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AN ASSESSMENT OF TURBULENCE PROFILES IN RURAL AND URBAN ENVIRONMENTS USING LOCAL MEASUREMENTS AND NUMERICAL WEATHER PREDICTION RESULTS**

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Abstract. Profiles of velocity variances based on observations in flat rural areas are well established, and are used for modelling turbulent dispersion in all types of regions including those of complex terrain and urban areas. Surface-based and balloon observations are used to assess the profiles in both rural and urban areas. It is shown that, with good meteorological inputs for the locality of friction velocity and surface sensible heat flux, the profiles are equally well suited to urban areas. The sensitivity of the profiles to the input meteorological data, in particular using numerical weather prediction (NWP) data, is discussed. This highlights the limitations of NWP data for dispersion modelling and stresses the importance of schemes for modelling urban meteorology.

Keywords: Dispersion modelling, Lagrangian model, Turbulence, Urban meteorology, Velocity variances.

1. Introduction

Turbulence is an essential mechanism in the dispersion of air pollutants released into the boundary layer. Eddy structures, with a continuous spectrum of sizes and intensities, act to mix the material with the ambient air, thereby reducing concentrations of atmospheric pollutants. There are two main processes that generate turbulence within the atmospheric boundary layer: wind shear and convection. In neutral and windy conditions, turbulence is strong and continuous throughout the boundary layer. It is generated mainly by surface friction and wind shear, and is referred to as shear-generated or mechanical turbulence. In convective conditions, turbulent mixing can also be due to buoyant overturning over a heated surface, whilst in a stable boundary layer turbulence is weak and much suppressed and can be intermittent and patchy.

Accurate predictions of turbulence are crucial in atmospheric dispersion models for simulating the dispersion of pollutants. The computational cost involved in directly simulating the whole range of eddy sizes within the atmospheric boundary layer is extremely high. Consequently, a detailed

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description of the evolution of a turbulent flow is not practical within dispersion models. An alternative is to model turbulent dispersion using random walk techniques that employ analytical profiles of parameters of the turbulent motion.

Profiles of turbulence parameters have been derived using observations from a number of field experiments, most notably the Kansas experiment in 1968 (Izumi, 1971; Kaimal et al., 1972), designed to verify the Monin–Obukhov similarity theory within the surface layer, and the Minnesota experiment in 1973 (Izumi and Caughey, 1976; Kaimal et al., 1976), an extension of the Kansas experiment designed to study the entire boundary layer. These profiles are widely used but were derived from observations collected over flat and uniform terrain in the U.S.A. Dispersion modelling is often required in regions of complex terrain and in urban areas.

It is well known that the main differences between urban and rural meteorology are caused by increased surface roughness, creating greater mechanical turbulence, and the urban heat island (UHI), affecting thermally induced turbulence (Oke, 1987). The UHI is caused by buildings storing heat from the sun during the day and releasing the heat into the boundary layer in the evening. This can delay the onset of the evening transition to nighttime stable conditions, and in large cities these effects can lead to an almost complete absence of stable conditions, which would be present in the surrounding rural areas.

Our study was undertaken in order to assess the suitability of the profiles of turbulence parameters, used in a Lagrangian dispersion model, in urban areas. The turbulence profiles used are based on published results using observations collected in flat rural areas in the U.S.A. and hence are not obviously applicable in urban areas in the U.K. We begin by comparing the turbulence parameters with surface and balloon observational data from a flat rural site in the U.K. at Cardington, Bedford. This is done in order to provide a benchmark for comparisons against observational data from an urban site located in the city of Birmingham, U.K. We show that the profiles apply equally well in urban areas, and the accuracy of the turbulence profiles depends largely on having access to good predictions of local meteorological data.

2. Turbulence Modelling in NAME

The Lagrangian model NAME has a wide range of applications including air quality forecasting, emergency response scenarios (nuclear and chemical releases, volcanic eruptions, etc.) and episode analysis, (Maryon et al., 1999). Within NAME, large numbers of particles are released into a model atmosphere, with each particle representing a certain mass of the pollutant that is depleted over time, if appropriate, by wet and dry deposition processes, radioactive decay or chemical transformation. NAME is driven by three-dimensional (3-D) wind fields and other meteorological data obtained from the Met Office's numerical weather prediction model, the Unified Model (UM) (Cullen, 1993). The boundary-layer depth is calculated within NAME using a mixture of Richardson number and parcel techniques (Verver and Holtslag, 1992). The particles are advected each time step by

$$\mathbf{x}_{t+\Delta t} = \mathbf{x}_t + [\mathbf{u}(\mathbf{x}_t) + \mathbf{u}'(\mathbf{x}_t) + \mathbf{u}'_l(\mathbf{x_t})]\Delta t, \tag{1}$$

where $\mathbf{x}$ are the particle position vectors, $\mathbf{u(x)}$ are the mean ambient winds interpolated to the particle position, $\mathbf{u}'(\mathbf{x})$ are the turbulent velocity components, $\mathbf{u}'_l(\mathbf{x})$ are the low frequency meander vectors and Δt is the time step. Wind meander and dispersion due to atmospheric turbulence are simulated using random walk techniques. Turbulent parameters (velocity variances and Lagrangian time scales) used within the random walk scheme are not available directly from the UM and analytical profiles determined from empirical fits to observational data are therefore used. The form of the velocity variance profiles depends upon the thermal stability of the atmospheric boundary layer. Inhomogeneous profiles, in which the velocity variances are a function of height within the boundary layer, are used at short range. These profiles are designed to be continuous in the stable to unstable transition in near-neutral conditions and, in the case of vertical velocity variances, at the boundary-layer top. For simplicity, NAME does not distinguish between along-wind (u) and cross-wind (lateral, v) dispersion in the horizontal. Generally, lateral dispersion is considered more important than along-wind dispersion. Hence the u and v components of the velocity variances are set to be equal and represent cross-wind dispersion.

In stable conditions, the velocity variance profiles ($\sigma^2_{u,v,w}$) are given by

$$\sigma^2_{u,v} = \left[2.0u_*\left(1 - \frac{z}{z_i}\right)^{3/4}\right]^2, \tag{2}$$

$$\sigma^2_{w} = \left[1.3u_*\left(1 - \frac{z}{z_i}\right)^{3/4}\right]^2, \tag{3}$$

where u_* is the friction velocity, z_i is the boundary-layer depth and z is the height above ground. The power-law profile is well established for the stationary, stable boundary layer. In reality, however, the stable boundary layer is often non-stationary, particularly around the periods of dawn and dusk. Nieuwstadt (1984) showed that the 3/4 power law provided a good fit to observations of vertical velocity variances made in the nocturnal stable boundary layer at Minnesota (Caughey et al., 1979). Furthermore, 0.75 is the mid-value of the range 0.5–1.0 recommended by Arya (1999) for dispersion modelling applications. The constants of proportionality in Equations (2) and (3) are determined from observations at ground level in neutral conditions as reviewed by Panofsky and Dutton (1984). Garratt (1992) noted that values of the normalised velocity variances ($\sigma_{u,v,w}/u_*$) in stable conditions are typically equal to or slightly greater than those in neutral conditions, and hence the constants of proportionality used are the upper limits of the ranges of values given by Panofsky and Dutton (1984). In strongly stable conditions turbulence is intermittent and other effects such as gravity waves have a much greater influence. We note that in these cases the scope of Equations (2) and (3) is limited.

In convective conditions, the velocity variance profiles are a combination of profiles for strongly convective conditions and for mechanically driven turbulence, namely

$$\sigma_{u,v}^2 = 0.4w_*^2 + 4.0u_*^2\left(1 - \frac{z}{z_i}\right)^{3/2}, \tag{4}$$

$$\sigma_w^2 = 1.2w_*^2\left(\frac{z}{z_i}\right)^{2/3}\left(1 - \frac{z}{z_i}\right) + 1.69u_*^2\left(1 - \frac{z}{z_i}\right)^{3/2}. \tag{5}$$

The convective velocity scale w_* is defined by

$$w_* = u_*\left(\frac{z_i}{k|L|}\right)^{1/3}, \tag{6}$$

where L is the Obukhov length and k is the von Kármán constant (taken as 0.4). The strongly convective components are based on the profiles of Caughey (1982) and Hibberd and Sawford (1994) but are adjusted so that σ_w tends to zero at the boundary-layer top. The mechanical components of the velocity variances are chosen to agree with the stable profiles (Equations (2) and (3)) in the neutral limit in order that the profiles are continuous in the stable to unstable transition.

3. Observations

Observations were obtained from a rural and an urban measurement site. The rural site is the Meteorological Research Unit (MRU) at Cardington, where observations from both surface instrumentation and a tethered balloon are available. The turbulence data from this site are compared against the profiles given by Equations (2)–(5) and are used as a benchmark for comparisons against observations from the urban site. The urban site is located within a tyre factory complex (Dunlop Tyres Ltd.) in Birmingham, where surface observations were collected during three measurement campaigns.

3.1. Rural site

The Meteorological Research Unit (MRU) at Cardington (52.1000° N, 0.4167° W) is located in a river valley approximately 3 km south-east of the town of Bedford, U.K. The prevailing wind direction is from the south-west in which the fetch is flat, consisting of open fields. Approximately 0.5 km to the north-east of the site there are two large aircraft hangers. For a more detailed description of the site, see Grant (1994). MRU has a permanent surface instrument site in a grass field about 100 m from a main road. The roughness length, z_0, of the area is approximately 0.01 m. Routine surface-based measurements are made of temperature, wind, pressure, soil moisture and radiation. All components of wind velocity and temperature are measured at 4, 10 and 45 m above the ground using sonic anemometers mounted on masts. The surface-based measurements are logged at a frequency of 4 Hz and fluxes/variances computed over a 17.5-min interval. The data have been detrended and despiked, although spikes are occasionally missed by the despiking processing program and must be removed manually.

In addition to surface measurements, a turbulence probe developed by MRU Cardington is used with a helium filled tethered balloon system, which can be flown to heights of approximately 1.5 km on a steel cable tether. Up to eight turbulence probes can be attached to the cable at selected heights and each measures wind, temperature, pressure and humidity at a frequency of 4 Hz (Lapworth and Mason, 1988). Balloon-based measurements are not made routinely, although data are available from short-term campaigns.

3.2. Urban site

Urban measurement campaigns were conducted at Dunlop Tyres Ltd. during spring 1998, winter 1999 and summer 2000. Dunlop Tyres Ltd. is a tyre factory complex in the north-eastern sector of Birmingham, U.K. (52.5125° N, 1.8139° W). Birmingham is the second largest city in the U.K. with a large surrounding urban area. The city covers an area of 268 km^2 and has a population of approximately 1 million. The observing site itself is located within an industrial area and surrounded by residential buildings. The M6 motorway lies approximately 0.7 km to the south of the site, running east-west. Displacement heights at the observing site were estimated using the method of Rooney (2001). A large scatter, common in the determination of urban displacement heights from field studies (Grimmond and Oke, 1999), was found in the estimated values. The mean values were, respectively, 1.8, 5.3 and 6.0 m for 1998, 1999 and 2000 (G. Rooney, 2004 private communication), the increase in displacement height between 1998 and 1999 is thought to be due to building development to the north-west of the site. The mean estimated roughness length for the site ranges from 0.5 to 1.1 m.

The measurement campaigns covered the periods 8–30 April 1998, 20 January–15 February 1999 and 4 July–7 August 2000 and were conducted to study urban effects on the lower atmosphere. Instruments were sited on a rectangular area of grass measuring 100 m $\times$ 50 m; sonic anemometers were mounted on masts of 15 and 30 m in 1998, 15 and 45 m in 1999, and 15, 30 and 45 m in 2000. Data were sampled almost continuously at a frequency of 4 Hz, and hourly means, fluxes and variances computed accordingly. See Rooney (2001) for more details.

3.3. Derivation of meteorological variables

For both the rural and urban sites, components of wind velocity and temperature were used to derive u_*, L and sensible heat flux (H) using

$$u_* = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/4}, \quad H = \rho c_p \overline{w'T'}, \quad L = \frac{-u_*^3 T_s}{kg(\overline{w'T'})},$$

where T_s is a near-surface reference temperature, ρ is air density, c_p is the specific heat of air at constant pressure, g is the acceleration due to gravity and u', v', w' and T' are turbulent fluctuations from the mean.

4. Comparison of Turbulence Profiles with Rural Observations at Cardington

4.1. Surface measurements

Two months (January and August 2001) of surface-based velocity variance measurements at 10 and 45 m were obtained at Cardington. These measurements were compared with the velocity variances calculated using the turbulence profiles (Equations (2)–(5)). Mesoscale meteorological data from the UM, with a time resolution of 1 h and a spatial resolution of 12 km during 2001, were used as input data for Equations (2)–(5). Friction velocity (calculated from the UM wind stress) and sensible heat flux are interpolated to the location and time of the observations and are instantaneous values (in the sense that they are not time-averaged values and are valid at a specific time). The UM scheme uses Monin–Obukhov similarity theory with the unstable stability functions of Dyer (1974) and the stable stability functions of Beljaars and Holtslag (1991). Throughout this study the boundary-layer depth was calculated within NAME using UM temperature profiles as described in Section 2. The comparison of observed and calculated velocity variances showed that, overall, the calculated turbulence profiles capture the main features of the observations but are overpredicted at heights of 10 and 45 m during both January and August 2001. Figure 1 shows an example plot

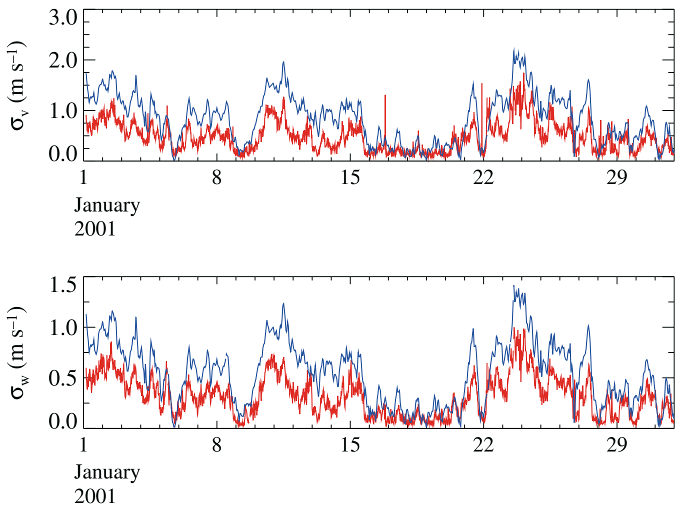

Figure 1. Observed (red) and predicted (blue) velocity variances using UM mesoscale meteorological data at a height of 10 m at Cardington, Bedford, U.K. during January 2001.

of the time series of observed and calculated velocity variances at 10 m during January with a time resolution of 17.5 min. The overprediction in calculated velocity variances is particularly evident in this example. The overprediction is less in August (not shown here), which suggests that velocity variances are predicted reasonably well in convective conditions but less so in neutral and stable conditions experienced more frequently during the winter. In August a stronger diurnal cycle in the velocity variances is evident, which is consistent with the strong diurnal cycle of boundary-layer properties experienced in summer months (Webster et al., 2003). Statistical measures obtained as part of the comparison between observed and predicted values of velocity variances include the mean, standard deviation (sd), normalised mean square error (NMSE) and correlation (*r*) (Hanna et al., 1991). The statistics, generated from a sample of 2487 observations, for both horizontal (cross-wind) and vertical velocity variances at a height of 10 m during January are given in Table I. The correlation values are good, reflecting that the main features of the time series of calculated velocity variances are similar to those of the observations. The over-prediction in calculated velocity variances is greatest at a height of 10 m during January, with the means of σ_v and σ_w overpredicted by very similar factors of 1.8 and 1.7, respectively.

In order to understand the reasons for the overprediction of velocity variances, UM mesoscale meteorological variables, used to calculate the velocity variances, were compared with the corresponding observed meteorological variables. Figure 2 shows a comparison of the time series of mesoscale UM surface u_* values and the observed values of u_* at a height of

TABLE I

Statistical comparison of 10-m horizontal (cross-wind) and vertical, observed and predicted velocity variances (using UM mesoscale meteorological data) at Cardington, U.K. during January 2001.

No. of obs. = 2487	Mean (m s^{-1})	sd (m s^{-1})	NMSE	r
Horizontal (cross-wind)				
Observed	0.48	0.30	0.00	1.00
Predicted (UM met)	0.84	0.47	0.51	0.83
Vertical				
Observed	0.32	0.21	0.00	1.00
Predicted (UM met)	0.55	0.30	0.47	0.84

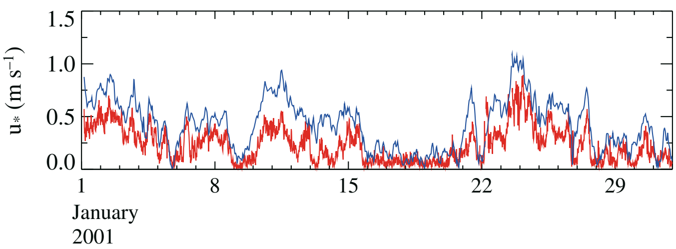

Figure 2. Observed (red) and UM predicted (blue) u_* at a height of 10 m at Cardington, Bedford, U.K. during January 2001.

10 m during January 2001 with a time resolution of 17.5 min. The main features in the time series of u_* are captured by the UM. In agreement with the velocity variances, u_* is overpredicted by the UM and the over-prediction in u_* is greatest at a height of 10 m during January. In August the observed and UM predicted values of u_* are in closer agreement. Statistical measures obtained in the comparison of observed and mesoscale UM values of u_* at 10 m during January are given in Table II. The mean of u_* at 10 m during January is overpredicted by a factor of 1.8, roughly the same value as for the overprediction in $\sigma_{v,w}$ at 10 m during January. This would strongly suggest, given the direct proportionality between $\sigma_{u,v,w}$ and u_* in Equations (2)–(5), that the overprediction in the calculated velocity variances is caused by an overprediction in u_*.

It is of interest to discuss the overprediction by the UM of u_* at Cardington for the periods studied here. The UM gives 12-km gridded averages and a roughness length of 0.078 m at Cardington; this roughness length is much larger than the observed local value of 0.01 m at the observation site and may reflect the heterogeneity of the local area, which includes the urban town of Bedford. Following the work of Hess and Garratt (2002),

TABLE II
Statistical comparison of 10-m observed and UM predicted friction velocity at Cardington, U.K. during January 2001.

No. of obs. = 2487	Mean (m s^{-1})	sd (m s^{-1})	NMSE	r
Observed	0.24	0.18	0.00	1.00
Predicted (UM)	0.42	0.47	0.51	0.83

the effect of a larger roughness length on u_* can be estimated. Assuming a steady-state, horizontally homogeneous, neutral, barotropic flow over a level surface of uniform roughness, we have

$$\frac{u_g}{u_*} = \frac{1}{k}\ln\left(\frac{u_*}{fz_0}\right) - \frac{1}{k}A, \tag{7a}$$

$$\frac{v_g}{u_*} = -\frac{1}{k}B, \tag{7b}$$

where A and B are universal constants for the neutral barotropic case, $\mathbf{u}_g = (u_g, v_g)$ is the geostrophic wind and f is the Coriolis parameter. Setting $A = 1.3$, $B = 4.4$ (Hess and Garratt, 2002), we obtain

$$\frac{|\mathbf{u}_g|}{u_*} = \frac{1}{k}\left[\left(\ln\left(\frac{u_*}{fz_o}\right)\right)^2 - 2.6\ln\left(\frac{u_*}{fz_0}\right) + 21.05\right]^{1/2}. \tag{8}$$

Assuming a typical geostrophic wind speed of $|\mathbf{u}_g| = 5.0$ m s^{-1}, we can solve Equation (8) numerically to yield u_*. For the UM mesoscale roughness length ($z_0 = 0.078$ m), Equation (8) yields $u_* = 0.21$ m s^{-1}. On the other hand, for the observed roughness length ($z_0 = 0.01$ m), Equation (8) gives $u_* = 0.17$ m s^{-1}, which shows that the larger predicted value of z_0 results in an overprediction in u_* of approximately 18%.

The calculation above assumes that the wind profiles have adjusted throughout the boundary layer to the underlying change in surface roughness length ($z_0 = 0.078$ m to $z_0 = 0.01$ m). In reality, the wind profile will only adjust up to some height, z, since the underlying surface is not of uniform roughness. Assuming a logarithmic neutral wind profile, and that the wind adjusts up to a height of 10 m only, gives an overprediction by the UM of approximately 42% in u_*. In other words, we can attribute some of the overprediction of u_* at Cardington by the UM to the overprediction of z_0. We do not, however, fully account for the magnitude of the overprediction in u_*.

Following the assumption that the overprediction in calculated velocity variances is caused by the overprediction in u_* by the UM, we calculate velocity variances using observed values of u_* as input to Equations (2)–(5). (Note that UM mesoscale values of heat flux and model-derived

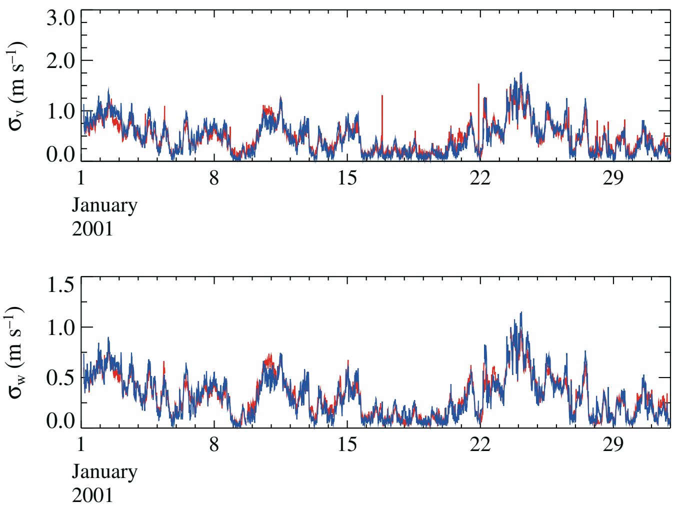

Figure 3. Observed (red) and predicted (blue) velocity variances using observed u_* at a height of 10 m at Cardington, Bedford, U.K. during January 2001.

boundary-layer depth are used as before.) Figure 3 shows plots comparing time-series of observed and calculated velocity variances (using observed u_*) at a height of 10 m during January with a time resolution of 17.5 min. The main features are captured, as before, although there is no evidence of the overprediction previously observed. The comparison between observed and predicted velocity variances is very good at both 10 and 45 m during January and August. The generated statistics at 10 m during January are given in Table III. The agreement between observations and predictions in Table III is excellent, with good prediction of the mean, small normalised mean square errors and high correlation values. This highlights the sensitivity of

TABLE III

Statistical comparison of 10-m horizontal (cross-wind) and vertical, observed and predicted velocity variances (using observed values of u_*) at Cardington, U.K. during January 2001.

No. of obs. = 2482	Mean (m s^{-1})	sd (m s^{-1})	NMSE	r
Horizontal (cross-wind)				
Observed	0.48	0.29	0.00	1.00
Predicted (observed u_*)	0.48	0.33	0.06	0.93
Vertical				
Observed	0.32	0.20	0.00	1.00
Predicted (observed u_*)	0.31	0.21	0.05	0.95

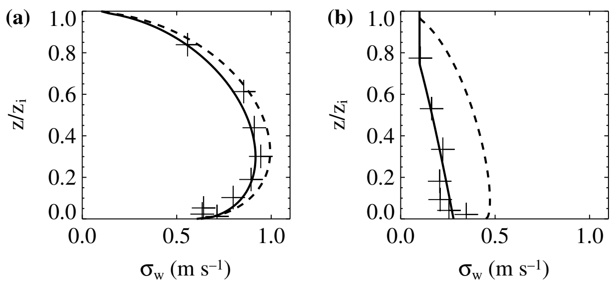

Figure 4. Observed σ_w (crosses), predicted σ_w using UM mesoscale meteorological data (dashed line) and predicted σ_w using observed meteorology (solid line) from a height of 10 m at Cardington, Bedford, U.K. in (a) unstable conditions and (b) neutral/stable conditions, based on local measurements.

Equations (2)–(5) to the input meteorological data but suggests that, given accurate meteorological data for the locality, the turbulence profiles are well suited at heights of 10 and 45 m to the wide range of stability conditions experienced at Cardington.

4.2. Balloon measurements

To validate the velocity variance profiles at heights above 45 m at Cardington, comparisons were made with observations from the tethered balloon system. Results are presented for σ_w only but the conclusions drawn are also true for $\sigma_{u,v}$. The quantity of balloon observations available was limited to 14 h. Figure 4 shows two examples of observations and σ_w profiles calculated using UM mesoscale meteorological data as input to Equations (3) and (5). Profiles of σ_w, calculated using observed meteorological data from the Cardington surface site as input to Equations (3) and (5), are also plotted. Figure 4a is an example taken from convective conditions and Figure 4b from neutral/stable conditions, based on local measurements.

Comparisons with surface-based measurements in Section 4.1 showed an over-prediction in velocity variances calculated using UM meteorological data. This overprediction is also seen throughout the boundary layer in Figure 4 and is again greatest in the neutral/stable case (Figure 4b), when the UM is predicting convective conditions. Values of σ_w calculated using observed meteorological data agree well with observations of σ_w.

The results here reinforce those made earlier that, given accurate meteorological data, the velocity variances are parameterised well. During the comparisons with surface-based measurements only the accuracy of u_* was considered, but with increasing height the w_* component of the convective velocity variance profiles (Equations (4) and (5)) becomes significant. Hence,

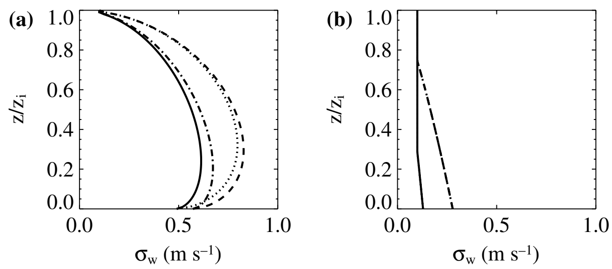

Figure 5. Predicted σ_w at Cardington, Bedford, U.K. using UM mesoscale meteorological data (dashed line), observed meteorological data (solid line), observed u_* and UM H and T_s (dotted line) and observed H and T_s and UM u_* (dot-dash line) in (a) unstable conditions and (b) neutral/stable conditions, based on local measurements.

the sensitivity of Equations (4) and (5) to sensible heat flux (H) and near-surface reference temperature (T_s), precursors to w_*, must also be considered. Figure 5 shows typical profiles of σ_w calculated using Cardington meteorological observations (solid profiles) and UM meteorological data (dashed profiles) as input to Equations (3) and (5). To test the sensitivity of Equations (3) and (5) to u_*, H and T_s, two more profiles are plotted. The dotted σ_w profile is calculated using observed u_* and UM H and T_s. The dot-dashed σ_w profile is calculated using observed H and T_s and the UM u_*. In stable conditions (Figure 5b) σ_w is dependent only on u_* (see Equation (3)). Hence, the dotted profile agrees with the solid profile as both use the observed u_*, and the dashed profile agrees with the dot-dashed profile as both use the UM u_*. In unstable conditions (Figure 5a) σ_w is dependent on u_*, H and T_s. The sensitivity of Equation (5) to u_* is a maximum at the surface ($z/z_i = 0$) and tends to zero at the top of the boundary layer ($z/z_i = 1$). The sensitivity of Equation (5) to H and T_s is zero at the surface and at the boundary-layer top, with a maximum at $z/z_i = 0.4$. Hence, near the surface there is good agreement between the profiles with the same u_*. However, with increasing height there is better agreement between profiles with the same H and T_s. The sensitivity of Equation (5) to errors in T_s is much less than to errors in H since a 5 °C error in near-surface temperature is quite small (about 2%) in absolute terms.

Figure 5 shows the sensitivity of vertical velocity variance profiles to the parameters u_*, H and T_s and how this differs with height in the boundary layer, and with stability. It confirms that the accuracy of u_* is crucial for modelling near-surface velocity variances; an overprediction of u_* results in an overprediction of velocity variances. However, to model velocity variances well throughout the depth of the boundary layer in unstable conditions, the accuracy of H is equally important; an overprediction of H results in an overprediction of velocity variances.

5. Comparison of Turbulence Profiles with Urban Observations at Birmingham, U.K.

Section 4 showed that the velocity variance profiles (Equations (2)–(5)) compare well with observations at a rural site if they are based on sound meteorological data. In particular, site representative values of u_* and H are important. In this section, the σ_w profiles are compared with observations from an urban site to assess how well turbulence parameters are modelled in urban areas. Results are presented for σ_w only, but the conclusions drawn are also true for $\sigma_{u,v}$. The urban observations used here are from three Birmingham field experiments described in Section 3.2.

Over recent years the urban capabilities of the UM have been improved, including a new surface exchange scheme. This allows for non-uniformity of the land surface in a model grid box and for separate temperatures and vertical fluxes to be calculated for each land type (Best et al., 2000). However, at the time of the Birmingham campaigns, and as such in this study, older versions of the UM were being used, with lower spatial resolution and less urban capabilities. The increased surface roughness of urban areas is included, at least in part, through the gridded averages. The improvements in the UM are significant for urban modelling, but are not central to this study. Instead, the conclusions we are able to draw about the sensitivities of dispersion modelling over urban areas is the main focus. As stated previously, increased surface roughness and the urban heat island effect, which is strongest at night, affect turbulence in urban areas. Figure 6 shows mean diurnal cycles of sensible heat flux for the three measurement periods during spring, winter and summer. Urban observations at 15 m are shown by the solid lines and the corresponding UM mesoscale heat flux by dashed lines. The urban observations show a clear heat island effect. It can be seen that during the night the mean stability of the UM boundary layer becomes stable, but the mean observed boundary layer stays neutral, and the evening

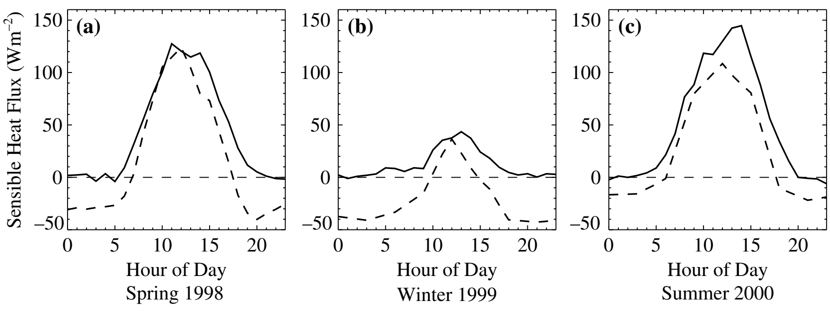

Figure 6. Mean diurnal cycle of 15-m observations of sensible heat flux, H, (solid line) and UM mesoscale H (dashed line) for the periods of the three urban measurement campaigns in Birmingham, U.K., (a) spring 1998, (b) winter 1999, (c) summer 2000.

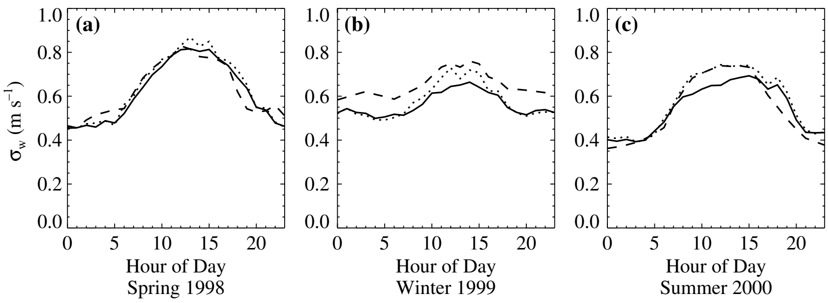

Figure 7. Mean diurnal cycle of 15-m observations of σ_w (solid line), predicted σ_w using UM mesoscale meteorological data (dashed line) and predicted σ_w using observed u_* in UM defined stable conditions and UM u_* in all other conditions (dotted line) for the periods of the three urban measurement campaigns in Birmingham, U.K., (a) spring 1998, (b) winter 1999, (c) summer 2000.

transition into the neutral state occurs later than the UM predicts. The extent of the difference between the observed and UM cycles varies according to season. During the winter period the mean UM boundary layer becomes unstable for a very short time during the day, and indeed on some individual days stays stable for the full 24 h. The mean urban observations for this period, however, shows that the boundary layer does not become stable, but stays neutral.

Figure 7 shows mean diurnal cycle plots of observed σ_w at 15 m from the urban site (solid lines) and σ_w calculated using UM meteorological data as input to Equations (3) and (5) (dashed lines). The calculated values of σ_w compare least well with the observations at night, or more specifically in stable conditions. As seen in the heat flux plots, the winter period shows the least agreement between σ_w observations and predicted values. If the stability for this urban area is wrongly diagnosed by the UM the stable turbulence parameterisation is used instead of the unstable parameterisation. However, the two parameterisations are designed to be continuous in near-neutral conditions and as such are approximately equal in these conditions. Therefore, an incorrect choice of profile should not be the cause of the disagreement between the magnitudes of σ_w.

We have previously discussed the dependence of the turbulence parameters on u_* in stable conditions. Mean diurnal cycles of σ_w calculated using urban measurements of u_* in stable conditions (as defined by the UM) and u_* from the UM in unstable conditions as input to Equations (3) and (5) are shown in Figure 7 (dotted lines). When the urban observed u_* is used in Equation (3), the calculated σ_w values agree well with the urban observations of σ_w. Statistical measures comparing observations of σ_w at Birmingham against those calculated using Equations (3) and (5) with the observed u_* in UM stable

TABLE IV

Statistical comparison of observed and predicted σ_w values (using only UM data) and predicted σ_w values (using observed values of u_*) at Birmingham, U.K. during the three measurement campaigns.

	Mean (m s^{-1})	Sd (m s^{-1})	NMSE	r
1998 (no. of obs. = 432)				
Observed	0.62	0.23	0.00	1.00
Predicted (UM met)	0.62	0.23	0.06	0.81
Predicted (observed u_*)	0.64	0.26	0.03	0.91
1999 (no. of obs. = 577)				
Observed	0.56	0.30	0.00	1.00
Predicted (UM met)	0.64	0.40	0.09	0.93
Predicted (observed u_*)	0.57	0.34	0.03	0.97
2000 (no. of obs. = 779)				
Observed	0.54	0.21	0.00	1.00
Predicted (UM met)	0.54	0.21	0.06	0.85
Predicted (observed u_*)	0.57	0.25	0.04	0.92

conditions and with UM meteorological data in all conditions are shown in Table IV. All three urban observation periods are considered. We see an improvement in the correlation and NMSE when the observed u_* is used in Equation (3) in stable conditions. This compares well with the statistical comparison for the rural case in Section 4.1. In particular, when the observed u_* is used in Equation (3) in stable conditions, NMSE and correlation values obtained for the urban area are very similar to those for the rural site (see Tables III and IV).

The results here are consistent with the conclusions of Section 4, namely that there is an improvement in accuracy of the calculated velocity variances, especially in stable conditions, if meteorological values appropriate to the site being modelled are used in Equations (2)–(5).

Evidence suggests that the velocity variance profiles are appropriate for use in urban areas given good input meteorological data for the locality.

6. Conclusion

The velocity variance profiles (Equations (2)–(5)) have been compared against a range of surface-based and balloon data in both rural and urban areas. In general, we have shown that the main features have been captured, but there is a tendency to overpredict velocity variances particularly during stable conditions. In rural areas we have shown that this overprediction is due mainly to an overprediction in local meteorological variables used by the profiles. The statistical agreement between observations and calculated velocity variances is very good when observed meteorological data are used by the turbulence profiles. Hence the turbulence profiles are appropriate for a wide range of stability conditions at rural locations.

In urban areas the NWP model often does not 'see' the urban conurbation and the effects of the urban heat island are not taken into account. This results in the stability of the atmospheric boundary layer being incorrectly diagnosed. We have shown that, since the turbulence profiles have been designed to be continuous in near-neutral conditions, the wrong choice of velocity variance profiles does not directly affect the predicted velocity variances. As in rural locations, there is some evidence of an overprediction of velocity variances in winter. When observed meteorological data appropriate to the local urban environment are used by the turbulence profiles, the predicted velocity variances agree well with observations. We conclude that the velocity variance profiles are equally suitable for use in urban as well as rural areas.

Our study has highlighted the importance of sound meteorological input data for turbulence modelling, in particular friction velocity and heat flux. We have discovered that, at Cardington, u_* is overestimated by the UM. This highlights the limitations of numerical weather prediction data and the effect this has on dispersion modelling. Each NWP grid box can cover both urban and rural areas, a range of roughness lengths and varying topography. Consequently, the gridded averages cannot resolve subgrid-scale variations. Further study is also necessary in modelling urban areas, as rural and urban meteorology can differ greatly and can have a large impact on model accuracy.

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