Local effects of wind turbines on near-surface wind speed in a desert steppe wind farm

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This research describes and interprets spatial variation in near-surface wind speed around a large scale wind generation operation in a desert steppe environment of Inner Mongolia. Wind speeds were measured at five different heights and distances in front of and behind turbines and compared to that measured simultaneously from reference points immediately outside of the wind farm. The results showed that wind turbines clearly influence the spatial distribution of near-surface wind speed. Relative to reference points, near-surface wind velocity profiles measured at various distances from wind turbines followed a logarithmic distribution. The correlation coefficients for all points were above 0.95 except for a coefficient of 0.8278 corresponding to wind speeds measured 20 m in front of turbines. The wind speed increment rate at 20, 100, and 300 m in front of and behind turbines demonstrated the varying influence of turbines at different points. The area 100 m behind the turbine experienced maximum wind speeds at all height levels observed in the measurement area. The overall wind speed at 300 m distance was relatively low and variation nearest to the turbine was the most complex.

Keywords. Wind energy generation; desert steppe; near-surface wind speed; spatial variation.

1. Introduction

As an energy alternative to fossil fuels, wind turbines do not emit or cause pollution in a traditional sense. Recent research has shown, however, that wind turbines do exert some adverse effects around wind farms and surrounding areas at different scales. Wind turbines can specifically impact climate, wildlife, noise, soil, vegetation scenery, and light pollution (An 2010; Gu 2010; Sun 2011; Saidur *et al.* 2011; Song 2011; Wang *et al.* 2011; Zhao 2011; Leung and Yang 2012; Xue *et al.* 2012; Zhang 2012; Abbasi *et al.* 2014; Wu *et al.* 2014; Kaoshan *et al.* 2015; Li 2015; Sa 2015; Shifeng and Sicong 2015; Bijian *et al.* 2017; Geng and Liming 2017). The grassland of Inner Mongolia has not only major wind energy potential and considerable installed production, but also provides important supporting and cultural ecosystem services, for example, to herdsmen who have lived in the area for millennia. Construction of wind energy projects in these grasslands has led some farmers and herdsmen to speculate that turbines have affected the local climate, stating specifically that 'the

clouds will avoid this place'. Popular opinion holds that the ongoing drought over the last two years may relate to installation of large-scale wind farms. Up to the end of 2016, the total installed capacity exceeded 28.064 million KW making this facility the largest one in China (Zhou and Hu 2018). The impacts of the construction and operation of the wind farm on the climate and habitat of the surrounding area have become a concern among residents and especially herdsmen who rely on local grassland for their livestock. As a critical factor of the local climate, near-surface wind speed can directly influence soil moisture and vegetation. Determining the exact effects of wind energy generation on the grassland requires a more detailed understanding of spatial variation in near-surface wind speeds in and around the wind farm.

Ongoing research concerning impacts of wind farm construction and operation on the surrounding ecosystem has specifically addressed climate, soil, vegetation, scenery, and avian wildlife (Yang 2014; Xie 2015; Li *et al.* 2016). Given the role of wind energy in managing climate change, this research has attempted to document impacts of wind generation at both global and local scales. In terms of global scale, research has found that large-scale construction of wind farms may contribute to global warming and reduction of wind speed (Wang and Prinn 2010; Zhao *et al.* 2011; Abbasi *et al.* 2016). However, these findings are relatively limited and derived from highly theoretical simulations with numerous assumptions that may not hold true in the real world. Research concerning local climate effects tends to consist of on-site observation and numerical modeling. Results have shown that construction and operation of the wind farm reduces wind speed in the wind farm and downwind direction especially in near-surface environments. It also affects air temperature, humidity, and evapotranspiration around the base areas of the wind farm (Keith *et al.* 2004; Roy *et al.* 2004; Somnath 2011; Jenell *et al.* 2012; Alona *et al.* 2016; Geng *et al.* 2016). Some researches based on site observations have identified near-surface wind speed as the salient factor affecting the grassland ecosystem (Xu 2014; Zhang *et al.* 2015). Current research methods typically treat the entire wind farm as a whole in comparing wind speed variation in upwind and downwind areas of the farm. Only limited research exists concerning more localized effects of wind energy generation on near-surface wind speeds. This parameter can strongly influence local climate and affect the spatial distribution of near-surface air temperature and humidity along with soil and vegetation.

The facility investigated in this research is located in a desert steppe environment. Observations and analysis were performed on near-surface wind speeds to determine effects on ground surface areas during wind turbine operation. This information can provide a theoretical foundation for understanding local climate variation and potential impacts of the wind farm. A better understanding of these impacts can support sustainable development of wind energy in similar arid steppe environments.

2. Materials and research methods

2.1 *A brief description of research methods*

In order to minimize topographic effects in near-surface wind speed, the wind farm selected for observation is situated in the town of Hailiutu, Ulat Middle County of Bayanor, Inner Mongolia. This area is flat (figure 1) and experiences strong, consistent winds. Along with southeastern coastal area and Chinese islands, this region experiences optimal conditions for wind energy generation. Winds blow predominantly north to northwest during the winter and spring, while a southern wind prevails in summer and autumn. The average annual wind speed is 3.5–5 m/s and the average wind speed in spring is 5–6 m/s. Maximum wind speeds of 20–25 m/s are primarily recorded from March to May. Fresh gales occur 15–30 days of the year. The wind farm investigated is operated by the Inner Mongolia Guohua Energy Investment Co., Ltd., Inner Mongolia Group of Shenhua Group. It consists of 266 wind turbines, each represent an installed capacity of 1.5 MW.

The observation area primarily represents a desert steppe environment. Grass and other vegetation is scarce and low. Perennial small bushes and tussock predominate. The main plants include *Stipa breviflora* Griseb., *Stipa glareosa* P. Smirn., *Agropyron cristatum* (Linn.) Gaertn., *Artemisia frigida* Willd. Sp. Pl., *Caragana spinifera* Kom., *Caragana intermedia* (Kuang et H.C. Fu etc.)

2.2 *Observation strategy*

Wind speed was measured at different heights and distances from wind turbines and compared to reference points outside the wind farm. Reference

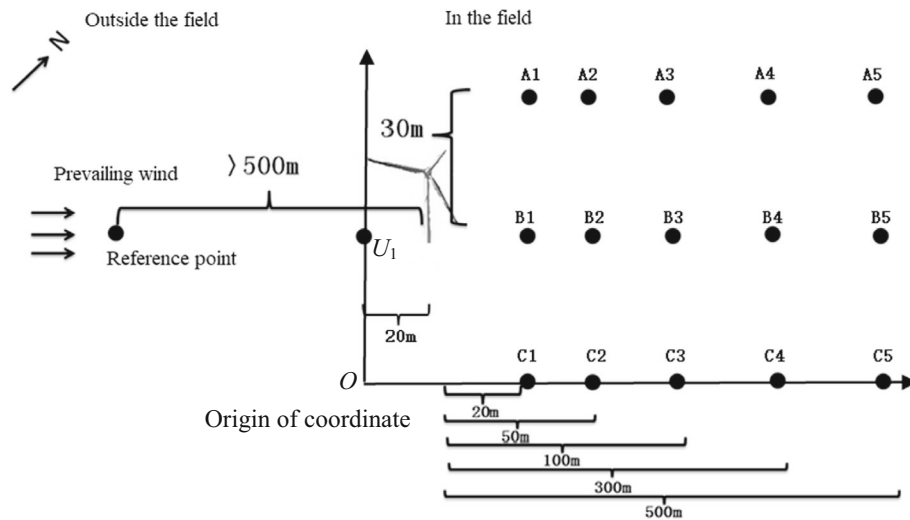Figure 1. Field geomorphology of Hailiutu Wind Farm.

Figure 2. Sketch map of the measuring point layout scheme. Observational distances from the turbine assumed a grid pattern with 20, 50, 100, 300, and 500 m distances downwind from the turbine. Rows A and C were arranged parallel to B (relative to wind direction) or at 30 m from observational turbine (rows A and C). Wind speeds were also measured from a single point 20 m upwind of the turbine parallel to prevailing wind (measuring point U_1).

points were located 500 m upwind and 20 m front of the leading row of upwind turbines (figure 2). (In this paper, the terms 'in front of' and 'behind' used in reference to turbines refer to the prevailing NE–SW upwind and downwind directions.) A relatively independent turbine along the prevailing spring wind direction and within the wind farm was also selected. The reference points and leading row

of turbines were free of barriers in the upwind direction. We measured near surface wind speed at different lateral distances in front of and behind turbines (20–300 m) and at different heights (0.2–2 m) from the ground surface. Previous research has indicated that the wind farm strongly influences wind in the downwind direction. Measuring points lay mainly in downwind areas of the turbine, while

upwind data were collected at 20 m distance from turbines (to be free of construction disturbance). Figure 2 shows the measurement point layout relative to the wind farm.

We used four HOBO automatic meteorological stations to measure near surface wind speed at different heights (0.2, 0.5, 1, 1.5, and 2 m) on windy days in mid-March 2017 for each reference point and upwind and downwind measurement points. The sampling interval was 2 s and the duration at each measurement point was 10 min. During each sampling cycle, one instrument recorded observations at the reference point, while the other three instruments collected data at different distances from the turbine.

We then calculated average wind speed at each measurement and reference point for every 10 min interval. These were then standardized and processed following the published methods (Wu *et al.* 2013; Zhou *et al.* 2018) so as to be comparable in contour line calculations for a given period. The standardized formula is:

$$U'(z) = \frac{U_{\text{comparison}}(t_0, z = 2)}{U_{\text{comparison}}(t, z = 2)} \times U(t, z),$$

where $U'(z)$ is the standardized wind speed at an observation point at height z, $U(t, z)$ is the wind speed at an observation point at time t, $U_{\text{comparison}}(t_0, z = 2)$ is the wind speed at 2 m height at time t_0, and $U_{\text{comparison}}(t, z = 2)$ is the reference point wind speed at 2 m height and time t.

The increment rate of wind speed

$$R = [(U_2 - U_1)/U_1 \times H] \times 100\%,$$

where H is the height difference between z_2 and z_1, and U_2 and U_1 are the wind speed values at heights z_2 and z_1.

The horizontal distribution of wind speed at different vertical heights was estimated by Surfer software. Figure 2 shows layout and reference coordinates necessary for the software's measurement parameters and data processing.

3. Results and analysis

3.1 *Near-surface wind velocity profiles*

Given a neutral layer in the atmosphere, near-surface wind velocity profiles exhibited the expected logarithmic variation with height (Tennekes 1972; Stull 1988; Zhou *et al.* 1991). Wind speed is specifically proportional to the logarithmic value for height

measured as the altitude as the vertical axle is the monotone increasing line. Under roughly consistent surface conditions, variation in the wind velocity profile for various measurement points may arise from turbine turbulence in near-surface air flow. Figure 3 shows linear functions fitted to the near-surface wind speed profiles for reference points and measurement points at different distances from the turbine.

Figure 3 shows that near-surface wind velocity profiles for different distances from turbines follow a logarithmic distribution. Nearly all goodness-of-fit coefficients exceed 0.95. The fitting function calculated for wind velocity 20 m in front of turbines gave a lower goodness-of-fit value of 0.8278, but still indicates near-surface wind speed contours following a logarithmic tendency. For this location, wind speed at 1 m decreased relative to the reference point and showed the greatest decrease at 1.5 m height. Given consistent underlying surface conditions, this variation probably reflects turbulence from turbine operation in near-surface air flow. Also, it may be caused simply by absorption of wind energy. Along the prevailing wind direction, greater distances from turbines lead to greater differences between wind speed contour lines. The slope of the wind velocity profile at various measurement points relative to reference points changed at different points. The slope and distance as measured 20 m behind the turbine were very close. Distances remained close at 50 m. Near surface wind speeds showed greater variation at 100 m distance in front of the turbine for various measurement points. This variation showed consistent trends. While near-surface wind speed around turbines followed the expected logarithmic trend, wind speed showed some unexpected variation at different measurement points. Above a certain wind speed, the turbines clearly affect the spatial distribution of near-surface winds. Both vertical and horizontal projecting distances from the turbines were consistent. Variation in direction and linear distances caused variation in the wind velocity profile at different measurement points.

3.2 *Increment rate of wind speed*

The increment rate is an important index for capturing variation in wind velocity profiles and the vertical distribution of air flow energy. Wind speed increases with height, while increment rate typically decreases. Table 1 compares the increment rate at different heights from the ground

(a) 20 m in front of turbine

(b) 20m behind turbine

(c) 50 m behind turbine

(d) 100m behind turbine

(e) 300 m behind turbine
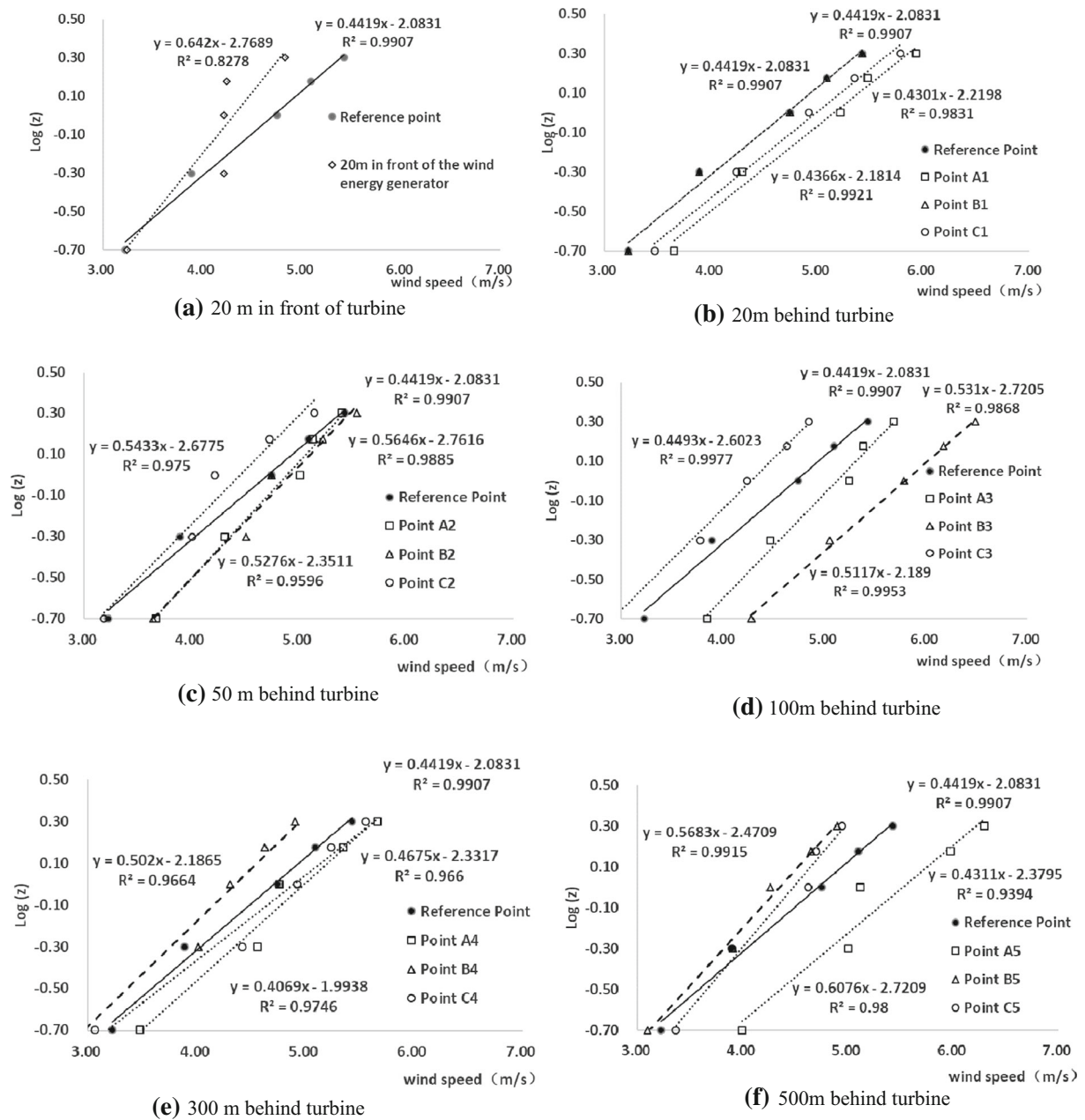
(f) 500m behind turbine

Figure 3. Fitting of the linear and logarithmic functions of wind velocity profile with different distance from wind turbine. The observed height of wind speed at each measuring point is 0.2, 0.5, 1, 1.5, and 2m.

Table 1. *Wind velocity at different distances from wind turbines and at different heights (0.2–2 m) above ground surface.*

Distance from turbine	0.2–0.5 m	0.5–1.0 m	1.0–1.5 m	1.5–2.0 m
Reference point >500 m from farm	69.16	43.99	14.65	13.12
20 m in front of turbines	99.74	0.00	1.21	27.71
20 m behind turbines	67.08	39.68	13.89	15.33
50 m behind turbines	74.11	17.93	15.84	13.36
100 m behind turbines	69.73	29.61	11.99	10.29
300 m behind turbines	126.73	15.32	17.54	11.92
500 m behind turbines	74.99	18.57	18.81	10.77

(0.2–0.5, 0.5–1.0, 1.0–1.5, 1.5–2.0 m) and distances from the turbine.

The increment rate of wind speed for windward reference points (over 500 m) followed expected variation tendencies, namely that wind speed increases with height while the increment rate decreases. The increment rate beneath 1.0 m height is obviously larger than that above 1.0 m height. The increment range of wind speed at 0.2–0.5 and 0.5–1 m height were 69.16% and 43.99%, respectively. The increment range at 1.0–1.5 and 1.5–2 m height were only 14.65% and 13.12%. Throughout the measurement area, the increment rate 20 m in front of and behind the turbine exhibited different variation patterns. At 20 m in front of the turbine, wind speed increases rapidly below 0.5 m with an increment rate of 99.74%. This rate does not change from 0.5 to 1 m. The increment rate barely increases at 1.21% in the height range of 1.0–1.5 m. The 1.5–2 m height range gives further increases perhaps due to turbine operation. At 20 m behind the turbine, though wind speed generally conforms to the tendency of increases with height and decreases in increment, variation in increment range decreases and then increases in the 1.0–1.5 and 1.5–2.0 m height range. The wind speed increment rate at 50, 100, and 500 m distance from the turbine was generally consistent. Wind speed increased rapidly in the 0.2–0.5 m height range (74.11%, 69.73%, and 74.99%, respectively). Wind speed increased smoothly in the three height ranges, from 0.5 to 2.0 m. The wind speed increment range at 0.5–1 m height behind the turbine was 29.61%. The increment range at different heights for all other points ranged from 10 to 20%. Variation in increment rate 300 m behind the turbine obviously differed from the common values. Wind speed increased sharply at 0.2–0.5 m height at a rate of 126.73%.

To sum up, turbines strongly influence near-surface wind speed. In terms of the wind speed increment rate, areas 20 m in front of the turbine and 20, 100, and 300 m behind the turbine showed variation tendency with obvious differences.

3.3 *The distribution of the wind speed at different vertical heights around turbines*

For a given height, wind speed varies at different distances from the turbine and in different directions. Figure 4 shows the wind speed distribution around the turbine at different vertical heights (2.0, 1.5, 1.0, 0.5 and 0.2 m). Data processing using Surfer software used horizontal distance from the turbine relative to the main wind direction as the horizontal coordinate. The vertical coordinate was the distance from the turbine perpendicular to the main wind direction.

Figure 4 shows that five height levels for the area 100 m behind the turbine experienced maximum wind speed. The overall wind speed at 300 m was relatively low. Wind speed variation surrounding the turbine is fairly complex, but this complexity decreases with height. Data measured at 0.2 m height give wind speed isotachs showing rapid variation at different distances throughout the entire measurement area. This variation is highly complex at 20–100 m behind the turbine. This variation may arise from turbine operation or surface conditions such as vegetation or topographic relief. Wind speed variation at 0.5 m height 100 m behind the turbine was also very complex. The isotach for this area exhibits intensive variation. While topography may affect wind at this height, low-speed centers appear both upwind and downwind of the turbine. These features indicate turbulence in near-surface air flow generated by the turbine. From 1.0 to 2.0 m height, complexity in the horizontal distribution of near-surface wind speed decreases while wind speed increases from points in immediate proximity to the turbine to 100 m behind it. Wind speed also decrease gradually with increasing distance from the turbine.

4. Discussion

(1) The research described here supports previous findings that induced variation in near-surface wind speed is non-negligible and can influence vegetation and soil parameters around a wind farm. Determining the spatial character and scale of this variation during turbine operation can help rigorously constrain environmental impacts at different scales. A drought-prone desert steppe environment may be especially sensitive to this variation. This research determined spatial variation in near-surface wind speed during turbine operation. Near-surface wind speed contours and increment rates as measured at different heights and at different lateral points surrounding turbines recorded clear and systematic disruption of near-surface winds. These effects varied according to different upwind and downwind directions and at different distances from the turbine.
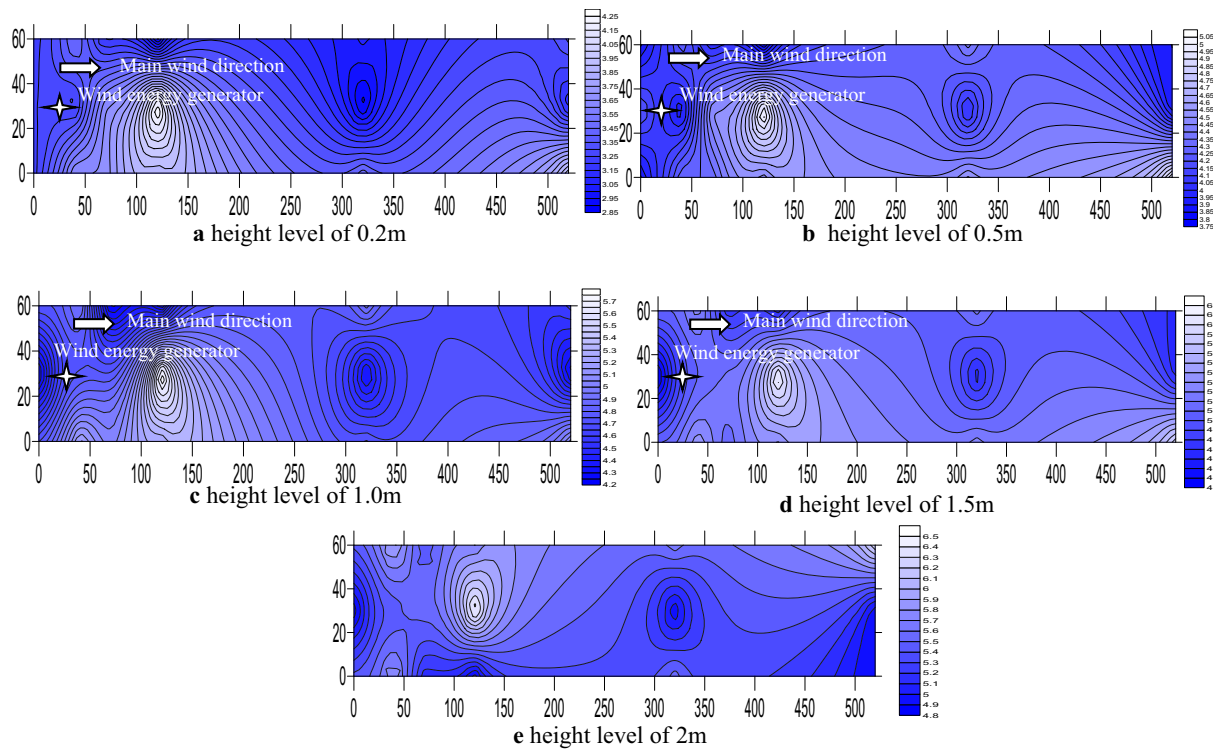
Figure 4. Horizontal distribution pattern of wind velocity at different vertical height near the surface.

(2) Previous research on how wind farms influence wind speed has primarily compared wind conditions within the wind farm to those downwind at a certain distance from the facility. This type of research treats the wind farm as a single unit whose influences on wind speed occurs primarily at larger spatial scales. The research described here, however, demonstrates that the influence of individual turbines on near-surface wind speed depends on distance and direction relative to the turbine. Previous research has shown that wind speed at lower heights within the wind farm can be 20–40% less than that at higher heights. This variation results from turbine operation. Li Qingguo and others have concluded that turbines influence local grassland environments according to different mechanisms inside and outside the wind farm. Turbines generally exert negative impacts on vegetation inside the wind farm, but have beneficial impacts on vegetation just outside the wind farm. Negative impacts arise primarily from induced variation in near-surface conditions. Changes in wind speed affect air temperature, evaporation rates, and other climatic conditions. Determining the effects of spatial variation in wind speed on surface conditions can help further constrain impacts within the wind farm.

(3) The research described here, showed that turbines exert only minor influence on wind speed at upwind distances greater than 20 m. Turbines exert stronger and more immediate influence in the downwind direction. Data at different heights 20 m in front of the turbine show significant differences with data collected from reference points. This research used a spatial framework that was primarily perpendicular to the main wind direction to identify local effects at smaller scales than previously documented. Future research should conduct more detailed observations from points downwind of the main wind direction. Expanding spatial understanding of local, small scale effects can help identify mechanisms causing variation in conditions and minimize their impacts.

5. Conclusions

(1) Wind turbines clearly influence the local spatial distribution of near-surface wind speeds. Relative to reference points, near-surface wind speed

contours determined from various measurement points followed a logarithmic distribution. Except for the wind speed contour line determined for areas 20 m in front of turbines, wind speed data gave relevant correlation coefficients greater than 0.95.

(2) Wind speed increment rate measured 20 m in front of turbines as well as those measured 20, 100, and 300 m behind turbines generally showed systematic and complex variation tendencies. Wind speed increases with height did not always lead to increment rate decreases. The relationship between wind speed increment and height is very complex.

(3) Of the five height levels above the ground surface around the turbines, areas 100 m behind turbines experienced maximum wind speeds. Areas 300 m behind turbines experienced relatively low wind speed. Areas closest to turbines exhibited the most complex wind speed patterns but this complexity decreased with height above the ground surface.

Acknowledgements

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