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Simulating the Vertical Structure of the Wind with the Weather Research and Forecasting (WRF) Model

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Abstract

Mesoscale numerical weather prediction models are now widely used to forecast wind conditions and to assess regional wind energy resources. As most of these models have been developed to serve the wide meteorological community, they need to be cautiously implemented/adjusted for use in wind energy applications. To obtain an optimal model configuration, careful verification of the boundary-layer winds simulated by these models at several levels is therefore a must.

At EWEC 2010 [1] we presented results from the verification of a real-time weather forecasting system for Denmark based on the Advanced Research WRF (ARW-WRF; Weather, Research and Forecasting) mesoscale model against cup anemometer measurements from a tall mast at the Risø National Test Station for Large Wind Turbines at Høvsøre, Denmark. The results showed that the most widely used planetary boundary layer (PBL) parameterisation in WRF, the Yonsei University (YSU) PBL scheme, fails to properly represent the observed vertical wind shear at this location. Consequently, wind speeds are usually over-estimated at 10 meters, the level of most conventional wind measurements. In contrast, winds at a height of 100 meters are fairly well simulated.

Here we expand our previous analysis to diagnose the model errors, in particular with their relationship to atmospheric stability. We also study the sensitivity of the simulated vertical wind profile from seven PBL parameterisations available in WRF.

This study is unique because: (1) it uses the high quality meteorological observations at Høvsøre, and (2) accurate forecasts at this site are often difficult because stability changes dominate over topographic and mesoscale thermal forcing in determining the wind profile.

Experimental Design

Risø maintains a real-time weather forecasting system for Denmark based on the WRF model. The model domain and the basic model configuration is presented in Figure 1 and Table1.

To explore the sensitivity of the WRF-simulated wind profiles to the PBL scheme used in the model simulations, a set of forecasts were run using the basic model configuration but changing the PBL and corresponding surface layer and land surface schemes. The seven schemes used are quickly described in Table 2.

The simulated wind profiles are validated against measurements at Høvsøre National test center for large wind turbines (Western Denmark). The terrain around the site is relatively flat and homogeneous and situated at a distance of 1.7 km from the coast.

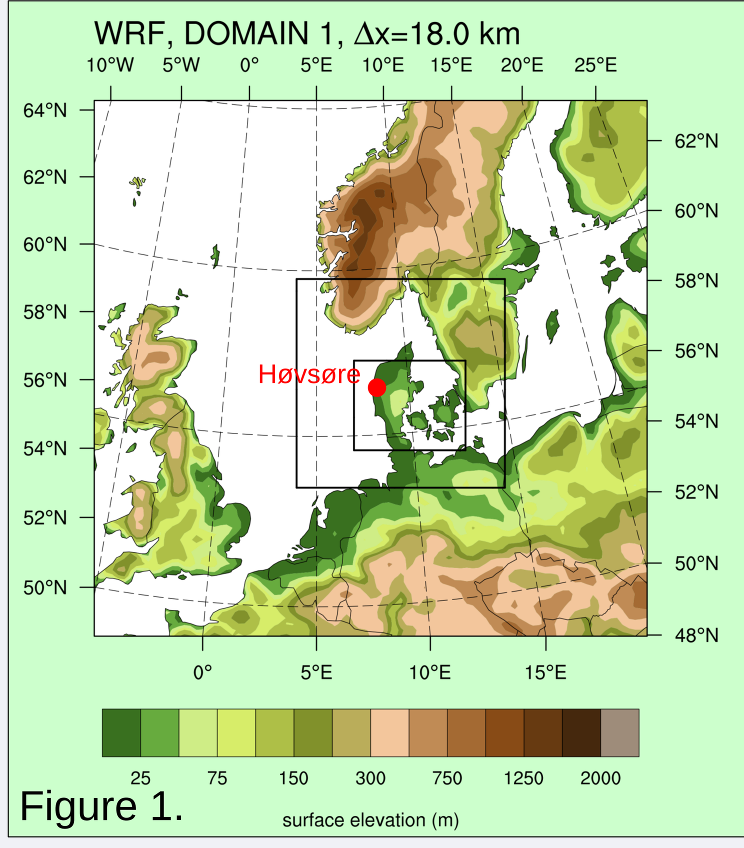

Figure 1.

Table 1. WRF configuration
Daily runs at 12 GMT driven by GFS(1º × 1) initial and boundary conditions for the period 1-30 October 2009;
SST from NCEP at 0.5º × 0.5º horizontal resolution
Each simulation lasts 30 hours; hours 0-5 are not used in the analysis
Model domain: 18 km parent domain and two nests at 6 and 2 km
37 vertical levels; lowest 4 at 14, 52, 104, and 162 meters.
No data assimilation or nudging
Besides various PBL and surface layer schemes (see Table 1), the model uses: Thompson graupel scheme, Kain-Fritsch cumulus parameterization

Table 2. Description of the PBL schemes used in the WRF experiments

PBL Scheme	PBL Scheme type	Land Surface Model	Surface Layer Scheme
ACM2	First order closure	Pleim-Xu	Pleim-Xu
MRF	Non-local-K mixing	NOAH LSM	Monin-Obukhov
MYJ	TKE closure (1.5-order)	NOAH LSM	Eta similarity
MYNN2	TKE closure (1.5-order)	NOAH LSM	MYNN
MYNN3	TKE closure (2nd-order)	NOAH LSM	MYNN
YSU	Non-local-K mixing	NOAH LSM	Monin-Obukhov
QNSE	TKE closure (1.5 order)	NOAH LSM	QNSE

Results

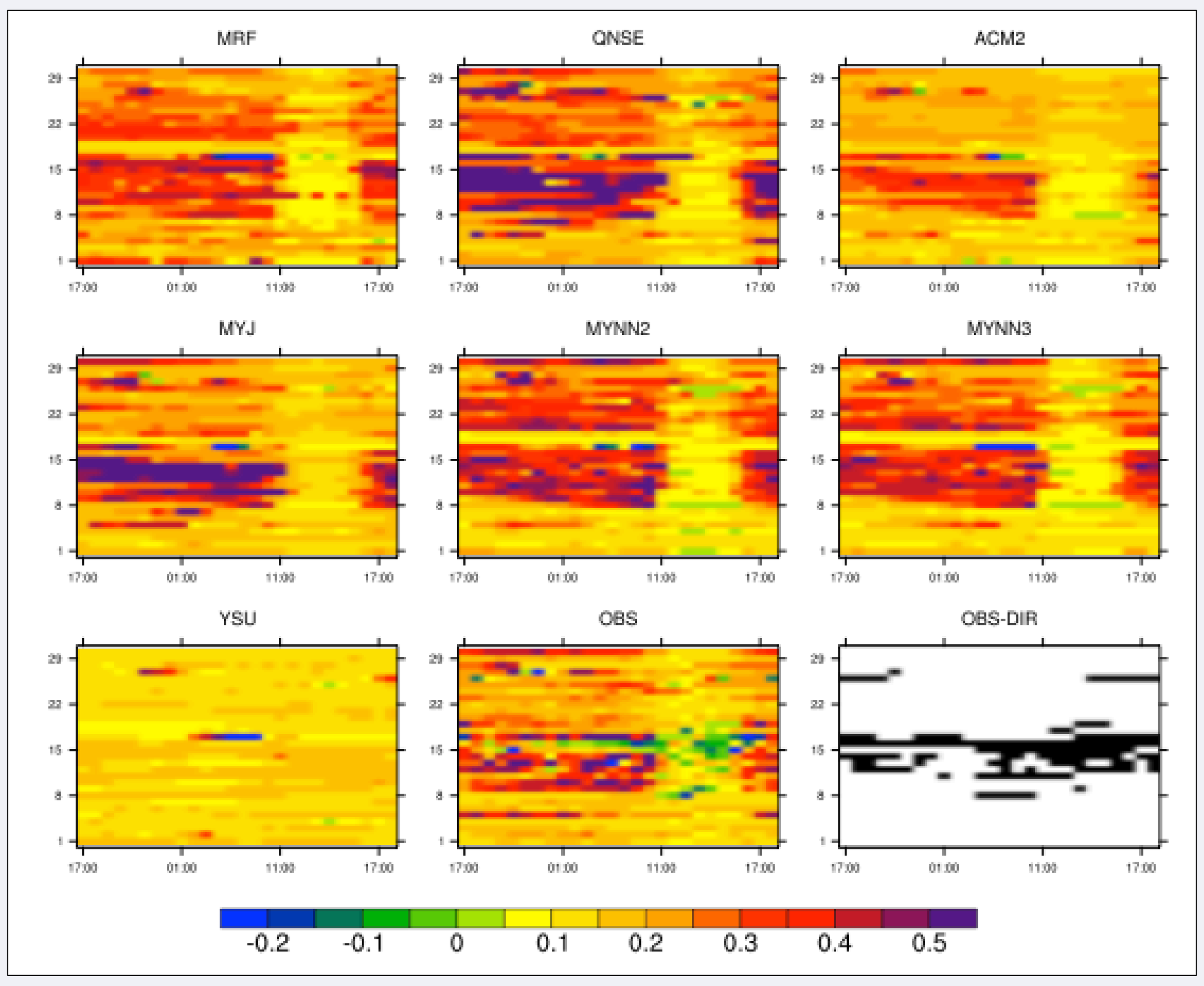

Figure 2. Shear parameter (α) as a function of time of the day (x-axis) and day of the month (y-axis) for October 2009 for each PBL scheme in Table 1. The bottom center plot represents α computed from the wind observations at Høvsøre at 10 and 60 m. The model equivalent is computed at the closest model grid point over land from two levels at ~14 and 56 m. The black boxes in the bottom right plot display the hours when the observations are in the wake zone of the wind turbines (330º−30º).

Table 3. RMSE between model simulations and observations at Høvsøre. The verification is grouped into 5 stability classes based on the observed Monin-Obukhov length. Hours when the observations are in the wake zone of the wind turbines (330º−30º) are not used in the calculations.

	MYJ	ACM2	MYNN3	MRF	QNSE	YSU
UNSTABLE; $-50 > L > -500$						
wind 100 m	2.394	2.409	2.410	2.556	3.011	**2.169**
profile error	2.280	2.307	2.345	2.433	2.828	**2.116**
α	0.074	0.078	0.077	0.084	**0.069**	0.107
NEUTRAL; $L < -500, L > 500$						
wind 100 m	2.435	2.342	**2.276**	2.364	2.616	2.442
profile error	2.410	**2.281**	2.310	2.422	2.607	2.434
α	0.052	**0.048**	0.084	0.109	0.081	0.054
NEAR STABLE; $500 > L > 200$						
wind 100 m	2.021	**1.970**	2.027	2.210	2.048	2.142
profile error	1.974	**1.855**	1.947	2.060	2.059	2.091
α	0.099	**0.067**	0.131	0.126	0.139	0.074
STABLE; $200 > L > 50$						
wind 100 m	**1.981**	2.178	2.086	2.417	2.117	2.012
profile error	**1.900**	2.087	2.002	2.224	2.021	2.100
α	0.146	**0.113**	0.137	0.123	0.254	0.145
VERY STABLE; $50 > L > 10$						
wind 100 m	**1.572**	1.938	1.825	2.193	1.696	2.066
profile error	**1.497**	1.778	1.717	1.973	1.564	2.027
α	**0.175**	**0.175**	0.207	0.213	0.230	0.307

The parameter α is often used to diagnose the shape of the wind profile. It comes from the expression

$$\frac{u(z_1)}{u(z_2)} = \left(\frac{z_1}{z_2}\right)^{\alpha}$$

where $u(z_1)$ and $u(z_2)$ are the wind speeds at heights z_1 and z_2, respectively. α varies with height, surface roughness length, and atmospheric stability. Using similarity theory, for neutral conditions, surface roughness length of 5 cm, and z_1=10 m and z_2=60 m, α=0.162. Smaller (larger) values represent unstable (stable) atmospheric BL conditions.

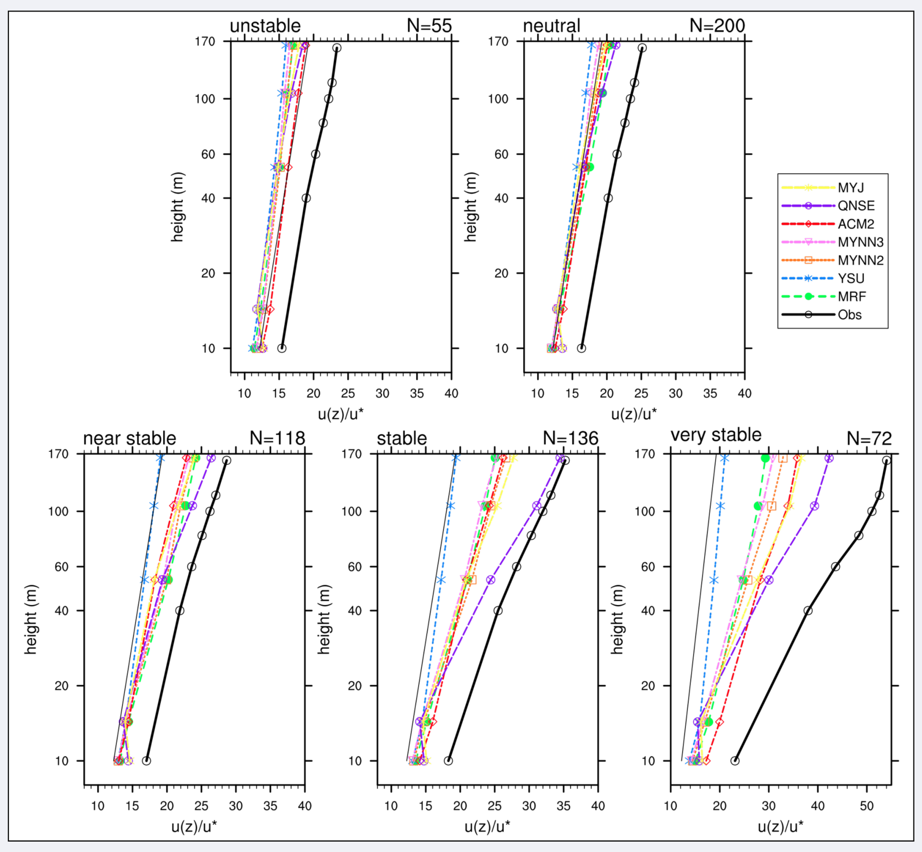

Figure 3. Comparison of observed (black solid line) and simulated (7 PBL schemes in Table 2) wind profiles at Høvsøre during October 2009. Profiles are grouped into 5 stability classes based on the observed Monin-Obukhov length. Unstable: -500<L<-50, neutral: L<-500, L>500, near stable: 200<L<500, stable: 50<L<200, very stable: 10<L<50. Hours when the observations are in the wake zone of the wind turbines (330º−30º) are not used in the calculations.

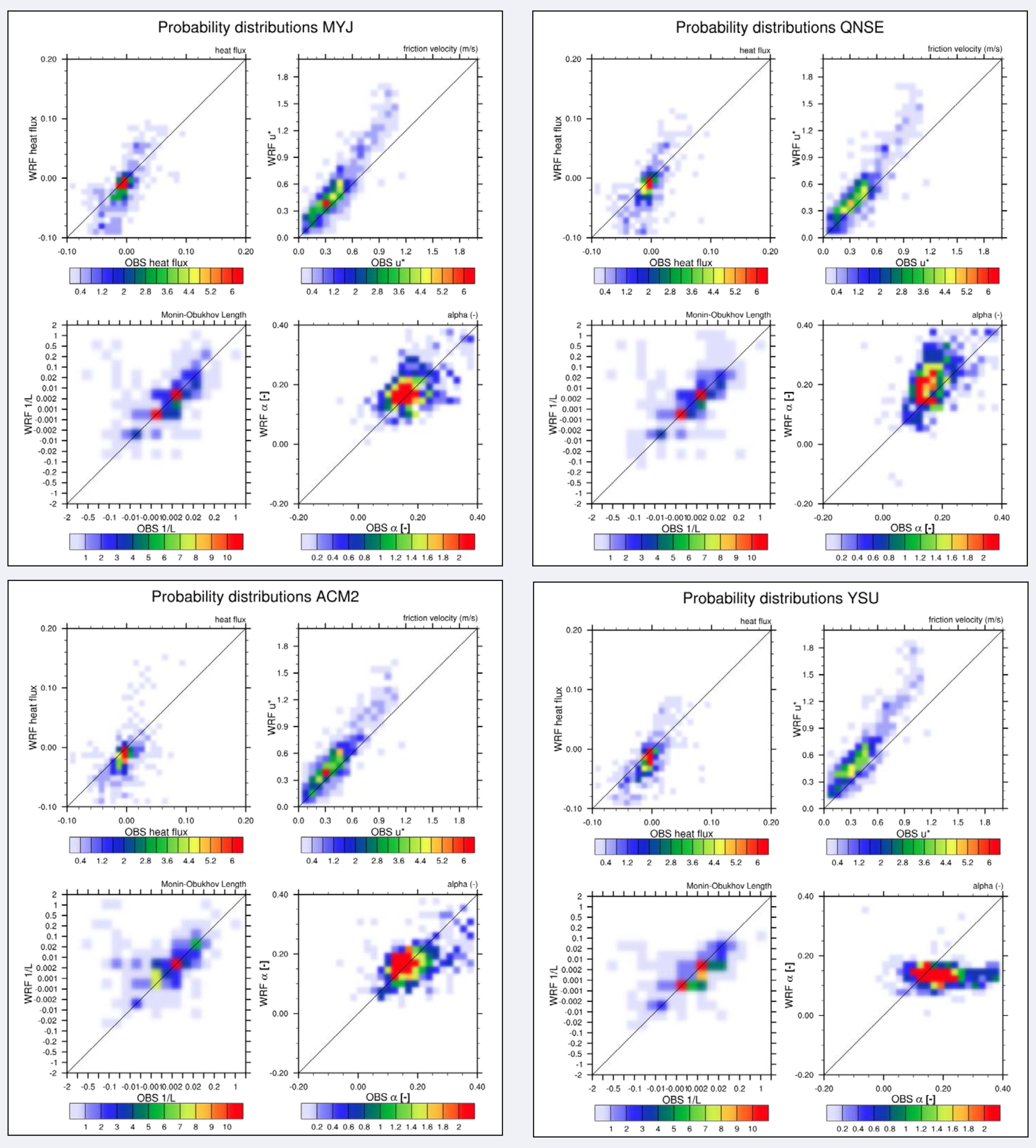

Figure 4. Probability density functions (%) of various parameters as a function of observed (x-axis) and WRF-simulated values (y-axis). Each panel contains 4 graphs: heat flux (upper left), friction velocity (upper right), 1/L (lower left) and α parameter (lower right). The panels are repeated for 4 PBL schemes: MYJ, QNSE, ACM2, and YSU. Hours when the observations are in the wake zone of the wind turbines (330º−30º) are not used in the calculations.

Conclusions

The average wind profile forecasted by WRF using the QNSE scheme generally compares best with the observed profiles for a range of stability classes (Figures 2 and 3). However, the RMSE errors (Table 3) suggest that different schemes fit better particular stability conditions (for example, YSU for unstable conditions, MYJ for very stable conditions).

Although the surface parameters (i.e. sensible heat and momentum flux) simulated by WRF with different PBL schemes do not exhibit significant variations compared to the observations, the wind profile, and thus the α parameter, does.

The results clearly indicate that 10-meter winds cannot be used for verification of mesoscale model simulations, at least when applied to wind energy. In such applications verification against high-quality wind profiles is a must.

References

[1] Hahmann, A.N. and A. Peña, 2010: Validation of boundary layer winds from WRF forecasts over Denmark. *EWEC 2010*, Warsaw, Poland.