Forecasting the Diabatic Offshore Wind Profile at FINO1 with the WRF Mesoscale Model

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Introduction

The offshore wind capacity installed up to now in Europe is about 4 GW. Currently, almost 6 GW of offshore wind capacity are under construction, 17 GW have been consented by EU Member States and there are future plans for a further 114 GW. Therefore, it is expected that during this decade, offshore wind power capacity will grow tenfold to reach an estimated installed capacity of 40 GW for 2020 [1]. In order to make such a development feasible, mesoscale models play a key and promising position both for the optimization of the location of wind farms (wind resource assessment) and for the daily energy production once the wind farm will be in operation (short term forecasting).

Up to now, evaluation of wind resource assessment models at the offshore mast FINO1 was limited by the constraint in the height of the measurement mast (100 m). Nowadays, 5 MW wind turbines are typically operating in offshore wind farms, like is the case of the recently installed Alpha Ventus wind farm nearby FINO1. In that situation, the ability of mesoscale models to forecast "tall" wind profiles needs to be properly addressed as well as its applicability for wind energy purposes.

In the offshore environment, special attention has to be paid to the role of atmospheric stability. The atmospheric stability leads to notably different shear conditions and thus different velocity distributions across the rotor swept area, which dramatically influences, among others, the power production and fatigue loads on the wind turbine. The effect of the vertical mixing due to turbulence in the planetary boundary layer (PBL) is not explicitly resolved by mesoscale models. Such models parameterize this effect employing the so-called closure techniques based on gradients of resolved quantities. For some applications, such as wind energy, where the near-surface atmospheric processes are crucial, the choice of PBL modelling becomes an important issue and thus, needs to be carefully analyzed.

In the present study, the ability of different turbulent flux parameterizations in the Weather Research and Forecasting model (WRF-ARW) to account for the atmospheric stratification is thoroughly evaluated at FINO1. For the first time, we took advantage of the recent LiDAR measurement campaign carried out at FINO1 up to 250 m height, encompassing the rotor area of the tallest wind turbines, in order to accomplish this objective. All this information allowed us to perform a complete validation based on turbulent fluxes and surface stability parameters, as friction velocity, $u^*$,
**Stability Regime**

<table>
<thead>
<tr>
<th>Stability Regime</th>
<th>$zL^{-1}$ [-]</th>
</tr>
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<tbody>
<tr>
<td>Very Unstable</td>
<td>$-4 \leq zL^{-1} \leq -0.2$</td>
</tr>
<tr>
<td>Unstable</td>
<td>$-0.2 &lt; zL^{-1} \leq -0.04$</td>
</tr>
<tr>
<td>Near Neutral</td>
<td>$-0.04 &lt; zL^{-1} \leq 0.04$</td>
</tr>
<tr>
<td>Stable</td>
<td>$0.04 &lt; zL^{-1} \leq 0.2$</td>
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**Fig. 1:** Research platform FINO1. (a) General view of the mast. (b) Detailed view of a sonic anemometer.

**Fig. 2:** WRF domain configuration. The horizontal resolutions of the four domains are 27 km, 9 km, 3 km and 1 km, from the parent to the most inner domain, respectively. Color bar indicates surface elevation in meters.

**Tab. 1:** Limiting values of $zL^{-1}$ for the four stability classes in which the data is grouped (for $z=40$ m).

**Fig. 3:** Two-dimensional histogram of FINO1 against WRF data (colour bar indicates number of data points). (a) Friction velocity, $u_*$. (b) Sensible heat flux, $<w'\theta'>$. WRF values correspond to MYNN scheme and fluxes are 30 min averaged in all the cases.
heat flux, $<w'\theta>$, and Obukhov length, $L$ (derived from sonic anemometry) and on tall wind profiles measured with LiDAR.

Field Measurements

The German research platform FINO1 is located 45 km off the Borkum Island (lat. 54°0.87'N, lon. 6°35.24'E) in the North Sea and is in operation since 2003 (Fig. 1a). In the present work, measurements from one year period (Jan. 2010 - Dec. 2010) investigated by [2] are used. Sonic anemometer data (Fig. 1b) at 41.5 m, 61.5 m and 81.5 m were used to derive turbulent fluxes of momentum and heat (10 Hz sampling) while slow profile response sensors (10 min averages): wind speed (cup anemometers), wind direction, relative humidity, air pressure and temperature, are mainly used for data processing.

In addition, a ground-based pulsed LiDAR system, the so-called “WindCube”, developed and manufactured by the French company Leosphere has been used in this study [3]. The LiDAR system was positioned on a container roof at approximately 10 m distance to the north-west of the mast FINO1. It performed continuous measurements from July 2009 to February 2010, scanning the wind profile up to a height of 250 m. This LiDAR has been proven to be applicable for wind speed and wind direction measurements by comparison against mast-based sensors [3, 4]. Once turbulence fluxes of heat and momentum are calculated, the atmospheric stability as described by the Monin-Obukhov Similarity Theory (MOST) was computed based on the Obukhov length, $L$ (Eq. 1).

$$L = \frac{\theta u^2}{g \kappa \langle w' \theta \rangle},$$

where $u_*$ is the friction velocity, $<w'\theta>$ is the heat flux, $g$ is the acceleration due to gravity, $\kappa$ is the von Kármán constant (equal to 0.40) and $\theta$ is the potential temperature. Angle brackets denote ensemble averaged values.

According to the values of $zL^{-1}$ (where $z$ stands for height above the surface), the data has been grouped into different stability classes (Tab. 1). From the developed database, long periods corresponding to each stability class have been chosen and simulated with WRF, as is shown in the upcoming sections.

WRF Model Setup

In this study we use the Numerical Weather Prediction model of the National Center for Atmospheric Research in USA (NCAR): Advance Research WRF-ARW v3.2. WRF-ARW is a conservative finite differences model that solves the unsteady non-hydrostatic compressible Euler equations [5]. Our computational domain is composed by 4 domains centered over FINO1 platform. The parent domain has a horizontal grid spacing of 27 km and covers an approximate surface of 3,000 km$^2$, including most of Europe. Grid spacing is refined progressively by a factor of 3 through three nested domains until 1 km resolution is achieved for the most inner one, which covers approximately 100 km$^2$. On the vertical coordinate, 46 levels are placed. Grid spacing is of 10-20 m up to 300 m height to

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accurately resolve the lower part of the boundary layer. Above 300 m, grid spacing is progressively stretched in order to reduce the computational cost. Interactions of the meteorological fields between the domains are accounted for by two-way nesting. The domain configuration is shown in Fig. 2. The timestep is consistently reduced from the parent domain to the most inner domain in order to respect numerical stability constraints (CFL<1). WSM 3-class simple ice scheme microphysics, rapid radiative transfer in the longwave, the Dudhia shortwave scheme, NOAH surface scheme and cumulus Kain-Fritsch scheme (not applied into the two most inner domains) were used. Each PBL parameterization is tied to a particular surface layer scheme [5], all of them based on Monin-Obukhov similarity theory [6]. The parent domain is initialized and 6-hourly forced at the boundaries by meteorological fields derived from the NCEP Climate Forecast System Reanalysis data, CFSR [7], with a horizontal resolution of 0.5° x 0.5°. The first 24 hours are discarded as spin-up time of the model and subsequent forecasts are considered. Previous studies have already shown that the parameterization of the vertical mixing in the PBL plays a major role on the vertical structure of the wind profile, e.g. [8]. To account for that, five different PBL schemes have been tested. One first order scheme: the Yonsey University (YSU [9]), and four one-and-a-half order (or TKE closure) schemes: Mellor-Yamada-Janič (MYJ [10]), Mellor-Yamada-Nakanishi-Niino (MYNN [11]), Quasi-normal Scale Elimination (QNSE [12]) and Bougeault-Lacarrère (BouLac [13]). The differences on the order of closure are briefly described in the next section. The effect of other model parameters as: number of nested domains, horizontal resolution, physical parameterizations, etc., was investigated so the setup proposed is optimized regarding the conditions at FINO1.

### Turbulence Closure Techniques

The turbulent fluxes from momentum, heat and other species in both first and one-and-a-half order closure techniques are formulated similarly [14].

\[
\langle w' \phi' \rangle = -K_z \left( \frac{\partial \phi}{\partial z} - \gamma \right),
\]

where \( \phi \) is a prognostic variable. This kind of modelization is known as gradient transport theory or K-theory. The term \( \gamma \) represents the non-local mixing due to larger convective eddies and it is included or not depending on the scheme. \( K_z \) is the eddy diffusivity coefficient, which sometimes has different formulations for momentum and heat. The manner in which \( K_z \) is computed introduces the differences be-

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**Fig. 4:** Two-dimensional histogram of FINO1 against WRF data for the inverse of the Obukhov length, \( L^{-1} \) (colour bar indicates number of data points).
between first and one-and-a-half orders. In first order closure techniques (YSU) the eddy diffusivities are calculated in the following way:

\[ K_x(z) = \psi(zL^{-1}) \cdot z \left( 1 - \frac{z}{h} \right)^2 \]

where \( h \) is the BL height, \( L \) is the Obukhov length and \( \Psi(zL^{-1}) \) is a function of stability based on the nondimensional profile functions of heat and momentum [15]. The one-and-a-half order schemes solve an additional prognostic equation for the turbulent kinetic energy, \( q \), and the parameterization of fluxes depends on \( q \), on the master length scale, \( l \), and on the flux Richardson number, \( Ri \).

\[ K_x(z) = \chi(Ri) \cdot l \cdot q^{0.5} \]

The diagnostic equations to obtain \( l \) and \( \chi(Ri) \) differ from MYJ, MYNN and QNSE. In BouLac scheme the stability function is considered as a constant coefficient.

**Surface Fluxes**

In the WRF model, turbulent fluxes for momentum, heat and moisture at the surface are computed based on Monin-Obukhov Similarity Theory, as previously introduced. They represent the linkage between the surface and the atmosphere and provide lower boundary conditions for the integration of the PBL schemes. The momentum flux is parameterized based on the square of the friction velocity as showed by Eq. 5:

\[ \tau_s = u_s^2 \rightarrow u_s = \frac{kU_1}{\ln(z_1/z_{om}) - \psi_{om}} \]  

where the subscript 1 stands for the conditions at the first grid point in the vertical coordinate (~10 m) and \( z_{om} \) is the roughness length for momentum (here modeled for off-shore conditions using the Charnock’s equation). Regrouping the terms from Eq. 5 it can be easily shown that the momentum flux depends on the square of the wind speed at the first grid point. For the sensible heat flux, a similar expression is used.

\[ <w'\theta'>_s = -C_H U_1 (\theta_1 - \theta_s) \rightarrow C_H = \frac{k\nu_s}{\ln(z_1/z_{oh}) - \psi_{om}} \]

**Fig. 5:** Mean wind shear profiles grouped by stability.
where \( \theta_t \) is the sea surface temperature and \( z_{oh} \) is the roughness length for heat. In this case the parameterization of the sensible heat flux depends on the product of wind speed and \( \Delta \theta \). Furthermore, there is a dependency on the momentum flux via the surface exchange coefficient for heat \( C_u \).

Surface fluxes of momentum and heat are compared on Fig. 3. The numerical results correspond to MYNN scheme since similar conclusions are drawn for the other PBL parameterizations. Friction velocity (Fig. 3a) is overestimated by WRF for the whole range of measurements. Indeed, a decrease on the momentum flux with height is expected when being out of the surface layer. So this effect explains the values for the selected periods are lower compared to those measured for the convective scenarios. This gives more weight to the ones measured for the convective conditions and moderate instabilities. The bias is not constant anymore and it grows with \( \langle w' \theta' \rangle \) (Fig. 3b).

In order to evaluate the ability of WRF to forecast surface stability in offshore conditions it is worthy to compare the Obukhov length. This comparison is shown in Fig. 4. Despite the fact that similar trends were obtained for \( u_* \) and \( \langle w' \theta' \rangle \), the combination of the two trends could produce rather different results. Under unstable atmospheric stratification \((L^-<0)\), the overestimation of both momentum and heat fluxes by the numerical model have opposite effects on the sensible heat flux, WRF predicts higher values both for unstable and stable conditions. The bias is not constant anymore and it grows with \( \langle w' \theta' \rangle \) (Fig. 4a). It can be observed that QNSE (Fig. 4b) reproduces the lowest momentum and heat fluxes by the numerical model have opposite effects on the sensible heat flux, WRF predicts higher values both for unstable and stable conditions. The bias is not constant anymore and it grows with \( \langle w' \theta' \rangle \) (Fig. 4b).

Vertical Structure of the Wind Profile

All the numerical results presented in the previous section in terms of surface fluxes are derived from Monin-Obukhov similarity theory. For the rest of the profile, the influence of turbulent mixing on the wind speed profile is determined by the PBL tendencies, briefly described in previous sections. In order to analyze the performance of the PBL schemes, FINO1 profiles obtained from a combination of sonic anemometers and LiDAR data up to 250 m are considered. The obtained results are shown in Fig. 5 in terms of mean shear (referenced to the wind speed at 41.5 m, \( U_{41.5m} \)). It can be noticed that, as expected, the shear increases dramatically from very unstable conditions, in which it is much reduced or non-existing (0.2 ms\(^{-1}\) at 250 m), up to stable stratification, where the shear reaches its maximum amplitude (3.5 ms\(^{-1}\) at 250 m). Most of the time, the PBL schemes are not able to reproduce much shear as it occurs under stable conditions (Fig. 5a). QNSE outperforms the others and BouLac and YSU produce the highest bias. The difficulties of YSU and BouLac schemes to reproduce stable profiles of wind speed are due to an excessive enhancing of the turbulent mixing in the lower part of the boundary layer. This problem of the BouLac scheme is due to the assumption of constant \( \chi(Ri) \) in Eq. 4. The lack of link with stability, through the Richardson number, makes it fail under stable conditions. Better agreement was found under neutral and convective conditions most probably because the coefficient is more suited for such stability regimes [8]. The failure of YSU is attributed by [8, 16] to an excessive mixing during stable stratified conditions [17]. For neutral conditions (Fig. 5b), MYNN and QNSE match the FINO1 data up to 170 m. Above, MYNN deviates slightly. Again YSU and specially BouLac schemes are the most diffusive while MYJ does not show noticeable bias for neutral and convective stability. Those effects create a displacement of the probability density function of \( L^- \) from positive towards negative values. Further analysis on this concern is needed to better understand how different factors interact to yield such pdf displacement, i.e.: different measurement heights, humidity correction on the sonic heat flux and discrepancies among simulated and measured sensible fluxes and friction velocities.
modification from stable stratification. For the convective atmosphere (Figs. 5c–d), WRF simulations generates higher shear and the bias decreases for larger values of \( L^{-1} \). The root-mean-square error (RMSE) of the wind shear as a function of stability has been plotted in Fig. 6. These values correspond to the average over the rotor swept area of a 5 MW wind turbine, as the ones installed in the nearby wind farm Alpha Ventus. This allows us to obtain an equivalent shear RMSE which would be “seen” by the typical wind turbines operating offshore nowadays. The results from the mean shear profiles are reflected in Fig. 6. The shear RMSE is maximum for stable conditions and shows the largest spread among the five PBL schemes. BouLac has an error of almost 1.4 ms\(^{-1}\) and QNSE and MYNN drop up to about 0.9 ms\(^{-1}\). There is a step reduction towards neutral conditions (\( \approx 0.4 \) ms\(^{-1}\)) with higher errors for MYJ and BouLac. In convective conditions the errors continue decreasing and reach its minimum for very unstable stability (\( \approx 0.2 \) ms\(^{-1}\)) except for MYJ, which has the highest errors for all the unstable range and remains almost constant (\( \approx 0.35 \) ms\(^{-1}\)).

**Conclusions**

Five WRF Planetary Boundary Layer formulations were compared against field observations at FInO1 platform. Four nested domains allowed us to perform high resolution mesoscale simulations with grid spacing of 1 km in the most inner domain. Different stability scenarios were selected based on measurements of \( L^{-1} \) from the closest sonic anemometer to the surface. The observational database was composed of combined sonic anemometers and LiDAR wind measurements in order to have both the best spatial coverage possible and including turbulent flux information. Results concerning turbulent fluxes showed a constant over-estimation of \( u_* \), partly due to the expected decrease of \( u_* \) with height from the surface to the sonic height. For \( \langle w' \theta' \rangle \) the errors are larger for higher values of \( \langle w' \theta' \rangle \). In terms of \( L^{-1} \), a displacement of the probability density function of \( L^{-1} \) from positive towards negative stabilities was found. WRF wind shear was evaluated at tall heights where 5 MW WTGS operates and beyond, by using a LiDAR measurement campaign carried out at FInO1. In general terms, convective boundary layers present lower errors which increase with \( L^{-1} \) and with height. The shear is underestimated for stable stratification, especially for MYJ and BouLac schemes, which are too diffusive. Some differences were found between surface and profile stability indicating that vertical mixing formulation can differ from surface forcing features. From all the results presented here, we conclude that MYNN and QNSE are best suited to reproduce the offshore environment corresponding to open sea conditions for wind energy purposes, having considered surface turbulent fluxes and tall wind speed profile data for validation.

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**References:**


