Atmospheric stability assessment for the characterization of offshore wind conditions

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Abstract. Based on the Fino-1 offshore met mast database, different instrument set-ups and methodologies for stability characterization have been tested using non-dimensional numbers like the gradient and bulk Richardson number, and their equivalences with the Obukhov parameter $\tilde{\alpha} = \frac{z}{L}$, which can be measured locally with the use of a sonic anemometer. These equivalences depend to a large extent on the suitability of empirical stability functions obtained in horizontally-homogeneous conditions. The bulk Richardson number method, based on Grachev and Fairall (1997) empirical function, is the least demanding measurement method for stability characterization offering a more practical approach to wind farm designers than using the sonic method. Alternatively, the AMOK method, used by FUGA wake model and also based on the bulk Richardson number, assumes surface-layer theory and avoids using stability functions, which results in a more robust formulation. A 9-class stability classification based on Sorbjan and Grachev (2010) is used to generalize the categorization of wind conditions. Based on flux-profile analysis it was concluded that unfortunately the local $\tilde{\alpha}$ is not sufficient to describe the scaling behaviour of the stable boundary layer. Indeed, larger wind shear than predicted by classical onshore stability functions is found, probably as a result of lower boundary layer depths.

1. Introduction

Offshore wind power (onshore as well) is challenging many traditional wind resource assessment methodologies that have traditionally relied on a rather simplistic description of the wind climate distribution based on velocity and wind direction. Large wind farms are immersed in the marine atmospheric boundary layer (ABL) where wind conditions are modulated by atmospheric stability throughout the entire operating range of wind turbines. Low turbulence intensities due to the very low aerodynamic roughness of the sea surface are responsible for slow decaying wakes that last much longer than in onshore conditions [1].

Traditional wind farm design tools, developed for onshore wind deployment, typically assume neutral atmospheric stratification resulting in higher turbulence intensities and larger wake decay coefficients than in offshore conditions [2]. As a result these models will systematically underestimate wake effects in offshore conditions.

High fidelity wind assessment tools need to account for a thermally stratified turbulent structure of the marine ABL to produce accurate wind farm models. The addition of a third dimension to the
description of the wind climate based on atmospheric stability will produce a more detailed spectrum of wind conditions which will allow a more complete wind farm design eventually leading to improved performance. On the other hand, it is necessary to make sure that the added complexity is not detrimental to the robustness and uncertainty of the design methodology. Hence, best-practice guidelines will be produced to guide wind analysts on the characterization of atmospheric stability and its influence on the wind profile.

2. Stability assessment from measurements

2.1 The Obukhov length method from sonic anemometer measurements
Local-scaling theory [3] generalizes Monin-Obukhov (M-O) surface-layer theory [4] to the ABL. It states that any dimensionless turbulence characteristic will only depend on a reduced set of scales which, by dimensional analysis, lead to the Obukhov length scale \( L \):

\[
L = -\frac{u^3}{\kappa g \overline{w} \theta_0}
\]

where \( g \) is the gravity, \( u_* \) is the friction velocity, \( \theta_0 \) is the surface temperature and \( \overline{w} \theta \) is the kinematic heat flux. The dimensionless height \( \zeta = z/L \) is used as stability parameter (\( \zeta < 0 \) indicates unstable, \( \zeta > 0 \) stable and \( \zeta = 0 \) neutral conditions). The Obukhov length is obtained from sonic anemometers using eddy-correlation techniques. The result is a local evaluation of stability based on turbulent fluxes averaged over periods from minutes to one hour to account for the energy in the microscale turbulence range. Since the Obukhov length method based on sonic measurements does not require any hypothesis, produces a local value of stability and is the most widely used stability parameter in ABL theories, we will use the \( \zeta \) parameter as our target stability metric and the sonic method as our benchmark to compare other profile-based methods.

According to local-scaling theory, any dimensionless turbulent characteristic will depend solely on this parameter evaluated at any given height within the ABL. For example, the nondimensional wind shear:

\[
\phi_m(\zeta) = \frac{\kappa z}{u_*} \frac{\partial U}{\partial z}
\]

is equal to 1 in neutral conditions, where \( \kappa = 0.41 \) is the von Karman constant and \( U \) is the horizontal velocity. In non-neutral conditions several stability functions \( \phi_i(\zeta) \) can be found in the literature, being the ones from Dyer [5], based on flux-profile measurements in Kansas, the most widely used:

\[
\phi_x(\zeta) = \begin{cases} 
(1-a_m \zeta)^{p_m} & \zeta < 0 \\
1+b_m \zeta & \zeta \geq 0
\end{cases}
\]

with \( a_m = a_h = 16, b_m = b_h = 5, p_m = -1/4 \) and \( p_h = -1/2 \), where the subscript \( m \) is related to the wind speed shear and \( h \) to the temperature shear. Integrating (2) between the surface roughness \( z_0 \) and a given height yields the well known logarithmic wind profile:

\[
U = \frac{u_*}{\kappa} \left[ \ln \left( \frac{z}{z_0} \right) - \psi_m(\zeta) \right]
\]

where \( \psi_m(\zeta) \) is the integrated stability function for momentum [6]. In offshore conditions the Charnock relation links the roughness length to the shear stress [7]:

\[
\frac{z_{0w}}{u_*} = C \frac{\overline{w} u_*}{u_*}
\]

where \( C \) is a constant relating the friction velocity to the shear stress.
where the Charnock constant \( C_{ch} \) ranges from 0.008 to 0.06 in the literature [8]. This constant can obtained by fitting equation (4) in neutral conditions. Peña and Gryning [8] found a value of 0.012 from measurements at Horns Rev and Sanz Rodrigo [9] found a value of 0.006 at Fino-1, both met-
nast located in open-sea conditions in the North Sea. Lange et al [10] found a value of 0.03 at Rodsand, 11 km from the coast in the Baltic Sea. This higher value is related to a dependency of the surface roughness with the fetch (distance to the coast). A fetch-dependent model is proposed by [11].

2.2 The gradient Richardson method from profile measurements

The gradient Richardson number is the ratio of turbulent kinetic energy generation by buoyancy to that generated by shear. Using eddy-viscosity assumptions, the turbulent fluxes are defined in terms of velocity and temperature gradients to yield:

\[
Ri(\zeta) = \frac{\frac{\partial \Theta}{\partial z}}{\frac{\partial U}{\partial z}^2} = \frac{\phi_0(\zeta)}{\phi_0(\zeta)}
\]

(6)

By iteration in (6) it is possible to derive \( \zeta \) from \( Ri \) if suitable stability functions are available. Alternatively, there are empirical functions that relate directly \( \zeta \) and \( Ri \) like Sorbjan and Grachev [12].

\[
\zeta = \begin{cases} 
Ri & \zeta \leq 0 \\
Ri \left( 1 + 300Ri^2 \right)^{5/4} & \zeta > 0 \\
0.9 \left( 1 + 250Ri^2 \right)^{3/2} & \zeta 
\end{cases}
\]

(7)

Computing the Richardson number gradients using finite differences between sensors (finite-differences \( FD \) method) will typically result in biased assessments due to a sensor resolution of about the same order of the temperature differences. This method shall only be used in connection with differential temperature measurements. Alternatively, gradients can be obtained by fitting a logarithmic function of the type \( X = A \log(z) + B \) to the observational data (profile-fit \( PFIT \) method). This method is recommended if more than 3 sensors are available in order to produce a more robust local estimate of \( Ri \). Nevertheless, the accuracy of this method depends, to a large extent, on the adequacy of the underlying empirical relationship to the target site conditions.

2.3 The bulk Richardson method from profile measurements

A more robust estimate of stability is the bulk Richardson number \( Ri_b \), defined in terms of a temperature difference and a single velocity level:

\[
Ri_b(\zeta) = \frac{\alpha z \Delta \Theta}{\Theta_0 U^2}
\]

(8)

where the height \( z \) is taken here as the mean height between the two levels of temperature. Grachev and Fairall [13] derived a relationship between the \( Ri_b \) and \( \zeta \) for offshore conditions:

\[
\zeta = \begin{cases} 
\frac{C_c Ri_b}{1 - C_c Ri_b} & \zeta > 0 \\
C_c Ri_b & \zeta \leq 0 
\end{cases}
\]

(9)
with $C_1 = 10$, $C_2 = 5$, implying a critical bulk Richardson $Ri_b = 1/C_2 = 0.2$. $\Delta \Theta$ in (8) is derived from the air to water temperature difference, where the water temperature should be as close to the surface as possible and $z$ in (9) is therefore half the air temperature height. Similar to the $Ri$ method, $\Delta \Theta$ should be based on differential temperature measurements or well calibrated absolute temperature sensors to avoid biased $Ri_b$.

The definition of the $Ri_b$ number in (8) is generally applicable to any velocity or temperature heights, resulting in a variation of $Ri_b$ with height. In connection to wind resource assessment methodologies, the resulting value from (9) in absolute terms is only meaningful if the same definition is used in the flow model. For practical reasons, we could take two alternatives: 1) to refer to surface-layer stability by measuring velocity and temperature at low heights (<20 m), equivalent to the experimental conditions of Grachev and Fairall, or 2) to refer to a “hub-height stability” by measuring velocity and temperature at hub-height. The first option will be more meaningful to implement in surface-layer models, while the latter is more appropriate in the context of wind energy applications. We typically speak of hub-height wind speed and turbulence to classify wind conditions so we could do the same for stability and refer it to hub-height.

Ott and Nielsen [14] propose a method, also based on the bulk Richardson number, that eliminates the dependency on empirical functions by assuming surface-layer M-O theory and near-neutral conditions ($\zeta < 0.1$). Then the relation between the $Ri_b$ and $\zeta$ is:

$$\zeta = Ri_b \left( \frac{\log z_u / z_0}{\log z_t / z_0} \right)^2$$

(10)

where $z_u$ and $z_t$ are the heights above sea level of the velocity and temperature sensors and $z_0$ is obtained by iteration using the M-O logarithmic velocity profile (4) combined with the Charnock relation (5).

3. The Fino-1 test case

The Fino-1 offshore platform is located 45km off the Borknun Island in Germany (54.014°N, 6.5905°E). A 100-m mast fully equipped with meteorological and oceanographic instruments is measuring since 2003 [15]. Profile measurements of velocity at 8 levels (33, 40, 50, 60, 70, 80, 90 and 100 m), temperature and relative humidity at 5 levels (33, 40, 50, 70 and 100m) are averaged at 10min intervals. Three sonic anemometers located at 40, 60 and 80m measure at 10 Hz the 3D velocity components. Sonic anemometer measurements are available for the year 2006 although the 60 m sensor only works during the first half of the year.

Sonic anemometer measurements are rotated to the mean streamline coordinate system using the planar fit method [9][16][17]. In order to reduce the scatter from flux measurements, both the profile and the flux data are averaged to an hourly database. Only open water conditions are considered, without mast distortion effects, reducing the analysis to the wind direction sector 225°±45°. The analysis filters out velocities outside of the typical operating conditions of wind turbines (4 to 25 m/s). The quality control on the data and a detailed description of the flux-profile method can be found in [9].

4. On the validity of local-scaling offshore

Based on flux-profile analysis [9] it is possible to test whether general ABL local-scaling theory work offshore similarly to onshore conditions. This would allow extending the applicability of onshore stability functions over homogenous flat terrain like (3) to the offshore environment.
Figure 1 shows the non-dimensional wind shear derived from the three sonic levels based on (2), compared to the stability function from Dyer (3) obtained from onshore conditions. The local wind shear is obtained from a profile fit to the cup velocity measurements as it is done for the $R_i$ method. If local scaling theory would apply all the data points from the three levels would align along the same trend. While the unstable and near-neutral regimes are well described by this function, the stable regime shows a larger wind shear, with larger deviation from Dyer's function as we look to levels closer to the sea surface. This indicates that, local scaling theory is not sufficient to account for the vertical structure of the stable marine boundary layer at Fino-1.

Other multi-scale similarity theories [18] might be more appropriate to account with the Coriolis and free-atmosphere stability effects of the ABL, which influence the height of the boundary layer that can be particularly shallow in offshore conditions. The surface-layer can be also affected by the state of the sea. Smedman et al. [19] show that M-O theory is only valid in growing sea conditions, i.e. when wind is increasing and the waves are created by the local wind and move slower than the wind (wave age lower than 0.8). In these conditions the undulated surface is equivalent to a roughness length as predicted by the Charnock dependency on the friction velocity. In swell conditions, when long waves travel faster than the wind due to a distant storm, the wind profile is not logarithmic and develops a kink at some height above the wave surface.

Nevertheless, for practical reasons, boundary layer models in wind energy applications rely on M-O theory to predict the wind profile in offshore conditions. This is not only for the convenience of using models developed previously for onshore conditions but also due to the adequacy to the available measurements from resource assessment campaigns, which do not include measurements of the wave regime or the free-atmosphere stability. For the same reasons we shall also simplify the
analysis by considering only atmospheric stability, based on the local $\zeta$ parameter, as the most important scale for the thermally stratified boundary layer over relevant wind turbine operating conditions. Then, we can fit a specific offshore stability function based on stability bin averages from the three sonic levels (Figure 1). Instead of the linear behavior predicted by Dyer's function, the stable range follows a somewhat parabolic shape, similar to the function found by Duynkerke [20] in the 200-m Cabauw mast (Netherlands):

$$\phi_m(\zeta) = 1 + b_m \zeta \left( 1 + \frac{b_m}{a_m} \zeta \right)^{a_m^{-1}}$$  \hspace{1cm} (11)

with constants $a_m = 0.8$ $b_m = 5$. The Fino-1 case fits to this function with coefficients $a_m = 0.6$ $b_m = 30$.

5. Equivalence among stability assessment methods

Figure 2 shows the regression of both $R_{1/4}$-based methods for estimating $\zeta$ versus the sonic method as reference at two levels of the Fino-1 mast, 40 and 80 m. They both show reasonably good performance although larger spread is observed when using air temperature measurements far from the surface layer. This is to be expected since the Fuga method is based on surface-layer theory and the Grachev and Fairall empirical expression was also obtained from measurements close to the sea surface.

![Figure 2: Regression of the $\zeta$ parameter obtained from the Grachev and Fairall (top) and FUGA (bottom) methods versus the sonic method using the 33 m (left) and 80 m (right) air temperature levels at Fino-1.](image)
6. Atmospheric stability classification

It is relevant to define stability classes that can allow us to categorize wind conditions. Gryning et al. [21] define a seven-category classification based on the Obukhov length. This definition is somehow ambiguous since the Obukhov length depends on the height above ground level when measuring beyond the surface layer. A more generalized categorization is based on the dimensionless stability parameter $\zeta$ associated to a given height. Based on this parameter, Sorbjan and Grachev [12] identify four regimes in the stable boundary layer: "nearly-neutral" ($0 < \zeta < 0.02$); "weakly-stable" ($0.02 < \zeta < 0.6$); "very-stable" ($0.6 < \zeta < 50$); and "extremely stable" ($\zeta > 50$). In the "near-neutral" regime, $Ri$ is a linear function of $\zeta$, while in the "very stable" regime the $Ri$ is an exponential function of $\zeta$.

![Figure 3: Wind shear (top), turbulence intensity (middle), and number of samples (bottom) vs sonic stability at Fino-1 (80 m). The blue and red shading indicate the different stability classes as given in Table 1. Yellow dots represent bin-averages and blue squares stability class-averages.](image)

**Table 1**: Classification of atmospheric stability (symmetric for the unstable range)

| Category         | Range       |
|------------------|-------------|
| near-neutral (n) | $0 < \zeta < 0.02$ |
| weakly stable (ws)| $0.02 < \zeta < 0.2$ |
| stable (s)       | $0.2 < \zeta < 0.6$ |
| very stable (vs) | $0.6 < \zeta < 2$ |
| extremely stable (xs) | $\zeta > 2$ |

Figure 3 shows the wind conditions (wind shear and turbulence intensity) as a function of the sonic stability parameter at 80 m at Fino-1. The yellow dots show bin-averaged quantities based on a uniform bin-width of 0.2. The histogram of the stability parameter indicates that the most relevant
range is $|\zeta| < 2$. Beyond $|\zeta| > 2$ very few profiles are found, showing very large scatter. The blue square dots indicate the ensemble mean values of each stability class following Sorbjan and Grachev classification in the stable range and assuming a symmetric classification in the unstable range for simplicity. The "extremely un/stable" regime limit is shifted to $|\zeta| = 2$ in order to avoid contamination of the large scatter found at the high ends of the scale to the "very un/stable" class. An additional limit is added at $|\zeta| = 0.2$ to add higher resolution in the most frequent stability range. Hence, a nine-class symmetric stability classification is defined (Table 1).

The ensemble averages of the stability classes follow fairly well the variability of the wind conditions for the relevant range of stabilities in Fino-1. The wind shear is roughly constant in unstable conditions and progressively increases in neutral to stable conditions reaching a plateau in very stable conditions.

Figure 4: Class-averaged wind conditions at the open-sea sector of Fino-1 (225° ± 90°) as a function of the stability parameter $\zeta$ based on different stability assessment methods.

Figure 4 shows the class-averaged wind conditions (wind speed ratio between 100 and 33 m, $U_{100}/U_{33}$, and turbulence intensity at 80 m, $T_I$, based on the ratio of the standard deviation to the mean wind speed) at the open-sea sector of Fino-1 as a function of the stability class for different stability assessment methods of determining the $\zeta$ parameter. The $xs$ class shows large discrepancies due to poor statistics from low number of samples with large measurement uncertainties. It is noticed the good equivalence of the $Ri_b$ and the sonic methods, compared to the gradient $Ri$ methods that tend to overestimate the wind shear. In fact, the $Ri$ methods produce a very distinct distribution of stabilities compared to that of Figure 3 from the sonic. The histogram from the $Ri$ method has a larger number of unstable cases and a wider range of stabilities. As a result Figure 4 shows an offset of stability classes compared to the sonic method.

A local maximum of turbulence intensity is noticed for neutral conditions, a distinct behaviour in the offshore environment, caused by the increased roughness in connection with growing sea at high wind speeds. In fact, for $wu$ and $ws$ conditions, that take a very substantial share of the data, we find the same level of turbulence in this case. Hence, there is no monotonic decrease of turbulence with
stability and therefore we cannot take turbulence intensity as a proxy of stability. In this particular case, the wind shear would be a better proxy since there is a more distinct change when we move from unstable to stable conditions.

7. Stability distributions
Figure 5 shows the distribution of atmospheric stability against wind speed based on the four different methods of stability classification described below. It is observed how stability dominates the wind climate over operational wind turbine speeds. The wind climate is roughly divided into 60% of unstable range and 40% of stable range.

Taking the sonic method as a benchmark (Figure 5a), it is observed that the bulk methods reproduce reasonably well the stability distribution in the stable range. The unstable range overpredicts the number of extremely unstable conditions. This is due to situations with $R_i$, much larger than the critical value of 0.2 that are shifted to the unstable regime following Grachev and Fairall function (8). These situations are found when the water-air temperature differences are large (more than 1 ºC) and velocities are low. On the other hand, the method based on the gradient Richardson (Figure 5b) produces a distribution with too frequent extremely stable and unstable cases.

8. Conclusions and discussion
It is generally understood by the wind energy community that the next generation of wind farm tools will include atmospheric stability as a design driver. While model developers are already exploring this possibility, it remains difficult to deal with this extra dimension if suitable stability measurements are not routinely acquired in resource assessment campaigns. This work attempts to provide some
guidance as to how to perform these measurements that are particularly relevant in the offshore environment. Due to the inherent difficulty of the stability assessment methods, it is convenient to adopt certain conventions when it comes to measuring and defining stability. This will narrow down the stability assessment methods to a few practical ones that can be more consistently used in connection to state-of-the-art models.

The bulk Richardson method seems to be a robust approach to characterize stability offshore, requiring the minimum level of instrumentation while still providing good performance in the characterization of mean wind conditions compared to the sonic method, more elaborate and costly. The method requires differential temperature measurements or well calibrated absolute temperature sensors in order to reduce as much as the bias in the evaluation of potential temperature gradients. The sonic method however remains the only way of measuring local stability without the use of empirical functions or theoretical assumptions. In the long term, this instrument shall be the preferred add-on to mast or remote sensing campaigns to characterize not only stability but other turbulence quantities that are relevant for wind farm and turbine design models.

The universality of onshore stability functions has been demonstrated to be invalid in the stable marine boundary layer. It is important to use existing offshore masts, where flux-profile analysis can be done based on several sonic anemometers, to calibrate stability functions for the offshore environment and verify similarity theories including wave conditions. Based on this experimental approach, more accurate parameterizations will be included in mesoscale and microscale wind farm models to account for stable conditions. It is under these conditions that array efficiencies are the lowest and where wake effects take longer to dissipate due to the lower ambient turbulence conditions.

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