PAPER • OPEN ACCESS

Evaluation of the Weather Research and Forecasting (WRF) model with respect to wind in complex terrain

To cite this article: Kine Solbakken and Yngve Birkelund 2018 *J. Phys.: Conf. Ser.* **1102** 012011

IOP Conf. Series: Journal of Physics: Conf. Series **1102** (2018) 012011 doi:10.1088/1742-6596/1102/1/012011

Evaluation of the Weather Research and Forecasting (WRF) model with respect to wind in complex terrain

Kine Solbakken and Yngve Birkelund

Department of Physics and Technology, UiT, The Arctic University of Norway

E-mail: kine.solbakken@uit.no

Abstract. In this study the performance of the Weather Research and Forecast (WRF) model in a complex and coastal terrain has been evaluated with focus on wind resource assessment. The study area is a small community on the northern part of the island Senja, Norway. The community, with fishery and seafood as its main industry, is being limited by poor grid connection. One of the solutions is to increase the production of local power from wind energy. There are no in-situ wind measurements in the area, and therefore numerical weather prediction models, namely the WRF model, is being evaluated as a method for wind resource assessment. The WRF model has been run for the whole of 2017 with high resolution covering an area large enough to include the three closest weather stations. The model is compared to the observed wind speed and direction. It is found that the model is able to reproduce the average wind speed and wind direction quite well for two of the locations, while for the third location the average wind speed is considerably overestimated compared to the observations. The Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) found are larger than in other comparable studies.

1. Introduction

The aim of this study is to evaluate how well the Weather Research and Forecasting (WRF) model is able to reproduce the wind speed and the wind direction in a specific area in Northern Norway characterized by a complex and coastal terrain. A full year of WRF simulation results have been compared to in-situ wind observations retrieved from three weather stations provided by the Norwegian Meteorological Institute (MET).

The area of interest is a small community with a population of about 5000, located on the northern part of the island Senja, Norway. The main industry is fishery and seafood production. To be able to keep competing on a global market, the industry is currently facing large changes in terms of a more efficient and automated production line. The new technology, combined with a need for larger cooling and freezing facilities, will increase the energy demand. However, the grid capacity and the quality of the power supply have become limiting factors for economical growth. Already, the total power and energy load have, on several occasions, been higher than the grid capacity.

There are three suggested solutions for this problem. The first is to strengthen the regional power grid with a submarine power cable from the main land to the island. The second option is to supplement with power from a diesel generator, a solution that has been working for one of the neighboring islands.The third option is to introduce new local production of renewable energy and the use of a micro power grid to ensure efficient use of the energy in the community.

The local industry and the community want to keep a sustainable profile. Together with the grid owner, they are investigating the possibility of increasing the energy efficiency as well as the use of local renewable sources such as solar, wind and geothermal energy. In this study the focus will be on wind power resource assessment. Wind energy is considered a mature and economical technology and is currently one of the fastest growing renewable energy sources, both worldwide and in Norway [1, 2].

Some of the standard methods for assessing the wind energy potential are by local wind measurements, either wind measurement campaigns or from meteorological weather stations; extrapolation of free atmospheric wind from global data sets; or by use of wind atlases [3]. For the specific area of interest in this study, there are no in-situ measurements, and because of the complex terrain, use of global data sets or wind atlases might give insufficient results [4].

Another method, that has proven to give a good first approximation of the wind energy resource, is Numerical Weather Prediction (NWP) models. NWP models have certain advantages compared to real measurements, such as low cost, high resolution both horizontally and vertically over a large area, they do not have missing data and can provide long time series of data in a short amount of time [1]. However, NWP models are only an approximation to the real atmosphere due to simplification of the topography and the physical processes [5]. Therefore, for this study, performed in an area characterized by coastal and mountainous topography, it is important to emphasize that the observed wind can be affected by local conditions that the model is not able to capture. The wind retrieved from the model is generated over large grid cells with an average topography and roughness that can be very different from the real conditions [6]. Methods to achieve a better comparison of the simulations and the observations could for instance be by coupling of the NWP model with a micro scale model [5]; or by generalizing both the observed and simulated wind to a common elevation and roughness level as described in [6]. Further down scaling is consider to beyond the scope of this paper, and therefore the observations and the simulations will be compared directly.

The NWP model chosen for this study is the WRF model. Several studies have evaluated the performance of WRF with a special focus on the model's ability to reproduce the wind speed [7, 8, 9, 10]. A good agreement between the WRF model simulations and wind speed measurements for areas characterized by a complex terrain, are reported in [11, 12, 13]. Typically for these studies are low biases between the observed wind speeds and the simulated wind speed. When also the temporal simultaneity is considered, the deviation is larger. It is also found that the WRF model tend to overestimate the low wind speed and underestimate the higher wind speeds. In the study by [10], special attention is given to the WRF models ability to reproduce the wind direction.

The focus of this paper is the performance of the WRF model's ability to reproduce the wind speed and direction. In section 2 the method for the study is presented, in section 3 the results are presented and discussed and section 4 gives the conclusion.

2. Approach

2.1. Study area and the measured wind data

The study area is located at the northern part of the island Senja, shown in figure 1 at $69°18''$ N and $17°40''$ E. The area covers approximately $800km^2$ and consists of complex terrain with fjords and steep mountains. The elevation ranges from sea level to 1000 meters above mean sea level (a.m.s.l.). The main wind pattern along the coast of Northern Norway is dominated by both westerlies and polar fronts.

The focus of this study is the northern part of the island Senja. However, there are no available wind observations within this area. Therefore, the WRF model has been set up to

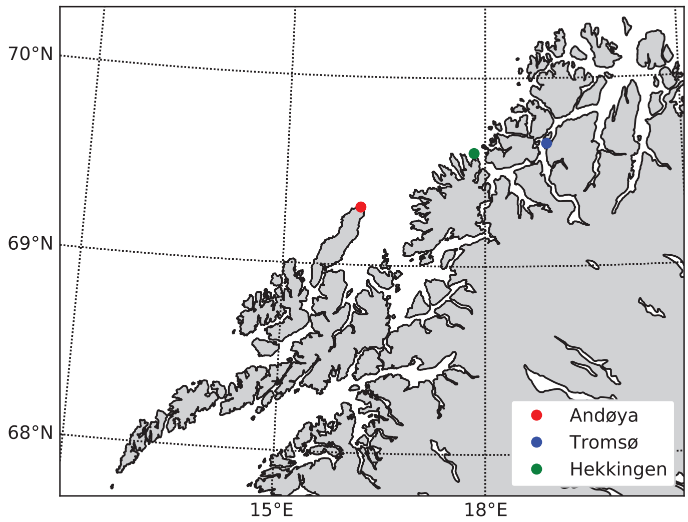

Figure 1: Map of the study area including the locations of the three meteorological stations.

Station name	Station number	Latitude ($°N$)	Longitude ($°E$)	Elevation (m a.s.l.)	Elevation in WRF (m a.s.l.)
Andøya	87110	69.3073	16.1312	10	7.6
Tromsø	90450	69.6536	18.9368	100	52
Hekkingen	88690	69.6013	17.8303	14	8

Table 1: Summary of the characteristics of the meteorological weather stations the wind observations are retrieved from. The elevation is given in meters above sea level (m a.s.l.). In addition, the model terrain heights of the closest grid point to each of the locations are also listed here.

cover an area of 18 000 km^2 to also include the three closest weather observation stations. The extended area has similar topography to that found on Senja. The three weather observation stations are operated by the Norwegian Meteorological Institute (MET) and the exact location and elevation above sea level can be found in table 1. All the wind measurements are retrieved from 10 meters above ground.

The quality of the data from 2017 retrieved from these station are good in terms of few missing data points. For Tromsø and Hekkingen less than 1% of the data for 2017 are missing. For Andøya, 2.3% of the data are missing, mainly in the short time periods 13th to 18th of July, 25th of July to 4th of August and 28th to 29th of August. For the time steps where observational data are missing, the corresponding data has been excluded from the model results.

2.2. Model set up and numerical simulations

The NWP model used in this study is the Advanced Research WRF (ARW) version 3.9.1. A detailed description can be found in [14]. The 20-category Moderate Resolution Imaging Spectroradiometer (MODIS) land use data and the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) have been selected. Both the datasets were retrieved from the National Center for Atmospheric Research (NCAR) and have a resolution of 30 arc-seconds. The numerical simulations were initialized by the ERA-Interim reanalysis data provided by the

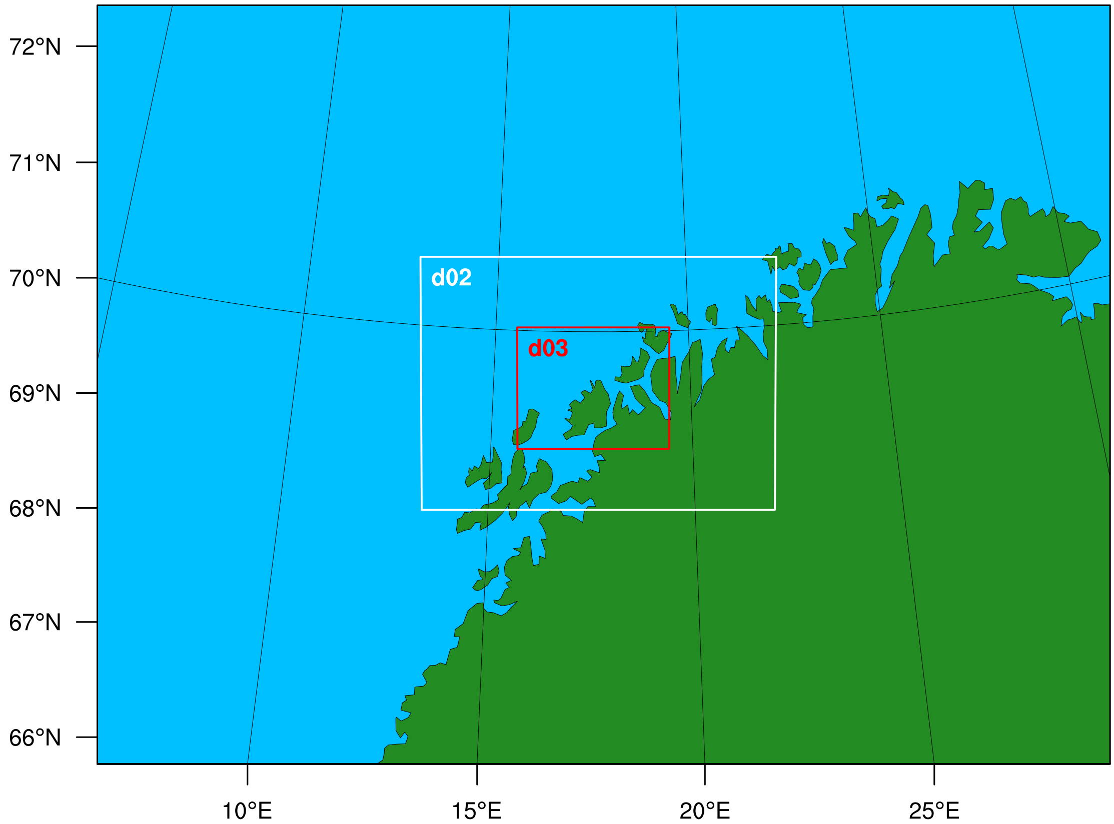

Figure 2: WRF domain d01, d02 and d03 with 25 km, 5 km and 1 km resolutions respectively.

European Center for Medium-Range Weather Forecast (ECMWF). The spatial resolution of the input data is approximately 80 km over 38 vertical pressure levels with a temporal resolution of 6 hours. The ERA-Interim data have been down scaled by the WRF model through three domains as illustrated in figure 2. The outermost domain is hereafter referred to as d01, the second as d02 and the innermost as d03. The grid size of the domains are reduced by a factor of 5 from 25 km in d01 to 1 km in d03. A one-way nesting strategy is applied, were the flow of information goes from the coarser domains to the finer domains, with no feedback. The center of d01 is at the latitude $69°154''42'$ N and longitude $17°66''00'$ E and corresponds to the north end of the island Senja. Polar stereographic projection is used as recommended for high latitudes. Domain d01 covers a large area of 775 km in north-south direction and 1025 km in east-west direction to ensure all large scale events are included. The inner domain, d03, covers an area that includes the locations of the three meteorological weather stations and stretches 121 km in north-south direction and 151 in east-west direction. The vertical structure consists of 50 terrain following vertical coordinates. To ensure numerical stability a time step of 5 seconds is used in d03.

For the physical configuration, the model offers a wide range of options for how to parametrize the physical sub-grid processes. This allows an optimal set up for the study case. In this study the CONUS configuration has been adopted, which consists of the following parametrization schemes: Thompson micro physics scheme, the Mellor–Yamada–Janjic scheme (MYJ) scheme to represent the planetary boundary layer physics, the Tiedtke scheme for the cumulus parametrization, the Monin-Obukhov Eta scheme for the surface layer processes, the Noah

Land Surface Model and the RRTMG schemes for short- and long-wave radiation [14].

The simulations have been initialized every week through 2017, and run for eight days. The first 24 hours of each week are considered to be spin up time for the simulations. A time period of one year is considered to be sufficient to determine diurnal and seasonal variations for wind resource assessment purposes [1]. Therefore, the same period has been considered to be sufficient also for this study. All the results discussed in this paper are 10 minute average values retrieved from the inner most domain at 10 meter height above ground from the same position as the meteorological stations. This is achieved by linear interpolation between the two closest grid points in the domain. The model terrain height for the closest grid point to each of the three stations have been listed in table 1

2.3. Evaluation methods

The following statistical measures are used to compare the deviation θ' between the numerical simulations and the measurements; root mean square error (RMSE), mean absolute error (MAE) and bias and are given by the following equations:

$$RMSE = \Big[\frac{1}{N}\sum_{i=1}^{N}(\theta_i')^2\Big]^{\frac{1}{2}} \tag{1}$$

$$Bias = \frac{1}{N}\sum_{i=1}^{N}\theta_i' \tag{2}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|\theta_i'| \tag{3}$$

Where for the wind speed, the deviation θ' is given by

$$\theta' = \theta^{sim} - \theta^{obs} \tag{4}$$

This is also true for the wind direction when the deviation is less than or equal to 180°. If $|\theta'| > 180°$ [12], then

$$\theta_i' = (\theta_i^{sim} - \theta_i^{obs}) \times \left(1 - \frac{360}{|\theta_i^{sim} - \theta_i^{obs}|}\right) \tag{5}$$

The MAE gives the mean of the deviation θ' between corresponding observation and simulation pairs. The RMSD gives the mean of the square of the deviation θ'. Due to the square operation, the RMSD emphasizes instances with large deviation. The bias gives the deviation between the observation sample mean and the simulated sample mean.

Another statistical measure often used to characterize the distribution of wind speed is the Weibull probability distribution function (PDF) [15]. The Weibull PDF is given by the following equation

$$f(U;\beta,\alpha) = \beta\alpha^{-\beta}U^{(\beta-1)}e^{-(\frac{U}{\alpha})^{\beta}} \tag{6}$$

The shape parameter β controls the shape of the function and the scale parameter α controls the width of the function.

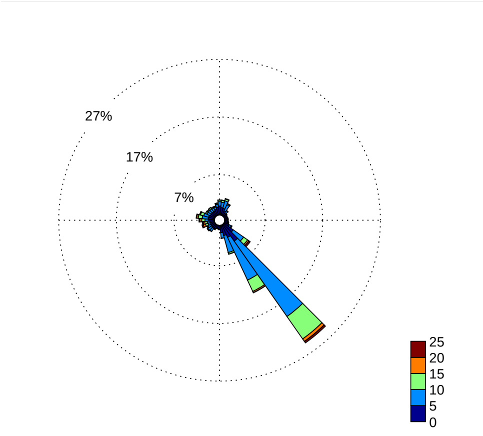

Figure 3: Observations, Hekkingen.

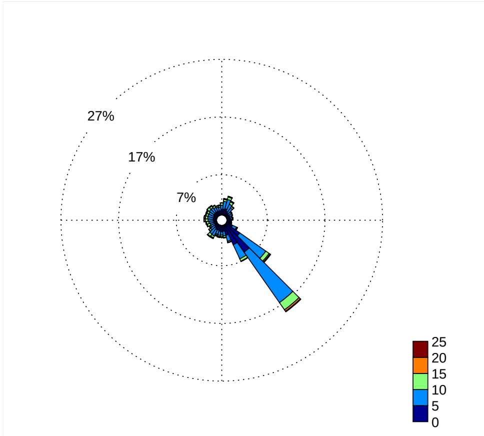

Figure 6: WRF, Hekkingen.

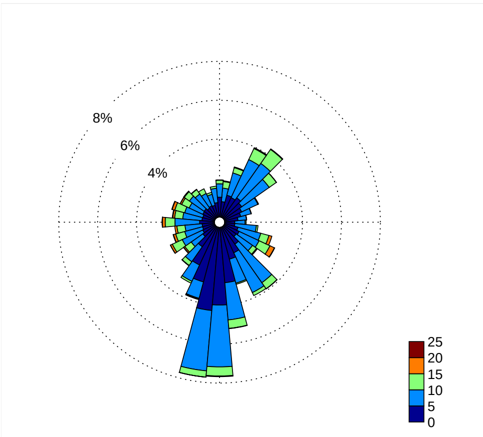

Figure 4: Observations, Andøya.

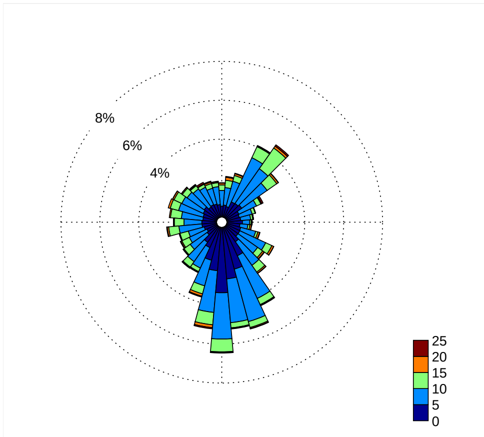

Figure 7: WRF, Andøya.

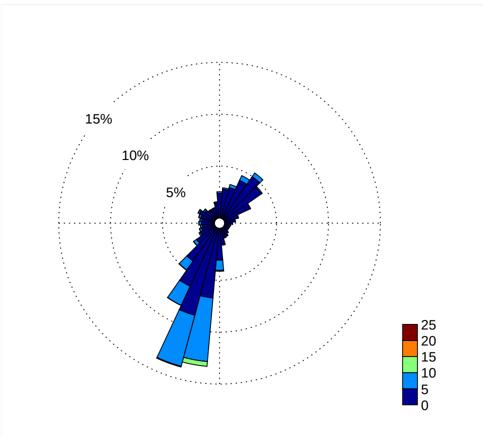

Figure 5: Observations, Tromsø.

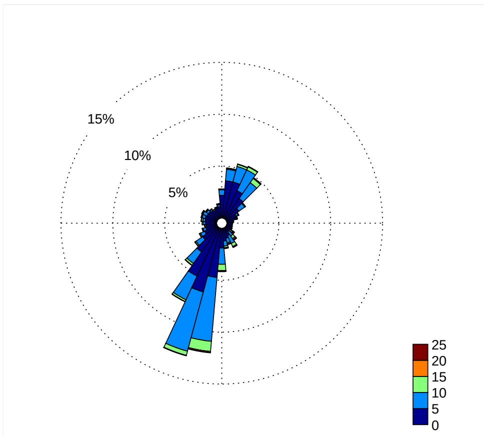

Figure 8: WRF,Tromsø.

3. Results

The WRF simulations are carried out over the year 2017 and compared to the in-situ measurements from the three locations Hekkingen, Andøya and Tromsø.

The observations from the three locations are presented as wind roses in figure 3, 4 and 5 and the model results in figure 6, 7 and 8. The circles represent in percentage how often the wind blows from a certain direction. The color bar gives the magnitude of the wind, where blue is the lowest wind speed and red the highest wind speeds. When comparing the wind roses for the observed data with the model results, it is evident that the model is able to reproduce the distribution of the wind directions well for all locations.

The observations for Hekkingen show a clear main wind direction from the south-east. The model is able to capture this but has some higher wind speeds than the observations. For Andøya the observations show a diverse distribution of wind direction with two main directions, one from the north-east and one from the south. The model show a similar distribution. Also for Tromsø the model is able to reproduce the main wind direction from south south-west. For all locations the model captures the main wind direction well, but with a slightly lower frequency compared to the observations.

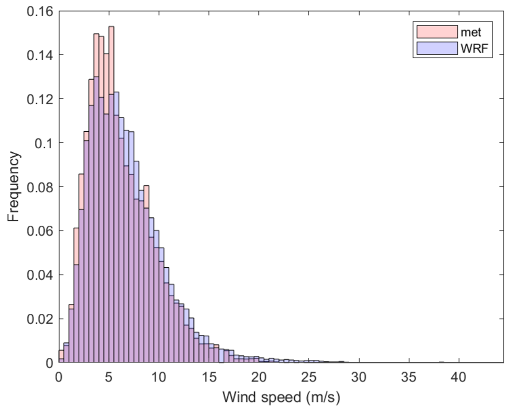

Figure 9: Wind speed PDF for Andøya.

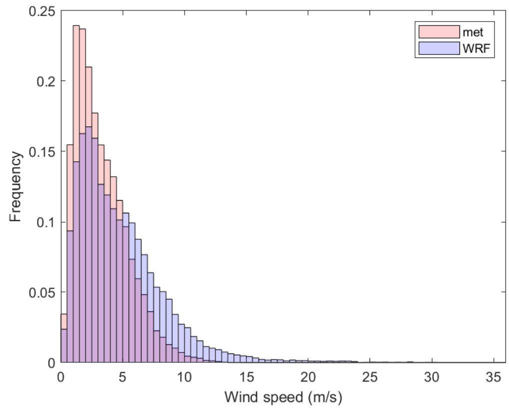

Figure 10: Wind speed PDF for Tromsø.

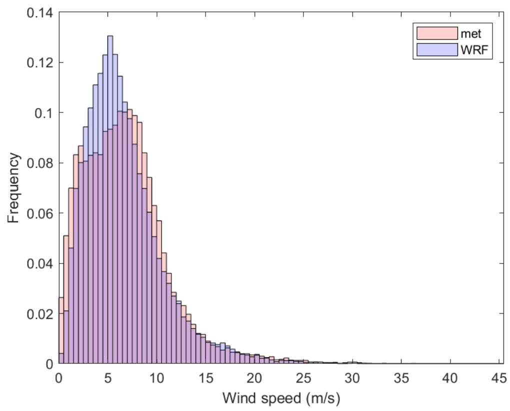

Figure 11: Wind speed PDF for Hekkingen.

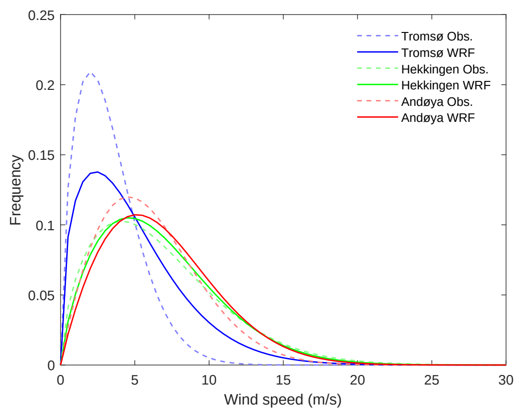

Figure 12: Weibull PDF plot for Hekkingen, Tromsø and Andøya.

The wind roses give a good indication on the model's ability to reproduce the observed wind field, especially with respect to the wind direction. To gain a better understanding of the model's ability to reproduce the magnitude of the wind, the distributions of the wind speeds are presented in figure 9, 10 and 11 for Andøya, Tromsø and Hekkingen respectively.

	Mean		Scale		Shape	
	Observations	WRF	Observations	WRF	Observations	WRF
Tromsø	3.26	4.84	1.61	1.44	3.65	5.36
Hekkingen	6.70	6.67	1.61	1.74	7.45	7.52
Andøya	6.11	6.81	1.88	1.88	6.88	7.70

Table 2: The mean of the observed and simulated wind speeds and the Weibull PDF scale and shape parameters.

For both Andøya and Tromsø the model tends to overestimate the frequency of the wind speeds above ∼6 m/s and underestimate for wind speeds below this. For Hekkingen, on the other hand, the model underestimates the frequency of wind speeds above ∼7 m/s and wind speed below ∼2 m/s, while it underestimates for the moderate wind speeds. For all locations, the difference in frequency is largest for the moderate wind speeds. The model performs better for Hekkingen than it does for Andøya and especially when compared to Tromsø. The wind observations are done at 10 meters above ground. It is therefore not unlikely that the observations are influenced by obstacles in close vicinity. The weather station Tromsø is located within the city area, while Hekkingen is a small unpopulated island in the ocean.

The Weibull PDFs in figure 12 derived from the observations and the simulations show similar results. For Hekkingen the Weibull PDFs are in good agreement with a slight shift to the right. Andøya have a larger deviation between the two Weibull PDFs but still comparable. For Tromsø on the other hand, the underestimation of the frequency of low to moderate wind speeds and the overestimation for the high wind speed is evident.

The corresponding scale and shape parameters are presented in table 2. The best results are found for Hekkingen, with only small differences between the scale and the shape parameters derived from the observed and the model results. However, when comparing to the study by [12] the difference between these parameters are larger. In the study by [12] the wind measurements the WRF simulation was compared with was done at 60 m agl., while in this study it is done 10 m agl. In the study by [11] the performance of WRF was evaluated against observations done at several heights. It was found that the biases were considerable larger at the lowest measuring point at 40 m agl. than for the measurements done higher up.

In table 3 a statistical evaluation of the performance of the model for both wind speed and direction is summarized in terms of RMSE, bias and MAE.

The wind speed bias gives an indication of the model's tendency to over- or underestimate the results compared to the observations. The wind speed bias for Andøya indicates a slight overestimation of the mean wind speed. The bias for Tromsø shows a considerable overestimation. The bias for Hekkingen is close to zero and therefore shows no clear over or under estimation of the model simulations. The larger biases for Tromsø and Andøya might be related to the model's representation of the topography. Due to the resolution of the model, the complex topography is smoothed. While the observed wind speed is slowed down due to the topography, the smoothed representation will result in a lower friction and therefore higher wind speed [12]. For the wind direction, the biases show a good agreement between the simulated and the observed wind direction for all locations. Andøya has the lowest bias, where the simulated direction is slightly rotated clockwise compared to the observations. For Tromsø and Hekkingen the biases are larger and show a counter clockwise rotation.

The RMSE and the MAE show a quite high deviation between the model and the observations both for the wind speed and direction. Compared to similar studies [9, 12] the RMSE is larger. Especially the RMSE for wind direction are larger than what is found in [10]. It is evident that even though the wind roses and the biases show a good agreement between the observed and

	RMSE		Bias		MAE	
	Speed (ms^{-1})	Dir.(°)	Speed (ms^{-1})	Dir.(°)	Speed (ms^{-1})	Dir.(°)
Tromsø	3.57	112	1.58	-5.25	2.40	72
Hekkingen	4.10	101	-0.02	-3.21	3.02	60
Andøya	3.50	92	0.69	0.21	2.43	52

Table 3: The RMSE, bias and MAE for Tromsø, Hekkingen and Andøya. The speed is given in m/s and the direction (Dir) is given in degrees.

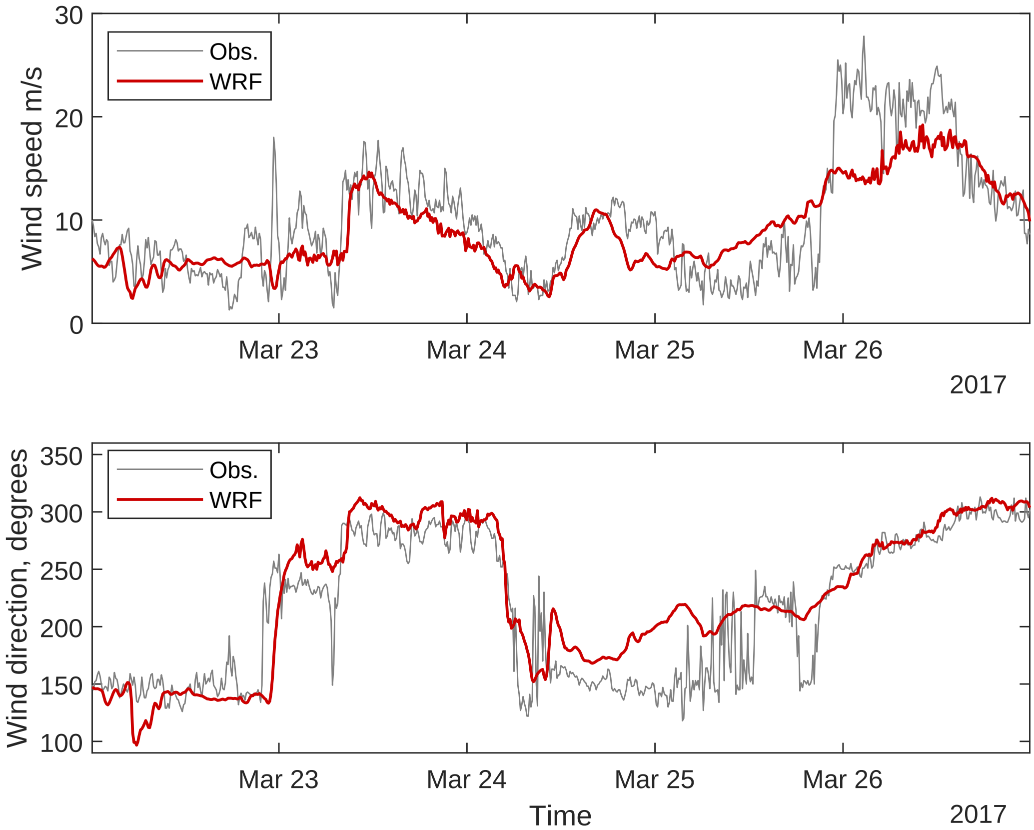

Figure 13: An example period of the observed and the simulated wind speed and direction for Hekkingen. The upper plot show the wind speed and the bottom plot show the wind directions for the observations (in grey) and the WRF simulations (red).

simulated wind direction, the RMSE and MAE indicates that the model has some challenges. The wind roses and biases show that the model is able to reproduce the annual average wind directions quite well, but when the temporal similarities is considered, the deviation between the simulations and the observations are more severe.

A short period of the wind speed time series are shown in the upper plot in figure 13 and the wind direction for the corresponding time in the plot under. The WRF wind speed and the direction follow the general trend seen in the measurements, but the model is not capable of reproducing the rapid variations seen in the measurements. An example of overestimation of low wind speed, and underestimation of high wind speed, can also be identified at March 25th and in the start of March 26th, respectively.

4. Conclusion

The aim of this study is to evaluate the performance of the WRF model in a complex and coastal terrain with respect to wind speed and direction. WRF simulations have been run for one year and compared to wind observations from three weather stations located close to the area of interest. A good agreement is found for two of the locations when comparing the annual averages of the WRF simulations and the observations. At the third location the model overestimates the wind speed but is able to capture the wind direction quite well.

The RMSE and the MAE indicate that there are still challenges when it comes to accurately reproducing the wind field in a complex terrain. Reasons for the high values for RMSE and MAE should be investigated further. Some of the deviations found can be related to the fact that the model results are compared to wind measurements done at 10 m agl. where obstacles in close vicinity might influence the measurements. A further study should therefore also include wind observations at wind turbine hub height to ensure a more accurate evaluation of the model for wind resource assessment purposes.

Meso-scale numerical weather prediction models have proven to give satisfactory first estimates of the wind fields and can be used to locate promising sites with respect to wind power. WRF is a widely used and tested model and gives results in good agreement with observations. However, near-surface wind modeling remains challenging, especially for areas with complex terrain. Further research must therefore be done to identify weaknesses and improve the models.

References

[1] Al-Yahyai S, Charabi Y and Gastli A 2010 *Renewable and Sustainable Energy Reviews* **14** 3192 – 3198 ISSN 1364-0321 URL `http://www.sciencedirect.com/science/article/pii/S1364032110001814`

[2] Weir D E and Aksnes N 2018 Vindkraft -produksjon i 2017/Wind Power -Production in 2017 Tech. Rep. 10 Norges vassdrag - og energidirektorat

[3] Landberg L, Myllerup L, Rathmann O, Petersen E L, Jørgensen B H, Badger J and Mortensen N G *Wind Energy* **6** 261–271 (*Preprint* `https://onlinelibrary.wiley.com/doi/pdf/10.1002/we.94`) URL `https://onlinelibrary.wiley.com/doi/abs/10.1002/we.94`

[4] Kunz M, Mohr S, Rauthe M, Lux R and Kottmeier C 2010 *Natural Hazards and Earth System Sciences* **10** 907–922 URL `https://www.nat-hazards-earth-syst-sci.net/10/907/2010/`

[5] Carvalho D, Rocha A, Santos C S and Pereira R 2013 *Applied Energy* **108** 493 – 504 ISSN 0306-2619 URL `http://www.sciencedirect.com/science/article/pii/S0306261913002705`

[6] Larsén X G, Badger J, Hahmann A N and Mortensen N G *Wind Energy* **16** 1167–1182 (*Preprint* `https://onlinelibrary.wiley.com/doi/pdf/10.1002/we.1544`) URL `https://onlinelibrary.wiley.com/doi/abs/10.1002/we.1544`

[7] Caroline D, N H A, Alfredo P and Gregor G *Wind Energy* **17** 39–55 (*Preprint* `https://onlinelibrary.wiley.com/doi/pdf/10.1002/we.1555`) URL `https://onlinelibrary.wiley.com/doi/abs/10.1002/we.1555`

[8] El-Samra R, Bou-Zeid E and El-Fadel M 2018 *Atmospheric Research* **203** 68 – 82 ISSN 0169-8095 URL `http://www.sciencedirect.com/science/article/pii/S0169809516305798`

[9] Giannaros T M, Melas D and Ziomas I 2017 *Renewable Energy* **102** 190–198 URL `http://dx.doi.org/10.1016/j.renene.2016.10.033`

[10] Jiménez P A and Dudhia J 2013 *Journal of Applied Meteorology and Climatology* **52** 1610 URL `https://journals.ametsoc.org/doi/10.1175/JAMC-D-12-0266.1`

[11] Fernández-González S, Martín M L, García-Ortega E, Merino A, Lorenzana J, Sánchez J L, Valero F and Rodrigo J S 2018 *Journal of Applied Meteorology and Climatology* **57** 733–753 (*Preprint* `https://doi.org/10.1175/JAMC-D-17-0121.1`) URL `https://doi.org/10.1175/JAMC-D-17-0121.1`

[12] Carvalho D, Rocha A, Gómez-Gesteira M and Santos C S 2014 *Applied Energy* **117** 116 – 126 ISSN 0306-2619 URL `http://www.sciencedirect.com/science/article/pii/S0306261913009847`

[13] Byrkjedal Ø and Berge E 2008 *Kjeller Vindteknikk AS*

[14] Skamarock W C, Klemp J B, Dudhia J, Gill D O, Barker D M, Duda M G, Huang X Y, Wang W and Powers J G 2008 1–113 URL `http://www2.mmm.ucar.edu/wrf/users/docs/arw`$_v$*3.pdf*

[15] Morgan E C, Lackner M, Vogel R M and Baise L G 2011 *Energy Conversion and Management* **52** 15 – 26 ISSN 0196-8904 URL `http://www.sciencedirect.com/science/article/pii/S019689041000227X`