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Analysis of the Turbulence Intensity at Skipheia Measurement Station

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Analysis of the Turbulence Intensity at Skipheia Measurement Station

Analyse av turbulensintensitet ved Skipheia målestasjon

Located on the island Frøya, off the west coast of Mid-Norway, Skipheia measurement station is exposed to both maritime winds and land breezes. The site is therefore assumed able to represent both onshore and offshore wind conditions. Two years of data from a 100-meter high meteorological mast are available, and the work here is to investigate the turbulence intensity (TI) at Skipheia.

The International Electrotechnical Commission (IEC) has conducted two guidelines [1, 2] on design requirements for wind turbines in onshore and offshore environments, respectively. These guidelines present the Normal Turbulence Model (NTM), in which three wind turbine classes are defined, depending on wind speed and turbulence parameters. NTM is based on onshore observations in Europe and America, and is originally meant for onshore wind turbine design only. However, due to incomplete insight in offshore wind characteristics, it is common practice to adopt onshore wind models to offshore wind turbine design. It is therefore necessary to review the IEC guidelines and consider whether they apply to offshore as well as onshore wind conditions. In this case, TI data from Skipheia should be used to evaluate the suitability of NTM, for winds representing both onshore and offshore environments.

[1] IEC, "International Standard IEC 61400-1," in *Wind turbines - Part 1: Design requirements*, ed. Geneva, Switzerland: International Electrotechnical Commission, 2005.

[2] IEC, "International Standard IEC 61400-3," in *Wind turbines - Part 3: Design requirements for offshore wind turbines*, ed. Geneva: International Electrotechnical Commission, 2009.

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☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
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Department of Energy and Process Engineering, 14. January 2015

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Analysis of the Turbulence Intensity at Skipheia Measurement Station

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***Abstract*—Two years of data from the coastal measurement station at Skipheia in Norway have been analysed to characterise the atmospheric turbulence intensity (TI) in the wind. In addition to consider all data at 70 meters in one, two direction sectors have been chosen to represent onshore and offshore conditions. The turbulence intensity has been investigated in terms of atmospheric stability, seasonal variations, diurnal patterns and measurement height. Additionally, the results are compared to predictions for TI given by the International Electrotechnical Commission (IEC) through the Normal Turbulence Model (NTM). Previous work has found NTM to be incompatible with coastal and offshore measurements, and this is also the case in the current study. For Skipheia, TI in the offshore sector was observed to be slightly less than in the onshore sector, and the diurnal TI pattern more pronounced in the latter. In addition, differences in TI between the two sectors are more distinct in summer than in winter. This work is hoped to contribute to a better understanding of coastal and offshore wind regimes, and for further research of the conditions at Skipheia.**

1 INTRODUCTION

Turbulence can be thought of as disorderly fluctuations in the wind, caused by dissipation of the wind's kinetic energy into thermal energy. This happens through formation and destruction of progressively smaller eddies, and seems to arise quite randomly. However, the wind's variability has some distinct features, which can be described by a number of statistical properties. One of these is turbulence intensity (TI), which can be referred to as the level of turbulence in the wind [1].

This work contains an analysis of the turbulence intensity at Skipheia measurement station, based on two years of data from a 100-meter high met-mast. Located on the west coast of Norway, the site gives possibilities to measure winds originating from both inland and ocean, and hence to some extent representing both onshore and offshore conditions. A main difference between the two is the surface interacting with the wind, i.e. the earth or the sea. Water is generally smoother than onshore surfaces, which leads to less turbulence from surface shear in offshore environments than in onshore environments. In addition, the marine atmospheric boundary layer is usually more stable than the atmospheric boundary layer over land, which leads to a less turbulent atmosphere offshore [2].

Turbulence intensity plays an important role in relation to wind turbines, regarding both fatigue loads, power performance and cost. With a growing demand of renewable energy, wind is an increasingly significant energy source and a relevant topic for discussion. However, building a wind farm is challenging, both technically and economically. Accordingly, the International Electrotechnical Commission (IEC) has conducted several standardising guidelines concerning wind turbines, where two revolve around design requirements for turbines in onshore and offshore environments, respectively [3, 4].

Due to incomplete understandings of offshore wind characteristics, current guidelines for offshore wind turbine design, like the one conducted by the IEC [4], adopt onshore wind models for offshore conditions [5]. This undoubtedly leads to poor predictions of wind conditions in offshore locations, as shown in previous research considering offshore turbulence intensity [5-8]. Common findings in these studies say that predictions for onshore turbulence intensity are far too high when applied to offshore environments. In addition, offshore turbulence intensity typically increases at high wind speeds, whereas onshore guidelines predict a monotonic decrease. Appropriate data from Skipheia have therefore been tested against the IEC guidelines, to see whether these findings apply here too.

The dataset and measurement site are presented in Chapter 2. Chapter 3 generally defines and describes turbulence intensity together with atmospheric stability, and Chapter 4 introduces the two IEC guidelines. In addition to be compared to recommendations in these guidelines, the turbulence intensity at Skipheia is analysed with respect to atmospheric stability, seasonal and diurnal variations, and measurement height, all in Chapter 5. Chapter 5.3 discusses similarities and dissimilarities in the turbulence intensities for onshore and offshore conditions at Skipheia.

2 MEASUREMENT SITE AND DATASET

Approximately two years of data (November 2009 – October 2011) from Skipheia measurement station are used for the investigations in this paper. The site is located off the coast of Mid-Norway, more specifically on the west end of the island Frøya, near the village Titran (see Figure 2-1). It can be seen that the measurement station is exposed to both maritime winds and land breezes, depending on the wind direction. This will be elaborated in Chapter 5.

The measurements are carried out at a 100-meter high met-mast, equipped with 12 ultrasonic anemometers measuring horizontal wind speed and wind direction. The anemometers are positioned in pairs at six different heights from ten to 100 meters. In addition, seven temperature probes are installed at heights between two and 100 meters. For a more detailed description of the instrument set-up, the reader is referred to Øistad [9].

The mast is placed approximately 20 meters above sea level, and the surrounding area is mainly covered by heather and moss. The local topography is typically characterised by small hills with an intermediate distance of 100-500 meters, and assumed to be homogeneous [10].

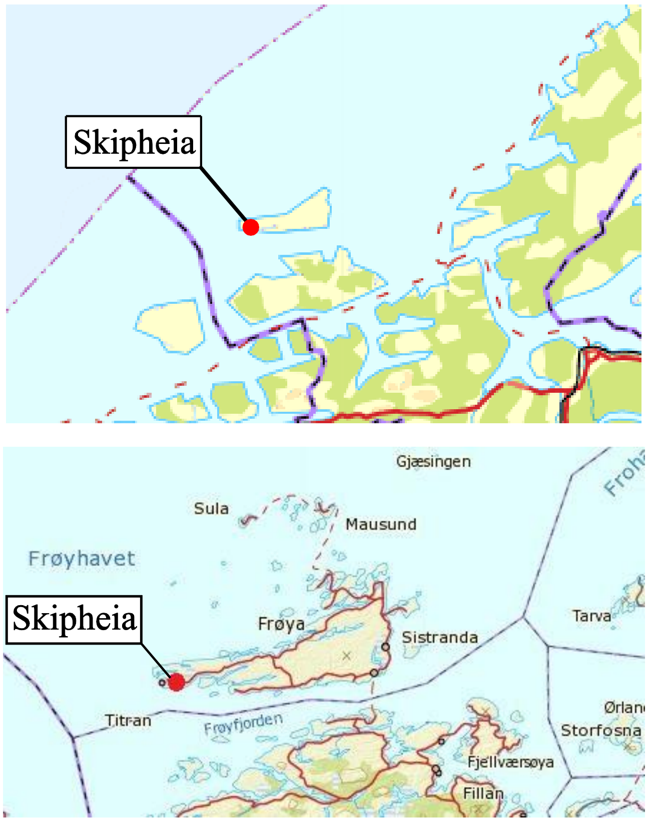

Figure 2-1 Map of Frøya showing Skipheia measurement station

The measurements are recorded at a rate of 1 Hz, and later averaged over a time period of ten minutes. These ten-minute averages and their corresponding wind speed standard deviations are the basis of this study.

In order to make sure the mast structure does not affect the measurements, data from the upstream anemometer are always used, providing one measurement at each height in a given time step. In addition, the wind analysis software Windographer is applied to ensure anemometer availabilities above 90% and to exclude visually observable flaws in the temperature time series.

A longer time period would be required to describe long-term trends and less frequent events (e.g. hurricanes) at Skipheia, but two years of measurements are considered sufficient to show typical patterns in the wind regime.

Winds coming from the northeast-east direction have been considered to represent onshore conditions. Accordingly, these winds are assumed to come from the inland, but this cannot be guaranteed. In addition, winds in the direction sector said to represent offshore conditions may have travelled over an island (see Chapter 5.3) before reaching Skipheia and hence not be entirely offshore. However, data in the two sectors are assumed to give an indicative picture of differences between onshore and offshore wind conditions in terms of the parameters considered.

3 WIND FIELD PARAMETERS

3.1 Turbulence intensity

Turbulence intensity is the most basic measure of turbulence, and is defined as the standard deviation of the wind speed within a time step divided by the mean wind speed over that time step [1]:

$$TI = \frac{\sigma_i}{U_i} \tag{3.1}$$

σ_i is the standard deviation of the wind speed within time step i, and U_i is the average wind speed.

As a function of wind speed, turbulence intensity clearly depends on wind shear and hence surface roughness. Onshore surface roughness is assumed to be independent of atmospheric conditions, and thus determined by surface characteristics only [1]. For offshore conditions, the surface roughness increases with wind speed, as the wave height increases. According to DNV [11], atmospheric stability has a larger impact on offshore wind profiles than the surface roughness length z_0.

Both onshore and offshore environments will be considered here, as the upstream conditions of the met-mast vary, depending on the geographical orientation. As mentioned in the introduction, sea usually has smoother surface than land, and the marine atmospheric boundary layer is typically more stable than the planetary atmospheric boundary layer. Therefore, offshore TI is expected to be weaker than onshore TI [2]. In addition, after reaching a minimum value at moderate wind speeds (8-12 m/s), offshore TI is expected to grow as the wind speed increases, due to growing wave heights. In onshore environments, TI is assumed to have a strict decrease (given a rigid surface) [5-7].

3.2 Atmospheric stability

A determining factor for wind speed gradients in the first few hundred meters above the ground is the atmospheric stability, often defined as the tendency to resist vertical motion or to suppress existing turbulence. This is governed by the vertical temperature distribution, which again results from the radiative heating or cooling of the earth's surface and the following convective mixing of the air adjacent to the surface [1].

Here the gradient of the virtual potential temperature, $\partial\theta_v/\partial z$, between heights of 40 and 100 meters is applied as a qualitative measure of the atmospheric stability at Skipheia. In lack of measurements for pressure and relative humidity, data from the nearby weather station Sula are used to calculate θ_v [12]. Use of e.g. the gradient Richardson or bulk Richardson methods [13] would have given a more detailed classification of stability, but also resulted in a large reduction of data due to necessary filter criteria.

Atmospheric stability is usually classified as stable, neutral or unstable. In a stable atmosphere the surface is cooler than the air, which indicates a positive temperature gradient. Because cold air has higher density than warm air, the buoyancy forces are negative and no spontaneous convection occurs. For unstable conditions, vertical motion is enhanced by buoyancy, as the surface is strongly heated. The temperature gradient is therefore negative. In a neutral atmosphere, the air is well mixed and the temperature gradient is close to zero [1].

In this work a simple distinction is made between stable and unstable conditions; when $\partial\theta_v/\partial z > 0$, the atmosphere is categorised as stable, and when $\partial\theta_v/\partial z < 0$, it is said to be unstable. This simple approach is used to give a brief look into how the atmospheric stability affects TI, and to see how stability and TI changes with wind direction and seasonality.

In an unstable atmosphere convective turbulence predominates and winds are weak. When significance of convection decreases and mechanical turbulence increases, the atmosphere tends to neutral conditions. As the convective turbulence die out and mechanical turbulence is dampened, there is no vertical mixing, and the atmosphere is stable [14].

4 THE IEC STANDARDS

IEC has conducted several international standards regarding wind turbines in the document series IEC 61400. Two of these are referred to in this paper; IEC 61400-1 [3] and IEC 61400-3 [4], concerning design requirements for wind turbines located in onshore and offshore environments, respectively. In Chapter 5 the turbulence conditions at Skipheia have been analysed in relation to the IEC documents.

The guidelines give requirements for external conditions to be considered when designing a wind turbine. These may affect the loading, durability and operation of the turbines, and are divided into environmental and electrical conditions. The environmental conditions are again subdivided into wind conditions and other environmental conditions. In addition, the wind regime is split into normal and extreme wind conditions. During normal operation of a wind turbine, normal wind conditions will occur frequently, whereas extreme wind conditions are defined to recur with a one-year or 50-year period [3]. With only two years of data, this study will focus on the normal wind conditions. To include extreme cases, a longer time period of measurements is preferred to obtain a comprehensive portray of typical recurrence periods and characteristics of extreme conditions at Skipheia.

When describing the environmental conditions relevant for the design of a wind turbine, IEC 61400-1 [3] categorises the intended sites or site types in different classes, based on wind speed and turbulence parameters. It is emphasised that the intention of the classes is to cover most applications, and hence represent many different sites rather than precisely represent any specific site. The basic parameters for the wind turbine classes are specified in Table 4-1, where V_{ref} represents the reference wind speed average over ten minutes and I_{ref} is the expected mean value of turbulence intensity at 15 m/s, both at hub height. Classes A, B and C represent high, medium and low turbulence intensities, respectively.

Wind turbine class		**I**	**II**	**III**
$\boldsymbol{V_{ref}}$	(m/s)	50	42.5	37.5
A	I_{ref} (-)		0.16	
B	I_{ref} (-)		0.14	
C	I_{ref} (-)		0.12	

Table 4-1 Basic parameters for wind turbine classes

4.1 Normal wind conditions

For normal wind conditions IEC 61400-1 [3] considers wind speed distribution, the normal wind profile model (NWP) and the normal turbulence model (NTM). Only the latter will be further discussed here.

For the NTM, the representative value of the horizontal wind speed standard deviation, σ_1, is given by the 90th percentile for the given hub height wind speed, V_{hub}, and the reference turbulence intensity, I_{ref}:

$$\sigma_1 = I_{ref}(0.75V_{hub} + b); \quad b = 5.6\,m/s \quad (4.1)$$

Like the rest of the given IEC guidelines, Equation (4.1) is based on onshore observations in Europe and America. In addition, the standards only consider neutral atmospheric conditions [8].

According to IEC 61400-1 [3], the value of σ_1 shall be greater or equal to the 90th percentile of the measured wind speed standard deviation at all values of V_{hub} between $0.2V_{ref}$ and $0.4V_{ref}$. In addition, σ_1 shall be assumed to be invariant with height and log-normally distributed for a given mean wind speed. The measurements from Skipheia will be analysed in terms of these requirements in Chapter 5.

NTM from IEC 61400-1 [3] is also recommended in IEC 61400-3 [4], but only for design of the rotor-nacelle assembly. For the support structure, the offshore turbulence intensity estimate is based on another approximation of σ_1, here referred to as $\sigma_{1,ss}$ [4]:

$$\sigma_{1,ss} = \frac{V_{hub}}{ln(z_{hub}/z_0)} + 1.28 \times 1.44 \times I_{ref} \quad (4.2)$$

where z_{hub} is the hub height and z_0 the surface roughness length. If not known, an approximation of z_0 is found iteratively as described in IEC 61400-3 [4].

As stated earlier, the main difference between onshore and offshore sites is that the offshore surface roughness increases with increasing wind speed, due to wind induced waves. This again leads to an increase in turbulence intensity for high wind speeds, as seen in Wang et al. [5], Ernst and Seume [6] and Türk and Emeis [7]. In addition to the loads on onshore wind turbines, as described in IEC 61400-1 [3], offshore wind turbines are exposed to e.g. hydrodynamic loads and sea ice loads. These may indirectly affect the rotor-nacelle assembly through vibration on the support structure. However, there is no justification for change to wind speed or turbulence parameter values, so the wind turbine classes stay the same for offshore as for onshore wind turbines.

5 ANALYSIS OF THE SKIPHEIA MEASUREMENTS

In this section, the two-year period of data from Skipheia is analysed in terms of wind speed, wind direction, atmospheric stability and seasonal variations. Subchapters 5.1 and 5.2 take care of the wind speed standard deviation and the turbulence intensity, respectively. As mentioned earlier, measurements of the two parameters have been compared to σ_1 and σ_1/V_{hub} as given by IEC 61400-1 [3].

If not specified, measurements are carried out at 70 meters above ground. To determine up to which wind speeds the measurements can be assumed representative, Windographer is applied, giving numbers of relative frequency of occurrence in each wind speed bin. E.g. for the whole two-year period, the measurements are assumed adequate up to about 20 m/s. This number will vary depending on season and wind direction.

Figure 5-1 shows the wind speed and wind direction distribution for the Skipheia dataset at 70 meters height. After filtering the data as described in Chapter 2, the dataset for this height contains 89 351 observations. From the wind direction distribution, it can be seen that the wind most frequently comes from southwest, and that this sector also represent the largest wind speeds.

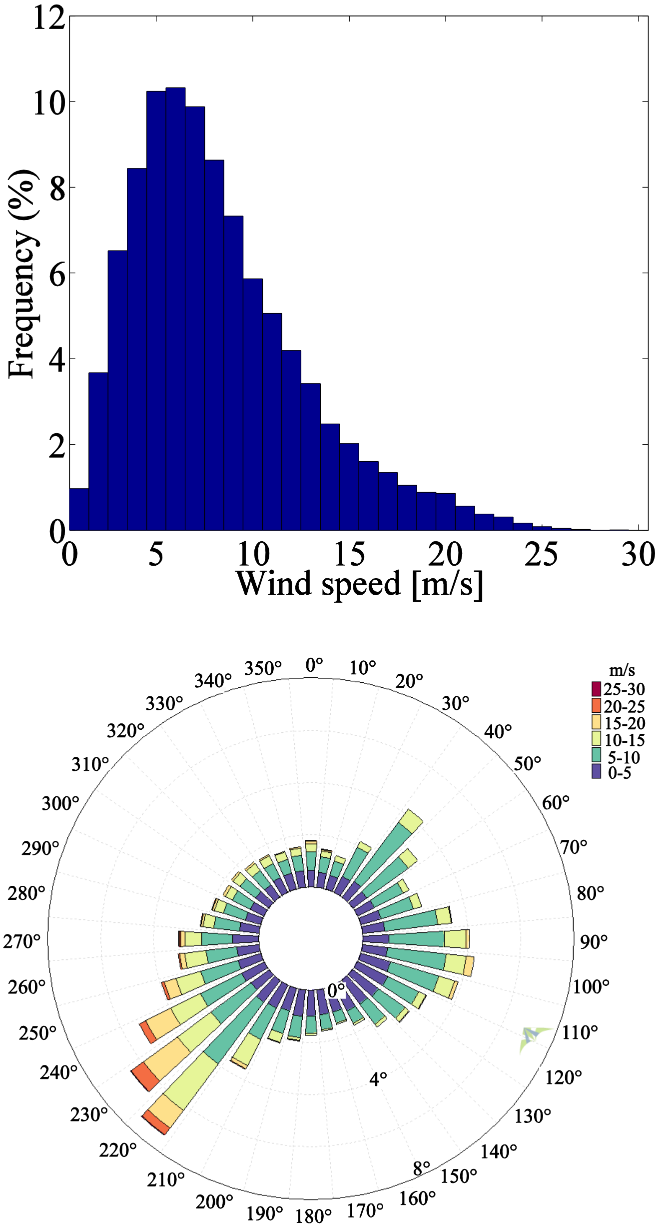

Figure 5-1 Wind speed distribution (upper) and wind direction distribution (lower) at 70 m

From Figure 2-1 it appears that winds can travel varying distances both over land and over sea before hitting the mast. In addition, the distance from the mast to the shore varies from about 300 meters to 25 kilometres. Therefore, the 360° sector is divided in five, depending on these two factors. The sectors are described in Table 5-1 and illustrated in Figure 5-2 [10]. Later, two sectors are selected to represent onshore and offshore conditions, respectively.

Direction	Description
0°-40°	The distance to the sea is 3-5 km
40°-100°	Wind that has passed the northeast part of Frøya for up to 25 km
100°-190°	Wind comes from inland, but have passed sea for the last 10 km
190°-270°	The sector with the most frequent wind direction and the highest average wind speeds. The distance to the sea varies from 300 m to 3 km
270°-360°	Maritime wind that have passed land for about 3 km

Table 5-1 Classification of wind direction sectors [10]

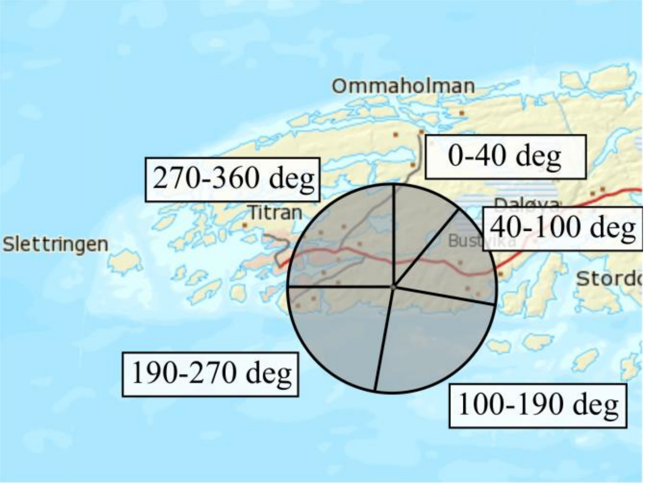

Figure 5-2 Skipheia and the five direction sectors

In previous studies, stable stratification is found to be characterised by high wind shear and low turbulence intensities, whereas an unstable atmosphere involves low wind shear and high turbulence intensities [7, 15]. Fechner [16] investigates wind shear, wind speed distribution and wind direction distribution for different stability classes at Skipheia, and confirms the findings of Türk [7] and Westerhellweg [15] for the wind shear. Fechner [16] found that the percentage of unstable conditions dominates at lower wind speeds and decreases as the wind speed increases. In addition, Fechner [16] states that winds coming from southwest, i.e. where the wind has travelled over sea and the distance from the mast to the shore is smallest, represent the largest relative frequency of unstable conditions.

The simplified atmospheric stability distribution for the current research is presented in Figure 5-3, and the turbulence intensities in the respective stability classes will be discussed in Chapter 5.2.2.

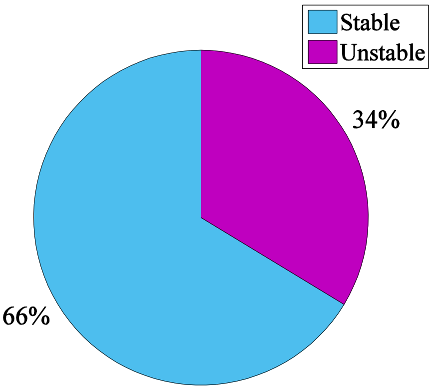

Figure 5-3 Atmospheric stability distribution

The figure above indicates that positive temperature gradients and hence stable atmospheric conditions are dominant between 40 and 100 meters at Skipheia. In Fechner [16], on the other hand, unstable conditions are found to be prevailing. This disagreement is believed to be a result of differences in data filtering and methods of stability classification. In addition, a strict limit concerning only $\partial\theta_v/\partial z = 0$ as neutral conditions omits near-neutral measurements having a temperature gradient close to zero. However, the simple illustration makes it possible to see differences in atmospheric stability for e.g. different seasons and different direction sectors, as mentioned earlier.

In addition to atmospheric stability, there are considerable seasonal variations in the wind regime at Skipheia. The winter months (December, January and February) offer higher wind speeds than the summer months (June, July and August), and there are differences in wind direction frequencies and turbulence intensities, to mention some seasonally dependent parameters.

For the summer season, most of the wind comes from the northeast, with the majority gathered around 35°-50°. As for the whole two-year period, the strongest winds are mainly coming from southwest. The latter also applies to the winter season, which generally involves higher wind speeds than the summer months. In winter, most of the winds come from southwest.

Using $\partial\theta_v/\partial z$ as a measure of atmospheric stability, it was found that the summer months involve more unstable conditions than the winter season, in which the proportion of positive temperature gradients was larger than for the whole two-year period (Figure 5-3). This corresponds to the findings by Ashrafi and Hoshyaripour [14], researching the seasonal stability pattern in the atmosphere. They explain this matter with the fact that warm months implicate high insolation and no strong winds, resulting in convective eddies to dominate the atmospheric motions, and hence cause a more unstable atmosphere. In the winter season, the insolation is weaker and the winds stronger.

The differences in turbulence intensity as a result of seasonal variability will be discussed in Chapter 5.2.3.

5.1 Standard deviation of horizontal wind speed

The standard deviation of the horizontal wind speed is displayed in Figure 5-4. After arranging all observations in appropriate wind speed bins with bin width 1 m/s, the mean and representative (90th percentile) values of the standard deviation are calculated for each bin. σ_m and σ_{90} describe the mean and representative values, respectively.

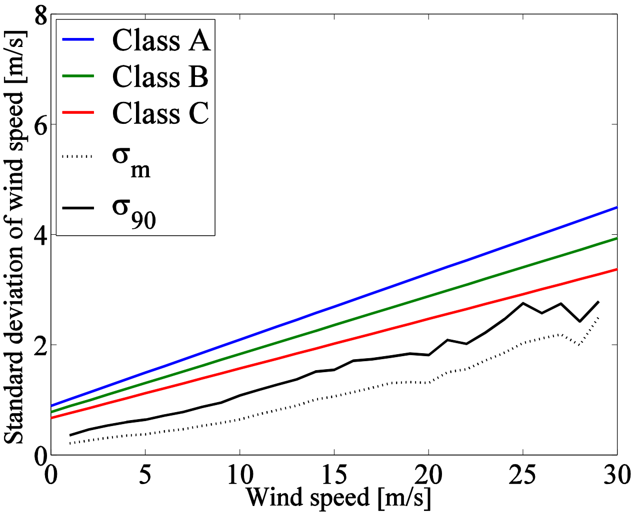

Figure 5-4 Standard deviation of horizontal wind speed as function of wind speed

The upper three lines illustrate σ_1 as given by Equation (4.1) for the respective wind turbine classes defined in Table 4-1. The two lower lines show the representative and mean standard deviations of the measurements, respectively. The representative curve describes the 90th percentile of the observations and is hence comparable to the ones given by IEC 61400-1 [3]. σ_{90} is found according to Equation (5.1) [3], in which σ_m is the mean value and σ_σ the corresponding standard deviation.

$$\sigma_{90} = \sigma_m + 1.28\sigma_\sigma \tag{5.1}$$

σ_{90} lies clearly below σ_1 for all wind turbine classes, but closest to Class C, which represents the lowest turbulence intensity. Up to about 15 m/s, the slope of the measured 90th percentile-curve corresponds relatively well to the slope of σ_1 for Class C, which has an inclination of $0.09V_{hub}$. At higher wind speeds, however, the representative curve of the measurements shows larger variations between neighbouring wind speed bins. This is assumed to be due to fewer observations above 15 m/s. Standard deviation of the horizontal wind speeds in the onshore and offshore sectors at Skipheia will be examined in Chapter 5.3.1.

According to IEC 61400-1 [3], σ_1 shall be assumed invariant with height. However, due to a decreasing influence on wind fluctuations from the surface roughness for increasing heights, the standard deviations and TI decrease with elevation. In addition, the NTM assumes σ in each wind speed bin to be log-normally distributed. The latter is not examined in the current study.

Wang et al. [5], who investigated atmospheric turbulence at three coastal sites, tested this and found that σ is generally not following a log-normal distribution, but tends to be positively skewed. Despite this, they state that the log-normal distribution in general is a good model for the TI distributions in the respective wind speed bins. However, the extreme cases of TI in Wang et al. do not follow a log-normal distribution, and are advised to be modelled separately by extreme turbulence models, such as the one defined in IEC 61400-1 [3].

5.2 Turbulence intensity

The turbulence intensity at Skipheia has been determined according to Equation (3.1), using the standard deviation and the mean wind speed in every available time step, both at 70 meters height. As for the standard deviation in the previous chapter, the observations for turbulence intensity are placed in appropriate wind speed bins. Further, mean and representative values of the turbulence intensity, TI_m and TI_{90}, are calculated for the respective bins, as showed in Figure 5-5. The curve of the mean turbulence intensity also includes bars presenting the standard deviation for each wind speed bin.

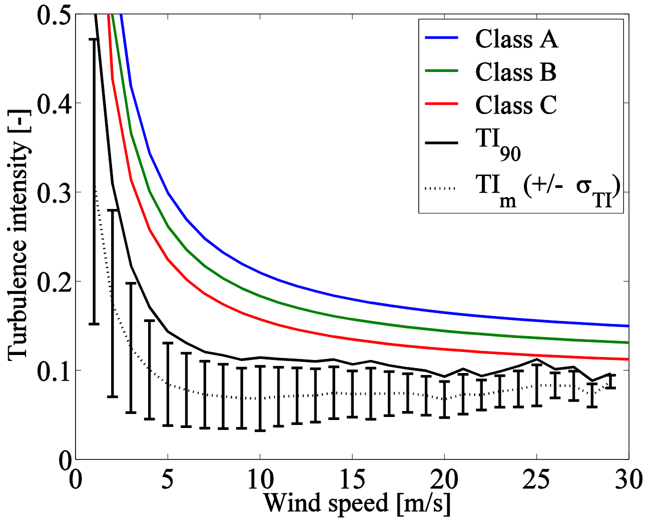

Figure 5-5 Turbulence intensity as function of wind speed

Not surprisingly do the curves of the measured turbulence intensity lie well below the three IEC-classes, as for the wind speed standard deviation in Figure 5-4. When again focusing on wind speeds up to 15 m/s, Figure 5-5 shows that the mean and representative turbulence intensity-curves seem to flatten out around 10 to 14 m/s. This corresponds to the results in Westerhellweg et al. [15] and Ernst and Seume [6]. At higher wind speeds, the variations between neighbouring bins once again grow.

Low TI is desired when considering fatigue loads on a wind turbine, as turbulence causes wear on the rotor blades [17]. When it comes to power performance, it cannot be said outright that turbulence specifically enhances or undermines the output. To determine the effect of turbulence on the turbine performance, a more thorough analysis has to be carried out, considering e.g. stability, turbine positioning, wind speeds and wind directions [2].

Figure 5-5 includes all wind directions, and does hence say nothing about differences in turbulence intensity due to variations in upstream circumstances, other than wind speed. In addition, it does not give any information about the atmospheric stability, which is found to be of great importance for the wind regime at Skipheia [16]. The following sections will therefore analyse the turbulence intensity with respect to the five wind direction sectors described in Table 5-1, the stability classifications from Chapter 3, and seasonal variations. Turbulence intensity for onshore and offshore conditions at Skipheia will be discussed in Chapter 5.3.2.

5.2.1 The five direction sectors

It was found that wind direction has a significance when analysing turbulence intensity at Skipheia. Figure 5-6 shows representative TI for the five direction sectors as presented in Table 5-1. The sectors are divided based on a selection of upstream conditions, i.e. distance to shore, what kind of environment (inland or maritime) the wind comes from and the distance the wind has travelled over land or water before it hits the mast.

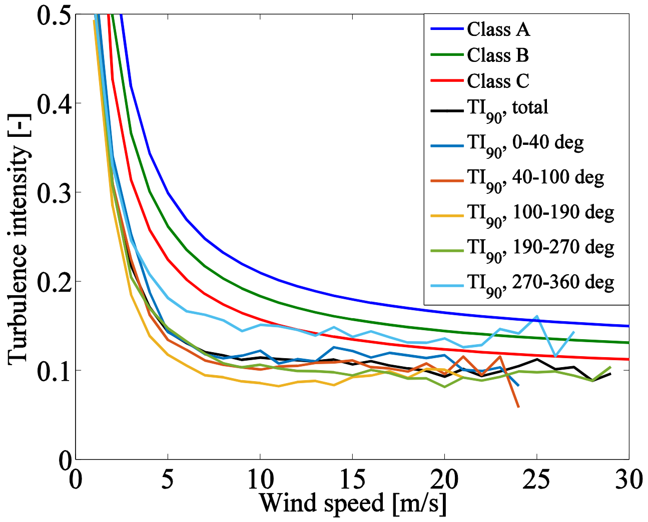

Figure 5-6 Turbulence intensity, the five direction sectors

The most remarkable result is for the sector going from west to north, i.e. 270°-360°. From around 3 m /s, the turbulence intensity here differs from the rest and stays consistently higher. After about 12 m/s, it also exceeds one or more of the IEC-classes. As previously mentioned, wind from this direction sector comes from the ocean and has passed land for about three kilometres.

The third direction sector, covering 100°-190°, has the lowest turbulence intensity of the five. This part includes winds coming from the inland, which have travelled over water for about ten kilometres before reaching the mast.

Sectors with short distances from mast to shore having lower turbulence intensities than sectors with larger distances to shore make sense when considering the upstream surface conditions. Even though there are some small hills at Skipheia, the topography is rather homogeneous. Vegetation in terms of heather and moss is mainly covering the ground, and there are no obstacles in near proximity of the mast that are assumed to influence the wind measurements [10]. However, the onshore topography still involves larger surface roughness lengths than both calm and blown sea [1]. In direction sectors where the distance to shore is sufficiently short, so that the water surface can be assumed to still have an effect on winds reaching the mast, it is hence reasonable to expect lower TI than in sectors with long distances to shore.

As a rule of thumb, changes in the surface affect the wind conditions up to a height of 10 % of the distance from the point where the surface changes to the measurement point. For example, if the wind has travelled several kilometres over water, and suddenly reaches land at Frøya 300 meters from the mast, the wind measurements up to about 30 meters height will be influenced by the change of surface conditions.

In Chapter 5.3 measurements in two of the sectors will be analysed with the aim of describing onshore and offshore conditions at Skipheia. Table 5-2 gives an overview of number of occurrences in each of the five direction sectors (cf. Figure 5-2). The fourth sector (from now called Direction sector 4) has the highest frequency of winds, and the highest wind speeds. After travelling over water for a long while, the winds hit the mast between 300 meters and three kilometres from the shoreline. This sector will therefore be considered as representing offshore wind conditions. Onshore conditions are described by winds coming from northeast to east, i.e. 40°-100° (Direction sector 2). Here, the winds have been travelling over the northeast part of Frøya for up to about 25 kilometres before hitting the mast.

Direction sector	Number of occurrences	%
1 (0°-40°)	7 055	7.90
2 (40°-100°)	17 316	19.38
3 (100°-190°)	19 114	21.39
4 (190°-270°)	30 986	34.68
5 (270°-360°)	14 880	16.65
Total	89 351	100

Table 5-2 Number of observations for the five direction sectors

5.2.2 Stability conditions

Eliassen et al. [18] investigated turbulence intensity at the offshore FINO 3 platform, and found a clear dependency on stability. As mentioned in the beginning of Chapter 5, a stable atmosphere is generally characterised by high wind shear and low TI, whereas an unstable atmosphere involves low wind shear and high TI.

Therefore, the measurements from Skipheia are expected to show differences in TI for the two stability classes.

The results for representative TI versus wind speed in the two stability classes are presented in Figure 5-7. For wind speeds just below 10 m/s, the unstable measurements show a slightly higher TI than the stable. Between approximately 10 and 18 m/s, the curves switch places, with stable TI just above unstable TI. For mean values of TI (not shown), however, the unstable measurements have higher TI than the stable for all wind speeds, with largest differences at low winds speeds.

Overall, Figure 5-7 shows small differences between stable and unstable conditions, which indicate that atmospheric stability does not have a great influence on turbulence intensity at Skipheia. However, based on previous studies, this result is considered to be unlikely and hence misleading [15, 16, 18, 19].

One reason why unstable TI lies below stable TI for growing wind speeds, might be the fact that most winds come from southwest. From Fechner [16], it is known that this sector involves a large portion of unstable conditions, but Figure 5-6 shows that it has a relatively low TI as well.

The small differences between stable and unstable conditions in Figure 5-7 are assumed to be a consequence of the rough stability classification scheme not considering e.g. wind speed and height differences. In addition, the data are not filtered for e.g. non-stationarity and surface layer height [16, 18]. Therefore, Figure 5-7 will be used only for comparison of results for different seasons and direction sectors, rather than to precisely describe TI as function of atmospheric stability.

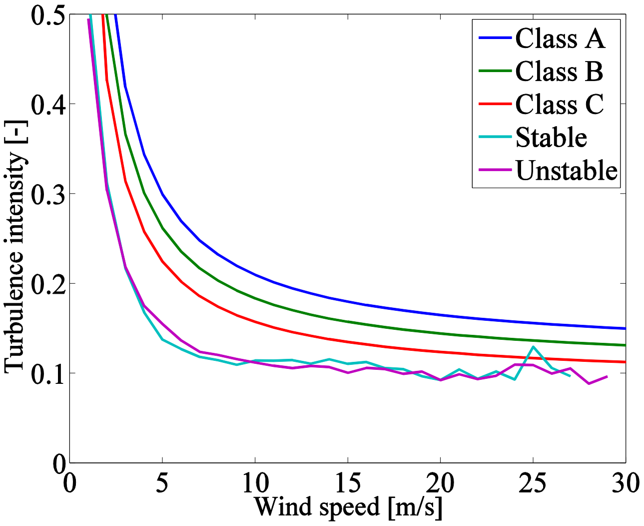

Figure 5-7 Turbulence intensity, stable and unstable conditions

5.2.3 *Seasonal variations*

As already discussed, turbulence intensity depends on the stability of the atmosphere, which again depends on the season. The Skipheia dataset has therefore been divided into summer and winter seasons, with the aim to investigate the turbulence intensities and uncover similarities and dissimilarities between the seasons.

Figure 5-8 illustrates the respective seasonal turbulence intensities as function of wind speed. Scatter plots (not included here) show that the winter observations contain higher wind speeds, as previously discussed. The summer measurements are assumed representative up to 15 m/s and the winter measurements up to 19 m/s.

In addition, winds in summer tend to have a larger span in turbulence intensity for each wind speed bin than the corresponding wind speeds in winter. E.g., below 5 m/s, the majority of the observations in summer has greater maximum values and lower minimum values than the same wind speed interval in the winter months. Another difference is the degree of scatter above the representative turbulence intensity-curve, which is more noticeable in winter than in summer.

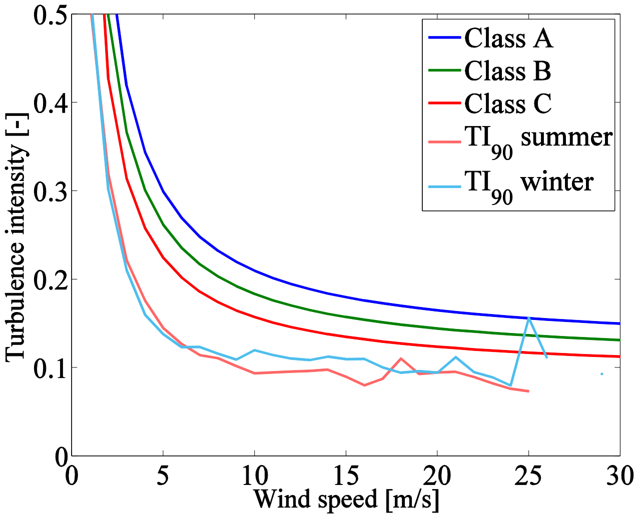

Figure 5-8 Turbulence intensity, summer and winter

Based on the dominating stability conditions in the respective seasons (cf. beginning of Chapter 5), the summer is expected to have higher turbulence intensity than the winter. The relative wind speed frequency for both periods peaks at 5-7 m/s, but the winter season contains larger proportions of higher wind speeds than the summer season. The large wind speeds and the cold surface in winter lead to a more stable atmosphere than in summer, as previously stated, and gives a good reason to expect lower TI for the cold season. This is not the case, however, when considering Figure 5-8.

A reason for this may be the large proportion of winds coming from southwest in winter, being influenced by an unstable atmosphere [16]. The winter season also includes weak winds coming from the sector spanning from east to southwest, likely to have high TI (cf. Chapter 3.2).

Overall, according to Figure 5-8, TI in winter seems to be dominated by weak winds and instability, whereas summer appears to be dominated by stable conditions and hence low TI. This does not fit the expectations discussed in the beginning of Chapter 5, and further investigations are needed to assess the results. The differences in TI with season for the onshore and offshore sectors are investigated in Chapter 5.3.2.2.

5.2.4 Other factors

Apart from already mentioned factors, there are additional elements affecting the atmospheric turbulence intensity. This section will look into how turbulence intensity at Skipheia is influenced by time of day and measurement height.

The diurnal pattern of TI is shown in Figure 5-9. For the whole two-year period, the diurnal turbulence intensity at 70 meters peaks between 13:00 and 15:00, i.e. during the hottest hours of day. The minimum TI is found between 05:00 and 06:00. According to BWEA [20], turbulence in the lowest 200 meters of the atmosphere follows a daily cycle caused by its strong relationship to atmospheric stability. During daytime, convection is triggered by solar radiation heating the surface, resulting in a well-mixed or unstable atmosphere reinforcing turbulence. At night, the atmosphere tends to be stably stratified and turbulence is suppressed to a minimum. This can be explained by the absence of the daytime buoyant heating forces.

From literature diurnal variations in TI are known to be most pronounced in spring and summer [21]. At Skipheia, the referred daily cycle is most evident in the months April-Septemper. For the rest of the year, diurnal differences in TI are less distinct. When considering the summer months (June-August) alone, TI peaks between 10:00 and 15:00. In winter (December-February), the peak is found between 13:00 and 16:00. The graph below shows the mean diurnal profile for turbulence intensity in the two-year period, in summer and in winter.

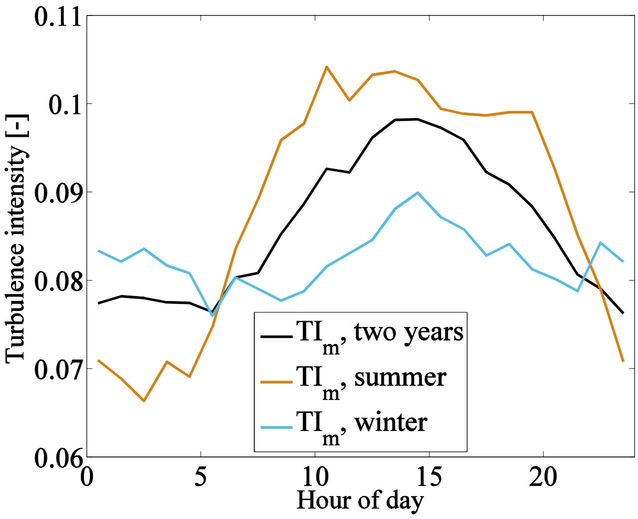

Figure 5-9 Diurnal TI pattern

The height of a wind turbine tower determines the size of the rotor, which again determines the possible power output of the turbine. As elevation above ground increases, the winds grow stronger and become less turbulent. Choice of tower height is based on an economic balance between increased energy capture and increased cost, but the tower is preferred to be as tall as practical [1].

IEC 61400-1 [3] does not give any requirements for preferred hub heights, but as the distance from the surface increases, the turbulence intensity decreases. A taller turbine will hence normally be exposed to less turbulent flows and thus lower fatigue loads than a smaller turbine [1].

At Skipheia, TI decreases as the measurement height increases, as expected. The differences in mean values are shown in Figure 5-10. The upswing at the end of each curve is most likely due to low numbers of observations at high wind speeds, and are hence neglected. Worth noticing is the differences in TI between neighbouring measurement heights. The vertical distances vary from six to 30 meters, but the change in TI between measurement heights stay at a relatively constant level. This indicates that the vertical gradient of TI diminishes with height, as the distance between the first and second height is six meters, and the distance between the two upper heights is 30 meters. This emphasises the fact that TI is more dependent on surface roughness closer to the ground.

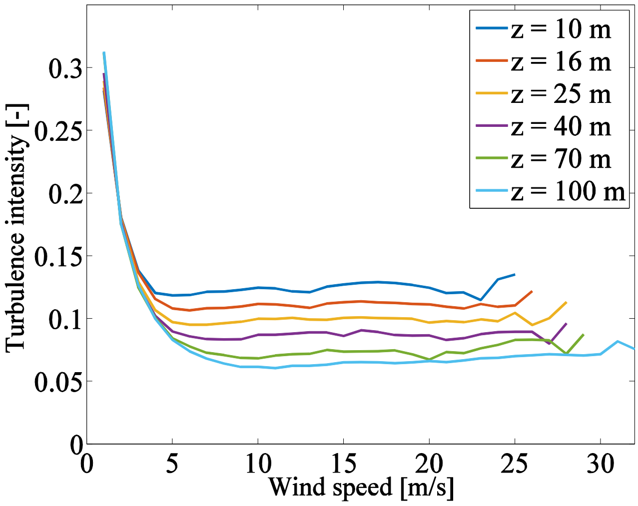

Figure 5-10 Mean TI, all measurement heights

5.3 Onshore and offshore conditions

As introductory implicated, Skipheia is a unique site in terms of environmental conditions. With its location outside the mainland of Norway, being exposed to both inland and maritime winds, it represents a complex range of surroundings. To utilise this, two specific direction sectors are chosen to represent onshore and offshore wind conditions, respectively, as mentioned in Chapter 5.2.1.

With the longest distance to shore and winds coming from the inland, Direction sector 2 is selected to represent onshore conditions. For offshore conditions, Direction sector 4 was found to give a better representation, due to the winds coming from the ocean and the short distance from the mast to the shore. However, to make sure the mast-to-shore distance can be assumed uniform, the range is confined to 190°-240°. As Direction sector 4 is said to represent offshore conditions and the mast is placed approximately 20 meters above sea level, the measurement height can be considered as 90 meters instead of 70 in this sector.

In Figure 5-6, the sector covering 100°-190° (Direction sector 3) shows lower TI than Direction sector 4 up to about 17 m/s. The reason why the latter still is chosen to represent offshore conditions is that winds in Direction sector 3 comes from inland and has travelled over the island Hitra before reaching Skipheia. In addition, Direction sector 4 contains a larger number of observations (c.f. Table 5-2). After narrowing the range, Direction sector 4 comprises 21 029 observations.

Figure 5-11 illustrates the wind speed distributions in the two featured sectors. As expected, the winds in Direction sector 2 are dominated by lower speeds than the ones in Direction sector 4.

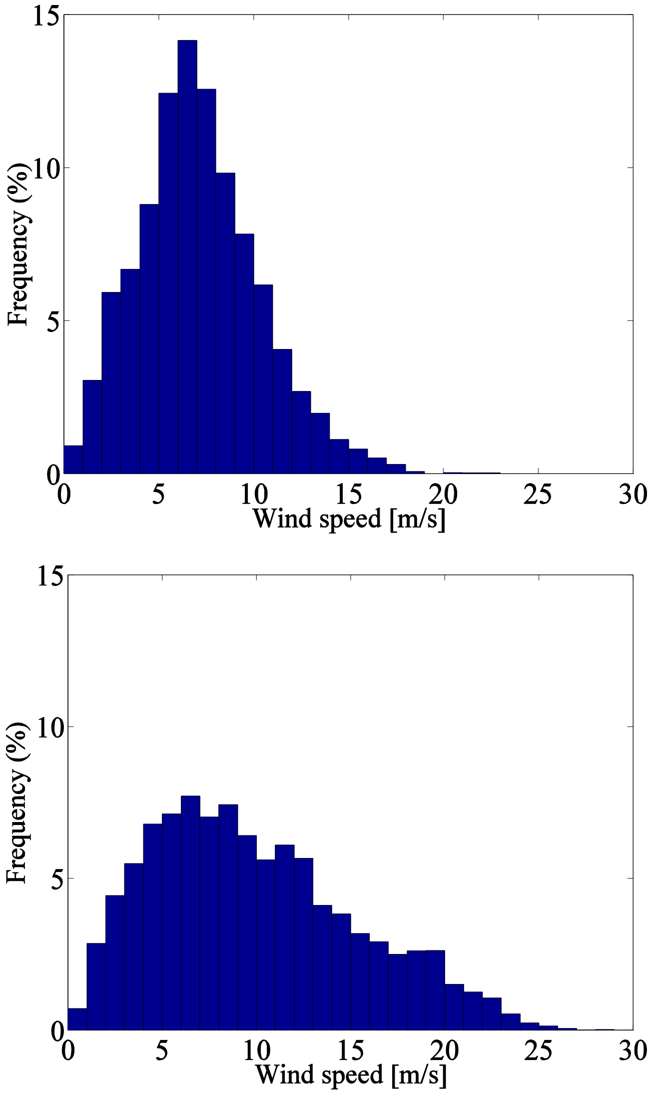

Figure 5-11 Wind speed distributions for Direction sector 2 (upper) and restricted Direction sector 4 (lower)

When it comes to stability differences in the whole two-year period, the offshore sector (restricted Direction sector 4) has the higher proportion of instability with 42%, against Direction sector 2 with 22%, using the simple classification introduced in Chapter 3.2. Qualitatively, this corresponds to the findings by Fechner [16], giving a higher relative frequency of unstable conditions in the southwest direction. Compared to the entire 360° sector (Figure 5-3), the conditions in the onshore sector are more stable, whereas they are more unstable in the offshore sector.

As discussed in the first part of Chapter 5, there are seasonal variations in the wind conditions at Skipheia. For both seasons, the onshore sector has a distinct peak in wind speed frequency at 6-8 m/s, whereas the offshore sector has a flatter wind speed distribution. In addition, higher wind speeds are represented in Direction sector 4 in both seasons (cf. Chapter 5).

When comparing the two seasons in the same sector, the summer contains higher frequency of low wind speeds, whereas there are stronger wind speeds present in winter. This applies for both sectors.

The stability distribution for the offshore sector does not change remarkably between summer and winter. For the onshore sector, the summer is characterised by significantly higher instability than the winter. Therefore, it is reasonable to expect a larger difference in TI between the two seasons for Direction sector 2 than for Direction sector 4.

Travelling about 30 kilometres southwest from the mast, one finds the island Smøla. Winds coming from this direction will hence be disturbed by land before reaching Skipheia, although they originate from the ocean. However, the water fetch over which the wind travels from Smøla before hitting the mast is assumed long enough to still consider it as offshore. Barthelmie et al. [22] stated that the effects of land on the climate are most important within 0-15 kilometres, and that the majority of adjustment of turbulence characteristics appears to occur within 20 kilometres from the coast.

With a lower endpoint at 190°, the observations in the restricted Direction sector 4 are also assumed uninfluenced by Hitra, located south of Frøya. The following subsections discuss similarities and dissimilarities in relevant observations between the two direction sectors.

5.3.1 Standard deviation of horizontal wind speed

Figure 5-12 shows σ_{90} as function of wind speed for the onshore and offshore sectors. Up to 10 m/s, the two curves lie close, and both well below σ_1 for the three IEC classes. After 10 m/s, the space between the two curves grow, with the onshore sector having consistently larger standard deviation values than the offshore sector. For

Direction sector 2, measurements above 15 m/s are neglected due to low numbers of observations. For Direction sector 4, the measurements are assumed representative up to 23 m/s.

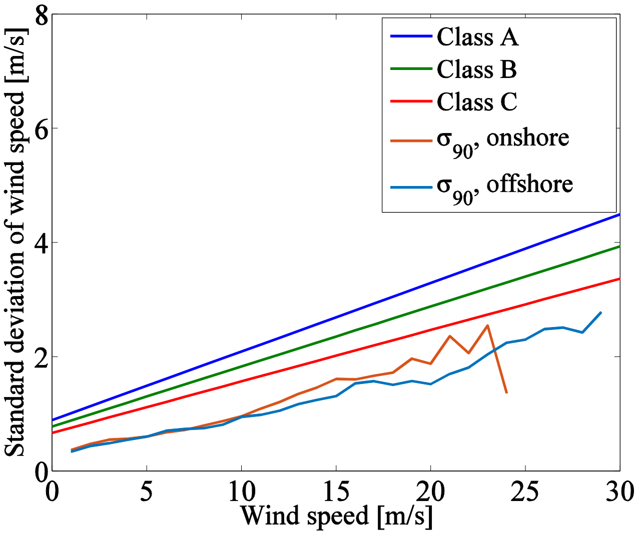

Figure 5-12 Standard deviation of horizontal wind speed, onshore and offshore

5.3.2 Turbulence intensity

Wang et al. [5] explain the trends for offshore TI, starting at high numbers for low wind speeds due to thermally derived turbulence. Thereafter, TI reaches a minimum at moderate wind speeds, typically between 8-12 m/s. Growing wind speeds then lead to an increase in the ocean surface roughness, which again results in an increase in mechanically derived turbulence and thus a stronger turbulence intensity. Hence does the strict decrease in TI from IEC 61400-1 [3] fit offshore conditions badly. As mentioned previously, the standard deviation σ_{90} decreases with height. This is also the case for TI, as the impact from the surface roughness decreases when distance to the ground increases.

From literature, offshore winds are known to be less turbulent than onshore winds [20]. Starting out high at low wind speeds, the turbulence intensity diminishes as the wind speed increases, before reaching a minimum at a threshold wind speed of about 8-12 m/s [5, 7, 20]. As mentioned earlier, the ocean waves grow bigger at increasing wind speeds, leading to a slow rise in wind shear and turbulence. Therefore, turbulence intensity in the offshore sector at Skipheia is assumed to lie lower than the onshore measurements, and to increase at higher wind speeds after reaching a minimum.

For offshore environments, Barthelmie [22] found stability to have a significant effect on turbulence intensity at low wind speeds. At higher wind speeds, wind and wave interactions appear to dominate.

The results for TI_{90} are shown in Figure 5-13. For wind speeds up to about 7 m/s, the curves for onshore and offshore TI are relatively similar and found well below the three IEC classes. Above 7 m/s, the two curves separate, with stronger turbulence intensity in the onshore sector, as expected.

As for σ_{90} in the previous subchapter, measurements above 15 m/s are neglected in Direction sector 2. For Direction sector 4, the curve is assumed to be representative up to about 23 m/s. After narrowing Direction sector 4 from 190°-270° to 190°-240°, TI_{90} becomes slightly lower.

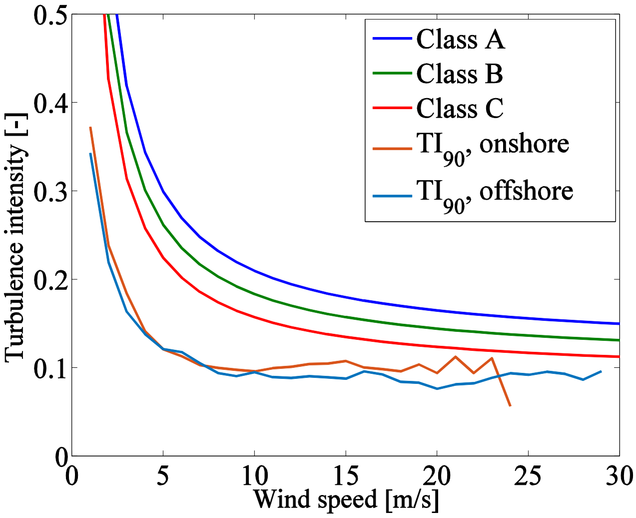

Figure 5-13 Turbulence intensity, onshore and offshore

Although the onshore TI is higher than the offshore, the difference is smaller than anticipated [23]. At 15 m/s, $TI_m = 0.084$ for Direction sector 2 and $TI_m = 0.064$ for Direction sector 4, in comparison to I_{ref} in the three wind turbine classes in IEC 61400-1 [3] (cf. Table 4-1). The small differences in TI may indicate that the upstream surface roughness do not have a significant impact on the turbulence intensity at the current site, but that it is rather determined by the stability of the atmosphere.

For the offshore case in Figure 5-13, it is hard to say anything about an increase in TI after reaching a minimum. However, the estimated TI in IEC 61400-1 [3] monotonically decreases as the wind speed increases, which corresponds poorly to previous investigations on offshore turbulence intensity [5, 7, 24]. The onshore TI in Figure 5-13, on the other hand, seems to increase after reaching a minimum at around 10 m/s. With up to 25 kilometres of land upstream in this direction, the increase is unlikely to be caused by increasing wave heights, but there are not found any other solutions to this behaviour.

5.3.2.1 Atmospheric stability

This chapter concerns onshore and offshore turbulence intensity when considering atmospheric stability. The results are showed in Figure 5-14 and Figure 5-15.

For the onshore sector, the number of measurements is assumed adequate up to about 15 m/s, where the two curves in Figure 5-14 have approached each other. As discussed earlier, it is reasonable to expect higher turbulence intensity for an unstable than a stable atmosphere. This is also the case in Figure 5-14 for wind speeds below 15 m/s. Compared to Figure 5-7, the result for the onshore sector shows clearer differences between the two stability categorisations for wind speeds between approximately 4 and 10 m/s. The respective curves representing unstable conditions lie on the same level, whereas the stable curve for the onshore sector is considerably lower than for all directions combined. This may indicate that atmospheric stability is more important for this direction sector than the rest, when considering turbulence intensity.

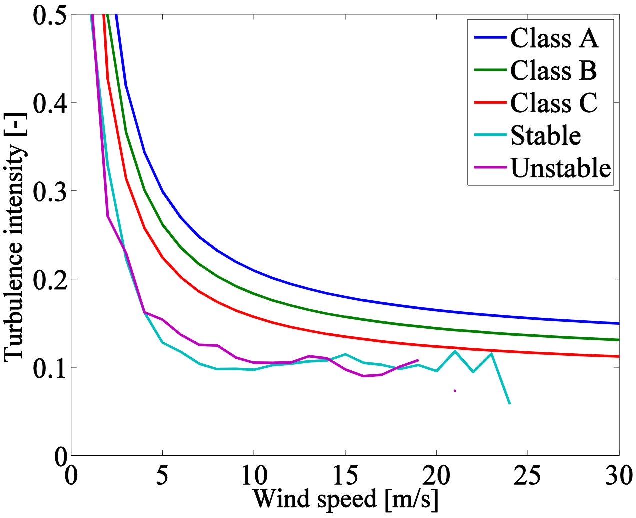

Figure 5-14 Turbulence intensity, stable and unstable conditions in the onshore sector

In the offshore sector, there are smaller differences between TI in the respective stability classes, similar to the case where all directions are considered. Compared to Figure 5-7, both curves are lower for the offshore sector, especially for stable conditions. Since the restricted Direction sector 4 is assumed to be the best approach for an offshore environment and hence have low TI, this result is expected.

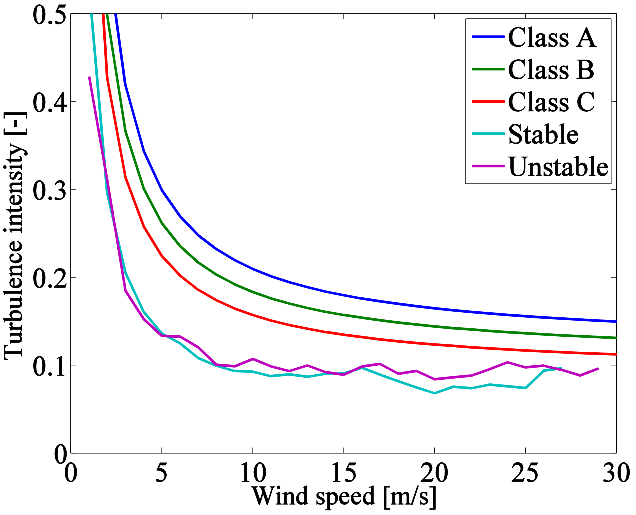

Figure 5-15 Turbulence intensity, stable and unstable conditions in the offshore sector

When comparing the two figures above, the offshore stable curve lies on the level of the onshore stable curve up to about 10 m/s, at which the stable TI seems to increase in the onshore sector. The offshore unstable curve lies slightly above the two stable curves. The biggest difference in representative TI between onshore and offshore sectors when considering stability is hence found in the unstable case.

Eliassen et al. [18] found atmospheric stability to have a large impact on turbulence intensity. Therefore, the differences between TI in the two stability classes are expected to be larger. However, with a rough classification between stable and unstable conditions, both classes are likely to include a significant number of near-neutral measurements. These will strengthen TI in the stable class and weaken TI in the unstable class, and hence make them harder to distinguish. Using $\partial\theta_v/\partial z$ as a stability measurement is therefore not regarded as a sufficient method to analyse TI as function of stability, but it gives an indication.

5.3.2.2 Seasonal variations

The representative TI for the two sectors in the summer months are illustrated in Figure 5-16. As for the entire two-year period, summer measurements in the onshore sector are assumed representative up to 15 m/s. For the offshore sector, up to 21 m/s.

Compared to TI in summer for all directions (Figure 5-8), the onshore measurements lie slightly above. The offshore measurements are clearly weaker. This demonstrates that the TI measurements for the whole sector are not descriptive for all different directions sectors in summer, and that onshore-like environments are dominating.

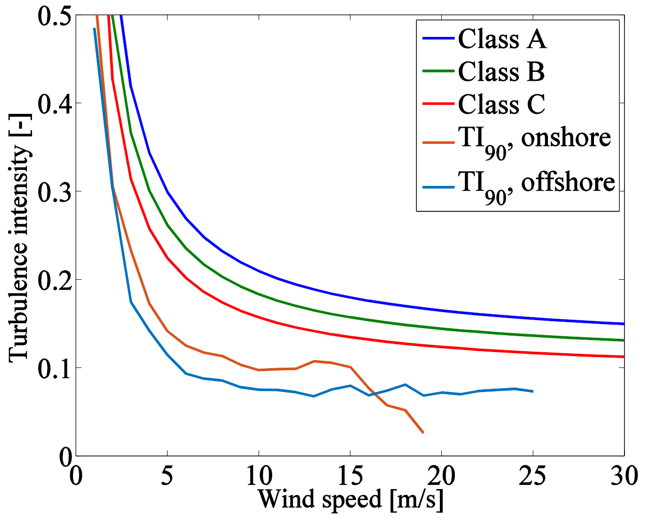

Figure 5-16 Turbulence intensity, summer

For the winter season, the same trend appears; the onshore TI measurements are close to the ones for all directions, and the offshore are weaker. For this season, the onshore measurements are assumed representative up to 18 m/s, and the offshore up to 23 m/s.

One difference is that the onshore winter measurements lie below the winter curve in Figure 5-8 for wind speeds up to about 10 m/s, and below the offshore winter measurements up to 7 m/s. The reason for this is unknown, but it might be related to the large increase in stable conditions from summer to winter in the onshore sector (cf. Chapter 5.3).

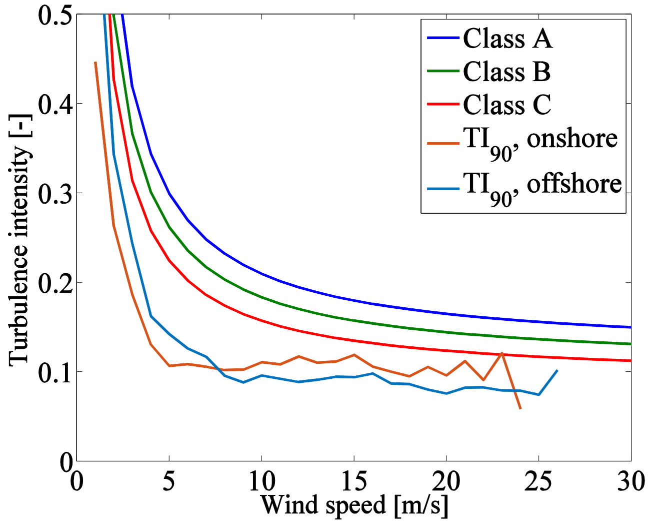

Figure 5-17 Turbulence intensity, winter

When comparing Figure 5-16 and Figure 5-17, offshore TI for summer is consistently weaker than offshore TI for winter. This corresponds to the findings in Chapter 5.2.3. Onshore TI for the two seasons are relatively similar, except for the low values at low wind speeds in winter, as discussed in the previous paragraph. Finding seasonal patterns to be more pronounced in offshore than onshore environments, correspond to the work by Bierbooms [23].

5.3.2.3 Other factors

Like in Chapter 5.2.4, this section considers TI in terms of diurnal variations and height differences, here for the onshore and offshore sectors. The diurnal pattern is shown in Figure 5-18.

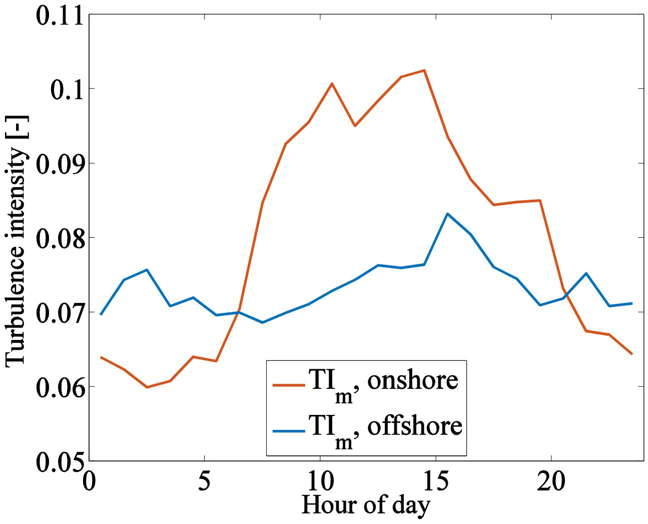

Figure 5-18 Diurnal TI pattern, onshore and offshore

When considering seasonality in diurnal TI variations, the summer in the onshore sector represents the largest differences between day and night. Both seasons in the offshore sector have relatively small variations, both smaller than the onshore sector in winter. Within both sectors, the diurnal variations in TI are larger in summer than in winter (cf. Figure 5-9).

For differences in TI with height, both direction sectors follow the trend in Figure 5-10, with decreasing TI for increasing distance to ground. However, for the offshore sector, the differences in TI between neighbouring measurement heights decrease as the height increases, whereas the change in TI between heights in the onshore sector stays at a fairly constant level.

6 CONCLUSIONS

A two-year period of wind data have been examined with the aim of analysing atmospheric turbulence intensity at Skipheia measurement station. Two direction sectors were chosen to represent onshore and offshore conditions, respectively, and have been investigated in terms of various parameters expected to influence TI. There is uncertainty in whether the respective sectors can represent onshore and offshore environments, but they are assumed to give an indicative picture of differences between the two.

In addition, measured TI has been compared to predictions given by the Normal Turbulence Model in IEC 61400-1 and IEC 61400-3 [3, 4]. It was found that NTM is not consistent with the observations at Skipheia, neither for the onshore and offshore sectors, nor for all directions sectors as a whole. Previous studies have promoted the needs of a new turbulence model for offshore environments [5-7], and this study supports those findings.

When considering all direction sectors in one, there are small differences in TI_{90} between stable and unstable conditions. However, the rough stability classification in this work is found not to be adequate for description of TI in the designated stability classes.

Investigating seasonal variations, TI is found to be weaker in summer than in winter, which is an unexpected result and needs further examination. The diurnal pattern shows a peak in TI during daytime, when the temperatures are high, and lower values for the night hours. These variations are more pronounced in summer than in winter. For increasing elevations, TI is found to decrease, being more sensitive to surface roughness closer to the ground.

Based on literature, the offshore sector is expected to have clearly lower TI than the onshore sector. When comparing the two, the offshore TI_{90} is slightly weaker than the onshore. The small differences may indicate that TI at 70 meters at Skipheia is more influenced by the state of the atmosphere than the surface roughness.

For the two seasons investigated, differences in TI between onshore and offshore sectors are more distinct in summer than in winter. As for the entire 360° sector, the diurnal pattern of TI is clearer in summer and in addition more definite in the onshore sector.

For further work, it is suggested to investigate vertical profiles of turbulence intensity at Skipheia, and to compare the measurements to earlier work, e.g. the research of Working Group 3 in the COST 710 report, regarding vertical profiles of wind, temperature and turbulence [25]. In addition, it would be interesting to examine the impact of turbulence intensity on the power performance of an intended wind turbine at Skipheia, and link the findings to the work by Fechner [16].

7 REFERENCES

[1] J. F. Manwell, J. G. McGowan, and A. L. Rogers, *Wind energy explained : theory, design and application*, 2nd ed. Chichester, U.K.: Wiley, 2009.

[2] J. Lundquist and A. Clifton. (2012, 27.05.2015). *How turbulence can impact power performance*. Available: https://wind-watch.org/doc/?p=3086

[3] IEC, "International Standard IEC 61400-1," in *Wind turbines - Part 1: Design requirements*, ed. Geneva, Switzerland: International Electrotechnical Commission, 2005.

[4] IEC, "International Standard IEC 61400-3," in *Wind turbines - Part 3: Design requirements for offshore wind turbines*, ed. Geneva: International Electrotechnical Commission, 2009.

[5] H. Wang, R. J. Barthelmie, S. C. Pryor, and H. G. Kim, "A new turbulence model for offshore wind turbine standards," *Wind Energy*, vol. 17, pp. 1587-1604, 2014.

[6] B. Ernst and J. R. Seume, "Investigation of Site-Specific Wind Field Parameters and Their Effect on Loads of Offshore Wind Turbines," *Energies*, vol. 5, pp. 3835-3855, 2012.

[7] M. Türk and S. Emeis, "The dependence of offshore turbulence intensity on wind speed," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 98, pp. 466-471, 2010.

[8] C. Obhrai, K. Siri, and O. Gudmestad, "A Review of Current Guidelines and Research on Wind Modelling for the Design of Offshore Wind Turbines," presented at the International Offshore and Polar Engineering Conference, Rhodes, Greece, 2012.

[9] I. S. Øistad, "Site analysis of the Titran Met-masts," Project thesis, Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway, 2014.

[10] T. Heggem, *Measurements of coastal wind and temperature: sensor evaluation, data quality, and wind structures*. Trondheim: Norwegian University of Science and Technology, Faculty of Physics, Informatics, and Mathematics, Department of Physics, 1997.

[11] DNV, "Offshore Standard DNV-OS-J101," in *Design of Offshore Wind Turbine Structures*, ed: Det Norske Veritas, 2011.

[12] R. B. Stull, *An introduction to boundary layer meteorology*. Dordrecht: Kluwer Academic Publishers, 1989.

[13] N. M. Zoumakis and A. G. Kelessis, "The dependence of the bulk Richardson number on stability in the surface layer," *Boundary-Layer Meteorology*, vol. 57, pp. 407-414, 1991/12/01 1991.

[14] K. Ashrafi and G. A. Hoshyaripour, "A Model to Determine Atmospheric Stability and its Correlation with CO Concentration," *World Academy of Science, Engineering and Technology*, vol. 2, pp. 117-122, 2008.

[15] A. Westerhellweg, B. Canadillas, and T. Neumann, "Direction Dependency of Offshore Turbulence Intensity in the German Bight," presented at the DEWEK, Bremen, Germany, 2010.

[16] S. Fechner, "Preprocessing of Meteorological Data for Atmospheric Theoretical/Numerical Models," Department of Energy and Process Engineering, Norwegian University of Science and Technology, 2015.

[17] S. Lee, M. Churchfield, P. Moriarty, J. Jonkman, and J. Michalakes, "Atmospheric and Wake Turbulence Impacts on Wind Turbine Fatigue Loadings," presented at the 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Nashville, Tennessee, 2012.

[18] L. Eliassen, J. B. Jakobsen, and C. Obhrai, "The Effect of Atmospheric Stability On the Fatigue Life of Offshore Wind Turbines."

[19] N. Carpman, "Turbulence Intensity in Complex Environments and its Influence on Small Wind Turbines," Department of Earth Sciences Uppsala University, Uppsala, 2011.

[20] BWEA, "Prospects for Offshore Wind Energy: A Report Written for the EU," The British Wind Energy Association (BWEA)2000.

[21] S. Emeis, *Wind Energy Meteorology: Atmospheric Physics for Wind Power Generation*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013.

[22] R. J. Barthelmie, M. S. Courtney, B. Lange, M. Nielsen, A. M. Sempreviva, J. Svenson*, et al.*, "Offshore Wind Resources at Danish Measurement Sites," presented at the European Wind Energy Conference, Nice, France, 1999.

[23] W. Bierbooms. (28.05.2015). *Offshore Wind Climate*. Available: http://ocw.tudelft.nl/fileadmin/ocw/opener/offshorewindfarmhfd3.pdf

[24] T.-S. Leu, J.-M. Yo, Y.-T. Tsai, J.-J. Miau, and T.-C. Wang, "Assessment of IEC 61400-1 Normal Turbulence Model for Wind Conditions in Taiwan West Coast Areas," in *International Journal of Modern Physics: Conference Series* vol. 34, ed. Taiwan, 2014.

[25] A. Cenedese, G. Cosemans, H. Erbrink, and R. Stubi, "Vertical Profiles of Wind, Temperature and Turbulence," Office for Official Publications of the European Communities, Luxemburg1998.