Abstract title

Mind the energy gap: how coastal transition and stable atmospheric conditions affect velocity profiles.

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Introduction

When talking about complex sites in terms of resource assessment, we tend to refer to complex terrain or complex forestry conditions. In this contribution we investigate a different type of complexity, associated with the presence of a coastal transition, which will be relevant for many offshore wind farms or onshore wind farms close to large water bodies. We discuss the potential pitfalls resulting from it, when working with data recorded at masts located within the developing Internal Boundary Layer (IBL), and vertically extrapolating the measurement to hub heights.

Approach

For a site with relatively flat terrain, with discontinuities in both aerodynamic roughness and surface stability conditions, we model the development of the wind speed profiles downstream of the transition with Computational Fluid Dynamics (CFD). The results are then compared with data from the literature, for idealised cases, and with wind speed data gathered at masts on a real site.

Main body of abstract

Validation on 2D cases

The first part of the analysis focuses on simplified 2D cases over flat terrain and compares the predicted growth rate of the IBL, downstream of the transition, with expressions from the literature derived from measured data. Two cases are presented: 1. A roughness discontinuity with purely neutral stability conditions, and 2. A land-to-sea transition, with stable conditions over the sea. In the second part of the study, we model a real site, an island off the Norwegian coast, and compare the simulation results with data gathered at masts on site.

For the purely neutral case, we model a roughness change with z_0 changing from 0.00002 [m] to 0.0025 [m], comparing the resulting velocity profiles with those measured by Bradley [1], for a relatively short fetch (distance downstream from the roughness transition). When investigating the IBL growth downstream of the roughness transition, we find that the IBL height from the CFD is well fitted by the expression

$$h_{IBL} = 0.09x^{0.8} \quad (1)$$

where x is the fetch. For neutral flows, with a smooth to rough transition, the dependency with $x^{0.8}$ is in good agreement with the literature (see e.g. reviews by Garratt [2] and Barthelmie and Palutikof [3]). Panofsky [4] proposed another relationship, from a diffusion analogue, leading to the implicit relationship

$$(h_{IBL}/z_{0r})[ln(h_{IBL}/z_{0r})-1]+1=Ax/z_{0r} \tag{2}$$

with $A\approx 1$. Pasquill and Smith [5] obtained a similar expression with $A=\kappa^2$, κ being the von Karman constant. The CFD results also agree well with equation (2) with a modified value of $A=1.25\kappa^2$ as shown in Figure 1.

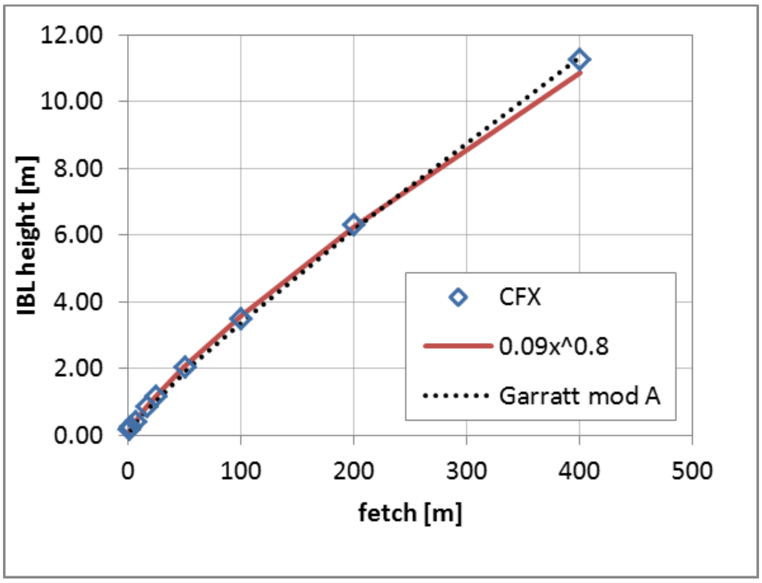

Figure 1. IBL height vs fetch for a smooth to rough transition in neutral stability conditions. Isolated symbols: CFD results, red continuous line: fit from equation (1), black dotted line: fit from equation (2) with $A=1.25\kappa^2$.

Another 2D case looks at the evolution of the IBL height downstream of a rough to smooth transition, with stable surface conditions downstream of the discontinuity. The IBL growth is compared with the expression by Mulhearn [6], derived for fetches of up to ~ 100km, which yields

$$h_{IBL}=\alpha x\left(\frac{g\prime x}{U^2}\right)^{-\beta},\ \alpha=0.0146, \beta=0.47\pm 0.047 \tag{3}$$

where $g'=g\frac{\Delta\rho}{\rho}$ is the reduced gravity associated with the sea/land temperature contrast.

As shown in Figure 2, the CFD results agree reasonably well with Mulhearn's expression (with a value of 0.43 for β, well within the range estimated by Mulhearn). It is worth pointing out the slow growth of the IBL in stable conditions: for a temperature contrast between the land and the sea in excess of 5K, the IBL height 10km downstream of the transition is typically less than 70m, a typical hub height for turbines.

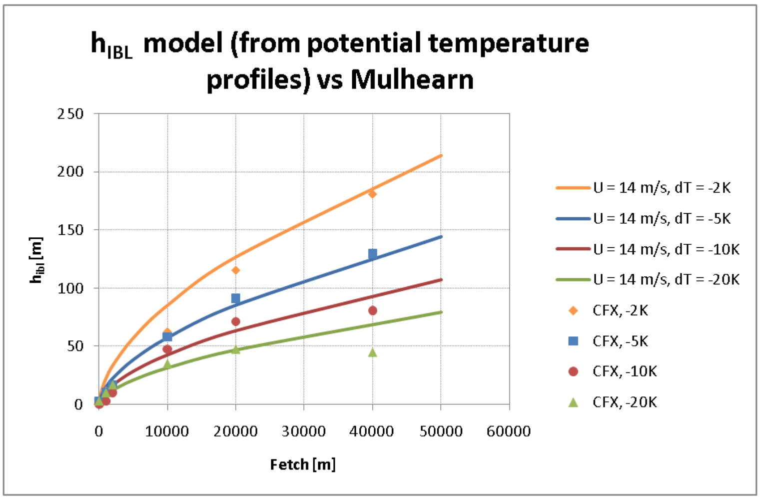

Figure 2. IBL height vs fetch for a land to sea transition with stable surface conditions over the sea. Isolated symbols: CFD results. Continuous lines: Mulhearn correlation with a slightly modified β of 0.43. Sea/Land temperature contrasts of -2K (yellow), -5K (blue), -10K (red) and -20 K (green) are compared.

Application to Coastal Site

The implications of the slow IBL growth in stable conditions are best illustrated by looking at the developing velocity profiles, examples of which are shown in Figure 3. These profiles are from the simulation of a real site, where the terrain is reasonably flat (terrain elevation varies between sea level and 40m). The flow direction was from the sea to the land, and the surface stability conditions were neutral over the sea, and stable on the land, with a sea/land temperature contrast varying between 0 (adiabatic) and -10K. As clearly seen from these profiles, the resulting IBL height is strongly reduced as the temperature contrast increases. For temperature contrasts between the sea surface and the land that are larger than 5K, the thickness of the IBL is typically 50m or even less at 10 km from the transition. The wind shear in the internal layer is significantly stronger than in the layer above. Should data from a mast shorter than the IBL height be used and extrapolated upwards to hub height for a resource assessment, then the extrapolated wind speed will significantly overestimate the actual wind speed at the hub (and in the upper part of the rotor). For example, for the temperature contrast of 10K, depending on the measurement heights selected, the wind speed at hub height can be overestimated by typically 7-10%. For a site where such stable conditions occur frequently, this will translate to a significant overestimation of the predicted resource.

The effect of unstable conditions downstream of the transition will also be discussed in detail in the paper.

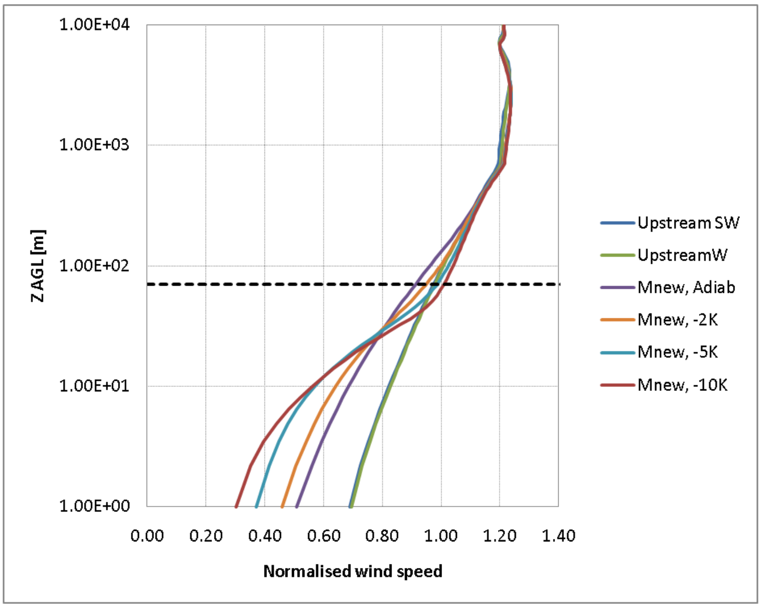

Figure 3. Velocity profiles for the sector 225° at location Mnew on the real site, located approx. 6km from the coast. The upstream profile over the sea is shown in green. The profiles at 'Mnew' from neutral (adiabatic) to increasingly stable conditions are shown, labelled with the applied sea/land temperature contrast. The horizontal dashed line marks a typical hub height of 70m.

Without sufficient temperature measurements on the site, surface stability conditions were instead derived and classified by the Richardson number from a WRF reanalysis data set concurrent with the mast data set. For some events the simulated normalised velocity profiles at the mast agree very well with those measured for the corresponding stability conditions as established from the WRF data set (see Figure 4). At other times, they disagree. Further analysis on the measured turbulence intensity suggests that the disagreement is associated with poor correlation between the actual stability conditions and those predicted by the WRF simulation.

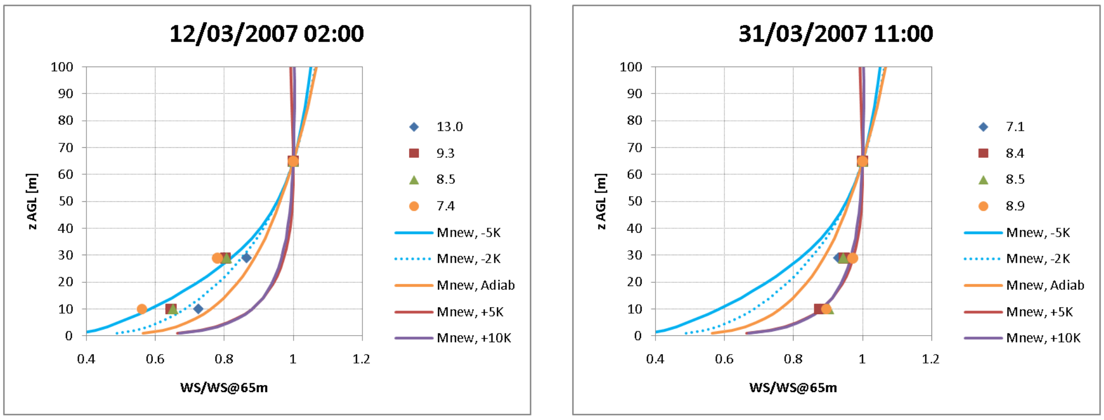

Figure 4. Symbols: measured velocity profiles at location Mnew, normalised by wind speed at 65m. The symbols blue to yellow correspond to 4 consecutive hours, with the label on the symbol showing the wind speed at 65m. Lines: simulation results for varying sea/land temperature contrasts. According to WRF data set: Left: Measured profiles evolving from mildly stable to strongly stable conditions, Right: Measured profiles all corresponding to strongly unstable conditions.

Conclusions

This investigation demonstrates that the CFD model is able to capture IBL growth downstream of a discontinuity, across which both roughness and surface stability conditions change. The resulting IBL growth agrees well with correlations from the literature, for both neutral and stable conditions downstream of the discontinuity.

This has significant implications for wind farms sited close to the coast. We show that when stable conditions prevail downstream of the coastal transition, the IBL grows very slowly. For fetches of the order of 5-10 km, the resulting IBL height tends to be smaller than a typical hub height of 70m, when the sea/land temperature contrast is in excess of 5K. If such conditions are frequent on site, then using mast data from within the surface layer can lead to significant overestimation of the resource at hub height when extrapolating with the measured shear.

Learning objectives

This contribution highlights the potential pitfalls of vertical extrapolation of the wind speed profile to hub height for sites downstream of a coastal transition.

References

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