A wind energy benchmark for ABL modelling of a diurnal cycle with a nocturnal low-level jet: GABLS3 revisited

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Abstract. The third GEWEX Atmospheric Boundary Layer Studies (GABLS3) model intercomparison study, around the Cabauw met tower in the Netherlands, is revisited as a benchmark for wind energy atmospheric boundary layer (ABL) models. The case was originally developed by the boundary layer meteorology community, interested in analysing the performance of single-column and large-eddy simulation atmospheric models dealing with a diurnal cycle leading to the development of a nocturnal low-level jet. The case addresses fundamental questions related to the definition of the large-scale forcing, the interaction of the ABL with the surface and the evaluation of model results with observations. The characterization of mesoscale forcing for asynchronous microscale modelling of the ABL is discussed based on momentum budget analysis of WRF simulations. Then a single-column model is used to demonstrate the added value of incorporating different forcing mechanisms in microscale models. The simulations are evaluated in terms of wind energy quantities of interest.

1. Introduction

Wind energy flow models are progressively incorporating more realistic atmospheric physics in order to improve the simulation capacity of wind turbine and wind farm design tools. Wind resource assessment tools, dealing with the microscale flow around and within a wind farm, have been traditionally based on Monin-Obukhov surface-layer theory (MOST), assuming steady-state and neutral atmospheric conditions [1]. At larger scales, the long-term wind climatology is typically determined from a combination of onsite measurements and simulations from mesoscale meteorological models using a horizontal resolution of a few kilometers. The transition from mesoscale to microscale to come up with a unified model-chain is an important subject of research in the wind energy community [2]. In order to make this possible, microscale models have to extend their range to simulate the entire atmospheric boundary layer (ABL) and include relevant physics like Coriolis and other large scale forcing, thermal stratification and appropriate turbulent scaling from the surface layer to the free atmosphere. The dynamics of these forcings determine the interplay between the wind climatology, relevant for the assessment of the wind resource, and the wind conditions relevant for wind turbine siting.

This paper analyzes the third GEWEX Atmospheric Boundary Layer Studies (GABLS3) model intercomparison study, developed by the boundary-layer meteorology community [3], as a relevant case for the benchmarking of wind energy ABL models. Previous GABLS studies used idealized
boundary conditions based on uniform geostrophic wind. GABLS1 simulated a quasi-steady stable boundary layer resulting from 9 hours of uniform surface cooling [4]. GABLS2 simulated a diurnal cycle, still with idealized forcing, by simplifying measurements from the CASES-99 experiment in Kansas [5]. GABLS3 simulated a real diurnal case with a strong nocturnal low-level jet (LLJ) at the Cabauw met tower in the Netherlands [6][7][8].

Based on the GABLS benchmark series, the challenges of stable boundary layers and diurnal cycles are reviewed by Hotlslag et al. [9], notably: the relation between enhanced mixing in operational weather models performance, investigate the role of land-surface heterogeneity in the coupling with the atmosphere, develop LES models with interactive land-surface schemes, create a climatology of boundary-layer parameters (stability classes, boundary-layer depth, and surface fluxes) and develop parameterizations for the very stable boundary layer when turbulence is not the dominant driver. These challenges are ultimately shared by wind energy applications. Therefore, it is relevant to study the GABLS3 case within the wind energy community and evaluate the state-of-the-art of ABL models in terms of rotor-based quantities of interest.

The methodology used by Bosveld et al. [6] to characterize large-scale forcing from mesoscale simulations will be revisited here using simulations from the Weather Research and Forecasting (WRF) model. A single-column ABL model (SCM) will be used to explain how a microscale wind farm model would be driven by this forcing. This model-chain was also used by Bass et al. [10] to design the GABLS3 case and perform a sensitivity analysis of various SCM settings. Following a similar philosophy, we provide some initial results with the SCM to evaluate the impact of different mesoscale forcing terms on wind energy quantities of interest.

2. The GABLS3 Case

The GABLS3 set-up is described in Bosveld et al. [6]. The case analyzes the period from 12:00 UTC 1 July to 12:00 UTC 2 July 2006, at the Cabauw Experimental Site for Atmospheric Research (CESAR), located in the Netherlands (51.971ºN, 4.927ºE), with a distance of 50 km to the North Sea at the WNW direction [11]. The elevation of the site is approximately -0.7 m, surrounded by relatively flat terrain characterized by grassland, fields and some scattered tree lines and villages (Figure 1). The mesoscale roughness length for the sector of interest (60º - 120º) is around 15 cm.

The CESAR measurements are carried out at a 200-m tower, free of obstacles up to a few hundred meters in all directions. The measurements include 10-min averaged vertical profiles of wind speed, wind direction, temperature and humidity at heights 10, 20, 40, 80, 140 and 200 m, as well as surface radiation and energy budgets. Turbulence fluxes are also monitored at four heights: 3, 60, 100 and 180 m. A RASS profiler measures wind speed, wind direction and virtual temperature above 200 m.

Figure 1. Roughness map for a 30x30 km area centred at the Cabauw site. Grassland (green) dominates the surface conditions with local values of the roughness length of around 3 cm. For the 60º - 120º sector of interest, the mesoscale roughness length is around 15 cm, characteristic of scattered rough terrain [12]. This value is also found in the default land-use model of WRF, based on the U.S. Geological Survey (USGS, 2011). Figure reprinted from KNMI's Hydra Project website [13].
The selection criteria for GABLS3 consisted of the following filters applied to a database of 6 years (2001 - 2006): stationary synoptic conditions, clear skies (net longwave cooling > 30 W m\(^{-2}\) at night), no fog, moderate geostrophic winds (5 to 19 m s\(^{-1}\), with less than 3 m s\(^{-1}\) variation at night) and small thermal advective tendencies. Out of the 9 diurnal cycles resulting from this filtering process, the one that seemed more suitable was finally selected: 12:00 UTC 1 July to 12:00 UTC 2 July 2006. This day is actually in between two cycles of similar characteristics, which can lead to interpreting the case as part of a cyclic process.

3. Mesoscale to Microscale Offline Coupled Model

We follow the same modelling approach used by Bass et al. [10] to define a microscale atmospheric boundary layer model driven by realistic mesoscale forcing. This meso-micro methodology allows to couple the models offline, facilitating the generalization of the downscaling methodology to any combination of mesoscale and microscale models working asynchronously.

The Reynolds-averaged Navier Stokes (RANS) equations in Cartesian coordinates \((x,y,z)\) for the horizontal wind components \(U\) and \(V\):

\[
\begin{align*}
\frac{1}{f c} \frac{\partial U}{\partial t} &= - \frac{1}{f c} \left( U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} \right) + V - V_g \frac{1}{f c} \frac{\partial u'w'}{\partial z} \\
\frac{1}{f c} \frac{\partial V}{\partial t} &= - \frac{1}{f c} \left( U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + W \frac{\partial V}{\partial z} \right) - U + U_g \frac{1}{f c} \frac{\partial v'w'}{\partial z}
\end{align*}
\]

where \(f_c\) is the Coriolis parameter, \(W\) is the vertical wind component, \(U_g\) and \(V_g\) are the components of the geostrophic wind and \(u'w'\) and \(v'w'\) are the kinematic horizontal turbulent fluxes for momentum. For convenience, all the components of the RANS equations have been divided by \(f_c\) in order to define the equations as the balance of different wind speeds:

\[
\begin{align*}
U_{\text{tend}} &= U_{\text{adv}} + U_{\text{cor}} + U_{\text{pg}} + U_{\text{pbl}} \\
V_{\text{tend}} &= V_{\text{adv}} + V_{\text{cor}} + V_{\text{pg}} + V_{\text{pbl}}
\end{align*}
\]

where \(U_{\text{tend}}\) and \(V_{\text{tend}}\) are the tendencies of the wind components, \(U_{\text{adv}}\) and \(V_{\text{adv}}\) are the advection wind components, \(U_{\text{cor}} = V\) and \(V_{\text{cor}} = -U\) are the Coriolis wind components, \(U_{\text{pg}} = -V\) and \(V_{\text{pg}} = U\) are the pressure gradient wind components and \(U_{\text{pbl}}\) and \(V_{\text{pbl}}\) are the turbulent diffusion wind components. In a meso-micro offline coupled model, the RANS equations are solved using mesoscale forcing as source terms in the microscale model. In horizontally homogeneous conditions:

\[
\begin{align*}
\frac{1}{f c} \frac{\partial U}{\partial t} &= U_{\text{adv}} + V + U_{\text{pg}} - \frac{1}{f c} \frac{\partial u'w'}{\partial z} \\
\frac{1}{f c} \frac{\partial V}{\partial t} &= V_{\text{adv}} - U + V_{\text{pg}} - \frac{1}{f c} \frac{\partial v'w'}{\partial z}
\end{align*}
\]

where the advection and pressure gradient wind components are derived from mesoscale simulations and vary with the time \(t\) and the height above ground level \(z\).

The diffusion terms in (1) are parameterized in numerical weather prediction models using so-called, planetary-boundary layer (PBL) schemes. These are single-column models that only account for vertical diffusion and relate turbulent fluxes with the gradients of mean flow quantities through the eddy viscosity \(K_m\),

\[
\begin{align*}
u'w' &= K_m \frac{\partial U}{\partial z} \\
v'w' &= K_m \frac{\partial V}{\partial z}
\end{align*}
\]
equivalent to the product of a mixing length and a mixing velocity. A simple first order closure scheme assumes a semi-empirical analytical expression for the turbulent mixing length \( l_m \) and scales the mixing velocity with the strain rate:

\[
K_m = \left( \frac{\partial U}{\partial z} \right)^2 + \left( \frac{\partial V}{\partial z} \right)^2 \right]^{1/2}
\]

(5)

\[
l_m = \frac{\kappa Z}{\phi_m(\zeta) + \lambda}
\]

(6)

where \( \kappa = 0.41 \) is the von Karman constant, \( \lambda = 0.00037 \ S_g0/|f| \) is the maximum mixing length in neutral conditions, proportional to the surface pressure gradient [14]. \( \phi_m \) is an empirical function that depends on the local stability parameter \( \zeta = z/L \) based on the Obukhov length \( L \). Functional relationships from Dyer [15] are commonly used:

\[
\phi_m(\zeta) = \begin{cases} 
(1-5\zeta)^{-1/4} & \zeta < 0 \\
1+5\zeta & \zeta \geq 0 
\end{cases}
\]

(7)

Similarly, the energy equation in the absence of radiative and phase-change heat transfer effects relates the tendency of potential temperature with the mesoscale advective temperature, \( \Theta_{adv} \), and the diffusion fluxes.

\[
\frac{\partial \Theta}{\partial t} = \Theta_{adv} - \frac{\partial w'\theta'}{\partial z} - \frac{\partial}{\partial z} \left( \frac{K_m}{\sigma_t} \frac{\partial \Theta}{\partial z} \right)
\]

(8)

where \( w'\theta' \) is the kinematic heat flux and the Prandtl number \( \sigma_t \) is assumed to be equal to 1. This first-order SCM was previously verified with the GABLS1 and 2 cases in idealized conditions [16][2]. Again, at microscale level, \( \Theta_{adv} \) is a source term derived from a mesoscale model.

In more general microscale conditions, local heterogeneous effects due to elevation changes, roughness changes or obstacles like wind turbines, would be simulated by adding horizontal diffusion and advection terms.

Surface boundary conditions are defined based on MOST, using the simulated surface-layer friction velocity \( u_{0t} \) and heat flux \( w'\theta' \). Hence, the surface potential temperature \( \Theta_0 \) can be related to the 2-m temperature \( \Theta_2 \) obtained from the mesoscale model by:

\[
\Theta_0 = \Theta_2 - \frac{\Theta_0}{\kappa} \left[ \ln \left( \frac{2}{z_{0t}} \right) + \frac{2}{L_0} \right] ; \quad \Theta_0 = -\frac{w'\theta'_{0}}{u_{0t}}
\]

(9)

where the thermal roughness length is \( z_{0t} = z_0/100 \) [6] and \( \psi(J) \) is the integral form of the stability function for heat.

4. Mesoscale Forcing From WRF

Mesoscale forcing is derived from simulations with the Advanced Research Weather Forecasting model (WRF), version 3.8 [17]. Kleczek et al. [18] made a sensitivity study of WRF showing reasonably good results of the vertical wind profile in stable conditions (at midnight). Still, they show a quite significant variability depending on the PBL scheme and grid set-up.

Mesoscale simulations are reproduced here using the same domain set-up used as reference by Kleczek et al., based on three concentric square domains centered at the Cabauw site. The model is driven by 6-hourly ERA Interim reanalysis data from ECMWF (European Centre for Medium-Range Weather Forecasts), which comes at a resolution of approximately 80 km. Three domains, all with
183x183 grid points, are nested at horizontal resolutions of 9, 3 and 1 km. The vertical grid, approximately 13 km high, is based on 46 terrain-following (eta) levels with 24 levels in the first 1000 m, the first level at approximately 13 m, a uniform spacing of 25 m over the first 300 m and then stretched to a uniform resolution of 600 m in the upper part. The U.S. Geological Survey (USGS) land-use surface model, that comes by default with the WRF model, is used together with the unified Noah land-surface model to define the boundary conditions at the surface. Other physical parameterizations used are: the rapid radiative transfer model (RRTM), the Dudhia radiation scheme and the Yonsei University (YSU) first-order PBL scheme. The WRF set-up follows the reference configuration of Kleczek et al. except for the input data (Kleczek et al. uses ECMWF analysis), the horizontal resolution (Kleczek et al. use 27, 9 and 3 km) and the vertical grid (Kleczek et al. uses 34 levels, 15 in the lowest 1000 m). Differences in the grid settings are due to a further study with additional nested domains with large-eddy simulation to study turbulent processes in the ABL. Following Kletzeck et al., we use a spin-up time of 24 hours, i.e. the model is initialized one day before the target evaluation day in order to allow enough time to develop mesoscale processes in equilibrium with the initial and boundary conditions of the reanalysis data.

Figure 2: Time-height contour plots of the longitudinal wind component $U$ and momentum budget terms: $U_{\text{tnd}} = U_{\text{adv}} + U_{\text{cor}} + U_{\text{p}} + U_{\text{pbl}}$.

To derive mesoscale forcing, the momentum budget components (also called tendencies) are directly extracted from WRF as they are computed by the solver [19]. Curvature and horizontal diffusion tendencies have been neglected since they are comparatively small compared to the other terms of the momentum budget. Figure 2 shows contour plots of the longitudinal wind component and the momentum budget terms of equation (2). These quantities have been spatial and temporal averaged in order to filter out microscale fluctuations. The spatial filter is based on 3x3 grid points surrounding the site from the second WRF domain, which defines a typical size of a microscale domain ($L_{\text{avg}} = 9$ km square box). A centered rolling average of $l_{\text{avg}} = 60$ min is also applied in order to remove high frequency fluctuations in the lower part of the boundary layer.

Figure 3 shows the effect of $L_{\text{avg}}$ on the mesoscale forcing, vertically averaged over a 40-200 m layer, which is approximately the span of a large wind turbine of 8 MW (diameter $D = 160$ m, hub height $z_{\text{hub}} = 120$ m). If site interpolated values are used ($L_{\text{sp}} = 0$ km), we can observe large fluctuations in the mesoscale forcing during convective conditions at the beginning of the cycle. Here, the fluctuations are filtered out when a spatial averaging of $L_{\text{avg}} = 9$ km is introduced, which indicates
that the scale of these disturbances are smaller than this size. Extending the spatial averaging to $L_{\text{avg}} = 30 \text{ km}$ does not show significant variations with respect to the 9 km case.

The derived mesoscale forcing is consistent with that obtained by Bosveld et al. [6], based on simulations with the RACMO model at a horizontal resolution of 18 km. In order to facilitate the implementation and interpretation of the mesoscale forcing in the GABLS3 SCMs intercomparison, simplified mesoscale forcing was defined by adjusting piecewise linear approximations of the RACMO tendencies to obtain a reasonable agreement of the wind speed at 200m.

The dynamical origin of the nocturnal low-level jet was originally described by Blackadar [20] as an inertial oscillation that develops in flat terrain due to rapid stabilization of the ABL during the evening transition under relatively dry and cloud-free conditions. The daytime equilibrium of pressure gradient, Coriolis and frictional forces is followed by a sudden decrease of vertical mixing due to radiative cooling during the evening transition. The residual mixed layer in the upper part of the ABL is decoupled from the surface and the Coriolis force induces an oscillation in the wind vector around the geostrophic wind, producing an acceleration of the upper air which is manifested as a low-level jet at relatively low heights. At Cabauw this happens 20% of the nights with jet heights between 140 and 260 m and jet speeds of 6-10 m s$^{-1}$ [21].

5. Results

Figure 4 shows time-height fields of wind velocity $S$, wind direction $WD$ and potential temperature $\Theta$ from the ERA Interim input data, the WRF mesoscale simulation and the SCM simulation using mesoscale forcing as described in sections 3 and 4, all compared to the observations at the Cabauw mast.
Figure 4: Time-height contour plots of wind velocity $S$ (top raw), wind direction $WD$ (middle) and potential temperature $\Theta$ (bottom) for the ERA-Interim input data (first column), WRF simulation (second), SCM simulation based on WRF mesoscale forcing (third) and observations (fourth). A reference rotor span (40 - 200 m) is delimited with the dashed lines.

Figure 5: Time-height contour plots of wind velocity $S$ (top raw), wind direction $WD$ (middle) and potential temperature $\Theta$ (bottom) for the four SCM simulations: with all the forcing terms (first column), without $\Theta_{adv}$ (second), without $\Theta_{adv}$ and $S_{adv}$ (third) and without advection and assuming that the geostrophic wind only varies with time following the surface pressure gradient (fourth).
The higher resolution of the mesoscale model compared to the reanalysis data allows the development of the LLJ to similar intensity and height as in the observations. The SCM shows similar footprint as the mesoscale model even though the simplified physics used. This confirms the consistency of the meso-micro offline coupling methodology. Comparing with observations, we can distinguish a LLJ of longer duration in the simulations than in the modelling, the simulations showing a double peak while observations show a more distinct velocity maxima. The evening and morning transitions are more gradual in the mesoscale model than in the observations.

Wind direction is reasonably well predicted by the reanalysis input data, with a ramp starting at 18:00 UTC 1 July and peaking at 6:00 UTC 2 July. However, the mesoscale model presents a sudden change around midnight, which is apparent in both the pressure gradient and advective forcing in Figure 3, and results in a broader wind direction peak. This peak has larger amplitude and shorter duration in the observations. The potential temperature fields are also reasonably well characterized by the input data during daytime conditions. At night the cooling is underpredicted by the reanalysis data but overpredicted by the mesoscale model.

The modulation of the LLJ evolution by the mesoscale tendencies in the GABLS3 episode is discussed by Bass et al. [10] and Bosveld et al. [6]. They use a SCM to switch on and off different forcing mechanisms to show their relative impact in the evolution of the LLJ. Figure 5 shows time-height plots of different SCM simulations: SCM with all mesoscale tendencies included (first column), SCM without $\Theta_{adv}$ (second), without $\Theta_{adv}$ and $S_{adv}$ (third) and without advection tendencies and assuming that the geostrophic wind only varies with time following the surface pressure gradient (fourth). In the first 100 m above the ground, where turbulence diffusion is important, advection tendencies are relatively small and using surface geostrophic forcing provides a reasonable evolution of the diurnal cycle. Above 100 m advective tendencies become a dominant force in the modulation of the equilibrium between Coriolis and pressure gradient forces. If surface geostrophic forcing is applied at greater heights, the wind speed and direction are way off.

6. Evaluation in terms of Wind Energy Metrics

Revisiting the GABLS3 in wind energy terms means evaluating the performance of the models with application specific quantities of interest. These quantities are evaluated across a reference rotor span of 160 m, between 40 and 200 m, characteristic of a 8 MW large wind turbine. Besides hub-height wind speed $S_{hub}$ and direction $WD_{hub}$, it is relevant to consider the rotor equivalent wind speed $REWS$, the turbulence intensity (not evaluated here), the wind speed shear $\alpha$, and the wind direction shear or veer $\psi$.

The rotor equivalent wind speed is specially suitable to account for wind shear in wind turbine power performance tests [22]. The $REWS$ is the wind speed corresponding to the kinetic energy flux through the swept rotor area, when accounting for the vertical shear:

$$REWS = \left[ \frac{1}{A} \sum_i \left( A_i S_i^3 \cos \beta_i \right) \right]^{1/3}$$

(10)

where $A$ is the rotor area and $A_i$ are the horizontal segments that separate vertical measurement points of horizontal wind speed $S_i$ across the rotor plane. The $REWS$ is here weighted by the cosine of the angle $\beta_i$ of the wind direction $WD_i$ with respect to the hub-height wind direction to account for the effect of wind veer.

Wind shear is defined by fitting a power-law curve across the rotor wind speed points $S_i$:

$$S_i = S_{hub} \left( \frac{z_i}{z_{hub}} \right)^\alpha$$

(11)

Similarly, wind veer is defined as the slope $\psi$ of the linear fit of the wind direction difference:

$$\beta_i = \psi (WD_i - WD_{hub})$$

(12)
In order to evaluate simulations and measurements consistently, these quantities are obtained after resampling, by linear interpolation, velocity and wind direction vertical profiles at 10 points across the rotor area and then computing the REWS and the shear functional fits. While these fitting functions are commonly used in wind energy their suitability in LLJ conditions is questionable. The regression coefficient from the fitting can be used to determine this suitability.

Figure 6 shows time series of these quantities of interest at the rotor plane as well as surface-layer quantities to evaluate the suitability of the surface boundary conditions of the models: friction velocity \( u_{\tau_0} \), heat flux \( w' \theta' \), stability parameter \( \zeta_0 \) and 2-m temperature \( T_2 \). As we did with the mesoscale forcing, a centred rolling average of 60 min is applied to simulations and observations in order to have all the quantities evaluated at a common timeframe.

\( T_2 \) is prescribed to the mesoscale values through equation (9). While the mesoscale model shows good prediction of the heat flux for the whole cycle, the friction velocity is overpredicted in diurnal conditions. The SCM partly mitigates this overprediction but underpredicts the heat flux in diurnal conditions. In nocturnal conditions surface fluxes behave well.

At the rotor area, the peak of the REWS is well predicted by both the mesoscale and the SCM while they both tend to overpredict in the convective and transitional parts of the cycle. The LLJ lives longer in the simulations than in the observations. This is attributed to an incorrect timing of the advection tendencies. Switching off these tendencies in the SCM sifts the LLJ peak of wind speed and direction 3 hours ahead. Wind shear is not predicted well by the models. The reanalysis data predicts surprisingly well the wind shear but, due to the very coarse vertical resolution of the data, this is consider an artefact from the linear interpolation. Wind veer suffers the consequences of the phase error in the wind direction, underpredicting the maximum wind veer.

![Figure 6](image)

**Figure 6:** Time series of surface layer characteristics (left) and rotor-based quantities of interest (right).

These evaluation results can be quantified based on an error metric, for instance, the mean absolute error **MAE**:
where $\chi$ is any of the above mentioned quantities of interested, predicted ($\chi_{\text{pred}}$) or observed ($\chi_{\text{obs}}$), and $N$ is the number of samples evaluated in the time series. Here, the main objective is to demonstrate consistency of the meso-micro methodology for the coupling of asynchronous models. Since the microscale model is not bringing additional complexity to the model-chain, we can consider the mesoscale model as our reference and compute a normalized mean absolute error by:

$$\text{NMAE} = \frac{\text{MAE}_{\text{SCM}}}{\text{MAE}_{\text{WRF+YSU}}}$$

(14)

Table 1 shows this metric applied to the full diurnal cycle. In terms of $\text{REWS}$ or $S_{\text{hub}}$, we notice that adding more realistic mesoscale forcing generally improves consistency with the mesoscale model and performance vs observations. At the surface level, momentum flux is better predicted by the SCM than the mesoscale model, which shows relatively low dependency on the advective forcing. This is not the case for the surface-layer heat flux, which seems more sensitive to the applied tendencies.

**Table 1: Ratio of mean absolute error SCM simulations with respect to the mean absolute error of the mesoscale model.**

| NMAE   | SCM   | SCM, no $\Theta_{\text{adv}}$ | SCM, no $S_{\text{adv}}$ | SCM, $S_{g0}$ |
|--------|-------|-------------------------------|--------------------------|---------------|
| $\text{REWS}$ | 1.36  | 1.30                          | 1.46                     | 1.81          |
| $S_{\text{hub}}$ | 1.25  | 1.19                          | 1.44                     | 1.69          |
| $W_{\text{D hub}}$ | 0.98  | 1.14                          | 0.87                     | 0.83          |
| $\alpha$ (shear) | 1.48  | 1.62                          | 1.92                     | 2.30          |
| $\psi$ (veer)   | 0.94  | 1.11                          | 1.38                     | 1.48          |
| $u^{*}$ | 0.45  | 0.42                          | 0.41                     | 0.52          |
| $w'\theta'$ | 1.20  | 1.70                          | 1.57                     | 1.58          |

SCM: with all the mesoscale tendencies
SCM, no $\Theta_{\text{adv}}$: without potential temperature advective tendencies
SCM, no $S_{\text{adv}}$: without all advective tendencies
SCM, $S_{g0}$: without all advective tendencies and geostrophic wind only varies with time following the surface pressure gradient

In terms of wind energy specific metrics, one could filter the time series and include only samples within the operational range of 4-25 m s$^{-1}$. The errors could also be classified in terms of surface stability conditions ($\zeta_{0}$) in order to segregate model performance (also in terms of wind direction sectors if the terrain is heterogeneous). These makes more sense when analyzing the model performance from a climatological perspective with long-term time series.

7. Discussion and Conclusions

The GABLS3 diurnal cycle case for ABL models has been revisited and evaluated in terms of wind energy specific metrics. The case is analyzed in the context of the design of a mesoscale to microscale model-chain that extracts mesoscale forcing from WRF and uses them asynchronously to drive a microscale SCM. This SCM is a proxy to any computational fluid dynamic (CFD) model used in connection to wind energy design tools. Good consistency is found between the SCM results and the mesoscale simulations which demonstrates the adequacy of the meso-micro methodology in flat terrain conditions.

The SCM simulations are entirely driven by the mesoscale model output data. From a meteorological context, further improvements will come mainly from better quality reanalysis input
data and better physical parameterizations in the mesoscale model. In the wind energy context, where wind profiles are routinely measured as part of wind farm development, the improvement can come from data assimilation at the microscale level.

This and previous GABLS3 studies show the complexity of interpreting mesoscale forcing. While the pressure gradient force is dominated by large scales and will be reasonably well captured in the reanalysis data, advection tendencies depend on the physical parameterizations of the mesoscale model. As discussed in [6] and [10] these are real physical processes but their representation in the dynamics of mesoscale models is not clear. Indeed, Bass et al. [10] presented an alternative case based on the ensemble averaging of nine diurnal cycles that meet the GABLS3 selection criteria. This composite case is entirely based on forcing from a mesoscale model, and facilitates the assessment of the main features of the diurnal cycle by cancelling out the mesoscale disturbances of the individual days. As a result, the composite case shows great improvement versus considering any single day separately. Hence, the assessment of mesoscale to microscale methodologies is more appropriate in a climatological than in a deterministic sense.

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