SIMULATION OF NEUTRALLY STRATIFIED OFFSHORE BOUNDARY LAYER BY LARGE EDDY SIMULATIONS (LES)

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Summary

Large eddy simulation (LES) outputs of the near neutral atmospheric boundary layer are compared to observational data from the offshore platform (FINO1). The main objective of this study is to check how realistic the LES simulation is in reproducing the wind flow in off-shore conditions and to understand better the turbulent flow within this regime.
Not only mean values (profiles) are compared in this study but also the turbulence unsteady effects are checked by using a statistical approach (probability density function and autocorrelations).

1. Introduction

The neutral stratified offshore boundary layer is of special interest for wind energy applications, since such conditions are often observed during periods of high wind speed. A special focus is given here for the understanding of turbulence effects which are important for the design and operation of wind turbines.

Whereas in most CFD approaches 100% of the turbulence is parameterized, the advantage of the Large Eddy Simulation (LES) Model is that it solves the large turbulent scales (large eddies), which are important for the interaction with the wind turbine, directly, while the smaller part is parameterized with a sub grid (SGS) turbulence model.

One of the most important characteristics of the LES model is that it can produce instantaneous time series of turbulent wind field containing realistic coherent structures, as they are observed in the atmosphere. Improving synthetic wind field generators as used in wind turbine design, is one of the applications for that.

Furthermore the LES model is an important tool for understanding the mean flow characteristics (wind profiles) and the unsteady effects of turbulence in the atmosphere.

In order to test the general consistence of LES simulation setup, model results have been compared to observations making used of from the offshore FINO-1 platform located in the North Sea (lat. 54º0.87′N, long. 6º35.24′E) at around 45km (fetch) north of the Borkum Island. The reader is referred to [1] and [2] for a detailed description of the measurement data.

2. Simulation set-up. Grid resolution

The large-eddy simulation (LES) ,using PALM code [3], is carried out for a near neutral Boundary Layer (BL), taking a domain size of 3x2x1km^3 with a mesh size in the x, y and z directions respectively.

The initial state was starting from a barotropic environment, where u_g = 10 ms^{-1} (in the east-west direction) is constant with height and v_g = 0 ms^{-1}. Small random perturbations are applied to trigger the turbulence.

The simulation is performed for 54000s (i.e. 15 hours). The potential temperature is assumed constant in the entire domain. Lateral boundary conditions are cyclic.

The bottom surface is flat and in order to take into account the roughness over the sea, the Charnock roughness length parameterization is considered. The effective surface roughness leads to u_{*s} =0,23m/s, which is close to the value derived from the sonic anemometer using the eddy-correlation method as

$$u_{*s}=(\langle u'w'\rangle^2 + \langle v'w'\rangle^2)^{1/4}$$

where u′, v′, w′ are the turbulent velocity components about the mean value and brackets <> refer to time averaging and subscript s denotes values at the surface.

Prior to carry out any real simulation, several simulation tests have been performed in order to determine the optimal set-up in terms of domain dimension, roughness, eddy sizes...etc. The eddy size for instance is an important parameter concerning dynamic loads on the wind turbine and is related to the grid spacing chosen in the model setup.

For a well resolved LES simulation the modeled SGS stress should only contribute a small fraction of the total turbulent stresses. Since wind energy applications take place within the surface layer and taking into account that near surface layer the dominant turbulent structures are small compared to the rest of the BL the grid resolution must be fine enough to resolve most of energetic content in the flow. Here two resolutions have been checked for 5m and 10 meters resolution. Due to the high amount of computational tine it is hardly possible to run a grid spacing much smaller than 5m.

The contribution for both grid resolutions considered are evaluated in Fig. 1 by plotting the resolved and subgrid scale of the mean Turbulent Kinetic Energy (TKE) profiles.

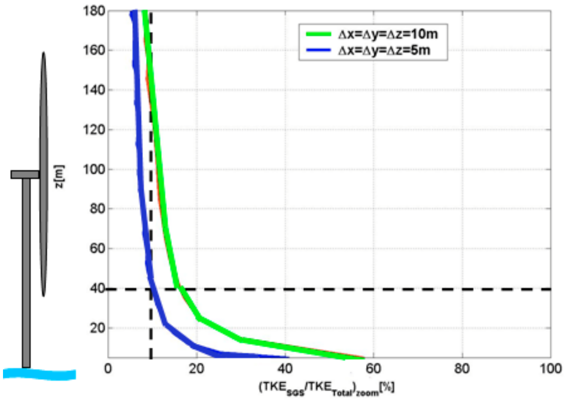

Figure 1: Ratio between the subgrid and total (resolved+subgrid) contribution of the TKE (for the fist 180m of the boundary height).

As it is expected, close to the surface the sub grid (SGS) contribution to energy is larger for 10m than for 5m. The contribution of the SGS model is approximately 10% of the total TKE below 40m and smaller than 6% above about 100m for 5m grid resolution (Fig. 1). Therefore it is assumed that, the SGS is small enough in this model run to provide a consistent model set-up.

3. Period selected for the comparison purpose

Before comparing LES results with observational data an exhaustive pre-processing and correction procedure was carried out with the observational data and by mean of brevity, it has been omitted in this paper.

To carry out a fair comparison between both data sets, the following criteria have been considered for choosing periods for this study:

- No Synoptic-driven events like front, rainfall,...
- Humidity below 70%.
- Heat flux close to zero.
- Charnock correlation is implemented and therefore periods with wave-age bellow 28 (‘young’ waves) have been considered.
- Wind speed periods within mast shadow are excluded.
- Data are classified according to the wind speed at 30 m, since the geostrophic wind value is not directly available.
- In order to eliminate the effects of larger frequencies structures that might be present in the FINO1 data (and which are not allowed in the limited LES model domain) not only a high-pass has been used but also a low-pass filter because the LES grid size.

Finally taking into account of all those criteria the final data base was highly reduced.

4. Mean profiles

Time-averaged profiles of shear horizontal velocity (Shear), wind direction (dir) and Turbulent Intensity (TI) for LES simulation (shown by blue line) as well as the computed from FINO1 measurements (shown by red line) are presented in Fig. 2, respectively.

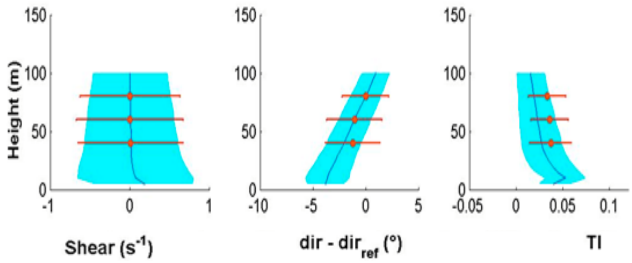

Figure 2: Profile comparison between LES simulation and FINO1 data for shear, direction and TKE. Horizontal bars and shadow represent a standard deviation

As it can been seen in Fig. 2, the quantitative agreement between both data sets is good, as the overall trend is captured by the LES simulation. For any of the considered parameters, the simulations fall within the error bar, taken as one standard deviation.

5. Turbulence

Here statistical method as probability density function and temporal autocorrelation functions are used to quantify the turbulence.

The probability density function (pdf) for the normalized horizontal wind velocity fluctuation time series of LES simulation (blue dotted line) and FINO1 measurements (red dotted line) are shown in Fig. 3. the vertical axis represents the probability of occurrence of the velocity fluctuation for each interval.

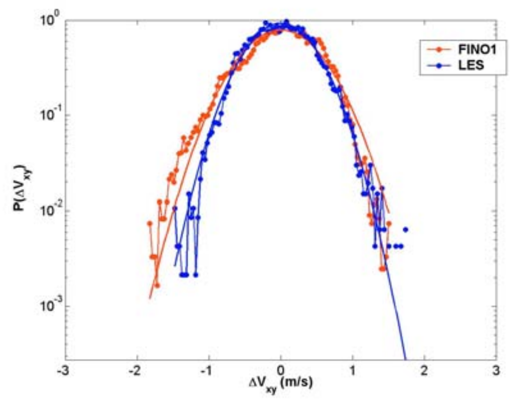

Figure 3: pdf for the horizontal wind velocity fluctuations: LES simulation and FINO1 measurements

The agreement of modeled and measured pdf's is striking good, especially when taking into account that in LES the structure of the large eddies depends on the characteristics of the sub-grid scheme and the interpretation must always be subject to caution. This might explain some differences with the pdf's obtained from FINO1 measurements, especially in the extreme values.

For a quantitative comparison with the Gaussian distribution, the skewness ($S = (x-\langle x\rangle)^3/\sigma_x^3$) and the kustosis ($K = (x-x)^4/\ \sigma_x^4$) factors for the pdf are summarized in the following table:

	Skewness	*Kurtosis*
x_{FINO1}	-0.382 ± 0.001	3.032 ± 0.006
x_{LES}	0.101 ± 0.002	2.946 ± 0.003

Table 1: Summary of Skewness and Kurtosis factors. The error values are due to the change of the bin size in the computation of the pdf 's

The temporal autocorrelation functions of the horizontal wind velocity fluctuations computed for the LES simulation (blue line) and FINO1 measurements (red line) are depicted in Fig. 4 in order to quantify the horizontal extension of turbulence eddies in the flow (turbulence length scale).

As it can be seen in Fig. 4, both graphs present similar decay to its first zero crossing, after which they become negative and proceed to oscillate about zero.

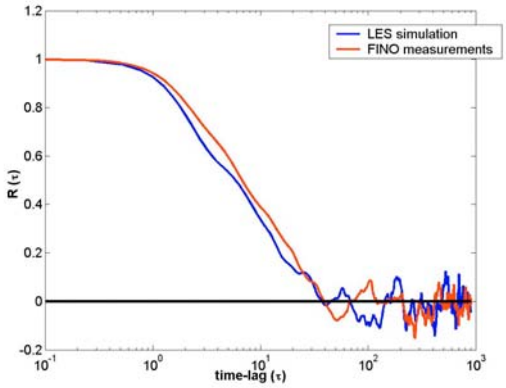

Figure 4: Autocorrelation function for the horizontal wind velocity fluctuations: LES simulation (blue) and FINO1 data (red)

In this study, the procedure used to estimate the time-scale is given by the time-averaged of the shifted product of the autocorrelation coefficients up to the first zero-crossing of the autocorrelation function. The length-scales obtained are presented in the following table:

Data	*time − scale*[*s*]	*length − scale*[*m*]
FINO1	10.8	101.5
LES	9.3	97.8

Table 2: Integral scales: LES simulation and FINO1 measurements

6. Conclusions

This comparison highlights how difficult is to compare the LES results to observations since there is no a standardized criteria guiding validation. Despite of that it could be proved that LES reproduces main parameters (short term and long term) of the measured offshore BL very well. Especially mean values as well as turbulence are captured reasonably well with LES for the neutral stratified case.

A higher grid resolution is however needed to check extreme values

Some uncertainties are still remaining in this comparison, as:

- Boundary layer height is unknown although a reasonable value has been selected for the model setup.
- Dependence of the LES results on the grid resolution
- Short time series of measurements are compared

7. Acknowledgements

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8. References:

[1] T. Neumann, K. Nolopp, K. Herklotz, First Operating Experience with the FINO1 Research Platform in the North Sea. DEWI Magazin Nr. 24, February 2004

[2] T. Neumann, V. Riedel. FINO 1 Platform: Update of the Offshore Wind Statistics. DEWI Magazin Nr. 28, February 2006

[3] Raasch, S. and Schröter, M. (2001): PALM – A large-eddy simulation model performing on massively parallelcomputers. Meteorol. Z., 10, 363–372. 7, 15, 18.