10th Deep Sea Offshore Wind R&D Conference, DeepWind'2013

Experimental characterization of the marine atmospheric boundary layer in the Havsul area, Norway

Konstantinos Christakos[a,*], Joachim Reuder[a], Birgitte R. Furevik[a,b]

[a]*Geophysical Institute, University of Bergen, Allegaten 70, 5020 Bergen, Norway*
[b]*Norwegian Meteorological Institute, Allegaten 70, 5020 Bergen, Norway*

Abstract

Offshore wind energy applications depend strongly on an improved knowledge of the physical processes taking place in marine atmospheric boundary layer (MABL). In particular the better understanding of the complex interactions between wind shear, atmospheric stability and turbulence and the effects of wind-wave interactions on offshore vertical wind profiles are essential for the development of offshore wind projects. This paper presents an analysis of the relation between turbulence parameters, such as horizontal and vertical turbulence intensity, and turbulence kinetic energy and average vertical wind profiles and wind shear. The investigations are based on 4 years of wind lidar measurements on the small island of Storholmen in the Havsul area about 8 km off the coast of the Norwegian mainland. The results show systematic dependencies between the investigated turbulence parameters, both with respect to average wind speeds and average wind shear. The results indicate that in particular the horizontal turbulence intensity has the potential to act as a proxy for atmospheric stability in cases where corresponding temperature profiles are not available.

1. Introduction

The offshore wind power production has grown rapidly over the last two decades. In 1991, the first off-shore wind farm was inaugurated for a total capacity of 4.95 MW, 2.5 km off the Danish coast at Vindeby [1]. By the end of 2011, 1662 turbines installed and grid connected 4.995 MW in 55 wind farms spread across Europe [2]. A better understanding of the physical processes in the marine atmospheric boundary layer (MABL) becomes critical important for the development of offshore wind farms. Measurements of the offshore wind field are of essential relevance for the characterization of the MABL. However the main problem is the lack of observational data in the relevant altitude range. For this reason meteorological remote sensing instruments are used in this field, such as LIDAR (LIght Detection And Ranging) and

* corresponding author: Konstantinos Christakos
E-mail address: Konstantinos.Christakos@student.uib.no

SODAR (SOnic Detection And Ranging). The lidar is an active remote sensing instrument which relies on the the measurement of Doppler shift of laser radiations backscattered by particles in the air [3].

Lidar systems can take simultaneous measurements of the wind velocity up to several hundred meters, a region hardly accessible by meteorological masts. In addition they are more flexible with respect to positioning and handling. This remote sensing technique has progressed significantly during the last years and is on its way of being widely accepted as essential part of wind resource analysis and related scientific investigations of the MABL.

On the other hand atmospheric conditions can limit the data availability of lidar systems. The availability is in general dependent on the carrier to noise ratio (CNR) of the reflected lidar signal, mainly influenced by the distance from the light source and the amount of aerosol particles in the scattering volume. Reliable wind profile measurements require a minimum value of the CNR, measurements below this threshold are omitted from the data set. Other atmospheric parameters, as atmospheric turbulence and relative humidity also can affect the CNR [4]. In case of precipitation, the vertical velocity measured by the lidar is in addition biased by the fall velocity of the rain droplets [4].

During the last years, many studies are focused on the effect of atmospheric stability characteristics on the wind power generation. Rareshide et al. (2009) [5] studied the sensitivity of power curves to wind shear in the regions of the US Great Plains/Midwest region. They found that high positive wind shear is related to higher wind power than when wind shear was low. On the other hand, Wagner et al. (2009) [6], found that high wind shear decreased power output in comparison with no wind shear, based on wind turbines on flat terrain at Høvsøre in the northwest of Denmark. Kaiser et al. (2003) [7] suggested that measured wind power curves are influenced by the turbulence intensity. Unfortunately wind lidars, can not provide the required temperature structure of the atmosphere for direct stability analysis. However, Wharton and Lundquist (2012) [8], [9] recently presented a method to determine atmospheric stability from various turbulence related parameters, as horizontal and vertical turbulence intensity, turbulence kinetic energy, and wind shear, derived by a SODAR system. These measurements took place at a wind farm at the North American West Coast. The study presented here aims to transfer and investigate the applicability of the method based on SODAR measurements for an onshore boundary layer to offshore conditions, probed by a lidar system. It examines the relationship between the corresponding turbulence parameters, including horizontal turbulence intensity (I_U), vertical turbulence intensity (I_w) and turbulence kinetic energy (TKE) on average wind speed and average wind shear.

2. Data and Methods

2.1. Data Overview

Wind profile data were collected from January 2008 to January 2012 at the small island of Storholmen in the Havsul area (Fig. 1), located about 8 km northwest of the island of Vigra on the West coast of Norway. The measurements were taken with a lidar wind profiler (WindCube v.1 by Leosphere) deployed at 20 m above sea level (asl). Wind speed and wind direction was measured at eight height levels between 60 m and 200 m asl. The basic sampling rate of the instrument was set to 1 Hz, providing independent wind profiles every 4 seconds. The investigations are based on 10 minute average wind profiles and wind speed variances over this time period. Due to the processes discussed above in the introduction, the data availability of the lidar system decreases with the height in the atmosphere. While the lowest level of 60 m asl reaches an average data availability of 76.82%, this value is reduced to 75.87% at 100 m asl and 42.54% at 200 m asl. For the further analysis, only data sets of complete profiles between 60 m and 150 m asl have been used, leaving a total of 75249 profiles for this investigation.

2.2. Theory

The horizontal turbulence intensity (I_U, %) is a dimensionless parameter which measures the turbulence fluctuations in the wind field. Mathematically it is defined as the standard deviation of horizontal
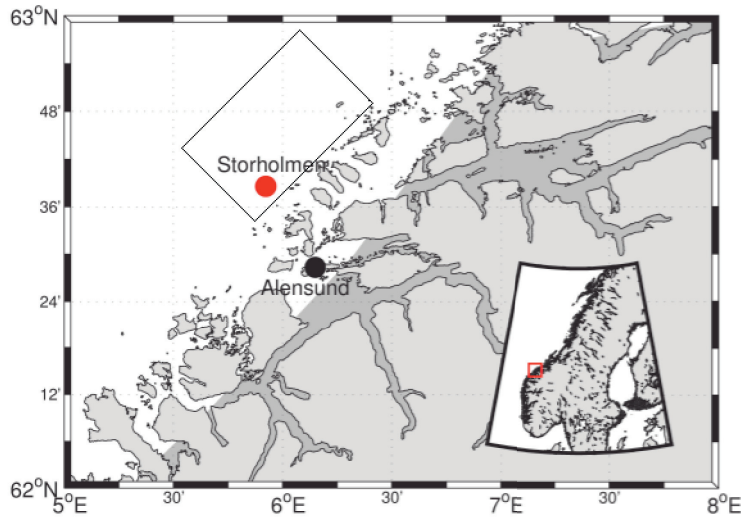
Fig. 1: Location of Storholmen island (red dot) in Havsul (selected area) off the coast of Alesund, Western Norway.

velocity fluctuation divided by the mean horizontal wind speed (U in m/s), in this study taken at a reference height of 100 m asl:

$$I_U = \frac{\sqrt{\sigma_u^2 + \sigma_v^2}}{U} \tag{1}$$

The horizontal wind speed U is calculated form latitudinal and longitudinal velocity components measured by the LIDAR as $U = \sqrt{u^2 + v^2}$. The vertical turbulence intensity (I_w, %) can be calculated correspondingly based on the standard deviation in the vertical velocity:

$$I_w = \frac{\sigma_w}{U} \tag{2}$$

Finally, the turbulence kinetic energy (TKE, m^2/s^2) is an important variable in boundary layer meteorology because it is a direct measure of the three dimensional turbulence. TKE is defined as the sum of the velocity variances in latitudinal (u), longitudinal (v) and vertical (w) direction divided by 2.

$$TKE = \frac{1}{2}(\sigma_u^2 + \sigma_v^2 + \sigma_w^2) \tag{3}$$

3. Results

3.1. Horizontal Turbulence Intensity

According to previous studies of offshore wind, e.g. [10] , a log-normal distribution has been applied to describe the turbulence intensity distribution. Fig. 2 presents the resulting distributions of turbulence intensity for different classes of wind speed at 100 m asl. The height of 100 m asl is selected as typical level for the nacelle heights of state of art wind turbines. The distribution parameters were computed using the maximum likelihood estimates (MLEs).

The results show a distinct dependency of the probability density distributions on the wind speed. For increasing wind speed the distribution narrows while its center moves towards lower turbulence
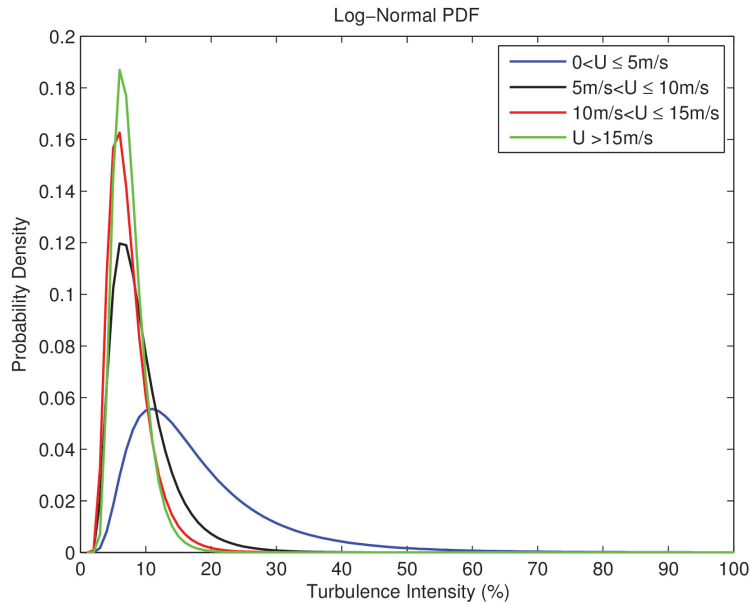
Fig. 2: Log-normal distribution of the horizontal turbulence intensity I_U for different classes of wind speed at 100 m asl.

intensities. Simultaneously the peak value increases. In general there is a decrease of turbulence intensity for an increase in wind speed. However, for wind speeds greater than 10 m/s, the turbulence intensity remains nearly constant. Average vertical wind profiles for different horizontal turbulence intensity classes are presented in Fig.3 (left). For classification of the turbulence intensity the level 100 m asl has been selected. There is a clear dependency between turbulence intensity and average wind profiles. For turbulence intensities greater than 6% (51396 vertical wind profiles, corresponding to 68 % of the data), an increase of U is related to decrease of turbulence intensity. For turbulence intensities below 9% (46663 vertical wind profiles, 62% of the data) the average profiles are closely grouped between 10 m/s and 12 m/s. For an easier comparison of the dependency of wind shear on horizontal turbulence intensity, the profiles have been normalized to 1 at 100 m asl. The results (Fig. 3, right) show a general increase in wind shear for decreasing turbulence intensities. For $I_U \geq 20\%$ (6603 vertical wind profiles, corresponding to 8.77 % of the data) which is related to low wind speeds (ca. 2m/s), the profile shows a distinctly enhanced wind shear in particular at the highest levels. However this wind speed region is hardly of interest for offshore wind energy applications.

3.2. Vertical Turbulence Intensity

The vertical turbulence intensity can also be used for the classification of atmospheric stability [8], [9]. Average vertical wind profiles for different vertical turbulence intensity classes at 100 m asl are presented in the left panel of Fig. 4. For a vertical turbulence intensity greater than 4 % (31333 vertical wind profiles, corresponding to 41.63 % of the data), the higher I_w, the lower the wind speed. For turbulence intensities below 4 % (43916 vertical wind profiles corresponding to 58 % of the data) the average profiles are grouped again between 10 m/s and 12 m/s. In the right panel of Fig. 4 the vertical wind profiles are again normalized to 1 at 100 m asl. The results show that for levels below 100 m asl a decrease of the wind shear is related to an increase of I_w. For levels above 100 m asl there is a weaker dependency between wind shear and I_w than closer to the ground.
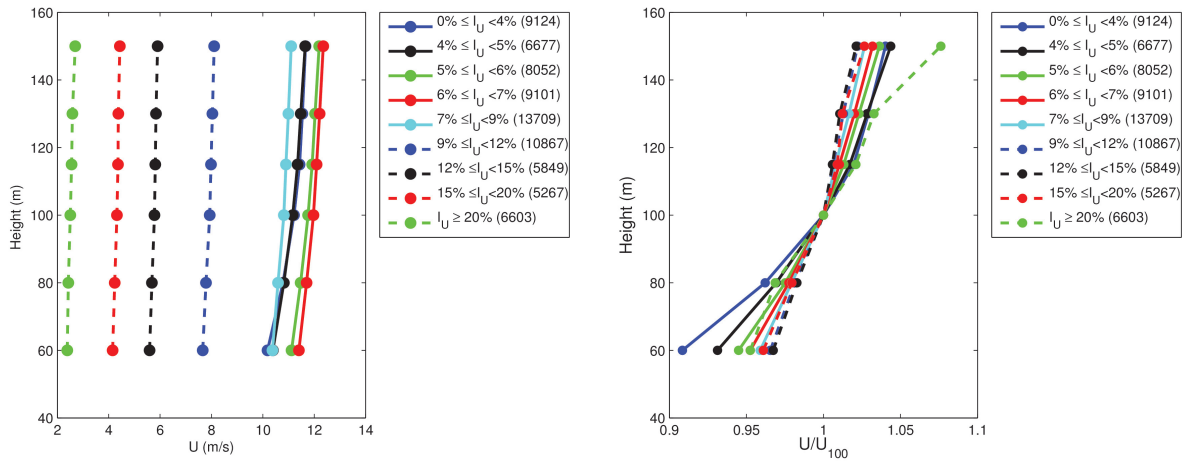
Fig. 3: Average vertical wind profiles for different classes of I_U at 100 m asl (left) and the corresponding normalized profiles right). The number of profiles for each class is given in parenthesis.
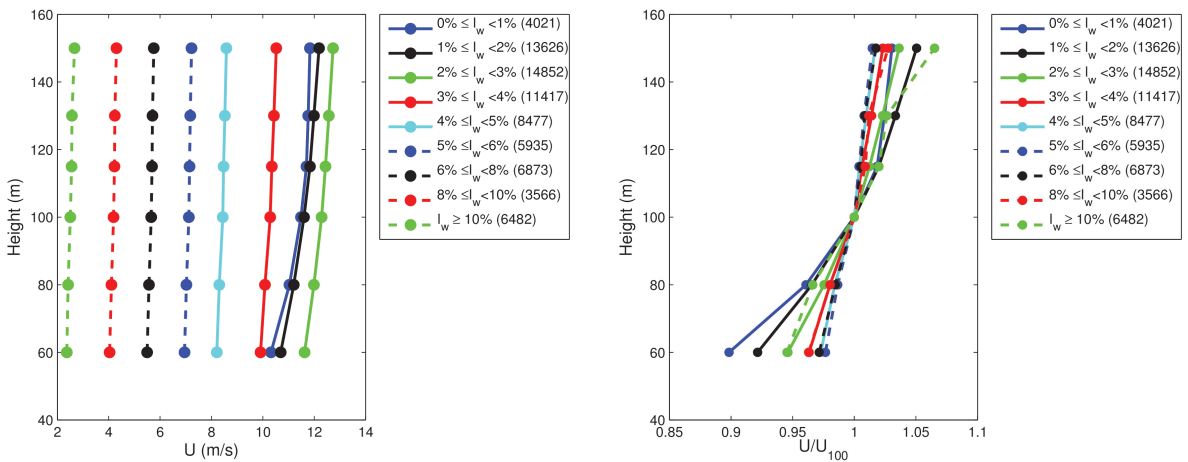

Fig. 4: Average wind profiles for different classes of I_w at 100 m asl (left) and the corresponding normalized profiles (right). The number of profiles for each class is given in parenthesis.

3.3. Turbulence Kinetic Energy

TKE is a measure for the energy content related to the 3-dimensional eddy motions in turbulent flow and is also indirectly related to the ability of transporting heat, moisture, and momentum through the boundary layer. TKE can be produced both by buoyancy and wind shear. Buoyancy production is related to thermally induced convection, while the shear production term of TKE represents the interaction of the turbulent momentum flux with the mean vertical wind shear that generates turbulence as described by e.g. Stull (1988) [11]. Fig.5 (left) presents average wind profiles for different TKE classes. For the classification the height of 100 m asl has been selected.

There is a clear relationship between the TKE and the wind profiles. The higher the TKE, the higher the wind speed. The highest TKE class i.e. TKE$\geq 1.4 m^2/s^2$ (3577 vertical wind profiles, corresponding
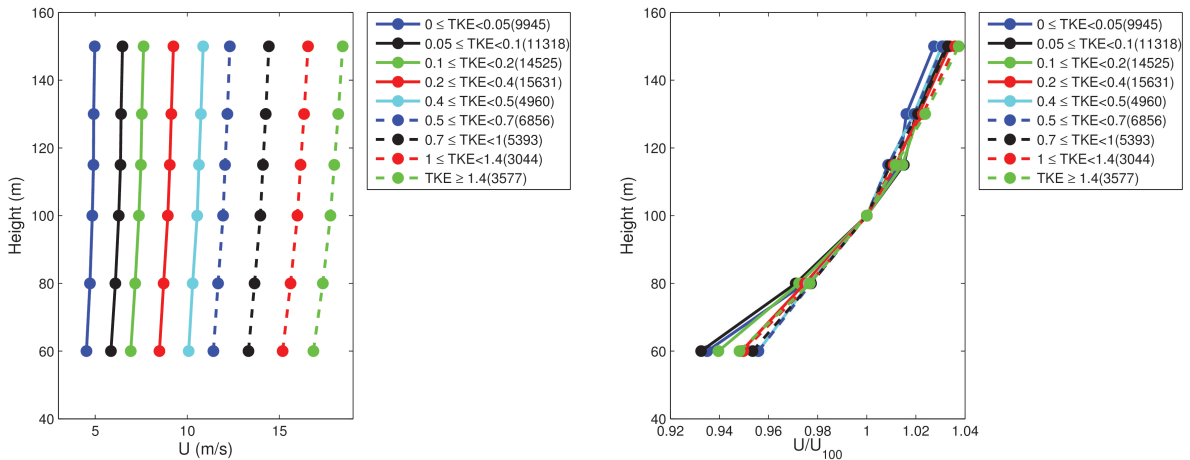
Fig. 5: Average wind profiles for different classes of TKE at 100 m asl (left) and the corresponding normalized profiles (right). The number of profiles for each class is given in parenthesis.

to 4.7 % of the data) corresponds to wind speeds greater than 16 m/s. On the other hand, for low TKE$\geq 0.1 m^2/s^2$ (21263 vertical wind profiles, corresponding to 28.25 % of the data), the wind speed is much lower (4-6 m/s). This behavior indicates that the TKE is predominantly generated by wind shear in the lowest 100 meters of the MABL. For an easier comparison between TKE and wind shear the vertical wind profiles are normalized to 1 at 100 m asl in the right panel of Fig. 5. For lower levels (60 m and 80 m asl), the wind shear is decreasing for increasing TKE. For levels above 100 m asl the wind shear becomes nearly independent of the TKE level.

4. **Summary and Outlook**

In the present study an analysis was performed to investigate the relationship between different turbulence parameters and offshore wind profiles based on 4 years of lidar measurements on the island of Storholmen off the Western coast of Norway. The results show that the investigated turbulence parameters, such as horizontal turbulence intensity, vertical turbulence intensity and turbulence kinetic energy, are strongly related to the average wind speed and the average shear of the profiles. The results indicate that it should be possible to adapt the general idea of determining stability classifications without temperature profile measurements, originally described for SODAR measurements onshore by Wharton and Lundquist (2012) [8], for offshore conditions and LIDAR measurements. Based on the presented study, the horizontal turbulence intensity seems to have the best potential for a corresponding stability classification for offshore conditions. However, the further development of this method, in particular the selection and validation of relevant threshold values of I_U, will require a tailored measurement campaign with parallel measurements of temperature and wind profiles offshore.

References

[1] EWEA. Wind in our Sails - The coming of Europe's offshore wind energy industry. 2011;.

[2] EWEA. The European offshore wind industry - key trends and statistics 2012. 2013;.

[3] LEOSPHERE. Windcube User's Manual. March 2008;.

[4] Aitken ML, Rhodes ME, Lundquist JK. Performance of a Wind-Profiling Lidar in the Region of Wind Turbine Rotor Disks. J Atmos Oceanic Technol. March 2012;29:347–355.

[5] Rareshide E, Tindal A, Johnson C, Graves A, Simpson E, Bleeg J, et al. Effects of complex wind regimes on turbine performance. Proceedings American Wind Energy Association WINDPOWER Conference (Chicago, IL). 2009;.

[6] Wagner R, Antoniou I, Pedersen SM, Courtney MS, Jørgensen HE. The influence of the wind speed profile on wind turbine performance measurements. Wind Energy. 2009;12(4):348–362.

[7] Kaiser K, Hohlen H, Langreder W. Turbulence correction for power curves. Proceedings European Wind Energy Conference and Exhibition (Madrid). 2003;.

[8] Wharton S, Lundquist JK. Assessing atmospheric stability and its impacts on rotor-disk wind characteristics at an onshore windfarm. Wind Energy. 2012;15(4):525–546.

[9] Wharton S, Lundquist JK. Atmospheric stability affects wind turbine power collection. Environmental Research Letters. 2012;7(1):014005.

[10] Larsen GC. Offshore fatigue design turbulence. Wind Energy. 2001;4(3):107–120.

[11] Stull RB. An Introduction to Boundary Layer Meteorology. Atmospheric Sciences Library. Kluwer Academic Pub; 1988.