

Long-Term Profiles of Wind and Weibull Distribution Parameters up to 600 m in a Rural Coastal and an Inland Suburban Area

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Abstract An investigation of the long-term variability of wind profiles for wind energy applications is presented. The observations consists of wind measurements obtained from a ground-based wind lidar at heights between 100 and 600 m, in combination with measurements from tall meteorological towers at a flat rural coastal site in western Denmark and at an inland suburban area near Hamburg in Germany. Simulations with the weather research and forecasting numerical model were carried out in both forecast and analysis configurations. The scatter between measured and modelled wind speeds expressed by the root-mean-square error was about 10 % lower for the analysis compared to the forecast simulations. At the rural coastal site, the observed mean wind speeds above 60 m were underestimated by both the analysis and forecast model runs. For the inland suburban area, the mean wind speed is overestimated by both types of the simulations below 500 m. When studying the wind-speed variability with the Weibull distribution, the shape parameter was always underestimated by the forecast compared to both analysis simulations and measurements. At the rural coastal site although the measured and modelled Weibull distributions are different their variances are nearly the same. It is suggested to use the shape parameter for climatological mesoscale model evaluation. Based on the new measurements, a parametrization of the shape parameter for practical applications is suggested.

Keywords Doppler wind lidar · Coastal rural · Inland sub-urban · Weibull distribution · Wind profile · Weather research and forecasting model

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1 Introduction

Electricity production due to airflow in the lower atmosphere has increased during recent decades, accompanied by technological developments and requirements for wind information up to 300–400 m above the surface. To fulfil these needs mesoscale models are frequently employed; the applications of such models extend from long-term simulations for wind-resource assessments to short-term forecasts. Therefore, evaluation of modelled wind profiles against observations in the entire boundary layer is essential.

Measurements from instrumented meteorological masts provide inexhaustible sources of wind observations to study the lower boundary layer; however the number of tall high-quality meteorological masts reaching heights of 150–200 m, well beyond the surface layer, is very limited. Sodar is an affordable alternative for tall masts but its use is hindered in populated areas due to the noise disturbance from the operation of the instrument and the measurements are affected by ambient noise. Doppler radar wind profilers are operated by a few meteorological services but are large, cumbersome instruments that typically do not resolve the wind profile in the lowest few hundred metres (Emeis 2010). Recent developments within Doppler lidar wind measurement technology have proven coherent-detection based profiling systems to be very promising research instruments for high-resolution ground-based measurements of the wind profile. Currently, the measurements can reach several km in altitude under favourable conditions and the technique is under rapid development (O'Connor et al. 2010; Peña et al. 2010; Floors et al. 2013; Peña et al. 2013).

Although numerical weather prediction models can reproduce the variability of the wind velocity, there is still a requirement for empirical statistical distributions to describe the variability of the wind profile for applied use in wind-resource assessments. The Weibull distribution is commonly used in wind-energy applications to describe the distribution of the wind speed due to its flexibility, adequate description of the observations and its simplicity for performing wind power-density estimates (Auwera et al. 1980). However, Tuller and Brett (1984) showed that the ideal theoretical conditions required for the wind speed to behave as a Weibull distribution are seldom fulfilled by observed winds, and so it provides an approximate representation of the wind speed only, with the closeness of the fit varying from station to station. Sardeshmukh and Sura (2009) proposed a distribution that can be better justified from a theoretical point of view but it is less attractive for practical use. The two-parameter Weibull distribution is described by the scale and shape parameters. As noted by Zimmer et al. (1975), the shape parameter reaches a maximum value around 100 m, in agreement with the observations of Hellmann (1917) and Justus and Mikhail (1976), who suggested a relationship between the wind-speed profile, when expressed as a power law and the Weibull distribution. Pavia and O'Brian (1986) found that the spatial variability of the Weibull parameters over the ocean showed seasonal and latitudinal variations in the Northern Hemisphere, while the pattern was less clear for the Southern Hemisphere. Lun and Lam (2000) reported that the Weibull parameters varied over a large range over the city of Hong Kong. Aspects on the accuracy of the Weibull distribution for describing wind-speed observations were further discussed by Doran and Verhokle (1978), who also examined the method of vertical extrapolation of the Weibull parameters proposed by Justus and Mikhail (1976). It was pointed out that the method can lead to significant errors in individual cases. A parametrization of the profiles of the shape parameter, which today is commonly used in wind-energy assessment studies, was presented by Wieringa (1989), based on a large set of observations from tall masts. Methods for estimating the Weibull parameters are discussed in Scholz (1996) and Seguro and Lambert (2000).

Mesoscale numerical models have typically been used to investigate case studies of roughness, thermally-induced winds and coastal effects (Anthes 1984; Doran and Gryning 1987; Gryning and Batchvarova 1990, 1994; Batchvarova and Gryning 1998; Batchvarova et al. 1999; Tombrou et al. 2007; Freitas and Rozoff 2007; Dandou et al. 2009). The Coriolis effect may result in local jets in coastal winds for flow parallel to the coastline, and for flow perpendicular to the coastline; the effect can generate detached jets at sharp edges of the coastline (Hunt et al. 2004). This was also modelled by Ström and Tjernström (2004) for flows along the Californian coast. Similarly, Savijärvi et al. (2005) found strong coastal afternoon flow along the Gulf of Finland. Pielke (2002) pointed out that mesoscale modelling now allows long-term sophisticated simulations with realistic atmospheric and surface conditions. Because the atmospheric boundary layer is parametrized in a mesoscale model, and current parametrizations do not consider the impact of locally generated turbulence on the wind profile, model-based studies have a major limitation in investigating the detailed structure of the wind profile in the atmospheric boundary layer. Increasing the horizontal resolution has little impact on processes dominated by scales not accounted for in the parametrizations. Rife et al. (2004) demonstrated that the required resolution cannot be explicitly given but is dependent on the scale of the forcing of the flow. Comparison of ensemble forecasts of the wind speed with observations covering large parts of Europe was discussed by Pinson and Hagedorn (2012), and the largest deviation between wind-speed measurements and model simulations was found in the Alps and in coastal areas, illustrating that local near-surface effects are difficult to resolve.

In this study, we extend the parametrization in Wieringa (1989) of the shape parameter based on a new dataset obtained with a Doppler wind lidar providing high resolution profiles of wind speed up to about 1 km. In addition, we compare the long-term wind measurements from tall masts and long-range Doppler wind lidar with winds simulated by the weather research and forecasting (WRF-ARW) model (Skamarock et al. 2008) in a rural coastal and an inland suburban area. We investigate the ability of the WRF model to simulate the wind-speed variability by deriving the scale and shape Weibull parameters up to 600 m in height. This is important since the Weibull distribution is commonly used in wind-power analysis for long-term energy assessments.

2 Wind Observations

The measurements were carried out in the period April 2010 to March 2011 at a rural coastal site Høvsøre in Denmark, and during the period June 2011 to March 2012 at an inland suburban site in Hamburg, Germany.

2.1 Høvsøre

The measurements were performed at the Danish National Test Station of Wind Turbines at Høvsøre, which is located on the western coast of Jutland, Fig. 1 (left). Except for the North Sea to the west and the shallow fjord to the south, the terrain is flat and homogeneous consisting of grass, various agricultural crops and a few shrubs. The intensively instrumented 116.5 m meteorological mast (56°26'26.0"N; 08°09'03.1"E) is located about 1.8 km east of the coastline and 200 m south of the closest wind-turbine stand (Gryning et al. 2007; Floors et al. 2011). Observations from the top of a 160 m tall light tower 300 m north of the meteorological mast are also used. 10-min averaged wind speeds are calculated at 10, 40, 60, 80, 100, 116.5 and 160 m from Risø cup anemometer measurements, together with the wind direction at 10, 60, 100 and 160 m measured using wind vanes.

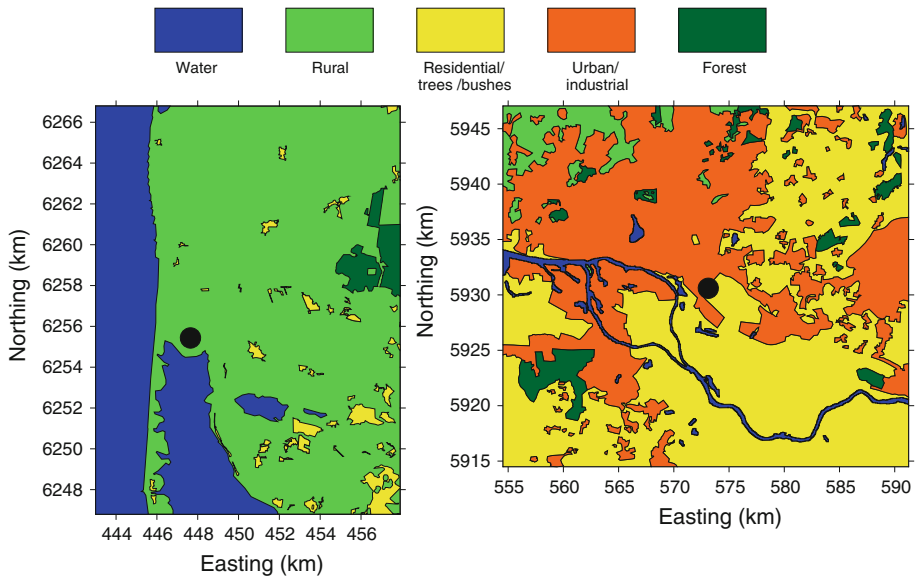


Fig. 1 Map showing the roughness/land use at the Høvsøre site (*left panel*) and Hamburg site (*right panel*). The position of the tall meteorological mast at both sites is shown by a black circle. The coordinate system refers to UTM32

2.2 Hamburg

The Hamburg site is located in Billwerder, a suburb about 8 km south-east of the city centre, Fig. 1 (right). Measurements of wind speed and direction were performed at a television tower ($53^{\circ}31'09.0''\text{N}$; $10^{\circ}06'10.3''\text{E}$) at 50, 110, 175 and 250 m height with METEK USAT-1 three-dimensional sonic anemometers, as well as on a 12-m mast ($53^{\circ}31'11.7''\text{N}$; $10^{\circ}06'18.5''\text{E}$) in a nearby meadow 170 m east-north-east of the tower (Brümmer et al. 2012). The sonic anemometer signals are sampled with a frequency of 20 Hz (10 Hz at the 12-m mast) and the variables calculated with an averaging time of 1 min, from which 10-min averages are derived and used in this study. The site surroundings are characterized by a mixture of agricultural land, fallow ground, spoil areas, with sparsely populated hamlets in the east, and industrial sites with mostly low buildings to the north, west and south.

2.3 Wind Lidar

At both sites, a pulsed Doppler wind lidar (Leosphere WLS70) was operated during the campaigns. At Høvsøre the lidar was located close to the meteorological mast, and at Hamburg in the meadow adjacent to the small mast. The lidar has a rotating silicon prism providing an optical scanning cone of 15° from zenith, and measures the radial wind speed at four azimuth angles separated by 90° . One 360° full scan (rotation) is performed about every 30 s, and the radial velocities are obtained with 50-m resolution from 100-m to 2-km altitude depending on the attainable sensitivity determined by the 10-min averaged carrier-to-noise-ratio (CNR). The upper limit was often determined by the cloud base, after which the lidar signal was severely attenuated. The laser pulse transmitted by the WLS70 is close to Gaussian in shape with a pulse length of approximately 200 ns, corresponding to an effective vertical sampling length of ≈ 50 m. Due to temporal and spatial averaging between the four beams the

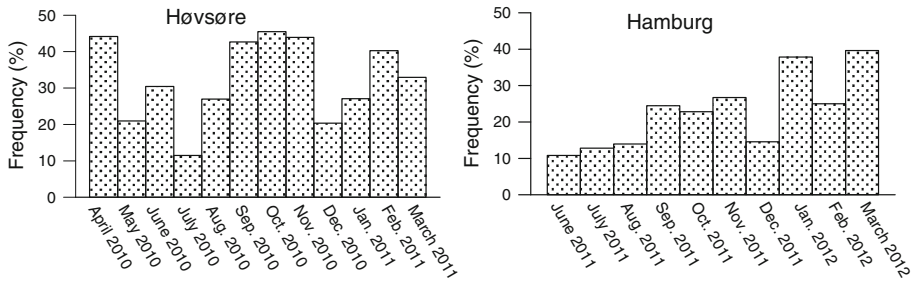


Fig. 2 Monthly recovery percentage of the 10-min averaged data from the wind lidar with CNR > - 22 dB for all levels up to 600 m. *Left panel* represents measurements at Høvsøre, and the *right panel* at Hamburg

horizontal sampling length increases linearly with height from 50 to 300 m between 100 and 600 m height. The uncertainty in the wind measurements is dependent on the signal strength and is typically 0.1 m s^{-1} (Mikkelsen 2009). To ensure high data quality, only measurements from the lidar up to 600 m, where all heights were concurrently measured and had a mean CNR > - 22 dB were selected. This strict CNR requirement was partly the cause for the rather small recovery percentage, see Fig. 2. Finally, at Høvsøre (23 April 2010–31 March 2011) 15359 (31 %) and at Hamburg (15 June 2011–23 March 2012) 9309 (23 %) 10-min average data were available for analysis. When compared with hourly forecast data (modelling set-up is described in Sect. 4), the evaluation for Høvsøre (14 October 2010–31 March 2011) and Hamburg (15 June 2011–23 March 2012) was based on 1707 and 2035 averaged profiles respectively, composed of the latest available 10-min average prior to the end of the hour.

3 Weibull Distribution Parametrization

The long-term frequency distribution of the horizontal wind speed is often used in applied modelling of the wind resource in the form of a two-parameter Weibull distribution. A prominent example is the wind atlas analysis and application program (WASP), originally developed by Troen and Petersen (1989), where the Weibull distribution is applied in relation to wind-speed observations. The two-parameter Weibull distribution can be expressed as

$$f(u) = \frac{k}{A} \left(\frac{u}{A}\right)^{k-1} \exp\left(-\left(\frac{u}{A}\right)^k\right) \tag{1}$$

where $f(u)$ is the frequency of occurrence of the wind speed u , the scale parameter A has units of speed and k is the non-dimensional shape parameter. The A and k parameters are related to the average wind speed $\langle u \rangle$ by

$$\langle u \rangle = A\Gamma(1 + 1/k), \tag{2}$$

and the variance, σ^2 , can be expressed as

$$\sigma^2 = A^2 \left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right) \right], \tag{3}$$

where Γ is the gamma function. For typical wind-speed distributions observed over homogeneous terrain, k falls in the range 1.5–3 (Wieringa 1989; Lun and Lam 2000) and $\Gamma(1 + 1/k)$ is nearly constant. For decreasing k and constant A the most frequent value (mode) in the distribution shifts to lower wind speeds and the probability for higher wind speeds increases.

Investigations over land have revealed that k is basically controlled by two atmospheric regimes: the large-scale synoptic pattern and the local boundary-layer winds (Hellmann 1917; Wieringa 1989). On average during daytime over land the boundary layer is deep with a well-developed wind profile throughout the entire layer. At night the boundary layer is shallow with inhibited diffusion of momentum resulting in a decreasing surface wind. Above the stable boundary layer the wind speed increases in response to the decoupling from the surface. This typical diurnal variability in both atmospheric stability and boundary-layer depth results in a characteristic climatology of the wind profile; the shape parameter in the Weibull distribution of the wind speed increases from near the ground to a maximum located at around 100–200 m height and then reverts to its upper air value. The height at which the maximum in the shape parameter occurs depends on the balance between the diurnal variation of the local meteorological conditions and the variability of the synoptic conditions prevailing in the region.

We suggest a simple extension of the parametrization of the k profile that originally was proposed by Wieringa (1989), viz.

$$k = k_s + c_k (z - z_s) \exp\left(-\frac{z - z_s}{z_r - z_s}\right) \quad (4)$$

where k_s is the value of k near the ground at height z_s , z_r is the height of the maximum in the k profile, also known as the reversal height, and c_k is a coefficient estimated from measurements ($\approx 0.02 \text{ m}^{-1}$). In Eq. 4 k in the upper part of the boundary layer reverts to the value near the ground. Wieringa (1989) pointed out that this is not certain to be the proper value, but according to the limited data available at the time of his investigation, it was of the right order of magnitude.

Higher quality data have now become available. With the aim of eventual use in applied wind-energy resource assessments, we propose a new parametrization of the k profile for $z > z_s$, which extends well beyond the height of the maximum. To derive it, we non-dimensionalize Eq. 4 and add a term that allows k to approach a given value k_t at z_t , in the upper boundary layer, viz.

$$k = k_s + c \frac{z - z_s}{z_r - z_s} \exp\left(-\frac{z - z_s}{z_r - z_s}\right) - (k_s - k_t) \exp\left(-\frac{z_t - z_s}{z - z_s}\right) \quad (5)$$

The shape parameter thus increases from its value near the ground reaching a maximum near z_r and then decreases with height, asymptotically approaching the value of k_t in the upper part of the planetary boundary layer (PBL). A typical value of the parametrization constant, c , is ~ 1 , while $z_t \approx 800 \text{ m}$, and $k_t \approx 2$, see Table 1.

Many methods exist for the derivations of the parameters in the Weibull distribution. Here we estimate the scale (A) and shape (k) parameters from the measurements of the wind speed using the Climate Analyst utility (Mortensen et al. 2007) in version 10 of WAsP. The results were checked by a graphical method described in Scholz (1996). Figure 3 illustrates the measurements and the fitted parametrizations, Eqs. 4 and 5. For both Høvsøre and Hamburg, Eq. 4 overpredicts the shape parameter above the height of the maximum.

4 Numerical Modelling

In order to evaluate at which degree of confidence mesoscale models can be used for wind-energy assessment studies, wind-speed and direction profiles were simulated using the WRF

Table 1 Fitted values of the parameters in Eq. 5 based on the measured profiles, and forced through k_s at height $z_s = 10$ m

Observation period	k_s	Fitted			
		c	k_t	z_T (m)	z_L (m)
Høvsøre					
23 April 2010–31 March 2011	2.26	1.0	2.0	200	800
14 October 2010–31 March 2011	2.42	1.4	2.3	150	800
Hamburg					
15 June 2011–23 March 2012	2.34	2.5	1.5	275	800

The k parameter was derived using the method of the European Wind Atlas (Troen and Petersen 1989; Mortensen et al. 2007)

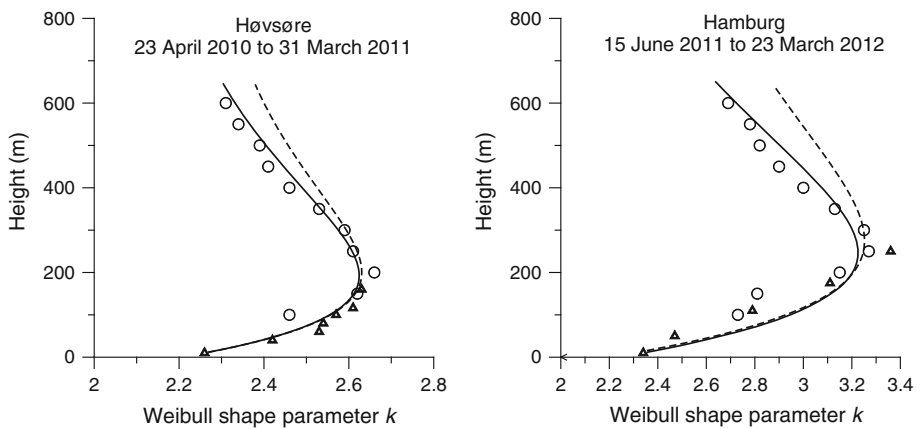


Fig. 3 Parametrizations and measurements of the shape parameter in the Weibull distribution. The *dashed line* represents Eq. 4 by Wieringa (1989); the *full line* is the suggested parametrization, Eq. 5; *triangles* show mast and *open circles* lidar measurements. *Left panel* shows the results for Høvsøre 23 April–31 March 2011 and *right panel* for Hamburg 15 June 2011–23 March 2012

model (Skamarock et al. 2008). It is a numerical weather prediction and atmospheric simulation system designed for both research and operational applications. Model simulations were performed both in short-term forecast and long-term analysis modes. When the model was operated in analysis mode, the initial and boundary conditions were taken from the Global Final Analyses Data (FNL) and for the operational forecast mode from the Global Forecast System (GFS), both derived from the National Center for Environmental Prediction (NCEP) global model. All simulations were performed with the Noah land-surface scheme (Chen and Dudhia 2001), the MYNN surface-layer scheme (Nakanishi and Niino 2009), the Thompson microphysics scheme (Thompson et al. 2004), and the 1.5-order closure Mellor-Yamada Nakanishi and Niino level 2.5 (MYNN, Nakanishi and Niino 2009) PBL scheme. The WRF model was configured to calculate the meteorological parameters at 41 vertical levels from the surface to the pressure level 100 hPa. Eight of these levels were within the height range of 600 m and the first model level was at 14 m.

When the model was run in forecasting mode, it used the GFS forecast boundary conditions every 3 h on a $1^\circ \times 1^\circ$ grid. Three nested domains with a horizontal grid size of 18, 6 and 2 km, respectively were used. The simulations were initialized every day at 1200 UTC and

after a spin up of 6 h a time series was created from fields every hour from 7 to 30 h. Neither data assimilation nor grid nudging was used to produce the forecasts. The operational forecast was available for Høvsøre from 14 October 2010 to 31 March 2011, and for Hamburg from 15 June 2011 to 23 March 2012.

In analysis mode, the model used the FNL global boundary conditions available every 6 h on a $1^\circ \times 1^\circ$ grid; two nested domains with a horizontal grid size of 18 and 6 km, respectively were used. The simulations were initialized every 10 days at 1200 UTC and after a spin-up of 24 h a time series of 10-min fields was selected from the simulated meteorological data from 25 to 264 h. In order to prevent the model from drifting from the large-scale features of the flow, the model was nudged towards the FNL analysis. Nudging was applied for the wind, temperature and humidity above the tenth model level (approximately corresponding to 1400 m), on the outermost model domain during the whole simulation period. The simulations in the analysis mode were performed from 23 April 2010 to 31 March 2011 at Høvsøre and from 15 June 2011 to 31 March 2012 at Hamburg.

5 Wind-Profile Climatology

Here, we compare the output from model simulations with measurements. Only simultaneously available profiles up to 600 m from the mast, lidar and simulations are used. The wind roses and total distributions of the wind speed from the lidar at 200 m (Fig. 4) show that the wind direction at both sites is predominantly westerly, corresponding to flow from the sea at Høvsøre and from the city at Hamburg, with the Weibull distribution constituting a good fit to the measurements at both locations.

5.1 Wind Profile

The model evaluation of the mean wind profile in terms of speed (Fig. 5) and turning with height (Fig. 6) is presented for the two periods at Høvsøre, and the whole period at Hamburg. While the whole (analysis) periods represent the near annual mean wind profile at both sites, the forecast period at Høvsøre represents autumn and winter. When comparing the left and right upper panels in Fig. 5, it can be seen that the mean wind speed generally is greater during the forecast period, in agreement with the fact that the autumn in Denmark is usually very windy. Good agreement can be noted between the lidar and mast measurements of wind speed at the overlapping heights both at Høvsøre and Hamburg (Fig. 5).

At Høvsøre, the agreement between the measurements and the WRF model simulations near the ground is good. Above approximately 60 m it is found that the model underestimates the mean wind speed for both periods (Fig. 5, upper panels) in agreement with Draxl et al. (2012) and Floors et al. 2013. For Hamburg (Fig. 5, lower panel), the simulated wind speed is greater than that measured below 500 m, and lower than that measured above. At Høvsøre the change in the wind direction is underestimated by the simulations, with larger differences in winter, (Fig. 6, upper right). It can be seen in Fig. 6 that at Hamburg the WRF model analysis performs well in predicting the mean change in wind direction with height up to about 300 m. In general for wind speed and direction, small differences are observed between the simulations in forecast and analysis mode at both sites.

In order to illustrate the scatter between the wind-speed measurements and model simulations the main statistical metrics characterizing a linear fit through the origin for all model simulations are provided at 100, 300 and 500 m height in Table 2. The root-mean-square

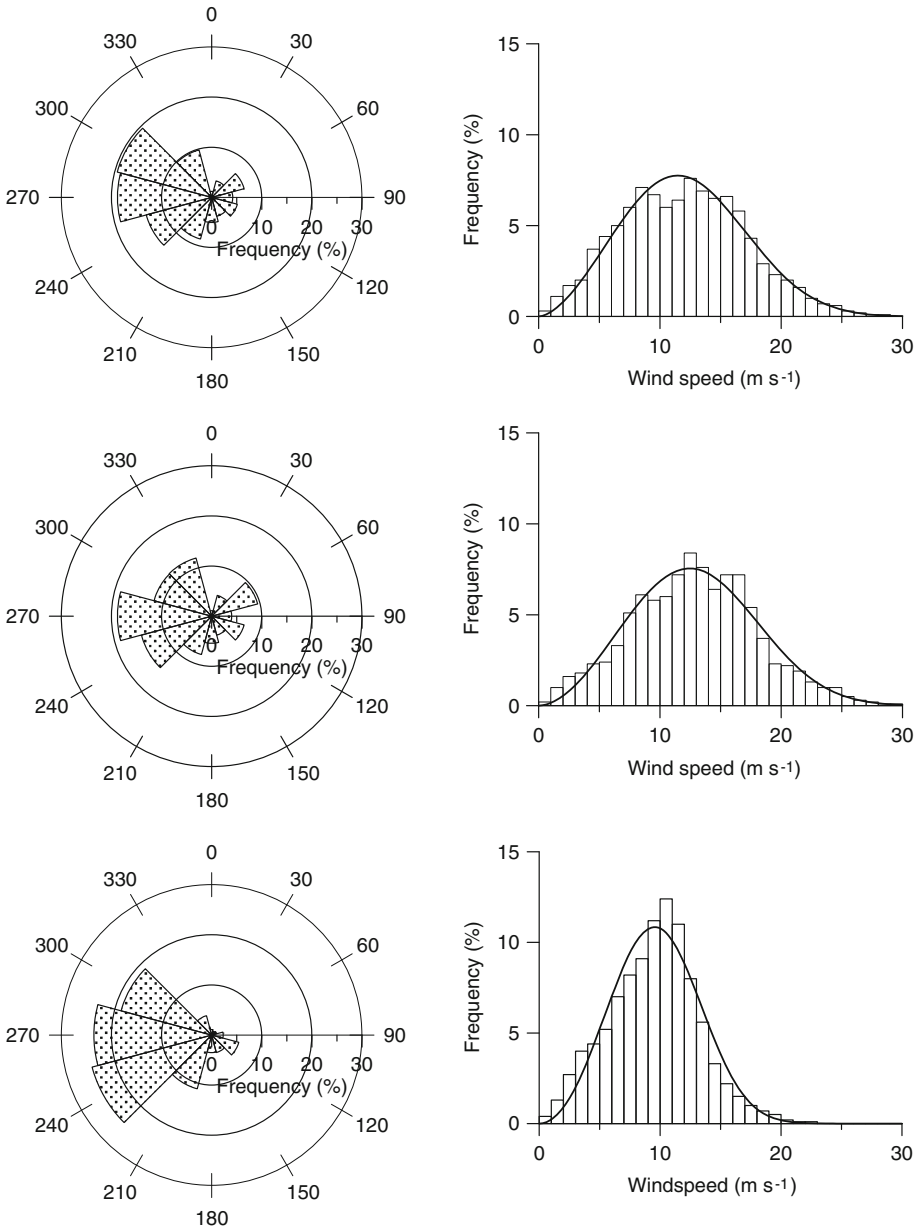


Fig. 4 Wind rose (left panels) and histogram of the wind speed with fitted Weibull distribution in solid lines (right panels) at 200 m measured by the lidar. The upper row represents Høvsøre 23 April 2010–31 March 2011; the middle row—Høvsøre 14 October 2010–31 March 2011 and the lower row—Hamburg 15 June 2011–23 March 2012

error (*RMSE*) between simulations and measurements at both sites is about 10 % smaller for the analysis compared to the forecast runs, and the *RMSE* values are in agreement with Haupt et al. (2013).

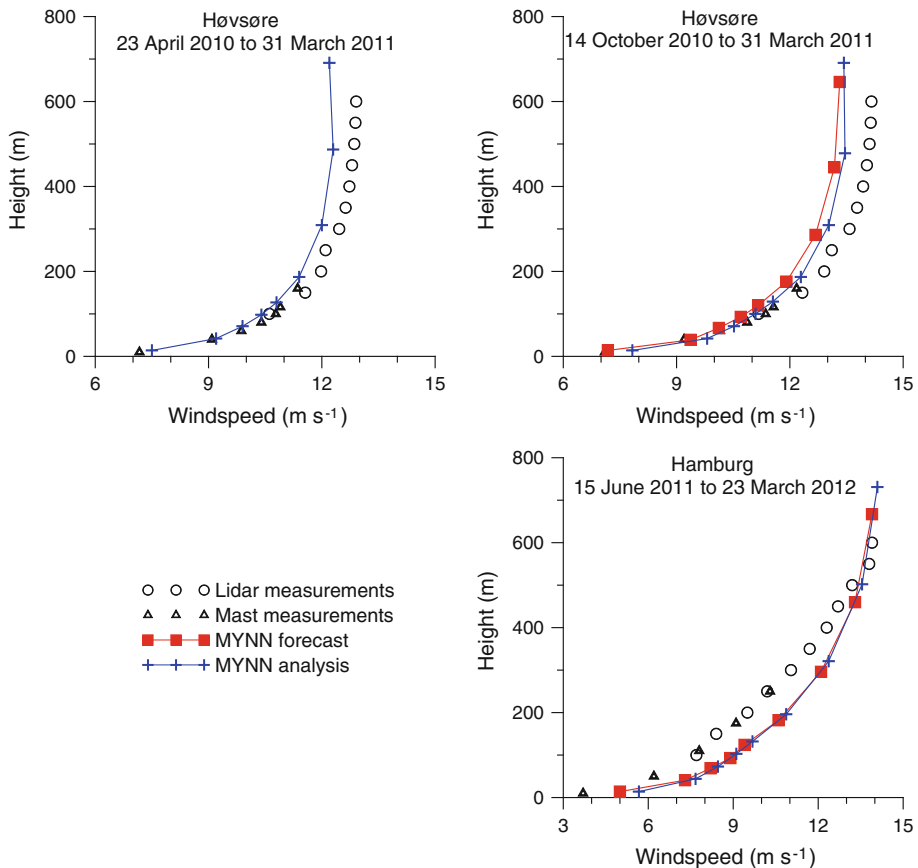


Fig. 5 Measured and simulated profiles of the mean wind speed. *Upper left panel* shows the results for Høvsøre 23 April 2010–31 March 2011, *upper right panel* for Høvsøre 14 October 2010–31 March 2011 and the *lower panel* for Hamburg 15 June 2011–23 March 2012

5.2 Weibull Distribution

In Fig. 7, the scale parameter A is presented for the same data and time periods as the mean wind-speed profiles in Fig. 5. Comparing Figs. 5 and 7, the profiles of the mean wind speed and scale parameter are rather similar, which is expected due to the weak dependence of k in the gamma function in Eq. 2 for the range of values in this study (Bhattacharya and Bhattacharjee 2010). Thus, the conclusions from the comparison between measured and simulated profiles of A are similar to those of the mean wind speed.

Contrary to the scale parameter, the vertical profile of the shape parameter has a very distinct form. During the period 14 October 2010–31 March 2011 at Høvsøre, which represents late autumn and winter conditions, it is found that above 100 m the WRF model underestimates the k parameter compared to that from the measurements, and that the forecast value is lower than that from the analysis, Fig. 8 (upper right panel). The height of the maximum in the k profile is at about 100 m for both measurements and simulations. Figure 8 (upper left panel) shows that during the period 23 April 2010–31 March 2011, the WRF analysis agrees well with measurements up to 100 m, while above this the model generally under-

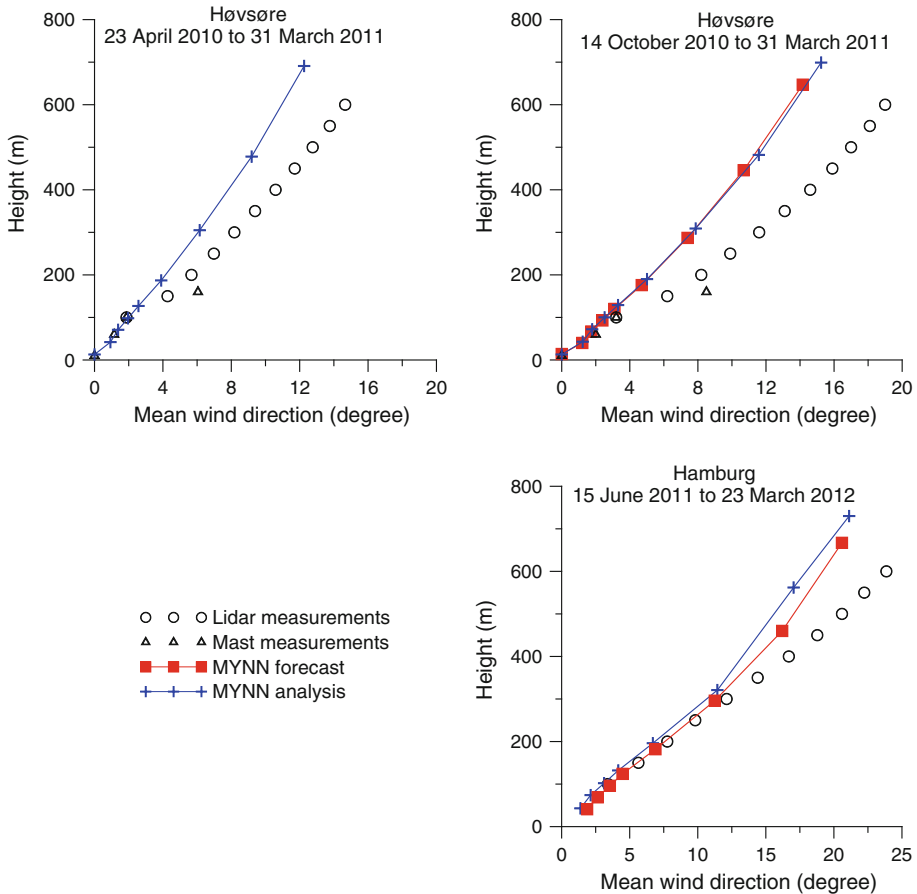


Fig. 6 Measured and simulated profiles of the mean wind direction. *Upper left panel* shows the results for Høvsøre 23 April 2010–31 March 2011, *upper right panel* for Høvsøre 14 October 2010–31 March 2011 and the *lower panel* Hamburg 15 June 2011–23 March 2012. For Høvsøre the lidar wind profile is relative to the mean direction at the mast at 100 m. For Hamburg only lidar measurements are shown, and in such a way that the measurements coincide with the modelling results at 100 m

estimates the k parameter. The WRF forecast underestimates the k parameter at all heights. The height of the maximum in the k profile from measurements is about 200 m; the model simulations suggest 120 m, indicating that the simulations do not capture the near-surface variability. The maximum value of the shape parameter for the whole period is reduced when compared to the winter period, in agreement with the seasonal variation of the shape parameter over water reported by Bilstein and Emeis (2010). In addition, the height of the maximum is lower in the winter period than over the whole period (Fig. 8, upper panels). The model simulations capture this seasonal variation of the size of the maximum in the shape parameter rather well, but not the seasonal variation of the height of the maximum. For the Hamburg site, the maximum in the observed k profile is at about 250 m, while it is about 200 m for the forecast and analysis (Fig. 8, lower panel). The analysis overestimates k below 100 m and underestimates k above, while the forecast underpredicts k at all heights.

Table 2 Comparison between model simulations and measurements: slope coefficient, a , of a linear fit through origin, $Y = aX$, where Y is the simulated and X is the measured wind speed; bias $((Y) - \langle X \rangle)$ where a bracket denotes an average; normalized bias $100((Y) - \langle X \rangle)/\langle X \rangle$; and root-mean-square error $RMSE = \sqrt{\sum_{i=1}^N (Y_i - X_i)^2/N}$, where N is the number of samples

Site		Høvsøre			Hamburg	
Height	Period:	23 April 2010–31 March 2011	14 October 2010–31 March 2011		15 June 2011–23 March 2012	
	Simulation	Analysis	Analysis	Forecast	Analysis	Forecast
100 m	Slope coefficient	0.95	0.97	0.95	1.15	1.11
	Bias (m s^{-1})	-0.28	-0.07	-0.32	1.35	1.22
	Normalized bias (%)	-2.6	-0.7	-2.9	17.5	15.9
	$RMSE$ (m s^{-1})	2.18	2.24	2.45	2.36	2.68
300 m	Slope coefficient	0.95	0.95	0.93	1.09	1.08
	Bias (m s^{-1})	-0.53	-0.55	-0.82	1.09	1.13
	Normalized bias (%)	-4.2	-4.0	-6.0	9.9	10.3
	$RMSE$ (m s^{-1})	2.30	2.42	2.67	2.62	3.02
500 m	Slope coefficient	0.94	0.94	0.93	1.02	0.99
	Bias (m s^{-1})	-0.57	-0.66	-0.86	0.41	0.22
	Normalized bias (%)	-4.4	-4.7	-6.1	3.1	1.7
	$RMSE$ (m s^{-1})	2.25	2.36	2.74	2.57	3.41

5.3 Power Density

The wind-power density, E , is an estimate of the effective wind power at a particular location and can be estimated from the Weibull parameters as,

$$E = \frac{1}{2} \rho A^3 \Gamma(1 + 3/k), \quad (6)$$

where ρ is air density. Therefore, the calculation of the power density is related to the scale and shape parameters (Troen and Petersen 1989). The wind-power density was calculated by use of the Climate Analyst utility in WAsP (Mortensen et al. 2007). In this method it is required that the total wind energy in the fitted Weibull distribution is equal to the observed distribution. At the coastal rural site (Høvsøre) good agreement is found near the ground between the power density estimated from the measurements and model simulations, see Fig. 9. Above heights of 60–100 m, it is found that the simulations begin to underestimate the power density, both forecast and analysis being very close. At the inland suburban site (Hamburg) the simulated power density is overestimated below 600 m, partly due to an overestimation in A , and partly to the underestimation in k .

6 Discussion and Conclusions

Long-term measurements of the wind profile within the ABL at a rural coastal site and at an inland suburban site have been analyzed and compared to simulations with the WRF model. At both sites, the novel long-range Doppler wind lidar measurements agree well with the mast

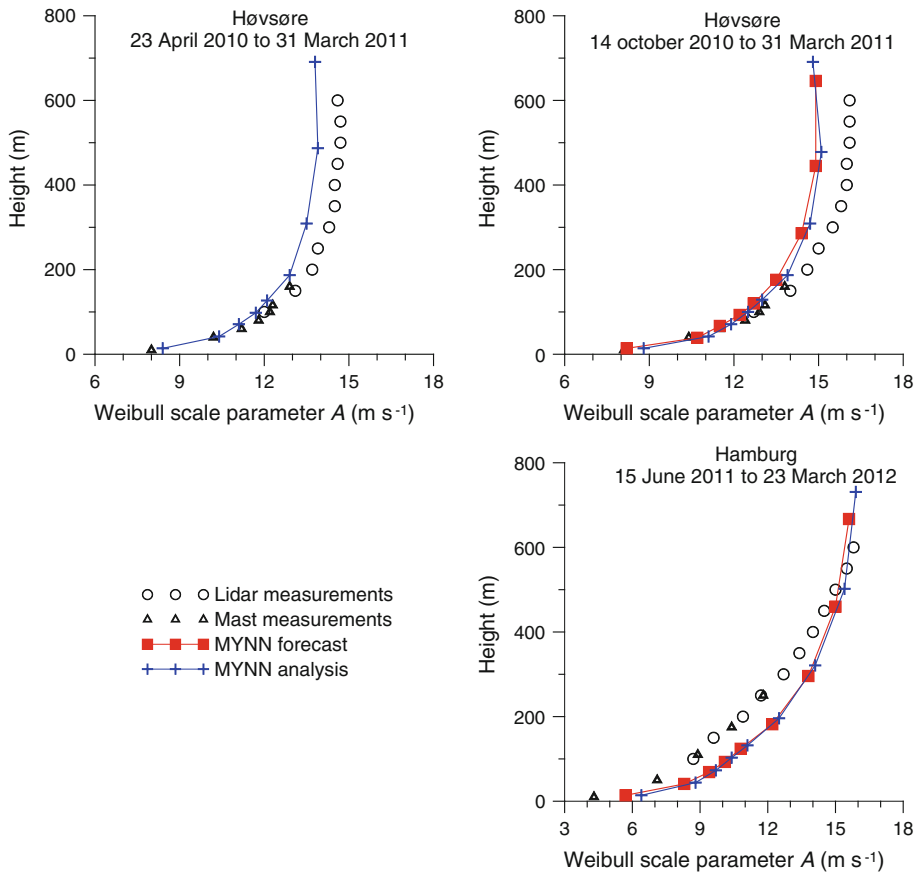


Fig. 7 Measured and simulated profiles of the scale parameter in the Weibull distribution. *Upper left panel* shows the results for Høvsøre 23 April 2010–31 March 2011, *upper right panel* for Høvsøre 14 October 2010–31 March 2011 and the *lower panel* Hamburg 15 June 2011–23 March 2012

measurements. The wind roses derived from the wind lidar at both Høvsøre and Hamburg indicate predominantly westerly winds, i.e. from the sea at Høvsøre and from the city centre at Hamburg.

A commonly used configuration of the WRF model is applied. The profiles of wind speed, wind direction, as well as the scale parameter in the Weibull distribution are rather alike in the forecast and analysis simulations at the rural coastal as well as the suburban site. However, measurements, forecast and analysis disagree for the shape parameter in the Weibull distribution giving a lowest value from the forecast simulations, intermediate from the analysis, and highest (above 100 m) from the observations. The effect is also reflected in the *RMSE* values between model simulations and observations, where it is 10 % lower in the analysis than in the forecast mode. This agrees with the findings in Gryning et al. (2013) on the difference between nudged and non-nudged simulations.

Underestimation of the shape parameter in the simulations indicates that the probability for higher wind speed increases (a wider distribution is related to lower *k* values). For the coastal rural site it was found that although *k* was smaller for the model than the observations,

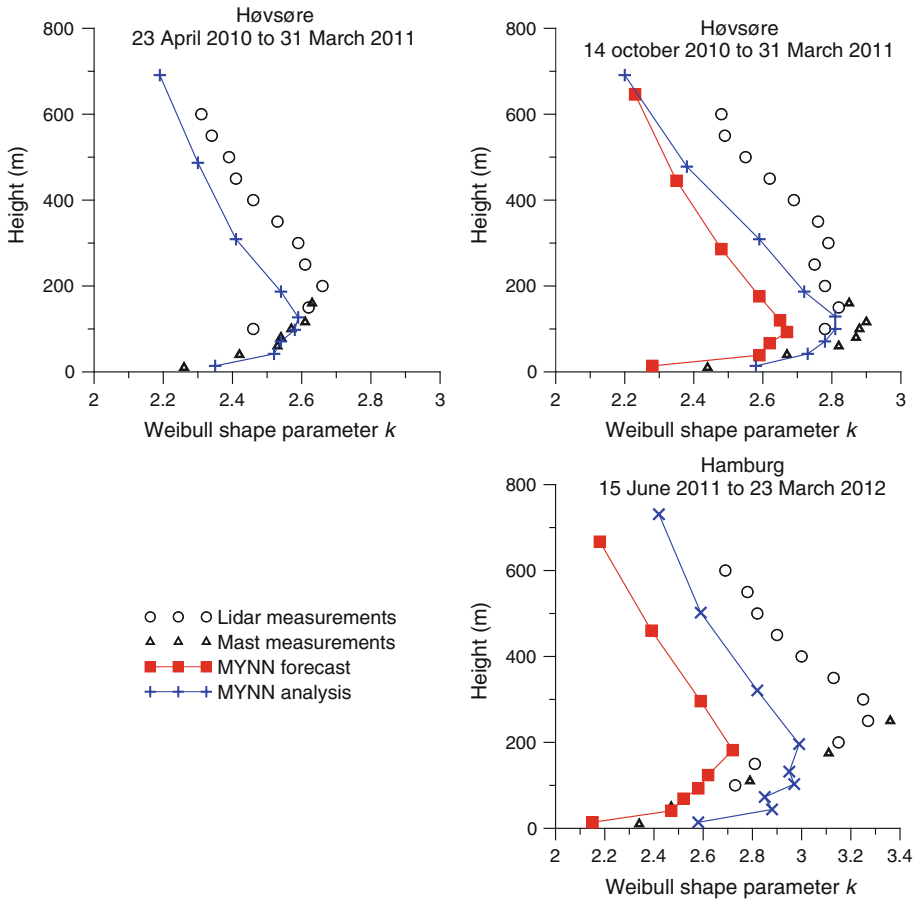


Fig. 8 Measured and simulated profiles of the shape parameter in the Weibull distribution. *Upper left panel* shows the results for Høvsøre 23 April 2010–31 March 2011, *upper right panel* for Høvsøre 14 October 2010–31 March 2011 and the *lower panel* Hamburg 15 June 2011–23 March 2012

the variance (as calculated in Eq. 3) was nearly identical, indicating that the discrepancy in k is more related to the difference in the mean than the difference in the variances. In a study of Floors et al. (2013) with an identical configuration of the WRF model except for the vertical resolution, a 4-week period was simulated at the same rural coastal site, and the model simulations were carried out with a fine (63 model levels) and a coarse (41 model levels) vertical resolution. It was found that the wind profile was not sensitive to the vertical resolution, while herein it was found that the shape parameter is also not sensitive to the vertical resolution, see Fig. 10.

Simulations (not shown) performed in 2011 with the first-order closure Yonsei University PBL scheme (YSU, Hong et al. 2006) predicted the wind speed well, but not the characteristic profile of the shape parameter. Later an error in the programme was reported and corrected in WRF 3.4.1 (September 2012). Simulations with the corrected YSU PBL scheme reproduced the features of the shape parameter profile in a similar way to the MYNN scheme. We report here on the performance of the incorrect YSU PBL scheme in order to illustrate that a problem that is not recognized in the wind speed and scale parameter can clearly show up in the shape

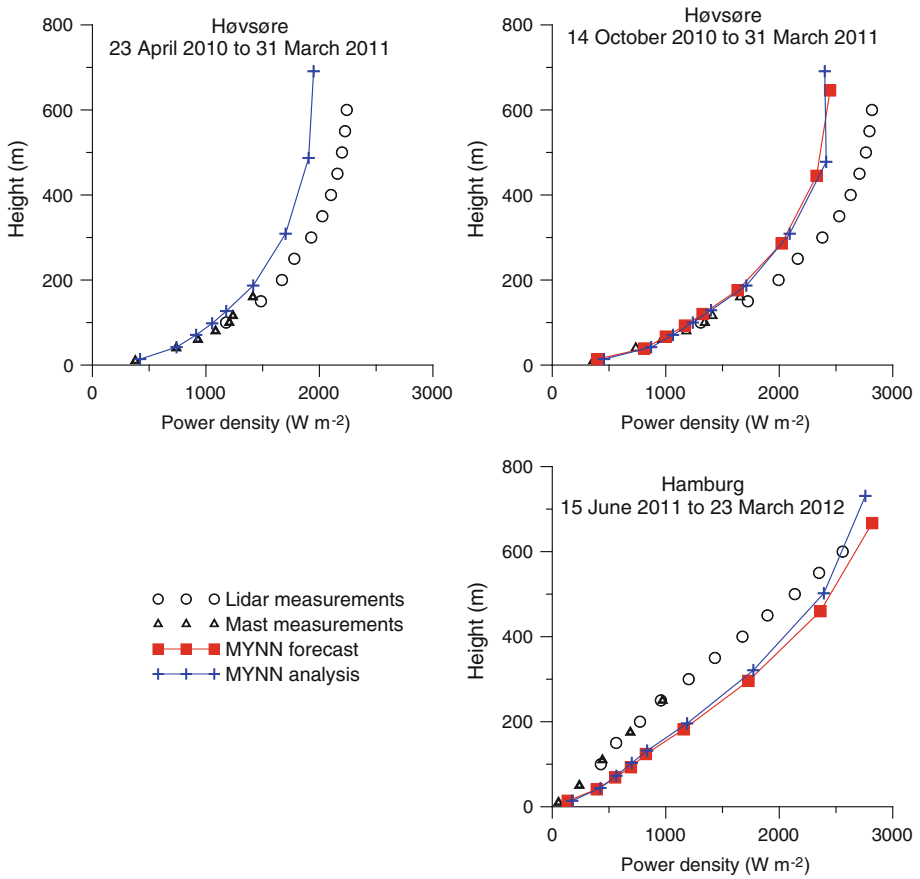
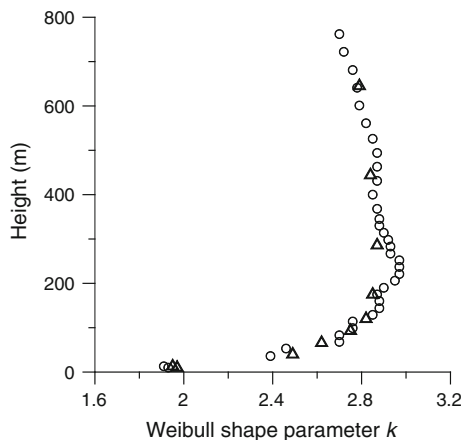


Fig. 9 Measured and simulated profiles of the wind power density. *Upper left panel* shows the results for Høvsøre 23 April 2010–31 March 2011, *upper right panel* for Høvsøre 14 October 2010–31 March 2011 and the *lower panel* Hamburg 15 June 2011–23 March 2012

Fig. 10 Derived profiles of the Weibull shape parameter k from simulations with 41 (*triangles*) and 61 vertical model levels (*circles*), respectively



parameter profile. We consider that the profile of the shape parameter is a good indicator for model performance, because it reflects both the variability of large-scale synoptic features and the local-scale stability conditions.

In conclusion, from a comparison of two datasets of wind measurements up to 600 m with WRF model forecast (2-km resolution, two-way nesting, GFS forcing and no nudging) and analysis simulations (6-km resolution, one-way nesting, FNL forcing and nudging) it was found that: (i) the shape parameter in the forecast simulations is smaller than in the analysis and both are smaller (above 100 m in coastal rural and 150 m in suburban) than the measurements, (ii) the *RMSE* between measurements and modelling is generally larger in the forecast simulations as compared to the analysis, and (iii) the profile of the shape parameter is a good candidate for climatological evaluations of mesoscale models. Also a new parametrization of the shape-parameter profile in the Weibull distribution is proposed for eventual use in wind-resource assessment studies.

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