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Surface Roughness Around a 325-m Meteorological Tower and Its Effect on Urban Turbulence

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ABSTRACT

Based on slow- and fast-response measurements under neutral stratification conditions from a 325-m meteorological tower located in a built-up area of north-central Beijing as well as a descriptive survey of surface roughness elements (i.e., buildings and trees) around the tower site, urban roughness lengths, z_0, with zero-plane displacement height are estimated using logarithmic wind profile and morphometric methods in eight 45° directional sectors. When comparing their results with each other, the slow-response method tends to give smaller z_0 values. At a given location, considerable directional variations in values are observed. The effect of surface roughness on urban turbulence characteristics in terms of non-dimensional standard deviations of three-component velocity, σ_i/u_{*l} (where $i = u, v, w$ and u_{*l} is local friction velocity), is investigated.

Key words: urban turbulence, surface characteristics, logarithmic wind profile, surface roughness length, zero-plane displacement length, velocity standard deviations

1. Introduction

The evaluation of surface roughness parameters, especially in the center of large urban areas, is an essential feature in many meteorological and wind-engineering applications concerned with local wind structure, local urban climate, air pollution modellings and the behaviour of turbulent structures. The values of roughness length, z_0, in continuously developing cities, e.g., Beijing city, are rapidly increasing as the shapes and heights of roughness elements such as buildings and trees, and their spacing change. Such developments and modifications will be associated with mechanical and thermal distortions of flow across a city.

There is an uncertainty regarding the relation between surface roughness and turbulence parameters, which is mainly caused by the slow progress of better knowledge of atmospheric turbulence resulting from experimental difficulties and the absence of a suitable framework for the analysis and the presentation of turbulence data. Yersel and Goble (1986) estimated roughness lengths over Worcester, Massachusetts, using a logarithmic wind profile under neutral conditions and found that non-dimensional standard deviations of wind components σ_i/u_*, where $i = u, v, w$ and u_* is the friction velocity, decreased with increasing roughness lengths. This behaviour has also been observed in some other experimental studies (e.g., Duchêne-Marullaz, 1979 and Clarke et al., 1982). Recently Roth (2000) reviewed more than fifty studies that investigate turbulent structures over cities. Based on high-quality experiments, he could not find a significant influence of high roughness on quantities σ_i/u_*.

The main goal of this contribution is to evaluate the urban surface roughness lengths over Beijing under neutral conditions in terms of three methods which adopt a logarithmic wind profile using slow and fast response anemometries and analysis of surface morphometry, and to investigate the effect of roughness lengths on urban turbulence characteristics.

2. Aerodynamic and morphometric methods for roughness length

In order to determine the surface roughness length, z_0, estimates over the central urban area of Beijing,

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which has very tall obstacles distributed irregularly, and also to relate z_0 values to turbulence features, three methods were employed, which are enumerated in the following subsections.

2.1 *Turbulence measurements*

z_0 can be calculated directly from the measurements of fast-response sensors using the logarithmic vertical wind profile under neutral conditions for the heights $z \gg z_0$ as follows

$$z_0 = (z - z_{\rm d})e^{-\bar{u}k/u_{*{\rm l}}} \tag{1}$$

where

$$u_{*{\rm l}} = \sqrt{|\overline{-u_{\rm l}'w_{\rm l}'}|}\ ,$$

and u' and w' are the fluctuation values of longitudinal and vertical velocity components, respectively. $\bar{u}$ is the mean wind speed at a measurement level z above the ground, $z_{\rm d}$ the displacement height and k is von Karman's constant (here taken to be 0.4). The subscript "l" denotes local values.

2.2 *Mean wind measurements*

With mean wind measurements obtained from slow-response sensors during neutral stability and available at more than two levels, a graphical technique described in Panofsky and Dutton (1984) and Stull (1988) is useful for estimating z_0 by extrapolating the straight line drawn through the wind speed data on a semi-log graph to the height where the value of mean wind $\overline{U}$ is zero (i.e., extrapolating the line towards the ordinate axis). This line follows the log wind profile as given by:

$$\overline{U} = \frac{u_*}{k}\ln\left(\frac{z - z_{\rm d}}{z_0}\right)\ , \tag{2}$$

where the quantity u_*/k is the slope of the line and lnz_0 is the intercept of line with the ordinate axis.

2.3 *Morphomertic analysis*

Various formulae for estimating z_0 have been comprehensively reviewed by Grimmond and Oke (1999). They were not able to judge which one was best, but they recommended Bottema (1995). Bottema (1995) presented a method (below) used in urban areas, which was also employed by Grimmond et al. (1998). In the present study, this method is used to compare z_0 values to those that will be obtained from observations (i.e., the two previous methods) for all wind directions.

$$z_0 = (\overline{z_{\rm H}} - z_{\rm d})\exp\left(\frac{-0.4}{0.5\dfrac{\sum C_{\rm Db}L_{\rm b}z_{\rm Hb} + \sum C_{\rm Dt}L_{\rm t}z_{\rm Ht}}{A_{\rm T}}}\right) \tag{3}$$

where $z_{\rm Hb}$ and $z_{\rm Ht}$ are the heights of buildings and trees, $\overline{z_{\rm H}}$ is the mean height for both and $A_{\rm T}$ the total area. $L_{\rm b}$ and $L_{\rm t}$ are the breadth of buildings and trees perpendicular to the wind direction and $C_{\rm Db}$ and $C_{\rm Dt}$ are the drag coefficients for buildings and trees, and these are assigned a value of 0.8 for $C_{\rm Db}$ and 0.48 for $C_{\rm Dt} = C_{\rm Db}(1-p)$ where p is a coefficient to allow for the porosity of trees. Since the observational data analyzed in this study was collected during the spring season, the porosity coefficient is set to 0.4 (see Grimmond et al., 1998 and Grimmond and Oke, 1999 for further details). For an extensive review on computing z_0, the reader can refer to Bottema (1995).

3. Displacement length

Over very rough surfaces (e.g., forests and cities), the displacement length, $z_{\rm d}$, must be incorporated to obtain reliable z_0 estimates, particularly in cases of wake-interference or skimming flow where z_0 is large. One of the major reasons for excluding many studies in the studies of Grimmond et al. (1998) and Grimmond and Oke (1999) is that $z_{\rm d}$ is not included. It can be interpreted as the level of mean momentum sink, and in continuously developing areas, i.e., those that experience the addition of roughness elements, a new surface datum may be created at $z_{\rm d} \rightarrow z_{\rm h}$. This case occurs only for (non-homogeneous) skimming flow. The previous studies using wind tunnels, analytical investigations, numerical modellings and field observation have shown that $z_{\rm d}$ and z_0 depend on the size, shape, density and distribution of surface elements (for further details, see Wieringa, 1993).

There are two common approaches to estimate $z_{\rm d}$: firstly, the use of field observation of wind (e.g., Rooney, 2001), and temperature (e.g., Rotach, 1994); and secondly the use of surface morphometry (or geometry) by estimating aerodynamic parameters (see Grimmond and Oke, 1999 for more details). The advantages and disadvantages of these approaches are also given in detail in their review. In the present study, the latter approach is chosen to determine $z_{\rm d}$ using the formula (below) given by Bottema (1995) intended explicitly for urban areas, since it does not depend on airflow to be perpendicular to the buildings and also for its simplicity compared to other approaches.

$$z_{\rm d} = \overline{z_{\rm H}}\left[\frac{\sum A_{\rm pb} + \sum(1-p)A_{\rm pt}}{A_{\rm T}}\right]^{0.6}\ , \tag{4}$$

where $A_{\rm pb}$ and $A_{\rm pt}$ are the plan areas of buildings and trees, respectively. Although this method is simple, it requires information on both the heights and plan areas of the buildings and trees around the site. It is probably the best method when compared to others; see Grimmond and Oke (1999).

4. Observation site and instrumentation

4.1 *Observation site*

The data presented in this paper were obtained from a 325-m meteorological tower located in North central Beijing. The tower was set up in 1978 as a largely permanent facility for basic scientific research by the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences. The elevation of its base is about 48.63 m above sea level and is located at 39°58′N, 116°22′E. The metal tower has a 2.7-m face width and open construction to avoid wake effects near the instruments, and thus the measured data are high quality according to the criteria recommended by Grimmond et al. (1998) and Grimmond and Oke (1999).

Within a radius of about 1 km of the tower, the land is flat with mixed low- and high-rise residential houses and buildings, parklands with many tall trees of 15–20 m height, and many very tall buildings (skyscrapers) with heights of 70–90 m for offices and departments built up irregularly. Most skyscrapers south of the site are about 100 m away and those north of the site are about 300 m away (see Fig. 1). Typically, buildings and trees cover about 35% of the surface area.

To avoid large variability in the spatial density of roughness elements as well as to obtain the maximum possible roughness length data points, which can be related to the turbulence characteristics, it is appropriate to divide the area around the tower site into eight directional sectors of 45°: N–NE, NE–E, E–SE, SE–S, S–SW, SW–W, W–NW and NW–N. Photographic views of each sector, taken from the tower at a height of about 150 m facing these directions are presented in Figs. 1a to 1h, respectively. These pictures show surface characteristics and also continuous changes occurring in the building designs in the surrounding areas. Surface characteristics in each sector up to a distance of 1 km are considered. Changes in construction can be seen as from the south (tall buildings) to the southwest-west (low-rise houses and a long parkway around a narrow 8-m wide river) in Figs. 1d and 1e, as well as from east-southeast of this park (low houses with two high buildings that are about 400 m away from the tower) to the southeast-south (low houses and new and old tall buildings near to the tower and 200 m away from the tower), as shown in Figs. 1c and 1d. Characteristic values for the surface, such as percentage of land use, mean geometric height (defined as the sum of heights for roughness elements surrounding the tower up to 1 km over their number) with their standard deviations, $\overline{z_{\rm H}} \pm \sigma_{z_{\rm H}}$, and an actual fetch, x, defined as a distance from a rural/urban border for each sector separately to the site and estimated from a Beijing map, are presented in Table 1.

Grimmond and Oke (1999) made comparisons for the mean heights of buildings $\overline{z_{\rm Hb}}$, trees $\overline{z_{\rm Ht}}$, average based on plan area, $\overline{z_{{\rm H}\lambda_{\rm p}}}$, and average based on frontal area, $\overline{z_{{\rm H}\lambda_{\rm F}}}$, for eleven (sub-)urban areas (see their Table II). From this table, if the average heights, $\overline{z_{\rm H}}$, for both buildings $\overline{z_{\rm Hb}}$ and trees $\overline{z_{\rm Ht}}$ are taken together, then the differences between $\overline{z_{\rm H}}$ and $\overline{z_{{\rm H}\lambda_{\rm F}}}$ (not more than 10%) are smaller than those between $\overline{z_{\rm H}}$ and $\overline{z_{{\rm H}\lambda_{\rm p}}}$ (within about 20%). $\overline{z_{\rm H}}$, thus based on mean height, is adopted in this work.

4.2 *Instrumentation*

The tower has two sets of instruments. The first system is comprised of fast-response instruments for measuring atmospheric pollutants (O_3, NO_x, CO) and meteorological variables (wind, temperature and humidity) mounted at the 47, 120 and 280 m levels. Since October 1999, instantaneous three-component velocity (u', v', w') has been continuously measured by a three

Table 1. Directional sectors (45°) around the tower site up to 1-km of distance, including percentage of area covered by buildings and trees, their mean heights with standard deviation and actual fetch.

Sector	Direction (°)	Buildings (%)	Trees (%)	$\overline{z_{\rm H}}$ (m)	Fetch (x) (km)	No. of runs
I	0–45	19	11	7.7±10.7	7.9	35
II	46–90	36	14	8.7±15.6	13.1	14
III	91–135	19	30	10.2±5.5	22.0	21
IV	136–180	20	31	14.9±17.9	19.7	20
V	181–225	32	5	18.7±19.5	21.1	82
VI	226–270	8	18	11.9±11.2	15.0	63
VII	271–315	20	5	6.1±16.0	7.9	34
VIII	316–360	19	8	11.0±22.8	5.9	20

Fig. 1. Photographic views of the urban Beijing surface around the tower, taken from the tower.

dimensional ultra-sonic anemometer-thermometer (designed by Professor Zhao Yijun, Institute of Atmospheric Physics, Chinese Academy of Sciences) placed at the end of a boom extending 4 m northeast from the tower. Measurement results are transmitted via cables to the computer system in the room of a 7-m high building 20 m away from the tower. In our experiment, these measurements with a sampling frequency of 10 Hz were compared with both the SAT211/3k (Applied Technologies Inc., US) and DAT300 (Kaijo Denki, Inc., Japan) instruments located at the tower at the same heights as our instruments. The instantaneous values of absolute temperature, T', were obtained with the same method as Al-Jiboori et al. (2002).

The other system is comprised of slow-response instruments such as a three-cup anemometer, vane, platinum resistance thermometer and hygroscopic sensors placed at the two booms of 4 m extending northwest and southeast from the pole, mounted at 15 levels (8, 15, 32, 47, 63, 80, 102, 120, 140, 160, 180, 200, 240, 280 and 320 m), to measure the profile data of wind speed, wind direction, temperature and humidity. Similarly to the above, all measurements were transmitted to the computer system with a sampling frequency of 0.05 Hz.

4.3 *Observation data*

The time series of turbulence and mean profile data were collected for all available levels on a CD-ROM with length of 1 hour during 10–20 April, 2000, in which the leaves grew in the canopy. Hourly runs from both systems were chosen during sunrise and sunset times and then split into lengths of 15 min for averaging for two reasons: first to get more data under neutral conditions, and second to minimize some possible errors resulting from non-stationarity in these series caused mainly by the diurnal forcing of the sun.

Turbulence data were processed, including rotation of the coordinate system so that the mean wind direction is the x-axis, and a second-order polynomial was fit for detrending. To perform the first method for computing z_0, the atmospheric stability for each period was determined by calculating the local Monin-Obukhov length, Λ $(= -u_{*l}^3\overline{T}/gk\overline{w'T'}$, where $\overline{T}$ is the mean temperature and g the acceleration of gravity). More than 280 15-min runs of neutral stability ($|z'/\Lambda| < 0.1$ with $z' = z - z_{\rm d}$) were obtained for the present analysis. Fortunately, for each directional sectors, there are a number of runs with a majority in sectors V (181°–225°) and VI (226°–270°). Detailed numbers of turbulence runs for each sector are also presented in Table 1. This enables us to compare the results of z_0 with those that will be estimated by the methods of a logarithmic wind profile and analysis of surface form.

The vertical profile of wind velocity data in the windy 15-min periods from the slow-response instruments is used in the second method for calculating z_0, when Richardson number, $Ri[= (g\Delta\overline{T}/\Delta z)/\overline{T}(\Delta U/\Delta z)^2]$, computed between the two lowest levels, is between 0.01 and –0.01. This method has the advantage that the $z_{\rm d}$ value is not required in determining which hours should be analyzed.

5. Results and discussion

5.1 *Roughness length*

5.1.1 *Fast response anemometry*

The reliability of representative roughness data in urban areas is important for wind engineering applications and for dispersion modelling. Primarily, this performs by applying some criteria such that the lowest observation level $z_{\rm min}$ should be at a height $\gg 1.5\overline{z_{\rm H}}$ (Wieringa, 1993) or $\gg 2\overline{z_{\rm H}}$ (Raupach et al., 1980). This means that, as shown in Table 1, our measurement lowest level of 47 m (i.e., $z_{\rm min} = 47$ m) across all sectors is larger than the range of ($1.5\overline{z_{\rm H}} = 9.2 - 28.1$ m) or ($2\overline{z_{\rm H}} = 12.3 - 37.7$ m). Therefore, these criteria are met in the present work. Also, measurements for turbulence at 280-m high are not used for estimating z_0 because this height does not meet the fetch requirement as explained below. The fetch, $x_{\rm F}$, that is necessary to ensure that a particular observation level is still in the equilibrium layer fully adapted to upwind surface roughness, can be estimated from the following equation suggested by Wieringa (1993),

$$x_{\rm F} \approx 2z_0 \left[\frac{10z'}{z_0}\left(\ln\frac{10z'}{z_0} - 1\right) + 1\right] . \quad (5)$$

He shows that this equation generally agrees with the common rule of thumb that $x_{\rm F} \approx 100z'$. If we use average wind-based values of z_0 in applying Eq. (5), $x_{\rm F}$ would be in the ranges 2.1–4.3, 8.6–12.7 and 25.7–35.0 km for observational levels 47, 120 and 280 m respectively. Therefore, the fetch requirements for the 280-m level are not sufficient (Table 1), so consequently, the wind structure will not be affected completely by upwind roughness.

To compute z_0 with its u_{*l} and $\bar{u}$ from Eq. (1) at the two levels 47 and 120 m, $z_{\rm d}$ was calculated using Eq. (4) for each sector as will be shown in subsection 5.2. It should be noted that the determination of z_0 by Eq. (1) is generally valid when the criteria mentioned above are applied. In addition, for a good representation of the surface roughness, typically at least 20 values are required to determine z_0 for a given sector (as recommended by Beljaars, 1987). As illustrated in Table 1, this criterion does not meet the reported number for sector II (46°–90°), and consequently, z_0 results are excluded from this study. However, surface roughness lengths are averaged for the remaining sectors. They are in the range 2.1–6.3 m with an average of 4.4±1.7 m. The average values of z_0 with error bars of standard direction, $\pm\sigma_{z_0}$, are denoted by the open circles in Fig. 2 and are plotted against the wind direction sectors. As demonstrated in the figure, large $\overline{z_0}$ values for sectors IV (136°–180°) and V (181°–225°) correspond to an area covered by high buildings (see Figs. 1d and 1e), while the low $\overline{z_0}$ value for sector VI (226°–270°) corresponds to the area covered by a mixture of park and sparse buildings (see Fig. 1f).

5.1.2 *Slow response anemometry*

Lettau (1957) proposed a method to calculate both z_0 and z_d using only data from times of near neutral conditions which meet the stationarity requirement (i.e. not near sunrise or sunset). Given that these forbidden periods are used in this work (see section 4.3), Lettau‘s method was not used in the present study. Fortunately, about 150 15-min runs of the vertical profile of wind speed data measured by slow-response sensors under neutral conditions are distributed randomly from all wind direction sectors. Those sectors with less than 20 runs were excluded. In order to know if at any measurement level, the neutral wind profile deviates from the log law, the wind data from each level of the tower, and for given sector, are averaged (Figs. 3a–g). Under these conditions, the mean wind data increase almost logarithmically above the height of 47 m. These profiles have some random departures from logarithmic, which may be associated with irregularities of terrain. This result was also seen in a wind tunnel by Raupauch et al. (1980).

Through the measurement layer of the tower, the wind profiles are not completely logarithmic, especially below the level 47 m, because the flow is strongly influenced by individual roughness elements of buildings and trees. As shown in Figs 3a–g, the data of the mean wind at upper measurement levels ($z > 63$ m) fit well to a logarithmic profile. To estimate z_0 using mean wind vertical profiles, z_d values morphometrically calculated from Eq. (4) for each sector, as shown in subsection 5.2, were incorporated into Eq. (2). By plotting the straight line through the data points at the upper levels, which obeys and follows Eq. (2), and extrapolating to the vertical axis, where $\overline{U} = 0$, the roughness length for each sector was estimated. Across all directional sectors, the values of z_0 lie in the range of 2.5–3.4 m with $\overline{z_0} = 3.0 \pm 0.34$ m and are presented in Fig. 2 as closed circles. The values range from the largest value of z_0 for sector IV (136°–180°) to the smallest in sector VI (226°–270°).

5.1.3 *Morphometric analysis*

This method provides a good relationship between the sector variability around the site of the tower due to changes in the size and spatial arrangement of the roughness elements. To apply this method and Eq. (4), detailed inventories for land cover around the tower site up to a distance of 1 km have been prepared for each 45° sector. Surface roughness lengths, obtained morphometrically from Eq. (3), lie in the range 2.1–8.7 m with an average value of 4.8±2.2 m (Fig. 2). Similar to subsection 5.1.1, the largest value also occurs in sector IV (136°–180°), while the lowest value occurs in sector VI (226°–270°), which is close to the same value as predicted by the fast-response anemometry.

Across all directional sectors, the variability among z_0 values is not high, except for sector IV in which the z_0 value seems to be unrealistic. Thus, this method gives a reasonable value at sites with smaller and moderated densities, but seems to fail at high densities.

5.1.4 *Comparison of the methods*

None of these methods can be considered a standard one, but it is interesting to compare these approaches for all directions except for sector II. Similarly, Grimmond et al. (1998) also performed this comparison but for limited wind directions. The mean roughness lengths, $\overline{z_0}$, of the three datasets determined by the three methods above are presented in Fig. 2 versus the wind direction sectors. With the inclusion of z_d in the logarithmic wind profile equation, the z_0 estimations and their wind directions for the same tower site were previously made by Hu (1995) and Yin and Hong (1999). Their results are also plotted in this figure.

In general, the anemometrically evaluated z_0 results follow the same trend obtained from the morphometric method. On the other hand, we find that

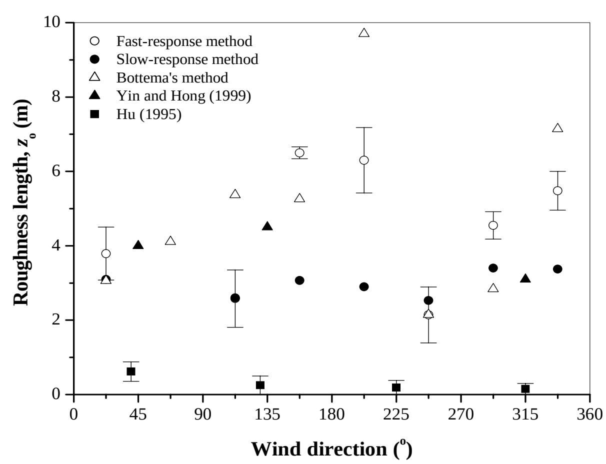

Fig. 2. Surface roughness lengths, z_0, with vertical bars of standard deviation $\pm\sigma_{z_0}$ for sectors of 45° around the tower site estimated from morphometric and logarithmic wind profile methods explained in the key of the panel. The number of data points for the wind-based methods are indicated in Table 1 and the text.

the slow-response results are generally smaller than those determined by the fast-response and morphometric methods. Relative differences between the values derived from the slow- and fast-response sensors, especially in sectors IV (136°–180°) and V (181°–225°), are expected because the wind data and z_0-estimations are derived from two different instruments and methods, respectively. This difference is also observed in some studies (e.g., Grimmond et al., 1998).

Across all wind direction sectors, $\overline{z_0}$ values occur in the ranges 2.1–6.3, 2.5–3.4 and 2.1–8.7 m obtained by the fast- and slow-response and morphometric methods, respectively. In sector V (181°–225°), an area with large observed spatial variability shows the largest differences among the three methods. In this sector, there are high-rise buildings, which are up to 70 m tall located within 100 m of the tower. These values are not surprising, because in the center of Vancouver, Canada, Grimmond and Oke (1999) found a wide range of values (2–7 m), and they are as expected based on Tables IV and VI given by Wieringa (1992) and Grimmond and Oke, respectively.

The dependence of surface roughness on the wind direction intervals in which the inhomogeneous characteristics of the underlying surface around the tower site is evident as shown in Fig. 2. Directional dependence of roughness length has been observed in many experimental studies over urban cities (e.g. Clarke et al., 1982; Yersal and Goble, 1986; Hu, 1995; Rooney, 2001). Therefore, any physical flow parameter dependent upon surface roughness will exhibit some uncertainties if a single z_0 value is used to describe this flow.

The impact of the continuing development and changes in Beijing can be considered from z_0-estimates obtained from this and several previous studies carried out using neutral wind profile data from the same tower over the last fifteen years (Fig. 2). Unfortunately, we could not find photographs of the Beijing surface in these studies, where only a simple description was found.

In 1986, according to Hu (1995), the area around the tower was a mixture of farmland for wheat and short grass, and low-rise residential houses surrounded by trees and shrubs. By 1993, there were buildings 30–40 m tall that were located within 1 km northeast, southeast, south and southwest of the tower and single-story houses and markets were within 1 km (Zhang et al., 2001). Later, many very tall buildings for offices and departments were randomly built 100 m south of this tower, as reported in Yin and Hong (1999), and there were several scattered houses no taller than 4 m around the tower for technicians and recording instruments. The low and high z_0 values and their averages $\overline{z_0}$ for all wind directions from these studies are given in Table 2.

The impact of the fast changes and developments occurring around the tower site can be deduced from Table 2. The mean value of $\overline{z_0}$=0.6 m in 1986 corresponds to that value expected from analytical observation for the surface type of dense low buildings, dubbed "suburban", by Wieringa (1992); $\overline{z_0}$=1.0 m corresponds to estimated values for medium density with houses and trees reported by Grimmond and Oke (1999); and lastly, the values of $z_0 \geqslant 2.0$ m are in agreement with those reported by Wieringa, and Grimmond and Oke for centers of large towns with a mixture of low- and high-rise buildings.

5.2 *Displacement length*

Since the terrain surrounding the tower site is flat, geometric dimensions of roughness elements were used to determine displacement length, $z_{\rm d}$, using Eq. (4). The results of $z_{\rm d}$ and the average height of roughness elements $\overline{z_{\rm H}}$ (this includes buildings and trees together) are presented in Fig. 4 for all direction sectors. The behaviours of both these parameters have the same trend at their respective directions. As demonstrated in subsection 4.1, a large variation is also observed from sector V (181°–225°) to sector VI (226°–270°) as well as from sector III (91°–135°) to sector IV (136°–180°). The larger values in sectors IV and V would reflect a significant development in these sectors.

The values of $\overline{z_{\rm H}}$ are roughly two times larger than those of $z_{\rm d}$ for each sector. $z_{\rm d}$ and $\overline{z_{\rm h}}$ are in the ranges 2.2–9.7 m and 6.1–18.7 m respectively, across the sectors surrounding the tower, and the average values of $\overline{z_{\rm d}}$ and $\overline{\overline{z_{\rm H}}}$ around the site are 5.4 m and 10.6 m. Considering the simple rule of thumb $f_{\rm d} = \overline{z_{\rm d}/\overline{z_{\rm H}}}$, the mean value of all sectors is 0.51 which is very close to 0.51 suggested by Hanna and Chang (1992) in their

Table 2. Comparisons of z_0 values obtained from the present and previous studies using observational data for the same tower site.

References	z_0 range (m)	$\overline{z_0}$ (m)	Data date	Instruments	Surface type
This study	2.1–6.3	4.4±1.7	Apr. 2000	Fast-response	Urban
	2.5–3.4	3.0±0.3	Apr. 2000	Slow-response	Urban
Yin and Hong (1999)	3.1–4.5	3.8	Sep. 1998	Fast-response	Suburban-urban
Zhang et al. (2001)	–	1.0	May 1993	Fast-response	Suburban
Hu (1995)	0.5–0.6	0.6±0.2	Aug.–Oct. 1986	Slow-response	Suburban

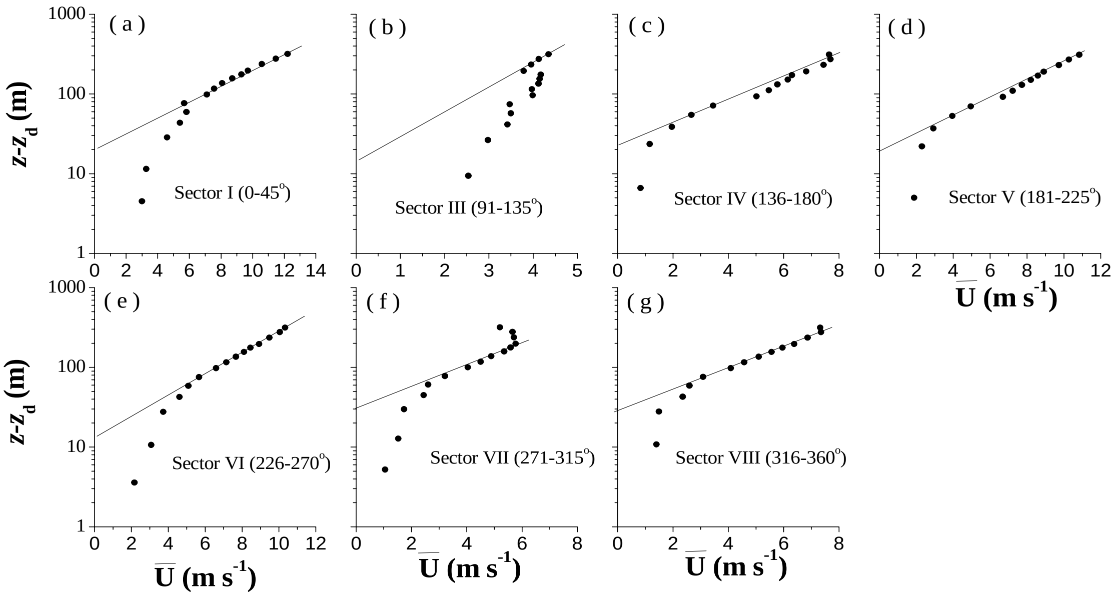

Fig. 3. Vertical profiles of mean wind for seven direction sectors around the tower through the measurement layer. The solid line is the best fitting with slope u_*/k.

survey of urban dispersion parameterizations and 0.54 as the average reported by Grimmond and Oke (1999) derived by morphometric and wind-based methods in their analysis of the surface form of urban areas.

5.3 *Effect of surface roughness on turbulence*

The possible effect of high roughness surfaces on turbulence levels in urban cities can be investigated in the urban boundary layer. Local similarity theory as a tool to describe turbulence characteristics in the urban boundary layer is adopted for two reasons. First as mentioned in section 5.1, Beijing is highly heterogeneous and then the turbulent shear stress will vary with height through the measurement layer as reported by Högström et al. (1982). Secondly, this is adopted to eliminate the effects that may result from the large differences between the observational levels on the tower. To deal with these situations, it is much more convenient to describe the behaviour of turbulent variables as non-dimensional in terms of a local similarity framework. The theoretical predictions for standard deviations of longitudinal, lateral and vertical velocity components, σ_i $(i = u, v, w)$, scaled with local friction velocity, u_{*l}, $A_i = \sigma_i/u_{*l}$, under neutral conditions approach constant values, i.e., $\lim\limits_{|z'/\Lambda| \to 0} A_i$=constant (e.g., Högström et al., 1982 and Yersel and Goble, 1986).

The average values for σ_i/u_{*l} and other relevant data with their standard deviations at the observational levels 47, 120 and 280 m in the same period are listed in Table 3. To investigate the urban turbulence characteristics within and over Beijing, the data of the 280-m level are also included in this table. In order to isolate the influence of the roughness elements mechanically on turbulence levels, all mean corresponding values under neutral conditions, and those that are available from other studies such as Miyake et al. (1970) over a water surface as an ideal uniform surface and Högström et al. (1982) on the roof of a hotel situated in the central part of Uppsala, Sweden, as an urban surface, are also presented in Table 3.

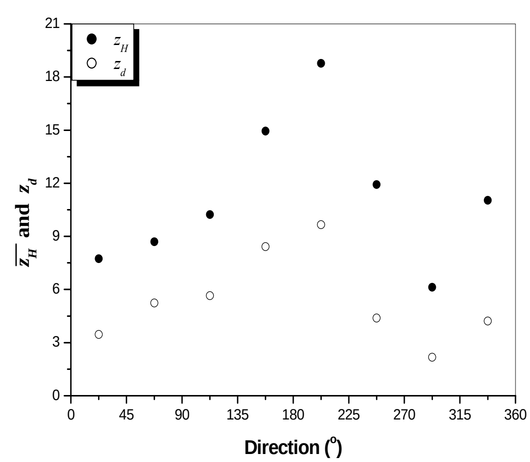

Fig. 4. Displacement height z_d and mean height $\overline{z_H}$ of roughness elements with standard deviations for the eight directional sectors.

Table 3. Average values of atmospheric turbulence parameters derived from fast-response instruments for all wind directions.

Surface type	Height (m)	$\bar{u}$ (m s^{-1})	σ_u/u_{*l}	σ_v/u_{*l}	σ_w/u_{*l}	$\sigma_u/\bar{u}$	$\sigma_v/\bar{u}$	$\sigma_w/\bar{u}$	No. of runs	$\overline{z_0}$ (m)
	47	2.80±1.3	2.27±0.3	2.35±0.3	1.67±0.1	0.39±0.14	0.40±0.17	0.29±0.15	191	5.71±2.3
	120	4.74±1.2	2.43±0.4	2.23±0.4	1.32±0.2	0.29±0.06	0.26±0.06	0.16±0.03	70	2.49±1.3
	280	9.60±5.4	2.84±0.4	2.35±0.4	1.62±0.3	0.17±0.14	0.14±0.12	0.09±0.07	24	–
Urban	Mean	3.79±2.6	2.61±0.3	2.23±0.4	1.53±0.2	0.36±0.10	0.31±0.11	0.21±0.07	285	4.4±1.7
Urban[1]	27	3.00±0.2	2.51±0.1	2.12±0.1	1.45±0.1	0.36±0.4	0.30±0.03	0.20±0.02	4	0.89±0.20
Uniform[2]	2.4	5.80±1.8	2.91±0.5	2.35±0.2	1.49±0.2	0.10±0.01	0.08±0.02	0.05±0.01	7	0.0002[3]

[1] Högström et al. (1982).
[2] Miyake et al. (1970).
[3] As expected from Wieringa (1993).

The non-dimensional horizontal velocity standard deviations, $\sigma_{u,v}/u_{*l}$, at the height of 47 m significantly decrease with increasing surface roughness, while they increase at levels 120 and 280 m with the same magnitudes approximately over both the Uppsala urban and the water sites. This effect, of course, is due to the high surface roughness around the tower. At observational level 47 m ($z/\overline{\overline{z_{\rm H}}} = 4.4$ if $\overline{\overline{z_{\rm H}}}$=10.6 m) across all wind directions, the values of $\sigma_{u,v}/u_{*l}(= 2.27 \pm 0.3, 2.35 \pm 0.3)$ are similar to the corresponding ones (2.32±0.16, 1.81±0.2) reported by Roth (2000) for urban surfaces when $z/z_{\rm H} > 2.5$ (see his Table 4) with a slightly large value of $\sigma_{u,v}/u_{*l}$ in this study. Meanwhile, the $\sigma_{u,v}/u_{*l}$ values as an average of the three levels are very close to those observed by Högström et al. (1982) for the 27-m level in a neutrally stratified urban atmosphere of central Uppsala (see Table 3), and larger than the mean values of 2.4 and 1.91 reported by Roth.

As demonstrated in Table 3, the order of non-dimensional three-velocity components $\sigma_u/u_{*l} > \sigma_v/u_{*l} > \sigma_w/u_{*l}$ observed remains valid above roughness elements near to the levels 120 and 280 m with the same characteristics over the uniform site given by Miyake et al. (1970), but it is quite different at the lowest measurement level of 47-m near the roughness elements, whereas the value of the σ_v/u_{*l} ratio is larger than that of σ_u/u_{*l}. The difference between the ratio values of σ_u/u_{*l} and σ_v/u_{*l} is significantly smaller, indicating an increased transverse component of the urban turbulence. The σ_v/u_{*l} values were also found to be larger in some studies over urban and complex surfaces. For example, Högström et al. (1982) reported that $\sigma_u/u_{*l} \approx \sigma_v/u_{*l}$ at the 8-m height in the city of Gränby, Uppsala, and $\sigma_u/u_{*l} \geqslant \sigma_v/u_{*l}$ was observed at the Heihe River Basin, Gansu Province, Western China by Al-Jiboori et al. (2001) when the substantial and abrupt changes in the surface roughness are. As the same order of the σ_w/u_{*l} values at all measurement levels in this study and over different surfaces is observed as shown in Table 3, they are independent of the surface roughness.

The values of turbulence intensity defined as the standard deviations of the three components of velocity divided by the mean wind speed, $\sigma_i/\bar{u}$, are found to be greater at the 47-m measurement height and smaller at the upper measurement 120- and 280-m heights. When making the average for the quantities $\sigma_i/\bar{u}$ over the three levels, their values become very similar to those of the urban surface of Uppsala, and then these values for both sites are larger than those observed over a uniform site (see Table 3).

Similar to the discussion for the order of σ_i/u_{*l} demonstrated above, the order of $\sigma_u/\bar{u} > \sigma_v/\bar{u} > \sigma_w/\bar{u}$ is right at the 120- and 280-m heights as well as over the uniform and central Uppsala city surfaces observed by Miyake et al. (1970) and Högström et al. (1982), respectively, but this order is different at the lowest 47-m level of the measurement layer adjacent to the roughness elements, where $\sigma_v/\bar{u} \geqslant \sigma_u/\bar{u}$, with the remaining $\sigma_w/\bar{u}$ valid at the end of the order (see Table 3). This indicates that turbulence intensity near the roughness elements is also influenced.

From the above discussion, it can be concluded that the urban turbulence characteristics in the lower part of the measurement layer of the tower are significantly influenced by high surface roughness elements and are different from those characteristics in the upper part of the measurement layer in which the air flows away from these elements. Therefore, atmospheric turbulence characteristics at high enough heights over urban surfaces seem to have similar behaviour approximately to that observed over flat surfaces. This is evident from a comparison of the values of σ_i/u_{*l} and $\sigma_i/\bar{u}$ at the level 280 m to those observed over a uniform surface.

A few studies have been published that are concerned with the surface roughness length effects on

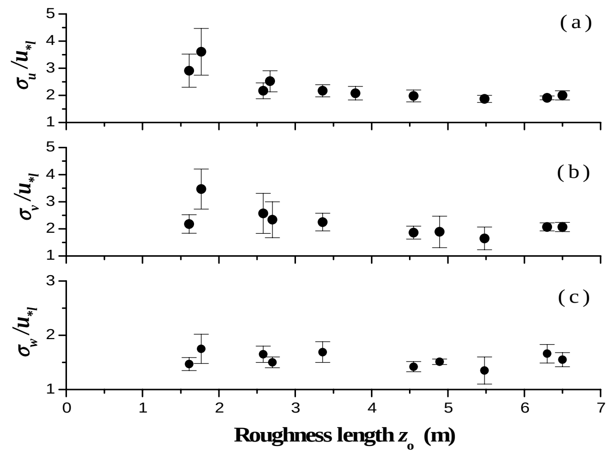

Fig. 5. Variation of $\sigma_i/u_{*l}, (i = u, v, w)$, with surface roughness lengths z_0.

urban turbulence levels in terms of the normalized three-component velocity standard deviations, σ_i/u_{*l}. The reason is that the adequately large z_0 estimates as well as a deficit analysis in yielding several values of z_0 according to wind direction conditions, especially in inhomogeneous surfaces of urban areas, are not available in most studies. There is still a controversy in the literature on the behaviour of σ_i/u_{*l} as a function of surface roughness. However, the observed decrease in σ_i/u_{*l} with increasing roughness lengths was found by several authors (e.g., Duchêne-Marullaz, 1979; Clarke et al., 1982; Yersel and Goble, 1986). In contrast, Roth (2000) could not confirm this behaviour in the review of summarized observations from other studies.

Since a large number of 15-min observations under different wind directions was available in this study (see Table 1), the values of σ_i/u_{*l} for the two measurement levels 47 and 120 m were divided into groups in which the variability (standard deviation) of individual point data is shown with an error bar. These values with the corresponding urban z_0 values derived by fast-response anemometries are presented in Fig. 5. The influence of the z_0 increase on the horizontal velocity standard deviations $\sigma_{u,v}/u_{*l}$ is obvious in Figs. 5a and 5b, with a little scatter in the v-component. Meanwhile, the increase in z_0 does not influence the normalized vertical component σ_w/u_{*l} (see Fig. 5c), which is approximately constant about the value 1.55, the same as that reported in Table 3.

6. Conclusions

Measurements under neutral conditions obtained from slow- and fast-response anemometers placed on a 325-m tower at levels 47 and 120-m, and detailed inventories for the basic information about irregularly distributed obstructions around the tower site as a first-order approximation, have been used to determine roughness length parameter and morphometry-based displacement height. The main results obtained from this study are summarized in the following.

(1) Comparing the z_0 estimates with each other, the slow-response method gave lower values in the range of 2.5–3.4 m.

(2) The variability in urban roughness lengths strongly depends on spatially directional variations of roughness elements and changes in the upwind fetch. This implies that instead of fixed roughness-length values, a variable roughness length is more appropriate for a given area in the atmospheric model (as others have found).

(3) Increasing surface roughness length affects the non-dimensional standard deviation of horizontal velocity, but the case is different for that of vertical velocity.

(4) The differences between mean values of σ_u/u_{*l} and σ_v/u_{*l}, and of $\sigma_u/\bar{u}$ and $\sigma_v/\bar{u}$ for the lowest 47-m level were found to be smaller than the corresponding values at the upper measurement levels of 120 and 280 m and for a uniform surface. This means that the atmospheric turbulence at high levels over a urban cities behaves roughly the same as that over a uniform surface, while turbulence adjacent to the surface roughness elements is strongly influenced by them.

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