Study of Aerodynamic Parameters on Different Underlying Surfaces*

MAO Yuhao\textsuperscript{1,2}\textsuperscript{1}(茅宇豪), LIU Shuhua\textsuperscript{1,2}\textsuperscript{2}(刘树华), ZHANG Chenyi\textsuperscript{2}\textsuperscript{2}(张称意), LIU Lichao\textsuperscript{3}\textsuperscript{3}(刘立超),
and LI Jing\textsuperscript{1,2}\textsuperscript{2}(李 婧)

1 Department of Atmospheric Sciences, School of Physics, Peking University, Beijing 100871
2 Laboratory of Climate Research, National Climatic Center, China Meteorological Administration, Beijing 100081
3 Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000

(Received January 6, 2007)

ABSTRACT

Aerodynamic parameters including the zero-plane displacement ($d$), roughness length ($z_0$), and friction velocity ($u^*$) on the different underlying surfaces of heavy-grazing site, medium-grazing site, light-grazing site, no-grazing site, dune, inter-dune, grassland, rice paddy site, wheat site, soybean site, and maize site have been computed based on the Monin-Obukhov similarity theory by utilizing the micrometeorologically observed data of dune and vegetation in the semi-arid area at Naiman, Inner Mongolia of China, conducted jointly by the Institute of Desert Research, Chinese Academy of Sciences and the National Institute of Agro-Environmental Sciences of Japan in 1990-1994. And their relationships between wind speed and Richardson number are analyzed. The aerodynamic characteristics of different man-made disturbed grassland ecosystems are also compared. Result shows that the vegetation coverage and the above-ground biomass decrease with the increase in man-made stress of the grassland. The roughness length for different underlying surfaces is closely related to vegetation height, above-ground biomass, and ground surface undulation, and Richardson number $R_i$ is also its influencing factor. The friction velocity varies largely on different underlying surfaces, and it is positively proportional to wind speed and roughness length. The aerodynamic parameters of various times on the same underlying surface are different, too. Above results indicate that grassland and vegetation are of significance in preventing desertification, especially in the arid and semi-arid land ecosystems. And the results of this paper are also important for constructing the land surface physical process as well as regional climate model.

Key words: different underlying surfaces, aerodynamic parameter, different man-made disturbed grassland ecosystems

1. Introduction

The mutual transport of physical quantities between land surface and atmospheric boundary layer is some complex geophysical processes, which vary evidently on different underlying surfaces and form different weather and climate phenomena. Therefore study of every kind of process on land surface becomes extremely important (see Stull, 1988; Wieringa, 1993; Masao, 1997; Thom, 1972). The vegetation and aerodynamic characteristics on land surface directly affect the transport of energy and substances between land surface and atmosphere boundary layer, as well as the regional environment and climate. Then how to compute and analyze aerodynamic parameters accurately becomes a key problem to establish the land surface physical processes. However, aerodynamic parameters were always computed and analyzed on one kind of homogeneous underlying surface (see Liu, 1989; Liu et al., 1997). There were only a few studies about characteristics of aerodynamic parameters on different underlying surfaces (see Gao et al., 2000; Sadani and Kullarni, 2001), especially on the different man-made disturbed ecosystems. And the studies of aerodynamic characteristics, simultaneously on the heavy-grazing site, medium-grazing site, light-grazing site,
no-grazing site, dune, inter-dune, grassland, rice paddy site, wheat site, soybean site, maize site underlying surfaces, were fewer in the world. In this paper, based on the Monin-Obukhov similarity theory, the zero-plane displacement \((d)\), roughness length \((z_0)\), and friction velocity \((u_*)\) have been computed by calculating the ultimate value of the maximum correlation of the five-level wind speed profiles on underlying surfaces. And their relationships between wind speed and Richardson number \((Ri)\) have been analyzed. The aerodynamic characteristics on the different man-made disturbed grassland ecosystems have been compared too. After these studies, we have obtained many significant results. These results could be used to compare the aerodynamic characteristics and transport of substances and energy on different man-made disturbed underlying surfaces. And they are also important to provide useful aerodynamic parameters for constructing land surface physical processes and the regional climate models (Liu et al., 2004).

2. Sites and measurements

2.1 Sites

The micrometeorological measurements were carried out in Naiman area of Inner Mongolia in China as the cooperative studies by Chinese Academy of Sciences and National Institute of Agro-Environmental Sciences of Japan from 1990 to 1994 (Yoshinobu et al., 1999). The climate of this region is classified as the semi-arid zone. The main kinds of underlying surfaces are dune, grassland, and agriculture fields. At sandy area, longitudinal dune spreads wavelikely from north-west to southeast that is created by prevailing wind. And the relative height of general dune is 5-15 m. The micrometeorological measurements were conducted at dune, inter-dune, grassland, four grazing experiment sites (light-, medium-, heavy-, and no-grazing sites), and four agriculture fields (soybean, wheat, maize, and rice paddy site) around Naiman Station of Desertification Research, the Institute of Desert Research, Chinese Academy of Sciences. Naiman Station (42°58′N, 120°43′E) is located about 15 km north of Naiman City, and altitude is 363 m. The detailed locations of each site are as follows:

2.1.1 Dune

The site is located on a dune, 1.9 km northeast from Naiman Station. The dune spreads about 400 m for each direction. There were few plants, and the vegetation coverage at the site was less than 5%. The vegetation height was approximately 0.05 m.

2.1.2 Inter-dune

In the sandy land, there exist hollows at lowlands among dunes. The hollow is 3-5 m lower than the surrounding dunes and extends over a distance of 100-500 m for both width and length. The measurements were conducted at one of the inter-dunes near Naiman Station. The vegetation coverage was more than 90% and the vegetation height was 0.6-1.2 m.

2.1.3 Grassland

The grassland observed in the study is categorized as meadow steppe. This grassland site extends over a distance of 500 and 350 m in north-south and east-west direction, respectively. At the measurement site, the vegetation height of the grass was less than 0.15 m, and the vegetation coverage and the above-ground biomass were 70%-80% and 100 g m\(^{-2}\) (dry weight).

2.1.4 Grazing experiment sites

Four different grazing strength sites were designed in the research and the longer side of the four rectangles was directed north-south for prevailing wind direction during the observation period. Each of the four areas was treated by different grazing densities (different sheep numbers in each area) from May 1992. The grazing strength of the areas was set as 6, 4, and 2 sheep hm\(^{-2}\), namely “heavy-grazing site”, “medium-grazing site”, and “light-grazing site”, respectively. No sheep area was named “no-grazing site”. The range of the vegetation height during the measurement period was 0.05-0.12, 0.2-0.3, 0.1-0.5, and 0.25-0.8 m for heavy-, medium-, light-, and no-grazing site, respectively.

2.1.5 Agricultural fields

1) Soybean site

The micrometeorological measurements were conducted at soybean fields of the no-irrigated fields 1.5-km northeast from the Naiman region. The no-irrigated field was about 40 m from north to south
and 250 m from east to west, and the canopy height was approximately 0.3 m.

2) Wheat site

In Naiman region, wheat was cultivated under irrigated condition. The observed field was about 0.5 hm² (100 m from north to south and 50 m from east to west). The canopy height was 0.08 m in early May and grew up to 0.85 m in July.

3) Maize site

Maize was normally cultivated at irrigated fields. The area extended more than 1.2 hm². The canopy height was 0.4 m and this field was surrounded by sandy land, which was sparse grassland or fixed dune.

4) Rice paddy site

The test field of the rice paddy was made at a dune beside Naiman Station using a plastic film sheet to prevent the penetration of water and fertilizer. The plastic film was laid 0.45-m depth at the bottom of the soil. The area of the test field was 600 m² and the water depth was kept at 0.1 m continuously. In the measurement period, the growing stage of rice at the site was beginning of the filling stage, and the average height of the canopy was about 0.95 m from the water surface.

2.2 Measurements

The instruments employed for observing temperature, humidity, and wind speed and their accuracy in the study are shown in Table 1. Measurements of air temperature and humidity were conducted at two or three heights of the measurement tower using several sensors. The cup anemometers were set at five heights above the canopy at the range of 0-5 m (agriculture fields: 0-5.6 m). The data were the average of half an hour. A typical setting of the sensor is illustrated in Fig.1.

<table>
<thead>
<tr>
<th>Measurement term</th>
<th>Instruments</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Type-T thermocouple thermometer</td>
<td>±0.1°C</td>
</tr>
<tr>
<td></td>
<td>Platinum resistance thermometer</td>
<td>±0.5°C (10-40°C)</td>
</tr>
<tr>
<td></td>
<td>HU-1A, NORTH HIGHTECH Co., Ltd., Tokyo</td>
<td>±0.3°C (25°C, 30%-90%)</td>
</tr>
<tr>
<td>Humidity</td>
<td>Electrostatic capacitive humidity sensor</td>
<td>±3% (1-10 m s⁻¹)</td>
</tr>
<tr>
<td>Wind speed</td>
<td>HU-1A, NORTH HIGHTECH Co., Ltd., Tokyo</td>
<td>±3% (1-10 m s⁻¹)</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Photo-electric cup anemometer</td>
<td>±3% (1-10 m s⁻¹)</td>
</tr>
<tr>
<td>Wind speed</td>
<td>AF750S, Makino Applied Instruments, Tokyo</td>
<td>±3% (1-10 m s⁻¹)</td>
</tr>
</tbody>
</table>

Fig.1. Schematic illustration of the setting of instruments.
3. Methodology

The most common way to determine the zero-plane displacement \( d \), roughness length \( z_0 \), and friction velocity \( u_* \) relies on the Monin-Obukhov similarity theory (MOST). The basic theory behind this approach is described by the wind profile equation adjusted for stability

\[
\phi_M\left(\frac{z-d}{L}\right) = \frac{k(z-d)}{u_*} \frac{\partial u}{\partial z},
\]

where \( u \) is the surface layer average wind speed \((\text{m} \text{s}^{-1})\) at height \( z \), \( k(=0.35) \) is von Karman’s constant (see Businger et al., 1971), \( d \) is the zero-plane displacement \((\text{m})\), \( \phi_M \) is the stability correction function for momentum, and \( L \) is the Monin-Obukhov length \((\text{m})\), which can be written as

\[
L = \frac{-\rho c_p T u_*^3}{g H}.
\]

where \( g \) \((=9.8 \text{ m} \text{s}^{-2})\) is the gravity acceleration, \( c_p \) \((=1005 \text{ J} \text{ kg}^{-1} \text{K}^{-1})\) is the specific heat of air at constant pressure, \( \rho \) is the density of air \((\text{kg} \text{m}^{-3})\), \( T \) is the temperature of the air \((\text{K})\), and \( H \) is the sensible heat flux \((\text{W} \text{m}^{-2})\).

Integrating Eq.(1), we obtain the logarithmic wind profile equation

\[
\frac{ku}{u_*} = \ln\left(\frac{z-d}{z_0}\right) - \psi_M(\zeta),
\]

let \( \zeta = \frac{z-d}{L} \) and \( z_0 = \frac{z_0}{L} \). And \( \psi_M(\zeta) \), the stability correction function of the logarithmic wind profile, is expressed as

\[
\psi_M(\zeta) = \int_{\zeta_0}^{\zeta} [1 - \phi_M(\zeta')] d\ln\zeta'.
\]

In this paper, we choose the forms of \( \phi_M(\zeta) \) suggested by Businger—Dyer—Webb (see Businger et al., 1971; Dyer and Hicks, 1970; Dyer, 1974; Webb, 1970),

\[
\phi_M = \begin{cases} 
(1 - 16\zeta)^{-1/4} & \zeta \leq 0 \\
1 + 5\zeta & \zeta > 0.
\end{cases}
\]

The relationship between \( \zeta \) and Richardson number \( (R_i) \) can be expressed as follows

\[
\zeta = \begin{cases} 
R_i & R_i \leq 0 \\
\frac{R_i}{(1 - 5R_i)} & R_i > 0.
\end{cases}
\]

In calculation, Richardson number \( (R_i) \) is defined as

\[
R_i = \frac{g \frac{\partial T}{\partial z}}{T (\frac{\partial u}{\partial z})^2}.
\]

From Eqs.(4) and (5) (see Businger et al., 1971; Dyer and Hicks, 1970), we get

\[
\psi_M = \begin{cases} 
2\ln\left(\frac{1+\zeta}{2}\right) + \ln\left(1 + \frac{1+\zeta^2}{2}\right) - 2\arctan\zeta + \frac{\pi}{2} & \zeta \leq 0 \\
-5\zeta & \zeta > 0.
\end{cases}
\]

where \( x = (1 - 16\zeta)^{1/4} \).

Rearranging Eq.(3), we get the following equation for each run and each level,

\[
\ln(z_{ij} - d) = \frac{k}{u_{*i}} u_{ij} + \ln z_0 + \psi_M(\zeta),
\]

where the subscript \( i \) indicates the run number \((i = 1,2,3,\ldots,I)\) and the subscript \( j \) denotes the level number \((j = 1,2,3,\ldots,J)\).

Mean square deviation \( P \), according to Thom (1972), is then defined as follows:

\[
P = \frac{1}{N} \sum_{i=1}^{I} \sum_{j=1}^{J} \left\{ \ln(z_{ij} - d) - \frac{k}{u_{*i}} u_{ij} - \ln z_0 - \psi_M(\zeta) \right\}^2.
\]

where \( N = I \times J \), the total number of used wind data. If value \( d \) is explicitly given, the necessary conditions where Eq.(10) has a minimum value are written as

\[
\frac{\partial P}{\partial a} = 0,
\]

\[
\frac{\partial P}{\partial b_i} = 0,
\]

where \( a = \ln z_0 \) and \( b_i = k/u_{*i} \).

Equations (11) and (12) can be written as

\[
\begin{bmatrix} N \\ \sum_{i=1}^{I} \sum_{j=1}^{J} u_{ij} \end{bmatrix} = \begin{bmatrix} a \\ b_i \end{bmatrix} - \begin{bmatrix} \sum_{i=1}^{I} \sum_{j=1}^{J} (\psi_M(\zeta) - \ln(z_{ij} - d)) \\ \sum_{i=1}^{I} \sum_{j=1}^{J} (\psi_M(\zeta) - \ln(z_{ij} - d)) u_{ij} \end{bmatrix}.
\]
When we find a maximum value of the correlation coefficient $R$ within a reasonable range of $d$, the solutions of $d$, $u_{si}$, and $z_0$ will be obtained.

The correlation coefficient $R$ is defined as follows:

$$R = \frac{(y_{ij} - \bar{y}_{ij})(Y_{ij} - \bar{Y}_{ij})}{\sqrt{(y_{ij} - \bar{y}_{ij})^2 \sqrt{(Y_{ij} - \bar{Y}_{ij})^2}},$$

where $y_{ij} = \frac{ku_{ij}}{u_{si}} + \psi_M(\zeta)$, $Y_{ij} = \ln\left(z_{ij} - d_{z_0}\right)$, and the values of $d$, $u_{si}$, and $z_0$ can be obtained from Eq.(13).

4. Results and discussions

The profiles of the diurnal average wind speed on different underlying surfaces are given in Fig.2, which include different man-made disturbed grassland ecosystems, dune and grassland ecosystems, and four different agricultural fields. The profiles of wind speed are smooth, showing an outward curving form because of the instability of atmospheric stratification, which is favorable to turbulence and transfer of the energy.

The wind speed decreases rapidly under the vegetation canopy. The observation of the wind speed sets at five layers from 30 to 560 cm, which is not consistent on different underlying surfaces because of the discrepancy of the canopy heights.

A linear relationship between the normalized wind speed and $\ln(z-d)$ is obtained in Fig.3 (see Villani et al., 2003), which is in accord with the Monin-Obukhov similarity theory. From the data, we know that the above-ground biomass, vegetation coverage, and canopy height are closely related with man-made disturbance. The above-ground biomass and vegetation coverage obviously decrease with the increase in the grazing stress, which causes the smaller roughness length (see Yoshinobu et al., 1999). In different man-made disturbed grassland ecosystems, the slope of the normalized wind speed enhances with the grazing strength (Fig.3a). At the same height, the normalized wind speed is higher at medium and heavy grazing sites with the small vegetation biomass.

![Fig.2. Profiles of the average wind speed on different underlying surfaces. (a) Different grazing sites (no-grazing site, 1994-06-10; light-grazing site, 1993-06-24; medium-grazing site, 1994-08-23; heavy-grazing site, 1994-06-02); (b) dune and grassland sites (grassland, 1991-06-21; dune, 1993-07-09; inter-dune, 1991-07-20, 21); and (c) different agricultural fields (rice paddy site, 1993-08-15, 16; maize site, 1994-06-15, 17; wheat site, 1991-06-02; soybean site, 1993-08-10).](image-url)
The wind speed profile is steeper on dune (Fig.3b), and it becomes larger just above the surface. These facts reflect the high temperature in the daytime, which strengthens the vertical turbulence. In contrast, the wind speed at the grassland site is smaller. Because of the underlying surface undulation, the value of the roughness length on inter-dune site is larger than that of dune. Among four different agricultural fields (Fig.3c), the wind speed profile is smoother on the soybean site with the lower canopy height and smaller roughness length. On the other hand, the canopy height is larger on the rice paddy site, and thus the wind speed profile is steeper. The results are in accord with different man-made disturbed grassland and dune-grassland ecosystems.

Zero-plane displacement \((d)\) and roughness length \((z_0)\) are in an obvious relation to Richardson number \(R_i\) that \(z_0 + d\) increases linearly with the atmospheric stability (Fig.4). Zero-plane displacement and roughness length are the ultimate value of the maximum correlation by utilizing the wind speed profile of five levels. The correlation coefficient can reach 0.99 with stability correction on every underlying surface. Stull (1988) summarized the roughness length with a range of 0.01-0.1 m on the agricultural fields and grassland, and our results are in accordance with it. The values of \(z_0 + d\) are smaller under unstable condition \((R_i < 0)\) and neutral condition \((R_i = 0)\) than that under the stable atmospheric stratification \((R_i > 0)\). The probable reason is that: under unstable condition, the wind speed is always large (see Chen et al., 1993) and turbulence transport is strong, which causes the momentum easy to transfer downward; under neutral condition, the momentum is also easy to transfer downward because of the gale, though the turbulence transport is weak. But when the atmospheric stratification is stable, \(z_0 + d\) is large (see Liu, 1989; Hikaru et al., 2005), due to the small gust and weak turbulence transport. The value of \(z_0 + d\) at the heavy grazing site is conspicuously smaller than that at the other three light grazing sites, which is in accordance with the result we have got before.

As we can see from Fig.5, there is an obvious relation between \(z_0 + d\) and the dimensionless wind speed \(U\), which is the ratio of the wind speed at the highest level to the fourth height from the top. We get an inflexion (defined as \(u_0\)) at the dimensionless wind speed of about 1.5 m s\(^{-1}\). Less than it, the
Fig. 4. The relationships between $z_0 + d$ and $R_i$ on different underlying surfaces. (a) No-grazing site, 1994-06-10; (b) light-grazing site, 1993-06-24; (c) medium-grazing site, 1994-08-23; (d) heavy-grazing site, 1994-06-02; (e) grassland, 1991-06-21; (f) dune, 1993-07-09; (g) inter-dune, 1991-07-20, 21; (h) rice paddy site, 1993-08-15, 16; (i) maize site, 1994-06-15, 17; (j) wheat site, 1991-06-02; and (k) soybean site, 1993-08-10.

dimensionless wind speed and $z_0 + d$ have an obviously negative correlation. And there is an inconspicuous positive correlation between the dimensionless wind speed and $z_0 + d$ when the former is more than 1.5 m s\(^{-1}\), and the points are very scattered in the chart. In other words, if $U < u_0$, for the same wind speed at the upper level, the wind speed at the lower level decreases with the reduction of $z_0 + d$; on the contrary, the wind speed at the lower level increases with the reduction of $z_0 + d$ when $U > u_0$. The value of the inflexion is decided by the condition of the underlying surface: On grassland and dune underlying surfaces, the difference of $u_0$ is large, i.e., the minimum is at dune site and the maximum is at the inter-dune, which is consistent with the roughness length. On agricultural fields, the value of $u_0$ at maize sites, with a large roughness
length, is bigger than that at wheat and soybean sites. But the value of \( u_0 \) on rice paddy site, with the largest roughness length, is smaller than that on the maize site. Thus we can see that the value of \( u_0 \) is also in relation to the wind speed, the condition of the surface, etc. In general, the vegetation, the basic condition of the underlying surface and the wind speed are sensitive to the value of roughness length.

A linear relationship between friction velocity and wind speed is shown in Fig. 6. The friction velocity becomes larger with the increase of the wind speed, and it varies largely on different underlying surfaces. The friction velocity on the grassland is larger than that on the dune at the same wind speed; on different man-made disturbed underlying surfaces, the friction velocity is larger on the underlying surface with the more above-ground biomass; the average height of the vegetation has a positive correlation with the friction velocity on agricultural fields. In association with Figs. 2 and 3, dune and heavy grazing sites have small

Fig.5. As in Fig.4, but for the relationships between \( z_0 + d \) and the dimensionless wind speed on different underlying surfaces.
friction velocity, because the large wind speed exerts big pressure to the surface to prevent the plant growth and to strength the undulation of the ground, as well as the movement of sand. On the contrary, the grass can increase friction of the surface at no-grazing site and grassland, which can slow down the wind speed and increase the friction velocity. And it can restrain the sand from jumping and moving away. Through these studies, we found that grassland and vegetation are of significance in preventing desertification, especially for the arid and semi-arid land ecosystems, which is in agreement with many scholars. In recent years, many studies were carried out on desert oasis. For example, an observation and experiment study for land-atmosphere interaction in semi-arid region of West China developed by China and Japan from June 1990 to October 1991 (HEIFE); the cooperative study program among China, Japan, and Korea was founded to carry out some experiments of land surface physical processes in the north-central Tibetan Plateau from...
April to September 1998 (GAME/Tibet); and from May 2000 to June 2005, a study developed for land-atmosphere interaction was conducted in the semi-arid region of Dunhuang in Northwest China. And a lot of achievements have been obtained.

Giving \( z_0 + d \) at various times on dune and grassland in Fig.7, we can see that the value of \( z_0 + d \) increases with the above-ground biomass and vegetation coverage. On the grassland site, \( z_0 + d \) gradually increases from May to June and from August to September. In contrast with it, there is an evident augment from June to August, which is the flourishing growth period. But the relationship between \( z_0 + d \) of the dune and the season is not so clear, though the whole trend rises. We notice that there is a drop in June and August, and thus the vegetation has a small impact on \( z_0 + d \) because of sparse plants and the vegetation coverage on the dune.

Comparing aerodynamic parameters with above-ground biomass at various times for different man-made disturbed grasslands, we know that \( z_0 + d \) decreases with the increase in the man-made stress. Roughness length, and zero-plane displacement are the biggest on the no-grazing site. Except the heavy grazing site, the value of \( z_0 + d \) enhances when the above-ground biomass becomes large. Because of the severe man-made disturbed grassland, roughness length and zero-plane displacement on heavy grazing site are affected by a lot of factors, and different from the other three underlying surfaces.

Table 2. Aerodynamic parameters at various times for different man-made disturbed grasslands

<table>
<thead>
<tr>
<th>Types of underlying surface</th>
<th>Date (YYYY-MM-DD)</th>
<th>Roughness length ( z_0 ) (cm)</th>
<th>Zero-plane displacement ( d ) (cm)</th>
<th>( z_0 + d ) (cm)</th>
<th>Above-ground biomass (g dry-weight m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light-grazing site</td>
<td>1993-06-24</td>
<td>0.8889</td>
<td>0.000</td>
<td>0.8889</td>
<td>37.7</td>
</tr>
<tr>
<td></td>
<td>1993-08-05</td>
<td>3.1234</td>
<td>7</td>
<td>10.1234</td>
<td>115.3</td>
</tr>
<tr>
<td>Medium-grazing site</td>
<td>1994-06-04</td>
<td>1.0329</td>
<td>0</td>
<td>1.0329</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>1994-08-23</td>
<td>0.2570</td>
<td>23</td>
<td>23.2570</td>
<td>99</td>
</tr>
<tr>
<td>Heavy-grazing site</td>
<td>1994-06-02</td>
<td>0.1235</td>
<td>2</td>
<td>2.1235</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>1994-08-21</td>
<td>0.0510</td>
<td>0</td>
<td>0.0510</td>
<td>30.8</td>
</tr>
<tr>
<td>No-grazing site</td>
<td>1994-06-12</td>
<td>2.6496</td>
<td>15</td>
<td>17.6496</td>
<td>67.6</td>
</tr>
<tr>
<td></td>
<td>1994-08-04</td>
<td>21.4590</td>
<td>4</td>
<td>25.4590</td>
<td>315.6</td>
</tr>
</tbody>
</table>

5. Conclusions

From the discussion and analysis above, we have obtained some conclusions as follows:

(1) The vegetation coverage and the above-ground biomass decrease with the increase in man-made disturbance. The vegetation coverage, the above-ground biomass, canopy height, and wind speed etc. are the influencing factors of roughness length. And the condition of the surface affects roughness length too.

(2) Under unstable condition \( R_i < 0 \) and neutral condition \( R_i = 0 \), the value of \( z_0 + d \) is smaller than that under the stable atmospheric stratification \( R_i > 0 \). There is an obvious relationship between

![Fig.7. Aerodynamic parameters at various times for the same underlying surfaces in 1991. (a) Dune and (b) grassland.](image-url)
$z_0 + d$ and $U$, and an inflexion $u_0$ exists at the dimensionless wind speed of about 1.5 m s$^{-1}$. Less than it, $U$ and $z_0 + d$ have an obvious negative correlation. And there is an inconspicuous positive correlation between $U$ and $z_0 + d$ when the dimensionless wind speed is more than 1.5 m s$^{-1}$.

(3) A linear relationship between friction velocity and wind speed is obtained. The friction velocity is becoming larger with the wind speed, and it varies largely on different underlying surfaces. The friction velocity on the grassland is larger than that on the dune at the same wind speed; on different man-made disturbing underlying surfaces, the friction velocity is larger on the underlying surface with the above-ground biomass; the average height of the vegetation has a positive correlation with the friction velocity on agricultural fields. Through these studies, we found that grassland and vegetation are of significance in preventing desertification, especially for the arid and semi-arid land ecosystems.

(4) A positive relationship between $z_0 + d$ and month is obtained. This result is distinct on grassland and not so clear on dune. There is an evident augment during the flourishing growth period on grassland. And the value of $z_0 + d$ enhances with the above-ground biomass and the man-made stress.

Acknowledgements. We would like to sincerely acknowledge the Institute of Desert Research, Chinese Academy of Sciences and the National Institute of Agro-Environmental Sciences of Japan for providing the valuable data.

REFERENCES


Hikaru, K., H. Norifumi, et al., 2005: Classification of vertical wind speed profiles observed above a sloping forest at nighttime using the bulk Richardson number. *Boundary-Layer Meteorology*, 115, 205-221.


