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Estimation of aerodynamic roughness length and displacement height of an urban surface from single-level sonic anemometer data

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A method for estimating the aerodynamic roughness length and displacement height of an underlying surface from single-level sonic anemometer data is applied to an urban surface in Beijing. Both surface roughness length and displacement height are found to vary considerably with wind direction. The results show that during the selected period average values of the aerodynamic roughness length and the zero-plane displacement height were 1.6 m and 36.0 m respectively. Comparison of the present results with previous studies for this site demonstrates that the roughness length and zero-plane displacement have increased over the last eight years. These increases were associated with an increase in the height of urban buildings.

Introduction

Realistic specifications of the roughness length and zero-plane displacement are crucial in the boundary-layer parametrisation that plays an important role in numerical mesoscale models (Abdella and Mcfarlane 1996). Martano (2000) proposed a method for estimating the surface roughness length (z_0) and the displacement height (d) from single-level sonic anemometer data. This method reduces the problem of finding joint values of both z_0 and d to a simpler least-squares procedure for one variable.

In this method, the standard deviation σ_S of the function $S(z_0, d)$, defined below, is minimised with respect to d, resulting in a direct estimate of d and z_0, together with their statistical uncertainty. The function $S(z_0, d) = \{kU/u_* + \psi[(z - d)/L] - \psi(z_0/L)\}$ is a statistical quantity that depends on the data. Here, k is the von Karman constant (0.35), U is the horizontal wind speed at height z, $u_* = (-<uw>)^{1/2}$ is the friction velocity, $L = u_*^2T/(kg\theta_*)$ is the Monin-Obukhov scale height, and $\theta_* = -<w\theta>/u_*$. In the above u, w and θ are fluctuations in horizontal wind speed, vertical wind speed, and potential temperature respectively, T is the absolute temperature and g is the gravitational acceleration. The function $\psi[(z-d)/L, z_0/L] = \psi[(z-$

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$d)/L]$ - $\psi(z_0/L)$ is the integrated stability correction function (Panofsky and Dutton 1984). The procedure also depends on the function $\sigma_{z_0} = (z - d)e^{-S}\sigma_S$, where σ_{z_0}, the standard deviation of z_0, represents the relative uncertainty of the roughness length z_0. Martano (2000) tested the scheme against two datasets under homogeneous and heterogeneous surface conditions, strongly indicating the appropriateness of his method.

Sonic-anemometer data were collected over the Beijing area during the intensive observing period (IOP, 20 February to 2 March 2001) of the Urban Environment of Beijing Project. The objective of this study is to determine the aerodynamic parameters at this site using the Martano (2000) method.

Methodology

The original Martano method

In the Monin-Obukhov similarity law, the wind speed profile $U(z)$ is written as:

$$U(z) = (u_*/k)\{\ln[(z - d)/z_0] - \psi[(z - d)/L, z_0/L] \quad \ldots 1$$

The least squares method is used to estimate z_0 and d in Eqn 1. The mathematical formulation of the problem then becomes:

$$<\{kU/u_*-\ln[(z-d)/z_0] + \psi[(z-d)/L, z_0/L]\}^2> = \min(z_0,d) \ldots 2$$

where the operator $< > \equiv (1/N)\sum_{i=1}^{N}$ is defined to be the average over the dataset of N groups of time-averaged quantities U_i, T_i, u_{*i}, and L_i, all at height z. The expression $\min(z_0,d)$ indicates the minimum with respect to both z_0 and d, and this is, in principle, a two-dimensional nonlinear least squares problem.

Equation 2 can be written as:

$$<S[(z_0, d) - \mathrm{p}(z_0, d)]^2> = \min(z_0,d) \qquad \ldots 3$$

where the parameter $\mathrm{p}(z_0, d) = \ln(z - d)/z_0$ is a function of z, z_0 and d only.

Averaging of Eqn 1 leads to the condition:

$$<S(z_0, d)> - \mathrm{p}(z_0, d) = 0 \qquad \ldots 4$$

or

$$\ln[(z - d)/z_0] = <kU/u_* + \psi[(z - d)/L, z_0/L]> \quad \ldots 5$$

Equation 3 can be written as:

$$<[S(z_0, d) - p(z_0, d) - <S(z_0, d) - p(z_0, d)>]^2> = \min(z_0,d) \ldots 6$$

where p is a parameter such that $<p> = p$. Then

$$<[S(z_0, d) - p(z_0, d) - <S(z_0, d) - p(z_0, d)>]^2>$$
$$= [S(z_0, d) - <S(z_0, d)>]^2 = \sigma_S^2 \qquad \ldots 7$$

which shows that the variable σ_S depends on both d and z_0. Taking the partial derivative of Eqn 7 with respect to d and setting it to zero, we find the minimum in σ_S^2 and corresponding value of d and then, using this value, evaluate z_0 from Eqn 5.

Simplification of Martano's method

Martano's method assumes that z_0 and d are independent, so the problem of finding the value of d which produces the minimum standard deviation of $S = kU/u_* + \psi[(z - d)/L, z_0/L]$ subject to the constraint $<S> = \ln[(z - d)/z_0]$, is equivalent to the problem of finding the minimum deviation of $S_1 \equiv kU/u_* + \psi[(z - d)/L]$ with respect to d when $\psi(z_0/L) = O(z_0/L)$. We used this approach to determine d, after which the aerodynamic roughness length was found from Eqn 5 by applying the minimum deviation principle.

The datasets

The observation tower of the Institute of Atmospheric Physics of the Chinese Academy of Sciences is in cross-section an equilateral triangle one metre on each side, and has sonic anemometers mounted at 47 m, 120 m and 280 m above ground level. Three identical three-dimensional ultrasonic anemometers (Model DAT 300 with TR-61C probe, Kajio Denki Inc., Japan) were mounted vertically at the ends of three horizontal arms, each one metre long, in the northeast corner of the tower. All signals from the sensors were recorded at a sampling rate of 20 Hz and were averaged over 30-minute periods. Screening by the tower body resulted in errors in the computation of the aerodynamic roughness length and zero-plane displacement when the wind was southwesterly.

The area surrounding the tower was covered mainly by 10 to 20-storey buildings with heights of 30 to 60 m. They were in all directions from the tower at distances ranging from about 200 m to more than 5 km. Meanwhile, within 200 m of the tower, the roughness elements were two to eight-storey buildings with heights of 6 to 24 m. A west-east highway is also present 100 m north of the tower. This environment around the tower is typical of urban areas of Beijing and other large Chinese cities. As shown in the following section, this complex underlying surface results in a strong dependence of the roughness parameters on wind direction.

Considering the height of the roughness elements, the question we must ask is whether the data collected at a height of 47 m are reasonable for use in this research. To answer this question we examine the data collected at three heights. Figures 1 and 2 show the variations of the measured momentum fluxes ($\rho <wu>$) and sensible heat fluxes ($\rho C_{pd}<wu>$)

at three heights on clear days during this observation period. The data from snowy and foggy periods are ignored, resulting in gaps in the record, as shown in Figs 1 and 2. It is apparent that the daily patterns of momentum fluxes and sensible heat fluxes at the three layers are almost the same. The daily maximum sensible heat flux reached 200-320 Wm^{-2}. Figure 3 shows plots of momentum and sensible heat fluxes measured at levels of 47 m and 280 m (y axis) compared to corresponding values measured at 120 m height (x axis). The lines corresponding to equality of fluxes at the two heights compared are shown. We find that the points are distributed fairly evenly around these lines. The data collected at 47 m height are closer to those collected at 120 m than are the data collected at 280 m.

To quantify the difference in mean flux at the three levels, let

$$Bias_{\tau 1} = \sum_{i=1}^{n} \frac{\tau_{47} - \tau_{120}}{n}, \quad Bias_{\tau 2} = \sum_{i=1}^{n} \frac{\tau_{280} - \tau_{120}}{n},$$

$$Bias_{H1} = \sum_{i=1}^{n} \frac{H_{47} - H_{120}}{n}, \quad Bias_{H2} = \sum_{i=1}^{n} \frac{H_{280} - H_{120}}{n},$$

where τ_{47} (H_{47}), τ_{120} (H_{120}) and τ_{280} (H_{280}) are the momentum fluxes (sensible heat fluxes) measured at levels 47 m, 120 m and 280 m respectively. The total number of data points is $n = 201$. We find that $Bias_{\tau 1} = 0.0027$ Nm^{-2} and $Bias_{\tau 2} = -0.036$ Nm^{-2}, $Bias_{H1} = -3.43$ Wm^{-2} and $Bias_{H2} = -9.37$ Wm^{-2}. These results show that there is no substantial bias among momentum fluxes or sensible heat fluxes measured at the three levels.

Figure 4 shows the empirical probability distribution functions (PDF) of the difference of sensible heat fluxes at two different layers. The number (n) of samples in each case is 201. The figure shows that the sensible heat fluxes measured at each of the three levels do not differ significantly. In Fig. 4, the variable H_{120m} represents the sensible heat flux measured at the height of 120 m. Figures 1-4 seem to show that all three levels (47, 120 and 280 m) are within the constant flux layer.

The adequacy of the fetch may be confirmed using footprint analysis (e.g., Leclerc and Thurtell 1990; Schuepp et al. 1990; Harazono et al. 1998). The cumulative normalised contribution to the surface flux from upwind locations, $C_F(x_L)$, can be expressed as:

$$C_F(x_L) = e^{-\bar{U}(z-d)/(ku_* x_L)} \qquad \ldots 8$$

where $\bar{U}$ is the average wind speed between the surface and observation height z, and x_L is the distance upwind of the measuring point. The contributions of the cumulative flux computed using Eqn 8 indicate that, for cases of neutral stability, an average of approximately 90 per cent of the measured momentum fluxes at the measurement height (47 m) were expected to come from within the nearest 5000 m of the upwind area during this period. We find the minimum fetch was 4800 m in all directions.

Fig. 1 **Variation with time of measured sensible heat fluxes on clear days in an urban area of Beijing at three heights: (a) 47 m, (b) 120 m, and (c) 280 m.**

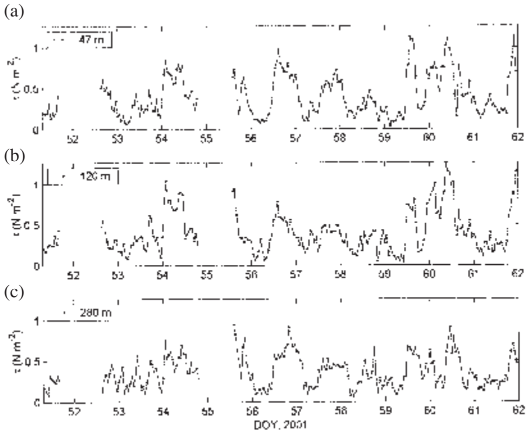


Fig. 2 **Intercomparison of measured sensible heat fluxes (H) at the three levels given in Fig. 1.**

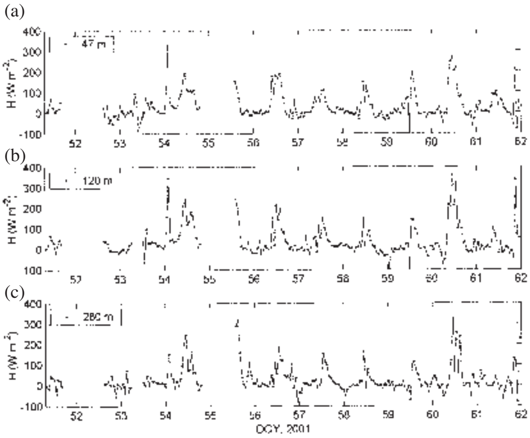


Fig. 3 **Momentum and sensible heat fluxes measured at levels of 47 m and 280 m (y axis) compared to corresponding values measured at 120 m height (x axis). The lines corresponding to equality of fluxes at the two heights compared are shown.**

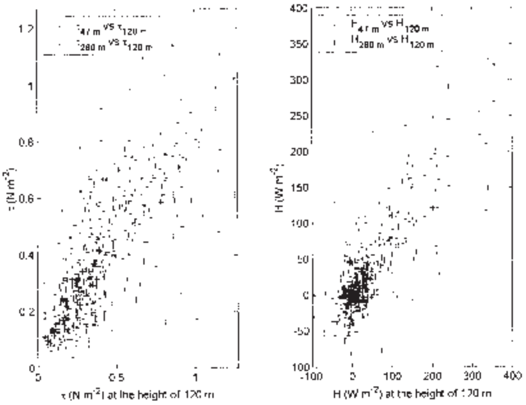
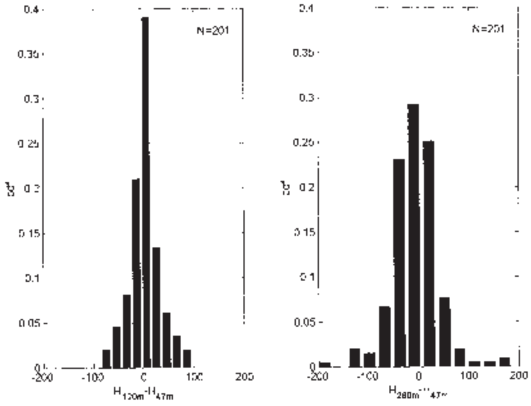


Fig. 4 **Empirical probability distribution function of (H_{120m}-H_{47m}) and (H_{280m}-H_{47m}), the differences between the sensible heat flux at 47m and that at 120 m and 280 m.**



Results

Zero-plane displacement

To find the value of the zero-plane displacement *d* that minimises the standard deviation, the displacement was allowed to vary from 0 to 47 m in discrete intervals of 0.1 m, treating different wind direction sectors separately. The standard deviation exhibited a clear minimum in each case, as shown, for example, in Fig. 5. Figure 6 shows that there was a large difference in *d* among the wind direction sectors, ranging from 29.30 to 40.12 m. This corresponds to heights of the surrounding buildings in the range 40 to 60 m. For the sector 180° - 270°, it was not possible to determine a value for *d* because the sonic anemometer was situated in the lee of the tower, resulting in distorted measurements in this sector. Assuming $d = 5z_0$, Hu (1994) estimated *d* by applying the minimum deviation principle in Eqn 1 and using data collected from this tower and at the same height in 1986. Hu's results are also shown in Fig. 6. They show the zero-plane displacement *d* having negligible variation with wind direction, and a value of only about 3 m. This can be explained by the fact that there were neither large buildings nor tall trees around the tower in 1986, but some houses with heights of 5-6 m. Zhang and Chen (1997) estimated *d* using the sonic data collected at the same height (47 m) on this tower in 1993, using the experimental formulas proposed by Tillman (1972), i.e.

$$\sigma_\theta/\theta_* = -C_1(C_2 - (z - d)/L)^{-1/3} \qquad \ldots 9$$

where σ_θ is the standard deviation of temperature. There remained only one parameter to be found when they assumed that $C_1 = 0.95$ and $C_2 = 0.32$. Meanwhile, they used the empirical fitting equation proposed by Su and Hong (1994) to determine *d*. The fitting equation of Su and Hong (1994) is

$$\sigma_\theta/|\theta_*| = 5(1 - 16(z - d)/L)^{-1/2} \qquad \ldots 10$$

Their results are also shown in Fig. 6. In 1993, *d* varied with wind direction because there were some five to six-storey buildings with heights of 15 to 20 m in most directions around the tower. In this case, the average values of *d* from Eqns 9 and 10 are 10 m and 7 m, respectively. The average value of *d* obtained in the present research is 36.8 m, much larger than those determined in 1993 and 1986. To distinguish the difference caused by the change in the urban morphology from that due to the change in the methods used to determine *d*, the data collected in 2001 were input into Eqns 9 and 10. These results are also shown in Fig. 6. It is clear that the results obtained using Eqn 9 are very close to those from Martano's method, but the values of zero-plane displacement found using Eqn 10 are less than those from the other methods. The good agreement between the results using Martano's method and those using Eqn 9 shows that the significant increases in *d* over the latest eight years are attributable to increases in the heights of the buildings within the fetch.

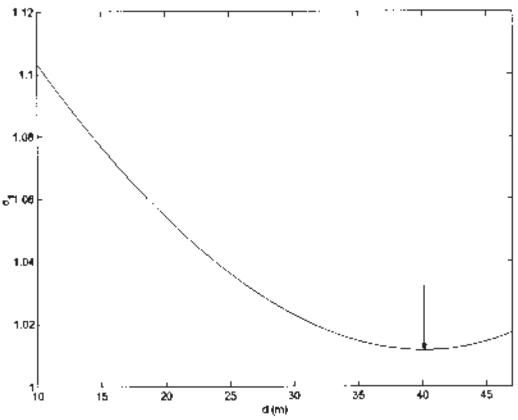


Fig. 5 **Example of the standard deviation σ_s for varying estimates of zero-plane displacement *d*, in this case for wind direction sector 0-90°.**

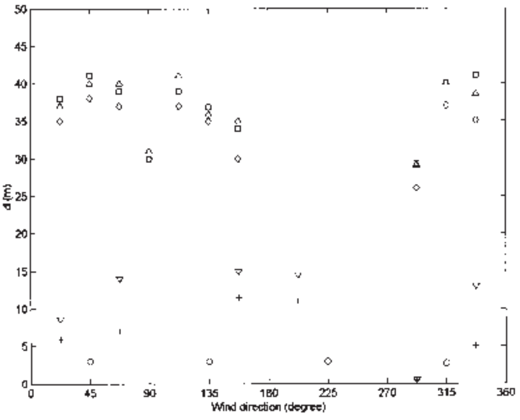


Fig. 6 **Comparison of zero-plane displacement *d* from Martano's methods and previous works at the same site (square - Martano's method; up triangles - temperature deviation method (Zhang and Chen 1997); diamonds - fitting relationship of Su and Hong (Zhang and Chen 1997) in 2001; down triangles - 1993 values using temperature deviation-method (Zhang and Chen 1997); plus signs - 1993 values using fitting relationship of Su and Hong (Su and Hong 1994; Zhang and Chen 1997); circles - 1986 values (Hu 1994).**

Theoretically, the displacement height derived from Martano's method applies to momentum, and those from Eqns 9 and 10 are for heat, so our comparison of these values is based on the assumption that the displacement height for momentum is the same as that for heat. On the other hand, Eqn 9 is valid for free convection only, so in calculating *d* using it, only data from periods with light winds (< 3 m s^{-1}) were used. Equation 10 is valid for unstable convection only, so in using it, only data satisfying the condition that ($z/L < -0.5$) were used.

Aerodynamic roughness length

Once *d* is determined, the aerodynamic roughness length z_0 can be readily found by applying the minimum deviation principle. Figures 7 and 8 show corresponding results to those in Figs 5 and 6. However, because the values of *d* derived using the three different methods with the 2001 data are very close to each other, we use only the values of *d* obtained from Martano's method in the calculation of z_0 for 2001 in this section. It is evident that z_0 also changed with the wind direction over this heterogeneous surface in all three experimental periods. Average values of z_0 were 0.58 m in 1986, 0.72-0.83 m in 1993 and 1.60 m in 2001. Note that all values of z_0 in Fig. 8 are for momentum because they were obtained from Eqn 5 by applying the minimum deviation principle, although the methods used to determine *d* were different.

Figure 9 shows the horizontal wind speeds estimated by the Businger-Dyer forms of the Monin-Obukhov similarity U_E versus the measured values (U_M). The 90 per cent and 95 per cent confidence intervals and the regression equation, $U_E = 0.92\ U_M$, are shown. The results obtained here show that the current values of *d* and z_0 might cause the Businger-Dyer forms of the Monin-Obukhov similarity to underestimate the horizontal wind speed by about eight per cent at this site.

Discussion

Howell and Sun (1999) examined the averaging period for fast data, and suggested that an averaging period of 20 minutes would be better than 30 minutes. We consider that, for measurements of heterogeneous urban surface fluxes, there should not be a significant difference between results obtained using 20 and 30 minute averaging periods. A 30 minute averaging period, most commonly used in previous studies, was used in the present study.

Typically, two approaches have been used to estimate the values of *d* and z_0: (a) morphometric relations, and (b) wind-based methods (see Grimmond and Oke (1999) for detailed comments on these methods). Most morphometric methods are based on

Fig. 7 **As in Fig. 5 except for aerodynamic roughness length z_0; σ_U is standard deviation of wind speed U, referred to in Eqn 5.**

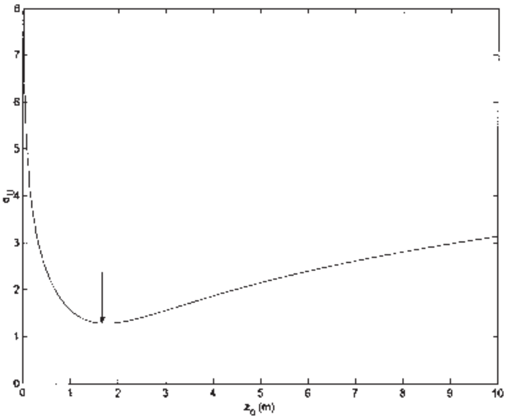
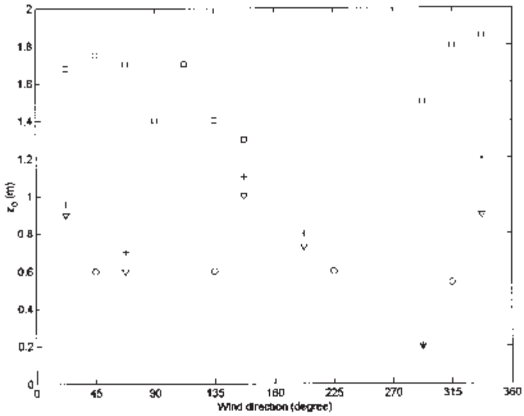
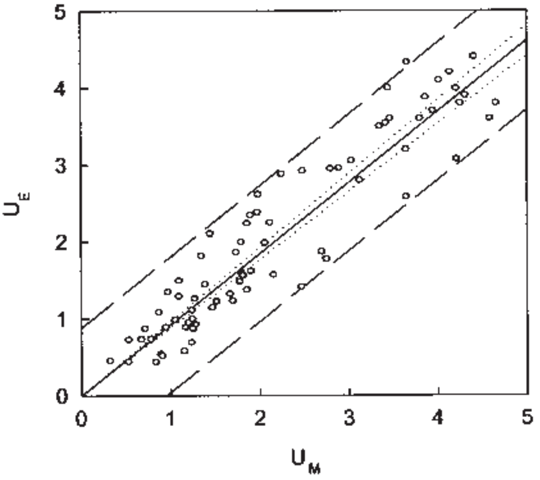


Fig. 8 **As in Fig. 6 except for aerodynamic roughness length z_0.**



empirical relations derived from wind tunnel work that concern idealised flows over simplified arrays of roughness elements, so they can be used to determine the values of d and z_0 for a regular urban surface. In reality, and especially in developing countries, most cities have irregular surfaces, which change rapidly, and modellers require only average values of d and z_0 over a scale of several kilometres. So wind-based methods are, and will continue to be, significant for the determination of the values of d and z_0. Grimmond and Oke (1999) systematically reviewed wind-based approaches for estimating d and z_0 for urban surfaces. They specify nine criteria for selection of high-quality data, noting that the measurement height should be greater than a so-called blending height, z_r, which represents the minimum elevation above a city at which observations are representative of the integrated surface rather than of its individual elements. In his wind tunnel studies, Bottema (1997) used, as criteria for the least and greatest height of measurement, $z_{min} > 2z_H$ and $z_{max} > 0.25\delta$, where z_H is average height of the roughness elements, and δ is the height of the internal boundary layer of the surface concerned. According to Roth (2000), for a homogeneous urban surface morphology, the fetch $x_L > 100z$, where z is the height of the sensor above the ground. In the present research, the measurement height was 47 m, so the fetch reached about 5 km. Roughness elements with heights in the range 40 - 60 m were found in all directions around our PBL tower, at distances from the tower ranging from about 200 m to more than 5 km. In other words, the PBL tower was not close to any of the largest buildings, but rather in their downwind fetch. The height of the buildings around the base of the tower ranged in height from 6 to 24 m, so that the measurement height of 47 m was

Fig. 9 **Scatter plot of wind speeds estimated by Businger-Dyer forms of Monin-Obukhov similarity U_E versus measured speeds U_M. The dataset and estimates of d and z_0 used are those of Figs 6 and 8. Solid line is best-fit curve, dotted lines are 95% confidence intervals, and dashed lines are 90% confidence intervals.**



approximately twice the height of the tallest local roughness element. This implies that the 47 m measurement height is appropriate for our downwind analysis.

Grimmond and Oke (1999) give four urban roughness categories, according to the urban density and flow regime: (1) low density/isolated flow; (2) medium density/wake interference flow; (3) high density/skimming flow; and (4) high rise/chaotic or mixed flow. In the present research, the physical nature of the urban surface was more complicated: there was a greater density of towers around our site in Beijing than those in Fig. 8 (j-k) of Grimmond and Oke (1999), and these towers were clustered and jutted up from dense urban surroundings in Beijing, so our site corresponded to category 3 of Grimmond and Oke (1999). Martano's method depends on the validity of the relationship $\psi(z_0 / L) = O(c / L)$ for $z_0 << L$.

In order to satisfy $z_0 << z - d < |L|$ and $\psi[(z - d) / L, z_0 / L] = \psi[(z - d) / L] - \psi[z_0 / L] \approx \psi[(z - d) / L]$ in the present research, the constraint $|z/L| < 0.5$ is used to filter data when using Martano's method. Because $z = 47$ m, the minimum of $|L|$ should be larger than 94 m. The values of d and z_0 obtained from Martano's method strictly satisfy $z_0 << z - d < |L|$. However, restricting the data using $|z/L| < 0.5$ rules out free convection, so this restriction was not applied when using Eqn 9.

Combining $z_0 = z_{0e} + \Delta z_0$ and the 'single-point' relationship $z_0 = (z - d)e^{-S}$, the standard deviation of z_0 can be estimated by expanding $z_0 = (z - d)e^{-S}$ in a Taylor series up to first order in $S = \langle S \rangle + \Delta S$ and taking Eqn 4 into account. This results in $\sigma_{z_0} = (z - d)e^{-S}\sigma_S$ so that $\sigma_S \approx \sigma_{z_0}/z_{0e}$. Because σ_d coincides with $z - d$, using a Taylor series again leads to $\sigma_d \approx (z-d)\sigma_S$. This means that σ_d increases with increasing measurement height z (Martano 2000). We were unable to calculate d and z_0 using the data collected at 120 m height. This is as expected and illustrates that the uncertainty in d increases with the measurement height. As the measurement height increases, the distance of uniform fetch required for the flow to be in equilibrium with the underlying surface increases. In the present study the requirements for uniform fetch were probably not met for the 120 m data.

Considering the direct dependence of d and z_0 upon the height of the roughness element h, Garratt (1992, p.87) suggested using the empirical formulas $d = 2h/3$ and $z_0 = \gamma_1(h - d)$, where γ_1 is a constant in the range 0.2 to 0.4. The results obtained in the present research are used to validate these formulas. Over the urban surface of Beijing, in the wind direction sector of 0-90°, the average height of the roughness elements is 60 m, so Garratt's formulas lead to $d = 2h/3 = 40$ m and $z_0 = \gamma_1(h - d) = 4$ m under the condition that $\gamma_1 = 0.2$. We thus deduce that $d = 2h/3$ is reasonable, but that the roughness length derived using $z_0 = \gamma_1(h - d)$ is two to three times larger than that from Martano's method. Some data collected by Stull (1988) gave a z_0 value between 1.5 and 2.7 m for 'centers of cities with very tall buildings'. The average z_0 obtained over the urban surface of Beijing in the present research is 1.60 m, which is in good agreement with Stull (1988). Wieringa (1993) summarised the values of roughness of rather homogeneous built-up areas in his Table VII. The average z_0 obtained at the Beijing site in this research is close to those of regular city buildings given by Wieringa (1993), but the zero-plane displacement is larger. The reason for this is that the height of the roughness elements in Beijing was larger than in the cities studied by Wieringa.

How does one explain why Martano's method systematically underestimates the wind speed? Was it because turbulence production and dissipation were not in equilibrium due to the proximity of large, irregularly distributed roughness elements, which introduced errors in the U and u_* measurements? No, because wind speed was also underestimated in the case of a homogeneous surface (Martano 2000). We consider that the underestimation of wind speed was probably caused by the empirically determined constants given by Businger et al. (1971).

Summary and conclusions

The zero-plane displacement and surface roughness over a heterogeneous urban surface can be determined using Martano's method. The results obtained in the present research show that over the urban surface, in the wind speed profile given by the Monin-Obukhov similarity law (Eqn 1), both z_0 and d change with the wind direction due to the heterogeneity of the underlying surface. On average, $z_0 = 1.60$ m and $d = 36.0$ m at the urban observation site. Comparison of the results obtained at this site with previous work and a test of the previous method using current data demonstrates that the roughness length and zero-plane displacement have increased over the latest eight years. The increases of aerodynamic roughness and zero-plane displacement corresponded to an increase in the height of urban buildings.

Acknowledgments

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