PREVIENTO meets HORNS REV
Short-Term Wind-Power Prediction – adaptation to Offshore Sites

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Abstract

Excellent offshore conditions with mean windspeeds of more than 9 m/s in 62m height as well as shortage of onshore-sites motivate the current wind farm intentions in the North Sea. It will become vitally important to know the offshore electricity production two days in advance: Liberalised electricity markets call for reliable wind power predictions because balancing power is expensive.
Previento is a wind power prediction system providing the expected power output of wind farms up to 72 hours in advance and is in operational use for German onshore sites. It includes advanced regional upscaling and in addition to the prediction an estimate of the uncertainty of the actual forecast. For offshore sites, wind power prediction tools have to deal with the special meteorological conditions above the sea. Important effects are in particular thermal air-sea interaction, a dynamic roughness length of the sea surface and the influence of the land-sea-discontinuity.
How good is the wind speed forecast offshore? We present first promising results of short term wind speed predictions for potential offshore sites in the North Sea. For verification, we used recent measurements from Horns Rev and synoptic met-masts. Because of the presented high accuracy of the offshore wind speed forecast, *Previento* will allow for an economic grid integration of future offshore wind farms.
Surprisingly, in all possible thermal conditions measured speeds of westerly winds coming from the sea show a larger wind shear compared to the logarithmic profile. This fact might be due to a decreased thickness of the atmospheric Prandtl Layer above the sea. Further analysis is required and in progress.

Keywords: wind power prediction, offshore, grid integration, wind speed profile, marine boundary layer meteorology

1. Introduction: Challenges of Marine Meteorology

Certainly the 160 MW Horns Rev offshore wind farm has to be considered as a step to new dimensions in wind power production. Many companies in Europe have ambitious goals to install Gigawatts of wind power offshore in the years to come. Due to the amazing dimensions of these power-plants on the high seas, it becomes economically crucial to predict their fluctuating electricity production 48 hours in advance, considering the costs of balancing power. Furthermore, offshore power production will show far smaller spatial smoothing effects than the decentralised production of all wind farms onshore. For these reasons, we are adapting our onshore prediction system *Previento* [1-5] to offshore conditions (Figure 1).

Figure 1: The windsea in a "moderately high and breaking" condition. From Reuter, http://las.physik.uni-oldenburg.de

As it is the basis for the wind power forecast, we evaluated the quality of the Numerical Weather Prediction (NWP) of wind speeds in the North Sea, provided by the German Weather Service DWD. We investigated which wind speed profiles can be used to optimize the wind speed forecast in hub height with physical methods. In contrast to onshore sites, the boundary layer of the marine atmosphere shows special meteorological conditions. Effects to be considered for offshore wind power forecasts are in particular [6,7]:

Thermal air-sea interaction:
Sensible and latent heatfluxes between water and air, combined with the large heat capacity of the sea, result in thermal stratifications different to those onshore.

Dynamic wind-wave interaction:
The dynamic sea surface roughness due to nonlinear interactions between wind and waves (the “windsea”, Figure 1) shows extremely small values ranging from millimeters to micrometers. These values are related to comparatively small fluxes of momentum from wind to sea.

Internal stratification of the marine boundary layer:
The land-sea discontinuity can cause an internal boundary layer (IBL) that can significantly modify the wind speed profile of winds blowing offshore, i.e. from mainland to sea.

Displaced height of the marine boundary layer:
For pure marine winds (blowing from the sea towards the coast) it might occur more frequently than onshore that the height of the Prandtl layer decreases and a descent of the atmospheric Ekman layer occurs.

2. Overview of Previento

Previento is a system for wind power prediction which has been developed at the University of Oldenburg. By now, it has been in operation for German onshore sites for several years. The system follows the physical approach of modelling the relevant fluiddynamic phenomena of the boundary layer that influence the power output of a wind farm.
Based on a numerical weather prediction model (in this case the Lokal-Modell LM of the German Weather Service DWD), the wind speed at hub height is calculated. The coarse forecast of the weather prediction model is refined considering the environment of the specific site, e.g. orography and surface roughness. Furthermore, the thermal stability of the atmosphere is modeled in detail. Especially for hubheights above 50 m, the influence of the thermal stratification is very important. The output of the wind farm is calculated considering farm layout effects and the turbine power curves. An advanced upscaling algorithm uses 50 representative sites to produce a regional prediction up to area diameters of 1000 km. Including spatial smoothing effects, the root mean square error of the power prediction for entire Germany amounts to 6% of the installed capacity. The prediction system is described in detail in [1-4]. The meteorological aspects of the reliability control system are described in [5].

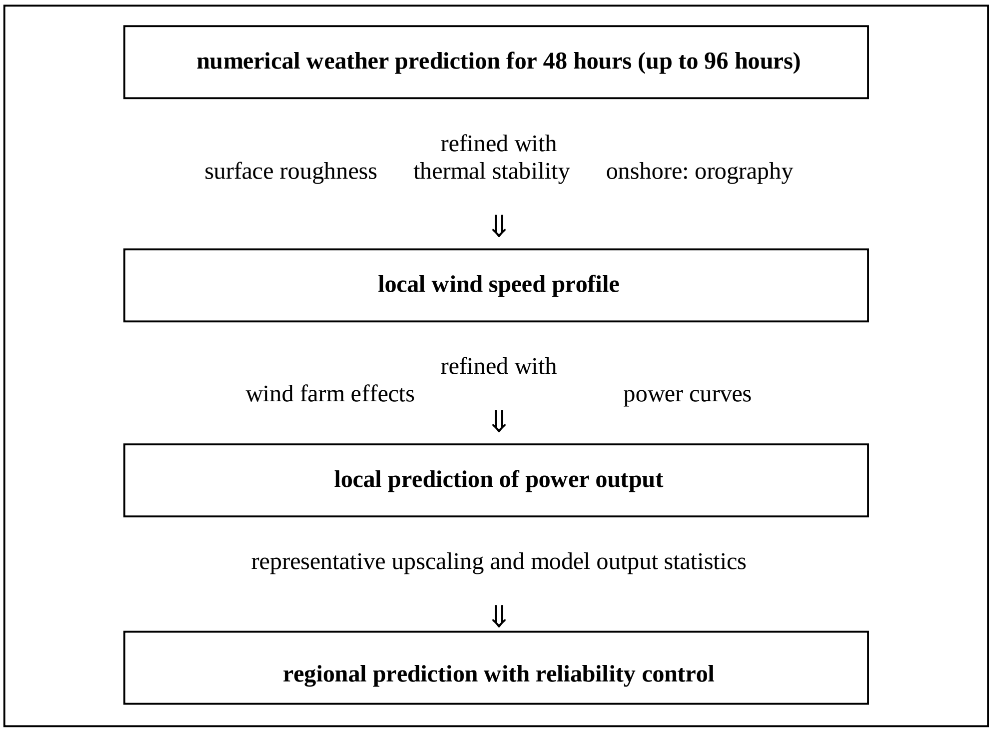


Figure 2: Principle of the prediction system Previento *with a spatial refinement of the numerical weather prediction leading to a local prediction of power output at one site, subsequently used for regional upscaling*

3. Forecasts for the North Sea

Previous investigations onshore [1-4] showed that the NWP is the major source of errors in the whole power forecast. We therefore evaluated the quality of the German weather forecast with meteorological 10m-measurements at 9 coastal sites at the German Bight and two real offshore sites (lightships "Ems" (emsx) and "Deutsche Bucht" (deut)). For Horns Rev, only 6 month of data could be analysed as reported further below.
The coastal sites are represented here by the measurements at three sites, i.e. "Norderney" (nord), "Cuxhaven" (cuxh) and "List auf Sylt" (list). The offshore measurements are probably effected by flow distortion above the lightships, but are sufficient for our purpose.

Investigated period:	01/2002 till 12/2002
Resolution:	1 hour
Forecast horizon:	48 hours
Height:	10m above ground

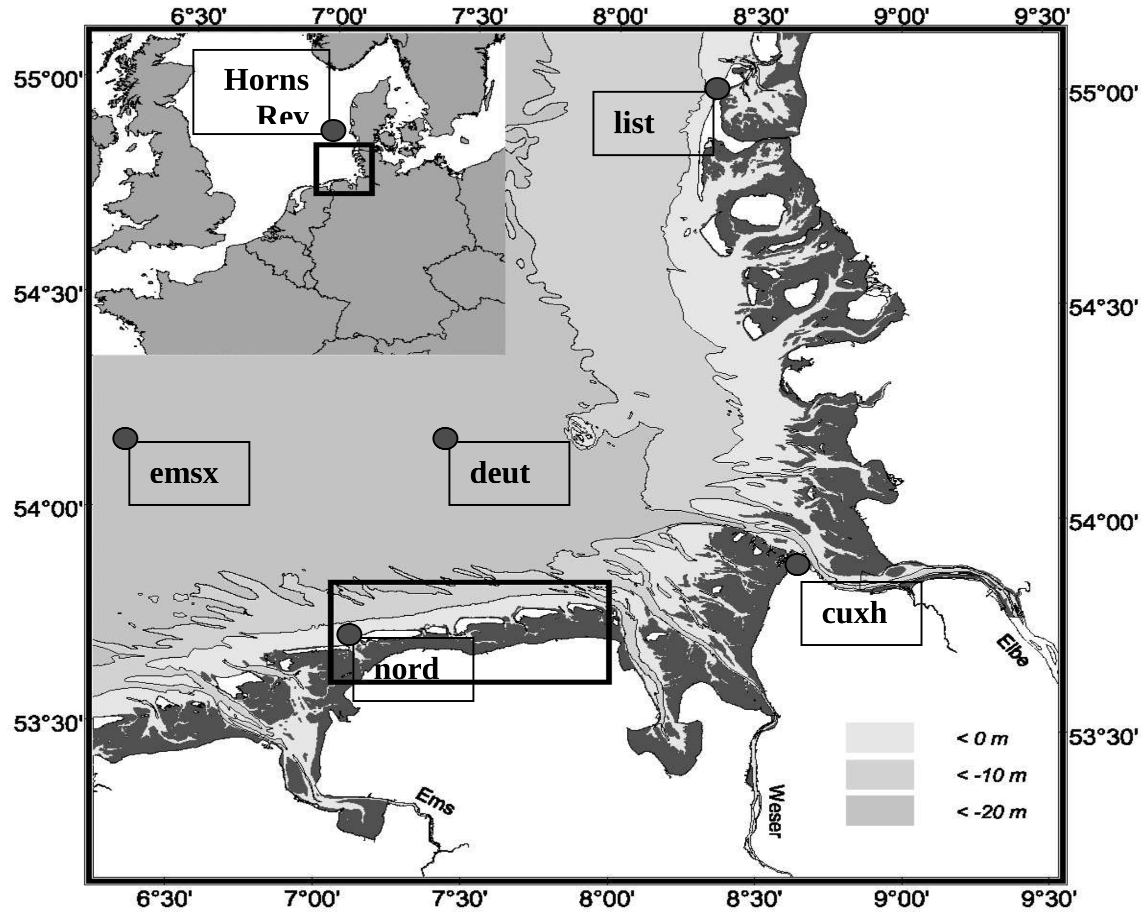


Figure 3 : Map of the German Bight in the North Sea, showing the sites investigated in this paper

Mean measured wind speeds ("umeasmean") in 10m height are compared with the forecast ("upredmean") using one year of data (2002). The results are displayed separately for 3-hourly time steps up to 48 hours in figures 4 to 8.

The mean measured wind speeds in figure 4 show a significant diurnal variation for the coastal sites. The higher wind speeds at noon at 10m height are primarily caused by convective turbulence. Remarkably, this effect still occurs so close to the sea. The NWP is not able to resolve this situation at the coast (further onshore, it does [3,10]) as the mean predicted wind speeds in figure 5 reveal. The resulting mean difference between forecast and measurement (bias) is shown in figure 6.
In contrast to the coastal sites, at both offshore sites the mean wind speed of 8 m/s does not vary and is well predicted: The bias diminishes to insignificance.

The cross correlation between forecast and measurement is a second measure of quality of the NWP, independent from the bias. The offshore forecast impresses with correlations ranging from 0.95 for 3 hours to 0.75 for 48 hours (figure 7).

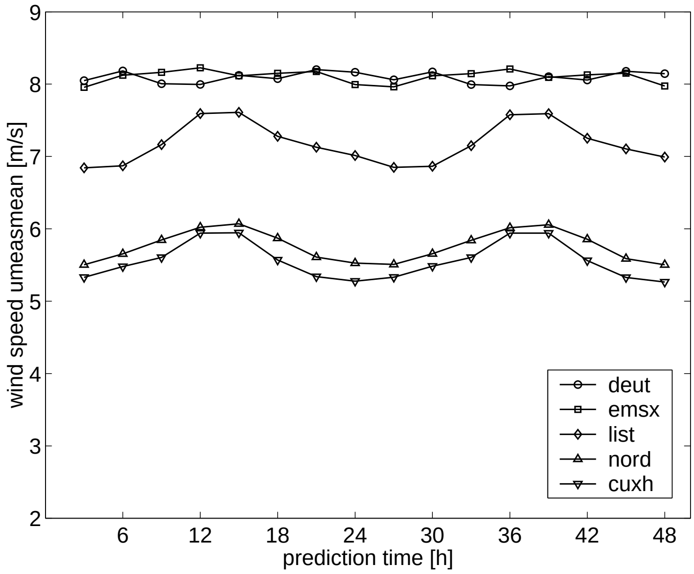


Figure 4:
Diurnal variation of mean measured wind speeds in the German Bight; "deut" and "emsx" are the real offshore sites with constant wind speeds while "list", "nord" and "cuxh" are located at the coastline and are subject to significant diurnal fluctuations; averages of 2002

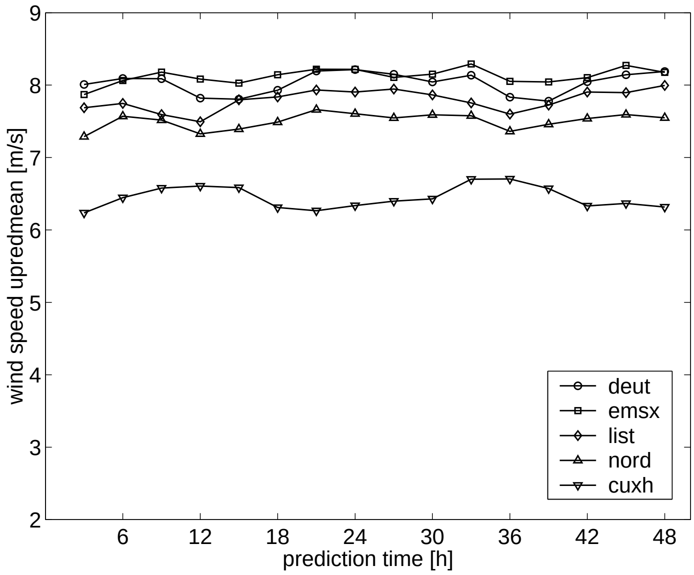


Figure 5:
Diurnal variation of mean predicted wind speeds; averages of 2002

The forecast overestimates the speed at the coastline and does not reproduce the diurnal fluctuations there, cp. Figure 6

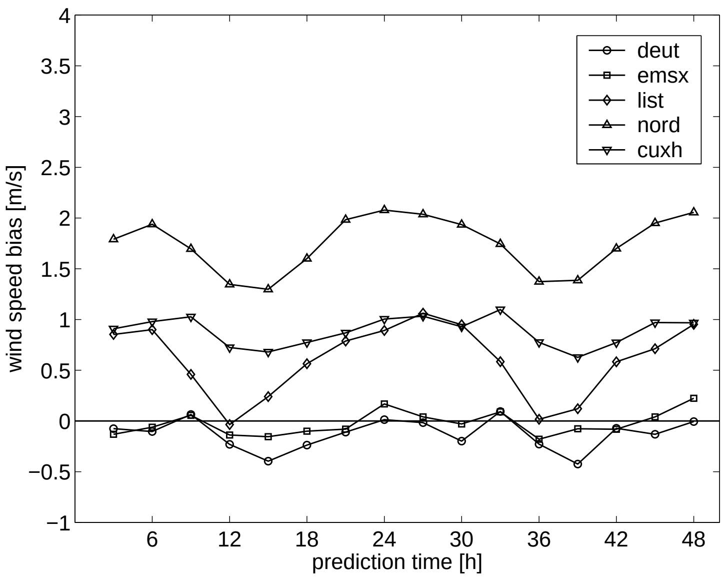


Figure 6:
Diurnal variation of the mean difference (bias) between predicted and measured wind speeds; averages of 2002

The insignificant bias at the offshore sites is a first indication of the high quality of the offshore forecast.

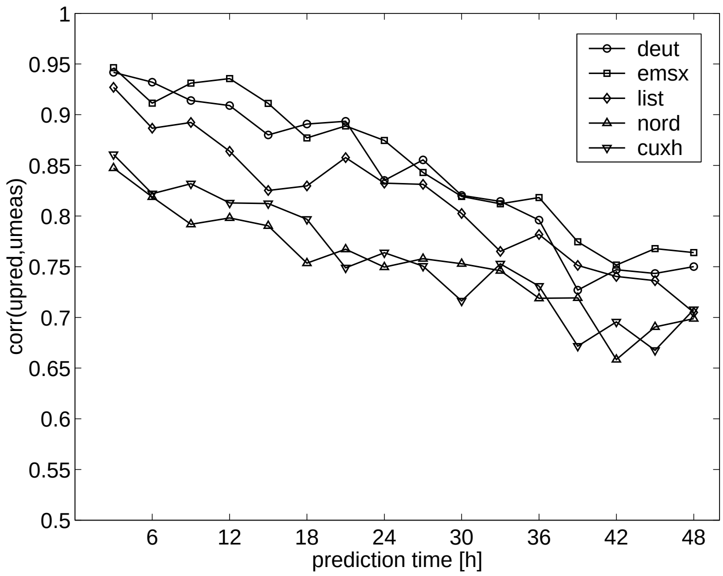


Figure 7:
Cross correlation between predicted and measured wind speeds showing high values for the offshore forcast; averages of 2002

Probably, the land-sea discontinuity causes significant problems in the numerical weather prediction model due to the resolution of 7x7km^2. Tidal effects may also significantly change the wind speed profile in the wadden sea. But fortunately, major discrepancies between forecast and measurement are limited to the coastal sites and do not affect the offshore forecast.

Figure 8 characterises the forecast error for the lightship "Deutsche Bucht" in more detail. The root mean square error (rmse) of predictions can be separated in the bias (the mean difference between prediction p_i and measurement m_i), the stdbias (the bias of the standard deviations) and the dispersion (a "phase" error increasing with decreasing correlation):

$$\text{rmse}^2 = \text{bias}^2 + \text{stdbias}^2 + \text{disp}^2$$

where rmse = $\sqrt{\frac{1}{n}\sum_{i=1}^{n}(p_i - m_i)^2}$ bias = $\overline{p} - \overline{m} = \frac{1}{n}\sum_{i=1}^{n}(p_i - m_i)$

stdbias = [std(p) – std(m)] disp^2 = 2*std(p)*std(m)*[1 - corr(p,m)]

overbars denote mean values, std(_) usual standard deviation and corr(p,m) usual cross correlation

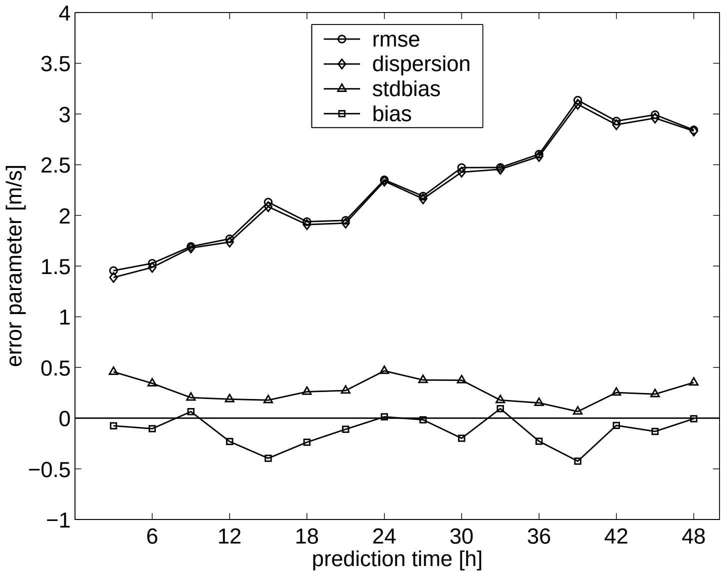


Figure 8:
Decomposition of the root mean square error for a single offshore site, i.e. lightship "Deutsche Bucht", dominated by the individual dispersion of the forecast; averages of 2002

The bias and the stdbias measure the systematic components of the temporally averaged prediction error. They can be corrected by subtracting the bias and by inflating or deflating the standard deviation of the prediction. The dispersion error (disp) is proportional to (1–corr): Due to "phase" errors rather than amplitude errors, it cannot be calibrated out linearly as the correlation is invariant under linear corrections of the time series. [8]

For the investigated offshore sites, bias and stdbias are negligible and the individual dispersion determines the rmse (Figure 8). Hence, additional linear postprocessing (e.g. MOS) will not lead to major improvements.

But for a single site with no spatial smoothing effects, the relative rmse of 20% to 30% in the first 24 hours (normalised to the mean wind speed of 8m/s) is favourably small compared to single site errors onshore (30% to 45%) [1-4] and will facilitate offshore power forecasts.

4. Forecasts for Horns Rev

In order to forecast the power output of a turbine, the wind speed in hubheight has to be calculated. We evaluated calculated forecasts for hubheight with Horns Rev data. Horns Rev is the only site in the North Sea were wind speeds have been measured continuously in different heights up to 62m during the last years. The meteorological mast at Horns Rev is located approximately 18 km west of Blaavands Huk at the Danish coast of the North Sea and is run by Techwise A/S [9].

We investigated the period from 10/2001 till 04/2002 for which the numerical weather prediction (NWP) of LM in three relevant heights (10m, 34m, 110m) and measurements in four heights were concurrently available:

- the wind speed measurements of the cup anemometer pairs in 15m, 30m, 45m and 62m height (refered to as umeas15, umeas30, umeas45 and umeas62, respectively)
- and temperatures from 13m and 55m height (T13 and T55)

The data is provided by the Database on Wind Characteristics "WindData.com". Further information can be found at www.winddata.com.

Because of the spatial homogeneity of the sea surface roughness and the thermal conditions over the sea, the $7x7km^2$-resolution in LM seems to be sufficient for offshore applications. We therefore did not try to refine the NWP spatially. It is important to note that in the Lokal-Modell LM of the DWD, algorithms for dynamic sea surface roughness and thermodynamic stability of the flow are well implemented. [10]

The analytic form of the stability functions Ψ in LM follows the formulation in the ECMWF-model using the gradient Richardson number Rig as a stability parameter instead of the Monin-Obukhov Length L (formula for Rig as stated further below in equation (*)). Above the sea surface, the stability functions are empirically modified.
Since waves are themselves generated by the wind, the sea surface roughness that influences the wind speed profile is in turn dependent on the windfield: A nonlinear wind-wave-interaction, the "windsea", develops, additionally influenced by tidal currents. The dynamic roughness length is a measure of dissipation of momentum and not directly of the waveheight.

To account for that, a modified Charnock-relation (left) is used in LM. The roughness length z_0 of the sea surface is either related to the friction velocity u_* used in the well-known logarithmic profile (right) or to w_*, the scaling velocity for free convection.

$$z_0 = \frac{0.0123}{g} \cdot \max\left(u_*^{\,2}, w_*^{\,2}\right) \qquad u(z) = \frac{u_*}{\kappa} \cdot \left[\ln\left(\frac{z}{z_0}\right) - \Psi\left(Rig(z)\right) \right]$$

As reported in [6], including wave parameters into the Charnock-relation does not generally lead to improvements in modelling the profile. Even using the pure Charnock-relation does not enhance calculations eminently compared to the commonly used constant sea surface roughness of z_0 = 0.2mm.

Since we found the same LM-forecast quality at Horns Rev at 15m and at 30m height as shown above for the lightships in the German Bight, we were encouraged to calculate a speed prediction for 62m height (denoted as "upred62").
To take advantage of the full information in the numerical weather prediction concerning the dynamic roughness and thermal corrections, we interpolated the wind speed at 62m with the prediction for 110m and 34m by deriving the friction velocity and an individual dynamic roughness length. Interestingly, we found almost the same mean quality of the prediction when extrapolating the wind speed from only one height with a neutral logarithmic profile and a constant z_0 = 0.2mm.

Compared to the measurements, the correlations vary from 0.93 for 3 hours to 0.75 for 48 hours. The high correspondence is visualised in figure 9.

As observed for the 10m-forecast at both lightships, the bias is negligible and the root mean square error rmse is again determined by the individual dispersion error of the forecast (Figure 10).
Normalised to the mean wind speed of 10.3 m/s in the investigated winter period, the relative rmse errors increase from 20% to only 33% during the forecast horizon. Onshore, normal values for single sites increase from 30% to 45% [1-4].

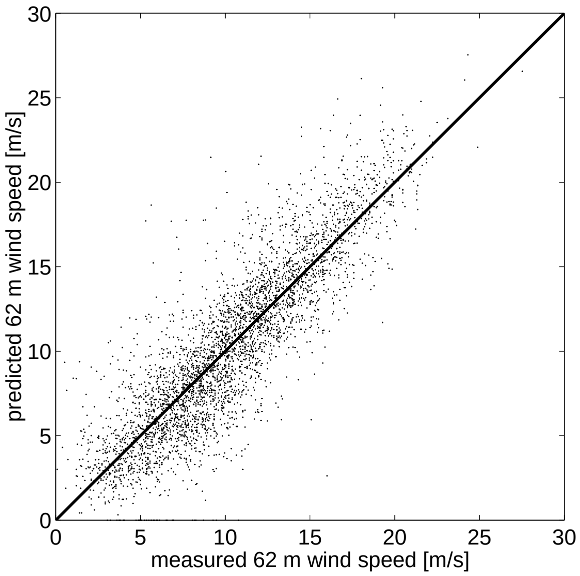


Figure 9:
Forecasted wind speeds in 62m height at Horns Rev visually compared to the measurement. (dynamic roughness used)

Winter period 10/2001 till 04/2002

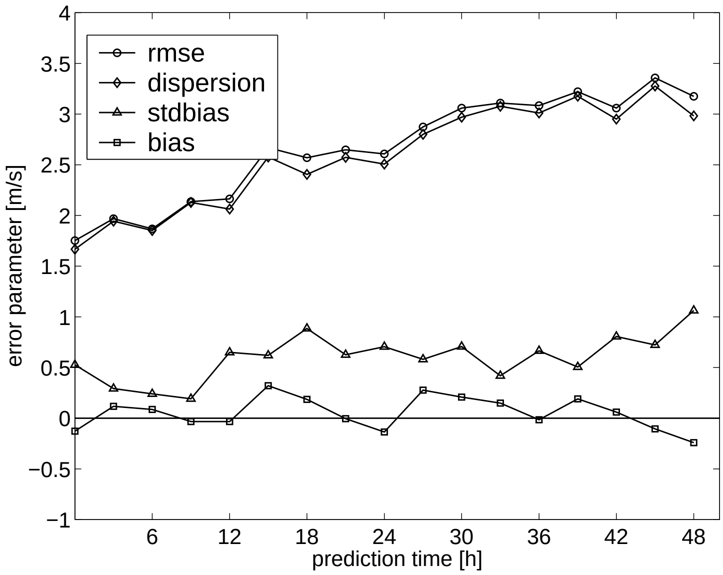


Figure 10:
Decomposition of the root mean square error of the prediction in 62m height at Horns Rev. The rmse is again dominated by the dispersion of the forecast.
(dynamic roughness used)

Winter period 10/2001 till 04/2002

5. Wind speed profiles at Horns Rev

In order to calculate the wind speed in hub height, a robust algorithm for the shape of the wind speed profile is required. But contemporary theory does not capture all the modifications in offshore wind speed profiles [6,7]. Before thermal corrections can be applied correctly, further research is necessary.
Analysing the thermal stratification at Horns Rev in terms of the gradient Richardson number Rig, we found pronounced differences in the wind speed ratios umeas62/umeas15 for unstable (Rig<0, convective) and stable (Rig>0) atmospheric conditions. Rig measures the ratio between the turbulent kinetic energy generated by convection and that generated by shear forces and is defined by

$$\mathrm{Rig} = \frac{\frac{g}{\Theta}\left(\frac{\Delta\Theta}{\Delta z_\Theta}\right)}{\left(\frac{\Delta u}{\Delta z_u}\right)^2} \qquad (*)$$

Where we used g = 9.81m/s^2; Θ = T55 + 0.55K as the potential temperature at 55m height , $\Delta\Theta$ = T55 – T13 + 0.4K as the potential temperature difference between 55m and 13m (with Δz_Θ = 42m), and Δu = umeas62–umeas15 as the wind shear between 62m and 15m (with Δz_u = 47m).

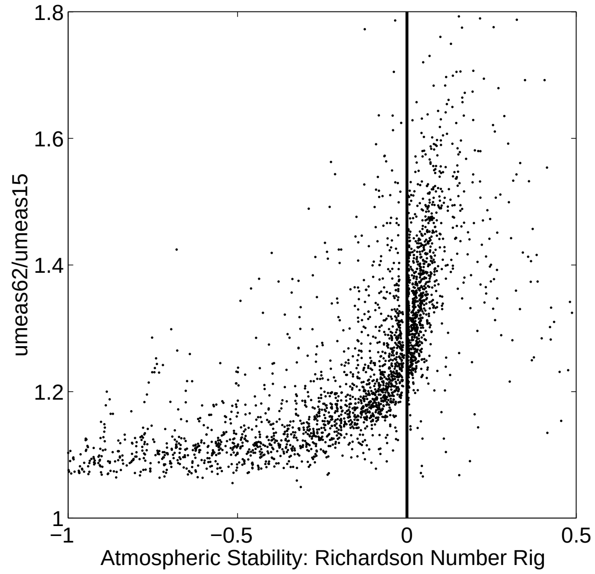


Figure 11:
Ratios between wind speeds at 62m and 15m height against the gradient Richardson Number Rig as a measure of stability of the atmospheric flow;
Winter period 10/2001 till 04/2002

The thermal stratification has an important impact on the flow: As to be expected, the wind speed ratios between 62m and 15m increase with increasing thermal stability of the flow, measured by the gradient Richardson number Rig. But the increase, from ratios of 1.1 (convective situations) to 1.4 (stable situations), is steeper than normally observed onshore.
Similar results were found by Lange [6] for the Baltic Sea, but with relatively small fetches to the coastline (10-50 km). At Horns Rev, winds are mainly coming from the open North Sea with fetches of several hundred kilometres. (Figure 12)

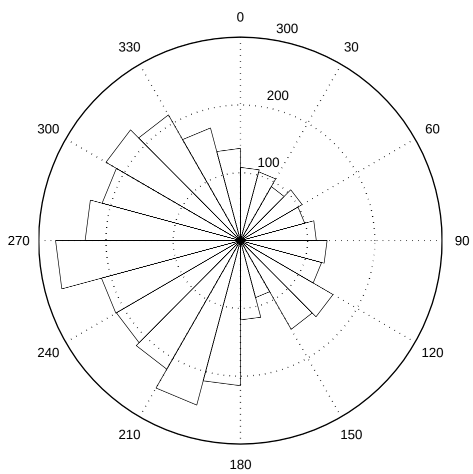
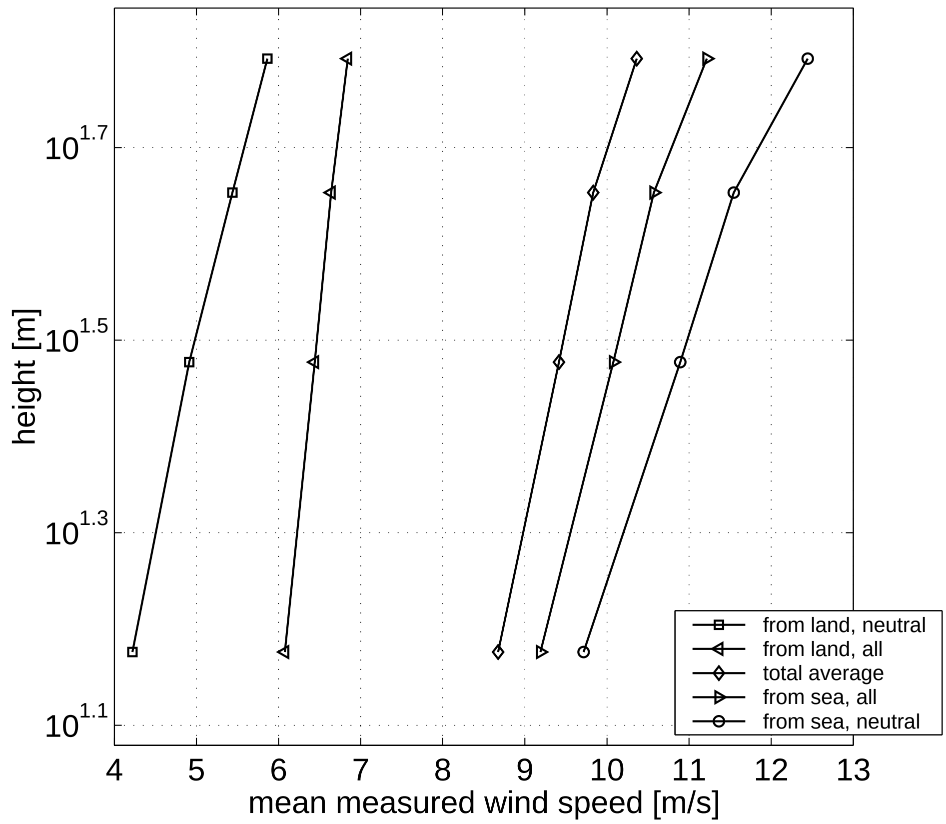


Figure 12:
Frequency of hourly averaged wind directions (from where the wind blows) in 43m height at Horns Rev.
Main wind directions: westerly winds from sea to land;
Winter period 10/2001 till 04/2002

Looking at the observed average wind speeds at the four levels in Figure 13, the high wind speed ratios are related to significant deviations from a logarithmic profile.
Surprisingly, just the average profile of the wind coming from land with fetches of 20 to 40km is logarithmic, whereas especially the seawind-profiles (i.e. of wind coming from the high seas) show higher wind speeds at 62m than could be extrapolated logarithmically, even in thermally neutral conditions.

Figure 14 shows only these seawind-profiles, for all significant classes of potential temperature differences. Compared to the conditions onshore, unstable thermal conditions occur more frequently offshore due to the higher temperatures of the North Sea compared to the air above it in the investigated winter period.
The "excessive" speeds in 62m height can be identified for all thermal situations. Hence, they cannot be explained with usual Monin-Obukhov theory, especially not for thermally unstable situations. But when looking at the linear scale plot (figure 14, bottom), the profiles turn out to be almost linear for all thermal classes when considering only the wind speeds at heights above 30m.
One cause for those excessive speeds in 62m height could be flow distortion around the lattice mast that affect the cup anemometer pairs below 60m height, whereas the anemometer at the top in 62m height measures the free flow.
A meteorological reason could be a frequent or general descent of the atmospheric Ekman layer in which the validity of the logarithmic profile ends. Presently, we are investigating different models of atmosphere-ocean interaction which lead to this effect.



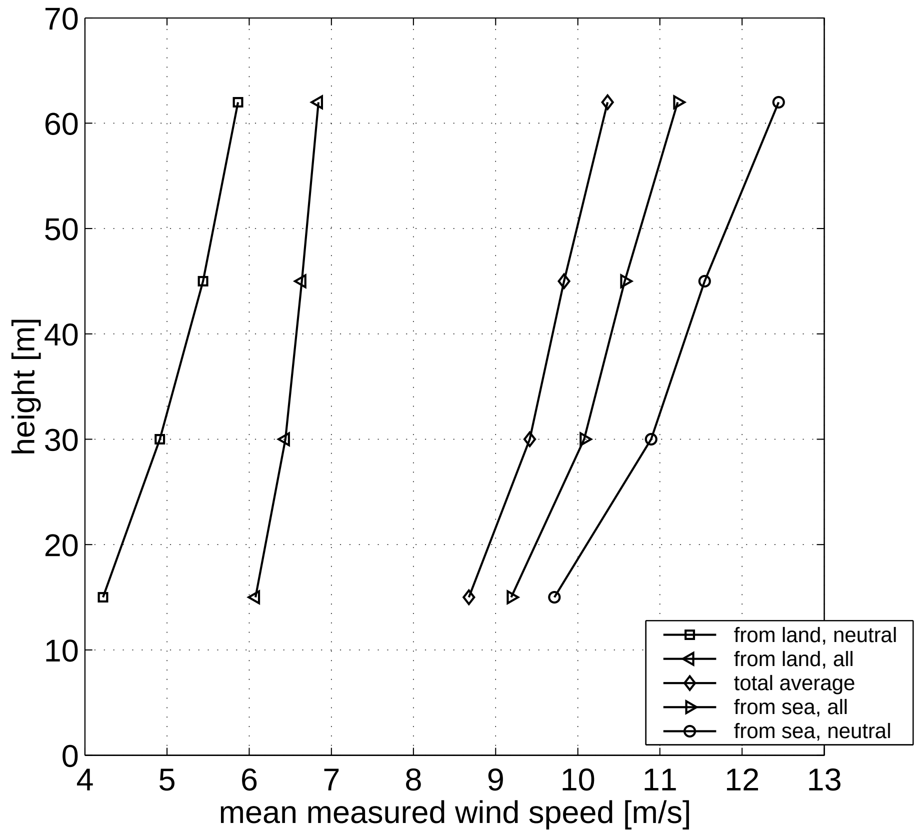
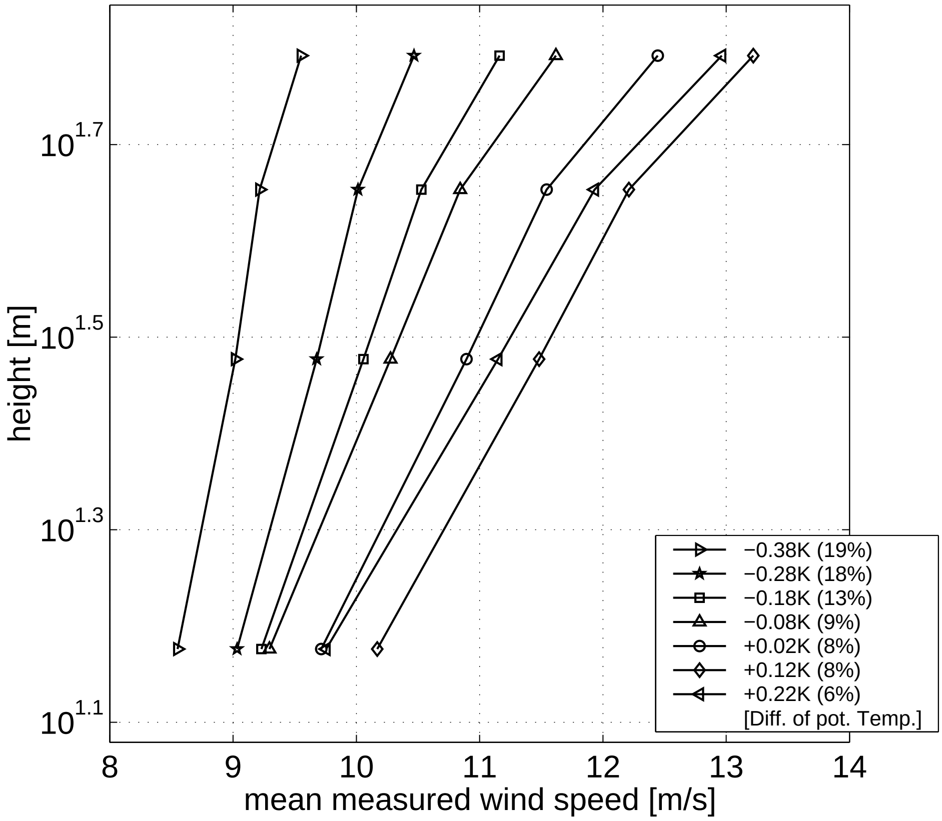


Figure 13: Mean profiles of wind speed; blowing from land to sea, from all directions and from sea to land. Neutral profiles have no difference in potential temperatures in 55m and 13m height. Sea-wind speeds in 62m exceed logarithmically extrapolated values. Winter period 10/2001 till 04/2002; Top: *Lognormal scale,* Bottom: *linear scale*



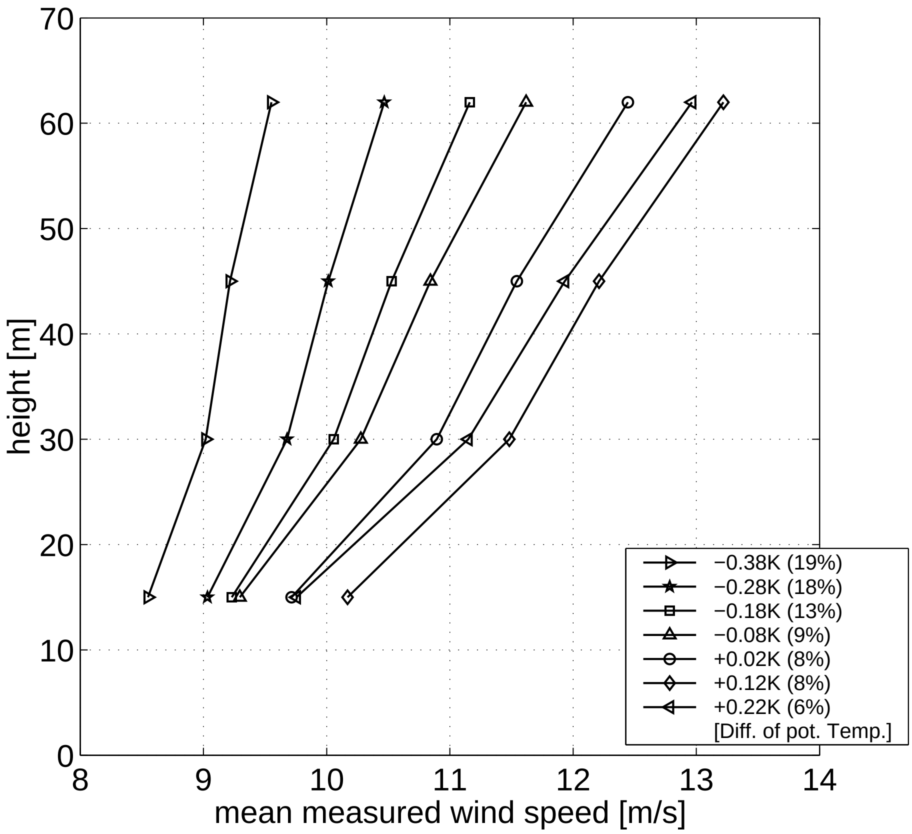


Figure 14: Sea-wind speed profiles depending on potential temperature difference [T55-T13+0.4K]. Frequency of occurrence in brackets. The wind speeds in 62m exceeding the logarithmic extrapolation seem to follow an almost linear increase. Winter period 10/2001 till 04/2002; Top: *Lognormal scale,* Bottom: *linear scale*

6. Conclusion

Because of the presented high accuracy of the Numerical Weather Prediction at sea provided by the German Weather Service, the power prediction system *Previento* is now expected to perform very well for future offshore farms. For single sites like Horns Rev and lightships in the German Bight, the correlation between prediction and measurement decreases from 0.95 to 0.75 during the predicted period of 48 hours. The wind speed forecasts for coastal sites are not satisfying and require additional examination and major corrections.
For the quality of the power prediction it is necessary to avoid additional errors when extrapolating the wind speed for heights above 50m. We therefore investigated the measured wind speed profiles at Horns Rev in the North Sea. They show an almost linear increase instead of a logarithmic shape, revealing completely different properties than onshore.
Thermal stratification seems to have an important impact on the profile. As onshore investigations have shown, the performance of Previento is improved by applying thermodynamic corrections following Monin-Obukhov theory with advanced algorithms from DeBruin et alii [11]: Halving the extrapolation-error, the rmse can be reduced by 5%. [3,12]
Hence, we are now examining different models of kinematic and thermal atmosphere-ocean interaction. Following corrections can be expected to improve the already favourable results in offshore wind power prediction.

Acknowledgement

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References:

[1] Focken U, Lange M, Waldl H-P. Previento – Regional Wind Power Predictions with Risk Control,
Proc. Global Windpower Conference, 2002, Paris

[2] Focken U, Lange M, Mönnich K, Waldl H-P, Beyer HG, Luig A: Short-term predicton of the aggregated power output of wind farms - a statistical analysis of the reduction of the prediction error by spatial smoothing effects.
J. Wind Eng. Ind. Aerodyn. 03/2002; **90:** pp.231-246

[3] Focken U. *Leistungsvorhersage räumlich verteilter Windkraftanlagen unter besonderer Berücksichtigung der thermischen Schichtung der Atmosphäre, Dissertation at the University of Oldenburg*, VDI Verlag, Düsseldorf, 2003

[4] Lange M, Heinemann D. Accuracy of Short Term Wind Power Predictions Depending on Meteorological Conditions,
Proc. Global Windpower Conference, 2002, Paris

[5] Lange M, Heinemann D. Relating the uncertainty of short term wind power predictions to meteorological situations with methods from synoptic climatology, *Proc. European Wind Energy Conference EWEC,* 2003, Madrid

[6] Lange B. Importance of thermal effects and sea surface roughness for offshore wind ressource assessment.
Proc. European Wind Energy Conference EWEC, 2003, Madrid

[7] Watson SJ, Montavon C. CFD Modelling of the Wind Climatology at a Potential Offshore Wind Farm Site.
Proc. European Wind Energy Conference EWEC, 2003, Madrid

[8] Hou D, Kalnay E, Droegemeier KK. Objective Verification of the SAMEX ’98 Ensemble Forecast.
Monthly Weather Review 2001; **129:** pp.73-90

[9] Sommer A, Techwise A/S. Off Shore Measurements of Wind and Waves at Horns Rev and Laesoe, Denmark. *Preliminary edition for the OWEMES Conference*, Naples, Italy, 2003; pp.65-71

[10] Doms G, Schättler U,: The Nonhydrostatic Limited-Area Model LM (Lokal-Modell) of DWD, *Part I : Scientific Documentation*. DWD Deutscher Wetterdienst, D-63004 Offenbach, Germany, 1999

[11] DeBruin HAR, Ronda RJ, van de Wiel BJH. Approximate Solutions for the Obukhov Length and the surface fluxes in terms of Bulk Richardson Numbers. *Journal of Applied Meteorology*, **29:** pp.251-261

[12] Focken U, Heinemann D. Influence of Thermal Stratification on Wind Profiles for Heights up to 140m.
Proc. European Wind Energy Conference EWEC, 2003, Madrid