids. If the corresponding measurement systems are well maintained, however, their data are truly indicative of the conditions at the point at which the measurements are made. Thus, such data could hold considerable promise for guiding forecasts of dispersion in urban areas as well as for many other applications for which there are many such surface stations.

Consider the hypothetical case in which the surface roughness layer (below the level of conventional meteorological concern) is instrumented in great detail, with enough sensors to describe all of the motions that are controlling local dispersion. An accurate dispersion calculation could then be based on the data stream from this dense network. The operational question of current relevance is "How dense must such a network be to yield useful information and what measurements should be reported?" One might reasonably expect that about 10 WeatherBug sites (described below) in the near vicinity of a selected location might yield useful measures of wind averages and turbulence statistics. The question then arises as to what constitutes "near vicinity."

On admittedly heuristic grounds, it is expected that a handover between local roughness layer dispersion and larger-scale surface boundary layer dispersion might occur at a range of 1–10 km (depending on the location and especially on the homogeneity of the surroundings). Until that handover occurs, the notion of "representativeness" is largely irrelevant, since no single measurement could possibly represent all of the wind-field complexity encountered within and among street canyons. It is only when the behavior of interest is that of air above the influence of the streets and individual buildings that a "representative" measurement location is likely to be appropriate. A related consideration is to what extent such representative data, if available, can be used to describe dispersion in the urban roughness layer where people might be exposed.

The purpose of this paper is to examine some basic properties of turbulence statistics as revealed by a dense network in an urban area, potentially leading to the use of such data to augment standard dispersion-modeling methods. Near-surface network data are obtained from the national meteorological network operations of Earth Networks, Inc. The Earth Networks WeatherBug network (see online at http://earthnetworks.com) makes use of mechanical anemometers with starting speeds of about 1 m $s^{-1}$. As a consequence, it is expected that one of the difficulties will be with light-wind situations. Data are recorded at a rate of 0.5 Hz. WeatherBug instruments are typically deployed on 2–3-m masts attached to the edges of the roofs of buildings, most often educational institutions and first-responder facilities. Although the initial focus of this commercial network is on the contiguous United States, expansion to other geographies is well under way, and hence the analysis presented here is expected to have wider application in the near future.

Use will be made of supporting information from DCNet, a network of sonic anemometers mounted 10 m above the rooftops of selected buildings in Washington, D.C., and its surrounding area (see online at http://dcnet.atdd.noaa.gov). DCNet is a research program of the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory. DCNet installations are distant from the edges of roofs so as to minimize the consequences of edge effects and local obstructions. Nevertheless, both the near-surface WeatherBug and the more-elevated DCNet installations do not comply well with the guidelines for urban meteorological measurements published by the World Meteorological Organization (Oke 2004) and would therefore not be considered in many models. There are two additional stations in New York City, New York, that use the same protocols that DCNet does. Figure 1 shows the locations of Earth Networks WeatherBug and NOAA DCNet stations in the Washington (left panel) and New York City (right panel) areas. DCNet data are recorded at a rate of 10 Hz. Data collected by both the DCNet and WeatherBug networks are available through the Meteorological Assimilation Data Ingest System (MADIS) of NOAA (see online at http://MADIS.NOAA.gov/).

Reference to any of the available sources of satellite imagery will reveal some of the constraints that affect DCNet data collected at the sites used here. In particular, the "DOC" site is on a multistory building that

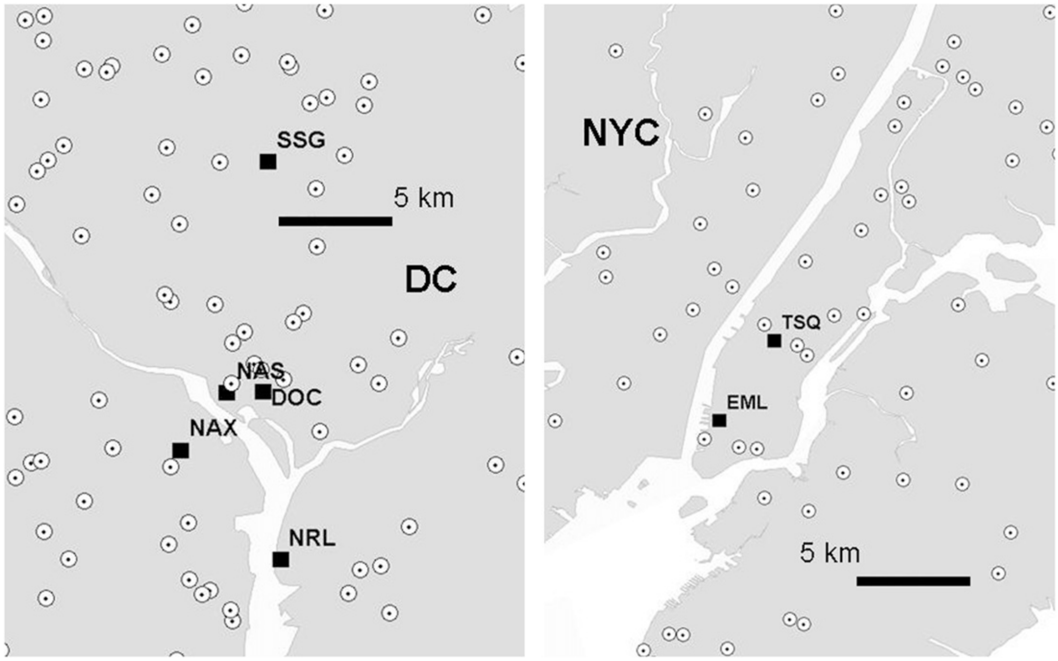


FIG. 1. Locations of DCNet (filled squares) and WeatherBug (circled dots) sites in the (left) Washington, D.C., and (right) New York City areas. There are other DCNet stations in the Washington area. The stations identified in this diagram are those emphasized in the current analysis and were selected to represent a cross section of urban areas ranging from city center to distant suburban.

occupies most of a city block but that is similar in height to most of its neighbors. Independent analysis indicates that the turbulence measured by this station is influenced by local effects that are associated with the building itself, especially in convective conditions. Site ''SSG'' is atop a tall building at the NOAA headquarters complex in Silver Spring, Maryland. This complex is surrounded by much smaller structures, dominated by urban residences to the north and east and by growing commercialization to the south and west. Site ''NAS'' is on the roof of the National Academy of Sciences building, which is bordered by the Washington Mall (and the Vietnam Memorial) to the south but is strongly influenced by the much larger U.S. Department of State building to the north. Site ''NAX'' refers to the Navy Annex of the Pentagon, in Virginia, directly across the Potomac River from Washington itself. NAX data are expected to be affected by the presence of the Pentagon to the east. Otherwise, the surroundings of NAX are dominated by parkland (such as the Arlington National Cemetery). The ''NRL'' site is above a comparatively small but multistory building, in an area sparsely populated by similar structures. All of the D.C. sites considered here are in areas with ratios of street width to building height that are much greater than is typical of the two sites in New York City (''EML'' and ''TSQ''). The EML station is bordered by a complex of similar multistory structures to the south, but to the north it is bordered by much smaller buildings and nearby parkland. TSQ is above one of the tallest buildings of the Times Square area, which is characterized by many skyscrapers within an area of densely packed commercial buildings.

The selection of which situations to examine has been influenced by the need to consider differences in the DCNet installations that could influence the conclusions to follow. For this reason, DOC and NAS are included in the analysis because they are sufficiently close to each other that they share many of the corresponding WeatherBug stations in their near vicinity. It is acknowledged that most of the DCNet stations are within the roughness sublayer. Hence, the more-elevated SSG and TSQ stations have also been considered here. Also, it is obvious that some of the WeatherBug stations are affected by nearby obstacles. In this regard, note that the analysis to follow does not exclude any WeatherBug stations, regardless of their individual exposure.

## 2. Data aggregation

The mean values and turbulence statistics collected by a subnetwork of stations around some selected location must be combined with considerable care. As an obvious example of the difficulties involved, consider the case in which average winds reported by an array of stations are such that some are on one side of north (360°) and some are on the other side. Taking an average of the wind directions is obviously misleading. Difficulties of this kind are often handled by referring to a 540° direction system (e.g., Yamartino 1984). An alternative is to compute averages and statistics using Cartesian velocity coordinates. The latter approach is adopted here. The data-averaging period used is 15 min.

Consider a subnetwork with $n$ stations surrounding a location of special interest. Each of these stations reports quasi-instantaneous values of the wind speed $u$ and direction $\theta$, from which east–west and north–south velocity components ($U$ and $V$, respectively) are calculated. Over a 15-min period, the average velocity components $\overline{U}$ and $\overline{V}$ are derived for each location, as are the corresponding standard deviations $\sigma(U)$ and $\sigma(V)$. In this discussion, overbars are used to denote time averages generated from a time series of measurements at a single location and angle brackets are used for the spatial statistics.

The intent here is to quantify two separate components of the overall velocity field, extending the conventional site-specific considerations so that the spatial dimension is also considered. The time variance is readily quantified as the average of the variances reported by each individual site. The spatial variance is quantified using the average velocity components reported from the separate sites. Thus, from the $n$ sets of site-specific, time-averaged variables, spatial measures are then computed: $\langle\overline{U}\rangle$ and $\langle\overline{V}\rangle$ as the averages of the $n$ values of $\overline{U}$ and $\overline{V}$, $\sigma(\overline{U})$ and $\sigma(\overline{V})$ as the standard deviations associated with $\langle\overline{U}\rangle$ and $\langle\overline{V}\rangle$, and $\langle\sigma^2(U)\rangle$ and $\langle\sigma^2(V)\rangle$ as the best estimates of the conventional velocity-component variances across the spatial domain. Note that the best estimates of the velocity-component standard deviations in time are then derived as the square roots of $\langle\sigma^2(U)\rangle$ and $\langle\sigma^2(V)\rangle$. Some additional statistical variables are then derived to characterize further the aggregate wind over the array of $n$ stations:

$$\begin{aligned}
\overline{\overline{V}} &\equiv (\langle\overline{U}\rangle^2 + \langle\overline{V}\rangle^2)^{1/2} = \text{the vector mean velocity across the array,}\\
\sigma^2(t) &\equiv \langle\sigma^2(U)\rangle + \langle\sigma^2(V)\rangle = \text{the combined velocity component variance in time,}\\
\sigma^2(s) &\equiv \sigma^2(\overline{U}) + \sigma^2(\overline{V}) = \text{the combined velocity component variance in space,} \quad \text{and}\\
\sigma^2(\mathrm{TOT}) &\equiv \sigma^2(s) + \sigma^2(t) = \text{the overall total velocity component variance.}
\end{aligned} \tag{1}$$

The left-hand symbols of the set of equations in Eq. (1) will be used in the remainder of this treatment to simplify notation. The corresponding mean and variance of the resultant-vector wind reported at the associated DCNet site are designated as $\mathbf{V}_{\mathrm{DCN}}$ and $\sigma^2(\mathrm{DCN})$, respectively. Note that many of the variables considered here are like the familiar turbulence kinetic energy, differing mainly in the lack of a vertical velocity component and the classical factor of one-half. Note also that the matter of how best to combine the variances in time and in space is likely to be contentious. Here, it is assumed that the variance in time is best represented by the average of the variances derived from the individual stations and that the variance in space is best quantified on the basis of the differences among the average velocities reported by the same stations. This follows the procedure used by Hanna and Zhou (2009). For comparison with data derived from DCNet anemometers at greater heights, however, these two variances (in space and in time) are assumed to be additive.

The ratio $R_{st} \equiv \sigma(s)/\sigma(t)$ can then be used to explore the basic questions mentioned above: how many stations are needed to construct a meaningful aggregate and how large an area should be considered. To address the issue in a general sense, it is necessary to account for the inherent site-to-site differences. The goal is to identify a sample size $n$ such that there is negligible improvement in confidence as the sample size increases. To this end, Fig. 2 plots coefficients of variation of the quantity $R_{st}$, for datasets obtained in two months (March and June of 2007), over areas defined by circles centered on DCNet locations (see Fig. 1 and Table 1). The radii of these circles are taken to be 3, 5, 7, and 10 km. The coefficients of variation (COVs) are the ratios of standard deviations to average values. The COVs are measures of the variability within each sample after fluctuations in the averages are taken into account. (Note that the DCNet data will be used later to examine the linkages between the combined surface observations and turbulence statistics obtained 10 m above the tops of buildings.) The lines drawn in the diagrams of Fig. 2 are eyeball interpretations

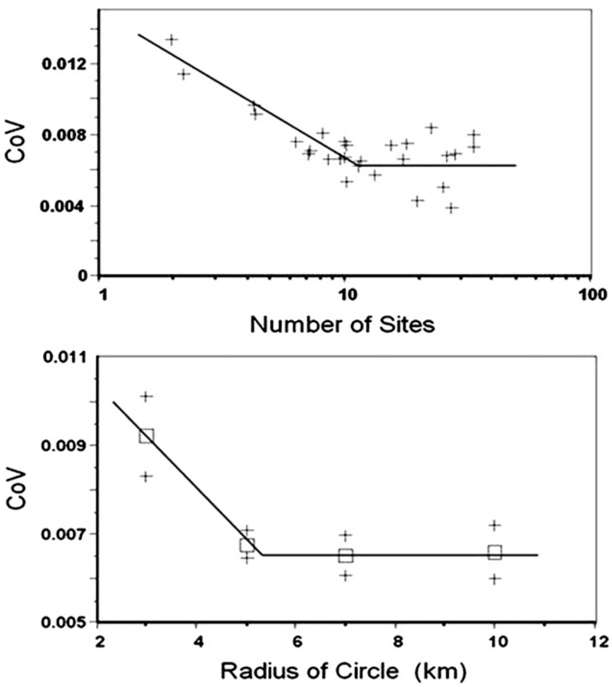


FIG. 2. Coefficients of variation of the space–time velocity standard deviation ratios $R_{st}$, derived using 15-min data from a selection of DCNet locations, for March and June 2007. (top) Each point represents the results obtained from data obtained over a single month, for a particular DCNet center and for a specified area around this center of radius 3, 5, 7, or 10 km. Data are plotted against the number of stations contributing to each average. (bottom) As in the top panel, but as a function of the radius of the prescribed circular area for selecting surface network sites. Plus signs indicate the 1 std dev limits on the averages (plotted as squares).

of the results. The data suggest the following conclusions: 1) 10 or more stations are indeed required to yield a meaningful picture of the surface roughness layer and 2) the area over which the data are collected should not be less than about 5 km. It is also clear that surface complexity will affect all such conclusions, however, and that a large area will yield more spatial variability than will a small one. The ideal circumstance would be to select the smallest size for which both criteria are applicable. For the analysis that follows, data collected over circular areas of 5-km radius will be employed. Table 1 lists the average number of surface subnetwork stations contributing to each aggregation, as well as details of the DCNet sampling station around which they are centered. The average number of stations is not necessarily integral, because not all stations always report complete datasets.

## 3. Comparison with DCNet—Velocities

Near the surface, the turbulent fluctuations that cause dispersion are due to mechanical drag of the wind on surface obstacles, convection, surface traffic, and similar factors. Instrumentation located above surface obstacles will respond to the wind field affected by the upwind area, in both its mean and fluctuating quantities. Hence, the DCNet instrumentation is intended to provide measurements indicative of some poorly defined upwind area that serves as a sink for momentum and a source of turbulent kinetic energy. If the area in question is sufficiently spatially homogeneous, then we might expect to find strong relationships between the aggregated information derived from near-surface instrumentation and the wind data reported by the higher-elevation (and centrally located) DCNet sensors. In the analysis that follows, DCNet data will be used as a reference for examining the relevance and utility of aggregated surface network data. Note that in its early years, DCNet became a favored source of urban data for numerical modelers, including those providing emergency response support for the Washington, D.C., area. Since 2006, DCNet data have been made available to any outside user through MADIS and are now routinely used by a wide variety of academic institutions and government

TABLE 1. Locations of DCNet stations considered in this analysis. Note that instrument heights are given in meters AGL. Here, $N$ is the average number of contributing stations in the 5-km-radius circular area centered on each DCNet site.

| Site | Lat (°N) | Lon (°W) | Height (m AGL) | $N$ |
|---|---|---|---|---|
| Washington, D.C., and environs | | | | |
| Department of Commerce (DOC) | 38.8937 | 77.0325 | 40 | 11.7 |
| National Academy of Science (NAS) | 38.8930 | 77.0478 | 25 | 10.7 |
| Naval Research Laboratories (NRL) | 38.8212 | 77.0248 | 30 | 10.2 |
| Navy Annex (Pentagon complex) (NAX) | 38.8683 | 77.0679 | 30 | 11.4 |
| NOAA complex, Silver Spring, MD (SSG) | 38.9924 | 77.0303 | 60 | 8.5 |
| New York City | | | | |
| Department of Homeland Security Environmental Measurements Laboratory (EML) | 40.7260 | 74.0076 | 36 | 4.7 |
| Times Square (TSQ) | 40.7603 | 73.9837 | 125 | 7.3 |

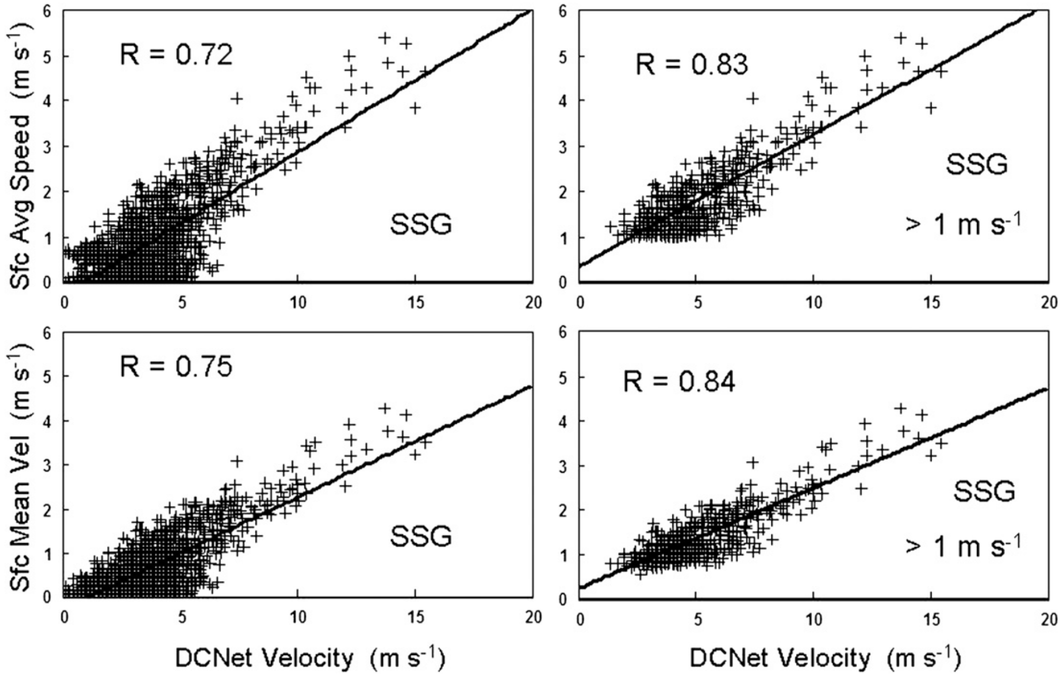


FIG. 3. The relationships between Earth Networks station and DCNet tower velocity statistics, for October 2006 and for the 5-km radius area containing SSG. (top) The average speeds plotted vertically are the linear averages of the speeds reported by each station ($\langle\overline{u}\rangle$). (bottom) The vector-mean velocities are derived by combining, vectorially, the averages of the $U$ and $V$ components reported by these same stations ($\overline{\overline{V}}$). Note the evidence of a low-speed sensor limitation for the surface dataset. Data obtained when the average surface wind speed $\overline{u}$ was below 1 m s$^{-1}$ are excluded from the panels on the right.

agencies in both research and emergency-response applications. In a similar way, WeatherBug data are made freely available to researchers either through MADIS or directly from Earth Networks, Inc. These data are also used widely by emergency-response officials for enhanced situational awareness and decision making.

Figure 3 shows 15-min data from the Silver Spring DCNet location and simultaneous aggregated data from the WeatherBug near-surface network stations within 5 km of it. The top pair of diagrams in Fig. 3 shows the relationship involving the average surface wind speed. The bottom pair shows the dependence of the mean velocities derived vectorially—as the resultant $\mathbf{V}_{\mathrm{DCN}}$ for the DCNet dataset and as $\overline{\overline{V}}$ for the surface array [see Eq. (1)]. The left panels in Fig. 3 are for all winds and show (as expected) evidence of near-surface subnetwork sensor shortcomings at low wind speeds. The diagrams in the right panels are constrained to include only data for which the average surface wind speed exceeds 1 m s$^{-1}$. The relationships are then improved. The correlation coefficients $R$ shown in the plots support the contention that the association is strong (as must be expected) and is best for the constrained wind speeds (>1 m s$^{-1}$) and for the vector-mean cases, although the differences are minor.

The exclusion of winds below 1 m s$^{-1}$ has two unwelcome consequences. First, nighttime cases are preferentially excluded. Second, conditions classically characterized as "light and variable" are also excluded. Both sets of conditions are important to the major application considered here: the prediction of dispersion that affects people. This shortcoming can only be overcome by the use of more-sensitive instrumentation. For the analysis that follows, all 15-min datasets for which the average surface network wind speed is below 1 m s$^{-1}$ will be excluded.

Figure 4 extends the analysis of velocities to a number of other locations. Here, ratios of near-surface subnetwork average velocities (derived vectorially) to the corresponding values derived from the central DCNet station are plotted against the local time of day. Because the statistical distribution of the individual values of this ratio is closely lognormal, mean values and bounds corresponding to ±1 standard deviation are plotted in Fig. 4 (and in the similar diagrams to follow) on a linear scale, even though they are computed logarithmically. The data used are for October of 2006. The purposes are 1) to explore the variability in the relationship between aggregated surface velocities and values collected well

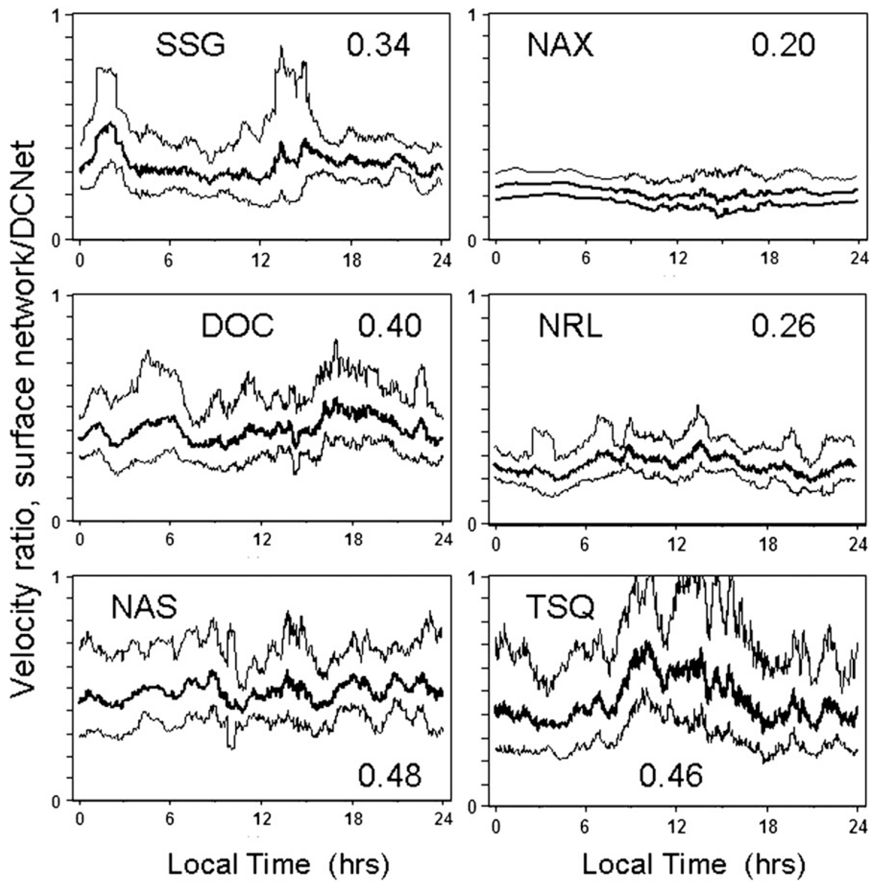


FIG. 4. The middle (thick) line shows geometric-mean velocity ratios (surface network over DCNet: $\overline{\overline{V}}/\mathbf{V}_{\mathrm{DCN}}$, computed using a 20-point running mean) as a function of time of day for a selection of locations in the Washington metropolis and for one station (TSQ) in New York City. The other lines show the corresponding $\pm1$ std dev bounds. Note that the distributions are closely lognormal and hence that the statistics have made use of the logarithms with the results plotted arithmetically.

above local structures and 2) to look for any consistent dependence on the time of day (and for the implicit influence of atmospheric stability). For each site, average values of the ratio are shown. Note that not all sites are represented in Fig. 4. The selection of sites is intended to be a sampling of available datasets. The average of the D.C. velocity ratios shown in Fig. 4 is 0.34 but has considerable site dependence (ranging from 0.20 to 0.48). Also shown is the corresponding result for the Times Square location in New York City: TSQ. In this case, the data are far more scattered, with a mean of 0.46.

There is no consistent variation with time of day evident in the diagrams in Fig. 4. It is obvious, however, that the omission of data for which the average wind speed is below 1 m $\mathrm{s}^{-1}$ for the surface network has a severe effect on the number of values that can be plotted for the nighttime.

## 4. Comparison with DCNet—Turbulence

Figure 5 extends the analysis to velocity turbulence: $\sigma$(TOT) versus $\sigma$(DCN). The diagrams are for the locations considered in Fig. 4. Two of the plots in Fig. 5 appear to be far more highly scattered than the others, presumably because of the greater complexity of the surroundings of the relevant DCNet locations (DOC and NAS). The site with the most-convincing relationship is SSG, for which the DCNet measurements are at a greater elevation and the surroundings are relatively uniform in different directions. The TSQ data seem similarly well behaved. Figure 6 parallels Fig. 4, plotting the ratio of the two measures of velocity standard deviation against the time of day. There is little consistent time dependence. For the DC stations, the average ratios range from 0.79 to 1.37. On average, the total turbulence level at the surface exceeds that reported above the surface

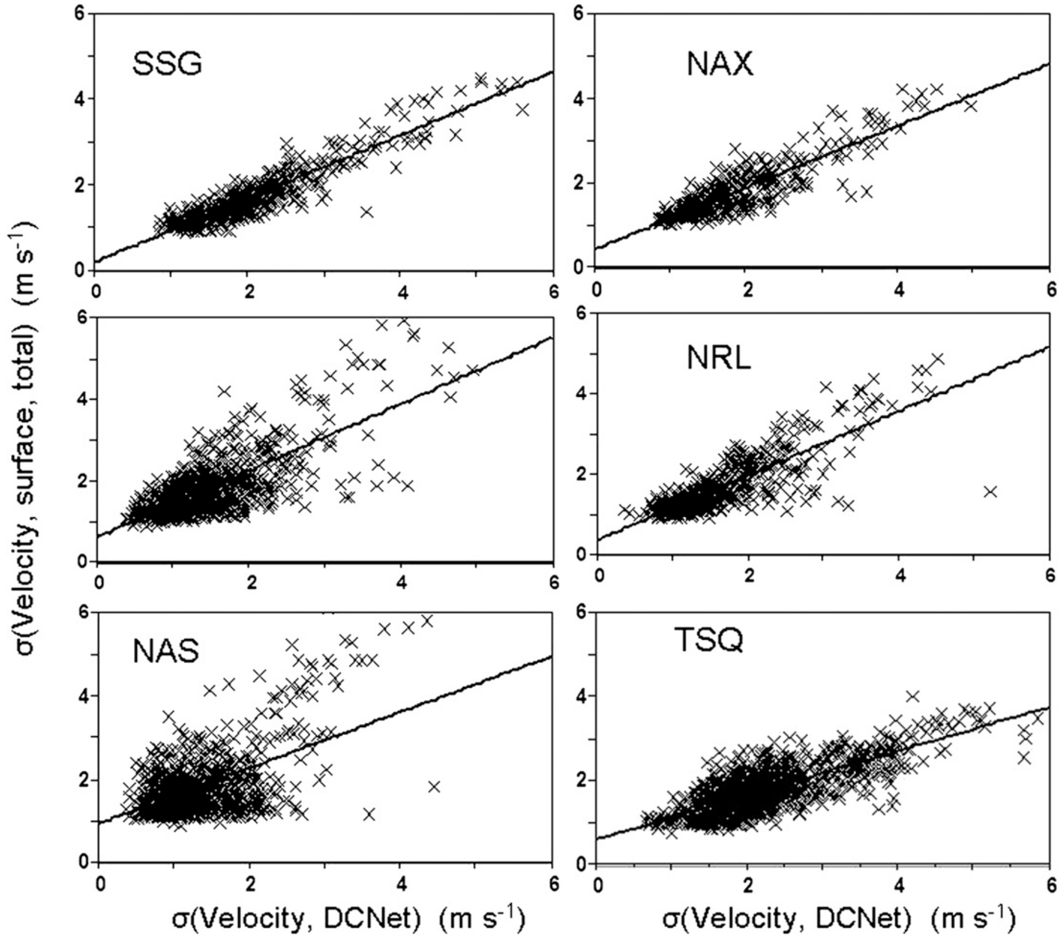


FIG. 5. Comparisons of surface network values of velocity standard deviation with the central DCNet equivalent [$\langle\sigma(\mathrm{TOT})\rangle$ vs $\sigma(\mathrm{DCN})$] for the same selection of stations as in Fig. 4.

layer by a small (and statistically insignificant) amount. None of the individual averages is statistically different from unity (at the two-sigma, ~95% probability level), nor is the grand average: 1.07. The result shown for the single New York City situation (TSQ) is the lowest of the set, at 0.79.

The proximity to unity for the ratios plotted in Fig. 6 is expected and reassuring, since the driving force lies in the roughness sublayer (which the near-surface subnetwork is sampling), and the central stations at greater heights reflect and respond to this surface-layer behavior. It is not clear how the omission of the vertical component in this discussion might affect the conclusions to be drawn, but such topic cannot be explored with this dataset because the WeatherBug network does not measure vertical wind components.

Figure 7 concentrates on the near-surface network data alone, showing the relationship between the two measures of areal velocity standard deviation: that in space versus that in time. The plots in Fig. 7 are less scattered than in either of Figs. 3 or 5. This is as anticipated, since the data are all derived from a set of similarly exposed instruments, whereas the DCNet data are derived from single sensors exposed at greater heights. Figure 8, like Figs. 4 and 6, plots the ratio $R_{st}$ (space–time) versus local time of day. The results appear to be far more tightly confined than for the other variables illustrated in this way. Note that the ratios are, once again, close to unity. Note also that there is some evidence of a coherent diurnal cycle for most stations, however, with (in general) the lowest value of the ratio occurring in daytime and hence in unstable stratification. There is also considerable similarity among some of the datasets illustrated, especially for the NAS and DOC cases. This is as expected, being a consequence (or at least partially so) of overlaps between the areas that are considered in combining surface data.

The average value of the ratio $R_{st}$ for the Washington cases is 1.10. Although the individual datasets illustrated yield average values of $R_{st}$ that range widely (from 0.86

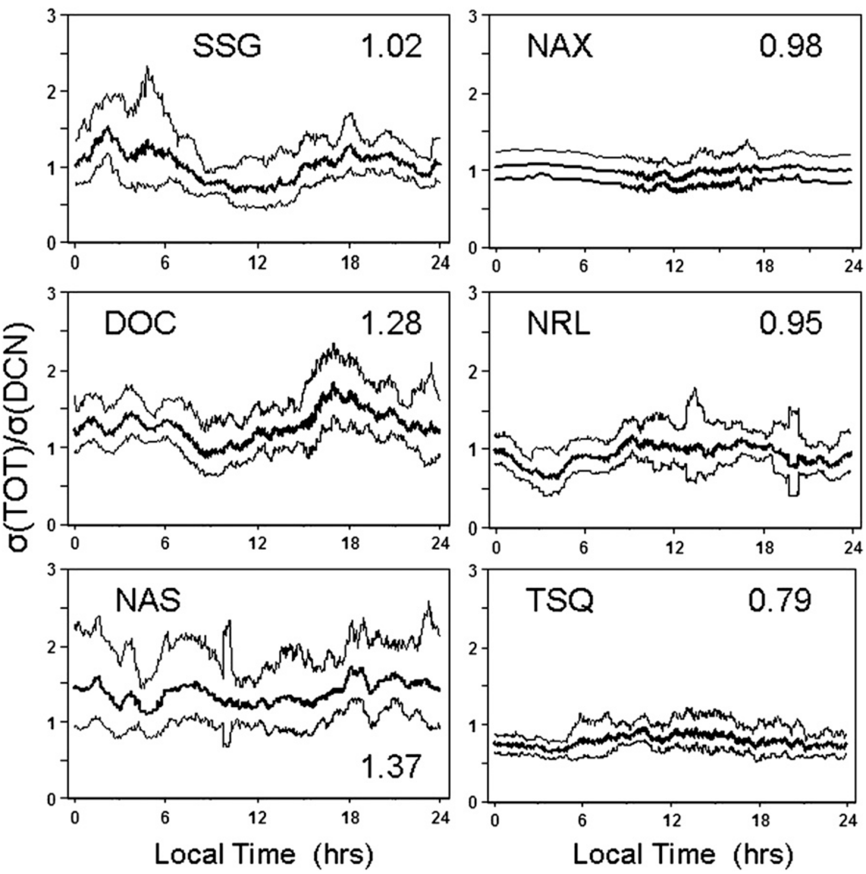


FIG. 6. The data of Fig. 5 expressed as ratios (as in Fig. 4) and plotted against the local time of day. Daily geometric means are shown.

to 1.30), it is clear that there is an approximate equality between the time and space components of the total velocity standard deviations among the near-surface network stations. The single New York City case is within the range of the Washington values: 1.17.

In all of Figs. 3, 5, and 7, the lines shown are best fits, determined by linear regression. In several of the cases for which the lines of best fit do not pass near the origin, a better visual fit would result if the lines were constrained to do so.

## 5. Discussion

It is often argued that the meteorological information content of surface data like those used here is small, because the data are not representative of the grid cells used in today's conventional numerical models. Many samples of such data appear to yield information that is indeed representative of the layer of the atmosphere in which people are exposed, however. If the intent is to take forecasts to where they directly affect people, then we must learn how to make use of the many data sources already available, yielding information on the actual air affecting people. The fact that these data have not been used extensively in the past for improving mesoscale meteorological models does not negate their potential utility for forecasting on a more local scale. The near-surface rooftop networks sample the complexity of the surface regime, and the rooftop systems of DCNet sample the consequences of this complexity.

The velocities yielded by aggregating the data from near-surface anemometry are well correlated with the wind measured by central DCNet stations, although not as well correlated as for the velocity standard deviations. The average ratio of near-surface mean velocity to DCNet rooftop velocity is 34% (±11%) for the Washington situations considered here. This is in accord with the summation presented by Hanna et al. (2006), who conclude that "[t]he mean wind speed at street level is about ⅓ of the mean wind speed at the tops of tall downtown buildings." For the purposes of operational application, a transport velocity in the surface roughness layer of 30%–40% of the wind speed aloft appears to be appropriate for the two cities considered here.

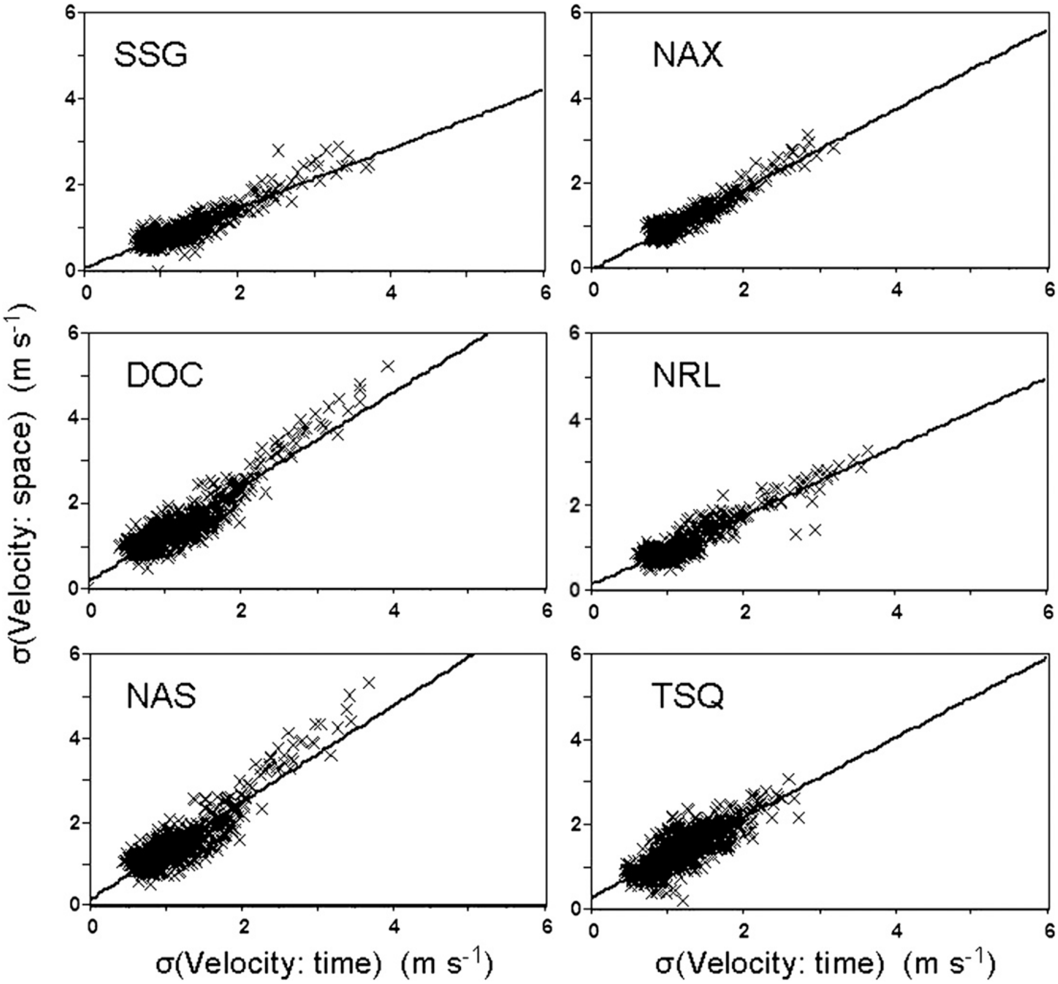


FIG. 7. Comparisons of two measures of velocity standard deviation derived from the surface networks: the standard deviation (in time) derived by averaging the variances reported by the contributing stations and the standard deviation derived on the basis of the velocities reported by each individual contributing station. In the language of Eq. (1), it is a plot of $\sigma(s)$ against $\sigma(t)$.

Examination of all DCNet locations and their surrounding near-surface network sites reveals that the examples given here are typical.

The spatial and temporal components of the surface turbulent kinetic energy contribute approximately equally to the total turbulence measured aloft. This result appears to hold for all of the sites in the DCNet array, covering a large part of Washington, D.C., and also for central New York City. In this regard, note that the matter of turbulence within the roughness sublayer has been the subject of several papers that address the case of forest canopies. Katul et al. (2004), for example, conclude that the subcanopy turbulence regime tends to be ergodic. That is, that averages of measurements in time at any selected location will approximate (or even equal) averages of the same quantities in space. Their interpretation clearly parallels the case of an urban canopy that is presented here. Hanna and Zhou (2009) have also addressed this matter, using data obtained in an intensive short-term study of downtown Manhattan Island, New York. It is apparent that the matter is a function of the details of the surface canopy within which measurements are made.

The high correlations associated with the wind-variability statistics support the expectation that surface anemometry can indeed contribute to the improvement of dispersion calculations for the surface boundary layer. The situation for wind variability is more secure than for velocities. The wind speed and velocity-component relationships are more influenced by local surface inhomogeneities than are those for the turbulence quantities. This is in accord with the pragmatic and operational observation that turbulent kinetic energy has a far longer "memory" than does the average velocity field.

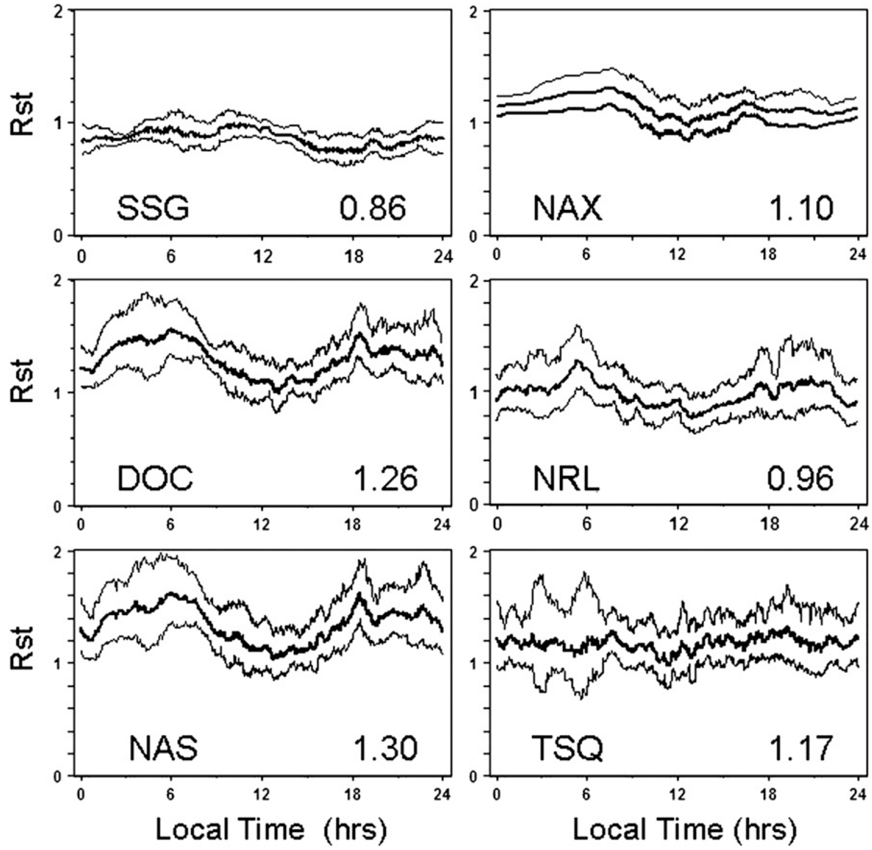


FIG. 8. The data of Fig. 7 expressed as ratios [$R_{st} = \sigma(s)/\sigma(t)$] and plotted against the local time of day in the same way as in Fig. 4.

The discussion so far omits the New York EML case. In reality, the EML DCNet station was poorly located, and the DCNet data quality suffered as a result. Another complicating factor is the heterogeneity of the surrounding area. These factors combine to make the EML data more scattered than those for any other DCNet site. Figure 9 shows the EML datasets that parallel those discussed above. Even in this case, however, the basic results found above are repeated, with the most-well-behaved set of variables being that derived from the near-surface network alone (the space–time standard deviation ratio) and the worst being the relationship between vector velocities derived from the two sources.

Table 2 summarizes correlation coefficients derived from among the quantities discussed above, for the Washington data and for the two New York cases for October 2006. Correlation coefficients are generally significantly different from zero, as must be expected considering the dynamics of the circumstance with the wind aloft providing the energy source, with turbulence in the roughness sublayer being associated with surface drag, and with the wind speed in the roughness sublayer being confined by these two controlling factors. The data of Table 2 permit computation of partial correlation coefficients, which quantify the agreement between two variables apart from that which results because both are correlated with a third variable. When evaluated, these partial correlation coefficients support the contention that there is no significant relationship of $\sigma$(TOT) with $\underline{\mathbf{V}}_{\mathrm{DCN}}$ aloft, apart from the correlation of each with $\overline{\overline{V}}$ and $\sigma(\underline{\mathrm{DCN}})$. In fact, $\sigma$(TOT) is highly correlated with both $\overline{\overline{V}}$ and $\sigma(\underline{\mathrm{DCN}})$. Further, $\sigma$(DCN) is not positively correlated with $\overline{\overline{V}}$ apart from its strong correlation with $\mathbf{V}_{\mathrm{DCN}}$, as must be expected. The overall picture that results does not depart from conventional understanding: turbulence at the surface is generated by the wind aloft, and turbulence above the buildings relates to this turbulence. What the denser network of surface sensors adds is the consideration of spatial as well as temporal components of the means and variances of the wind through the roughness sublayer.

Inspection of Table 2 reveals that two sites appear to depart from the norm: NAS and EML. The NAS location is bounded to the north by large buildings and to the

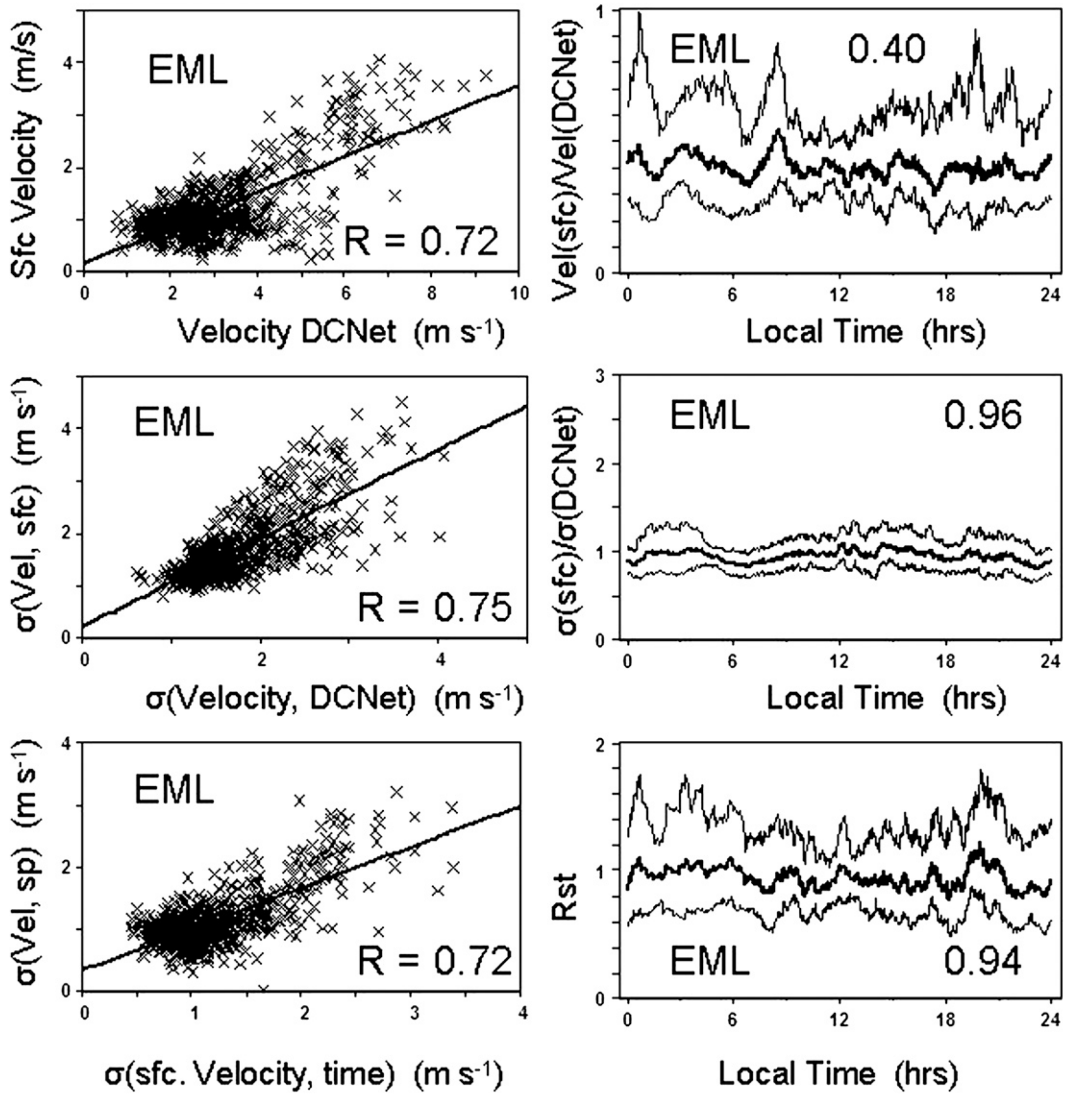


FIG. 9. An extension of the analysis to a site yielding unusually scattered data (EML). Because of the scatter in the EML DCNet data and the difficulties in interpreting them, EML data are no longer archived. The 5-km-radius surface subnetwork data appear to be as tightly confined as for the other locations addressed here, however.

south by wooded gardens (the Washington Mall). Hence, for this site there should be a large directional dependence that would doubtlessly influence the averages considered here (see Figs. 4 and 5). For the EML case, it has already been emphasized that the site in question has subsequently proved to be sufficiently affected by local obstructions that measurements there have been curtailed.

It should be emphasized that the results presented here are doubtlessly affected by the omission of light-wind data. The fact that only a few of the regression lines that define the present correlation coefficients pass through the origin constitutes a warning about extrapolating the corresponding results.

## 6. Conclusions

A number of conclusions can be drawn from the analysis presented here:

1) Data consolidated from (typically) 10 observing stations within the surface roughness layer are well behaved when compared with observations made above tall buildings in the same area. On this basis, there are grounds to expect agglomerated surface data to provide guidance that is useful for assessing dispersion in retrospect, in forecasting, and in nowcasting as would be required for emergency-response applications.
2) For the case of Washington, D.C., the average wind within the surface roughness layer, as observed here,

TABLE 2. Correlation coefficients $R_{xy}$ among DCNet and surface network variables, where the key for $x$ and $y$ is as follows: 1 is DCNet wind velocity $\mathbf{V}_{\mathrm{DCN}}$, 2 is DCNet velocity standard deviation $\sigma$(DCN), 3 is surface network average velocity $\overline{\overline{V}}$, 4 is surface network spatial velocity standard deviation $\sigma(s)$, 5 is surface network temporal velocity standard deviation $\sigma(t)$, and 6 is surface network total velocity standard deviation $\sigma$(TOT).

| | DOC | NAS | NAX | NRL | SSG | EML | TSQ |
|---|---|---|---|---|---|---|---|
| $R_{12}$ | 0.841 | 0.581 | 0.860 | 0.796 | 0.819 | 0.780 | 0.747 |
| $R_{13}$ | 0.659 | 0.519 | 0.662 | 0.865 | 0.830 | 0.702 | 0.400 |
| $R_{14}$ | 0.619 | 0.685 | 0.888 | 0.804 | 0.801 | 0.620 | 0.472 |
| $R_{15}$ | 0.648 | 0.608 | 0.873 | 0.831 | 0.789 | 0.752 | 0.583 |
| $R_{16}$ | 0.648 | 0.672 | 0.894 | 0.840 | 0.814 | 0.770 | 0.544 |
| $R_{23}$ | 0.686 | 0.423 | 0.463 | 0.822 | 0.877 | 0.602 | 0.569 |
| $R_{24}$ | 0.715 | 0.563 | 0.820 | 0.737 | 0.861 | 0.549 | 0.686 |
| $R_{25}$ | 0.756 | 0.506 | 0.893 | 0.841 | 0.919 | 0.821 | 0.799 |
| $R_{26}$ | 0.742 | 0.554 | 0.869 | 0.815 | 0.920 | 0.925 | 0.769 |
| $R_{34}$ | 0.919 | 0.522 | 0.757 | 0.817 | 0.925 | 0.756 | 0.822 |
| $R_{35}$ | 0.929 | 0.471 | 0.682 | 0.914 | 0.937 | 0.708 | 0.840 |
| $R_{36}$ | 0.941 | 0.515 | 0.731 | 0.894 | 0.960 | 0.804 | 0.868 |
| $R_{45}$ | 0.921 | 0.603 | 0.940 | 0.910 | 0.889 | 0.631 | 0.821 |
| $R_{46}$ | 0.987 | 0.658 | 0.986 | 0.969 | 0.956 | 0.861 | 0.965 |
| $R_{56}$ | 0.971 | 0.603 | 0.984 | 0.984 | 0.983 | 0.935 | 0.940 |

is about one-third of that measured above tall buildings in the same area (range: 0.20–0.48).

3) When observations from near-surface anemometers are combined vectorially to derive spatial and temporal measures of the wind-component standard deviations, the resulting total standard deviation for the near-surface array is much the same as the vectorially computed wind standard deviation derived from observations by a central elevated anemometer system. The corresponding ratio is found to be about 1.1 for Washington and its surroundings. For two sites in New York City, the average ratio is 0.9.
4) The spatial and temporal components of the total velocity standard deviation computed from surface network data are very similar, with an average ratio of 1.1 for the Washington data considered here. The two New York City sites also yield an average of about 1.1. Although it needs to be explored further, an initial conclusion is that (like in forest meteorology) the urban subcanopy turbulence regime tends to be ergodic.

Without examination of similar data from other urban areas, the generality of these conclusions can certainly be questioned. These conclusions might be little more than an indication of behavior patterns that apply well to the Washington, D.C., complex and perhaps to the surroundings of New York City. Blind extrapolation should be avoided. Future work will extend the current analysis to other situations, with the expectation that similar behavior will be found but with differences that might be substantial. In this regard, remember that Washington presents an excellent test bed because of its fairly uniform density of buildings and its constraint on the height of these buildings. Neither of these considerations applies to the case of New York City, and indeed some differences are seen (in the figures presented here) between the datasets for Washington and New York.

The above conclusions are influenced by the limited performance of the near-surface network anemometers. Better results are obtained when data with winds below 1 m s$^{-1}$ are excluded, but this then excludes light and variable winds and preferentially affects nighttime conditions. Both of these situations are of importance in the context of plume dispersion. To remove this limitation, there is no option but to use anemometry with better starting-speed performance (both for speed and direction). Nevertheless, it is clear that the results obtained here invite the use of aggregated near-surface network data in modified plume dispersion models. It is accepted that at some downwind distance the diffusing material will become integrated with the skimming flow aloft, at which time the more-conventional regional-scale dispersion approaches will become more relevant. At this time, it is not clear where this handover might occur, but it will certainly depend on the characteristics of the area.

There is a related question that is worthy of consideration: How can we identify sensor systems that do not yield useful data? Most of the instruments used to derive the results that were presented here are exposed in situations conventionally deemed unacceptable, but even poorly exposed instruments can accurately report on the conditions they experience, so long as they are well maintained and comprehensive metadata are collected, and these conditions are indisputably part of the total atmospheric environment under consideration. By considering an ensemble of such instruments, the analysis above shows that meaningful information can be derived for the city and surroundings of Washington, D.C., and, perhaps to a smaller extent, to the island of Manhattan. It would appear, therefore, that the analysis approach suggested here is relatively forgiving to exposure "difficulties." A result of the analysis above might well be that the emphasis of quality control should be on the performance of the instrumentation and the elimination of egregious exposure rather than on classical "representativeness." Future work will test the applicability of the results obtained here to other cities and will demonstrate how data aggregation might be employed in dispersion models.

*Acknowledgments.* Several staff members of the NOAA Air Resources Laboratory assisted with the analyses presented here—especially Ed Dumas of ARL Oak Ridge and Rick Eckman of ARL Idaho Falls. In addition, the constructive comments from several unidentified reviewers proved to be very useful in the revision of this paper. The surface data used here were provided through a memorandum of understanding between NOAA and Earth Networks, Inc. (formerly AWS Convergence Technologies, Inc.) of Germantown, Maryland. The principal author serves as a consultant to Earth Networks.

## REFERENCES

Allwine, K. J., J. H. Shinn, G. E. Streit, K. L. Clawson, and M. Brown, 2002: Overview of Urban 2000. *Bull. Amer. Meteor. Soc.,* **83,** 521–536.

Arnold, S., and Coauthors 2004: Dispersion of Air Pollution and Penetration into the Local Environment—DAPPLE. *Sci. Total Environ.,* **332,** 139–153.

Baik, J.-J., J.-J. Kim, and H. J. S. Fernando, 2003: A CFD model for simulating urban flow and dispersion. *J. Appl. Meteor.,* **42,** 1636–1648.

DePaul, F. T., and C.-M. Sheih, 1985: A tracer study of dispersion in an urban street canyon. *Atmos. Environ.,* **19,** 555–559.

——, and ——, 1986: Measurements of wind velocities in a street canyon. *Atmos. Environ.,* **20,** 455–459.

Draxler, R. R., 1987a: Accuracy of various diffusion and stability schemes over Washington, DC. *Atmos. Environ.,* **21,** 491–499.

——, 1987b: One year of tracer dispersion measurements over Washington, DC. *Atmos. Environ.,* **21,** 69–77.

Hanna, S. R., and Y. Zhou, 2009: Space and time variations in turbulence during the Manhattan Midtown 2005 field experiment. *J. Appl. Meteor. Climatol.,* **48,** 2295–2304.

——, J. White, Y. Zhou, and A. Kosheleva, 2006: Analysis of Joint Urban 2003 (JU2003) and Madison Square Garden 2005 (MSG05) meteorological and tracer data. Preprints, *Sixth Conf. on the Urban Environment,* Atlanta, GA, Amer. Meteor. Soc., J7.1. [Available online at http://ams.confex.com/ams/pdfpapers/104131.htm.]

Katul, G., D. Cava, D. Poggi, J. Albertson, and L. Mahrt, 2004. Stationarity, homogeneity, and ergodicity in canopy turbulence. *Handbook of Micrometeorology,* X. Lee et al., Eds., Kluwer Academic, 161–180.

Oke, T. R., 2004. Initial guidance to obtain representative meteorological observations at urban sites. World Meteorological Organization Rep. 81, WMO/TD 1250, 47 pp.

Rotach, M. W., and Coauthors, 2005: BUBBLE—An urban boundary layer meteorology project. *Theor. Appl. Climatol.,* **81,** 231–261.

Sykes, R. I., and R. S. Gabruk, 1997: A second-order closure model for the effect of averaging time on turbulent plume dispersion. *J. Appl. Meteor.,* **36,** 165–184.

Xie, Z.-T., and I. P. Castro, 2009: Large-eddy simulation for flow and dispersion in urban streets. *Atmos. Environ.,* **43,** 2174–2185.

Yamartino, R. J., 1984: A comparison of several ''single-pass'' estimators of the standard deviation of the wind direction. *J. Climate Appl. Meteor.,* **23,** 1362–1366.