Answers to Review by Bjarke Tobias Olsen (RC2):

General Comments

The paper presents a case study of a cold front passage across a complex wind energy site in Germany, simulated in high-resolution by WRF and the OpenFOAM driven by WRF-derived lateral boundary conditions. In the study, the authors investigate the impact of including forest parameterization in the models and validates the simulations against measurements from a meteorological mast and UAS flights. Although the paper is generally well written and presents some interesting results, it lacks in describing important details to allow the reader to draw conclusions or allow the study to be reproduced. Specifically, the paper lacks details on the microscale model formulation and on the coupling between WRF and OpenFOAM. The UAS measurements are used for qualitative evaluation of the WRF simulations but add very little to the quantification of the improvement of the WRF model by using forest parameterization, or to the improvement of the results by using the high-resolution OpenFOAM model compared to WRF. At the same time, the mast measurements are not used to quantify the accuracy of OpenFOAM vs WRF results, e.g. via a comparison of error statistics.

We would like to thank the reviewer for his effort and the very helpful comments. We agree that more details describing the microscale simulations must be included in the manuscript. We have also improved the statistical evaluation by adding correlation plots, error statistics for all heights at which observations are available at the tower for all models. Furthermore we calculate these errors both for UAS and Tower-observations. We have removed some plots showing the general flow in favour of tables and plots supporting the statistical analysis.

Specific Comments

L63-64 - This sentence is inaccurate. It implies that the PBL/TKE scheme is not part of the turbulence parameterization.

You are right. The sentence should rather read:
Surface layer processes are parameterized using the revised MM5 surface layer scheme.

L74-75 - Six hours spin-up time for WRF is short compared to the existing literature. Why did you choose six hours? and are you confident that six hours are sufficient to spin up the model?

We have tried longer spin-ups (12 hrs, 24 hrs) as well, but found only small differences. For this reason we decided to use 6 hours to save some computational time. You may argue that we save very little computational time this way, but testing, development and sensitivity runs add up.

L87 - What WRF domain is used? domain 5?

The innermost domain. We clarified the statement in the manuscript.

L91-94 - Please be explicit about the details of the OpenFOAM model and the configurations used, e.g. is it a Finite-Volume model? does the model describe an incompressible fluid? are variables collocated or staggered? What vertical coordinate is used?

We add to the text:

The simulations for the second step of the model chain were conducted using the finite volume method of the OpenFOAM v6 (Open Source Field Operation and Manipulation) software, , provided by the OpenFOAM Foundation U.K (Weller et al., 1998). The transport equations were defined in a Cartesian coordinate system (x, y, z).

L94-95 - What modifications specifically was used? are they the same as in El Bahlouli et al. (2019)? i.e. based on Apsley and Castro (1997)? Please add specific details or state the reference.

The modifications were the same as in El Bahlouli et al. (2019) and are based on the work of Apsley and Castro (1997). There, a modified version of the $k - \epsilon$ model was used and the two modified transport equations for the turbulent kinetic energy and the dissipation ϵ read:

$$\frac{\partial(\rho_h k)}{\partial t} + \frac{\partial(\rho_h u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\left(\frac{\partial k}{\partial x_j}\right)\right] + P + G + S_k - \rho_h \epsilon \tag{1}$$

$$\frac{\partial(\rho_h \epsilon)}{\partial t} + \frac{\partial(\rho_h u_j \epsilon)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\left(\frac{\partial \epsilon}{\partial x_j}\right)\right] + C^*_{\epsilon 1}(P + G) + S_\epsilon - C_{\epsilon 2}\frac{\epsilon^2}{k}, \tag{2}$$

where P represents the production rate of turbulent kinetic energy due to shear and G represents the production/destruction of turbulence by buoyancy forces. The hydrostatic fluid density is ρ_h and is given in a hydrostatic reference state (subscript 0) as a function of the hydrostatic pressure and the temperature T_h as:

$$\rho_h = \frac{p_h}{R_d T_h} \tag{3}$$

$$T_h = \sqrt{T_0^2 - \frac{2Agz}{R_d}} \tag{4}$$

$$p_h = p_0\left(-\frac{T_0}{A} + \sqrt{\left(\frac{T_0^2}{A}\right) - \frac{2Agz}{R_d A}}\right) \tag{5}$$

with the constant reference pressure p_0 set to 1000 hPa, T_0 is the reference temperature equal to 288.5 K, $A = 50$ K and $R_d = 287.05$ J kg^{-1} K^{-1} according to Doms and Baldauf (2018); Dudhia (1993). The constant model coefficients σ_k, σ_ϵ , $C^*_{\epsilon 1}$ and $C_{\epsilon 2}$ in equations 1 and 2 are adapted to atmospheric conditions as proposed by Detering and Etling (1985). Their values are listed in Table 1. The maximum mixing length l is introduced by the equation:

$$C^*_{\epsilon 1} = C_{\epsilon 1} + (C_{\epsilon 2} - C_{\epsilon 1})\frac{l}{l_{max}}, \tag{6}$$

where the mixing length l is equal to the dissipation length defined as $l_\epsilon = (C_\mu^{3/4} k^{3/2})/\epsilon$. Several mixing-length models in the literature provide an estimation of l_{max}, the limiting size of turbulent eddies in the ABL. See Peña et al. (2009) for a review. For neutral flows, this length is computed using the Blackadar equation (Blackadar, 1962)

$$l_{max} = 0.00027\frac{U_g}{2\Omega \sin\lambda}, \tag{7}$$

where U_g is the geostrophic wind velocity.

Table 1: Constants used in $k - \epsilon$ turbulence models.

Turbulence model constants	C_μ	$C_{\epsilon 1}$	$C_{\epsilon 2}$	σ_ϵ	σ_k
Standard (Launder and Spalding, 1974)	0.090	1.44	1.92	1.00	1.3
Adapted (Detering and Etling, 1985)	0.256	1.13	1.90	0.74	1.3

L107 - Do you use the same forest height (20 m) for both the mesoscale and the microscale simulations? or 30 ± 5 *m for WRF like in Wagner et al. (2019)? If 20 m is used for the mesoscale simulations, how can 2-3 points be influenced by the parameterization when the lowest model level is at 10 m and* $\Delta z = 15$ *m?*

For the microscale simulation, a constant forest height of 20 m was used. For WRF, this is impossible; this would imply that only one cell is covering the forest.

L108-110 - The Boussinesq approximation permits gravity waves in the model. How did you treat gravity waves in the CFD model? e.g. did you use any damping layers? did you observe gravity waves during the simulations?

The coupling WRF-OpenFOAM was done for 9 hours: from 09 to 18 UTC. For this time period, the ABL was nearly neutral and no gravity waves are appearing at our microscale simulations.

L110 - What was the time-step used?

A time step of 0.1 second was used.

L110-112 - Additional information that describes the coupling is needed, including details on the following.

1. *What kind of spatial interpolation of WRF data to the microscale boundaries was used?*
2. *Was output written from WRF every 2 min? or did you interpolate in time? what kind of interpolation?*
3. *What did you prescribe at the microscale boundary below the lowest WRF vertical level?*
4. *What surface temperature did you use from WRF? the skin temperature ("TSK" variable)?*
5. *What processing did you do, if any, of the surface temperature before prescribing it in the microscale model?*
6. *Was the same surface temperature prescribed everywhere, or did it vary with surface elevation?*
7. *Did you treat the varying surface temperature and its impacts on the momentum and heat fluxes in the microscale model in any special way? to e.g. avoid surface detachment from the upper air during rapid surface cooling.*

1. WRF data is interpolated linearly to the microscale boundaries.
2. The WRF model has been set to provide boundary conditions, at 1 min intervals, to the CFD-model. A linar interpolation in time was used. We tried output frequencies of 1 s and 10 minutes as well, but came to the conclusion that the 1 minute interval results in similar results compared to 1 s.
3. A zero value for the velocity at the ground was used.
4. Yes, the skin temperature was used.
5. Surface temperature is just interpolated to the finer grid of the microscale model.
6. No, the prescribed temperature at the ground was non-uniform and based on the output from the WRF model.
7. No treatment has been applied. Please also note that the CFD model only runs from 9-18 UTC. No tests have yet been done during the night.

L114 - Please provide more detail about the microscale grid. Is the horizontal grid resolution finer near the ground? what about the vertical grid resolution? at what height is the first level? what is the Δz *near the surface?*

A resolution of 1.6 m near the ground was reached. 10 cells were used for the discretisation of the forest. Far away, near the top of the domain, a horizontal and vertical cell size of 80 m was used.

In Fig. 8. you present UAS measurements compared to WRF-F, why not also present the results for OF-F(WRF-F)?

We have modified Figure 8 and added OF-F data to the plot.
L134-137 - Please specify how long each flight leg took?

The ground-relative speed of the UAS depends on the wind speed. Upwind legs take about 2 minutes, downwind legs about 40 s. This is varies of course with height since the wind speed increases with height.

L140-145 - How did the atmospheric stability vary during the period?

The atmosphere is stable in the morning. Stability decreases in time and at approximately 08:30 UTC, the surface-near atmosphere is neutral. From 08:30 UTC to 14 UTC, it is slightly unstable. After 14 UTC until the front arrives, the atmosphere is stable again, due to advection of cold air near the ground in front of the cold front. The atmosphere is neutral or slightly stable for the rest of the day.
We have added this information to the paragraph.

L168-172 - How did the forest parameterization in WRF influence the temperature and atmospheric stability?

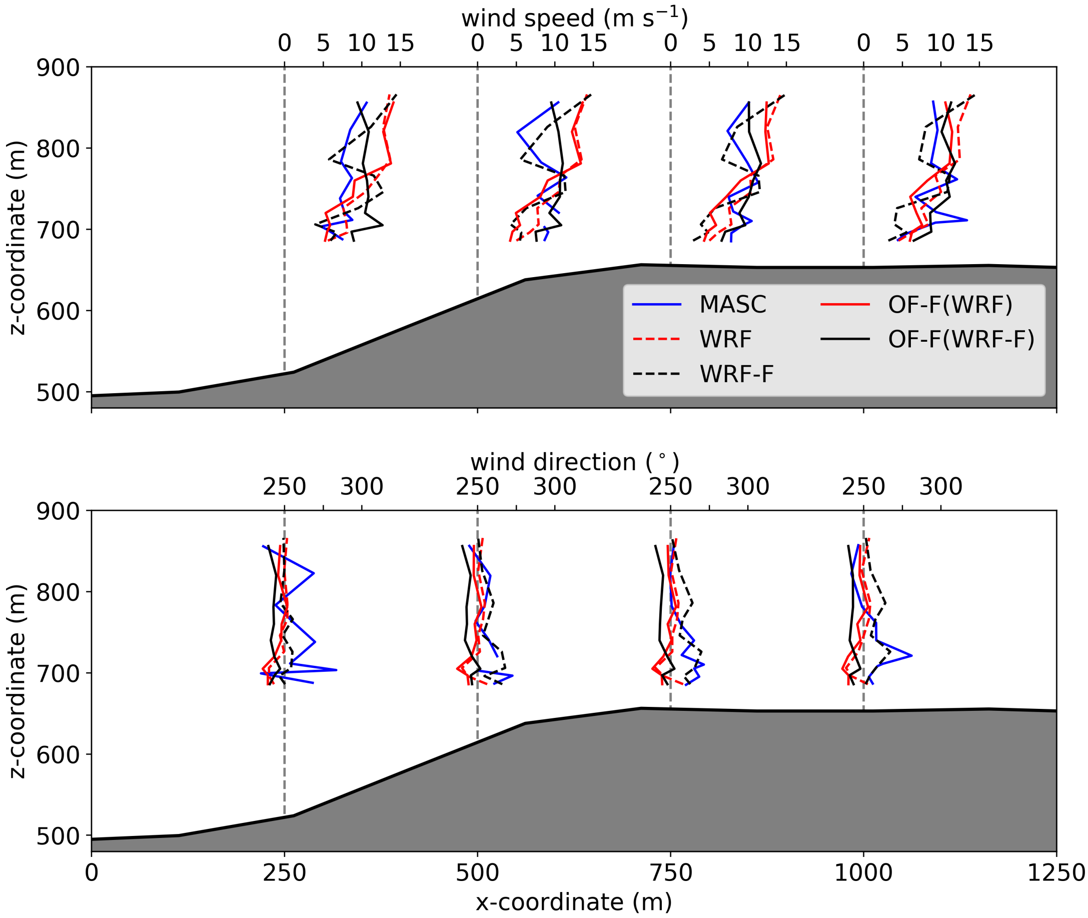
As of now, the forest parametrization has no impact on temperature. This part of the parameterization after Shaw and Schumann has not yet been implemented into WRF.

Fig. 4 - Please state whether the streamline thickness is related to the speed and what the approx. wind speed magnitudes are.

Yes, the streamline thickness varies with the wind speed. The relevant information has been added to the caption.

Fig. 8 - It is difficult to compare the data here. It may be helpful to the reader if you interpolate the WRF data to the UAS positions and plot the wind speed and direction differences between the model and UAS data in a separate plot or a third row in the existing plot.

Reviewer 1 has criticized this plot as well and we have decided to plot profiles of wind speed and wind direction at four locations for WRF-F, OF-F and UAS. This way, one can compare model and observation directly. The new plot:



L270-284 - It would be useful to have error statistics for WRF, WRF-F, OFF(WRF), and OF-F(WRF-F), just like you presented for WRF and WRF-F in section 3.2. Does OF-F(WRF-F) improve the results compared to WRF-F?

Both Reviewer 1 and 3 have criticized the lack of error statistics for OF and OF-F as well. We have added respective statistics for all models listed above.

L286-287 - This sentence is misleading. It is not the vertical resolution alone that makes the WRF model unstable but the combined effect of resolution, time-step and vertical velocity, i.e. the CFL number.

We have added the importance of wind speed. However, steep terrain also introduces numerical errors (Lundquist et al., 2010). We have added this reference as well.

L312 - This is very vague. It would be helpful to provide some quantification of how *well the models reproduce it.*

We agree. The new version of Figure 8 also helps to quantify how well the model reproduced the observations. UAS data is now also used to calculate bias.

In Fig. 8. you present UAS measurements compared to WRF-F, why not also present the results for OF-F(WRF-F)?

Results for OF-F added (see question above).

L275 - filed -> field?

Typo corrected.

L285 - Section 33.1 -> Section 3.3?

This reference should read Section 3.1. Corrected.

References

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