6.30 AN ASSESSMENT OF TURBULENCE PROFILES IN URBAN AREAS

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INTRODUCTION

Accurate predictions of turbulence are crucial in atmospheric dispersion models for simulating dispersion of pollutants released into the boundary layer. Turbulent dispersion is commonly modelled using random walk techniques that employ analytical profiles of parameters of the turbulent motion. Profiles of turbulence parameters have been derived using observational data 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 data collected over flat and uniform terrain in the USA. This study was undertaken in order to assess the suitability of the profiles of turbulence parameters, used in a Lagrangian dispersion model, in urban areas in the UK. We begin by comparing the turbulence parameters with surface and balloon observational data from a flat rural site in the UK 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, UK.

TURBULENCE PROFILES

The form of the analytical velocity variance profiles depends upon the stability of the atmospheric boundary layer. In stable conditions, the velocity variance profiles ($\sigma^2_{u,v,w}$) are given by

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

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

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 stationary, stable boundary layers. In reality, however, stable boundary layers are often non-stationary, particularly around the periods of dawn and dusk. Nieuwstadt (1984) showed that the ¾ 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 the stable formulae (equations (1) & (2)) 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 convective conditions, the velocity variance profiles are a combination of profiles for strongly convective conditions and for mechanically driven turbulence, namely

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

$$\sigma_w^2 = 1.2w_*^2\left(\frac{z}{z_i}\right)^{2/3}\left(1-\frac{z}{z_i}\right) + 1.69u_*^2\left(1-\frac{z}{z_i}\right)^{3/2}. \tag{4}$$

The convective velocity scale w_* is defined by

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

where L is the Monin-Obukhov length and k is von Kármán's constant (taken as 0.4). The strongly convective components are based on the profiles of Hibberd and Sawford (1994) 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 (1) & (2)) in the neutral limit in order that the profiles are continuous in the stable to unstable transition.

RURAL AREAS

Measurements of velocity variances at heights of 10m and 45m at Cardington were compared with those calculated using the turbulence profiles (equations (1) – (4)). Mesoscale meteorological data from the Met Office's numerical weather prediction model (the Unified Model (UM)), with a time resolution of one hour and a spatial resolution of 12km, was used.

Overall, the calculated turbulence profiles capture the main features of the observations but are over-predicted at heights of 10m and 45m for the periods studied. The means of σ_v and σ_w are over-predicted by factors of 1.75 and 1.72 respectively at a height of 10m during January 2001. A comparison of UM mesoscale meteorological variables, used to calculate velocity variances, with the corresponding observed meteorological variables showed that u_* is over-predicted by the UM. The UM gives 12 km gridded averages and a roughness length value of 7.8cm at Cardington. The roughness length is much larger than the observed value of 1cm and may reflect the variation in the locality which includes the urban town of Bedford. The over-prediction in u_* by the UM is consistent with a larger predicted value of z_0. The comparison between observed and predicted velocity variances using observed values of u_* is exceedingly good at both 10m and 45m. This suggests that the over-prediction in the calculated velocity variances is caused, at least in part, by an over-prediction in u_*. This highlights the sensitivity of the turbulence profiles to the input meteorological data but suggests that, given accurate meteorological data for the locality, the turbulence profiles are well suited at heights of 10m and 45m to the wide range of stability conditions experienced at Cardington.

Comparisons were also made with a limited number of observations from a tethered balloon system at Cardington. Figure 1 shows a sample of observations (crosses) and σ_w profiles calculated using UM mesoscale meteorological data (dashed curve) and using observed meteorological data from the Cardington surface site (solid curve). Figure 1(a) shows an example taken from convective conditions and 1(b) from neutral/stable conditions. Again an over-prediction in velocity variances is seen throughout the boundary layer in Figure 1 and is greatest in neutral/stable conditions. Values of σ_w calculated using observed meteorological data agree well with observations of σ_w.

Accuracy of u_* is crucial for modelling near surface velocity variances. With increasing height the w_* component of the convective velocity variance profiles becomes significant. Hence, to model velocity variances well throughout the depth of the boundary layer, accuracy of sensible heat flux and surface temperature is equally important.

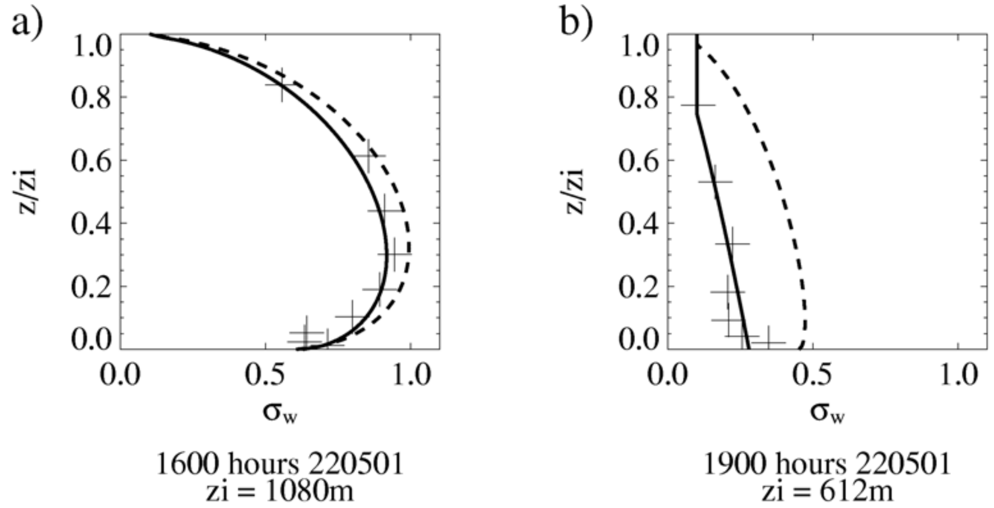

Figure 1. Observed σ_w (crosses), predicted σ_w using UM mesoscale meteorological data (dashed lines) and predicted σ_w using observed meteorology (solid lines) at Cardington in (a) unstable conditions and (b) neutral/stable conditions.

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 1990). 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 night-time stable conditions. In large cities these effects can lead to an almost complete absence of stable conditions, which would be present in the surrounding rural areas.

Observations of σ_w at a height of 15m at the urban site in Birmingham, UK, were recorded during a number of urban measurement campaigns. Figure 2 shows mean diurnal cycle plots of observed σ_w (solid lines) and σ_w calculated using UM meteorological data (dashed lines). The plot shown represents the winter 1999 campaign period when there is least agreement between observations and predictions. As in the rural case, an over-prediction in σ_w is evident. The dotted line in Figure 2 represents the mean diurnal cycle of σ_w calculated using urban measurements of u_* in stable conditions. When the urban observed u_* is used in stable conditions the calculated values agree well with the urban observations of σ_w.

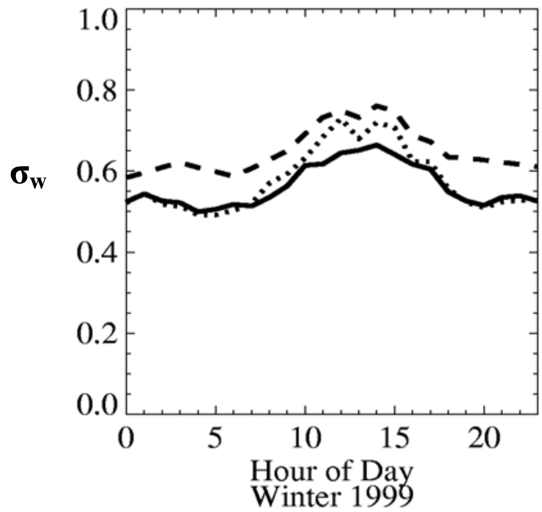

Figure 2. Mean diurnal cycles of 15m observations of σ_w (solid lines), predicted σ_w using UM mesoscale meteorological data (dashed lines) and predicted σ_w using observed u_* in UM defined stable conditions (dotted lines) for the winter 1999 measurement campaign in Birmingham.

Table 1 compares a number of statistical measures for the urban and rural measurement sites. In both rural and urban locations, there is an improvement in correlation (r) and normalized mean square error (NMSE) when observed values of u_* are used. In particular, the normalized mean square error and correlation values are both exceedingly good for urban and rural areas when observed meteorological data appropriate to the local environment are used. The statistics in Table 1 suggest that the velocity variance profiles are equally well suited for use in urban as well as rural areas.

Table 1. Statistical comparison of observed and predicted vertical velocity variances in both urban and rural areas.

Location	σ_w	**Mean (m/s)**	**Standard deviation (m/s)**	**NMSE**	**correlation**
Cardington (rural)	Observed	0.32	0.20	0.00	1.00
	Profiles (UM met.)	0.55	0.30	0.47	0.84
	Profiles (observed u_*)	0.31	0.21	0.05	0.95
Birmingham (urban)	Observed	0.56	0.30	0.00	1.00
	Profiles (UM met.)	0.64	0.40	0.09	0.93
	Profiles (observed u_* - stable conditions)	0.57	0.34	0.03	0.97

CONCLUSION

The velocity variance profiles in equations (1) – (4) have been compared against a range of surface-based and balloon data in both rural and urban areas. We have discovered that, for the locations and periods studied, there is a tendency when using meteorological data from the

UM to over-predict velocity variances particularly during stable conditions. However, if observed meteorological data is used then the agreement between observations and calculated velocity variances using equations (1) – (4) is exceedingly good. Furthermore, in urban areas, NWP models often do not 'see' the urban conurbation and the effects of the urban heat island are not taken into account. In 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 fluxes to be calculated for each land type (Best et al., 2000). Further study is, however, necessary in modelling urban areas.

This study has highlighted the importance of good meteorological input data for turbulence modelling and the limitations imposed by numerical weather prediction models. We can, however, conclude that, given accurate meteorological data, the turbulence profiles are equally well suited to urban and flat rural areas.

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