Wind resource assessment in complex terrain using a one-way coupled meso- and microscale model approach

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Introduction

Mesoscale models have become invaluable for resource assessment in wind energy applications. They serve as a cheap and efficient supplement meteorological masts for site assessment. However mesoscale models have been developed for atmospheric scales of a few kilometers or more and are unable to resolve local effects of orography and surface roughness. In complex terrain these effects can dominate the local wind climate.

Bridging the gap between the mesoscale and the microscale in atmospheric modeling is an important research topic that can allow for more accurate wind resource assessment in complex terrain. Several attempts of coupling meso- and microscale models have been made so far, e.g. Zajaczkiwski et al., 2011; Castro et al., 2014; Rodrigues et al., 2015.

Microscale models based on the Reynolds-Averaged Navier-Stokes (RANS) equations are attractive for resource assessment in complex terrain because of the reduced computational cost – compared to Large Eddy Simulation (LES).

During the last few decades advances have been made to enable Unsteady-RANS microscale models to simulate atmospheric boundary layer (ABL) flow, including the addition of a Coriolis term in the momentum equations and dry-atmosphere temperature equations to model stability effects (e.g. Castro et al., 2003; Koblitz et al., 2015). These advances combined with the development of high resolution orography and landuse maps helps the progress toward improved multiscale modeling.

In this study a model-chain methodology consisting of the Weather Research and Forecasting (WRF) model coupled with an usteady-RANS microscale model (Ellipsys3D) is developed. The emphasis of the study is the coupling process, and how to achieve the best possible initial and boundary conditions for the microscale model. The model-chain will be validated using existing and ongoing measurement campaigns from sites relevant to wind energy with wind climates influenced by both strong local effects from orography and landuse, and by mesoscale effects.

Mesoscale model

The mesoscale model is the Weather Research and Forecasting (WRF) model. The model is run in a grid nesting setup down to a grid spacing of a few kilometers. The results of the finest grid level will serve as input data for the microscale model. The exact configuration of grid spacing, Planetary Boundary Layer (PBL) scheme, land use data source, and the source of boundary and intial conditions will be decided by an initial sensitivity study.

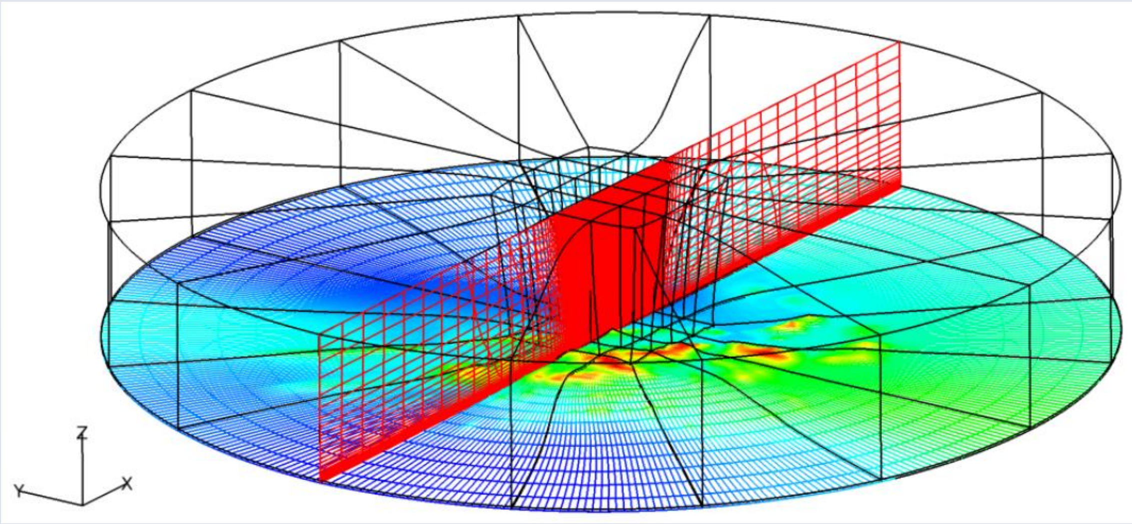

Figure 1. Ellipsys3D grid generated for ABL flow of complex terrain, Koblitz (2013).

Microscale model

The microscale model is the Ellipsys3D model. It is a finite-volume discretization of the incompressible RANS equations. It is formulated in curvilinear coordinates and uses collocated variable arrangement. The SIMPLE algorithm is used for velocity-pressure coupling, and the time stepping is done in a two-step iterative procedure. The momentum equations are solved decoupled using a red/black Gauss-Seidel solver.

The mesh is a structured hexahedral with an outer polar grid and an inner regular grid. Terrain-following coordinates are used, which ensures that steep orography is well resolved. The grid cells stretches towards the boundaries and the top and the solution is smoothed near the boundaries to ensure smooth inflow conditions. See figure 1 for an illustration.

The Unsteady-RANS formulation for ABL flow is based on the work by Sørensen et al. 1995, Koblitz et al. 2015 and others. The formulation includes equations for continuity, momentum and potential temperature.

Stability and Coriolis effects are included by adding the following source terms to the momentum equations:

$$S_v = g(\rho - \rho_0) + \epsilon_i f_c \rho U_i + S_{vol}$$

Where S_v is a source term in the momentum equation, g is the gravitational force, ρ is the density and ρ_0 is the reference density. Density variations are only included in the gravity term (Bousinesqq approximation for buoyancy). $\epsilon_i = (-1,1,0)$, f_c is the Coriolis parameter, U is the mean wind speed and i is the direction index.

The turbulence closure is based on the Boussinesq approximation for turbulence (eddy viscosity assumption) and is solved by a modified $k - \varepsilon$ model that allows it to represent non-neutral conditions (see Sogachev et al. 2012).

Coupling methodology

The initial attempts at a coupling methodology will focus on simulating single days or events where the microscale model is forced by a WRF-derived pressure gradient. The stability effects will be included by forcing the model with surface temperatures from WRF while also including a relaxation toward a reference temperature state consistent with the hydrostatic reference state of WRF. Early attempts using a similar approach with this model, using observations in place of WRF data, was made by Koblitz et al (2013), which showed encouraging results (see figure 2).

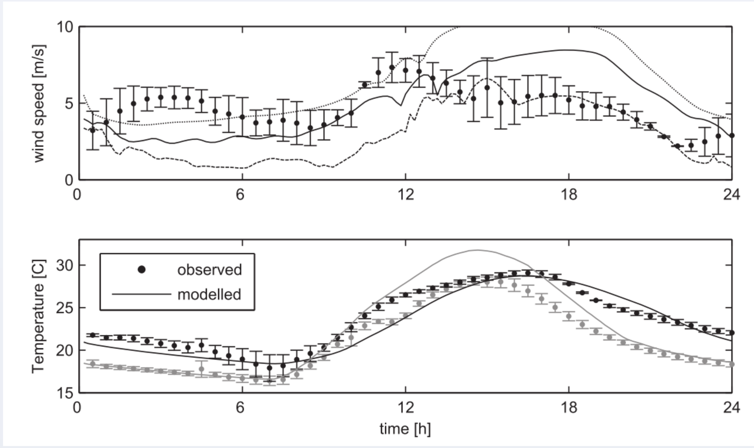

Figure 2: Observed and modeled wind speed and temperature at a single mast location at a complex site near the Benakanahalli hill in Indea, Koblitz (2013).

Eventually attempts at full one-way coupling of all model variables (velocity, temperature, and turbulence) using Dirichlet or Neumann boundary conditions will be made, but additional consideration must be made for that to happen, these include

- how to make initial conditions from WRF that are consistent and does not violate mass conservation?
- How to fill in gaps in microscale models if the domain is outside the WRF defined domain using for example wall functions?
- How to make boundary conditions and smooth transition between meso- and microscale domain?
- Additional considerations like avoiding noise propagation from meso- to microscale model for example by for example gravity waves
- How to ensure consistency in the grids between the meso- and the microscale model, for example via smoothing of the microscale grid heights toward the WRF gríd heights at the boundaries, similar to the method used by Rodrigues et al. (2015), see figure 3.

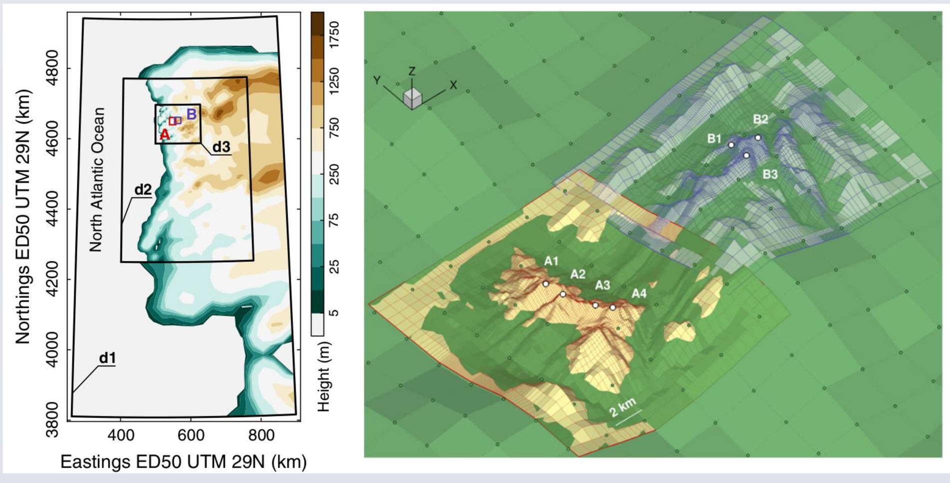

Figure 2: RANS grid smoothed near boundaries to match WRF grid, Rodrigues et al (2015).

Experiment sites

During the ongoing New European Wind Atlas (NEWA) project several measurements campaigns will take place in complex terrain. The measurements gathered from these campaigns will be used for validation of the model-chain approach.

The sites include:

- Perdigao in Portugal is a double hill experiments consisting of two parallel hill running perpendicular to the prevailing wind direction. This experiments will poses a great challenge to the models because of the complexity of the site and the surrounding area.
- Alaiz in Spain is a complex hill and valley experiment with strong mesocale features including channeling effects from the valley combined with effects of the complex terrain.
- Kassel in Germany is a forested hill experiment.
- Østerild in Denmark is a coastal experiment.

References

Castro F.A., Palma J.M.L.M., Lopes A.S. (2003) Simulation of the askervein flow. Part 1: Reynolds-averaged Navier-Stokes equations (k-eps Turbulence model). Boundary layer meteorology 107: 501-530

Castro F.A., Santos C.S., Costa J.C.L. (2014) One-way mesoscale-microscale coupling for the simulation of the atmospheric flows over complex terrain. Wind Energy

Koblitz, T., CFD modeling of non-neutral atmospheric boundary-layerconditions, PhD Thesis, 2013.

Koblitz, T., Bechmann, A., Berg, J., Sogachev, A., Sørensen, N., & Réthoré, P. E. (2014). Atmospheric stability and complex terrain: comparing measurements and CFD. In *Journal of Physics: Conference Series* (Vol. 555, No. 1, p. 012060). IOP Publishing.

Koblitz, T., Bechmann, A., Sogachev, A., Sørensen, N., & Réthoré, P. E. (2015). Computational Fluid Dynamics model of stratified atmospheric boundary-layer flow. *Wind Energy*, *18*(1), 75-89.

Rodrigues C.V., Palma J.M.L.M., Rodrigues A.H., Atmospheric flow over a mountainous region by a one-way coupled approach (2015), Boundary layer meteorology 159:407-437

Sørensen, N. N. (1995). *General purpose flow solver applied to flow over hills*

Sogachev, A., Kelly, M., & Leclerc, M. Y. (2012). Consistent two-equation closure modelling for atmospheric research: buoyancy and vegetation implementations. *Boundary-layer meteorology*, *145*(2), 307-327.

Zajaczkowski, F. J., Haupt, S. E., & Schmehl, K. J. (2011). A preliminary study of assimilating numerical weather prediction data into computational fluid dynamics models for wind prediction. *Journal of Wind Engineering and Industrial Aerodynamics*, *99*(4), 320-329.