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WIND RESOURCE ASSESSMENT USING WRF MODEL IN COMPLEX TERRAIN

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AbstractWeather Research and Forecasting model (WRF) was used to simulate near-surface winds in a complex terrain using six different boundary layer parameterizations. The model runs are for 2009 and are compared tomeasurements from 3 meteorological masts: Kalkumpei, Nyiru and Sirima. WRF run using Yonsei University PBL scheme produced the best annual results at Kalkumpei with a mean difference of 0.01 m/s and Index of Agreement (IOA) of 0.66. WRF run using Yonsei University PBL scheme produced the best annual results at Nyiru with a mean difference of 0.15 m/s and IOA of 0.61. The predominant wind direction is correctly captured by the model at these locations.WRF run using Mellor-Yamada-Janjic scheme produced the best annual results at Sirima with a mean difference of 0.56 m/s and IOA of 0.61. Possible explanations for the poor model performance at Sirima can be linked to its location. Sirima meteorological tower is atop a very exposed ridgeline that can be subject to sporadic wind gusts and rapidly changing wind directions which can be difficult to model. Based on the analysis and results presented in this work, it can be concluded that WRF model can be used to generate wind data that can be in wind resource assessment.

Keywords:WRF model, complex terrain, wind resource assessment, wind modeling, wind energy.

1. Introduction

The Numerical Weather Prediction (NWP) models are computer programs that solve the fluid dynamics equations that govern the atmosphere: conservation of mass, momentum and energy in a three-dimensional grid. Weather Research and Forecasting (WRF) model used in this study is a mesoscale model that is generallyconsideredtobethemostadvancedmesoscalemodel (Skamarock et al., 2008, UCAR, 2012&Wei Wang, 2012). Mesoscale modelsareof particular importanceforwind energydevelopersandwindprospectors,servingastheprimary inputused forwind integrationstudiesifmeasureddataarenotavailable.

Many of the topographic features and atmospheric behaviours within complex terrain occur on a smaller spatial scale than the commonly used synoptic-scale forecasting models can simulate, resulting in limited near-surface model accuracy (Reid and Turner, 2001). However, higher resolution mesoscale models, such as WRF, are better suited for resolving the near-surface atmospheric behaviour in complex terrain (Rife et al., 2004, Žagar et al., 2006&Jiménez et al., 2010). It has also been previously shown that WRF's cross-mountain flow modeling with respect to blocking, channelling, orography, and thermal forcing all correlate to observations at an acceptable level of accuracy (Rife et al., 2004, Žagar et al., 2006&Jiménez et al., 2010).

Mesoscalenumericalwind modelshavealsobeenusedfrequentlyinthecreation ofwind resourceatlasesinBolivia(3TIER, 2009), intheUnited States,thePhilippines, Mongolia (Brower et al., 2004), Montenegro(Burlando et al., 2009),Ireland(Frank and Landberg, 1997), theIberianPeninsula(Bravo et al., 2008), offshoreinNewEngland,Texas,andintheGreatLakesregion(Bailey and Freedman, 2008).

Wind energy assessment using modeling techniques relies on the predictability of atmospheric dynamics. Evaluating model accuracy is accomplished by comparing simulated and observed atmospheric conditions at the same time. However, observations are point recordings, while model simulations represent spatial means determined by a model's horizontal and vertical grid spacing (Hanna and Yang, 2001). Thus, differences are expected between observed and simulated conditions simply due to the differences of time and volume averages that each represents (Hanna and Yang, 2001).

WRF model was used to simulate near-surface winds using six different boundary layer parameterizations. The model runs are for the entire 2009 calendar year and the results are compared to measurements from 3 meteorological mast locations. The terrain around this region is complex and the prevailing wind direction is south east. Measurement masts at the 3 locations have been observing and recording winds at a height of 38.5 m, 46m and 38 m for Kalkumpei, Nyiru and Sirima respectively. Planetary boundary layer physics play schemes play a significant role in the evolution of the low-level wind structure. WRF was run with five different PBL schemes. Model results were evaluated in terms of their accuracy in forecasting wind speed and direction to determine a satisfactory model set-up.

2. Area of Study

The area of study is Northern Kenya which is an Arid and Semi-Arid Lands (ASAL) region. The mean annual maximum temperature is 43°C while the mean minimum annual temperature is 14°C. The mean annual rainfall is 230 mm. Nomadic pastoralism is the major economic activity in the area. Lake Turkana region has various topographic features that include the Ethiopian highlands to the northeast and East African highlands to the southwest. In between the Ethiopian highlands and the East African highlands lies a low-level region. This valley is referred to as the Turkana channel (Kinuthia and Asnani, 1982). It is above 500 m from the mean sea level and has a depth that varies between 610 and 1524 m, and a width that varies about 140 to 700 km. The channel is approximately 700 km long and oriented from southeast to northwest (Kinuthia, 1992).

3. WRF model set-up

WRF is a completely compressible Euler non-hydrostatic (with a hydrostatic option) model. The time integration is a 3rd order Runge-Kutta, with smaller time steps for the acoustic and gravity-wave modes. The spatial discretization in horizontal and vertical can be selected anywhere between a 2nd and 6th order advection option (Skamarock et al., 2008). WRF model has several options for various physics needs, including microphysics, cumulus, land-surface, planetary boundary layer (PBL) physics, and radiation parameterizations. PBL schemes in WRF have the largest impact on the wind speed within the lower atmosphere (Skamarock et al., 2008).

WRF model version 3.6 was used in this study to predict wind speed and direction.It was configured with three domains using two-way nesting, the horizontal resolution of the outermost domain is 18km, the intermediate domain is 6km and the third domain is 2km (figure 1). A configuration of 32 terrain-following hydrostatic pressure levels with the top most level at 50 hPa was used in the vertical for all three domains.

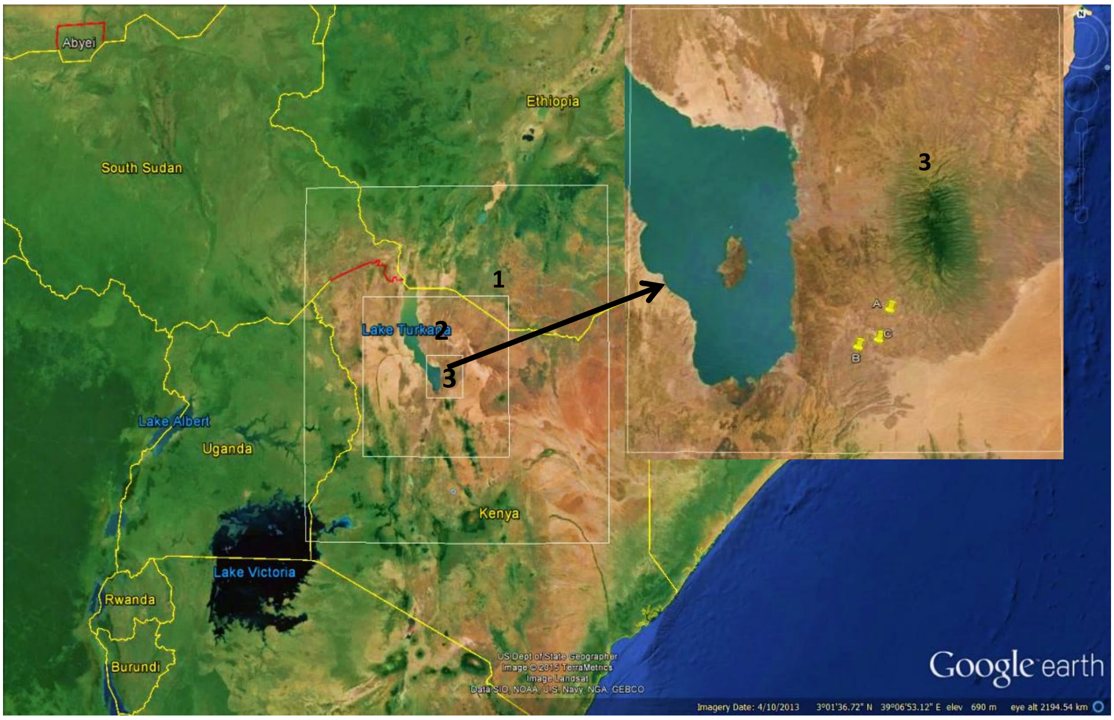

Figure 1: WRF simulation domains: three domains two-way nested with 18, 6, and 2 km horizontal resolution.

The topographic data were obtained from the USGS global dataset. The model is initialized and forced at the boundaries by 1° NCEP/FNL data. The model physics options include: Thompson graupel scheme except for experiment 1, Kain-Fritsch cumulus parameterization, 6th order numerical diffusion, and positive definite advection of moisture and scalars.

The model is run with five different BL schemes, as indicated in Table 1: Asymmetric Convective Model version 2 (Pleim, 2007), Medium Range Forecast Model (Troen and Mahrt, 1986), Mellor-Yamada-Janjic(Mellor and Yamada, 1982), Yonsei University Scheme (Hong et al., 2006) and the Quasi-Normal Scale

Elimination (Sukoriansky et al., 2006). For the land surface model and the surface layer physics we choose the recommended options as in (Wei Wang, 2012), also included in Table 1. Experiment 1 used WRF Single-Moment microphysics. All other parameterizations remain the same for the 6 experiments.

Table 1: Description of the six experiments: PBL parameterizations, their closure type (Turbulence Kinetic Energy; TKE) associated land surface models and surface layer physics schemes, as recommended in (Wei Wang, 2012).

Experiment	**PBL Physics**	**Surface Layer Physics**	**Land Surface Physics**
1	Yonsei University scheme	MM5 similarity (with WRF Single-Moment microphysics)	Noah Land Surface Model
2	ACM2 PBL scheme	Pleim-Xiu surface layer	Pleim-Xiu Land Surface Model
3	MRF PBL scheme	MM5 similarity	Noah Land Surface Model
4	Mellor-Yamada-Janjic scheme	Eta similarity	Noah Land Surface Model
5	Quasi-Normal Scale Elimination PBL	QNSE (Quasi-Normal Scale Elimination)	Noah Land Surface Model
6	Yonsei University scheme	MM5 similarity – (with New Thompson microphysics)	Noah Land Surface Model

4. Results and discussion: Annual statistics

Wind rose plots and comparative statistics were used to evaluate the performance of WRF model. The simulated wind speeds were verified against observations at Kalkumpei, Nyiru and Sirima. Presented in table 2 are error statistics between WRF forecast sets and the observations at Kalkumpei, Nyiru and Sirima for 2009. The smallest Mean Error (ME), Root Mean Square Error (RMSE), percent bias error (Pbias) per station and the largest Index of Agreement (IOA) are highlighted in bold.

Table 2: Error statistics between WRF forecast sets and the observations at Kalkumpei, Nyiru and Sirima for 2009.

Mean wind speed

	Observed (m/s)	Exp1 (m/s)	Exp2 (m/s)	Exp3 (m/s)	Exp4 (m/s)	Exp5 (m/s)	Exp6 (m/s)
Kalkumpei	10.44	10.48	8.38	10.33	11.56	11.36	10.45
Nyiru	10.75	10.59	8.58	10.59	11.57	11.34	10.58
Sirima	11.10	9.61	7.69	9.61	10.54	10.30	9.56

Kalkumpei

Simulation	MAST/WRF			
	ME (m/s)	RMSE	Pbias	IOA
1	-0.03	**2.30**	-0.3	0.65
2	2.06	3.13	24.6	0.52
3	0.11	2.49	1.1	0.61
4	-1.11	2.56	-9.7	0.65
5	-0.92	2.68	-8.1	0.59
6	**-0.01**	2.31	**-0.1**	**0.66**

Nyiru

Simulation	MAST/WRF			
	ME (m/s)	RMSE	Pbias	IOA
1	**0.15**	2.47	**1.5**	0.60
2	2.16	3.26	25.2	0.49
3	0.15	2.57	1.5	0.58
4	-0.82	2.65	-7.1	0.60
5	-0.59	2.82	-5.2	0.55
6	0.16	**2.46**	1.6	**0.61**

Sirima

Simulation	MAST/WRF			
	ME (m/s)	RMSE	Pbias	IOA
1	1.48	2.82	15.5	0.56
2	3.40	4.21	44.3	0.43
3	1.49	3.00	15.5	0.54
4	**0.56**	**2.52**	**5.3**	**0.61**
5	0.80	2.90	-7.8	0.55
6	1.54	2.85	16.1	0.56

Discussion

Boundary layer winds simulated by the WRF model using six different PBL schemes have been evaluated against observations at three locations in Lake Turkana with a focus on the representation of the wind characteristics under different atmospheric conditions. Table 2 shows that the modelled mean wind speeds are lower than the actual mean wind speeds at Sirima. On the other hand the modelled wind speeds are higher than the actual mean wind speeds at Kalkumpei for simulations that use Yonsei State University PBL scheme (with WRF Single-Moment microphysics), Mellor-Yamada-JanjicPBL scheme, Quasi-Normal Scale Elimination PBL scheme and Yonsei State University PBL scheme (with New Thompson microphysics). However, simulations that use Asymmetric Convective Model PBL scheme and MRF PBL scheme under-predicts wind speeds.

For Nyiru, the modelled wind speeds are higher than the actual mean wind speeds for simulations that use Mellor-Yamada-JanjicPBL scheme and Quasi-Normal Scale Elimination PBL scheme while simulations that use Yonsei State University PBL scheme (with WRF Single-Moment microphysics), Asymmetric Convective Model PBL scheme, MRF PBL scheme and Yonsei State University PBL scheme (with New Thompson microphysics) under-predicts wind speeds. Allmodelleddataunder-predictedthe annual average wind speed at Sirima.

The overall lowest bias (0.01 m/s) was that which used Yonsei State University PBL scheme at Kalkumpei while the highest bias is that which uses the Asymmetric Convective Model PBL scheme (3.40 m/s) at Sirima. The wind speeds simulated by the various PBL simulations except Asymmetric Convective Model PBL scheme are within 1 m/s of the observations at Kalkumpei and Nyiru stations. The Asymmetric Convective Model PBL scheme has the biggest mean errors and underestimates wind speeds at all three locations. Yonsei State University PBL scheme has small mean errors at both Kalkumpei and Nyiru mast locations. It underestimates wind speeds at Nyiru while overestimating at Kalkumpei. Mellor-Yamada-Janjic PBL scheme performs well at Sirima mast compared to the other four options.

The best RMSE values for Kalkumpei, Nyiru and Sirima are 2.30 m/s, 2.46 m/s and 2.52 m/s respectively. Based on these RMSE values, it can be deduced that WRF model performed well in predicting winds at Lake Turkana wind farm site. Similar results have been reported by Emery et al., 2001 who suggested that a benchmark for RMSE was less than or equal to 2 m/s. However, in complex terrain, like the current site, this value could easily be contaminated by a relatively small number of larger errors. In a validation study of TAPM (Hurley et al., 2002) in complex terrain at Cape Grim on the southwest corner of Tasmania, RMSE values of wind speed and the wind components were averaged to be 3.1 m/s. It was concluded that the model had performed well in predicting the observed meteorology at this site.

Overall, the IOA scores in table 5.2 are good with 0.66, 0.61 and 0.61 for Kalkumpei, Nyiru and Sirima respectively. These simulations used Yonsei State University PBL scheme (with New Thompson microphysics) at Kalkumpei and Nyiru and Mellor-Yamada-JanjicPBL scheme at Sirima.

WRF-modelled wind speeds were similar to those observed, with accurate wind direction simulation. Taking into account all the metrics in Table 5.2 and the discussion on Sirima presented in section 5.1.4.3, the best performing PBL scheme for Lake Turkana wind farm region was the Yonsei State University scheme. In summation, WRF performance using this PBL scheme was goodfor the near-surface wind field simulation at Lake Turkana wind farm domain.

5. Results and discussion: Monthly statistics

The discussion below focuses on the temporal monthly variation of mean wind speed at the 3 mast locations. We consider the experiments that best simulate the observed wind speed and reference will be made on figures 2, 3 and 4. In these figures; statistics are derived from experiment 6 for Kalkumpei and Nyiru and experiment 4 for Sirima.The seasonal variation of mean wind speeds over the three mast locations is discussed in this section, focusing particularly on the temporal variation both monthly and seasonally for the four northern hemisphere seasons of 2009. The statistics provide some interesting features in the mean wind speed pattern for different times of the year. It is clear from figures 2, 3 and 4 that the start of winter has the lowest mean wind speeds for all three locations. The wind speeds then increase gradually till the end of winter. Wind speeds then decline gradually throughout spring and start to increase again at the start of summer season. The summer season has the strongest winds in this region.

WRF simulations using Yonsei State University PBL scheme produced the best annual results at Kalkumpei with a mean difference of -0.01 m/s, percent bias of -0.1, RMSE of 2.30 m/s and Index of Agreement (IOA) of 0.66 and the predominant south east wind direction was correctly captured by the model at this location. Summer months have the highest IOA and lowest RMSE. WRF simulations using Yonsei State University PBL scheme produced the best annual results at Nyiru with a mean difference of 0.15 m/s, percent bias of 1.5, RMSE of 2.46 m/s and IOA of 0.61. The predominant south east wind direction was correctly captured by the model at this location. WRF simulation using Yonsei State University PBL scheme generated good results at both Kalkumpei and Nyiru because a topographic correction (topo_wind=1) was incorporated during WRF simulation. This correction improves surface wind biases using sub-grid variance and resolved topography to modify surface friction effect and enhanced flow at hill tops (Jiménez and Dudhia, 2012).

WRF run using Mellor-Yamada-Janjic scheme produced the best annual results at Sirima with a mean difference of 0.56 m/s, percent bias of 5.3, RMSE of 2.52 m/s and IOA of 0.61. July, August and September have the lowest root mean square errors of 1.95 m/s, 1.85 m/s and 1.74 m/s respectively while May, June and December have the highest IOA of 0.66, 0.67 and 0.72 respectively. The Mellor-Yamada-Janjic was the best PBL schemes for predicting wind speed at Sirima for all months except between October and January when Yonsei State University PBL scheme does a better job. The location of Sirima mast atop a very exposed ridgelinefavours WRF simulation using TKE closure PBLs. It therefore doesn’t occur as a surprise that MYJ PBL scheme performs better at this location. Based on the analysis and results presented in this work, it can be concluded that WRF model can be used to generate wind data that can be used directly in wind resource assessment.

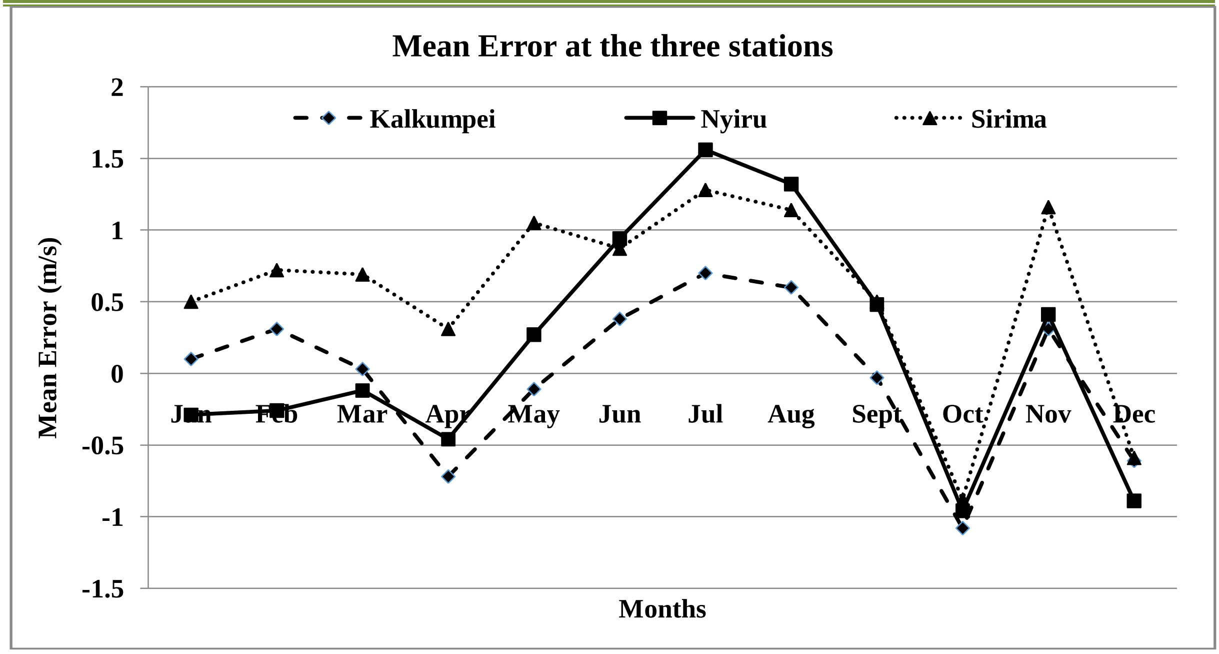

Figure 2: Monthly mean error at the three mast locations considering experiment 6 for Kalkumpei and Nyiru and experiment 4 for Sirima.

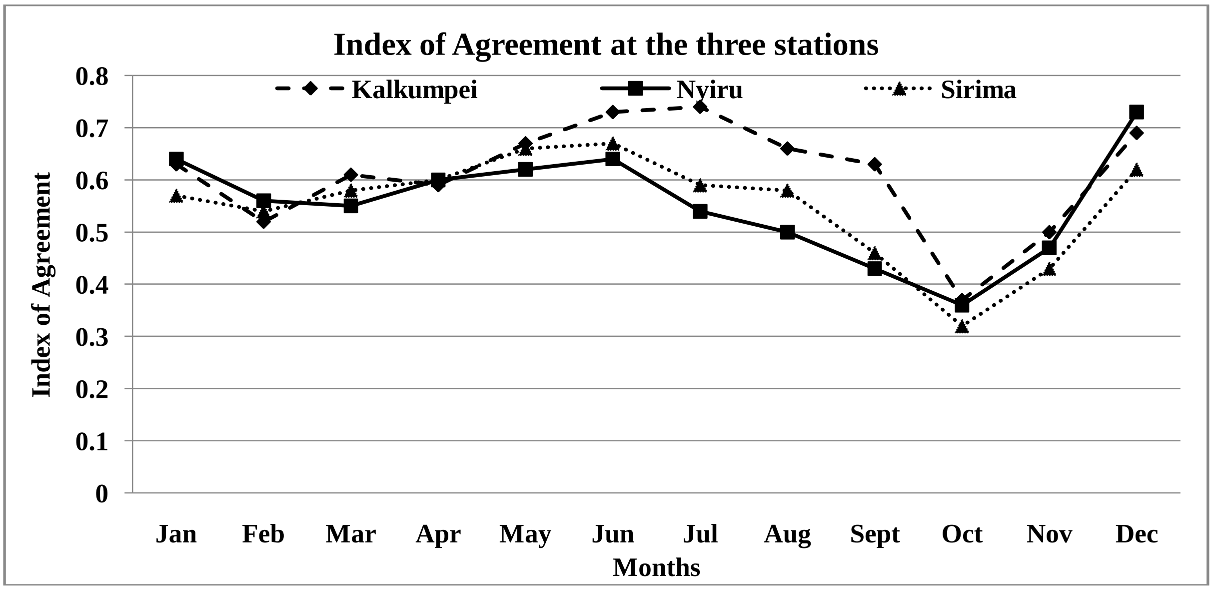

Figure 3: Monthly Index of Agreement at the three mast locations considering experiment 6 for Kalkumpei and Nyiru and experiment 4 for Sirima.

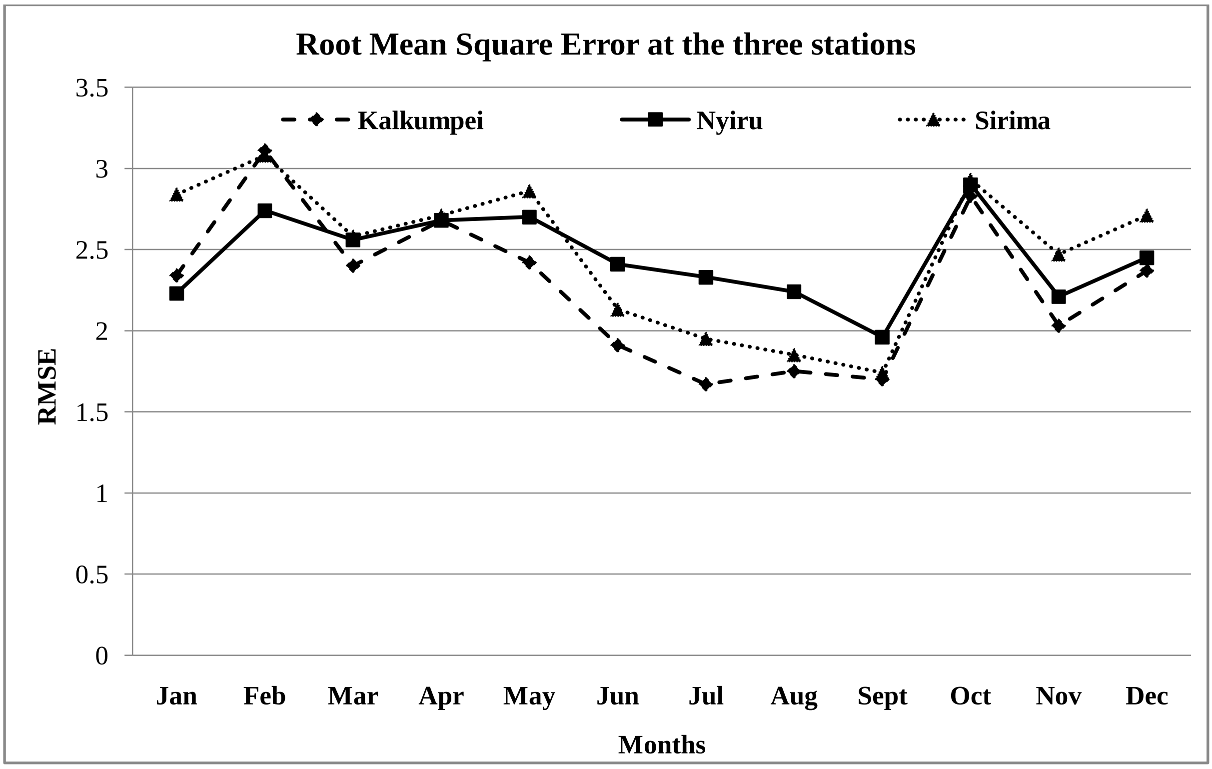

Figure 4: Monthly Root Mean Square Error at the three mast locations considering experiment 6 for Kalkumpei and Nyiru and experiment 4 for Sirima.

6. Conclusion

The main aim for study was to assess if wind data from specific locations of the WRF modelled region could be potentially used in wind resource assessment when no actual reliable wind data were available. Yonsei State University PBL scheme produced the best annual statistics for Lake Turkana wind farm site because it incorporates a topographic correction. The annual mean error of 0.56 m/s computed at Sirima was a fairly big difference compared to 0.01 m/s and 0.16m/s at Kalkumpei and Nyiru respectively. This was partly attributed to the location of Sirima mast which was atop a very exposed ridgeline that can be subject to sporadic wind gusts and rapidly changing wind directions which can be difficult to model. Careful consideration should therefore be made when selecting the site to erect meteorological masts to avoid areas with exposed ridgelines, unless the whole region is covered with exposed ridgelines. New modelling approaches will have to be adopted in the latter case. The results and validation analysis presented in this paper confirmed that WRF model can be used to generate wind data that may be applied directly in wind resource assessment at this complex topographic site.

7. Acknowledgements

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