Characteristics of abnormal vertical wind profiles at a coastal site

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Abstract. Phenomena such as internal boundary layers and low-level jets can cause short-term wind fluctuations resulting in the vertical wind profile deviating from its expected logarithmic shape. Analysis of several years of data from the 6 measurement heights on the 100m high coastal Skipheia mast reveals that the 10-minute averaged vertical wind profile deviates from the vertical wind profiles predicted by Monin-Obukhov similarity theory in 30 – 40% of the analyzed instances. Deviations were most commonly present in the form of 1 local maxima, and in more rare instances as 2 local maxima or a completely reversed and monotonically decreasing profile. Analyzing the onshore and offshore directional sectors reveals that offshore winds are less reliant on strong thermal gradients for local maxima to be present, and inflections also occur at higher wind speeds in the offshore sector. Inflections are found to be progressively more common at higher elevations regardless of the direction of incoming wind, and as the found inflection elevations are close to common wind turbine hub heights they represent a potential issue in wind engineering.

1. Introduction

Wind velocity varies both in time and space, vertically and horizontally. In order to estimate the power production from wind turbines, the wind speed at hub height must be estimated or known. Due to the wind speed rarely being measured at hub height, the common method used today is to measure the wind speed at a lower altitude, and thereby extrapolate it to hub heights, now typically around 100m [1]. Such vertical extrapolation enables predictions of wind turbine power output, a crucial part of wind resource assessment. Understanding the vertical wind profile development is in addition important when assessing rotor fatigue and turbine load control [2].

There is and has been an ongoing increase in coastal and offshore wind park development, the mesoscale and smaller-scale physical phenomena associated with offshore and coastal winds are as a result receiving more attention [3]. When the wind profile is averaged over a longer time period, the vertical wind profile is described by the logarithmic law (log-law) of Eq. 1, where $u_*$ is the friction velocity, $k$ the von Kármán constant, $z_0$ the roughness length and $\psi$ a stability dependant function which adopts a negative value during stable conditions, a positive value during unstable conditions and is zero under neutral conditions. The logarithmic law is derived from Monin-Obukhov similarity theory (MO-theory), the most commonly used framework for
describing exchange processes within the surface layer. The theory assumes constant vertical fluxes of temperature, velocity and shear stress, wind over a flat homogeneous terrain with a uniform and low surface roughness, as well as relying on sufficient time averaging of minimum 10-60 minutes [4] [5]. The special neutral conditions case removes the stability dependency of the vertical velocity development, and due to an assumed high degree of neutral conditions offshore the stability contribution is often disregarded for offshore purposes [6]. In non-neutral conditions the stability function $\psi$ needs to be determined empirically, a matter which received substantial attention after MO-theory was presented [7]. The empirical determination can however lead to deviations between measurements and theory during non-neutral conditions which is a persistent issue both onshore and offshore.

$$u(z) = \frac{u_*}{k} \left[ \ln \left( \frac{z}{z_0} \right) - \psi \left( \frac{z}{L} \right) \right]$$

While the logarithmic law is commonly used at both offshore and coastal locations, it does not describe the fluctuations in the vertical wind profile due to the sudden change in surface conditions [8]. This sudden change in surface conditions exposes coastal winds to internal boundary layers (IBL) formulations, as well as a varying roughness length with ocean wave conditions. In addition, both onshore and offshore winds have been shown to experience low-level jets which can cause more complicated vertical wind profiles [3].

Internal boundary layers are typically associated with the horizontal advection of air across a step change in surface. This change in surface is usually related either to surface roughness or surface heating capacity, which results in an internal boundary layer which can develop both temporally and spatially [9]. Internal boundary layers have in previous studies shown to result in higher than predicted wind velocities at both coastal and offshore locations [10–12]. These unexpected instantaneous wind velocity profiles represent a challenge when predicting the vertical wind profile, as they are fluctuating and thus more difficult to predict.

A low-level jet (LLJ) is typically categorized by a wind speed maximum at lower atmospheric altitudes, caused by a layer of air moving at an increased velocity. Evidence of low-level jets has been found in several onshore and offshore locations, and Nunalee et al. [3] presented an overview of the implications of coastal low-level jets for offshore wind farm development. The results from previous studies [3] show evidence of low-level jets at several measurement locations, often created due to the large temperature differences between the land and sea. In the Baltic Sea, evidence of a low-level jet has been found at an altitude as low as 30m for a stably stratified boundary layer [13]. The presence of IBL’s and LLJ’s in the North Sea has also been postulated by Beran et al. [14].

When identifying phenomenon such as internal boundary layers and low-level jets, a simple identification method is to categorize the profile in terms of local maxima, a method which was employed by Kettle [15] when studying abnormal vertical wind profiles at the FINO1 research platform in the North sea. The study revealed that most of the wind profiles had local maxima, thus showing that the expected modified logarithmic law does not sufficiently describe the instantaneous wind profile for a majority of cases. The results showed that cases with 1, 2 or 3 local maxima are common, and even cases of a completely reversed wind profile were found.

This study will investigate the presence of local maxima in the 10-minute averaged vertical wind profile at a coastal site in western Mid-Norway up to a height of 100m. The wind measurements will be categorized as arriving from an onshore or offshore wind direction, yielding insight into the occurrence of local maxima in onshore and offshore winds. The local maxima height and duration will be analyzed, and they will also be coupled with the atmospheric conditions under which they occur. This analysis could enable a further description of phenomenon such as internal boundary layers, low-level jets and sea-land breezes, and how
they affect onshore and offshore winds at a coastal site. These results could be of great importance for both future wind physics research, as well as wind farm developers and wind turbine designers.

2. Method
The vertical wind profile is within the scope of Monin-Obukhov similarity theory described by the modified logarithmic law, given in Equation 1. Due to the monotonically increasing nature of the modified logarithmic law, the vertical wind profile is not predicted to have any local maxima. Such local increases followed by a decrease in wind speed, are commonly associated with low-level jets and internal boundary layers. In order to evaluate to which degree the vertical wind profile deviates from its predicted behaviour, the profiles have been categorized by the number of local maxima found. This method of identification is the same as the one used by Kettle [15]. In this study the extent of the maxima was not evaluated, and no difference was made between small and large maxima.

The data used originates from a site with 6 vertical wind velocity measurement points, the wind profile can therefore have 0, 1 or 2 inflections. In addition, the velocity profile was also found to be completely reversed and decreasing with height for some instances. With this categorization of profiles, 4 different cases are possible. The wind profile either has no inflections, 1 inflection, 2 inflections or it is completely reversed. Figure 1 shows an example of the different vertical wind profiles possible.

![Figure 1: From left to right: 0 inflections, 1 inflection, 2 inflections and reversed profile](image)

2.1. Site description
The data used in this analysis is collected from the Skipheia measurement site. The measuring mast is located at the western mid-Norway coast on the island of Frøya, and can be seen in Figure 3a. The location can be seen in Figure 2, and a picture of the typical surroundings on the island is given in Figure 3b. The mast is located on land, approximately 20m above sea level and with the shortest distance to the ocean being 300m. The site experiences winds coming in from the Norwegian sea from the south-west, onshore winds from the east, and wind with mixed fetch from other directions. The measurement station has a 100m high mast measuring wind velocity and direction in 10-minute averages at heights 10m, 16m, 25m, 40m, 70m, 100m. The wind is measured by two ultrasonic anemometers at every height and recorded at a frequency of 1 Hz, before being averaged over 10-minute intervals. The temperature at the site is measured at 7 different heights. The temperature measurements were done by one Campbell Scientific 109 temperature sensor at each height. Table 1 summarizes the instrumentation and its accuracy.
Figure 2: Skipheia site location

| Sensor                                      | Accuracy   | Measurement heights [m] |
|---------------------------------------------|------------|-------------------------|
| Gill WindObserver II 2D Anemometer          | ± 2%       | 10, 16, 25, 40, 70, 100 |
| Campbell Scientific 109 Temperature sensor | ± 0.25K    | 0.2, 10, 16, 25, 40, 70, 100 |

Table 1: Site instrumentation

The pressure and humidity were not recorded at the Skipheia measurement site, and were therefore extracted from the nearby meteorological station Sula for calculation of the virtual potential temperature. The station is located on an island approximately 20 km north of the Skipheia site, and can also be seen in Figure 2. The pressure and relative humidity were recorded in 6h samples and have been assessed to sufficiently represent the time-variation of pressure and humidity at Frøya [16].

Figure 3: (a): The Skipheia mast, with two booms at each height. (b): The Skipheia rocky terrain surroundings.

2.2. Dataset and filtering

The data used in the study was recorded in the period November 2009 - December 2014. The dataset was filtered by wind direction so that the wind speed and direction from the upwind anemometer was used. In this way, one avoids flow distortion from the measuring
mast. The dataset was in addition filtered to remove any data entries where the recordings were incomplete or showing nonphysical measurements. After this filtering the dataset had 84 708 individual time-entries of 10-minute averages, yielding an availability of 31.5% in comparison to the unfiltered data. To avoid results bias the data was not filtered according to a standard deviation criterion or a minimum wind speed criterion.

Two directional sectors were defined to represent onshore and offshore conditions. Onshore wind was defined as any wind coming from the direction sector 40°-100°. This directional sector has winds coming from inland and subsequently crossing the island of Frøya from east to west. The offshore sector was defined as any wind coming in the direction 190°-260°, the sector where the fetch to shore is shortest and most uniform. These winds are categorized by having travelled over the sea for a substantial distance, and the wind characteristics therefore strongly resemble offshore wind.

2.3. Stability classification
In this study, the surface-layer Richardson number was used to analyze the atmospheric stability because of its increased robustness due to using only one wind speed measurement height [16]. In equation 2, $g$ is the gravitational acceleration, $\theta_v$ the virtual potential temperature, $z$ the height of upper temperature measurement, and $\bar{U}$ the mean velocity at this height. The velocity and virtual potential temperature are both evaluated at height $z$, and the change in virtual potential temperature is evaluated between the height $z$ and the ground. In this study, the height $z=40m$ was used in the stability analysis. The stability distributions showed little variance within the surface roughness range relevant for the site, the mean roughness length $z_0 = 0.01$ was therefore used [16].

$$Ri_s = \frac{g}{\theta_v} \frac{\Delta \theta_v z}{\bar{U}^2}$$

When relating the Richardson-number to the Monin-Obukhov stability parameter $\zeta$, the relations taken from Arya given in equation 3 were used, where $L$ is the Obukhov length and $z_0$ is the roughness length of Eq. 1 [5].

$$\zeta = z/L = \begin{cases} 
Ri_s \ln \left( \frac{z}{z_0} \right), & Ri_s < 0 \\
\frac{Ri_s}{1-5Ri_s} \ln \left( \frac{z}{z_0} \right), & 0 < Ri_s < 0.2 
\end{cases}$$

As seen in equation 3, no condition is given for $Ri_s > 0.2$, however instances of $Ri_s > 0.2$ were found frequently in this dataset. For $Ri_s > 0.2$, turbulence is suppressed and the atmosphere is considered very stable. Since only stability classes are considered in this dataset, all instances of $Ri_s > 0.2$ were put in the very stable class. The Monin-Obukhov length $L$ was then used to classify stability as follows [16].

| Stability     | Range |
|---------------|-------|
| Very stable   | $0 < L < 100$ |
| Stable        | $100 < L < 500$ |
| Neutral       | $|L| > 500$ |
| Unstable      | $-500 < L < -100$ |
| Very unstable | $-100 < L < 0$ |

3. Results and discussion
Anterior to the analysis of local wind speed maxima, the wind direction and wind speed distribution at the Skipheia site was analyzed. The results can be seen in Figure 4. The predominant wind-direction at the Skipheia site is from southwest, which is within the previously
defined offshore sector of 190°-260°. A large portion of the wind is also arriving within the onshore sector of 40°-100°. Knowing the typical wind speeds and directions at the Skipheia site, the analysis of local maxima was performed. The results of the inflection analysis for the entire dataset (no directional filtering), as well as for the onshore and offshore direction sectors, are shown in Table 2. The possibilities were no inflections, 1 inflection, 2 inflections or a completely reversed profile, all which are visualized in Figure 1.

The results of analyzing the local maxima in the vertical wind profile are given in Table 2, and show that the velocity profile with no inflections is the most common for all directional sectors, being present in 62.86% of the profiles. This could be considered an expected vertical wind profile, since the profile shape can be described within the scope of Monin-Obukhov (MO) theory. The remaining wind profiles do however exhibit one or more local maxima, or the profile is reversed and the wind speed monotonically decreases with height. While the reversed profiles can not be theoretically described within the scope of MO-theory, in inflected profiles MO-theory may be applicable up to the point of the local maxima.

In order to quantify the effect of low wind speed stochastic inflections, the effect of enforcing a minimum wind speed criterion was studied. Enforcing a minimum wind speed criterion of $U(z = 10m) > 2$ m/s resulted in 64.68% of 0-inflection profiles, the small change indicates that a minimum wind speed criterion does not significantly impact the results and was therefore not employed in the presented results to avoid the filtering causing results bias.

|               | No inflections | 1 inflection | 2 inflections | Reversed |
|---------------|----------------|--------------|---------------|----------|
| **Full dataset** |                |              |               |          |
| Number of cases | 52 090         | 26 794       | 3 229         | 750      |
| Percentage    | 62.86%         | 32.34%       | 3.90%         | 0.91%    |
| **Onshore sector** |            |              |               |          |
| Number of cases | 10 653         | 5 331        | 425           | 218      |
| Percentage    | 64.07%         | 32.06%       | 2.56%         | 1.31%    |
| **Offshore**   |                |              |               |          |
| Number of cases | 17 585         | 6 663        | 866           | 122      |
| Percentage    | 69.68%         | 26.40%       | 3.43%         | 0.48%    |

Table 2: Inflection analysis
Analyzing the results of the predefined directional sectors shows that the onshore sector has a higher prevalence of abnormal profiles (35.93%), which decreases slightly for the offshore sector (30.32%). The onshore sector also has the highest occurrence of wind profiles with 1 inflection (32.06%), while the offshore sector has a higher prevalence of wind profiles with 2 inflections (3.43%). The results also show that there is a lower percentage of reversed profiles within the offshore sector. These results may suggest abnormalities are more common onshore, the total difference in abnormal profiles is however less than 6%, and since the Skipheia site is on an island and evidently located in varying terrain, no conclusion should be based solely on this result.

Comparing to the recent analysis by Kettle [15], the results in this study have a significantly lower prevalence of the 1- and 2-inflection cases, and subsequently a higher occurrence of the 0-inflection case. This difference must however be seen in light of the fact that the study by Kettle was done using data from the FINO1 mast, which has 8 vertical measurement points at a resolution of 10m intervals, compared to the 6 vertical measurement points of the Skipheia site. The FINO1 mast is therefore able to record profile maxima with a smaller vertical span, which is the likely cause of the large differences.

3.1. Wind speed analysis

The results of analyzing the wind velocity at which inflections occur are visible in Figure 5, and show that the mean wind speed is decreasing as the profiles become inflected, regardless of the directional sector. The offshore incoming winds expectantly have a higher velocity, resulting in the offshore sector experiencing inflections at higher wind speeds than onshore. The offshore inflections are thus arguably of a larger importance due to the higher wind speeds at which they occur. The trend of a decreasing mean wind velocity in the presence of local maxima is the same as presented by Kettle [15].

![Figure 5: Frequency distributions of wind velocity with the various profile categories from onshore and offshore sectors](image)

The reversed profile cases occur at such low wind velocities that they are less relevant for wind
power estimation. Typical cut-in speed of wind turbines is around 4 m/s, since the majority of the reversed cases occur below this velocity, the turbine is unlikely to be producing power [1]. The reversed profile cases could however be of significance in fatigue and mast bending moment calculations due to the possible increase in wind shear.

3.2. Stability analysis

For onshore winds (Figure 6a-6d), inflected wind profiles result in an increase in a stable, very stable and very unstable atmospheric conditions. This also causes a lower occurrence of a neutral atmosphere, which is coherent with the wind speed analysis. For the offshore directional sector (Figure 6e-6h), the behaviour is generally similar to onshore, with a decrease in neutral conditions and an increase in very stable and very unstable conditions when inflections are present. However, the higher offshore wind speeds cause a higher amount of neutral conditions, which results in the offshore sector seeing more profiles inflected during neutral conditions. Onshore neutral conditions become close to obsolete for the 2-inflection case, and the inflections do seem to rely on larger thermal gradients to occur. The increase of unstable conditions with inflections was also found by Kettle [15], the increase in stable conditions was however not. This may highlight an important difference between inflection occurrence at offshore and coastal sites.

It is also of high relevance to analyze the severity of the found inflections through investigating the shapes of inflected profiles. The inflection severity is found to scale with the wind shear, which is largely decided by the stability of the atmosphere. MO-theory predicts highest shear during very stable conditions and medium shear during neutral conditions and lowest shear during very unstable conditions. This is reflected in the the severity of the inflected profiles, which is largest during stable/very stable conditions and lowest during very unstable conditions. The cause of this is related to the wind shear; an inflection in a flat profile is often minor and has little impact on the predicted shape, whereas an inflection in a higher shearing profile means that the difference between the predicted and actual shape becomes larger. Additionally, analyzing the inflected profiles shows that many inflected profiles retain their negative shear for several heights above the maximum, which causes even larger deviations during stable/very stable
conditions. Due to the higher number of inflected profiles during stable/very stable conditions onshore (48% of 1-inflection profiles), these conditions seem to be the cause of largest concern in such environments. Offshore the neutral conditions may be the larger concern, as these profiles also cause moderate deviations while occurring more often and also at higher mean wind speeds.

### 3.3. Inflection height

The inflection height was analyzed for the 1-inflection case due to this being the predominant abnormal profile type, and the results of the height of inflections along with the stability distribution of inflections at each height is shown in Figure 7. The results show that both the onshore and offshore direction sectors shows a higher number of inflections at a higher elevations, with the majority of the velocity maxima occurring at 70m, the highest possible. Both onshore and offshore neutral conditions are also predominantly associated with higher altitude inflections, with inflections occurring at the highest altitude \(z=70\text{m}\) for \(\approx 50\%\) of profiles. This may indicate that these inflections occur due to shallow surface layers where the inflection is caused by a discontinuity in the vertical layering of the atmosphere.

The unstable/very unstable inflections are both onshore and offshore seen to be more evenly distributed with height, most likely due to the low shearing profile in these conditions being less dependant on higher elevations for inflections to occur. The stable/very stable inflections do however show a clear difference, where the offshore sector experiences such inflections more commonly at intermediate heights. The onshore sector to the contrary experiences these inflections more commonly at higher altitudes. This could indicate that the offshore sector experiences inflections forced by an IBL, whereas the onshore sector stable/very stable inflections are linked with shallow surface layers known to occur during very stable conditions.

Since irregularities at higher altitudes are more relevant for wind farm developers, the increased occurrence at higher elevations could be a source of concern for wind energy applications. For example, Wagner et al. [17] found maximum in the wind profile occurring close to hub height to have a large effect on the available power. Inflections were also found to be more common at higher elevations by Kettle [15].

![Figure 7: Inflection height, onshore and offshore directions](image)

### 3.4. Inflection duration

The duration of inflections was analyzed to understand how long one profile state lasts before changing to another. The minimum duration is 10 minutes due to the wind speeds being recorded in 10-minute intervals. The duration was counted as how long one wind profile state prevailed before switching to another state. These results are visualized for the entire dataset.
(no direction filtering) in Figure 8, as no large differences were seen between the entire dataset and the separate directional results.

Figure 8: Inflection duration

Evident from the results, all cases show a similar profile fit when plotted logarithmically. The shortest duration is the most common, and the amount of cases is thereafter almost linearly decreasing when plotted logarithmically. The 0-inflection case has the longest maximum duration of above 30 hours, whereas for the 1-inflection case, the largest duration is just above 6 hours. A clear difference can also been seen in that the reversed and 2-inflection cases have considerably shorter durations, never lasting more than two hours.

4. Summary & Conclusion
This study has analyzed the occurrence of local maxima in the 10-minute averaged vertical wind profile at a coastal on-land site. The velocity, height, time, and duration at which the local maxima occur has been investigated, and the dependency of local maxima occurrences on atmospheric stability has also been analyzed.

The results of analyzing the vertical wind profile show that for the entire dataset, 37% of the recorded wind profiles showed deviations in the form of 1 or 2 inflections, or a completely reversed velocity profile. The onshore directional sector showed deviations in 36% of the profiles, a larger percentage-wise presence of abnormal wind profiles when compared to the 30% of the offshore sector and when comparing to the full dataset. The found abnormalities were predominantly in the form of one local maxima.

Due to analyzed site being on an island with much local terrain variations at the analyzed site, there is uncertainty related to whether the quantity of onshore and offshore inflections found in this study is representative of conditions in other locations. However one may conceptualize the implications of the found inflections. The results reveal that the inflections which should be of larger concern are the ones which occur during neutral to very stable conditions, due to their higher shear and continued decrease above the local maxima being a large source of error between predicted and actual wind speeds. Stable/very stable conditions are typically more common onshore, and these profiles may therefore be of larger concern at onshore sites. In the offshore incoming sector there is a higher degree of high wind speed neutral inflections which typically occur at higher altitudes. At coastal sites, both onshore and offshore winds are in this study found to show signs of shallow surface layers. The results reveal that the offshore incoming winds may also be effected by an internal boundary layer during stable/very stable conditions which is associated with a kink in the vertical wind profile.

The inflections found in this study indicate a coupling to surface-layer discontinuities under which circumstances Monin-Obukhov theory is not appropriate for describing the vertical wind profile, suggesting that a more versatile vertical wind profile description may be necessary. A solution could be a unified vertical wind profile description which is valid not only for the surface layer, but for the entire boundary layer [18]. Such formulations are however reliant on estimates
of the surface layer and boundary layer height, and studies which investigate such height scalings at a variety of conditions will therefore be important if such models are to be implemented.

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