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Climatology of North Sea wind energy derived from a model hindcast for 1958–2012

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ABSTRACT

Model-based wind speed data derived from the coastDat2 data set for the North Sea were used to assess wind power potential considering both spatial and temporal variability. The atmospheric part of coastDat2 was simulated with the regional climate model COSMO-CLM 4.8. The quality of the used wind speed data is analysed by comparison with buoy and QuikSCAT data. To determine where an offshore power plant can be cost-effectively developed, the distribution of the possible production dependencies on the offshore distance is one of the more important factors. A synthetic power function was used to convert the model-derived wind speeds at a height of 100 m to wind power. The data were analyzed for the period of 1958–2012, and the results obtained for the decadal and spatial variability were mapped. The site related summaries are discussed.

The inter-annual to decadal variability can reach up to 5% from the multi-decadal mean and therefore plays an important role in wind energy; wind power estimates based on short observational time series, particularly from the late 1990s, may exhibit high biases. The up-scaling from wind speeds at a height of 10 m using conventional power laws may result in similar biases. On inter-annual to decadal time scales, synergies are not expected from the different arrays in the North Sea, i.e., a decrease in the power output of an array may not be balanced by another.

1. Introduction

Ambitious targets by the European Union attempt to increase the share of renewable energy sources in the total production of electric power (European Commission, 2015). Offshore wind energy clearly plays an important role in these plans. Comprehensive assessments of offshore wind resources are needed to assess the economic feasibility of planned wind farms. The European Environment Agency (EEA) published an assessment of Europe's onshore and offshore wind energy potential and its environmental and economic constraints in 2009 (EEA, 2009). The assessment was based on so-called reanalysed wind fields particularly the ERA-40 reanalysis which is produced by the European Centre for Medium-range Weather Forecast (Uppala et al., 2005). Reanalyses are obtained from simulations that use present day state-of-the-art numerical models that project the state of the atmosphere based on a finite set of imperfect, irregularly distributed observations on a regular grid (Glickman, 2000). Typically, such simulations are limited to periods from 1950 onwards and are global in extent; the typical spatial grid sizes are on the order of 50 to a few hundred kilometres (e.g., Kalnay et al., 1996), although some regional simulations with higher spatial resolution exist (e.g. Feser et al., 2001; Mesinger et al., 2006). The EEA assessed the wind power potential using monthly, daily, and 6-hourly wind fields from the global ERA-40 reanalysis. Near-surface marine wind fields at a height of 10 m covering the period 2000–2005 were used. These data were converted to wind speeds at a hub height of 120 m; annual averages were subsequently derived. The variations in the wind speed over a year and the corresponding full load hours (FLH) were subsequently determined from a Weibull distribution, a regression and the power-velocity curves from four different wind turbines. In their report, the EEA (2009, p.16) defined the FLH as the number of hours per year that a wind turbine operates at rated power; in the literature, this is more commonly referred to as equivalent FLH (EFLH). A theoretical potential of more than 3000 EFLH was estimated for most offshore areas in the North Sea. Therefore, this area is one of the most interesting regions for offshore wind development in Europe. The EEA (2009) further emphasized that the annual variability in such estimates may be high. By providing individual estimates for 2003 and 2004, the EEA found variations on the

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order of approximately 10% due to the large wind speed differences between the two years. Given the high costs for the development of offshore wind farms, the inter-annual variability in the wind speed plays an important role in determining of the farms' economic efficiency and power output, because the wind power density (WPD, in W/m^2) scales with the cube of the wind speed (e.g. Pryor et al., 2012 and Frandsen and Petersen, 1993). Pryor and references therein also noted, in agreement with the estimates of the EEA (2009), that the inter-annual variability in the WPD is on the order of 10–15%. However, Pryor et al. (2012) further emphasized that the decadal variability may be substantially higher (approximately 30%).

The decadal variability is typically ignored when wind power potential is assessed. To our knowledge, a comprehensive assessment of long-term changes and decadal variability in wind energy potential for the North Sea is lacking. Most studies have been based on a limited number of years of data from either observations or global reanalyses. Some indications may be derived from the existing literature that has addressed corresponding changes in the storm climatology. For example, Schmidt and von Storch (1993) found pronounced decadal variability but no significant long-term trend in the German Bight and the North Sea by analysing geostrophic wind speeds back to 1876. These findings were later supported by corresponding analyses for larger areas within the European Atlantic sector (e.g., Alexandersson et al., 1998, 2000; Matulla et al., 2008). All studies have reported that storm activity was high at the end of the 19th century, it subsequently declined to a minimum around 1960 and then it increased to a maximum in the mid-1990s. The storm activity has been decreasing again since the mid-1990s. Similar findings have been obtained from the analysis of extreme sea levels using tide-gauges as a proxy for storminess (e.g., von Storch and Reichardt, 1997; Dangendorf et al., 2013), from the multi-decadal simulations of the regional atmosphere (e.g., Weisse et al., 2005), or from tide-surges (e.g., Langenberg et al., 1999; Weisse and Plü, 2006), and wave models driven by reanalysis data of wind fields (e.g., Weisse and Günther, 2007). Existing studies concerning decadal variability and long-term changes for, e.g., Korea Do-Yong et al. (2013) show in comparison to our findings that the decadal variability is not transferable to other regions on earth.

Although it appears plausible that wind power potential may have fluctuated in a similar manner, such assessments are not available to our knowledge. Therefore, the purpose of the present study is to provide such an assessment based on a novel regional atmospheric reanalysis for the North Sea. We propose that this regional reanalysis allows for a comprehensive assessment of both the climatology of the wind power potential and its decadal variability by providing hourly wind speed data for the period of 1958–2012 at a grid spacing of approximately 24 × 24 km. In particular, we aim to provide

- a comprehensive assessment of the wind power potential and variability in the North Sea based on hourly simulated wind speed data at a height of 100 m for the period of 1958–2012 and
- an assessment of the thermal effects on estimates of the wind power potential.

The latter objective is achieved by comparing conventional estimates derived from up-scaled model wind speeds from 10 m to hub height using conventional power laws (based on the assumption of a neutrally stable boundary layer) with estimates derived directly from the model output at hub height, in which thermal effects are included. Most of the assessment is made for theoretical values of the wind power potential. Moreover, the constrained potential, including concurrent uses of shipping, fishing and military practices, is also considered by using the present plans for developing offshore wind; only major planned arrays and their planned capacity are considered. Other constraints, such as those caused by array downtime due to maintenance, are not considered.

The paper is structured as follows. In Section 2, we briefly describe the regional atmospheric model used to simulate (hindcast) the period of 1958–2012, the simulation configuration and validation of the results against existing observations. Moreover, in Section 2, we briefly describe the synthetic power-velocity curve used to convert the hourly model output wind speeds into wind energy. In Section 3, our results are presented. In particular, we discuss the wind speed and wind energy climatology, along with their variability and long-term changes. The latter is presented in the form of two-dimensional maps and analyses of individual major arrays. The constraint for the entire North Sea is considered by integrating the results for the largest arrays and weighting them by the planned installed capacity. Finally, in Section 4, our results are summarized and discussed.

2. Data and methods

2.1. Description and model set-up of the COSMO-CLM model

We used a non-hydrostatic regional climate model for our multi-decadal hindcast. The model originates from the former Local Model (LM) of the Deutscher Wetterdienst (German Weather Service) that is now used and further developed by several other European weather services organized in the COnsortium for Small-scale MOdelling (COSMO model; http://www.cosmo-model.org/). In our case, we used the so-called climate mode extension, which was developed by the CLM community (http://www.clm-community.eu) to enable the COSMO model to run for long-term simulations of up to several centuries (COSMO-CLM or CCLM).

In particular we used the COSMO-CLM version 4.8 (Rockel et al., 2008; Steppeler et al., 2003) for a domain covering Europe and adjacent seas, including most of the northern North Atlantic, at a spatial grid size of 0.22 degrees on rotated coordinates. The latter corresponds to a horizontal grid spacing of approximately 24 km. Forty vertical levels were used up to a height of 27 km, with a higher resolution at the lower boundary. The upper boundaries of the lowest layers over water are in heights of 20, 49, 89, 143 and 214 m yielding to wind speed data in the heights of 10, 34.5, 69, 116 and 178.5 m respectively. The surface height and orographic roughness length were obtained from the Distributed Active Archive Center's gtopo30 data set (USGS, 2004), while the land–sea fraction, vegetation parameters, leaf area, root depth and lake fraction were derived from the Global Ecosystems V2.0 data set. The soil type was obtained from the Food and Agriculture Organization of the United Nations (FAO). The climatological deep soil temperature was provided by the CRU (Climate Research Unit at the University of East Anglia). Land surface processes, such as heat and water transport in the soil and the freezing and melting of soil water and ice, were parameterised using the TERRA-ML scheme (Schrodin and Heise, 2001; Doms et al., 2011); cumulus convection was parameterised using the Tiedtke scheme (Tiedtke, 1989). Clouds were determined by the prognostic variables cloud water and cloud ice. Vertical turbulent fluxes are calculated with a turbulence scheme (Raschendorfer, 2001; Mironov and Raschendorfer, 2001) based on a closure scheme on level 2.5 as described by Mellor and Yamada (1982). The horizontal turbulent fluxes are neglected as the boundary layer hypothesis of horizontal homogeneity is applied. The flux-gradient relationship is applied to estimate turbulent fluxes from resolved quantities. Calculations of turbulent diffusion coefficients are based on mixing length (Blackadar, 1962), the Turbulent Kinetic Energy (TKE) and stability