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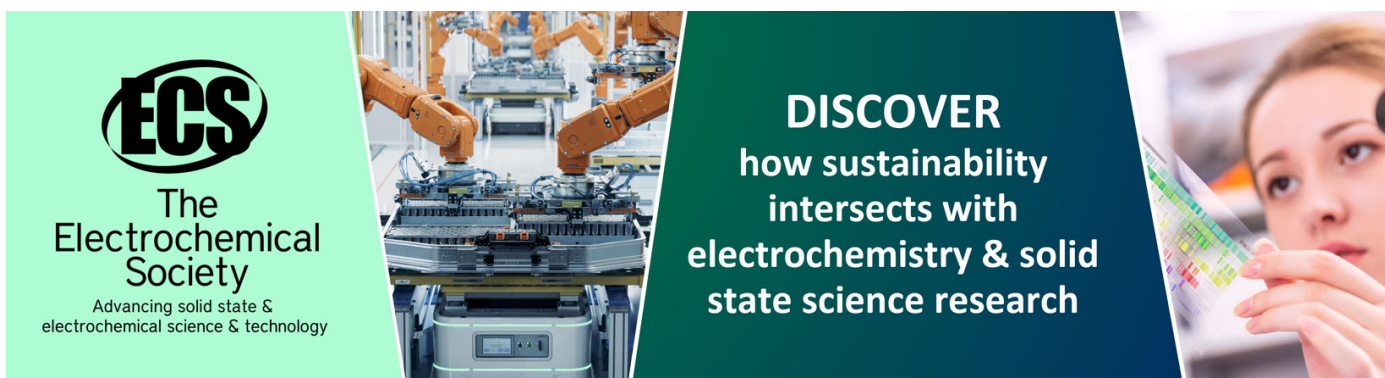
Characteristics of wind turbulence near the boundary layer in Three-North Regions of China

To cite this article: Yan Li *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **349** 012012

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Characteristics of wind turbulence near the boundary layer in Three-North Regions of China

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Abstract. Based on the daily 10-minute wind observation data of the wind tower in CWERPON from 2013 to 2017, this study analysed the distribution and variation characteristics of wind turbulence in different gradients and periods in wind resource rich regions in NEC, NC and NWC. Results showed that: 1) The average wind speed from ground to 100 m height was 6.7m/s, which increased with the height, and the dominant wind speed was 4.0 m/s. The average wind speed at the height of 10 m, 30 m, 50 m, 70 m and 100 m were 6.0 m/s, 6.4 m/s, 6.7 m/s, 7.0 m/s and 7.5 m/s respectively. The highest and the lowest wind speed frequency occurred at the heights of 10m and 100m layers, which accounted for more than 22.5 % and 12.5 %. Starting from the wind speed of 6.0 m/s, the proportion of lower layers wind speed decreased, while that of high layers wind speed increased. 2) The average I_t decreased from low layers to high layers. Each layer's I_t decreased gradually with the increasing of wind speed. The I_t values were different among these three regions in the study area, the NEC region was the largest, followed by the NWC, and the I_t value in NC stations were the smallest. Under the wind speed of 3.0-25 m/s and 15.0 m/s, the average I_t of each layer were 0.118 and 0.099 respectively; the maximum values were 0.189 and 0.120 at the height of 10 m in NEC region, and the minimum were 0.082 and 0.063, both of which appeared in the 100 m gradient in NC region and NWC region respectively. 3) The variation ranges of I_t among adjacent layers were different, the lower the layer was, the greater range of change occurred. The differences between the 10-30 m, 30-50 m, 50-70 m were 0.028, 0.013 and 0.003 respectively. 4) Each layer's I_t corresponded to the variation trend of the air temperature. I_t increased slowly from 06:00, which reached the maximum value around 14:00, and then decreased slowly. 5) The wind turbine reach the C and B turbulence intensity level respectively at the height of 30 m and 10 m in the study area when the average wind speed is lower than 6.0 m/s, and some stations' wind turbine type in these three regions should be at least A level.

1. Introduction

Three-North Regions of China including North-West area, NWC(containing Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang), North area, NC(containing Beijing, Tianjin, Hebei, Shanxi and Neimenggu), and North-East area, NEC(containing Heilongjiang, Jilin and Liaoning), and most area of them belong to non-monsoon climate zone, which is controlled by the belt of westerly. It's the place where the upstream of the weather process "entry in". The dry and cold currents from Siberia in winter and the



early spring seasons first land there area, which result serious sandstorm weather hazards. Study the characteristics of wind movement in these regions are vital to the downstream weather and climate research and the protection of ecological. Furthermore, this area is rich in wind and solar resource, the effective wind power density is approximately 200~300 W/m², and the percentage of effective wind time is about 70%, and the accumulated hours of wind speed greater than or equal to 3 m/s and 6m/s are above 5000h and 2000h throughout the year[1]. In 2020, followed the national wind power development plan[2], China government will build 70 million kilowatts of wind power bases in Gansu, Xinjiang, Hebei, Jilin, Neimenggu provinces and the coastal areas. By then, the total installed capacity will reach 12630 million kilowatts, the on-grid electricity will reach nearly 2810 billion kilowatts.

Wind power is the process of converting air kinetic energy near surface into electric energy. Due to the difference in thermal properties and underlying surface conditions, the motion characteristics of near-surface air show uneven distribution with height. Atmospheric turbulence is an irregular vortex motion caused by wind shear and atmospheric instability, whose main features are randomness and diffusivity [3-5]. The turbulence intensity (I_t), can reflect the wind turbulence characteristics to some extent. In the process of wind power generation, the decrease of wind speed and the increase of turbulence value in the deep wind field lead to the overlap of the upwind wind turbine wake [6-7]. Also, Medici et al and Wu et al believe that higher turbulence intensity may also have beneficial impacts. When the turbulence intensity level of the incoming flow is higher, the turbine-induced wake recovers faster, then the turbine in the downstream can generate more power [8-9]. When the wind turbine blade rotates, it will be disturbed by wind turbulence and generate abnormal load fluctuation, which will further affect the aerodynamic performance of the turbine. As a result, the wind passing through the turbine cannot be fully utilized and the wind energy utilization rate will be greatly reduced [10-11]. Therefore, the turbulence intensity at the hub height is one of the important indicators for wind resource assessment, also is the important parameter for the wind energy standard design, safety performance and selection of wind turbine [12]. According to the intensity of turbulence, the International Electro technical Commission (IEC) classifies the safety level of wind turbines into three levels: high, medium and low [13]. With the increasing popularization of wind energy resources, more and more studies and evaluations have been made on the characteristics of wind turbulence in the near-surface layer in wind resource assessment and electric field construction [14-16].

In this paper, based on the 10-minute gradient wind data obtained by CWERPON, the wind turbulence distribution and variation characteristics of the near-surface layer in Three-North Regions were studied, so as to provide a reference for the maximum utilization of wind resources and the understanding of wind motion characteristics in these areas.

2. Wind resources professional observation network

The data used in this study comes from the results of different gradient wind observations of China Wind Energy Resources Professional Observation Network (CWERPON).

CWERPON is a wind observation network for the detailed investigation of wind energy resources, which is built by China's meteorological departments in the place rich in wind energy resources, suitable for the construction of large-scale wind farms, and large-scale development and utilization of wind energy resources [17]. CWERPON is composed of 400 gradient observation towers distributed in 31 provincial-level regions in China, 75% of the towers lie in the rich wind resource places, such as North-East, North, North-West and low altitude area on the South-East coast of China.

CWERPON observation tower can be divided into three types, namely 70m height (total number is 329), 100m height (total number is 68) and 120m height (total number is 3). The observation elements contain the air temperature, the average wind speed, 10-minute wind speed standard deviation, maximum wind speed, extreme wind speed, wind direction, relative humidity, air pressure and ultrasonic wind and strong wind observations (mainly in coastal area tower). The maximum observation layer can be divided into 6 layers, 10m, 30m, 50m, 70m, 100m and 120m; The observation frequency includes two types: four times a day (at the time of 02:00, 08:00, 14:00, and 20:00) and 144 times a day (the observation gap is 10 minutes).

The gradient observing system is triangle truss type drawing tower, which is consisted of different sensor, data collector, a communication transmission, a power supply and a software system (**Figure 1**). The observation sensor includes 4 factors: conventional direction and speed of the wind, humidity, pressure. The data collector is responsible for the collection, processing, storage and management of various meteorological elements; the communication transmission works with wireless; the power is supplied by solar energy; the embedded system software in the collector is used to realize the features such as the acquisition, preliminary quality control and transmission of the data. The system's allowable working environment temperature is between $-50 \sim +50$ °C, the relative humidity is in the range of $0 \sim 100\%$, the pressure range is $500 \sim 1100$ hPa, and the gust resistance is up to 75 m/s. The EL15-2 three-cup wind speed sensor used in the study has a wind speed measurement range of $0\text{--}60$ m/s, accuracy of ± 0.1 m/s, a resolution of 0.1 m/s, and a sampling period of 1 s (**Table 1**).



Figure 1. Wind tower system.

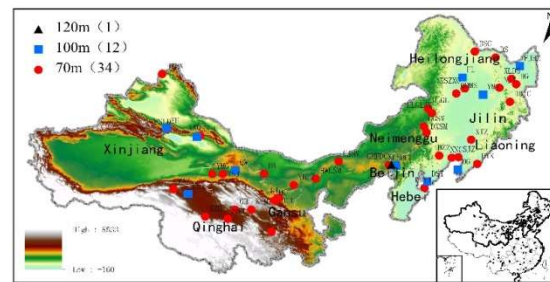


Figure 2. Station distribution map in the study area.

Table 1. Components of Automatic observing system for the wind resource gradient.

System name	Num.	Type	Principle	Range	Precision	Resolution	Sample period
Main collector	1	HY-3160-3	/	/	/	/	/
Sub collector	2	HY-MDL-02	/	/	/	/	/
Wireless communication module	1	CAWS-TG7118	/	/	/	/	/
Wind speed sensor	5	EL15-2	Three cups	$0 \sim 60$ m/s	± 0.1 m/s	0.1 m/s	1 s
Wind direction sensor	5	EL15-2	Single wing	$0 \sim 360^\circ$	$\pm 5^\circ$	3°	1 s
Temperature sensor	7	HMP45D	platinum resistor	$-50 \sim 50^\circ\text{C}$	$\pm 0.2^\circ\text{C}$	0.1°C	10 s
Humidity sensor	7	HMP45D	humicap	$0 \sim 100\%$	$\pm 4\%$ ($\leq 80\%$), $\pm 8\%$ ($> 80\%$)	1%	10 s
Air pressure sensor	1	PTB220	capacitor	$500 \sim 1100$ hPa	± 0.3 hPa	0.1 hPa	10 s
Strong wind speed sensor	1	XFY3	Screw propeller	$0 \sim 90$ m/s	± 0.3 m/s	0.1 m/s	1 s
Supersonic wind sensor	4	Wind Master Pro	Three-dimension	$0 \sim 65$ m/s	$\pm 1.5\%$ RMS	0.01 m/s	0.1 s
Electronic system	1	HY-DY1000	/	/	/	Article I.	/

Note: "/" means null.

3. Materials and methods

3.1. Data and processing

The analysis data containing surface meteorological observation results and boundary layer wind turbulence data. The former includes the average temperature, air pressure, and average wind speed, maximum and extreme wind speed and wind direction that comes from China's daily dataset of surface meteorological elements of the National Meteorological Information Center [18], from 1951 to 2015, which are subject to strict quality control to ensure their reliability.

The data used to calculate the intensity of gradient wind turbulence come from CWERPON [17]. There are 253 observation towers in Three-North Regions(**Figure 2**), and this study selects 47 stations

in 8 provincial area, namely NWC region (including Xinjiang, Gansu and Qinghai), 18 stations; NC region (including Neimenggu, Hebei and Tianjin), 12 stations; and NEC region (including Heilongjiang and Liaoning), 17 stations.

The data used for I_t analysis are the 10-minute observation results, including the average wind speed of 10-minute per gradient, the wind speed of standard deviation and the identifier of the corresponding data quality control; the analysis period is January 1st, 2013 to December 31th, 2017.

To ensure the reliability of the results, the strict data quality method is performed. Considering small wind has no influence on wind turbine and will become the noise of the results [18], 3~25m/s wind speed are selected to calculate I_t while some data are excluded if the wind speed standard deviation is greater than 5 or I_t is greater than 3.

In the time trend analysis, the I_t results of the 70m gradient of Gansu MC (station No. is 28003) and Qinghai GB (Station No. is 29006) are deleted. In MC, there are 24 times extreme high I_t during 2013-2014, and the variance tendency is disordered; in GB, the change amplitudes are too large for many times. Besides, the 100m gradient of some stations isn't analysed for too much missing data. Finally, the I_t are conducted in 5 gradients, 10-70 m and 100 m (some stations, namely Gansu QW Station; Qinghai HGL station; Xinjiang SSJF and YH station; Hebei GHFDC and HCL station; Tianjin DST station; Heilongjiang FJ, FL and YMT station; Liaoning DG station). No I_t are calculated in 120m gradient for too much missing data. The total amount of data finally calculated are 4289,599 records, and the effective data integrity rate is 95.7%.

3.2. Turbulence intensity

In aerodynamics, turbulence refers to the wind speed fluctuation within a short time (generally less than 10 minutes). The main causing factors are as follows: the underlying surface condition, that is, the friction or retardation with the surface caused by the difference in topography when the airflow moves; the vertical airflow caused by the atmospheric temperature difference and air density. Usually both of them lead to turbulence at the same time and affect each other. Such as, when airflow passes through mountains, it will be forced to flow to cooler areas, at this process, the heat balance between the airflow and the atmospheric environment is broken, which causing the wind speed to fluctuate. In the neutral atmosphere, the intensity of turbulence depends entirely on the surface roughness [3, 19]. Turbulence Index, I_t , is abbreviated as Turbulence degree or Turbulence intensity, which describes the degree of change of wind speed with time and space, reflects the relative strength of fluctuating wind speed, and is an important characteristic quantity to describe the motion characteristics of atmospheric turbulence.

I_t is usually expressed as the degree to which the instantaneous wind speed deviates from the average wind speed. The formula is:

$$I_t = \frac{\delta}{\bar{v}} \quad (1)$$

Where δ is the standard deviation of wind speed (m/s) in the calculation period, and $\bar{v}$ is the corresponding average wind speed (m/s). I_t is a dimensionless quantity that is related to factors such as geographic location, topography, surface roughness, and type of weather system.

In mathematics, I_t is similar to Relative Standard Deviation (RSD), Deviation Coefficient (DC), Coefficient of Variation (CV), etc., all of which are the preferred indexes used to detect the precision of analysis results.

In the wind resource assessment and wind farm construction, the I_t is calculated by the ratio of the standard deviation of the 10-minute average wind speed at the hub height to the average wind speed during the same period, which reflects the normal fatigue load borne by the wind turbine during operation. I_t is one of the important parameters that must be considered in the classification of wind turbines when wind resource assessment and wind farm construction [13]. Excessive turbulence can reduce the output power, and may also cause extreme loads, which will eventually weaken and destroy the wind turbine [20, 21]. Also, some researchers think that when the I_t level of the incoming flow is higher, the turbine-induced wake recovers faster, and then the turbine in the downstream can generate

more power [8]. For the calculation formula above, δ is the standard deviation of 10-minute wind speed (m/s), and $\bar{v}$ is the average 10-minute wind speed (m/s). In this study, the average wind speed and corresponding wind speed standard deviation selected to calculate the average I_t is at the observation range of 3 m/s to 25 m/s.

4. Study regional climate background

The multi-year average air temperature and station atmosphere pressure of the study area are $-4.1\text{ }^{\circ}\text{C}$ and 926.1hPa, and they show differences in different month and region. As can be found from **Figure 3**, the atmosphere pressure is lower in summer and higher in winter, and the average value can vary by as much as 15hPa. The average atmosphere pressures in NWC, NC and NEC regions are 811.7hPa, 980.1hPa and 996.3hPa. The average wind speed, average maximum wind speed and average maximum wind speed are 2.6m/s, 6.1m/s and 9.0m/s respectively. The multi-year average maximum wind speed over 5m/s and 10 m/s in the study area reach 209.3 days and 32.3 days, in Neimenggu the former reaches 266 days.

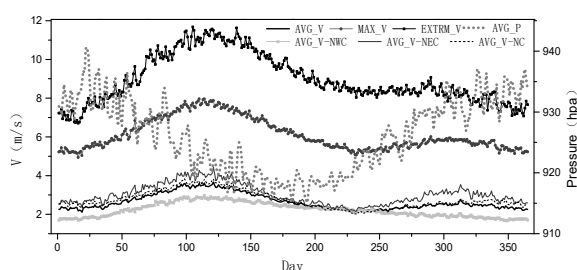


Figure 3. Daily variation of regional average wind speed and atmosphere pressure in 1951-2015.

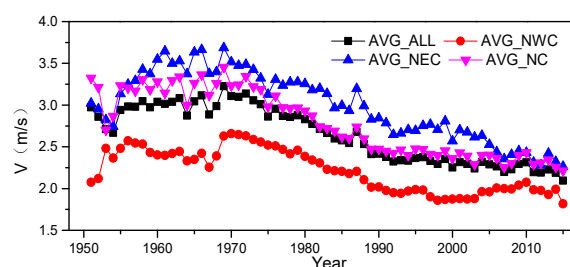


Figure 4. Annual variation of multi-year average wind speed in different regions in 1951-2015.

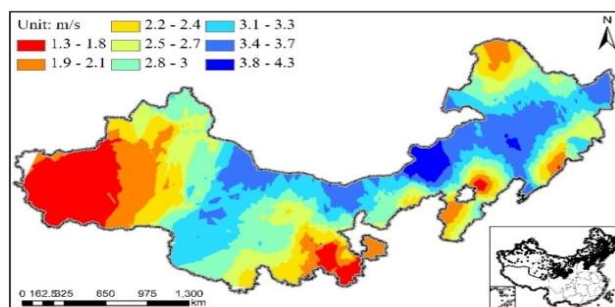


Figure 5. Spatial distribution of multi-year annual average wind speed from 1951 to 2015.

Figure 3-4 shows the overall downward trends of multi-year average wind speed in these three study regions. Except for the NWC region, both the NEC and NC regions show a bimodal distribution with the highest value in March and October to November, and the NEC region is the largest, followed by the NC region, the NWC region is the smallest. The average wind speeds are relative low in the southwestern Xinjiang, Qinghai, Gansu, Hebei, in the southeastern provinces of NEC, and also in the junction area of northeastern Neimenggu and Heilongjiang, while the rest areas have relatively high wind speed, especially in the central and western parts of Neimenggu and the eastern part of Xinjiang, with an average annual wind speed of over 4 m/s (**Figure 5**).

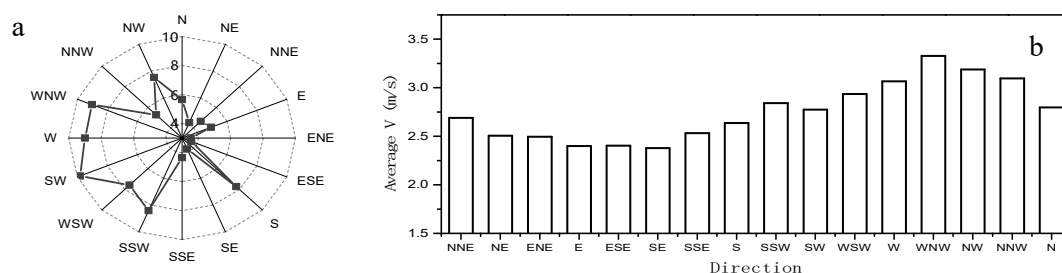


Figure 6. Sixteen-directional wind rose diagram and average wind speed.

Figure 6 shows that the wind direction of highest frequency is the southwest wind, accounting for 9.8%, and the average wind speed is 2.8m/s, followed by west wind and northwest wind, all accounting for 9.0%, and the average wind speed are 3.1m/s and 3.3m/s.

The topographical features of the Three-North Regions are high in the west and low in the east, and the terrain is undulating (**Figure 2**). The NWC and NC western area situate on the north-eastern edge of the Qinghai-Tibet Plateau. The special topography of the Qinghai-Tibet Plateau caused the westerly winds to be branched in the winter. The westerly winds of the north branch merged with the cold and dry polar continental air masses from the south of Siberia, turning into a strong north-westerly airflow, which affecting most of the central and eastern parts of China, and the other part interacts with the southeast wind from the northeast, affecting the northeast and east regions of China. Due to the influence of the underlying surface, the air disturbance is large, and the near-surface atmospheric turbulence and shear are common.

5. Results and analysis

5.1. General distribution characteristics of turbulence intensity

Figure 7 shows that the average wind speed from ground to 100m height is 6.7m/s, which increases with the height, and the dominant wind speed is 4.0m/s. The average wind speed at the height of 10m, 30m, 50m, 70m and 100m are 6.0m/s, 6.4 m/s, 6.7m/s, 7.0m/s and 7.5m/s respectively. The highest and the lowest wind speed frequency occurs at the heights of 10m and 100m layers, which account for more than 22.5% and 12.5%. The wind speed decreased from 6 m/s in the low layer, which increased in the high layer. Starting from the wind speed of 6m/s, the proportion of lower layers wind speed decreases, while that of high layers wind speed increases. The I_t values are different among these three regions in the study area, the NEC region is the largest, followed by the NWC, and the I_t value in NC stations are the smallest. Under the wind speed of 3.0-25.0m/s and 15.0m/s, the average I_t of each layer are 0.118 and 0.099 respectively; the maximum values are 0.189 and 0.120 at the height of 10m in NEC region, and the minimum are 0.082 and 0.063, both of which appear in the 100m gradient in NC region and NWC region respectively(**Table 2**).

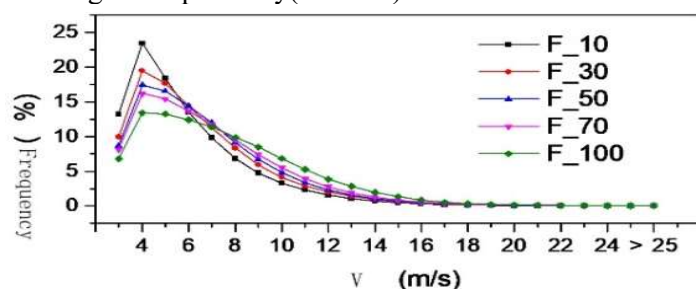


Figure 7. Velocity distribution of wind speed grades with different gradients.

The standard deviation, SD, of the pulse wind speed can clearly reflect the I_t to some certain extent. The wind speed SD of YH and SSJF in Xinjiang, YBLZ, HLGLSM and HLGL in Neimenggu, DZZ,

NNG and XTZ in Liaoning, YMT and DS in Heilongjiang are relatively large; the I_t in YBLZ, DZZ and NNG is relatively bigger than others; and the I_t is relatively high in all stations in Heilongjiang except FL, QDMS, KSZXC, NJT and FJ station (Figure 8).

Table 2. Multi-year average I_t at different gradients from 3~25 m/s and 15 m/s in different regions.

	3-25 m/s					15 m/s				
	I_{10}	I_{30}	I_{50}	I_{70}	I_{100}	I_{10}	I_{30}	I_{50}	I_{70}	I_{100}
NWC	0.139	0.119	0.112	0.11	0.105	0.118	0.102	0.095	0.08	0.063
NC	0.132	0.117	0.108	0.105	0.082	0.114	0.103	0.097	0.094	0.084
NEC	0.189	0.138	0.118	0.111	0.087	0.12	0.118	0.11	0.106	0.081
AVG	0.153	0.125	0.112	0.109	0.092	0.117	0.108	0.101	0.093	0.076

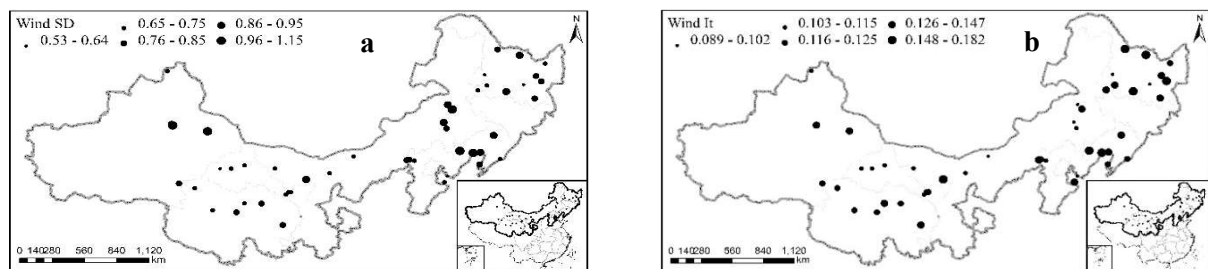


Figure 8. Multi-year average I_t and wind speed standard deviation distribution.

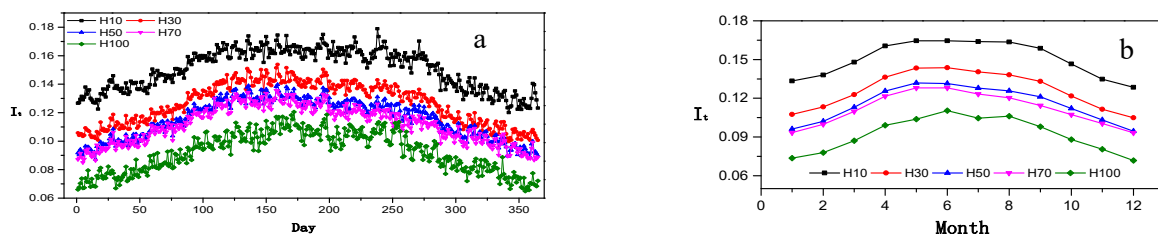


Figure 9. Daily and monthly variation of average gradient I_t .

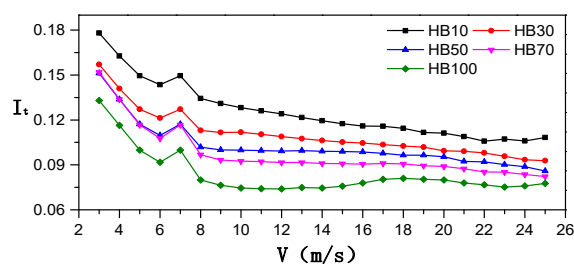


Figure 10. Average I_t of each gradient at different wind speed levels.

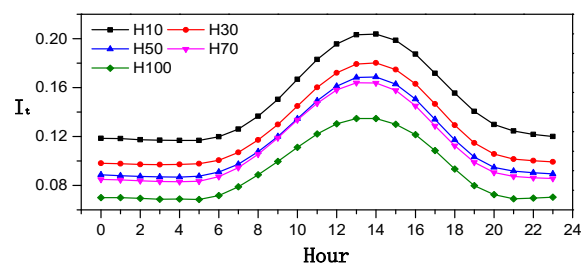


Figure 11. Hourly variation of mean I_t at 3-25m/s with various gradients.

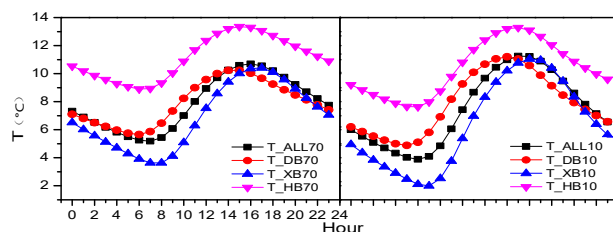


Figure 12. Daily variation of air temperature at height of 10m and 70m in each region (note: air temperature observation is only carried out at height of 10m and 70m in height wind tower below 100m).

Besides the relationship between wind speed and air density, the roughness of underlying surface is the main factor of atmospheric turbulence. Among these three regions, the NWC region has the highest relative altitude and the terrain is undulating (**Figure 2**). However, the underlying surface in this region is dominated by gobi desert, compared with the large-scale forest underlying surface of the Greater and Lesser Hinggan Mountains in the NEC region, the surface roughness in the NWC region is relatively low, and the overall wind turbulence is relatively small. In NC region, the terrain is more flat, the underlying surface is more uniform, and the disturbance to near-surface air is minimal, the I_t is also relatively low.

Figure 9 illustrates that each layer's I_t correspond to the variation trend of the air temperature. In summer, the near-surface temperature is the highest in the study area, and the I_t of gradients also reaches the maximum. The variation ranges of I_t among adjacent layers are different, the lower the layer is, the greater range of change occurs. The differences between the 10-30m, 30-50m, 50-70m are 0.028, 0.013 and 0.003 respectively. The I_t are basically the same at the height of 50 m and 70 m, which further confirms the statement that turbulence occurs in the boundary layer at the bottom of the atmosphere.

5.2. Temporal variation characteristics of turbulence intensity

There are two main causes of atmospheric turbulence. One is the ground friction or retardation, and the other one is the difference from the air temperature or air density; they refer to the atmospheric dynamic conditions and the atmospheric thermal conditions respectively. With the increase of wind speed, the turbulence intensity value decreases gradually. The lower the layer is, the greater the wind disturbance caused by near-surface friction, and the more obvious the turbulence occurs, especially in small winds; with the change of temperature, as the difference in thermal properties shows, land temperature changes more rapidly than atmosphere, so it has more obvious disturbance to the air.

As can be seen from **Figures 10-11**, with the increase of wind speed, the I_t value gradually decreases. In addition, each layer's I_t increases slowly from 06:00 on a daily scale, peaking at around 0.21 at about 14:00, then declining gradually for the rest of the day.

The stability of temperature stratification is extremely important for atmospheric turbulence. Under neutral and stable stratification conditions, the influence of temperature can be ignored, while under unstable stratification conditions, temperature has a significant influence on turbulence intensity, and the I_t increases with temperature in an approximate exponential rule [20]. As can be seen from **Figure 12**, both the height of 10 m and 70 m in the study area shows the lowest temperature around 07:00, then gradually increased, reached the highest value around 15:00, and then gradually decreased; the variation trend of atmospheric turbulence intensity is basically corresponding to the change of air temperature. The main reason is that the atmospheric disturbance increases with the temperature, and the instability trend of the atmosphere also strengthens. The temperature in north China is higher than that in other regions no matter 10 m or 70 m, which is mainly related to the geographical location of this region.

The turbulence intensity under high wind conditions should be calculated in the process of wind farm layout or wind resource assessment. In China's national standard for wind resource assessment in a wind farms, the maximum I_t within 10min of 1h is taken as the representative value of the I_t for that hour, and if the I_t value is 0.1 or less, it indicates the I_t is relatively small; the moderate turbulence intensity is 0.1-0.25; if the value is over 0.25, that indicates the I_t is too large [22]. Based on the average I_t at 15 m/s wind speed, the third edition of IEC61400-1 divides the wind turbine into three levels: A, B and C, respectively representing the turbulence characteristic level in high, moderate and low, and their values are 0.16, 0.14 and 0.12 [13]. It can be seen from the velocity spectra of different gradients of wind speed in the study area (**Figure 7**). Begin with the wind speed of 6 m/s, the proportion of low layer winds is reduced, and of high layer winds is increasing. Considering the

effects of low wind speed and low layer disturbance on overall turbulence, the I_t at wind speeds greater than 6 m/s (5.5 m/s to 6.4 m/s) is selected to analyse the time variation of wind turbulence intensity.

5.2.1. North-east China. Most station's I_t in NEC region generally increases from around 08:00, peaking the maximum value around 12:00, and then gradually decreases, dropping to the value of 08:00 at about 16:00 (**Figure 13**). Due to the influence of underlying surface forest land on the near-formation air, the turbulence intensity values of 10 m layer in all stations are the highest, except for NGT station; and the difference between 10-30 m is also the largest, especially in the stations of DS, DSC, HG and XLDS in Heilongjiang; besides, the I_t in this region is also the largest in the overall study area.

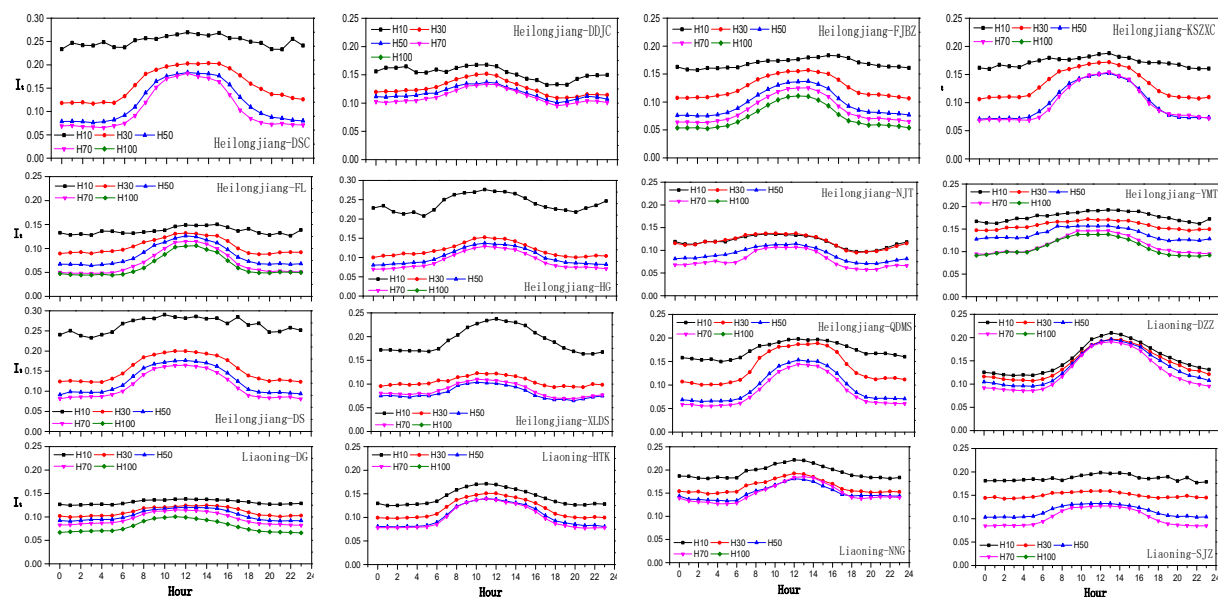


Figure 13. 24-hour trend of different gradient I_t at stations in North-East China.

5.2.2. North-west China. In the 19 stations in NWC region, except ESLD, HBHX, SSJF and YC in Xinjiang, the I_t of the most stations show obvious hourly change trend. Generally, the I_t gradually increase from about 10:00, reach the maximum value around 15:00, and then gradually decrease, and drop to the value of 08:00 around 18:00 (**Figure 14**). I_t difference between these 5 gradients are relatively small. In addition, the variation of the I_t of the 50 m gradient in the HBHX in Xinjiang is relatively bigger than other gradient's, which needs to be further analysed; for the geographical location reason, the gradient turbulence value of 100 m in SSJF shows a downward trend after 09:00. The SSJF station locates in the canyons of the two mountains, due to the narrow pipe effect, the wind speed in high layer is large, and the ground disturbance is small [16].

North China. In the 12 stations in NC region, the overall I_t is the lowest in the study area. Except for HCL in Hebei, YBLZ and HNLSM station in Neimenggu, the hourly I_t variation and the difference between the adjacent gradient in rest stations are relatively small (**Figure 15**). The 10 gradient time change is not significant in Tianjin DGYT station, which is related to the underlying surface of the waters [23].

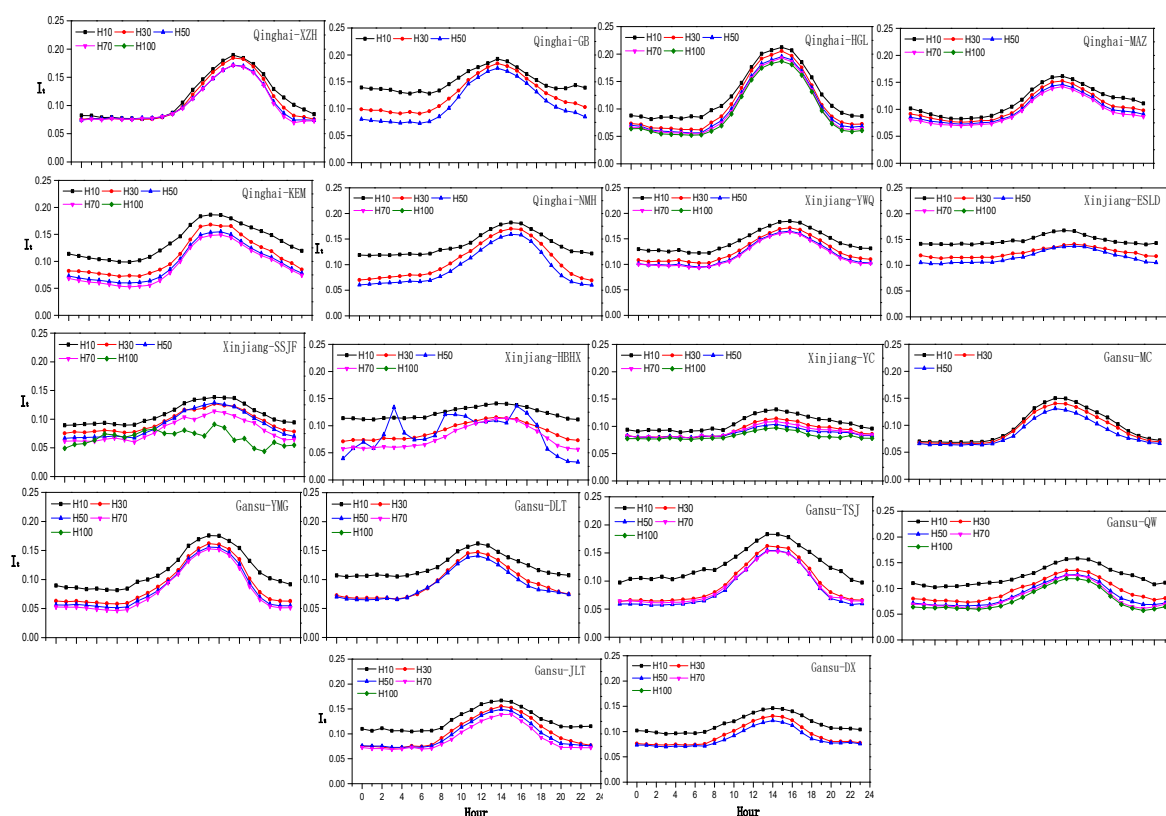


Figure 14. 24-hour trend of different gradient I_t at stations in North-West China.

5.3. Discussion

IEC classifies wind turbines into three grades A, B and C according to the I_t [13], which represents wind turbines of high I_t , medium I_t and low I_t in turn, the corresponding I_t values are 0.16, 0.14, and 0.12, respectively. **Table 3** illustrates that the average I_t at all layers in this study area is 0.118, when the wind speed range is greater than 3.0 m/s. 10 m layer's I_t in NEC region is the biggest in all of the three region, reaching 0.176, which reaches the A turbines level according to the IEC classification standard [13]; and the I_t in the NWC and NC regions are relatively low. The average I_t in the three regions of 50-100 m is about 0.106. I_t in the height of 100 m is lower than other, and the highest in the NWC region in 100 m is 0.103.

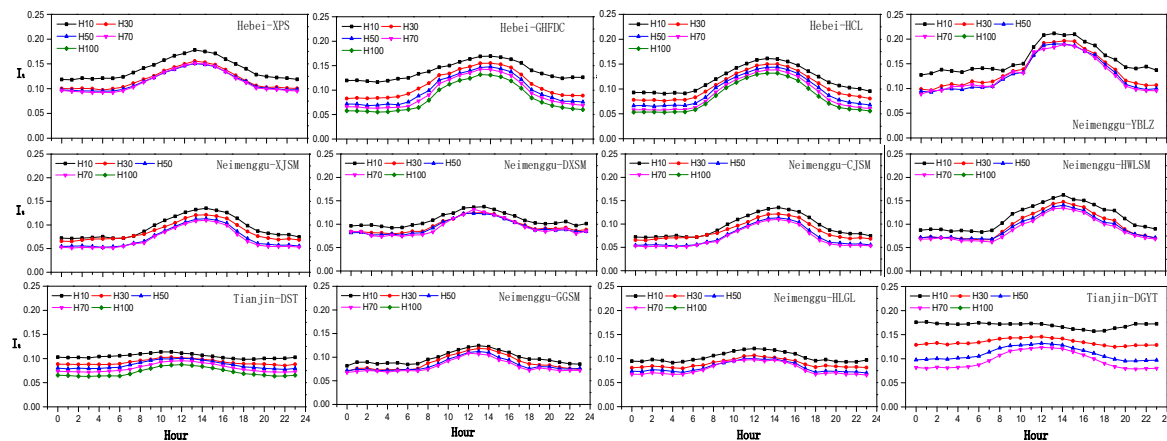


Figure 15. 24-hour trend of gradient I_t at stations in North China.

Table 3. The average I_t at all heights in the study area.

	Height 10m	Height 30m	Height 50m	Height 70m	Height 100m
NEC	0.176	0.141	0.120	0.115	0.092
NWC	0.138	0.119	0.114	0.113	0.103
NC	0.136	0.116	0.107	0.101	0.083
ALL	0.150	0.125	0.114	0.110	0.093

As can be seen from **Figure 10**, the wind turbine reach the C and B level respectively at the height of 30 m and 10 m in the study area when the average wind speed is lower than 6m/s. Based on the further analysis of the gradient distribution and temporal variation of I_t in the study area in **Figure 13-15** we can find that the value of I_t at all gradients of all stations is basically greater than 0.14, that is all the wind turbine type in these areas is basically at least at B level, except for DST in Tianjin, XJSM, DXSM, GGSM and HLSM in Neimenggu, SSJF and YC in Xinjiang, DG in Liaoning and NJT in Heilongjiang. Heilongjiang's DSC, Liaoning's DZZ and NNG, Gansu's YMT, Qinghai's XZH, HGL and HST, Neimenggu's YBLZ, which at 70m height and Qinghai's HGL at 100m height, whose I_t is greater than 0.16, and the wind turbine type in these stations at the corresponding heights should be at least A level.

What we should note is that the wind turbines in the wind farm are subjected to effective turbulence intensity, consisting of two parts: the ambient turbulence intensity and the turbulence intensity generated by the wake of the wind turbines. The I_t from ambient is the one that calculated in this study, which is the single point result of wind tower without considering the influence of the wind turbine wake, and the effective I_t in the actual wind farm is greater than the ambient turbulence intensity; in addition, the ambient turbulence intensity is generally calculated from the wind speed of 15 m/s, that is, the characteristic value of I_t , which will become the noise of actual I_t if calculating at the lower wind speed. The effective I_t in the actual wind farm is not only related to the local terrain, landforms and obstacles of the wind farm, but also related to the specific location of each wind turbine, the dominant wind direction of the wind farm and the height of the unit hub. For example, the ambient turbulence at each wind speed range at the hub height of the wind farm may not exceed the Class B standard. While due to the small spacing of the wind turbines along the dominant wind direction, the effective I_t of some units with severe downwind wake effects in some wind speed ranges will greatly exceeds the B standard.

The ambient I_t of individual stations in this study may be larger than actual. Selecting a wind turbine with a higher I_t level is necessary in the actual wind farm layout; besides, the height of the hub of the wind turbine can be appropriately increased in combination with the actual situation under the conditions of economic feasibility. Under normal circumstances, as the height of the hub of the unit increases, the average wind speed also increases. The higher the distance from the ground, the smaller the influence of the airflow on the surface roughness, the more stable the airflow is, and the effective I_t can be reduced in this process; in addition, widen the distance between the wind turbine and upwind turbine so as to reducing the influences from the wake of other turbines. As for how to determine the hub height of each station, a comprehensive consideration should be given to the richness of wind resources at each height and the wind speed shear at each layer.

6. Conclusions and prospects

The I_t at the hub height reflects the normal fatigue load borne by the wind turbine in operation, and it is one of the important parameters that must be considered in the wind resource assessment and wind farm construction. In this study, the automatic weather station, AWS, observation data is used to analyze the climatic background of the study area. Based on the daily 10-minute wind observation results of the wind tower in the Three-North Regions of CWERPON from 2013 to 2017, the wind turbulence conditions of different regions, different gradients and different time periods are analyzed, and the main conclusions were as follows:

1) The results of the ground AWS analysis show that the highest frequencies of wind direction in the study area is the southwest wind, followed by the west wind and the northwest wind. The maximum wind speed bigger than 5.0 m/s in the 10 m layer exceeds 200 days. The average wind speed generally shows a downward trend over the years. Except for the NWC region, the annual variation of the wind speed in the NEC and NC regions presents a bimodal distribution with the

highest value in March and October to November, highest in NEC region, followed by NC region, and the smallest is in NWC region. The southwest of Xinjiang, Qinghai, Gansu, Hebei and the southeast of three provinces in NEC region, and also in the junction of northeastern Neimenggu and Heilongjiang have relatively low wind speed, while the rest areas the wind speed are more bigger than other, especially in the mid-west of Neimenggu and eastern Xinjiang, the average multi-year wind speed is nearly 7m/s.

2) The average wind speed from ground to 100 m height is 6.7m/s, which increases with the height, and the dominant wind speed is 4m/s. The average wind speed at the height of 10m, 30m, 50m, 70m and 100m are 6.0m/s, 6.4 m/s, 6.7m/s, 7.0m/s and 7.5m/s respectively. The highest and the lowest wind speed frequency occurs at the heights of 10m and 100m layers, which account for more than 22.5% and 12.5%. Starting from the wind speed of 6 m/s, the proportion of lower layers wind speed decrease, while that of high layers wind speed increase.

3) The average I_t decreases from low layers to high layers. Each layer's I_t decrease gradually with the increasing of wind speed. The I_t values are different among these three regions in the study area, the NEC region was the largest, followed by the NWC, and the I_t value in NC stations are the smallest. Under the wind speed of 3.0-25 m/s and 15.0 m/s, the average I_t of each layer are 0.118 and 0.099 respectively; the maximum values are 0.189 and 0.120 at the height of 10 m in NEC region, and the minimum are 0.082 and 0.063, both of which appear in the 100 m gradient in NC region and NWC region respectively.

4) The wind speed standard deviation of YH and SSJF in Xinjiang, YBLZ, HLGLSM and HLGL in Neimenggu, DZZ, NNG and XTZ in Liaoning, YMT and DS in Heilongjiang are relatively bigger than others; the I_t in YBLZ, DZZ and NNG are relatively high. The I_t of all stations in Heilongjiang are relatively large except for FL, QDMS, KSZXC, NJT and FJ stations.

5) The variation ranges of I_t among adjacent layers are different, the lower the layer is, the greater range of change occurs. The differences between the 10-30 m, 30-50 m, 50-70 m are 0.028, 0.013 and 0.003 respectively. The I_t is basically the same at 50 m and 70 m. In NEC region, the I_t difference between adjacent gradients are relatively obvious. 10 m layer's I_t is the largest in all of the 5 layers, and the difference between the 10-30 m gradients is also the largest. The differences of I_t among the gradients in NWC region are relatively small; the overall I_t in NC is the lowest in the study area, and the difference among the gradients is also the smallest.

6) Each layer's I_t corresponded to the variation trend of the air temperature. I_t increased slowly from 06:00, which reached the maximum value around 14:00, and then decreased slowly. The specific conditions of different regions vary according to the conditions of the underlay surface. From the hourly I_t value of the wind speed above 6 m/s we can find that the I_t of most stations in NEC usually increase from around 08:00, reaching the maximum value around 12:00 and then decreasing gradually, till 16:00, dropping to the level of 08:00. Most of the stations in the NWC region generally increase gradually from around 10:00, peaking the maximum points at nearly 15:00 and then decreasing gradually, dropping to the value of 08:00 till 18:00. Most of stations' I_t in NC region are relatively small.

7) 10 m layer's average I_t in NEC region is the biggest in all of the three region, reaching the A turbines level. The average I_t in the three regions of 50-70 m is about 0.11, which in the height of 100 m is more lower than other. All the wind turbine type in these areas is basically at least at B level, except for DST in Tianjin, XJSM, DXSM, GGSM and HLGM in Neimenggu, SSJF and YC in Xinjiang, DG in Liaoning and NJT in Heilongjiang. Heilongjiang's DSC, Liaoning's DZZ and NNG, Gansu's YMT, Qinghai's XZH, HGL and HST, Neimenggu's YBLZ, which at 70m height and Qinghai's HGL at 100m height, and the wind turbine type in these stations at the corresponding heights should be at least A level. The wind turbine reach the C and B level respectively at the height of 30 m and 10 m in the study area when the average wind speed is lower than 6.0 m/s.

Future research will focus on the study of the beneficial impacts of turbulence intensity on wind energy harvesting and the relationship between the different turbulence intensity and the height of the turbines should be installed in these three regions.

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