WRF and The Marine Planetary Boundary Layer

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1. Introduction

Offshore wind energy is a rapidly growing field worldwide, both in a scientific, engineering, and in an economical point of view. In Europe 140 GW offshore wind projects are already in different planning stages, and at the time of writing 1136 offshore wind turbines are installed and connected to the European power grid. By 2020 the offshore wind power's economical potential in Europe is between 60% and 70% of the projected electricity demand[1]

The are many different scientific aspects between onshore and offshore wind energy. Perhaps the most obvious one is that we are dealing with a moving surface at the bottom boundary, namely ocean waves. Not very complex compared with valleys and mountains, as we have onshore, but complex enough to significantly alter both the mean and turbulent behaviour of the wind field in the Marine Boundary Layer (MBL), compared with a flat non-moving surface. Some LES-studies have already shown how the waves influences the wind field in the MBL, e.g. Sullivan et.al. (2010).

Here we will show some preliminary results on important atmospheric parameters connected to offshore wind energy in the MBL. To perform these sensitivity tests we have run the WRF-model for a whole year with 5 different PBL-schemes. The initialization- and boundary data are from the ERA-Interim dataset from ECMWF in England. The results are primarily compared with observations from the German research platform FINO1 in Southern North Sea. From this platform there exists meteorological and oceanographical observations back to 2004 with both wind (1 Hz and 10 Hz time resolution) and temperature measurements for every 10th meter from 30 to 100 m above sea level.

2. Experiment setup

WRF3.2.1 is used throughout this study, and is run on a Cray XT4 system at Uni Computing in Bergen, Norway, with 384 CPUs for this project.

[1] http://www.ewea.org/index.php?id=203

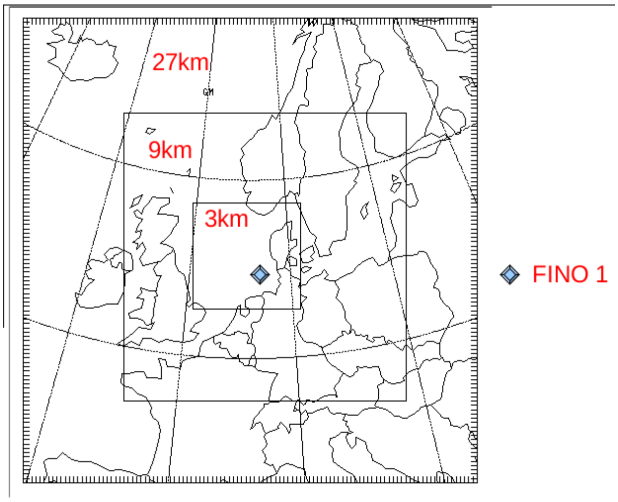


Figure 1: Horizontal domain and the German research platform Fino1.

2.1 Resolution

Three two-way nested domains are used with 27, 9, and 3 km horizontal resolution, Figure 1. The outermost domain is covering the whole NE-Atlantic, included Iceland, such that the main Low pressure systems, which almost always are moving in from the west, are within the domain.

The vertical resolution is

20 m from 0 m to 200 m.
50 m from 200 m to 500 m.
100 m from 500 m to 1000 m.
250 m from 1000 m to 5000 m.
500 m from 5000 m to 20 000 m.

The time step had to be set to 120s to fulfil the CFL-criteria.

2.2 Physics schemes

Micro physics: New Thompson scheme with ice, snow and graupel, suitable for high resolution simulations.
Long wave and short wave radiation: RRTMG schemes.
Land-surface: RUC land surface model, six soil layers, multilayer snow and frozen soil.
Cumulus parametrization: Grell 3D scheme with shallow convection turned on.

Whether to use or not to use cumulus

parametrization schemes for horizontal resolution below 10-12 km can be discussed. One important difference between the cumulus convection cells, e.g. over the US compared with extra tropical oceanic conditions, is that the typical scale of the cumulus systems over the ocean is in general much smaller than over the continents. This implies that it is probably more important to use cumulus schemes, also for high resolution domains, when we are dealing with mainly oceanic conditions than over continental conditions. So far this assumption is not tested in this study.

2.3 PBL schemes

The main task in this work is to study the behaviour of the different Planetary Boundary Layer (PBL) schemes over pure offshore conditions.

WRF3.2.1 has eight different PBL schemes. We have tested five of them. The MYNN3, the old MRF, and the BouLac scheme developed for urban meteorology is not tested. MYNN3 caused the WRF model to crash all the time, and the reason is not figured out yet.

A short summary of the different schemes is as follow:

Non-local closure schemes:

- YSU (Hong et. al, 2006). First order scheme. Slightly modified in WRF to give enhanced mixing in the stable boundary layer (Hong and Kim, 2008)
- ACM2 (Pleim, 2007). First order. Uses non-local transport only for unstable conditions, otherwise local closure.

Local closure schemes:

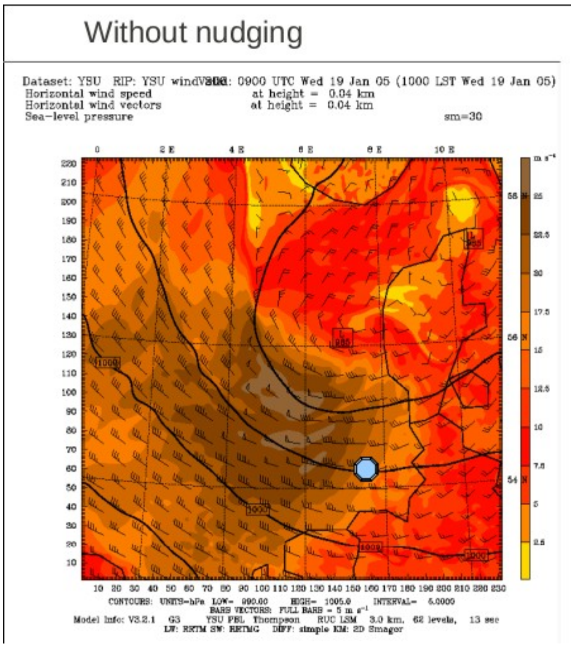
- MYJ (Mellor and Yamada, 1982. Janjic, 1990, 1994, 1996, 2001). Based on the original MY scheme from 1982. 1.5 order. Turbulent kinetic energy (TKE) prediction.
- MYNN2 (Nakanishi and Niino, 2004). 1.5 order. TKE predicition. An improved MY scheme.
- MYNN3-not tested yet: 2nd order. TKE, Θ'^2, q'^2, and $\Theta'q'$ prediction.
- QNSE (Sukoriansky et.al, 2005). 1.5 order. TKE prediction. Designed specifically for stably stratified conditions, otherwise rather equal to MYJ.

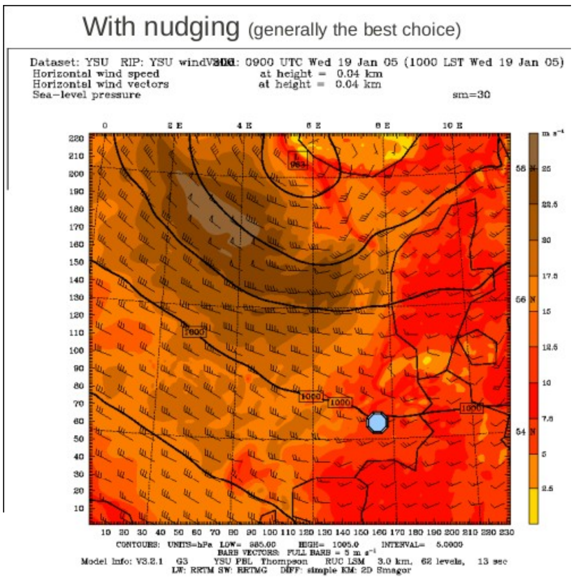
The experiment was run five times, one with each PBL-scheme, for the whole year 2005, which means nearly 700 000 CPU hours. This has generated a total of 18TB data only for the inner domain.

2.4 Nudging

A small test with and without nudging was also carried out before the main runs. According to the literature nudging can be an advantage for longer runs.

Weak spectral nudging only on the outermost domain was set up for January 2005 with the YSU scheme. Most of the time series for wind speed showed only minor differences, but one interesting case appeared when a small, intense Low pressure system passed over Southern North Sea 19th January. Then the Low pressure system was positioned quite differently in the two cases, causing large differences in the wind speed at the FINO1 research platform. It turned out that the run with nudging was the most correct one, so with the literature and this small test case in mind, we decided to run the whole experiment with a weak spectral nudging on the outer domain.





3. Results

The model data is verified against measurements from the German research platform FINO1. FINO1 is located 45 km north of the German coastline in Southern North Sea, and has an continuous time series of meteorological and oceanographical data since 2004. The shortest fetch is to the south, while towards NW the fetch is 2300 km, all the way to E-Greenland.

Wind and temperature measurements are taken every 10th meter from 30 m to 100 m, and there are also 3D-turbulence measurements from three ultrasonic anemometers at 40 m, 60 m, and 80 m above sea level. In addition there are humidity, rain, visibility, lightning, global and UV radiation, and also wave spectra from a nearby buoy.

Up to know only 100 m mean wind speed has been evaluated, and some of the results are shown below.

3.1 QQ-plot

A QQ-plot is a plot of the quantiles of two datasets against each other, and is an easy way to get an overall view of the model performance. If the two distributions being compared are identical, the Q-Q plot follows the 45° line $y=x$.

The PBL-schemes give quite different results. As seen in the QQ-plot for January-05, the YSU scheme comes up with rather large deviations from the measurements, while both the ACM2 and MYJ have a much better behaviour. The YSU scheme is clearly overestimating the wind speed, especially from 15-16m/s and higher winds. The 3rd quantile from the FINO1 measurements is 20.5m/s, while the same statistics for YSU is 22m/s. For MYJ and ACM2 the 3rd quantile is 20.1m/s and 20.2m/s, respectively, which is very close to the FINO1 data.

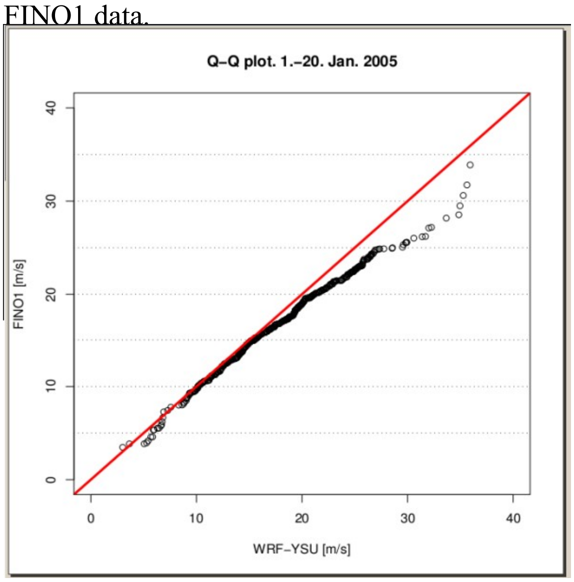


Fig. 4: YSU scheme compared with FINO1 data. 100m level wind speed. Jan-05

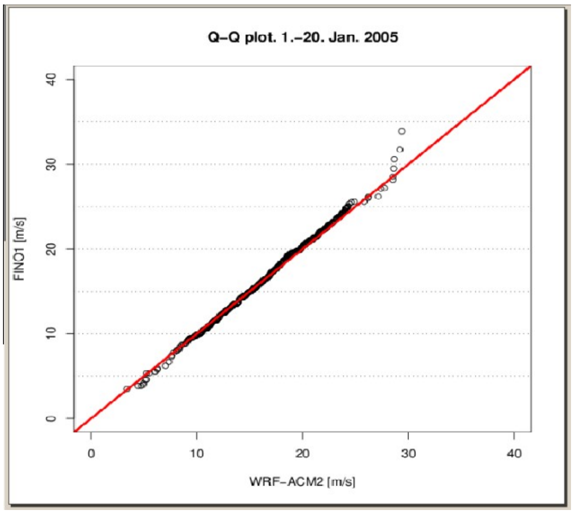


Fig. 5: ACM2 scheme compared with FINO1 data. 100m level wind speed. Jan-05

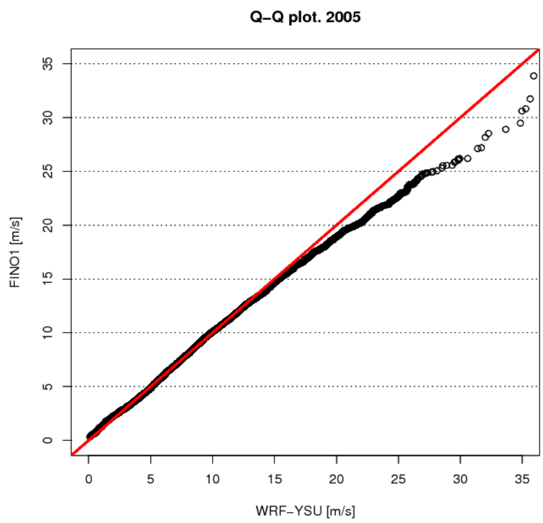


Fig. 6: YSU scheme compared with FINO1 data. 100m level wind speed. 2005

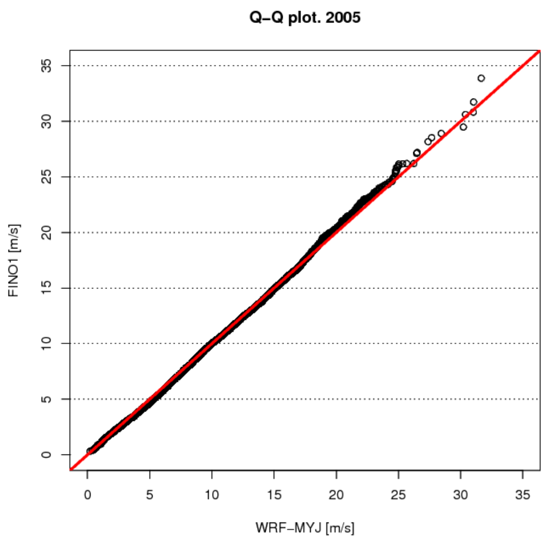


Fig. 7: MYJ scheme compared with FINO1 data. 100m level wind speed. 2005

If we look from month to month the results are of course somewhat variable. E.g. in June-05 the YSU scheme was the best one, while the MYJ was the worst one. But over a whole year we get a rather clear picture. Fig. 6 and 7 show the QQ-plot for the YSU and MYJ scheme for the whole 2005.

3.2 Objective hit Score, OhitS

There are several methods or scores that are being used to find the best model compared to observations. Here we develop a new method called Objective hit Score, Ohits, which is a method for statistically comparing several model runs with point observations.

The OhitS method uses the median, mean error (bias), mean absolute error, standard deviation, and 1st and 3rd quantile to the model variables and observations.

- The model statistics closest to the observation statistics, for the parameter of interest, get one OhitS point.
- The model statistics furthest away from the observation statistics, for the parameter of interest, get *minus* one OhitS point.
- All other model parameter statistics get zero OhitS points.

With this method it turns out rather easily which models, in this case the different PBL-schemes, that generally show the best/worst performance.

Example for Jan-05:

For Jan-05 we see that the YSU scheme has lowest score compared with the observations on every statistical parameter used in the method, and then get -6 OhitS points. The ACM2 scheme has the best score in three out of six statistical parameters, and then get three OhitS points for Jan-05.

If we make such tables for every month *plus* a table for the whole year, and then summarizes the OhitS points we get this result:

	+OhitS points	-OhitS points	Total OhitS points
MYJ	19	12	7
MYNN2	17	10	7
QNSE	16	15	1
ACM2	21	21	0
YSU	10	21	-11

Table 2: OhitS points for the whole year 2005.

Table 2 above show very easily that the MYJ and MYNN2 schemes have the highest score, while the YSU scheme clearly has the lowest score. The ACM2 scheme has both most positive OhitS points, but also most negative OhitS points, which means that its performance is very variable throughout the year.

Jan_05								
Wind, 100m	1st Qu	Median	3rd Qu	Mean error	Mean absolute error	Standard deviation	OhitS points	OhitS points
Fino1	12,66	16,68	20,49			5,26		
WRF-YSU	13,02	17,42	22,02	1,15	2,03	6,11	0	-6
WRF-MYJ	12,45	16,88	20,12	-0,15	1,63	5,07	1	0
WRF-QNSE	12,89	17,04	20,12	0,05	1,70	4,97	1	0
WRF-MYNN2	12,61	17,36	21,85	0,82	1,91	5,97	1	0
WRF-ACM2	12,73	16,69	20,17	-0,11	1,61	5,01	3	0

Table 1: OhitS points for Jan-05

4. Summary and further studies

A one year simulation with WRF3.2.1 and five of its PBL-schemes is carried out for the Nordic Seas.

This paper show the first few results from this experiment, which will have its emphasize on the Marine Boundary Layer and WRF's PBL schemes. Already now, with just simple statistics for the wind at 100 m level, we see that the PBL schemes give quite different results with highest scores for the MYJ and

MYNN2 schemes and lowest scores for the YSU scheme.

For the wind energy community it is very important to get as accurate wind forecast as possible, because the energy output is proportional to the third power of the wind speed, hence only small errors in the wind speed forecasts give large errors in the energy forecasts.

During the next months we want to find out the main reasons why we get such different results with the different PBL-schemes over the ocean. The WRF model itself has just a simple Charnock relation regarding how to compute the roughness length over the ocean, but this is in fact a function of wave height, wave age, wave direction etc.

During the next few months we will also have a coupled atmosphere-wave modelling system up and go (WRF-SWAN), and it will be very interesting to see how that will influence the mean wind and turbulence in the MBL.

Another interesting parameters that will be studied in more details are the atmospheric stability, and the turbulence. The latter one with observations from the sonic anemometers from FINO1, and the TKE output from some of the PBL-schemes.

References:

Berge, E., Ø.Byrkjedal, Y.Ydersbond, and D.Kindler, 2009: Modelling of offshore wind resources. Comparison of a mesoscale model and measurements from FINO 1 and North Sea oil rigs. *Proceedings of EWEC, Marseille, France.*

Bye, J.A.T., and A.D.Jenkins, 2006: Drag coefficient reduction at very high wind speeds. *Journal of Geophysical Research,* **111,** 1-9.

Drennan, W.M., P.K.Taylor, and M.J. Yelland, 2005: Parameterizing the Sea Surface Roughness . *Journal of Physical Oceanography,* **35,** 835-848..

Foreman, R.J., and S.Emeis, 2010: Revisiting the Definition of the Drag Coefficient in the Marine Atmospheric Boundary Layer . *Journal of Physical Oceanography,* **40,** 2325-2332.

Hong, S-Y., Y. Noh, and J. Dudhia, 2006: A New Vertical Diffusion Package with and Explicit Treatment of Entrainment Processes. *Monthly Weather Review,* **134**, 2318-2341.

Hong, S-Y., and S-W. Kim, 2008: Stable Boundary Layer Mixing in a Vertical Diffusion Scheme . *Extended abstract. 18th Symposium on Boundary Layers and Turbulence.*

Hu, X-M., J.W.Nielsen-Gammon, and F.Zhang, 2010: Evaluation of Three Planetary Boundary Layer Schemes in the WRF Model . *Journal of Applied Meteorology and Climatology,* **49,** 1831-1844.

Janjić, Z.I., 1984: Non-linear advection schemes and energy cascade on semi-staggered grids. *Monthly Weather Review,* **112***,* 1234-1245.

Janjić, Z.I., 1990: The step-mountain coordinate: physical package. *Monthly Weather Review,* **118**, 1429- 1443.

Janjić, Z.I., 1994: The step-mountain eta coordinate model: further developments of the convection, viscous sublayer and turbulence closure schemes. *Monthly Weather Review*, **122**, 927- 945.

Janjić, Z.I., 1996: The surface layer in the NCEP Eta Model. *Eleventh conference on Numerical Weather Prediction*, Norfolk, VA, 19-23 August 1996; Amer. Meteor. Soc., Boston, MA.

Janjić, Z.I., 2001: Nonsingular Implementation of the Mellor-Yamada Level 2.5 Scheme in the NCEP Meso model. *National Centers for Environmental Prediction Office Note #437* .

Kwun, J.H., Y-K. Kim, J-W. Seo, J.H.Jeong, and S.H.You., 2009: Sensitivity of MM5 and WRF mesoscale model predictions of surface winds in a typhoon to planetary boundary layer parameterizations . *Natural Hazards,* **51,** 63-77.

Mellor, G.L., and T. Yamada, 1982: Development of a Turbulence Closure Model for Geophysical Fluid Problems . *Reviews of Geophysics and Space Physics,* **30**, 851-875.

Nakanishi, M., and H.Niino, 2004: An Improved Mellor-Yamada level-3 Model with Condensation Physics: Its Design and Verification. *Boundary-Layer Meteorology,* **112,** 1–31.

Nakanishi, M., and H.Niino, 2006: An Improved Mellor-Yamada Level-3 Model: Its Numerical Stability and Application to a Regional Prediction of Advection Fog. *Boundary-Layer Meteorology,* **119,** 397-407.

Nolan, D.S., J.A.Zhang, and D.P.Stern, 2009: Evaluation of Planetary Boundary

Layer Parameterizations in Tropical Cyclones by Comparison of In Situ Observations and High-Resolution Simulations of Hurricane Isabel (2003). Part I: Initialization, Maximum Winds, and the Outer-Core Boundary Layer. *Monthly Weather Review,* **137,** 3651-3674.

Perdomo, B.C., 2010: A Study of the Marine Boundary Layer by LES-modelling and Experimental Observations with a focus on Offshore Wind Energy Applications. *PhD-Thesis.*

Pleim, J.E., 2007: A Combined Local and Nonlocal Closure Model for the Atmospheric Boundary Layer. Part I: Model Description and Testing . *Journal of Applied Meteorology and Climatology,* **46**, 1383-1395.

Semedo, A., Ø.Saetra, A.Rutgersson, K.K.Kahma, and H.Pettersson, 2009: Wave-induced Wind in the Marine Boundary Layer. *Journal of Atmospheric Sciences,* **66**, 2256-2271.

Smith, S.T., 1980: Wind Stress and Heat Flux over the Ocean in Gale Force Winds. *Journal of Physical Oceanography,* **10,** 709-726.

Sukoriansky, S., B. Galperin, and V. Perov, 2005: Application of a new Spectral Theory of Stably Stratified Turbulence to the Atmospheric Boundary Layer over Ice. *Boundary-Layer Meteorology,* **117,** 231-257.

Sullivan,P.P., J.C.McWilliams, and T.Hristov, 2010: *A* Large Eddy Simulation Model of High Wind Marine Boundary Layers above a Spectrum of Resolved Moving Waves. *19th Conference Boundary Layer and Turbulence, Keystone, Colorodo.*

Suselj, K., 2009: Modelling of the near-surface wind speed: Boundary Layer and Climate aspects. *PhD-thesis.*

Suselj, K., and A.Sood, 2010: Improving the Mellor-Yamada-Janjic Parameterization for wind conditions in the marine planetary boundary layer. *Boundary-Layer Meteorology,* **136**,301-324.

Türk, M., and S.Emeis, 2010: The dependence of offshore turbulence intensity on wind speed. *Journal of Wind Engineering. and Industrial Aerodynamics*. **98,** 466-471.

Vickers, D., and L.Mahrt, 2010: Sea-surface roughness lengths in the midlatitude coastal zone. *Quarterly Journal of the Royal Meteorological Society,* **136,** 1089-1093.