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Wind speed and direction predictions by WRF and WindSim coupling over Nygårdsfjell

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Abstract. In this study, the performance of the mesoscale meteorological Weather Research and Forecast (WRF) model coupled with the microscale computational fluid dynamics based model WindSim is investigated and compared to the performance of WRF alone. The two model set-ups, WRF and WRF-WindSim, have been tested on three high-wind events in February, June and October, over a complex terrain at the Nygårdsfjell wind park in Norway. The wind speeds and wind directions are compared to measurements and the results are evaluated based on root mean square error, bias and standard deviation error. Both model set-ups are able to reproduce the high wind events. For the winter month February the WRF-WindSim performed better than WRF alone, with the root mean square error (RMSE) decreasing from 2.86 to 2.38 and standard deviation error (STDE) decreasing from 2.69 to 2.37. For the two other months no such improvements were found. The best model performance was found in October where the WRF had a RMSE of 1.76 and STDE of 1.68. For June, both model set-ups underestimate the wind speed. Overall, the adopted coupling method of using WRF outputs as virtual climatology for coupling WRF and WindSim did not offer a significant improvement over the complex terrain of Nygårdsfjell. However, the proposed coupling method offers high degree of simplicity when it comes to its application. Further testing is recommended over larger number of test cases to make a significant conclusion.

1. Introduction

Renewable energy resource assessment is an important research field due to increasing energy demand as well as the need to reduce the dependency on fossil fuel. Wind energy is a good renewable energy option as its technology is already mature, it is economically competitive and already in use worldwide. According to [1] successful development of wind energy requires high accuracy of the predicted available wind resource to assure a lower investment risk. The classical methods for wind energy resource assessment is per date local wind measurement campaigns, extrapolation of free atmospheric wind provided by global data bases or by use of wind atlases [2]. Data provided from these different methods are used either alone or in combination with micro-scale models. The accuracy and the availability of these methods vary.

Wind measurement campaigns are costly and time consuming, as well as they require a certain preliminary knowledge of the wind regime [3]. Methods based on global databases or wind atlases can provide adequate results for simple terrains, but for complex mountainous terrain these methods might be insufficient [4]. In the study by [5] they compare low resolution wind data with high resolution data obtained from a numerical model to prove how the classical wind assessment method might lead to discard of areas that are suited for wind exploration.

Recently atmospheric mesoscale meteorological models are also being used for wind energy resource estimations and provide a good first approach in a research assessment [6, 7]. Benefits of mesoscale model are that it can be used worldwide, have a low operational cost as well as a high sampling resolution both horizontally and vertically [3]. In the study by [8] it is shown that meteorological mesoscale models perform well on simple terrains; however, complex terrain benefits from higher resolution to reproduce local wind forces. A recent method that allows for the largescale effects as well as the including the micro-scale topography of complex terrain is by coupling of mesoscale model with micro-scale model. Carvalho et al. [3] have investigated three different methods for coupling of WRF with the micro-scale model WAsP in a complex mountainous terrain in Portugal and found that the use of mesoscale output in microscale models should be seen as valid alternative to in situ data for preliminary wind resource assessment.

In this study the mesoscale wind outputs of WRF are used as virtual climatology in WindSim to capture the effects of local terrain on three katabatic wind events at Nygårdsfjell. These katabatic events are selected from the previous study conducted at the Nygårdsfjell wind farm [9]. The objectives of selecting these three events are: whether or not the local terrain plays a significant role on higher wind speeds and whether or not the seasonal variations play a role in predicting these katabatic events. Furthermore, the data used in this paper is also presented in other study dealing with the microscale modelling with two types of mesoscale modelling focussing only on the wind speed correlations [10]. Nygårdsfjell is located in a valley at 420 meters with an east west direction with surrounding mountain with heights up to 2000 meters above sea level and represents a complex terrain. In the east the large Tornetrask Lake is located, which is covered by ice through a large part of the year and is believed to give rise to high wind events in the area of the test case as described in [9]. The natural channel runs from the lake towards the western fjord and directs the winds over the Nygårdsfjell wind farm.

Section 2 describes the dataset and section 3 discusses the model setups of WRF and WindSim. Section 4 presents the coupling method proposed in this study and section 5 presents the results and discussion of the coupled model. At the end section 6 concludes the findings.

2. Data sets

2.1. Measured data

The measured data is taken from three 2.3 MW Siemens wind turbines (SWT-2.3-93) with hub height of 80 meters that were installed at Nygårdsfjell during the fall of 2005. The measured data set consists of selected days over three seasons that is from June 2008, October 2008 and February 2009 according to the previous study at the wind farm [9].

2.2. Mesoscale input winds

The mesoscale winds, used as input to WindSim, are generated through WRF version 3.5.1 of the Advanced Research solver, which is a widely used meso-scale model developed by the National Center for Atmospheric Research.

2.3. Data validation

Coupled model results are validated for the selected cases. The RMSE found are tested with 5 % confidecne level and all the values are found to be statistically significant.

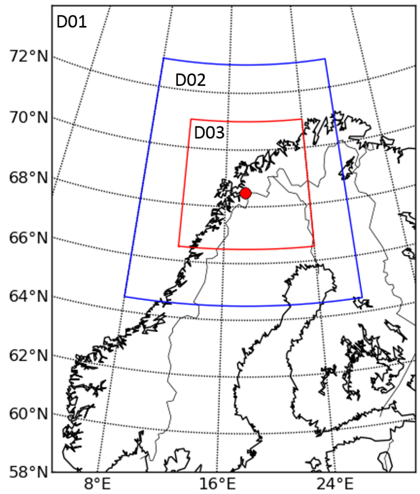
3. Model configurations

3.1. WRF

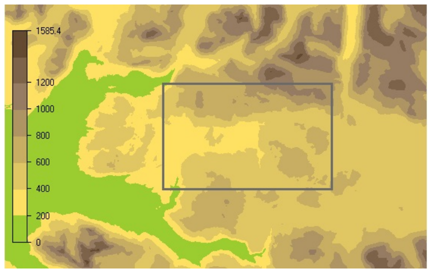
Local closure turbulent kinetic energy scheme Mellor-Yamada-Janjić is selected along with the short/long wave radiation scheme Goddard for the current simulation set. This combination may not be optimal for this site, but are similar to previous settings that have been used with success in other publications [11, 12, 13]. ERA-Interim data sets from the European Centre for Medium-Range Weather Forecasts are used to provide the initial and boundary conditions to the WRF model. The data has a spectral resolution of approximately 80 km on 60 vertical levels with 6 hours of temporal sampling. Land use and topographical properties are acquired from the US Geological Survey. The parent domain has a spatial resolution of 18 x 18 km indicated by $D01$, inner domains have spatial resolutions of 6 x 6 km and 2 x 2 km indicated by $D02$ and $D03$ respectively in figure Figure 1 (a). The vertical resolution of the model consists of 51 levels. All domains are centered around the wind turbine location: Latitude = $68° \ 30'' \ 27'$; Longitude = $17° \ 87'' \ 27'$. Interaction protocol feedback from nest to its parent domain is selected. All the results discussed in this paper lies within the inner most domain that is $D03$ and have hourly temporal resolution.

3.2. WindSim setup

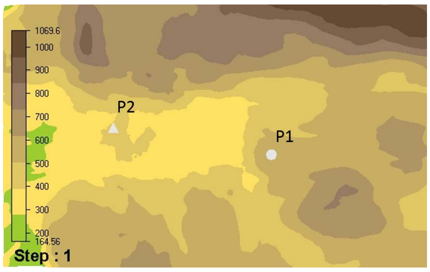
WindSim solver is based on the Reynolds Averaged Navier-Stokes equations. The model solves the atmospheric flow for a steady-state case for a chosen wind direction. The model runs for a given set of constructed boundary and initial conditions. The standard k-e turbulence closure scheme is adopted in the WindSim model [14]. Digital terrain model of the Nygårdsfjell wind farm is imported into WindSim. Figure 1 (b) describes the overall area domain. The area includes mountains on North and South sides and extends to relatively lower altitude areas on East and West with minimum elevation of 110.7 meters a.g.l, maximum of 1107.5 meters a.g.l and average of 550 meters a.g.l. The area represents an ideal test case for wind over complex terrain with maximum slope of 74.63 degrees and average slopes of 11 degrees. Figure 1 (c) shows the terrain model of the wind farm imported in WindSim and (d) shows the refined multi-mesh including the wind turbine and climatology points within it. The grid extends 6865 meters a.g.l above the point in the terrain with the highest elevation in WindSim. The grid is refined towards the ground. For our simulations, the boundary and initial conditions used are: no nesting, number of sectors 12, height of boundary layer 500 meters, speed above boundary layer height 10 meters per second, and at the top of boundary layer fixed pressure condition is used. The digital terrain model has spatial resolution of 20 meters x 20 meters. The output



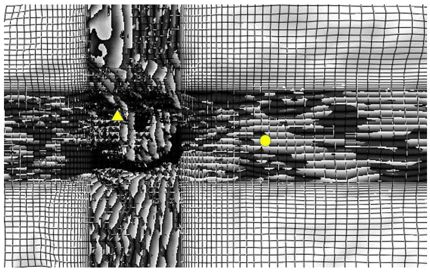
(a) WRF model domain



(b) Overall domain - box indicating wind farm premises



(c) Wind farm premises in WindSim



(d) WindSim multimesh terrain model

Figure 1: Modeling domain and terrain of the wind farm

data has hourly temporal resolution for coherent analysis with WRF outputs.

4. Coupling methodology

There are many possibilities, in terms of choice of parameters as well as choice of location, on how the mesoscale winds are coupled with microscale model such as WindSim. In this study, the WRF output winds are coupled through virtual climatology. That means the wind speed and direction extracted at a specific location are used as input at the same location in WindSim. All other parameters are fixed as described in section 3.2. This method of coupling mesoscale winds to microscale model is not the preferred method of coupling however this technique is applied and evaluated as it was easier to implement and to check if it could still give valuable results. Nearby point at eastern side of the windfarm (Latitude = $68^\circ\ 30''\ 00'$; Longitude = $18^\circ\ 00''\ 00'$) is selected as a virtual climatology. The reason of selecting the virtual climatology point in east is due to the fact that majority of winds come from east of the wind farm throughout the year [9]. WRF wind speed data is extracted at this point with an altitude of 80 meters that is then used as input to WindSim simulations.

4.1. Coupling challenges

WRF is a grid point model that performs its calculations on a fixed array of spatially disconnected grid points. The values at the grid points actually represent an area average over a grid box. In WRF model, one grid value represents an area average over 2 km x 2 km at this site. Undoubtedly WRF values are prone to have errors due to the effect of smoothing the complex terrain variations over large distances. Since the WindSim model has refined mesh with a resolution of 20 meters x 20 meters, therefore the coupled WRF-WindSim model is expected to capture the terrain influence on wind speed and its direction. Another potential error comes from interpolating to hub height from the grid values. This interpolation is required to compare the model values with one point measured values recorded at the hub height. However, these interpolation errors are not expected to be as large as the inherit sources of errors that weather models have in general resulting from e.g. initial and boundary conditions, domains sizes, vertical and horizontal resolution, terrain resolution, vegetation characteristics, nudging and data assimilation. In WRF cases, the error increases to maximum at the beginning and end of the simulation event whereas tends to be minimum in the middle. One of the reasons is the inherit initialization errors of WRF model, which are present usually in initial $6 - 12$ hours of the simulation. One other reason might be the abrupt change in wind speed and direction at the beginning and end of the event. These abrupt changes are not well captured by WRF.

5. Results and discussion

The data sets at the turbine location obtained directly from WRF, and the WRF-WindSim coupled model are compared to the measured data. Both the wind speed and the wind direction are compared to the measurements by root mean square error (RMSE), bias and standard deviation error (STDE). The RMSE allow us to investigate the deviation between the pairs of simulation-observation values. The bias allows us to investigate the tendency of the predicted values compared to the measured values, a negative bias indicate a tendency to underestimate, while positive bias indicates a overestimation of the wind speed and direction. The STDE gives us the variation of the data sets. Table 1 summarises the results.

	RMSE		Bias		STDE	
	speed (m/s)	dir.	speed (m/s)	dir.	speed (m/s)	dir.
WRF						
February	2.86	22.41	0.96	-5.76	2.69	21.66
June	4.61	36.61	-3.00	1.14	3.50	36.59
October	1.76	14.30	0.55	-1.76	1.68	14.19
WRF-WindSim						
February	2.38	22.64	0.27	-1.28	2.37	22.60
June	5.21	28.37	-3.32	-1.08	4.01	28.40
October	1.90	13.26	-0.03	-0.77	1.90	13.24

Table 1: RMSE, bias and STDE with respect to the measured data.

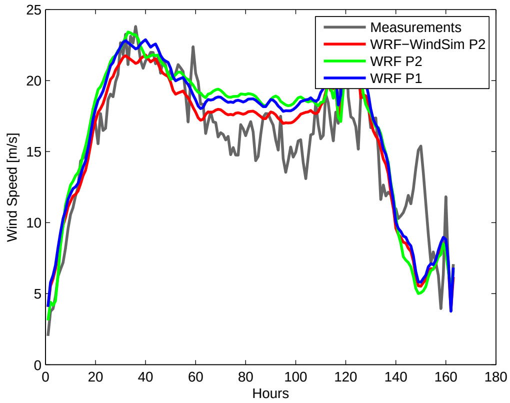
Figure 2 shows the wind speed and the wind direction from the turbine measurements, from WRF at the virtual point P1 and at the turbine P2, and the results from the coupled WRF-WindSim model at turbine location P2. From the figures, it is clear that both WRF and WRF-WindSim are able to reproduce the wind speed and direction well. These results are supported by table 1. For June case, both the wind speed from WRF and WRF-WindSim coupled model underestimated the measured wind speed considerably. Also, there are not found any improvements moving from the mesoscale model WRF to the microscale model WindSim, on the contrary, the wind speed results from WindSim have slightly higher RMSE, bias and STDE. For the wind direction, WindSim reproduce the real wind direction more or less similar to WRF predictions. This can also be seen in figure 3 where both the wind direction and speed is represented in wind roses. The results for October and February show that the outputs from both WRF and WRF-WindSim match the measured data quit well. This can also be seen in table 1, however there are no improvement from WRF to WRF-WindSim when it comes to the wind speed while for the wind direction there is a small improvement. Overall, the results gave an impression that the coupled WRF-WindSim model output is somewhat sensitive to quality of input mesoscale winds. For instance in June, the WRF model appeared to be sensitive to weather conditions. One of the other research papers stated, the potential reasons for underestimation of wind speed by WRF model is the failure of the selected PBL scheme to capture the terrain induced thermal circulations that are common in mountainous region during warm seasons [15]. This error is passed onto the output of WRF-WindSim model as well. Resource constraints only allowed limited simulation cases.

6. Conclusion

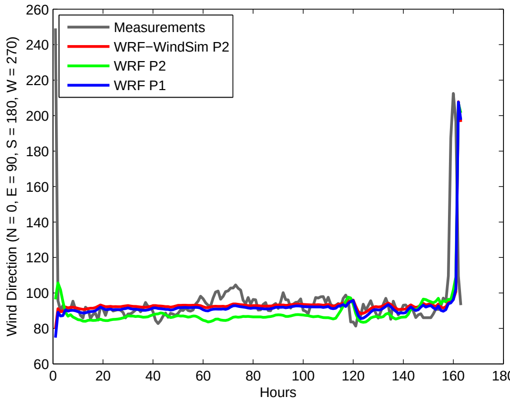
The results imply that the performance of the microscale model is mainly dependent upon the quality of input mesoscale winds used as virtual climatology. In terms of using WindSim, further testing is recommended on the sensitivity of the accuracy of the converged solution to the initial boundary conditions. That includes testing of different wind speeds at the inlet, but also testing different boundary layer height as a too low value might result in artificial blocking and speed up. Conducting tests with finer wind direction sectors is advised for future cases. The wind direction width for the current project was 30 degrees. By increasing the number of wind direction sectors, influence of local terrain could be captured with higher accuracy and that might improve the wind speed predictions.

When comparing the results at the wind turbine location between direct mesoscale winds and the output of coupled model, WindSim could not capture the complex terrain and the corresponding inflow angles as good as expected. Although WindSim has a resolution of 20 meters x 20 meters, one possible reason could be the mismatch between grid sizes of WRF and WindSim in this study. The coupled WRF-WindSim model takes a WRF wind speed which is an average value over a 2 km x 2 km grid box and uses this value as wind speed input in WindSim as constant value for several 20 meters x 20 meters grid boxes. This is a change in terrain of approximately 100 times without any change in wind speed.

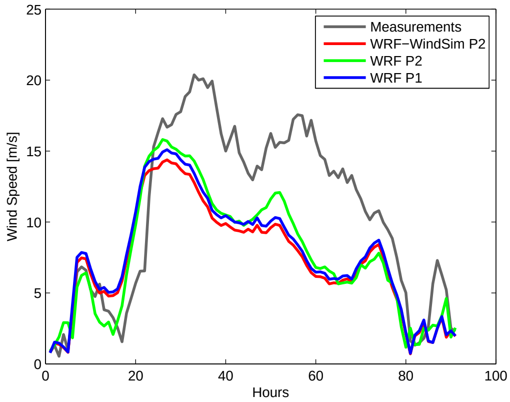
It could be said that the adopted coupling method of using WRF outputs as virtual climatology for coupling WRF and WindSim, did not offer a significant improvement over the complex terrain of Nygårdsfjell. Although the limited simulation cases cover three seasons, even then the data set is too limited to make any significant conclusions. Further simulations over larger period of times and with different combinations of WRF and WindSim settings are recommended.



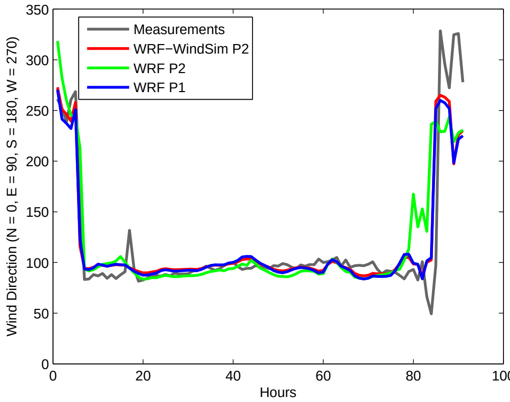
(a) Wind speed - February



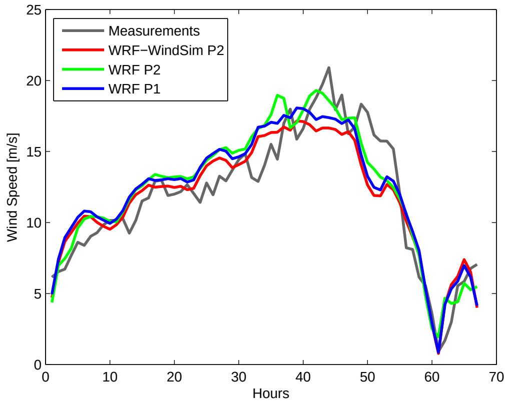
(b) Wind direction - February



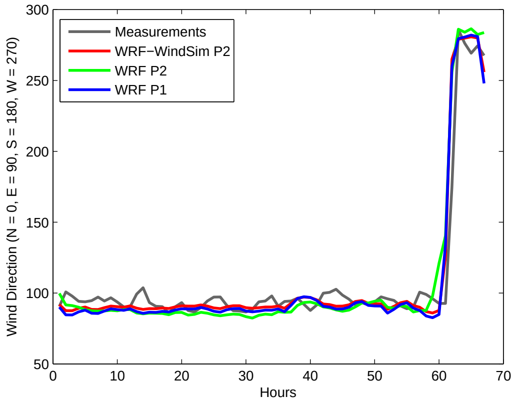
(c) Wind speed - June



(d) Wind direction - June

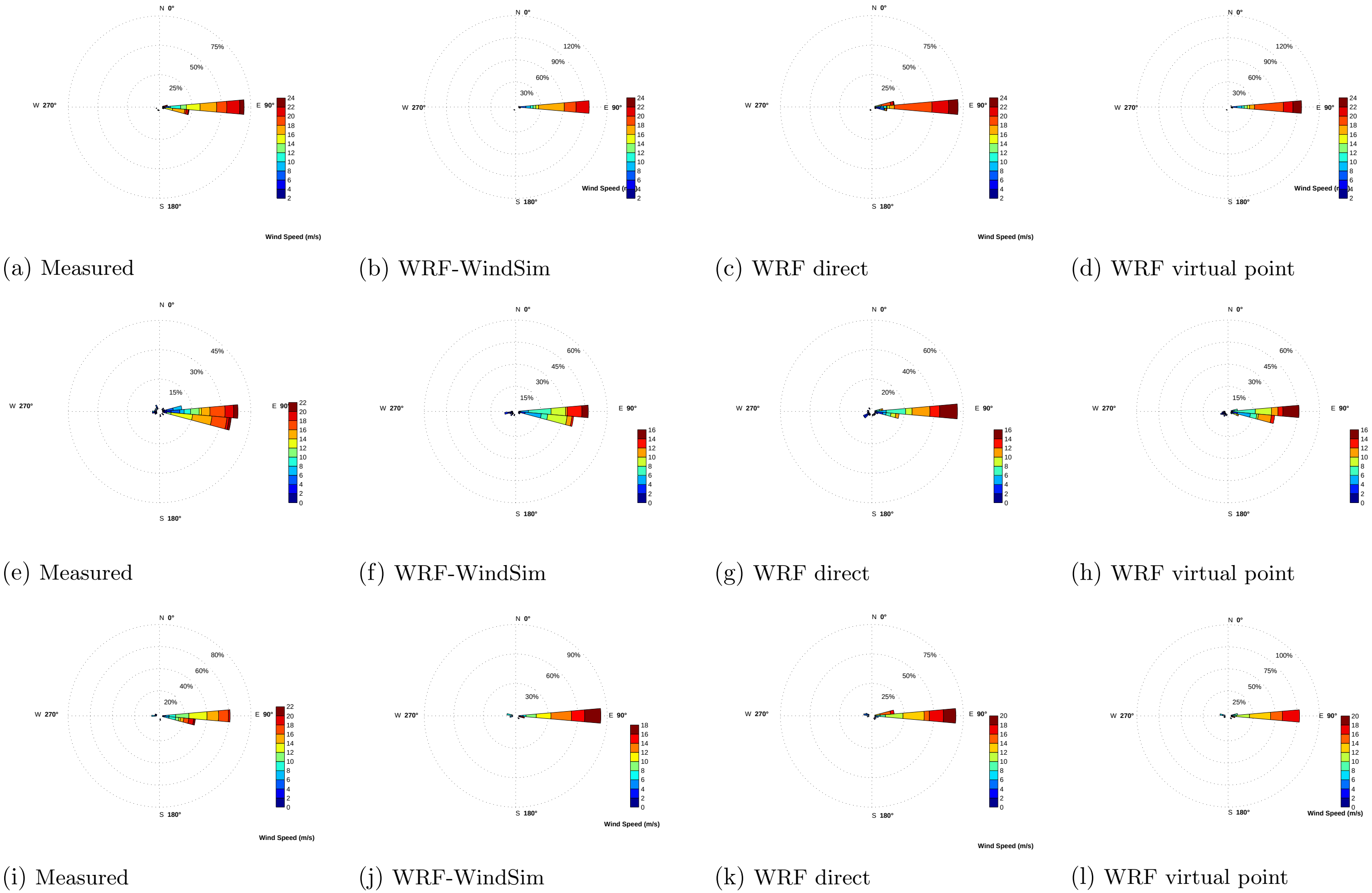


(e) Wind speed - October



(f) Wind direction - October

Figure 2: Wind speed and direction comparisons



(a) Measured (b) WRF-WindSim (c) WRF direct (d) WRF virtual point

(e) Measured (f) WRF-WindSim (g) WRF direct (h) WRF virtual point

(i) Measured (j) WRF-WindSim (k) WRF direct (l) WRF virtual point

Figure 3: Wind Roses: top row February, middle row June and last row October

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