Wind Climate Simulation over Complex Terrain and Wind Turbine Energy Output Estimation

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With 9 Figures

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Summary

A statistical-dynamical downscaling procedure is applied to investigate the climatological wind field over a complex terrain area in central Germany. The model domain, 80×87 km, is dominated by flat terrain in the westerly and northerly part and encompasses the Teutoburger Wald and the Wiehengebirge areas with hills up to 330 m a.m.s.l. in the southeasterly region. The downscaling procedure combines a large-scale regionally representative wind statistic and a high-resolution numerical atmospheric mesoscale model. A cluster analysis of a 12-years time series of radiosonde data provides 143 clusters each being a combination of the geostrophic wind components and the vertical temperature gradient. These parameter sets constitute the reference state for highly-resolved steady-state wind field simulations with a non-hydrostatic model. Weighting the resulting wind fields with the corresponding cluster frequency gives climatologically representative frequency distributions of the wind speed and -direction.

A comparison of observations at synoptic stations with simulation results shows a good agreement regarding the mean wind speed but larger differences for low wind speeds and an over-representation of southwesterly wind directions.

By combining the wind speed frequency distribution with the power curve of wind turbines the yearly energy output of 46 wind turbines inside the simulation domain was calculated and compared to the actual production. No bias or systematic trend in the deviation was found. The relative differences for the smallest turbines reach 100 percent with a decreasing tendency to larger units.

1. Introduction

The growing interest in renewable energy resources during the last decade has led to the establishment of a wind energy industry in Europe and resulted in a rapidly increasing number of installed wind turbines. The design, planning and operational aspects of wind energy systems require detailed knowledge of the wind field characteristics. We focus on the planning aspect, i.e. the wind resource estimation which ranges from a regional assessment of the available energy in the wind on a large scale to the calculation of wind speed statistics at particular wind turbine sites. Such studies are often based on long-term wind records from near-surface measurements at synoptic stations. The models available for wind turbine siting exhibit a wide range of complexity ranging from mass-consistent models to non-hydrostatic mesoscale models.

Troen and Petersen (1989) used a two-dimensional, two-layer boundary layer model to develop the European Wind Atlas and Analysis System WASP. This model chain corrects near-surface wind measurements for orographic, roughness and obstacle induced effects and calculates the wind climate at any particular site. Due to the simple turbulence parameterization and the linearization of the equations of motion the application of this model is restricted to flat or gently sloping terrain. A series of mass consistent models has also been developed to compute the wind field over complex terrain (Bhumralkar et al., 1980; Guo et al., 1990;
Sherman, 1978; Endlich et al., 1982). These models assume mass continuity and minimize the difference between the computed and the observed wind fields, with the latter being deduced by extrapolation and interpolation of surface measurements. The resulting wind field, however, depends much on the quality of the observed wind field (Guo et al., 1990; Groß, 1996) and in mountainous terrain in particular it is necessary that the observations already approximately represent the wind characteristics over the area under investigation (Endlich et al., 1982).

Over complex and heterogeneous terrain near-surface measurements are often influenced by local, dynamically or thermally induced circulations, and by close obstacles or vegetation which cannot adequately be corrected for (Wieringa, 1983). In addition, the spatial density of wind observation sites is usually inadequate to deduce high-resolution wind speed maps from measurements alone. To overcome these shortcomings statistical-dynamical downscaling approaches have been applied which combine a statistical or synoptic classification of the climatological regime and a high-resolution numerical model. Wipperman and Groß (1981) reproduced orographically influenced wind roses by downscaling the geostrophic wind speed distribution using a two-dimensional version of a mesoscale model. Segal et al. (1982) studied the wind energy characteristics over central Israel by use of a two-dimensional version of a hydrostatic mesoscale model. Bergström (1996) studied the wind field over the Baltic Sea area with a hydrostatic model and classified the overall climatology into four seasons (January, April, July and October), three wind speed classes (5, 10 and 15 m/s), eight wind direction sectors and three mean surface temperatures over land. The climatological wind field was derived by weighting 288 runs.

In a similar study Sandström (1997) ignored the variation in surface temperature and concluded that 96 model runs did cover the most important conditions that determine the boundary layer wind field. The difference between modeled and observed mean wind speeds at the location of two lighthouses ranged from 0.1 to 0.5 m/s. Comparisons with ship measurements showed differences of less than 0.5 m/s over the main part of the Baltic Sea. Heimann (1986) calculated the annual frequency distribution of surface winds over the Main-Taunus region with a three-layer hydrostatic model. Cycles of typical days for each of twelve wind direction sectors were simulated using an annual mean value for the geostrophic wind speed. This approach was extended by Frey-Buness et al. (1995) to the regionalization of climate change scenarios by classifying large-scale synoptic situations derived from multi-year episodes of global climate simulations. In order to include a classification criterion with emphasis on precipitation they selected a winter and a summer situation for twelve wind direction classes, respectively. They also distinguished further ‘fair weather’ and ‘poor weather’ situations which were classified with respect to cloudiness. In a different method to all other complex-terrain studies which use upper air data, Brücher et al. (1994) calculated the frequency of occurrence of the basic state classes from near surface observations by an inversion technique. Choosing 60 classes for the basic state defined by wind speed, direction and stratification they simulated the spatial distribution of orographically influenced wind roses.

The selection of appropriate parameters and their classification to define the climatological regime is as essential for any dynamic downscaling procedure as the choice of the numerical model and the mode of simulations. While all the previously mentioned studies used a fixed classification scheme here we apply a cluster analysis to group the reference states which are defined by geostrophic wind speed components and static stability. The advantage of this methodology is outlined in section 2. Use of a non-hydrostatic mesoscale model provides a spatial resolution high enough to compare model results with point observations even over complex terrain. The model and the simulation area are described in section 3. Section 4 comprises the climatological wind field and its comparison with observations. The relationship of this study to wind energy applications is then stressed in section 5.