6B.2 OBSERVATIONAL VERIFICATION OF URBAN SURFACE ROUGHNESS PARAMETERS DERIVED FROM MORPHOLOGICAL MODELS

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1. Introduction

In numerical simulation on urban areas, the two aerodynamic parameters (the roughness length, z_0, and the zero-plane displacement, z_d) are essential to represent properly the impacts of urban areas on weather and climate. However, so far, the determination of z_0 and z_d in urban areas has often been inadequate for use in numerical models (Grimmond and Oke, 1999).

Methods to determine z_0 and z_d can be generalized into two classes of approaches (Grimmond and Oke, 1999):

1) Morphological methods that relate aerodynamic parameters to measures of surface morphology, and

2) Anemometric methods that use field observations of wind and turbulence to solve for aerodynamic parameters included in theoretical relations derived from logarithmic wind profile (namely, the Monin-Obukhov similarity theory, hereinafter the MOS theory).

Morphological methods have the advantage that the values can be determined from the database of the distribution of roughness elements. Based on a Geographic Information System (GIS), a detailed database of urban surface elements can easily be obtained, and the values of z_0 and z_d can then be calculated for any direction surrounding the site of interest. However, these methods have the disadvantage that most are based on empirical relations derived from wind tunnel experiments that concern idealized flows over simplified arrays of roughness elements. In these simulations the flow is often relatively constant in direction, typically normal to the face of the elements, and the array is often regularly spaced. These conditions differ from those in real cities, where wind direction is ever changing and, even if the street pattern is relatively regular, the size and shape of individual roughness elements (buildings and trees) are variable. The performances of morphological methods in real cities need to be examined.

Wind-based methods have the advantage that the characteristics of the surface do not need to be specified. Grimmond and Oke (1999) reviewed more than fifty studies that provide anemometrically-based estimates of roughness parameters in cities. Unfortunately, only a few studies were found to be acceptable. Grimmond *et al.* (1998) analyzed the roughness parameters of urban areas derived from wind observations. The z_0s were derived from both slow-response and fast-response anemometry, while the z_d s were only derived from fast response anemometry. The results were not satisfactory and Grimmond *et al.* found there is no clear best choice of anemometric methods to determine roughness parameters. Actually, there exists inherent disadvantage in the anemometric methods they

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employed. Calculating the z_0 needs the z_d to be known, while the formula to estimate z_d has empirical coefficients. It is possible to fit the values to obtain the coefficients using the observed data, but in order to do this a value of z_d must be assigned. This is a circular argument which only generates the initially assigned value of z_d. On the other hand, it is difficult to find a satisfactory measurement site in a developed city to collect high-quality data.

Grimmond and Oke (1999) reviewed a series of morphological models and compared the values to the *in situ* measurement results. They found there is poor statistical agreement between even the highest-quality measurements and morphological estimates of roughness parameters for cities. How to verify the values derived from the morphological methods seems problematic and needs to be investigated further.

In our opinion, the z_d should be estimated from morphological models since the logarithmic wind profile is not sensitive to it, and the z_0 can then be estimated from anemometrical methods. The problem is how to verify the accuracy of the estimated roughness parameters in a proper way. For this purpose, we used anemometrical observation data, which were collected in a densely built-up area of Nanjing, China, in the summer and winter, to examine the morphological estimates of roughness parameters. The aims of this study are (1) to determine whether the MOS theory for the shear profile of wind speed is applicable to the urban surface layer, especially the roughness sublayer, and (2) to investigate how to verify the roughness parameters derived from morphological models.

2. Methodology

2.1 *About the MOS theory*

Although the applicability of the MOS theory is still questioned, it is often used in modeling the turbulent transfer statistics in urban boundary layers. Recently, Moriwaki and Kanda (2006) analyzed the shear profiles of momentum and heat using the data measured above an urban canopy. They proposed a scaling velocity ($u_* = (-\overline{u'w'})^{1/2}$, u_* is friction velocity, $-\overline{u'w'}$ is momentum flux) at the roof level, which is equivalent to 'surface' friction velocity. The results showed that the mean wind speed profile in the urban surface layer (including the roughness sublayer) followed a conventional stratified logarithmic profile when it is scaled by the 'surface' friction velocity. That is,

$$\frac{\bar{u}}{u_*} = \frac{1}{\kappa}\left[\ln\left(\frac{z - z_d}{z_0}\right) - \psi_m\left(\frac{z - z_d}{L}\right)\right] \tag{1}$$

and

$$u_* = (-\overline{u'w'}_{z=z_h})^{1/2} \tag{2}$$

where κ, the von Karman constant, equals 0.4; z is the sensor height; z_h is the mean building height; *L* is the Monin-Obukhov length; and ψ_m is an empirical function that is associated with the atmospheric stability (Businger et al., 1971; modified after Högström, 1988).

In this study, the shear stress $-\overline{u'w'}$ was measured at the level just a few meters above the mean building height, and the horizontal wind speeds were measured at three levels. The lowest level is at about $z/z_h = 1.5$. Since at this level z' ($z' = z - z_d$) is much smaller in comparison with the Monin-Obukhov length, it is assumed that the effect of ψ_m can be neglected ($\psi_m \approx 0$).

This above assumption appears reasonable and is supported by the measurement data. The observation results in Figure 2 (see Section 4) show that there are no indications of significant diurnal and seasonal variations of the values of $u_* / \overline{u}$, and the mean values show that they are not influenced obviously by stratification conditions. This result supports the argument that turbulence is dominantly produced by the mechanical process in the urban roughness sublayer when the wind speed is not very small, and thus it is reasonable to assume that the turbulent statistics behave well in terms of near-neutral stratification conditions.

In addition, this assumption is also supported by the other urban measurement data. In Figure 4 of Moriwaki and Kanda (2006), it can be seen that the logarithmic curve for neutral conditions almost coincides with the two others for stable and unstable conditions at the lower height. In other words, the differences of the turbulent statistics between the three stratification conditions are very small in the lower part of the urban roughness sublayer. This is the second reason for the assumption that the effect of the stability term in Equation (1) can be neglected.

We here prefer to use the dimensionless friction velocity, and it can be expressed as follows:

$$\frac{u_*}{\overline{u}_1} = \kappa \Big/ \ln\left(\frac{z - z_d}{z_0}\right) \qquad (3)$$

Here $\overline{u}_1$ is the mean wind speed at the first level of three levels of mean wind speed measurement. If z_d and z_0 are estimated from morphological models, the dimensionless friction velocity can be calculated according to the above equation, and then the values can be compared to the observationally-obtained counterparts. This is the verification method for the estimated roughness parameters.

2.2 *Morphological models*

The morphological methods used in the study are rule of thumb (Rt), Bottema (Ba) (Bottema, 1995), Macdonald (Ma) (Macdonald *et al.*, 1998) and Raupach (Ra) (Raupach, 1994, 1995) methods. The morphological models considered here are far from exhaustive. Grimmond and Oke (1999) are inclined to suggest that the methods of Ba, Ma, and Ra are the best, so verifications in the present research focus on these methods, which are applied to estimate the roughness parameters.

2.3 *Fetch/Source area*

Roth (2000) reviewed atmospheric turbulence over cities, and concluded that the extreme heterogeneity of urban surfaces, usually at all scales, makes the definition of a uniform fetch (or a source area) impossible, while the results on integral statistics suggest the existence of strong similarities between turbulent flows over cities and plant canopies. Thus, we use ‘local’ fetches (source areas) in this study. Based on the methods presented by Schmid (1994), and used by Grimmond and Oke (1999), the source areas for this study are determined. The source areas are set in a circle with a radius of 500 m centered on the observation site (Figure 1). The single source area is defined as an ellipse according to the wind direction, and the lengths of the major and minor axis of each source area are 500 m and 150 m respectively. Beginning with the direction due east as 90°, the major axes of the source areas are set anticlockwise with the interval of 15° in turn. Thus there are 24 source areas in total numbered 1, 2, 3, …, and 24.

3. Measurement site and data processing

The atmospheric boundary layer field observation campaign was carried out twice in Nanjing. The durations were from July 17 to 27, 2005 (summer) and from February 17 to March 6, 2006 (winter). The observation site in the urban area was on the rooftop of a building (32.04° N, 118.79° E). The height of the building is 22 m. The observation yard is the flat rooftop made of cement concrete materials. Typical residence and business districts are within the radius of 1 km around the observation site. Buildings stand densely in the districts. The mean height of the buildings within the radius of 500 m around the observation site is 19.7 m (Figure 1). The buildings and streets occupy about 70% of the total surface area. *In situ* investigations were carried out to collect information about the height and orientation of each building in the study area. The length, width and coordinate information of the buildings were obtained through a GIS (Geographical Information System).

The radiation, turbulence, temperature and mean wind were observed at the urban site. The three-dimensional wind speed fluctuations, virtual temperature, water vapor and carbon dioxide content in the air were measured. The sensor height is 2.2 m above the building rooftop. There is a 36 m tower on the building rooftop. On the tower mean wind speed, wind direction, temperature, humidity and pressure were measured at the height of 8.5 m, 15.2 m, and 27.7 m above the building rooftop. During the two observation periods, some data missing or incorrect were removed in the calculations.

The mean wind speed $\bar{u}$ was calculated over a period of 10 min through the mean wind observation data. The friction velocity u_* was calculated according to Equation (2) over a period of 10 min through the time series of the turbulent wind speed fluctuations. The dimensionless friction velocity was then calculated.

4. Results and discussions

Figure 2 is the temporal variation of the observationally-obtained dimensionless friction velocity at the first level (i.e. z = 30.5 m). The data of the mean wind speed with values less than l m s^{-1} have already been removed. It is shown in the figure that the mean value and standard deviation of the dimensionless friction velocities keep 0.20 ± 0.02 both in summer and winter. The patterns of the temporal variations of dimensionless friction velocity at the second and third level (i.e. z = 37.2 m and 49.7 m) are almost same as at the first level, while the standard deviations are slightly decreased (the results are not shown). Moreover, there are no indications of significant diurnal and seasonal variations of the dimensionless friction velocities, and the mean values show that they are not influenced obviously by stratification conditions. This result supports the argument that the turbulence is dominantly produced by the mechanical process in the urban roughness sublayer when the wind speed is not very small. According to Equation (3), the dimensionless friction velocities should only depend on height, so long as the observation period is not very short. It can be expected that the thermal effect will increase with height above the roughness sublayer (Figure 4 of Moriwaki and Kanda, 2006). However, as compared in Figure 3, when the wind speed is small, the fluctuations of dimensionless friction velocity increase significantly, and the statistical characteristic becomes unsteady. This might explain the existence of relatively large fluctuations in the first day of Figure 2b. Although the data with mean wind speed less than 1 m s^{-1} have already been removed, the strong oscillations of mean wind speed still influence the statistical characteristic of the flow.

Figure 4 shows the results of the surface roughness parameters calculated with the morphological models in each source area. It can be seen that each source area has a different z_d and z_0. The variation of roughness parameters is induced by different wind direction, and can be interpreted as the heterogeneity of distributions of roughness elements. It can also be seen that the differences between the roughness parameters derived from the four morphological models are not very small. On average, the Rt approach estimates the highest z_d, and the Ba approach estimates the lowest z_d, while the Ba approach estimates the highest z_0, and the Ra approach estimates the lowest z_0. The values of z_0 over z_d are calculated and shown in Figure 5. The biggest values are from the Ba approach, and the smaller values are from the Rt approach. For the existing buildings, the mean height is fixed. It can be empirically thought that, when the z_d is relatively large, the z_0 should be relatively small since less of the buildings above the z_d are portioned to the roughness elements. This situation is consistent with the relationship of z_d and z_0 described in Equation (3). In this context, the Ra approach gives acceptable middle values, while the Ma approach seems to have underestimated the z_0.

Figure 6 is the comparison between the observational results and morphological results. All the dimensionless friction velocities were calculated according to their corresponding source areas. For the observationally-obtained dimensionless friction velocities, the mean wind speed at the first level (i.e. z = 30.5 m) was used. In each source area, their mean value and standard deviation were calculated through all the dimensionless friction velocities within the same source area (i.e. within a certain range of wind directions). The morphologically-obtained dimensionless friction velocities were calculated with Equation (3) in each source area.

Figure 6 indicates that in most of the source areas the morphological results are in good agreement with the observational results. The overall differences between them are small. Most of the morphological results fall into the range of the standard deviations of the observational results. It proves that Equation (3) is valid and applicable as long as the wind speed is not smaller than 1 m s^{-1} and the observation period is not shorter than one week. The dimensionless friction velocities obtained from different morphological methods are not very different. Their deviations from the observational results are listed in Table I. The biases of the Rt, Ba and Ra approaches are almost the same. This situation is due to the correlation of estimated values, in which larger z_d accompanies smaller z_0, and they complement each other in calculation of dimensionless friction velocity according to Equation (3). That is to say, the logarithmic method can not distinguish which is the better one between Rt, Ba and Ra. However, the Ma approach produces the largest bias. Since the logarithmic method is more sensitive to z_0 than to z_d, this result supports the argument that the Ma approach underestimates the z_0.

5. Summary

A densely built-up urban area was divided into 24 source areas, and four morphological methods are applied in each source area to obtain the zero-plane displacement (z_d) and roughness length (z_0).

The turbulence and mean wind data in the urban roughness sublayer were used to calculate the observational dimensionless friction velocities. The dimensionless friction velocities do not demonstrate significant diurnal and seasonal variation characteristics. Their mean value over a long time keep a constant, and the standard deviation is small, indicating the dimensionless friction velocities are steady and not significantly changing with the time.

Based on the observations and the similarity theory in the urban roughness sublayer, a simple dynamical method is proposed to verify the morphological estimates of z_d and z_0, with which the calculated dimensionless friction velocities are directly compared to the observational data. Unlike some recent methods (e.g. Martano, 2000), there are *no priori* constants or undecided parameters in this method. Compared to previous studies, in which the method was applied in the inertial sublayer and limited to neutral conditions (Grimmond *et al.*, 1998; Rooney, 2001), there is no restriction and assumption on stratification conditions in the present study.

The four morphological methods recommended by Grimmond and Oke (1999) are verified, and the results show that they are not very different from each other. A good performance of the rule of thumb (Rt) method may be due to the fact that the distribution of buildings in the study area is regular. The Bottema (Ba) and Raupach (Ra) methods are likely to be better since they can give reasonable estimates of roughness parameters. Evidence indicates that the Macdonald (Ma) method underestimates the z_0.

For further evaluation of morphological approaches, the proposed method needs more available data, which can cover a wide range of roughness parameters. Actually, the logarithmic method can only give the relationship between z_0 and z_d. Sufficient data from different cities, with relatively large differences of z_0 and z_d, can help us determine whether the limited relationship is well obeyed or not, which could be the criterion of the accuracy of the estimated roughness parameters.

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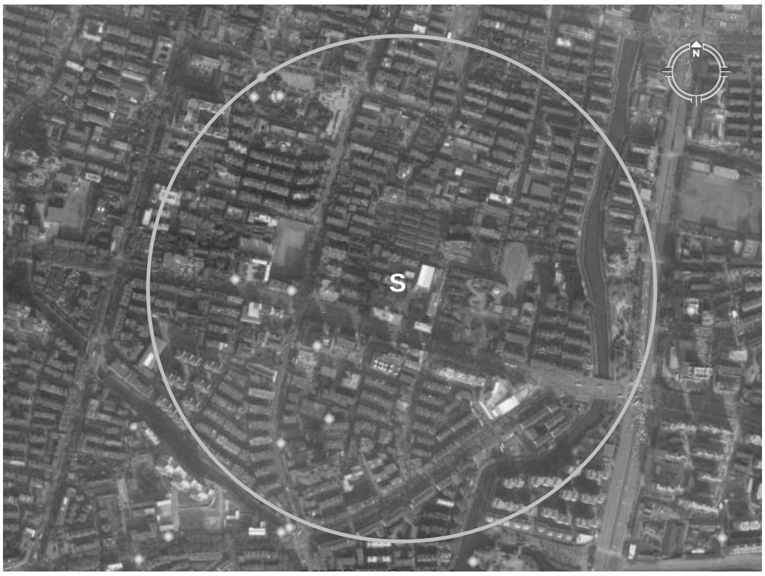

Figure 1 Aerial photograph of the study area. The centre of the circle is the observation site marked ‘S’. The radius of the circle is 500 m.

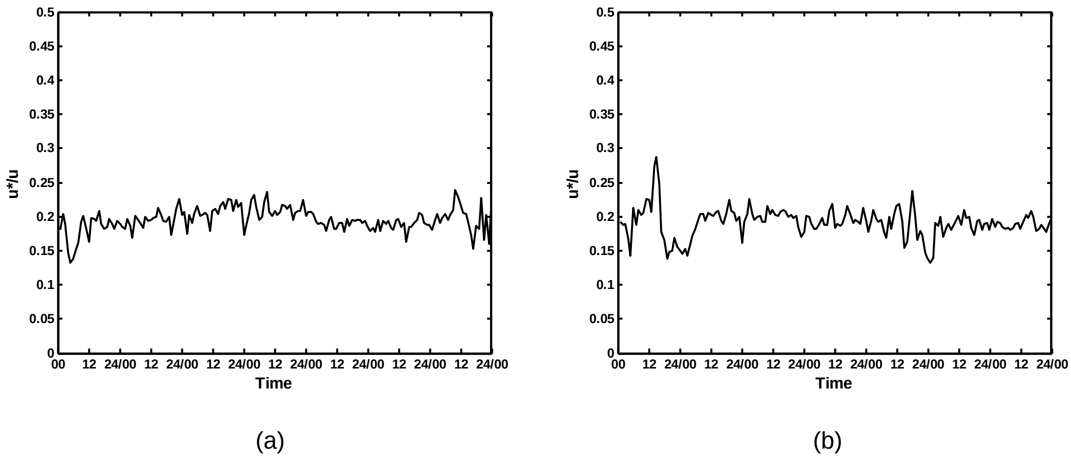

Figure 2 The temporal variation of the hourly-averaged dimensionless friction velocity obtained from the observations. The mean wind speed at the 1st level (z = 30.5 m) was used. (a) July 17, 0000 ~ July 23, 2400, 2005 (LST = UTC + 8). The mean value and standard deviation are 0.20 ± 0.02; (b) February 21, 0000 ~ February 27, 2400, 2006 (LST). The mean value and standard deviation are 0.20 ± 0.02.

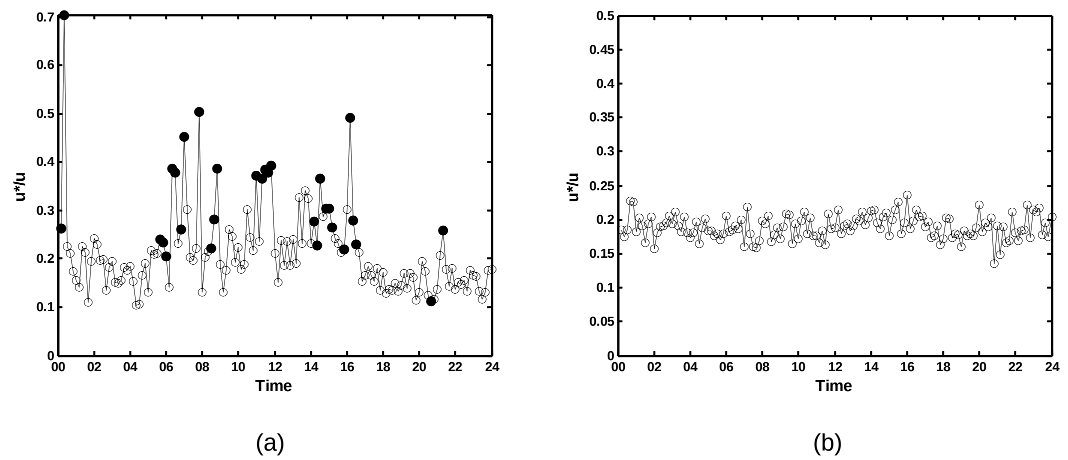

Figure 3 The temporal variation of the 10-minute-averaged dimensionless friction velocity obtained from the observations. The mean wind speed at the 1st level (z = 30.5 m) was used. The black dots represent the mean wind speed is less than 1 m s^{-1}; the circles represent the mean wind speed is not less than 1 m s^{-1}. (a) February 21, 0000 ~ 2400, 2006 (LST = UTC + 8); (b) February 27, 0000 ~ 2400, 2006 (LST).

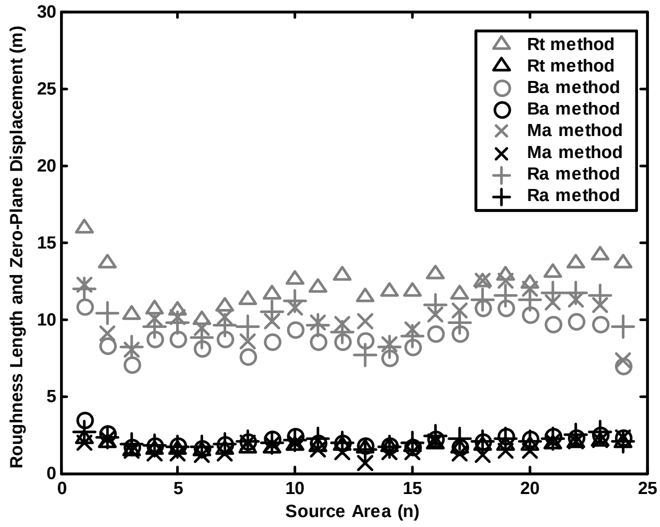

Figure 4 The z_d and z_0 of the urban area calculated with the morphological methods. The gray fonts represent the z_d; the black fonts represent the z_0.

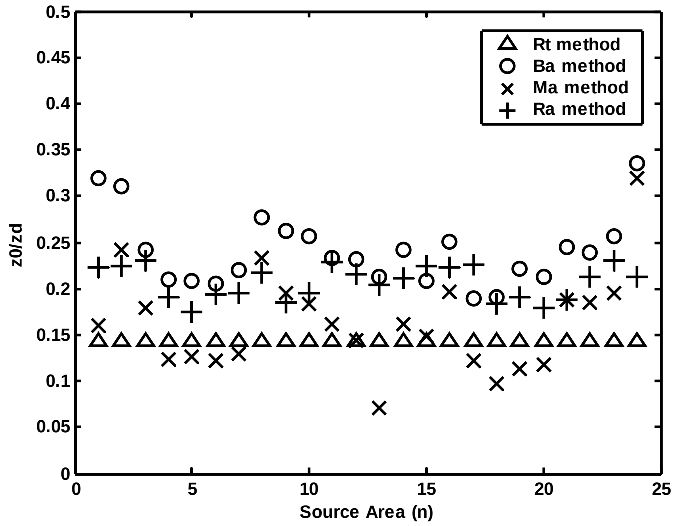

Figure 5 Values of z_0 over z_d

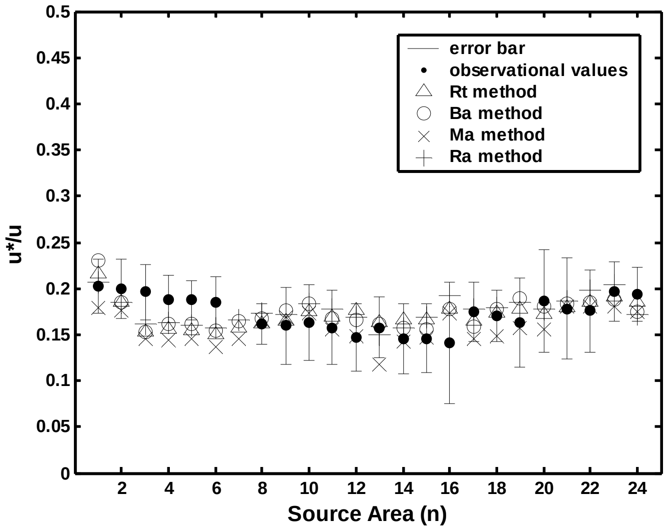

Figure 6 The observationally-obtained dimensionless friction velocities compared to the morphologically-obtained counterparts. The periods are July 17-23, 25 and 26, 2005; February 17, 19-27 and March 4-5, 2006 (LST = UTC + 8).

Table 1 Mean absolute bias between the observationally-obtained dimensionless friction velocities and the morphologically-obtained counterparts

Morphological model	Rt	Ba	Ma	Ra
Mean absolute bias	0.017	0.017	0.020	0.018

Note: The mean absolute bias is $\frac{\sum |y_{mo} - y_{ob}|}{N}$. Here y_{mo} is the morphological value; y_{ob} is the observational value; the summator represents the summation over all active source areas; N is the total of active source areas (N = 23, since no wind blew from the 7th source area).