High Resolution Atmospheric Modeling for Wind Energy Applications

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Disclaimer & Auspices

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EXECUTIVE SUMMARY

The ability of the WRF atmospheric model to forecast wind speed over the Nysted wind park was investigated as a function of time. It was found that in the time period we considered (August 1—19, 2008), the model is able to predict wind speeds reasonably accurately for 48 hours ahead, but that its forecast skill deteriorates rapidly after 48 hours. In addition, a preliminary analysis was carried out to investigate the impact of vertical grid resolution on the forecast skill. Our preliminary finding is that increasing vertical grid resolution does not have a significant impact on the forecast skill of the WRF model over Nysted wind park during the period we considered. Additional simulations during this period, as well as during other time periods, will be run in order to validate the results presented here.

1 INTRODUCTION

Wind speed is a difficult parameter to forecast due the interaction of large and small length scale forcing. To accurately forecast the wind speed at a given location, the model must correctly forecast the movement and strength of synoptic systems, as well as the local influence of topography / land use on the wind speed. For example, small deviations in the forecast track or strength of a large-scale low pressure system can result in significant forecast errors for local wind speeds.

The purpose of this study is to provide a preliminary baseline of a high-resolution limited area model forecast performance against observations from the Nysted wind park. Validating the numerical weather prediction model performance for past forecasts will give a reasonable measure of expected forecast skill over the Nysted wind park. Also, since the Nysted Wind Park is over water and some distance from the influence of terrain, the impact of high vertical grid spacing for wind speed forecast skill will also be investigated.

2 MODEL DESCRIPTION

The non-hydrostatic Weather Research and Forecast (WRF) atmospheric model was used in this study. WRF is a community-supported model suitable for applications on scales from meters to thousands of kilometers. The WRF model uses several physics schemes to parameterize sub-grid scale phenomena, such as mixing in the planetary boundary layer and sub-surface heat and moisture fluxes. WRF is used widely among atmospheric science researchers, as well as in the private sector for operational weather forecasting. One significant advantage of running WRF is the ability to run a simulation on multiple processors, making finer resolution forecasts in real time a possibility.

Initial and boundary conditions for the WRF simulations for this study were provided by the Global Forecast System (GFS) model. GFS input data are available at 0.5 degree resolution on 27 standard pressure levels. Forecast boundary conditions are updated at 3-hour intervals using GFS data. High-resolution sea surface temperature (SST) data at 1/12 degree resolution were also used for the simulations. Daily updated SST data were provided by the National Center for Environmental Prediction (NCEP). Running WRF with high-resolution SST data is essential to producing accurate wind speed forecasts for an offshore wind park, such as Nysted, because the ocean temperature plays a significant role in near-surface stability and momentum transport.

The WRF model was run from 00:00 on 1 August until 00:00 on 19 August 2008 at 12-hour cycles (00:00 and 12:00 UTC), resulting in 36 simulations. Each simulation was run to produce a 72-hour forecast. However, 3 forecast simulations did not complete due to Courant-Friedrichs-Lewy (CFL) condition violations associated with high wind speed events. These simulations failed even though a conservative numerical time step was used to account for the high vertical grid resolution in the lower atmosphere. As a result, a total of 33 complete 72-hour forecasts were generated. August of 2008 was selected as a study period due to the availability of quality controlled observations from several meteorological observation towers located within and just outside of the Nysted wind park. Also, there were several high and low wind speed events during August 2008, making it an ideal month to validate WRF performance over a variety of synoptic conditions.

A triple-nested model domain configuration was used for the WRF validation simulations, as shown in **Figure 1**. Horizontal grid spacing of the WRF domains is 27, 9, 3, and 1 km, respectively. For each domain, 70 terrain-following vertical levels are used with a resolution of approximately 10 meters in the lowest 200 meters of the atmosphere. The outer domain is large enough to cover most of Europe and resolve large-scale synoptic flow. The innermost domain is centered over the Nysted wind park. Detailed information about the numerical domains, such as the number of grid points, is provided in **Table 1**.

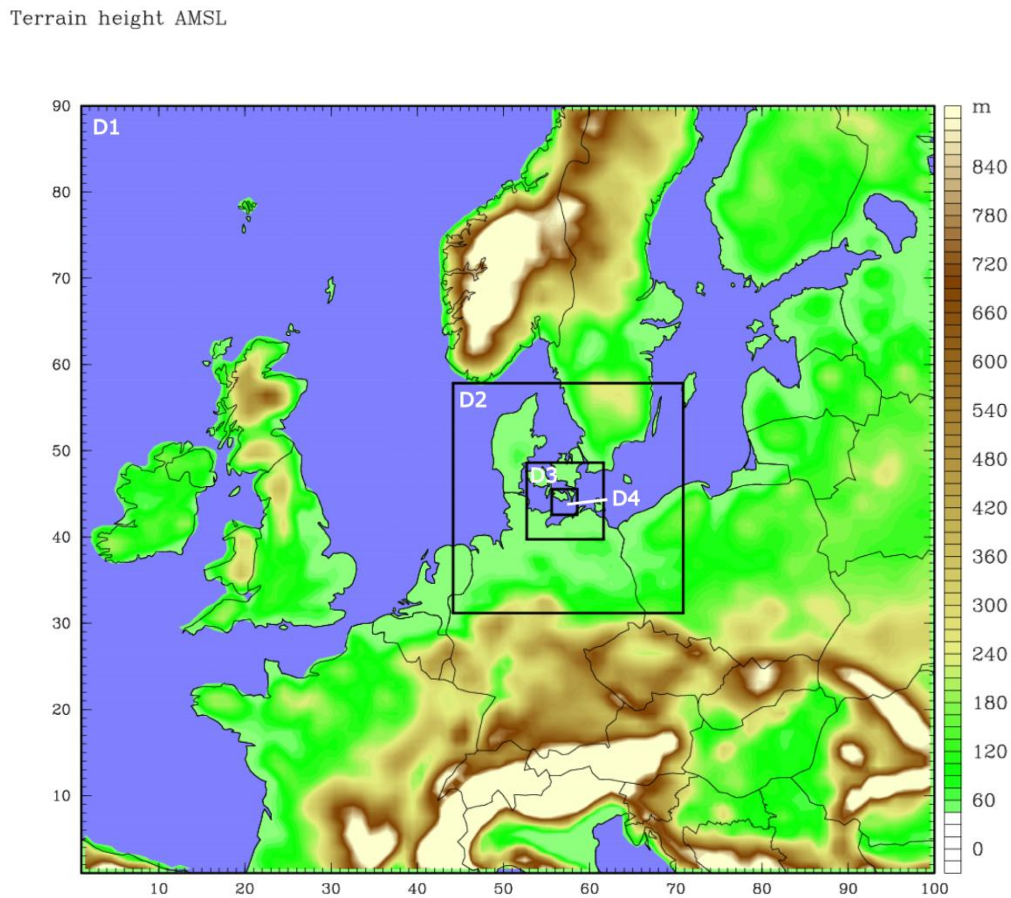

Figure 1. WRF model domains at 27, 9, 3, and 1 km horizontal grid spacing used for validation study over the Nysted wind park. Terrain elevation is shown in color contours.

Due to the large computational demand of running WRF at both high horizontal and vertical resolution, the WRF validation simulations were run with a single physics configuration producing a deterministic forecast. The physics schemes used for the simulations are provided in **Table 2.**

3 DISCUSSION OF RESULTS

Forecast winds are compared with observations from meteorology tower 84 at the Nysted wind farm. Wind speed observations at the Nysted wind park are available at 10-minute intervals. The wind speed observation at the top of the hour was used for comparison with hourly WRF wind speed forecasts.

Tower 84 is located 5 km east of the nearest row of wind turbines, as shown in **Figure 2**. A previous study (Christiansen and Hasager, 2005) has shown that there may be pronounced wake effects at this distance. While ideally a tower with minimal or no wake effects should be used in such a study, all the other towers, with the exception of towers 83, were found to have faulty wind direction values. Moreover, tower 83 would experience even greater wake effects than tower 84, so tower 84 was the best available source of wind speed data. As a result, due to the likely presence of the wake effects in the data that were used, the model forecast error presented in this report is probably larger than the actual error. A subsequent forecast skill report will account for wake effects by using multiple towers if sufficient wind direction data are available. Another option will be to remove tower 84 observations from the validation statistics when the wind direction is from the region of the turbine array.

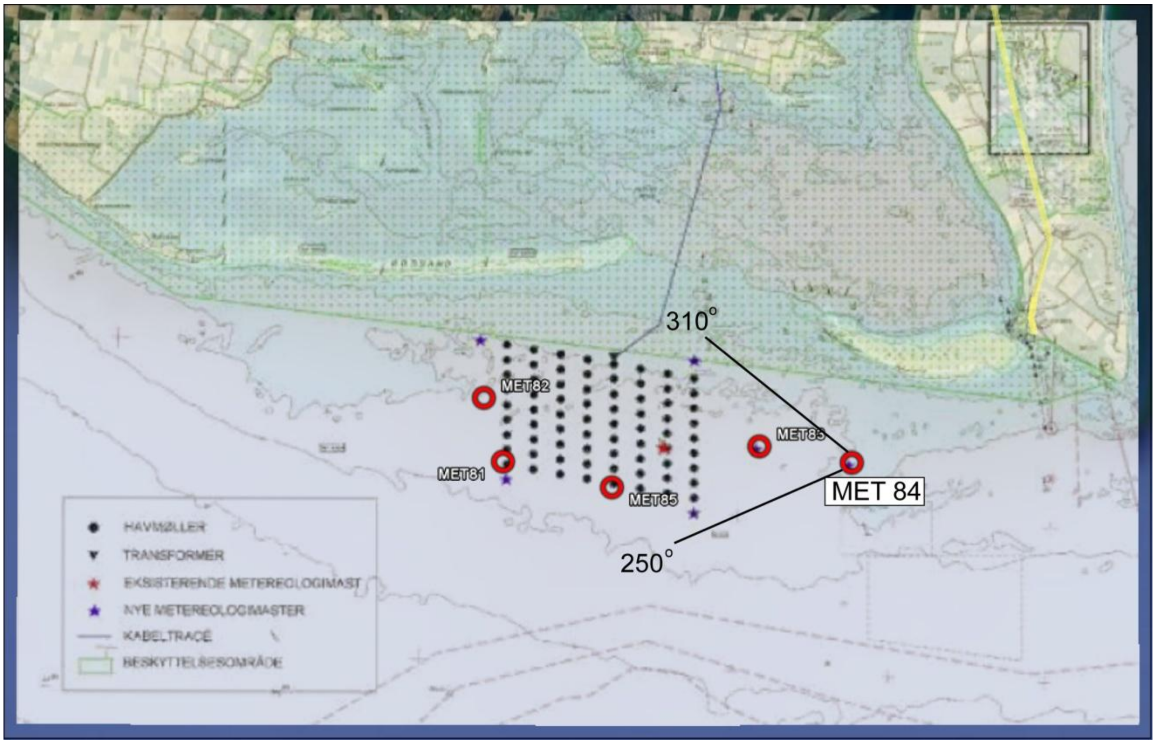

Figure 2. Map showing the location of meteorology tower 84 relative to Nysted wind park turbine array.

Mean absolute difference (MAD) is a statistical metric used to measure the average magnitude of error in a forecast data set without considering the direction of the error. MAD of WRF forecasted wind speed at 68 meters above ground compared with observations at Nysted meteorology tower 84 is shown in **Figure 3**. On average, during the first 12 hours of the WRF simulations, the forecasted wind speed was within roughly 1.6 m/s of the observed wind speed. After the first 12 hours, a continual increase in MAD is observed, illustrating the reduction in forecast skill with respect to forecast hour. By the end of the 72 hour forecasts, on average, the MAD was around 3.0 m/s.

One feature in the plot of MAD values versus forecast hour in Figure 3 is the steep rise and subsequent fall in the MAD values, occurring roughly every 12 hours. Since this does not occur at the beginning of 12-hour cycles, this is probably not due to the cold start effect. As the number of simulation runs was relatively small (33), this effect may be due simply to a random chance. We plan to run more simulations and if this effect is still present with a larger number of runs, investigate its possible causes.

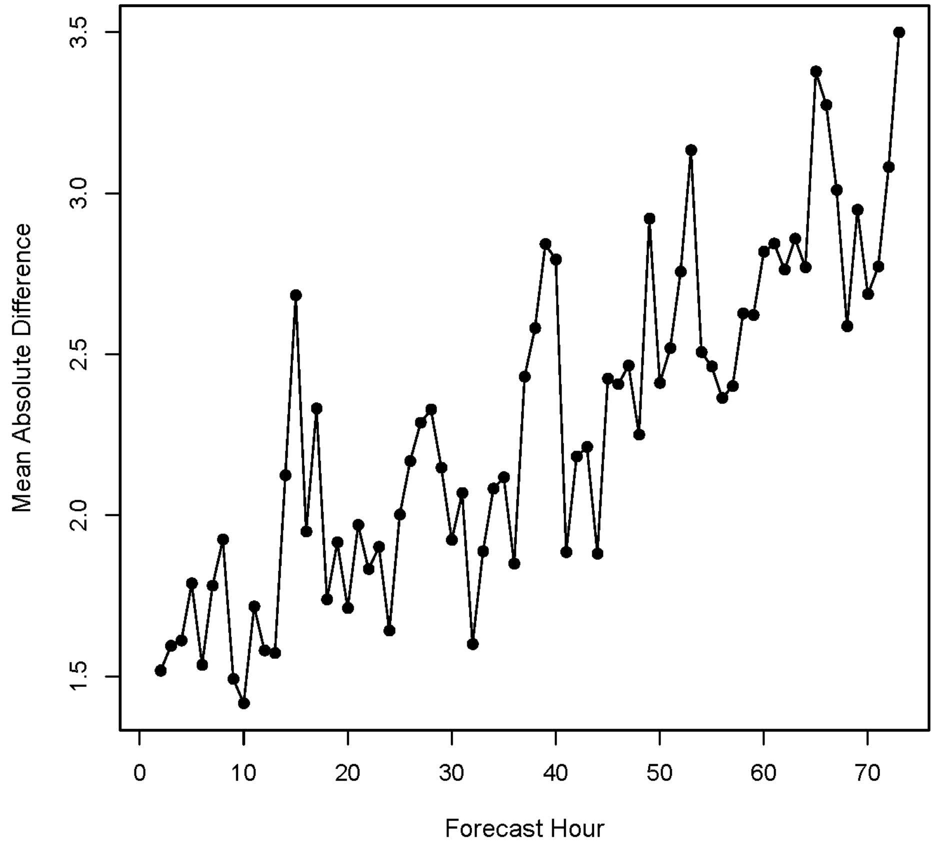

Figure 3. Mean absolute difference between WRF forecast and observed wind speeds as a function of forecast hour.

Since the MAD metric only reflects the mean forecast error, we also investigated the distributions of individual absolute differences (AD), grouped by 24-hour periods for easier exposition. The estimated probability density functions of the absolute differences for Day 1 (all ADs for forecast hours 0-24), Day 2 (all ADs for forecast hours 25-48), and Day 3 (all ADs for forecast hours 49-72) are shown in **Figure 4**. As expected, with each day, the distributions peak at slightly higher values and are more skewed toward larger values of AD. The vast majority of the Day 1 and 2 forecasts, the predicted wind speed was within ±4 m/s of the observed value. It is only on rare occasions that the AD was greater than ±5 m/s for Day 1 and

2 forecasts (4% of 780 individual Day 1 forecasts and 8% of 732 individual Day 2 forecasts, respectively). The equivalent proportion for Day 3 forecasts was much greater: 16% of 683 individual forecasts.

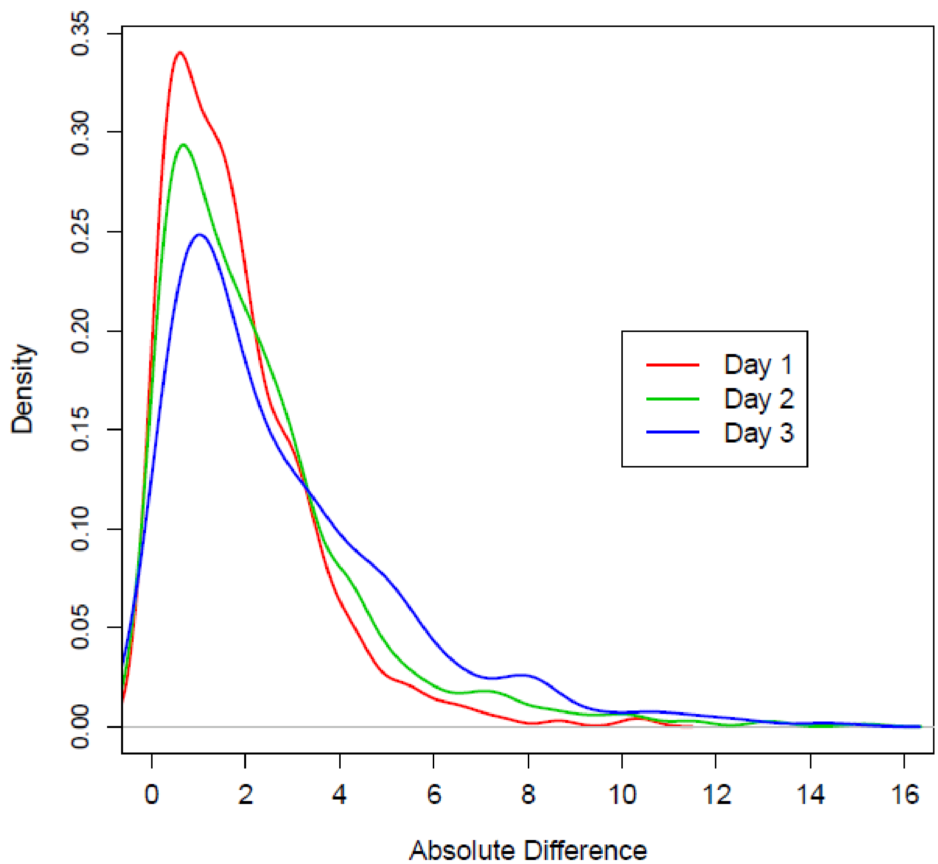

Figure 4. Estimated probability density functions of individual absolute differences for forecast Day 1, 2, and 3.

The mean difference (MD), or bias, is another useful metric for evaluating forecast skill. Bias represents the average magnitude and direction of the deviation of forecast values from observations. Investigating the model bias of WRF over the Nysted Wind Park will reveal if there is any systematic bias in the forecast, i.e., whether the model consistently over- or underpredicts the wind speed. The mean difference as a function of forecast hour for the Nysted WRF simulations is shown in

Figure 5. When considering the entire 72-hour forecast duration, the model appears to overpredict the wind speed more frequently than underpredict it. However, there does not seem to be a very clear trend, and additional simulations are likely necessary to make any definitive conclusions of model bias over Nysted.

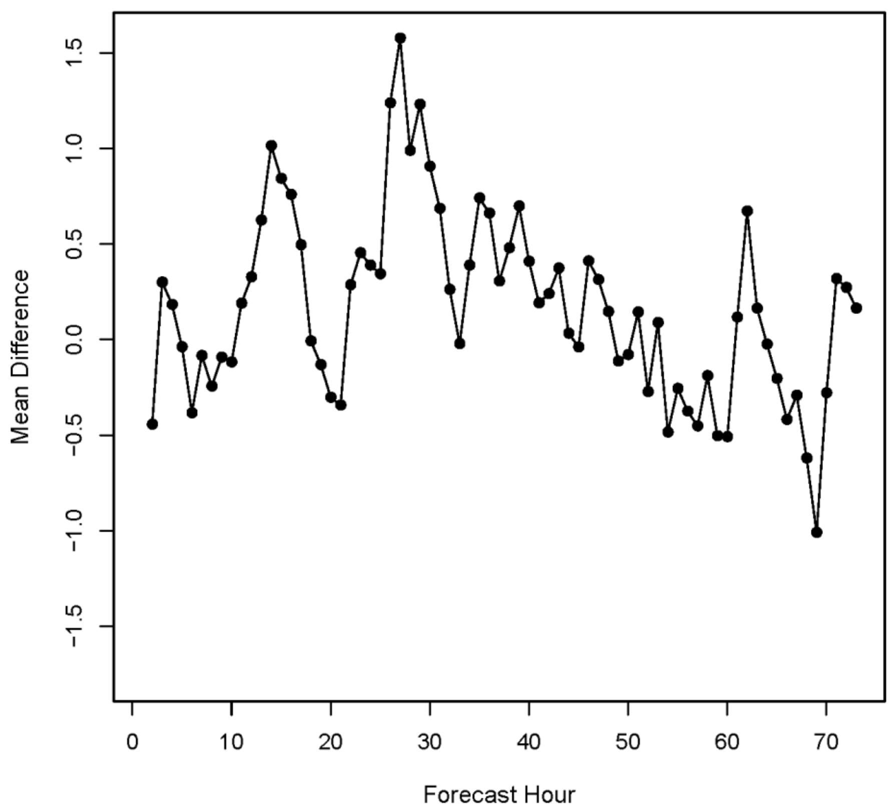

Figure 5. Mean difference (bias) of WRF forecast error with respect to forecast hour.

The performance of the WRF forecasts relative to the actual observations can also be visualized using scatter plots of observed wind speeds at Nysted met tower 84 versus predicted values. These are shown in Figure 6, separately for days 1, 2 and 3. As can be seen from the plots, a high degree of association between observed and predicted wind speeds is seen on forecast day 1. This means that WRF is able to predict wind speed trends extremely well during the first 24 hours of the forecast. The correlation coefficient between the forecast and observed data on day 1 is 0.87. On day 2, the degree of association between the forecasts and the observed values decreases, as seen from the scatter plot in Figure 6, as well as a lower correlation coefficient of 0.79, but WRF is still able to predict wind speed trends during day 2 to a large degree. Between day 2 and day 3, however, there is a large drop in the degree of association between the forecasts and observed values, as seen from the scatter plot and a much lower correlation coefficient of 0.68. The deterioration in the predictive ability of the model with each day can also be seen by comparing the least-squares fit (solid black line) to the perfect prediction line (red dashed line): the two get further and further apart each day.

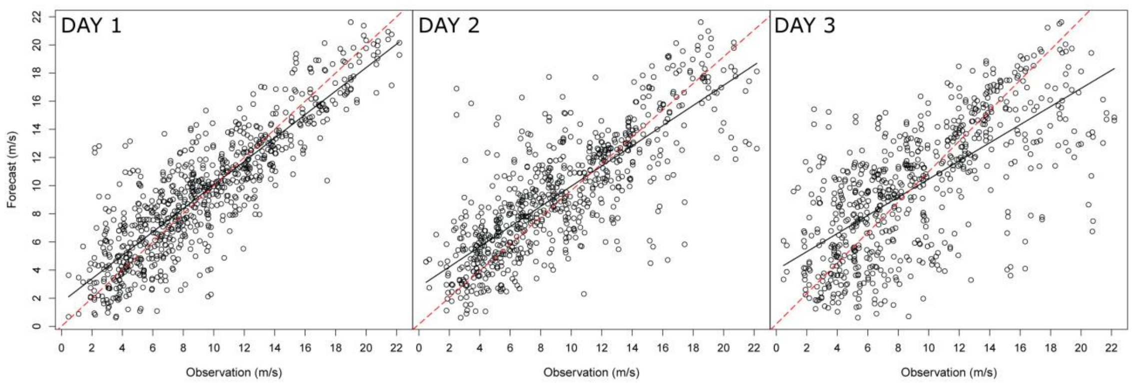

Figure 6. Scatter plots of forecast wind speeds versus observed hub height wind speeds for forecast day 1, 2, and 3. The solid line shows the least squares fit of the forecasts to the observations. The red dashed line corresponds to the perfect prediction (intercept = 0 and slope = 1).

The correlation as a function of forecast hour is shown in Figure 7. The plot exhibits a general downward trend as a function of time, with the decrease becoming even more drastic after 48 hours. It should be noted that the correlation captures the degree of a linear association between two variables and is thus not a useful measure if the relationship is not linear. However, the scatter plots in Figure 6 show no evidence of a non-linear relationship.

The scatter plots and the correlation analysis suggests that the WRF model's predictive skill deteriorates significantly after 48 hours. This is due to the expanding uncertainty of large scale flow. It is hoped that the predictive power of the model for periods longer than 48 hours can be improved by the proposed ensemble modeling system that perturbs initial conditions.

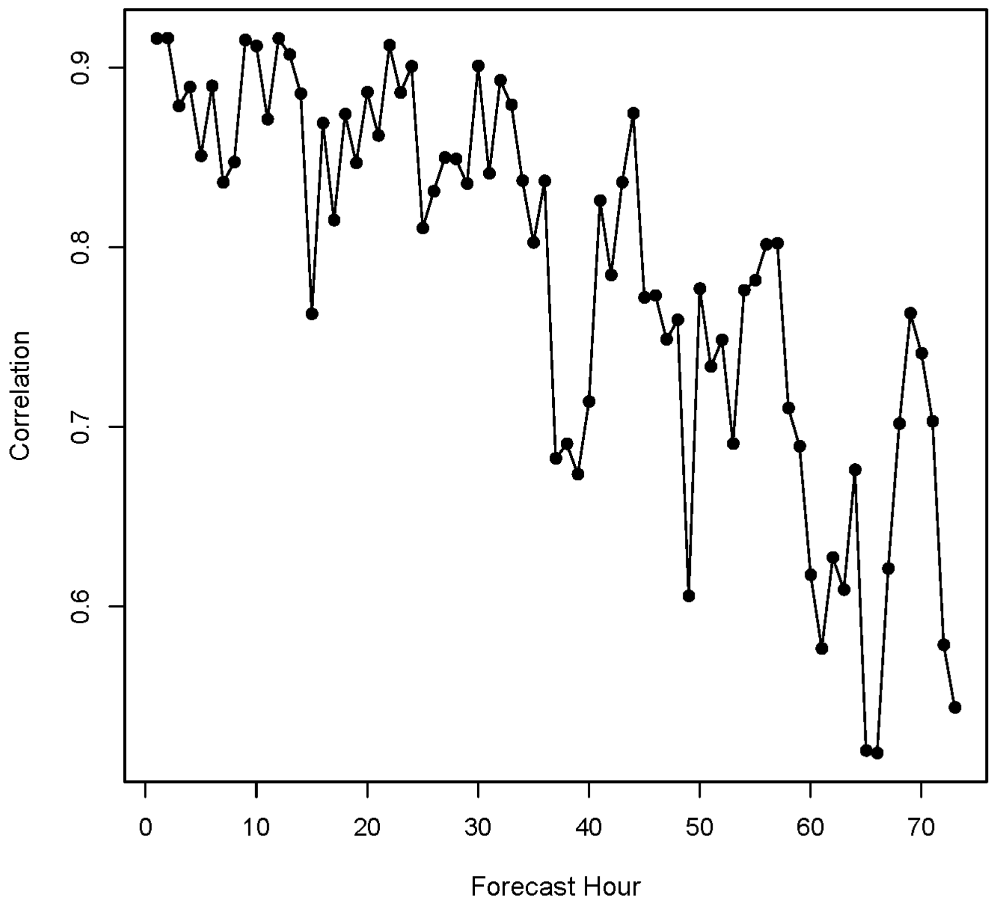

Figure 7. Hourly correlation values for WRF forecasted wind speeds compared with observations over Nysted Wind Park.

4 VERTICAL RESOLUTION SENSITIVITY

In addition to running WRF with 70 vertical levels, forecasts were made for the same study period of August 2008 over Nysted with 35 and 50 vertical levels to investigate the impact of vertical grid spacing on forecast skill. Mean absolute difference of WRF forecast wind speeds compared with observations at Nysted Met Tower 84 for simulations run with 35, 50, and 70 vertical levels is shown in **Figure 8**. All three vertical grid spacing configurations show a comparable increase in forecast error with forecast hour. Differences in forecast error among the 3 configurations appear to be minimal. The forecast data set strongly suggests that wind speed forecast error over the Nysted wind park is not significantly influenced by vertical grid spacing. In fact, the daily MAD values for the 35 vertical level configuration was smaller than the 50 and 70 vertical level simulations (**Table 3**). This finding would almost certainly not be true for a wind park over land, especially in a mountainous region since terrain-induced turbulence would play a much larger role in momentum transport over land than over water. Additional simulations will be made to further investigate this finding.

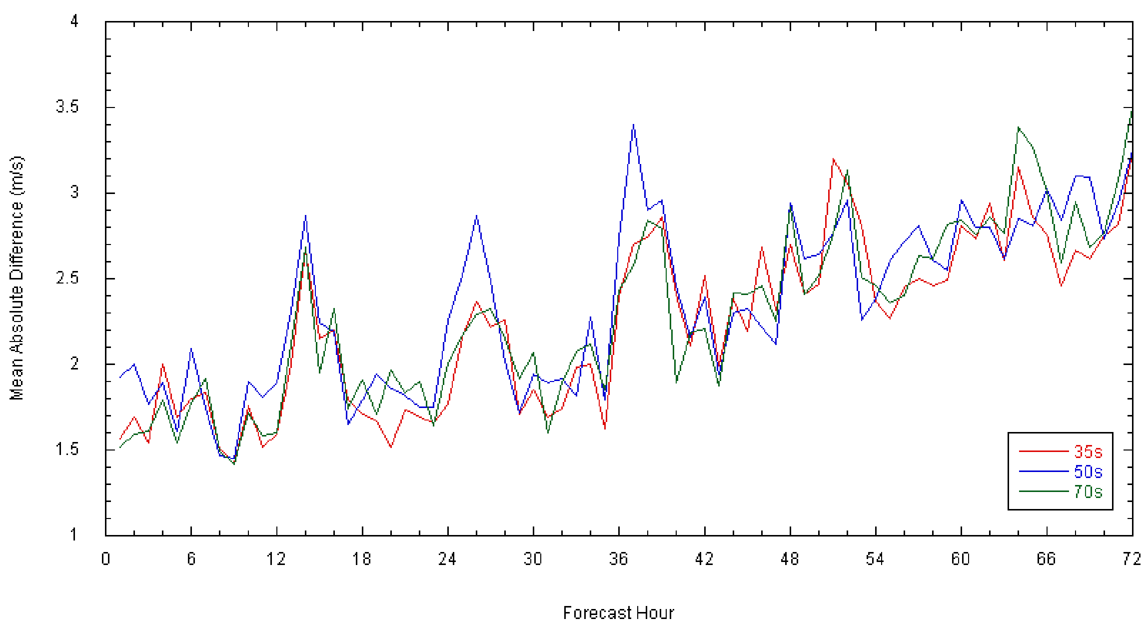

Figure 8. Mean absolute difference of wind speed forecast compared with observations based on 35, 50, and 70 vertical level configurations.

5 CONCLUSIONS

A comparison of WRF predicted wind speeds with observations over the Nysted Wind Park shows an increase in average forecast error from roughly ±1.8 m/s on forecast day 1 to ±2.8 m/s on forecast day 3. No discernable bias in the forecast error was observed in the forecast data set. Correlation coefficients reveal WRF is able to forecast wind speed trends with reasonable skill on forecast day 1 and 2 but with noticeably less skill on day 3. Wind speed forecasts over Nysted Wind Park were shown to not to be sensitive to vertical grid spacing.

The results presented in this paper provide a preliminary assessment of WRF forecast skill over the Nysted Wind Park. Additional forecasts will be made to increase the forecast data set to improve the confidence in the statistics. Simulations will also be made during cold / warm months to account for any possible seasonal bias. Once the framework for the WRF ensemble has been established, simulations will be run with the ensemble to quantify the expected increase in forecast skill.

6 REFERENCES

Christiansen, M. B. and Hasager, C. B. Wake effects of large offshore wind farms identified from satellite SAR. *Remote Sensing of Environment*, 98, 251 - 268.

Table 1. WRF domain configuration

Variable	**Domain 1**	**Domain 2**	**Domain 3**	**Domain 4**
Central Latitude (deg)	55.00	-	-	-
Central Longitude (deg)	8.85	-	-	-
Map Projection	Lambert	-	-	-
Grid Spacing (km)	27	9	3	1
Grid Points (E-W)	100	82	82	82
Grid Points (N-S)	90	82	82	82
Parent Grid Location (i)	-	44	27	27
Parent Grid Location (j)	-	31	27	27
Sigma Levels	70	70	70	70
Trulat1 (deg)	59.9395	-	-	-
Trulat2 (deg)	49.9665	-	-	-
Elevation Data Resolution	5 min.	2 min.	30 sec.	30 sec.
Model Time Step (sec)	90	45	15	5

Table 2. Physics schemes used for WRF deterministic forecast simulations.

PBL Scheme	MYJ - TKE
Land Surface Model	NOAH
Cumulus Parameterization	Kain-Fritsch (dx < 5km)
Shortwave Radiation	Goddard
Longwave Radiation	RRTM
Microphysics	Lin et al. Scheme (opt 2)
Feedback	One way feedback

Table 3. Mean absolute difference (m/s) of daily wind speed forecast for each vertical grid spacing configuration.

	DAY 1	**DAY 2**	**DAY 3**
35 levels	1.79	2.23	2.70
50 levels	1.92	2.34	2.78
70 levels	1.83	2.24	2.79