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Wind lidar profile measurements in the coastal boundary layer: comparison with WRF modelling

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Abstract

We use measurements from a pulsed wind lidar to study the wind speed profile in the planetary boundary layer (PBL) up to 600 m above the surface at a coastal site. Due to the high availability and quality of wind lidar data and the high vertical range of the measurements, it is possible to study the sensitivity of PBL schemes of mesoscale models to both lower and upper boundary conditions. We therefore run the mesoscale weather research and forecasting (WRF) model using two different roughness descriptions, two different synoptic forcings and two different PBL schemes at two vertical resolutions. When WRF is compared to the wind lidar data combined with measurements from a tall meteorological mast, it is found that the model surface layer fluxes are largely overestimated and that the vertical wind speed profile does not have enough shear in the lower part of the PBL, partly as a consequence of the smooth-to-rough transition at the coastline. When using a more representative roughness than the default, the biases in the surface friction velocity and heat flux are reduced and the wind speed is slightly improved. Both PBL schemes show too much mixing during stable conditions and an underestimation in the amount of observed low level jet. The wind speed predicted by WRF does not improve when a higher resolution is used. Therefore, both the inhomogeneous (westerly) and homogeneous (easterly) flow contribute to a large negative bias in the mean wind speed profile at heights between 100 and 200 m.

1 Introduction

The change of wind speed with height and its development in time are key issues for the wind energy industry. As wind turbines get taller, our knowledge of the wind speed above the surface layer has to be improved. Recent studies have shown that WRF often poorly represents turbulent parameters like the friction velocity u_* and heat flux H [1, 7]. For description, modelling and forecasting of the behaviour of winds and turbulence it is essential to have a realistic estimate of the magnitude of the surface layer fluxes. Verification of the vertical structure of the PBL often proves difficult, because of lack of data of sufficient resolution in time and space. One promising new method for measuring the wind profile is the wind lidar. They have been available for some time, but recently they improved in terms of reliability, accuracy and range [5]. Wind speed measurements from a wind lidar up to 600 m, combined with the observations from a meteorological mast at a coastal site in Denmark provide information about both upper air and near surface winds and turbulence. We study the sensitivity of the wind profile modelled by WRF with two PBL parameterizations and two vertical model resolutions to both lower and upper boundary conditions; the surface layer momentum flux (by redefining the landuse properties) and synoptic forcing (by using NCEP final analysis and ERA interim reanalysis data), respectively. We run WRF in prognostic mode on a domain covering Northern Europe for two 15 day periods.

2 Methods

2.1 Observations

A pulsed wind lidar (Windcube70) operates at the National Test Station of Wind Turbines at Høvsøre since April 2010. Wind speeds are measured at a near by meteorological mast together with turbulence parameters. The wind lidar measures wind speed and direction every 50 m starting at 100 m above the ground and reaching up to 2 km height depending on the aerosol content of the atmosphere. The wind lidar is equipped with a rotating silicon prism providing four azimuthal scans 90° from each other at a inclination angle (relative to the zenith) of 15°. One 360 degree full scan (rotation) is performed every 30 s. The data are stored into 10-min average quantities. The reported range of measurements depends on a threshold on the 10-min averaged carrier to noise ratio (CNR). This threshold (here -22 dB) can also be used as an estimate for PBL height: because the lidar needs

Table 1: Observations available at the Høvsøre site

Observations		
Data source		Heights [m]
Cup	C	10, 40, 60, 80, 100, 116.5, 160
Sonic	S	10
Lidar	L	100–600 (50 m interval)

aerosols to measure the wind speed it cannot measure above the PBL height and the signal becomes noisy.

The agreement between lidar and cup anemometer wind speed at 100 m height for the two analysed periods is excellent. Using linear regression fitted through origo, gives a correlation coefficient R^2 and slope coefficient of almost 1.00. Due to its high measuring frequency, the lidar gives very robust statistics compared to radio soundings.

At Høvsøre the flow is strongly influenced by the sea-land contrast. The data is classified into two categories based on the wind direction D at 60 m: the westerly sector ranges between 225 and 315 degrees and the easterly sector between 30 and 150 degrees.

2.2 Model

In WRF the vertical diffusion is modelled by the PBL scheme. We use the first order YSU scheme and the 1.5 order MYNN scheme. The YSU scheme prescribes the values of the eddy diffusivity K_m directly, while the MYNN scheme uses an additional prognostic equation for the turbulent kinetic energy. A detailed description of the PBL parameterization for YSU and MYNN can be found in Hong et al. [3] and Nakanishi & Niino [4], respectively. The surface layer scheme calculates the turbulent fluxes u_{*0} and H based on a bulk method using Monin-Obukhov similarity theory (MOST).

3 Results

3.1 Lower boundary conditions

Because u_{*0} and H are the most important parameters governing the shape of the wind profile, they were compared with the model simulation from WRF. The roughness length z_0 and the stability correction ϕ_m were calculated from observations. The roughness length in WRF was too high, $z_0 \approx 0.08$, so the value from the observations, $z_0 = 0.015$, was implemented in WRF (table 2). It is possible that the surface layer scheme calculates a too high u_{*0}, because the observed dimensionless shear in the coastal area can be different from the modelled one. In the internal boundary layer the dimensionless wind shear can be up to 50% larger than unity, because U decreases faster with height than u_* [6]. Although the ϕ_m functions was under predicted in WRF, it was found that this did not contribute significantly to the overestimation in u_{*0}. Also there was no significant difference between the ϕ_m function for the easterly and westerly sector, which shows that MOST was valid at the first model level.

For both easterly and westerly winds, the model runs M_{41} and Y_{41} overestimate u_{*0} (table 3). Using lower roughness in MC_{41} and YC_{41} reduces u_{*0} to more realistic values and similar results are found for the heat flux. For homogeneous conditions the YSU scheme still has a large positive bias for H, which was also observed in [7]. The MYNN scheme does not show this large overestimation in H. The 10 m winds were overestimated in most conditions, even when the surface layer fluxes showed no bias.

The internal boundary layer that forms at the smooth-to-rough change results in an high friction velocity at Høvsøre, which then decreases further inland (figure 1, right). This is in agreement with experimental and nu-

Table 2: Summary of the model runs and observations for the two periods 15–30 Sep. and 15–30 Oct.

Name	PBL scheme	No. vert. levels (in range lidar)	Boundary conditions	z_0 [m]
M_{41}	MYNN	41 (8)	FNL	0.080
Y_{41}	YSU	41 (8)	FNL	0.080
M_{63}	MYNN	63 (22)	FNL	0.080
Y_{63}	YSU	63 (22)	FNL	0.080
MC_{41}	MYNN	41 (8)	FNL	0.015
YC_{41}	YSU	41 (8)	FNL	0.015
ME_{41}	MYNN	41 (8)	ERA	0.080
YE_{41}	YSU	41 (8)	ERA	0.080

- Noah land surface scheme
- Thompson microphysics scheme
- RRTM longwave radiation
- Dudhia shortwave radiation
- New Kain-Fritsch cumulus scheme

Table 3: Results from linear regression through origin for the westerly sector (top, number of samples, $N = 1366$) and easterly sector (bottom, $N = 310$).

Var.	M_{41}	MC_{41}	Y_{41}	YC_{41}
u_{*0}	1.39	1.10	1.36	1.07
H	1.50	1.09	1.14	0.98
U_{10}	1.05	1.11	1.03	1.08
U_{100}	0.95	0.95	0.94	0.95
U_{650}	0.99	0.98	0.95	0.95
u_{*0}	1.10	0.99	1.30	1.14
H	1.38	1.07	1.50	1.34
U_{10}	0.95	1.11	1.10	1.26
U_{100}	0.83	0.87	0.91	0.95
U_{650}	0.97	0.97	0.96	0.96

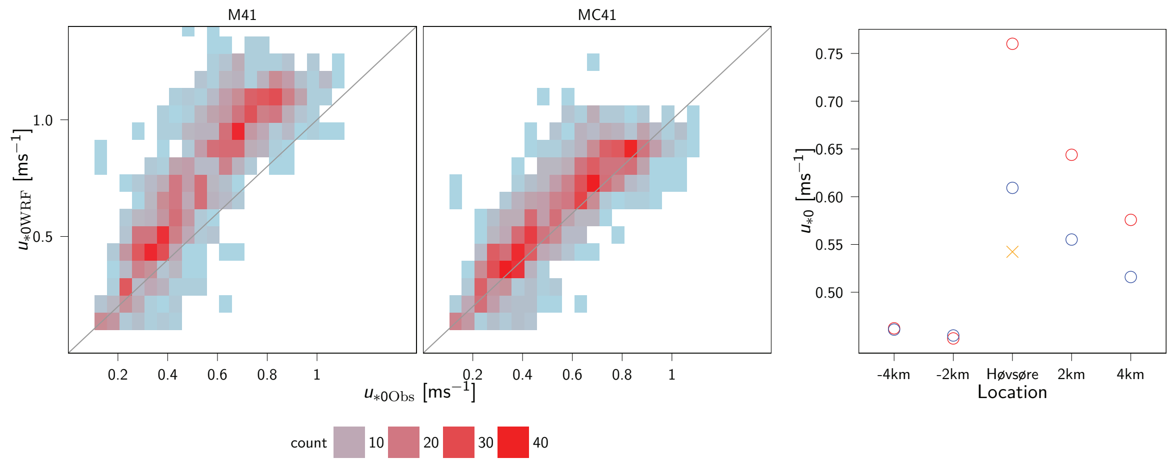

Figure 1: Scatter plot of the observed and modelled u_* with the default (left) and realistic (middle) surface roughness. The right figure shows u_* at 5 grid points (M_{41}=red circles, MC_{41}=blue circles and cross=observed) with westerly flow at Høvsøre

merical studies of the flow in the internal boundary layer, but the effect is found very close to the coastline only [6]. The equilibrium layer of the internal boundary layer, where the fluxes are in equilibrium with the new surface roughness, extents to approximately 16 m at the meteorological mast [2]. Therefore it is unrealistic that for both WRF simulations, the surface layer fluxes have not reached their equilibrium values after more than 2 km.

3.2 The wind profile and PBL schemes

For the westerly sector the wind speed profiles for the vertical cross section are shown in figure 2. Upstream at sea (-4 km), the profiles show a high near surface wind speed which decreases once the wind crosses the shoreline. The realistic surface roughness simulations (right) show a more realistic wind speed at 10 m when an equilibrium with the surface fluxes forms after several kilometers.

The MYNN scheme adapts quicker to the surface conditions and shows a higher decrease in wind speed at 10 m, whereas the YSU scheme shows deviations between upstream and downstream profiles up to larger heights. It is clear that none of the PBL schemes model the high shear in the layer between 0–200 m. Increasing the vertical resolution from 8 tot 22 levels did not have any noticeable effect on the shear in this layer. For the easterly sector there was a large under prediction in stable conditions, because WRF did not model the low level jet (not shown).

3.3 Upper boundary conditions

In figure 2 the observed and modelled wind profiles do not approach the same geostrophic wind near the top of the boundary layer. To investigate the effect the simulations were repeated but using the ERA-interim data. In table 4 the wind speeds at 650 m winds for the two sources of (re)analysis data are shown. The difference between NCEP final analysis data (M_{41} and Y_{41}) versus ERA interim data (ME_{41} and YE_{41}) is generally small. Therefore we discard the data used to initialize the model as the source of under prediction in high level winds.

Table 4: Results from linear regression through origin.

		U_{650}			
		M41	ME41	Y41	YE41
West	slope	0.99	0.96	0.95	0.93
	R^2	0.76	0.78	0.80	0.81
East	slope	0.97	0.98	0.96	0.97
	R^2	0.84	0.83	0.82	0.81

4 Conclusions

The momentum transfer in the coastal boundary layer and the shape of the wind profile was modelled with version 3.3 of the WRF-ARW model for a four week period with flow from the east with homogeneous upwind conditions and flow from the west with inhomogeneous upwind conditions. Simulations were performed with a first and a higher order closure scheme and two vertical resolutions.

The default roughness in WRF was too high, but simulations with a lower roughness still gave a over prediction of the surface layer fluxes. This was partially caused by the large changes in wind profile and surface layer fluxes in grid points near the coast. The flow adjustment in was too slow and the wind profile approach the corrected surface values only after several grid points in land. For flow with homogeneous upwind conditions WRF over estimates the surface layer fluxes with both the realistic and default surface roughness. This results in a slightly too high near surface wind speed in WRF.

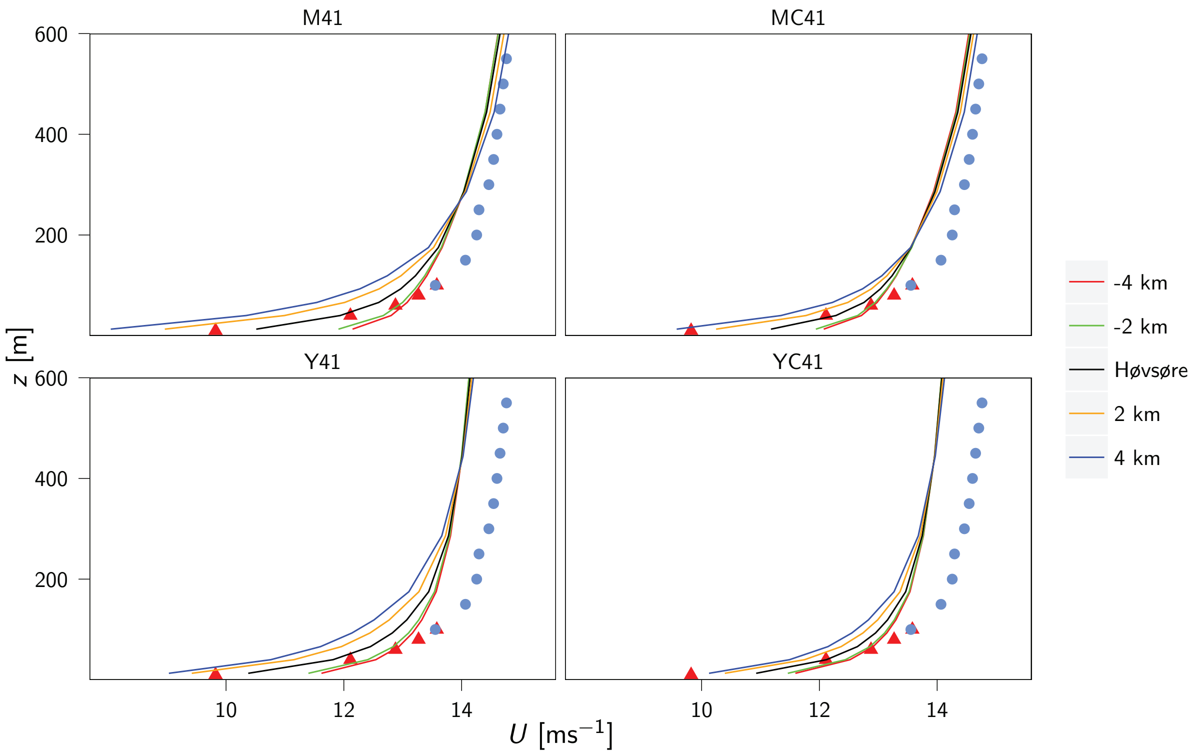

Figure 2: Measured and modelled mean wind speed profiles for westerly winds for different grid points in WRF. For the abbreviations, see table 2

At larger heights there is again an under prediction in wind speed. This is a consequence of the enhanced mixing of PBL schemes in stable conditions and was found for both first and second order schemes. The amount and strength of low level jets was under estimated. Increasing the vertical resolution and using different boundary conditions did not improve the results for both homogeneous and inhomogeneous conditions.

The observed behaviour of the surface layer fluxes and wind profiles suggest that output from mesoscale models should be treated with care near the coastline. The negative wind speed bias in both sectors results in an under estimation of mean wind speed, which is important for wind turbines that are often located near the shoreline and becoming larger in size. The new wind lidar measurements proved to be highly useful for evaluating the performance of the PBL schemes and will be further studied for different locations in the near future.

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