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Original article

Modeling and sensitivity of the seasonal ocean winds to local effects at west and south coasts of South Africa

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ABSTRACT

Accurate wind speed and power forecasts of wind farm production are essential in planning of economic load dispatch and for a reliable transmission system operation. In this paper, the sensitivity of mesoscale simulated winds to the local effects in the near coasts of South Africa is examined. Three ocean wind field simulations performed in the advanced weather research and forecasting, WRF, model at a 3 km grid spatial resolution were assessed by accounting for how the mesoscale model description of topography impacts the surface wind speed and direction. Based on the Monin Obukhov similarity theory (MOST) with satellite wind retrieval from the remote sensing systems, the model performance in seasonal wind simulations at 50 m height asl for the period of 5 years (January 2007 to December 2011) is evaluated. The WRF modeled wind after postprocessing method compared well with the satellite observed wind speed across the surface fields with correlation coefficient and monthly mean error values ranging from 0.633 to 0.931; and −0.0029 to 0.5070 m/s, respectively, in all the seasons. Results also revealed that the west coast has higher wind speed and power potential in summer and spring months while the south coast in the winter months recorded the highest potential. The findings in these studied regions are essential for bias correction of the WRF modeling over non-homogenous ocean surface wind field.

Introduction

Several studies have stressed the importance of considering the variations in the seasonal/interannual wind climates and diurnal cycles for wind power application at a proposed field [1–4]. An accurate estimate of the local wind speed profiles and the knowledge of the seasonal wind variations are both advantageous for: planning of the wind farms operation, scheduling of electricity generation units for optimal wind power share [5]; unit commitment decisions, developing day ahead electricity markets [6–7]; the operation of reliable transmission system and capacity expansion [8,9], among others. These have implications on the reliability of electricity network where timing of the power generation from the wind farms operation is required.

Within the planetary boundary layer (PBL), the performance of a wind turbine generator (WTG) is often influenced by the stability of the atmosphere, just in the same way the boundary layer wind speed and direction are both influenced by the local flow perturbations due to topography at a given wind site. The influence of the wind shear on power generation of the wind turbine has been examined in literature [10–13]. Wagner et al. [14] examined the impacts of wind shear on the power extraction over a swept area of a rotor-disk and found high positive wind shear to be responsible for power declination upto 26%. In another wind study, the cause of wake generated within a wind farm was investigated and found to be influenced by the prevailing stability conditions [15]. From these literature [10–15], the variations in the wind speeds across the rotor-disk and the power generation of a selected wind turbine may be attributed to a number of factors such as the atmospheric stability as function of height and time. To assess the economic viability of the offshore wind power field for wind farm development, it is important to examine the impacts of the stability conditions and local topography on the boundary layer wind speed and direction as well as the impact of wind shear on the rotor-disk of a selected wind turbine [16].

The long-term wind profiles and the wind climates over homogenous, and complex terrains at various locations have been assessed from historical wind climatology retrieved from: in-situ measurements from the synoptic stations [17–19]; the reanalysis winds such as ERA-Interim and CFSR [20–22], ground-based or remote-sensing systems (LIDAR, QuikSCAT, SODAR, WindSat, Sea-Winds, among others) [23–25], and the mesoscale simulations of the WRF model from a combination of ERA-Interim data with in-situ measurements or/and satellite wind observations [26–28]. Over the land and sea above the surface where: the capital and

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maintenance costs of deploying synoptic stations at vertical levels upto 200–300 m are higher, there are insufficient networks of high quality in-situ measurements and the local wind climates over the surface at offshore region are inaccessible, information regarding an offshore wind field potential is often assessed from the satellite wind retrieval from remote sensing instrument and the mesoscale models at different vertical levels. These are reliable tools which have been utilized at various locations for regional wind atlas development. Others include in: vertical wind speed estimation and annual wind power production of a site; long-term stability conditions analysis [29]; studying the wind speed and direction at geostrophic heights [30]; reproduction of surface wind statistics over uniform and complex terrains [31]; extreme wind calculation [32–34], among others. Furthermore, where the long-term geospatial information regarding the wind climate variability over large domains are needed, the mesoscale model such as the Weather Research and Forecasting (WRF) has shown to be more reliable [28,35]. For the accuracy of the mesoscale wind simulations as function of the heights and locations [36], factors such as the domain size, the spatial grid spacing of the WRF model, the initial and boundary conditions, the impact of in-situ measurements in the WRF model simulation, among others, have all played significant roles.

Despite great benefits of the mesoscale modeling in wind energy utilization, the modeled wind speed and direction from the WRF simulations at proximity to the coastline cannot be directly applied (due to some local effects in the WRF model wind speeds) but can be optimized with the postprocessing methodology for an accurate representation of the wind speed profiles at potential turbine sites. For satellite observed winds, the temporal resolution, ocean coverage and the height retrieval are the main limitations, compared to mesoscale modeling and in situ measurements.

The mesoscale simulated winds are known to have large deviations without postprocessing [37,38]. Because the mesoscale grid resolution is too large to explicitly resolve the processes responsible for smaller scale and subgrid-scale turbulent fluxes [36], the missing variance can be resolved (either partly/fully) with the post-processing procedure by removing the topographic effects (surface roughness changes and orography) influencing the WRF modeled wind speed and direction at a given height [39]. An accurate configuration and parameterization of the mesoscale model has led to wide application of the WRF in projection of the onshore and offshore wind energy resource at different locations, thus, an alternative tool for assessing the offshore wind climates at the coasts of South Africa.

In this study, the sensitivity of the seasonal simulated wind speed and direction in the WRF model to local effects at three offshore wind fields in the west and south coasts of South Africa is examined. For refinement of the local wind climates in the near coasts based on the knowledge of surface roughness length variations and stability conditions, the results of the statistical downscaled model wind speed and direction at 50 m height are presented. The time series of the offshore wind simulations recorded in 6-hourly resolution for the period of January 2007 to December 2011 are obtained from the WRF model at 43 and 72 heights. The ability of the model in wind simulations at 50 m height for the studied wind fields is determined by validating the satellite observed wind speed and power density from the remote sensing systems against the simulated wind speed and power density, with and without postprocessing method. With an improved WRF modeled winds at a 3 km spatial resolution, the offshore energy resource in wind farm planning can be accurately assessed upto 200–300 m above the surface. The studied findings are valuable in offshore wind climate assessment at the coastal regions of South Africa and other locations where network of in-situ measurements are unavailable and very expensive to deploy. Following this introduction, the rest of the paper is structured as follows: Section 2 presents the studied region, WRF model setup for WRF simulations, satellite wind retrieval and the mathematical model for computation of the seasonal ocean wind speed and direction. The downscaling methodology with the WRF simulated winds and the model performance (before and after postprocessing) against the satellite observations are outlined in Section 3 ‘Methodology’. Results of the studied findings at the west and south coasts with discussion are presented in Section 4 ‘Results and discussion’ while the conclusions for this study are provided in Section 5 ‘Conclusion’.

Wind data collection and processing

The model setup of the advanced weather research and forecasting (WRF) version 3.5 utilized for the mesoscale simulations over the land and coast of South Africa at 41 atmospheric vertical levels was produced on three nested domains at spatial grid resolutions of: 27 km (D1, large-domain); 9 km (D2, first nested-domain) and 3 km (D3, innermost nested-domain). The lowest 6 model levels produced by the WRF model are within 190 m height above the surface (14, 43, 72, 100, 129 and 190 m) with the top level at 50 hPa (41 level). For the numerical wind atlas development, the WRF wind was simulated on horizontal grids with 90×70 points in D1; 184×133 points in D2 and 426×310 grid points in D3 domain.

For the mesoscale wind simulations in the period of January 2007 to December 2011 across South Africa, the initial state of the atmosphere and the boundary conditions for WRF configuration were obtained from the global ERA-Interim reanalysis [40]. ECMWF Interim reanalysis are freely available from the period of 1979 to the present at 6 hourly resolution and spatial grid resolution of 0.75×0.75. Detailed description of the physical configuration and parameterization of the WRF model for the numerical wind simulations over South Africa have been presented and discussed in WASA project report [41].

The geographical description and the locations of the studied wind fields (F1, F2 and F3) at the coasts of South Africa are presented in Fig. 1. The offshore wind fields (F2 and F3) are located in the west coast with F1 situated in south coast region of the country. Within each wind field can be found a total of 63 grid points at 3 km grid resolution. The prevailing ocean wind in the study regions is influenced by the presence of cold Benguela current of the South Atlantic Ocean and the warm Agulhas current of the Indian Ocean which mainly produce the offshore wind climates in the west and south coasts of South Africa.

Unlikely the offshore hourly wind simulations produced in 33 vertical levels (1000–1 hPa) at 3 km spatial resolution for the central coast of Chile [42], the WRF model hourly simulations (41 levels) at the west and south coasts of South Africa were produced at 3 km spatial resolution in the second and third vertical levels (43 and 72 m heights) above the surface. The hourly simulations from the WRF model consist of the: wind vectors (u and v; m/s) at 10, 14, 43, 72, 100, 129 and 190 m height above the surface; time varying roughness length (m), friction velocity (m/s); latent heat flux at the surface (W/m^2); sea surface temperature (K); temperature at 2 m height (K); surface pressure (Pa); inverse of Monin Obukhov Length (m^{-1}), among others. The ocean wind vectors at 43 and 72 m asl from a 3-km model (D3, innermost nested-domain), representing 6-hourly instantaneous values for the period of January 2007 to December 2011 are obtained.

To assess the model's precision in simulating the ocean wind speed and direction over the studied fields, the time series of the calculated satellite wind speed and direction from the MOST at