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Meso-scale modeling of a forested landscape

Ebba Dellwik[1], **Johan Arnqvist**[2], **Hans Bergström**[2], **Matthias Mohr**[2], **Stefan Söderberg**[3] **and Andrea Hahmann**[1]

[1] Department of Wind Energy, Technical University of Denmark, Denmark
[2] Department of Earth Sciences, Uppsala University, Sweden
[3] WeatherTech Scandinavia AB, Sweden

E-mail: `ebde@dtu.dk`

Abstract. Meso-scale models are increasingly used for estimating wind resources for wind turbine siting. In this study, we investigate how the Weather Research and Forecasting (WRF) model performs using standard model settings in two different planetary boundary layer schemes for a forested landscape and how this performance is changed when enhancing the roughness by a factor four in one of the schemes. The model simulations were evaluated using data from a 138 m tall mast in southeastern Sweden, where an experiment with six sonic anemometers and standard meteorological instrumentation was performed 2010-2012. The land cover around the mast is dominated by forest and for the most common wind direction, the forest extends more than 200 km from the mast. The two low-roughness simulations showed differences both in terms of estimated wind resource and wind shear. The simulation with enhanced roughness results in an improved correlation with measured data for near-neutral situations in the observed height range, whereas the correlation is deteriorated relative to the standard setup for stable atmospheric stratifications for heights above approximately 80 m. The inclusion of the displacement height in the post-processing of the results is also discussed.

1. Introduction

Wind turbines are commonly placed in forested areas. With the increasing height of wind turbines, effects of smaller scale terrain variation and heterogeneous vegetation cover are often disregarded and meso-scale models are used directly for assessing the wind climate of a potential wind turbine site. However, the meso-scale models were not developed for wind resource assessment and the forest parametrization may need to be revised. In this study, we analyze the performance of a commonly used meso-scale model in relatively homogenous and flat forested terrain using standard and adjusted settings.

In most meso-scale models, a forested surface is parameterized by a high value of the aerodynamic roughness length relative to those for other land surface types. However, the values chosen are typically still significantly lower than those found by fitting measurements to a logarithmic profile [*e.g.* 1–4]. In addition to the increased roughness, the wind profile over forested areas is commonly adjusted by including a displacement height to describe the distance to the surface. This choice is typically not available for meso-scale models and may need to be accounted for in the post-processing of the model results.

Close to the forest, the wind profile deviates from typical surface layer behaviour, as it is influenced by relative large-scale eddies caused by the inflection point instability close to the crown layer of the forest [5]. The surface layer over forested areas is therefore subdivided into a roughness sublayer, where such influence is significant, and an inertial sublayer above, where the wind profile shows a similar behaviour as over short vegetation. The roughness sublayer can be viewed as the consequence of the vertical extent of the forest canopy, which would make its representation as a surface roughness inadequate. Recent modeling developments on canopy representation are discussed at the end of the paper.

2. Method

2.1. Site description

Validation data for the meso-scale model was taken from the 138m tall Ryningsnäs tower, where detailed wind measurements were taken between November 2010 and May 2012, using six sonic anemometers (Metek ApS, Germany). A detailed site description, as well as an analysis of the effect of two wind turbines located near the tower can be found in [6].

For the current study, we consider data from the westerly wind directions between 240° and 280°, where the effect of the turbines on the flow is considered negligible and the upstream terrain is predominantly forested for more than 200 km. An analysis of the sonic anemometer data was performed with the focus of describing the influence of atmospheric stability on turbulence statistics and determine if the measured data included typical roughness sublayer characteristics (not shown). However, no such influence was found and it was concluded that the roughness sublayer influence on the wind profile was confined to the region below the lowermost sonic anemometer at 40 m height, which corresponded to twice the tree height near the tower.

The measurement data were processed and quality-controlled [6]. The Obukhov length L, was calculated as

$$L = -\frac{u_*^3 T_S}{\kappa g \overline{w'T_S'}}, \tag{1}$$

where u_* is the friction velocity, T_S is sonic temperature, $\kappa = 0.4$ is the von Kármán constant, g = 9.82 m/s^2 the constant of gravity and $\overline{w'T_S'}$ is the sonic anemometer temperature flux which is approximated as the buoyancy flux. The friction velocity is defined by $u_* = (\overline{u'w'}^2 + \overline{v'w'}^2)^{1/4}$, where $\overline{u'w'}$ and $\overline{v'w'}$ are the vertical and transversal turbulent momentum fluxes, respectively. For the calculation of L, the 40 m sonic anemometer was used.

The roughness length z_0 and displacement height d of the forest at the site was estimated using standard surface layer (inertial sublayer) expressions and the mean wind U and u_* from the sonic anemometers at 40 and 59m height using a least square fit of the near-neutral data to

$$U(z) = \frac{u_*}{\kappa}\left(\frac{z-d}{z_0}\right). \tag{2}$$

The roughness was estimated to be $z_0 \approx 2.5$ m and $d \approx 15$ m. A more detailed analysis can be found in [6].

2.2. Model setup

The Advanced Research WRF version 3.2.1 was used to simulate the wind climate around the Ryningsnäs tower. We tested the performance of the two WRF boundary layer schemes MYJ [7] and the version of YSU [8] implemented in WRF 3.4.1 in combination with the Noah surface scheme [9]. To assess the effect of the roughness setting, two simulations with MYJ were run: one with $z_0 = 0.5$ m corresponding to the standard setting and a second simulation with $z_0 = 2$ m. This enhanced roughness was applied for the deciduous, mixed and evergreen forest classes. In the 3.2.1 version of WRF, the roughness is constant over the year and the annual cycle depending on the status of the forest, which is otherwise standard [*e.g.* 10], was not applied.

We use the model output from the inner domain with 5 km × 5 km horizontal grid spacing. For the vertical resolution, ten pressure levels were used below approximately 1000 m. Below

140 m, there were five model levels. Tests with higher vertical resolution were carried out and suggested that ten levels were sufficient [11]. Data from the Shuttle Radar Topography Mission (SRTM) was used for describing the location of the surface. Initial and boundary conditions, as well as fields for grid nudging come from the European Centre for Medium Range Forecast (ECMWF) ERA-Interim Reanalysis [12] at 0.7° × 0.7° resolution. More information on the setup can be found in [11]. The model runs consist of consecutive 11 day long pieces, where the first 24h were regarded as model spin-up and not used in the analysis. Horizontal winds, temperature and specific humidity fields above level 10 were nudged towards ERA interim data in the outer domain at 15 km horizontal resolution.

The modeled wind profiles were interpolated using cubic spline interpolation to the location of the sonic anemometers. The displacement height that accounts for the height of tall roughness elements is not implemented in the Noah scheme. To test the significance of this effect, $d = 15$ m was subtracted from the measurement heights.

2.3. Data selection

We investigated the performance of the WRF model for the whole year of 2011. Pairs of model and measurement data were further chosen according the following criteria:

(i) No instrumental errors, please see [6] for a description of screening of measurement data.
(ii) Measured wind direction at 98m within $[240°, 280°]$.
(iii) Near-neutral stratification: $-0.1 < 20/L < 0.07$, $U_{meas,98m} > 5$ m/s.
(iv) Stable stratification: $20/L > 0.1$.

This selection resulted in 893 and 374 near-neutral and stable data points, respectively. The reason for focussing on near-neutral and stable data is that these stratifications correspond to the situations with the highest wind speeds.

3. Results

The relative occurrence of different wind speeds for the westerly wind directions at $z = 98$ m show differences depending on PBL scheme and applied surface roughness (Figure 1). For this analysis only the first two criteria in Section 2.3 were applied. Compared to the observations, the simulation based on the MYJ scheme with $z_0 = 2.0$ m showed the closest agreement with data, and the YSU scheme with $z_0 = 0.5$ m showed the strongest underestimation of lower (< 8 m/s) and overestimation of higher (> 8 m/s) wind speeds.

The observed and modeled wind profiles for near-neutral and stable stratification are shown in Figure 2(a) and 2(c), respectively. The squares and stars in the graphs correspond to the location of the sonic anemometers. Within the observed height range, the shear of the MYJ $z_0 = 2.0$ m profile is not significantly altered, but wind speeds are reduced by a near-constant value relative to MYJ $z_0 = 0.5$ m. The YSU $z_0 = 0.5$ m simulation showed a strong overprediction relative to observation, but the shear of the modeled profile is closer to observations than for either of the MYJ simulations, especially for the stable situations (Figure 2(c)).

When taking the vertical extent of the forest into account by inclusion of d, the MYJ $z_0 = 2$ m simulation is still the closest to the observations for the near-neutral data (Figure 2(b)), but for the stable case with $d = 15$ m, the underprediction of the mean wind speed for the whole observed height range becomes considerable. As for the simulations with $d = 0$ m, the shear of the modeled wind profile is closer to the observed for the YSU stable case, although the simulation with MYJ $z_0 = 0.5$ m is closer to the observations.

4. Discussion and conclusion

With a fourfold increase of the surface roughness for all forest classes, the WRF 3.2.1 simulations resulted in a closer agreement to observed wind profiles at the Ryningsnäs site. The long fetch

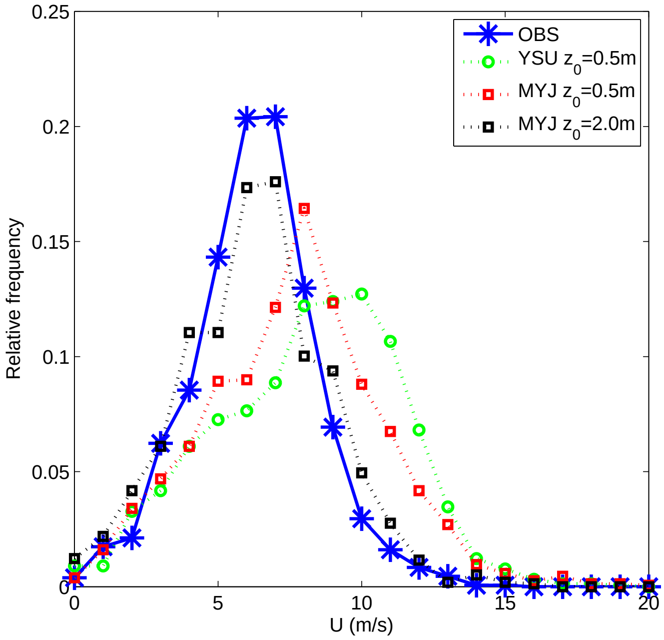
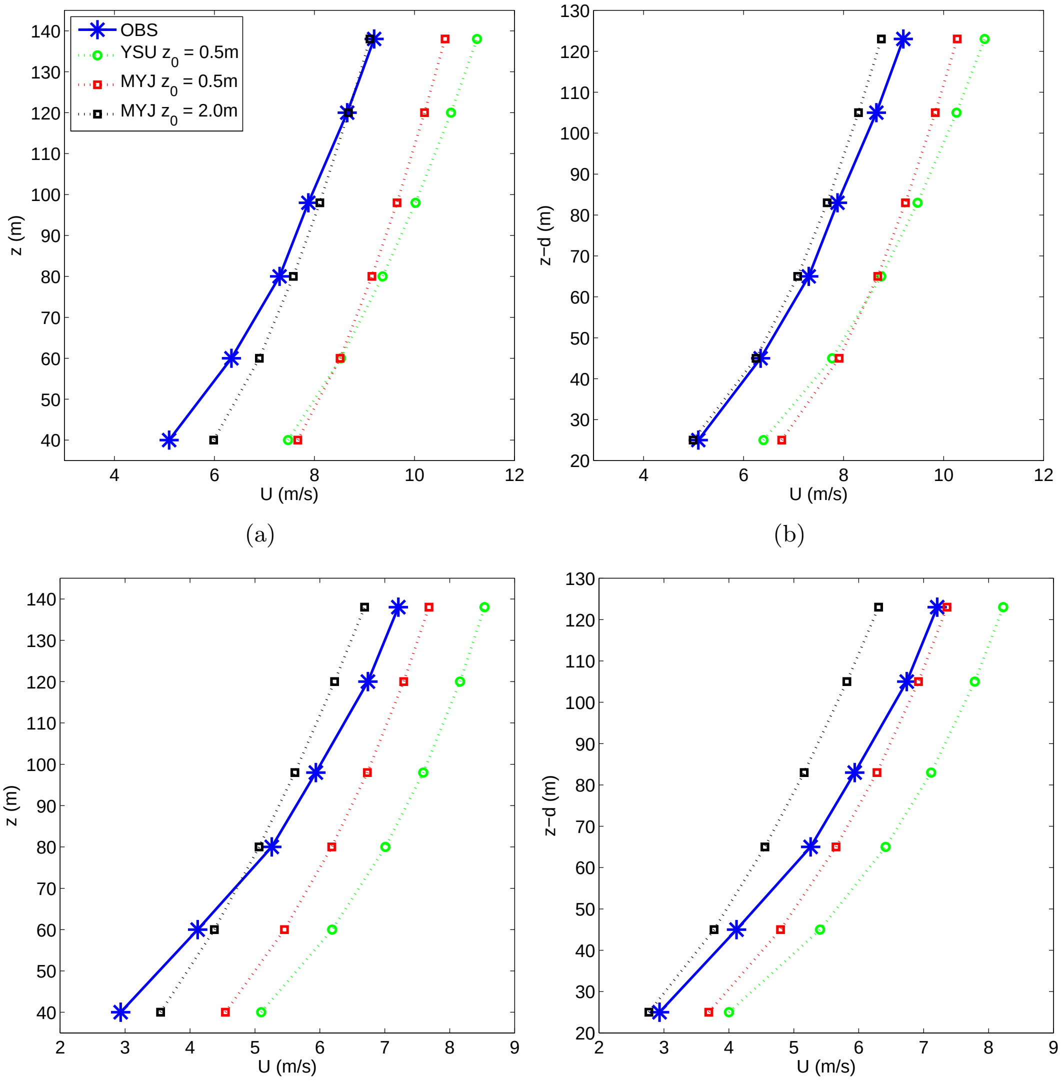


Figure 1. Histogram of mean wind speeds for the westerly wind directions using different WRF model simulations.

of forested surface upwind of the mast for the selected westerly wind directions makes the site a good test case for testing effects of forest roughness in meso-scale models like WRF. The topography at the site is rather flat and although the forest in general is not homogeneous, the micro-scale effects on the observed wind profile are expected to be small based on analyses of turbulence statistics. These factors to some extent justify the direct comparison of the meso-scale model with the observations. The reduction of the measurement height by d can, however, be viewed as a crude micro-scale correction of the local forest height, that allows both the model and measurements to be interpreted in relation to the level where the extrapolated wind profile turns zero. We therefore consider the comparison with $d = 15$ m in Figures 2(b) and 2(d) to be a more correct way of evaluating the model performance than an evaluation with $d = 0$ m as presented in Figures 2(a) and 2(c), and recommend its inclusion in the post-processing of meso-scale model results.

Based upon the presented results as well as published data [1–4], $z_0 = 0.5$ m, cannot be regarded as a realistic representation of the aerodynamic effect of mature forests, and wind resource modelers who apply WRF in predominantly forested regions are recommended to interpret such low-roughness model results with care. Given the approximately height-invariant change in wind speed between the two MYJ simulations and the good agreement in shear between YSU and observations, it is of interest to make additional roughness experiments with the YSU scheme in the WRF model. However, for the stable data, the high roughness case led to an underprediction of the wind speed. This result is consistent with the roughness model suggested by [13], that results in decreasing aerodynamic roughness for tall canopies with increasing stability.

Especially for non-neutral conditions, a more realistic canopy representation may improve the model results. In the Noah-MP LSM [14], a separate vegetation layer was introduced that allows the parametrization of the different physical properties of the vegetation and the ground. One of the many options available in the Noah-MP scheme is the use of a displacement height,



(a)

(b)

(c)

(d)

Figure 2. Comparison between observed and simulated wind speeds for the cases: (a) near-neutral with $d = 0$ m, (b) near-neutral with $d = 15$ m, (c) stable with $d = 0$ m and (d) stable with $d = 15$ m.

which would make the post-processing proposed here superfluous. In WRF-SPA [15], the forest representation is further refined into a multi-layer canopy, which allows for the calculation of the below-canopy wind profile. These refined forest canopy representations have the potential to improve the simulated surface energy balance over forested areas significantly and an improved surface energy balance leads to more realistic atmospheric stability and growth of the planetary boundary layer, which in turn should improve the modeled wind profile in the whole boundary layer.

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