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Wind modelling, validation and sensitivity study using Weather Research and Forecasting model in complex terrain

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ABSTRACT

A physically-based wind model is applied to determine wind speed and direction and to conduct a model sensitivity analysis. The focus is the East African site of the Lake Turkana Wind Farm, characterized by complex terrain and high diurnal variability that creates a nocturnal jet of typically 15 m/s. Observations from three tall meteorological masts are compared with Weather Research and Forecast (WRF) model outputs. WRF is configured with four domains nested down to 900 m spatial resolution. The model is tested with initialization fields from two different sources, optimised using different grid configurations and parameterization schemes. Comparing model and data from 3 tall masts A, B and C yields that the primary source of error in WRF model simulation in a complex terrain is due to incorrect specification of boundary fields used to initialize the model. RMSEs achieved in this research are ≤2 m/s representing good model performance (Emery et al., 2001).

Software/Data availability

The Weather Research and Forecasting (WRF) (Skamarock et al., 2008) model development started in 1990s and was a collaboration among National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration [represented by the National Center for Environmental Prediction (NCEP) and the (then) Forecast Systems Laboratory (FSL)], the Air Force Weather Agency (AFWA), the Naval Research Laboratory (NRL), the University of Oklahoma (OU), and the Federal Aviation Administration (FAA). The Meso and Microscale Meteorology division of NCAR is currently maintaining and supporting a subset of the overall WRF code.

The WRF users' page[1] is the central source for information, documentation, support and for the code itself. The software is continuously updated through inputs from various community members. There are no particular telephone, fax, or email addresses available but all questions regarding running and using the software can be emailed to wrfhelp (wrfhelp@ucar.edu). Also the WRF user forum is another venue for users to exchange experiences and help. The user forum is maintained by Matt Alonso at meso.com.

WRF is built in FORTRAN 90 and typical memory requirements for WRF are explained in Shainer et al. (2009) while the typical size of the software is 549 MB on a typical desktop. The model equations are not presented in the paper as they are available from the literature (Skamarock et al., 2008).

1. Introduction

The aim of this study is to apply an optimised configuration of the Weather Research Forecasting (WRF) model to a unique wind farm site in East Africa. The intention is to achieve an accurate simulation and prediction of near-surface winds. Since current atmospheric models present a broad spectrum of configuration options and parameters, selecting the best configuration among these options has its own inherent challenges (Nossent et al., 2011). The importance of the sensitivity of a model to changes in its configuration settings has been emphasized by Hirabayashi et al. (2011). Various model configurations and parameter settings along with different initialization fields have been evaluated in this study.

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[1] http://www2.mmm.ucar.edu/wrf/users/.

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Modelling results are presented for a final optimised configuration.

Carpenter et al. (2013) showed that WRF can be used for short-term forecasting, assimilating *in situ* and LIDAR observations and selecting the appropriate planetary boundary layer (PBL) scheme for a complex terrain. Cheng et al. (2009) examined sensitivity of fronts and cyclones over complex terrain to model physics in the WRF model at very high resolution. Kim et al. (2011) examined WRF sensitivity over complex terrain using two microphysics schemes and analysis nudging. Carvalho et al. (2012) suggested that error minimization in the wind simulation can be achieved by testing and choosing a suitable numerical and physical configuration for the region of interest. Carvalho et al. (2012) further reported that increasing horizontal and vertical grid resolution may lead to better reproduction of fine-scale meteorological processes but this may not necessarily be true due to uncertainties in the performance of the various physical parameterizations and their responses to grid resolution.

In this research, WRF version 3.4.1 has been used to conduct the simulations. It has the capability not only to run global simulations at spatial resolution of several kilometers but it may also be nested down to a few hundred meters. Skamarock et al. (2008) describes numerous physical parameterization schemes available for micro-physics, radiation (long wave and short wave), and clouds as well as boundary layer schemes including for: the surface layer (SL), the PBL, and the land surface model (LSM). Such schemes interact non-linearly with each other and with the dynamical core of the model; and therefore it becomes challenging to optimise the model due to these complex relationships. Further, certain assumptions used in these schemes may result in an erroneous analysis (Awan et al., 2011). Besides physical parameterization schemes and unconfined empirical parameters within these schemes, there are other sources of errors in the numerical model. Such model errors include the dependence on different numerical solvers, domain sizes, site location, initial and boundary conditions, grid resolution (both horizontally and vertically), and terrain and vegetation characteristics (Awan et al., 2011). Topography will also affect the meteorology by influencing the surface heat flux and the radiation reflected from the ground. In addition, the separation effects due to topographical features influence the wind speed and direction significantly.

Mesoscale models have been used in various applications, particularly when they are combined with statistical tools or micro-scale models in short-term forecasting for estimating wind farm energy production (Parks et al., 2011). They are valuable for power grid planning and for assessing potential sites for future wind farms. WRF has been used extensively in wind energy applications (Carvalho et al., 2012). Its efficiency could be improved further in short-term forecasting by optimizing its performance through avoiding its cold start (spin up period of the model-24 h in this study) and wind speed and direction sensitivity analysis (WSDSA). In conclusion, we demonstrate that, with *in situ* observations, appropriate optimisation for a specific site can lead to significant improvements in wind prediction.

The work presented in this paper uses WSDSA to obtain the best possible WRF model configuration for an East African wind farm site. The paper emphasizes on the importance of initialization fields used by WRF and, as such, also considers the analysis on a site in Western Australia (WA). The meteorology of these sites are discussed in detail in section 2. Section 3 provides information about methodologies followed to perform various comparisons. The initialization fields and domain configuration used for these sites are discussed in section 3.1 and 3.2 respectively. Section 3.4 discusses the methodology for establishing WRF performance in a well-defined meteorological environment in WA. The later part of the section 3 considers experiments on East African site and discusses the physical and parametrization schemes, terrain complexity and influence of the initialization fields. The criteria for validating the WRF model with observations is explained in section 3.8. Section 4 shows the results of experiments in both WA and East Africa and conclusions based on these experiments are discussed in section 5.

2. Selected terrain characteristics and wind masts

The East African site is a slightly hilly terrain, with elevations ranging between 700 m and 900 m above sea level (Fig. 1). It is a largely uninhabited, rocky arid desert area. The area has unique physical conditions in which daily temperature fluctuations support the generation of strong but very predictable winds. The climate is very hot and dry and the mean monthly temperatures are in the range of 27–29 °C. The mean minima lie around 13–20 °C and the mean maxima are 26–35 °C. The coolest months are July and August while February, March and October are the hottest. The average wind speed is 11 m/s from a consistent SE sector.

The winds in this region are generated by the low level jet indicated in studies of Indeje (2000) and Nicholson (2015). This jet is known as the "Turkana easterly low-level jet" which is created by the much bigger East African low-level jet and it blows throughout the year from the South East through the valley between the East African and the Ethiopian Highlands extending from the Indian Ocean to the deserts in Sudan (Kinuthia and Asnani, 1982). It was further observed that, throughout the year, the NE and SE monsoon near the equator branches off from the Indian Ocean, enters the Turkana channel and intensifies (Fig. 1). Indeje et al. (2001) concluded that the origin of the jet is orographic channelling but that thermal and frictional forcing also plays a role in its formation and maintenance.

The seasonal cycle of this region is shown by the monthly average wind vectors at 850 hPa (mbar) in Fig. 2. Clearly evident is the seasonal shift between prevailing southerly flow, coupled with the southwest monsoon of the boreal summer, and the prevailing easterly flow, associated with the northeast monsoon of the boreal winter. The flow pattern is rather persistent except April and October (Nicholson, 2015).

The existence of low level jet and its nocturnal nature are shown by the vertical profiles in Fig. 3. There is strong vertical shear above and below the maximum, in all months and low level jet is distinct from 1800 UTC to 0600 UTC in the monthly average. The jet core is usually between 825 and 900 hPa (mbar) at 0000 UTC and 0600 UTC as shown by these averages. The strongest shear is above the jet from May through September (the southwest monsoon season), but below the jet from November through May (the northeast monsoon season). In each month, the 1200 UTC average speeds are much lower than at the other times and there is only a broad wind maximum rather than a sharp peak in the flow. Also, the shear above and below is very weak. Thus, the Turkana Jet is clearly a nocturnal feature (Nicholson, 2015).

The site is instrumented with three elevated wind measuring stations each of which is used for model validation. These masts average wind speed and direction data with 10 min resolution. Each of these stations is located at approximately 40 m above ground level (a.g.l). The meteorological data was collected from these sites for the month of July 2009. Model temporal resolution is also averaged to 10 min to permit a direct comparison with the *in situ* measurements. The nearest grid point approach is used to compare measured data at the sites with that of the model simulations. The stations are designated as stations A, B and C and they are located within the simulation area, inside domain 4 within approximately 20 km of each other. As this is site is still being developed there are no turbines yet in the vicinity of the site therefore these stations are