Numerical Modelling for Optimization of Wind Farm Turbine Performance

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Summary

A novel technique for the optimization of wind farm turbine performance has been developed. Primarily a mesoscale model was benchmarked at a site with abundant observational data to confirm that data sparseness and quality of assimilated analysis can affect the accuracy of the model's performance. The model was then tested with different physical options and initialization fields at a more complex geographical location with aberrant changes in temperature. The resulting simulation was supported with *in situ* meteorological observations and Coherent Doppler LIDAR (CDL) derived wind speeds. In addition to point comparisons, spatial comparisons of wind speed with the CDL further strengthened confidence in simulated winds. The intensity of turbulence and vertical structure of wind were verified using meso and micro scale model coupling. The micro scale model employs Large Eddy Simulation (LES) which directly resolves the largest turbulent structures and filters the smallest, thus feasible to wind energy applications. Future work involves assimilation of *in situ* and CDL observations in meso scale model initialization to offset discrepancies associated with ingesting global initialization fields insufficient in surface data at complex geographical locations.

1. Introduction

Wind power generation is challenging because of the stochastic structure of winds which makes it difficult to predict it at any specific point in space and time. So, management of wind farms becomes complex compared with geothermal and hydroelectric power plants [1]. Balancing supply and demand & integrating wind energy into a power distribution system's grid requires accurate forecasting tools to predict the timing and strength of wind power ramps. Effective and efficient management feeds into attractive market price incentives [2].

Wind power forecasting requirements may be specified depending upon the application. Very short term forecasts (a few seconds to 30 minutes ahead) are usually employed in electrical market clearing and regulation actions while short term forecasts (30 minutes to 6 hours ahead) are used for economic load dispatch planning and load increment/decrement decisions [1]. Generally, short term forecasting can be associated with a prediction horizon of about 8 hours [3]. Hence, in order to attain economic advantage, both in national and international markets, it is incumbent on the transmission system operators (TSO) to focus on the methods and techniques required to improve short term forecasting. A 100-MW facility may experience losses around $12,000,000 over its lifetime for a forecast error as small as 1% in the wind speed [4].

It is therefore beneficial to apply research effort to refine modelling approaches that accurately represent detailed topography, that properly account for regional forcing fields, that are cost effective, that have real time data assimilation for locally acquired data and that permit downscaling of the physical processes as the spatial resolution is improved. Our current research direction couples the outputs of a mesoscale model [Weather Research Forecasting (WRF)] with a micro scale Computational Fluid Dynamics (CFD) model (OpenFOAM) and includes constraining model outputs by ingesting three dimensional wind observations from CDL.

The current research is focused on an East African complex terrain with high diurnal variability that creates a nocturnal wind jet of typically 15 m/s. The location is the designated site for the Lake Turkana Wind Farm. Accordingly, accurate numerical modelling of the wind field is a critical requirement for optimum management of power generation but also for the protection of infrastructure by providing advance warning of adverse weather events. The site has been characterised using observations from three tall meteorological masts. These *in situ* measurements are compared with outputs from a meso scale meteorological model, WRF, configured with four domains nested down to a high spatial resolution of 900 m. The model has been tested with initialization fields from two different sources, optimised using different grid configurations, with several choices of physical and parameterization schemes. The criteria for comparison are the Root Mean Square Error (RMSE) and the Correlation Coefficient (CC). Generally RMSE is 10 % of the installed capacity for most models [5].

Since WRF assimilates pre-processed initialization fields which are an objective combination of observations and a numerical model and these fields are dependants on the abundance of constraining *in situ* observations. The impact of these fields on model output field's decreases with the increase in the sparseness of observational data. Henceforth, in order to establish the validity of WRF performance it was initially tested in a more defined meteorological environment with ample availability of observation data in Western Australia (WA).

At the Lake Turkana site the CDL generated wind map on a terrain following layer at hub height was compared with the model generated wind map. Such spatially resolved wind map comparison may aid developers to gain a more complete understanding of the spatial variation of winds within a prospective wind farm. The region of high wind speeds can be easily located and compared via visual inspection.

Reliable micro-siting and cost energy estimation requires coupling of meso-micro scale model which attains details of wind evolution and turbulent transport for achieving accurate forecasts. Turbulence intensities are well predicted by the coupling approach as compared to using a mesoscale model independently [6]. In this research a customized version of OpenFOAM (version-2.1.1) buoyantBoussinesqPimpleFOAM (bBPF) solver is used that includes modifications to include Coriolis forces, a large scale driving pressure gradient to achieve desired wind speed at a given height and specified surface stresses and temperature fluxes.

2. Methodology

This research follows a physical approach for achieving accurate wind forecasts for a Lake Turkana wind farm. The steps in this workflow are:

a. WRF sensitivity analysis and validation via *in situ* and CDL observations.

b. Coupling the optimised WRF model with OpenFOAM for prediction of micro-scale winds for improving turbine energy output estimation.

c. Evaluating impact using comparisons with *in situ* meteorological measurements.

d. Improve initialization data for WRF using CDL observations

3. WRF Sensitivity Analysis

The initial design of the WRF sensitivity analysis focused on determining WRF performance in WA where abundant observational data was available and regularly delivered to the World Meteorological Organization (WMO) at 6 hourly intervals. Improved consistency between simulated wind speed and direction with a two week *in situ* observation (10 m automatic mast) established WRF performance and basis for sensitivity analysis. The model used 3 nested domains and 53 vertical levels with the lowest level at 7 m. The grid resolution was 5 to 0.55 km from 1st to 3rd domain. The model used initialization fields from the National Centre for Environmental Prediction (NCEP) FNL (Final) Operational Global Analysis data on 1° by 1°(6 hours) while time invariant data including topography, land water masks, landuse and land cover classification, and albedo were obtained from the NCAR data base at all available resolutions .The longwave and shortwave radiation schemes are based on [7] and [8], respectively. A version of the scheme in [9] was used for cumulus parameterization for the first domain only. The YSU planetary boundary layer (PBL) scheme [10] was used and tested for all three domains. The Ferrier microphysics scheme [11] was used. Finally, a four-layer land surface model based on the Monin-Obukhov similarity theory [12] was used. These settings yielded wind speed RMSE 1.27 m/sec, CC 0.70 & wind direction RMSE was 0.64 rad & CC was 0.78 (Fig 1).

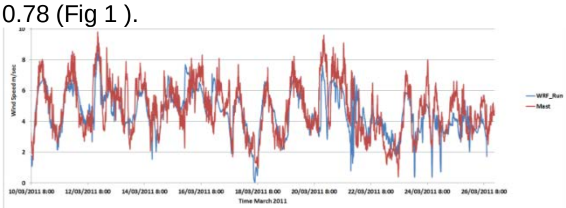

Figure 1 Comparison of wind direction between DEC 10 m mast at Swanbourne (10 mins sampling) and WRF predicted wind at 10 m (5 mins sampling) from 10 to 26 March 2011 (Time in UTC)

Sensitivity analyses for WRF were conducted at East African Terrain with three masts (designated as A, B and C) (Fig 2) and a CDL at an average height of 45 meters above ground level. WRF pressure levels were interpolated to this height at locations of masts and the CDL. Most of sensitivity experiments comprised of four domains nested down from a grid resolution of 27 to 1 km. Only for the test utilizing satellite data was the number of domains increased to 5 hence further reducing grid resolution to 0.33 km. Initially using initialization fields, parametrization and physical schemes from the WA experiment, inferior quality comparisons of wind speed and direction were achieved due to terrain complexity. Hence, in the next steps, the influence of change in parametrization scheme, physical schemes, influence of terrain complexity, different grid configurations and ingestion of satellite data from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) were observed but none of these improved the comparisons. Finally, replacing initialization fields from NCEP with European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis data having a horizontal resolution of 70 km and 60 model levels with 6 hourly temporal resolution improved the RMSE errors for predicted versus *in situ* mast-measured winds to 1.6, 1.7 & 1.9 m/sec & CC were 0.69, 0.57 & 0.48 for masts A, B and C respectively. This improvement in RMSE was 16.25%, 4% and 0.59% in case of mast A, B and C respectively. The wind direction RMSE for mast A & B were 12.01° & 13.23° & CCs are 0.44 & 0.24 respectively – see Fig 3 .These results were validated with CDL measured wind speed where wind speed RMSE and CC between mast and CDL were are 0.93 and 0.9 respectively.

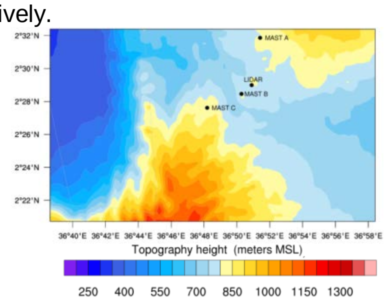

Figure 2 Wind speed and direction meteorological measuring stations designated A,B and C located on the Lake Turkana Wind Farm

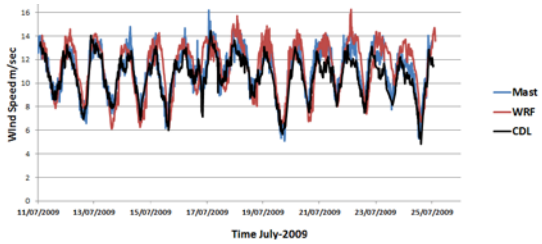

Figure 3 Comparison of wind speed comparison between mast A (10 mins sampling), WRF predicted wind (10 mins sampling) and CDL at 39 m height (Time UTC)

The WRF generated wind speeds were also compared with CDL wind speeds at some of the proposed turbine locations. Comparisons having RMSE and CC as good as 1.23 m/sec and 0.87 were obtained (Fig 4).

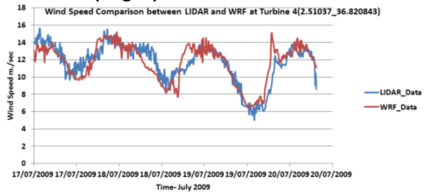

Figure 4 Comparison of wind speed between CDL and WRF predicted wind at 45 m (10 mins sampling) from 17 to 20 July 2009 (Time in UTC)

In addition, a spatial verification of the WRF model outputs with that of CDL was performed in order to identify the areas of maximum wind speed (Fig 5)

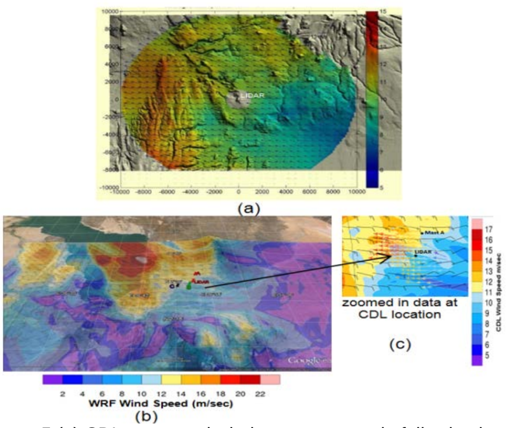

Figure 5 (a) CDL generated wind map on a terrain following layer at hub height (b) Comparison of CDL scan with the model generated wind map (b) arrows represent CDL wind direction coloured as wind speed magnitude while base represent WRF wind speed magnitude with wind barbs

4. WRF to OpenFOAM Coupling

Since mesoscale models such as WRF are unable to capture the micro scale terrain induced effects, prerequisites to reliable micro-siting, therefore time varying fields in these models require efficient integration with a micro scale CFD model like OpenFOAM. The coupling however is challenging as both models solve different physics and the spatial and temporal grids are inconsistent which can affect numerical stability and convergence. In this research the strategy followed by National Renewable Energy laboratories (NREL) is employed for coupling WRF to OpenFOAM. NREL's SOWFA package has a solver for complex terrains based on bBPF [13]. The solver has the added capability that OpenFoam's – standard sub grid scale models are fully compatible with this LES solver. It incorporates a local planetary surface stress model that does not require horizontal averages in a plane of homogeneity which allows it to compute flow over irregular terrain. A 4km x4km x2km grid was generated using SnappyHexMesh (SHM) as it has the flexibility to conform to any complex terrain (Fig 6). The STL file for the mesh was cropped out from the Shuttle Radar Topography Mission (SRTM) data at the designated site in Kenya with CDL at the domain centre. The OpenFOAM domain has Dirichlet conditions for velocity U, temperature T and pressure p at the south, top and east boundaries. These boundaries were considered as inlets and are fed from WRF via a "timeVaryingMappedFixedValue" boundary condition. The west and north boundaries were considered to be outlets and Neumann conditions for U, T and p. The bottom boundary or the terrain's surface is having a Dirichlet surface T flux from WRF, a Neumann condition for p and a surface stress model. The time step is set to 0.5 sec. The wind was considered to enter the domain from the south east specified by an angle of 135° and the simulation takes place at 37°E. In order to bring the fluxes up to the right values at processor boundaries the solver read some initial values from the setABLField's dictionary and the initial conditions file. These contained the initial values of velocity to be 13 m/sec while the reference temperature was set to 298 K. The virtual potential temperature was initialized from 300 K from surface up to 100 m. In addition, a vertical profile table was provided which derived values from the global ECMWF data for values of height, U, V and T. The surface aerodynamic roughness height is set to 0.1m. The standard Smagorinsky model with Cs= 0.168 was used as the LES model. The turbulence Prandtl number is fixed uniformly throughout the field at a value of 1.

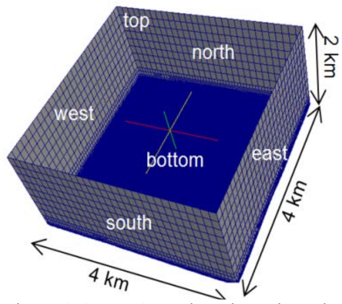

Figure 6 OpenFOAM domain and mesh with specified patches

The solver was run till a quasi-equilibrium condition was achieved. The values of vertical velocity were sampled along a line in the OpenFOAM domain at the CDL location. These values were then compared with the vertical velocity profiles generated by WRF and CDL and it was found that the profile generated with OpenFOAM was in close agreement to the actually observed CDL data as shown in (Fig 7). A low standard deviation of 3.35 m/sec compared to WRF's of 4.71 m/sec was achieved when validated against CDL winds.

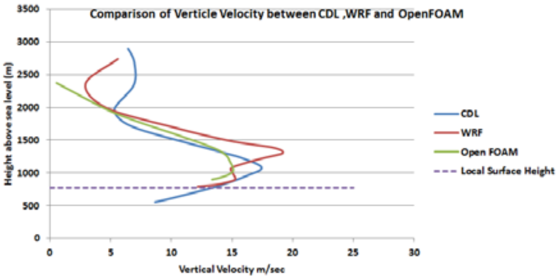

Figure 7 Comparison of Vertical Velocity between CDL WRF and OpenFOAM.[the local surface height is shown as dashed line]

5. Conclusions

A novel technique was developed for optimizing wind farm turbine performance. Improved WRF initialization fields for complex terrains achieved better results. Improved vertical structure of wind through micro scale modelling can further strengthen short term forecasts. Such reliable wind predictions will enhance the management of wind power generation.

6. Future Work

CDL has proved to perform better than meteorological masts in supporting short term forecasting due to its capability to both capture the complete evolution of wind and its large area coverage (including model constraining elevated winds). Accordingly, it is intended to integrate local observations from CDL and use them as initialization fields for WRF.

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