SCIENTIFIC REPORT

ACTION: ES1303 TOPROF
STSM: COST-STSM-ES1303-38266
TOPIC: The use of lidar measurements for evaluation of wind-speed prediction by numerical models
VENUE: DTU Wind Energy, Denmark
PERIOD: 08 August - 16 August, 2017

Host: Jake Badger (DTU Wind Energy, Denmark)
Applicant: Ekaterina Batchvarova (NIMH-BAS, Bulgaria)
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Introduction

The STSM was planned and approved in July 2017. It was realized in the period 8-16 August 2017 at DTU Wind Energy, Denmark.

Motivations and objectives

Observations by wind lidars are becoming increasingly common in connection with wind energy assessment studies and operation of wind farms (O'Connor et al. 2010; Floors et al. 2013; Peña et al. 2013). Wind lidars today are developing to replace tall meteorological masts. The quality of the individual wind- lidar observation is described by the so-called Carrier to Noise Ratio (CNR). To secure uncertainty below a certain value in the wind speed measurements, a threshold value is assigned for CNR, typically -22 dB as suggested by Frehlich (1996). The *CNR* of lidars is discussed in general by Fujii and Fukuchi (2005) and for pulsed wind lidars by Cariou (2013). Frehlich (1996) argued that if the *CNR* falls below a prescribed threshold (he recommended *CNR* > –22 dB), the uncertainty in the wind speed is too large for the measurements to be useful. Floors et al. (2013) and Peña et al. (2013) found good agreement between wind lidar and cup-anemometer measurements at 100 m for wind-lidar data filtered with *CNR* > –22 dB and deteriorated agreement for decreasing *CNR* thresholds.

Some consequences of the CNR filtering on the measured long-term wind speed have already been presented by Batchvarova and Gryning within the TOPROF COST Action community. Comparing wind speed observations from tall towers with lidar observations up to 600 m filtered with CNR threshold of -22 dB shows over-prediction of the long term mean wind speed over land (Gryning et al, 2016). High CNR threshold values filter the low wind speeds.

The study in this STSM is based on one year of wind speed measurements performed by DTU Wind Energy at the FINO3 Research Platform in the North Sea (Fig. 1). The effect of over-prediction of mean wind speed by filtering the data with different CNR is studied for the marine atmosphere, where measured profiles of wind up to several hundreds of metres are rarely available.

Figure 1 shows three sites at each of which about 1 year of lidar measurements up to 600 m were performed in the frame of Danish Science fund project "Tall wind", described in details in Gryning et al. (2014) and Gryning et al. (2016).

The Høvsøre site at the west coast of Jutland is analysed as land or coastal site depending on wind direction. Hamburg is a suburban-land and FINO3 a marine site.

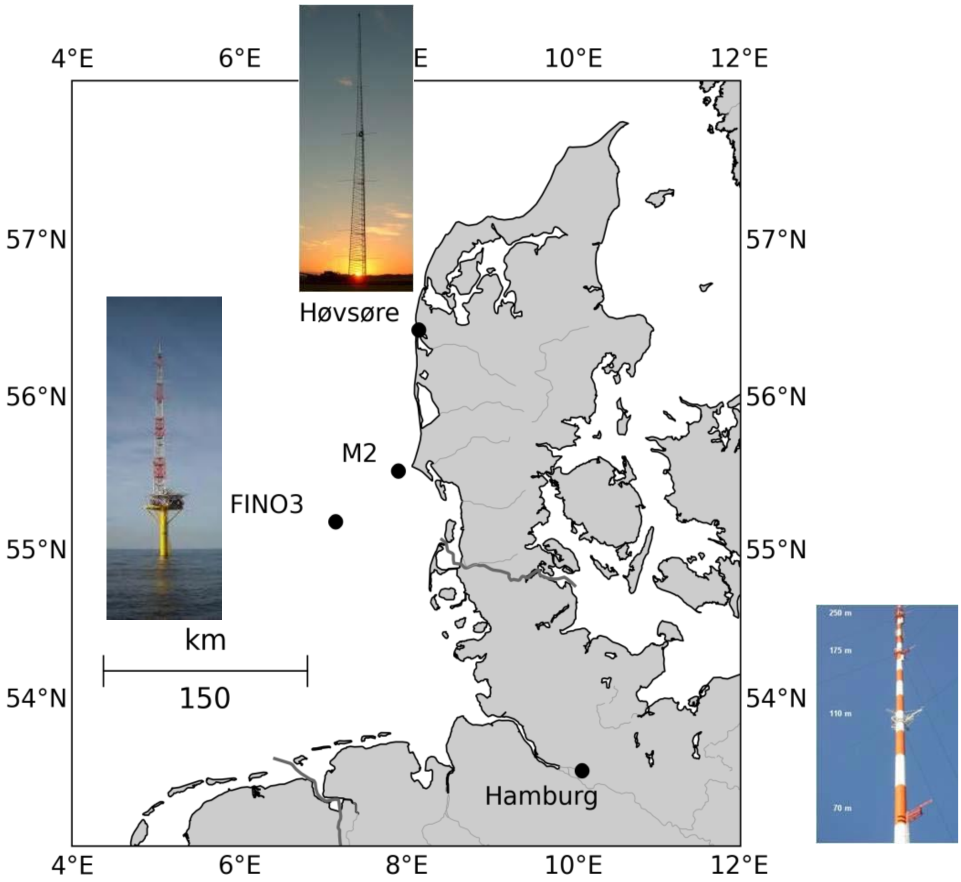

Fig.1. The Tall wind project observations sites Gryning et al. (2014) and Gryning et al. (2016)

Results or Achievements

Description of data

The measurements were performed with a heterodyne Doppler wind-lidar (Leosphere WLS70) at the German marine measuring site FINO3, Gryning et al. (2016). The wind lidar observations are compared to corresponding data sets derived from simulations with the mesoscale model WRF. The comparison is carried out for a number of CNR threshold values and cumulative distributions of the observations. This allows investigation on the question: “Does WRF predict all wind speeds equally well or is there a wind-speed dependence in the ability of WRF to predict the wind speed?”. The analysis is performed for several CNR threshold values and heights from 100 to 600 m.

The CNR depends not only on the characteristics of the specific wind lidar, but also on the size and concentration of atmospheric particles responsible for the backscattered signal. At sites with low concentration of aerosols, lidars retrieve data with generally lower CNR values, hence the availability of data is depending on CNR threshold. This aspect is illustrated in Fig. 2 (Gryning et al, 2016) for three wind-lidar sites (Hamburg, Høvsøre, and FINO3). Availability of 50 % of full wind-lidar profiles up to 600 m is obtained at a threshold CNR value of about –24 dB for the land sites (Hamburg and Høvsøre-land), about –22 dB for the marine site (FINO3) and –19 dB for the coastal site (Høvsøre-coastal).

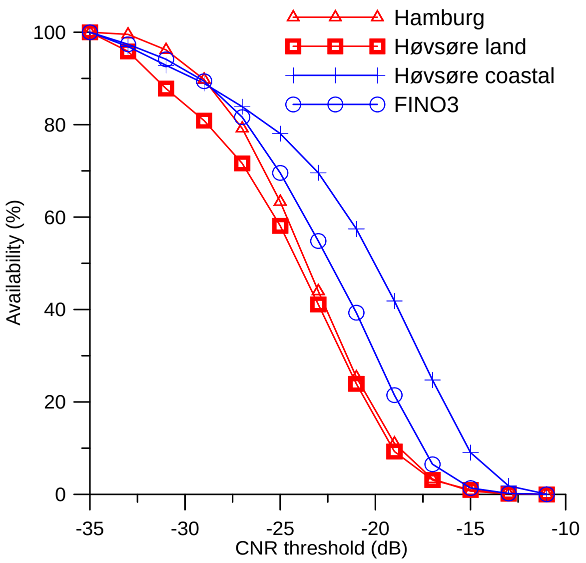

Fig. 2. Availability of full wind-lidar profiles as a function of the CNR threshold value. A full profile is identified when the CNR of the concurrent measurements at all levels between 100 and 600 m is above the threshold value; 100 % availability thus corresponds to the number of full profiles

Applying a high CNR threshold (-22 bB) for filtering data results in derivation of higher mean wind speed compared to the value when all data (threshold -35 dB) are used. In other words, applying high CNR threshold biases the climatology of wind profiles. Therefore, setting a CNR threshold should be done cautiously when creating wind-speed climatological profiles.

In addition to wind-speed profiles the dependence of wind-field statistics on CNR threshold values is investigated using the two-dimentional Weibull distribution, described by its scale and shape parameters in wind studies by Justus and Mikhail (1976). Based on a large number of measurements from land-based tall towers, Wieringa (1989) derived a simple empirical relation for the vertical profile of the Weibull shape parameter over land that revealed many of the observed features, such as the height of the maximum in the shape parameter (reversal height), that had already been discussed much earlier by Hellmann (1917). The shape-parameter profile of Wieringa (1989) uses dimensional parameters and contains a site-dependent dimensional constant; he pointed out that the parametrization was limited by the data available at the time, especially concerning the profile of the shape parameter above the reversal height. By use of heterodyne detection Doppler lidar measurements, Gryning et al. (2014) overcame this shortcoming in the measurements and proposed a parametrization that is also applicable well above the reversal height.

Figure 3 shows the substantial difference in Weibull shape parameter profiles over land and over sea according Gryning et al. (2016). This study also notes that the choice of CNR threshold value affects the Weibull shape parameter, hence the wind statistics, as shown in Fig. 4. Lower CNR threshold values suggest lower height for the maximum in the k-profile (the reversal height) compared to this feature at higher threshold values. It is interesting to note that the reversal height growth in Hamburg was mainly at CNR between – 27 dB and -22 dB (Fig.4, right panel). The k-value is related to the distribution of the wind speed, Fig.5. Larger k-values correspond to more narrow shape of the distribution, hence smaller variability of the wind speed. That is why the height of maximal k corresponds to the reversal height, where the diurnal variability of the wind speed the smaller.

The marine atmosphere is adjusted to the marine surface which is characterized with small diurnal variation of temperature. Therefore, no reversal height is observed within the marine boundary layer. Hence, there is no maximum in the k-profile at the marine observation site FINO3.

Description of model setup

The model data set is created with the Weather Research and Forecast model WRF (Skamarock et al, 2004) with the following settings: analysis mode; FNL global boundary conditions available every 6 hours on a 1° x 1° grid; two nested domains of horizontal grid size of 18 and 2 km; Noah land surface scheme (Chen and Dudhia 2001), MYNN surface layer scheme (Nakanishi and Niino 2009), 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) planetary boundary-layer (PBL) scheme.

The WRF model was configured to calculate the meteorological parameters at 41 vertical levels from the surface to 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. The simulations were initialized every 10 days at 12:00 GMT and after a spin up of 24 hours a time series of 10-min output was picked out from the simulated meteorological data from hour 25 to 264. In order to prevent the model from drifting away from the large scale features of the flow, the model was nudged towards the FNL analysis.

The WRF data sets in this study are composed as pairs from the filtered with given CNR lidar data.

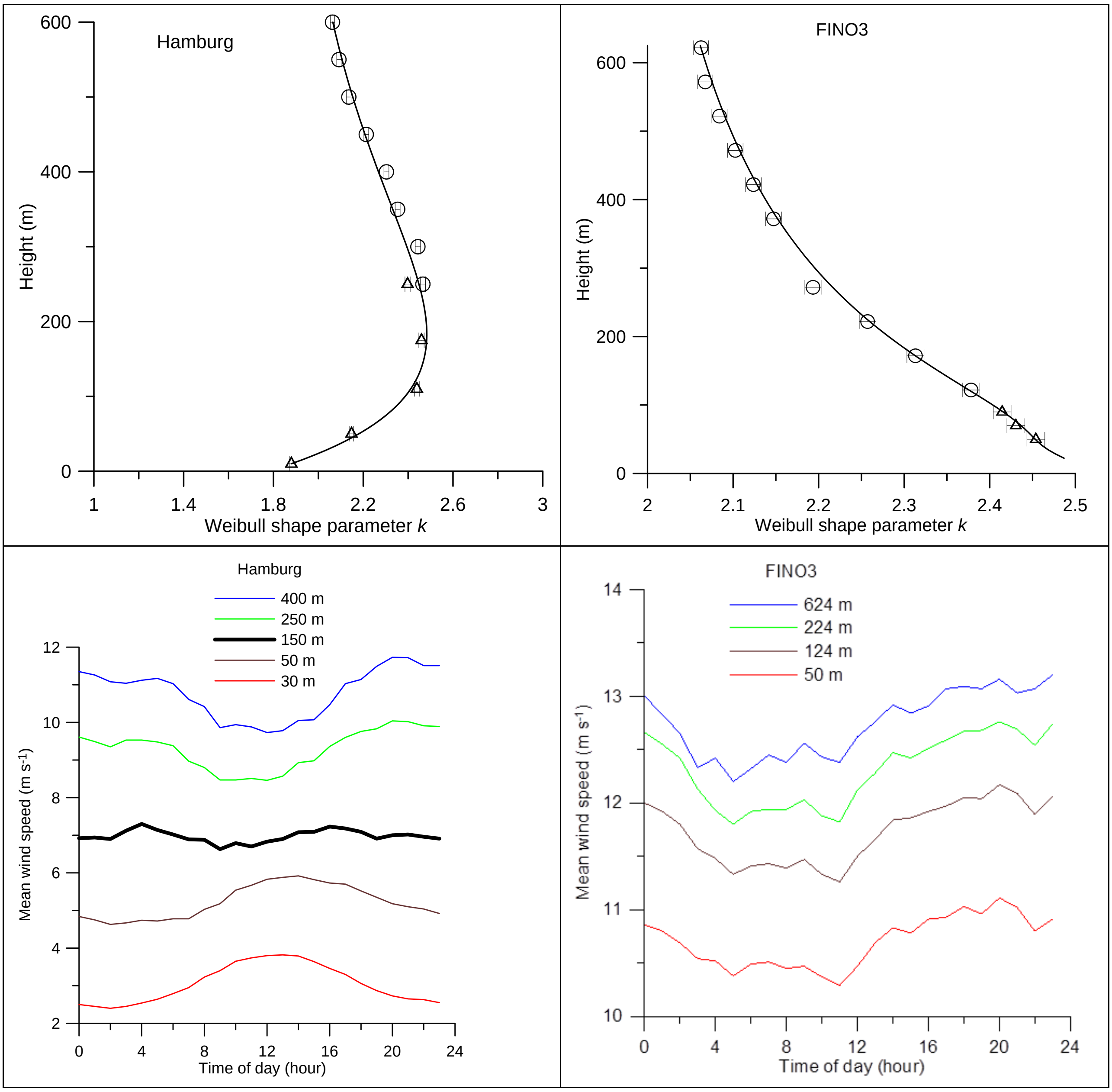

Fig. 3. Weibull distribution shape parameter profile (upper panels) and daily variation of the wind speed (lower panels) for a site over land (Hamburg) and over sea (FINO3), Gryning et al. (2014)

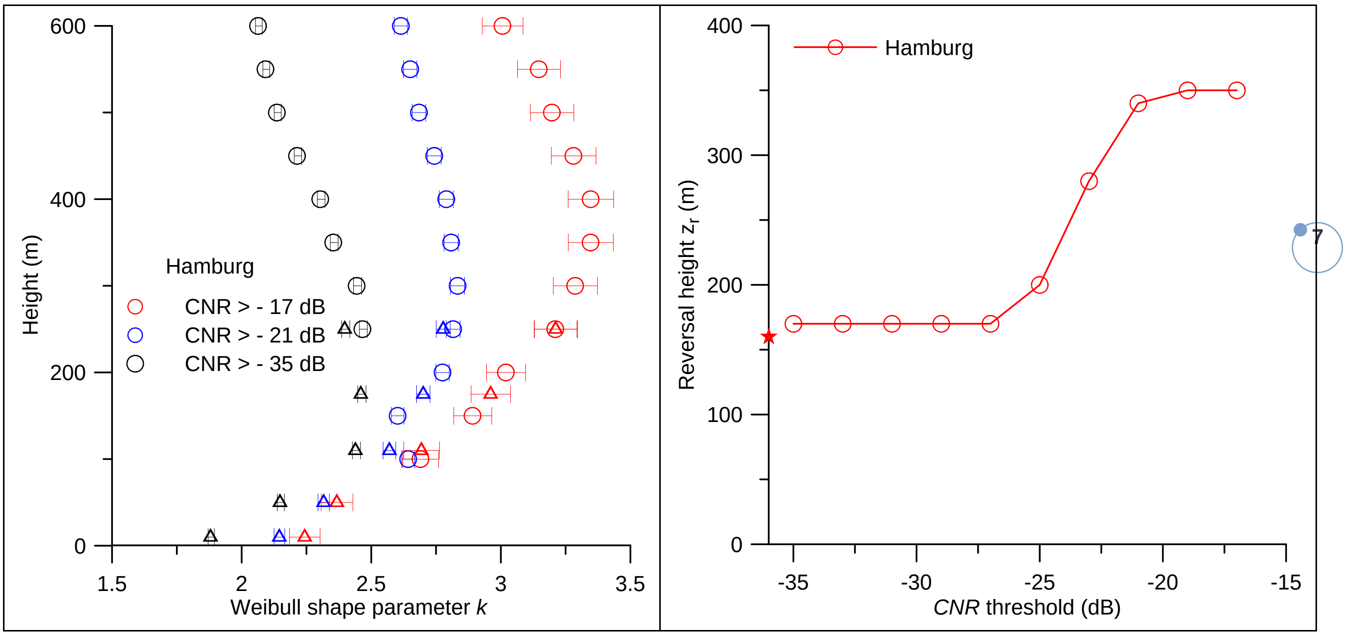

Fig. 4. The dependence of Weibull k-profile (left panel) and reversal height on CNR threshold value at Hamburg

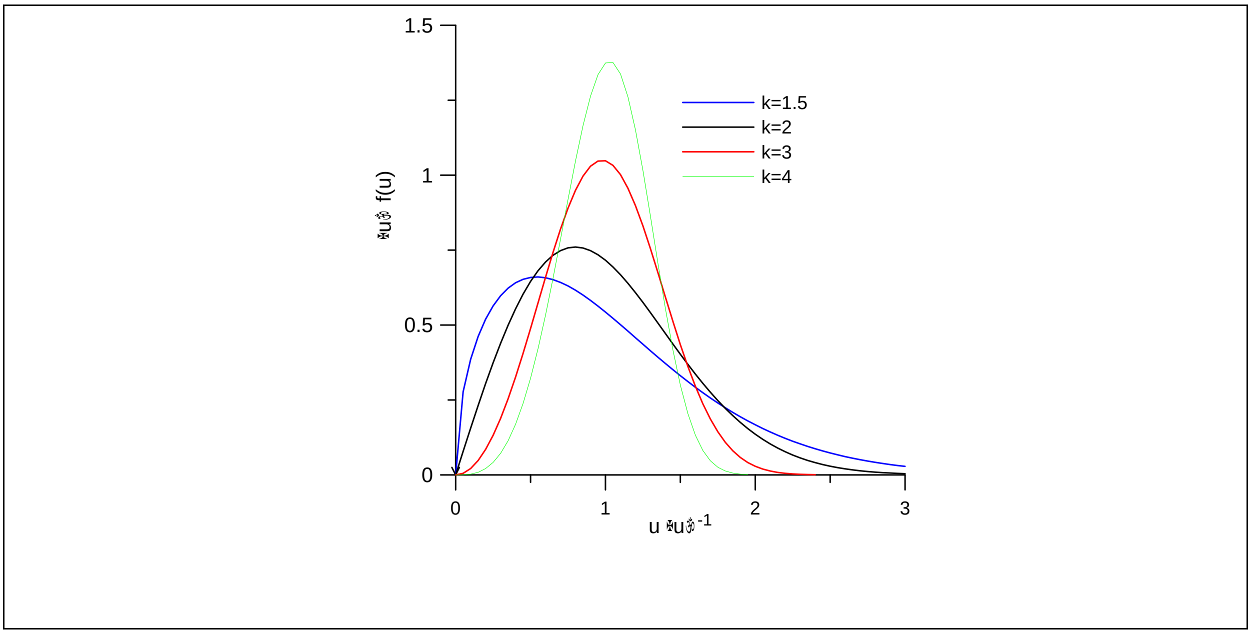

Fig. 5. Weibull distributions for varying k (shape parameter)

Figure 6 shows measured and modelled Weibull k-profiles (left) at FINO3 for different CNR threshold values. The measured k-profile values for CNR threshold -22 dB are higher compared to those for – 35 dB. In other words, the sample with –22 dB gives winds with lower variability compared to the sample with –35 dB. As the WRF data are extracted to match in time the two different observation samples, the modelled k-profiles show the same feature. As for the model-observation comparison, it has to be noted that WRF always overestimates the k-values, suggesting lower variability in the model data compared to observations.

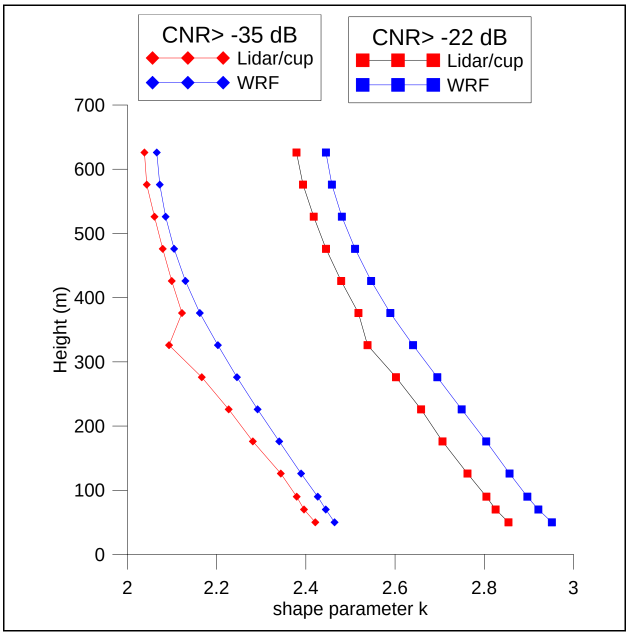

Fig. 6. Measured and modelled Weibull k-profiles (left) at FINO3 for different CNR threshold values

The wind speed model-observation comparison is presented in figure 7, based on percentile analysis – percentage of cases with lower wind speed than the corresponding profile. Concerning the CNR dependence, when more data are included (CNR -35 dB), the wind speed is lower than the one for stronger filtering (-22 dB) for all percentiles. WRF underestimates the wind speed at all levels, CNR values and percentiles, with the difference growing with percentile.

Analysing the observation data for different heights, Fig. 8, reveals that CNR threshold – 22 dB shifts the wind speed distribution towards higher wind speed at all heights – histograms in the upper panels of Fig. 8. CNR >= – 22dB corresponds to higher values of the cumulative distribution – lower panes of Fig. 8.

It has been shown here that the choice of CNR threshold value for Doppler lidar observations at a marine site affects not only the quality of data acquisition, but shifts the sample of measurements toward higher wind speeds, higher mean wind speed, smaller variability of wind speeds, etc. The CNR value influences all statistical measures for the wind fileld.

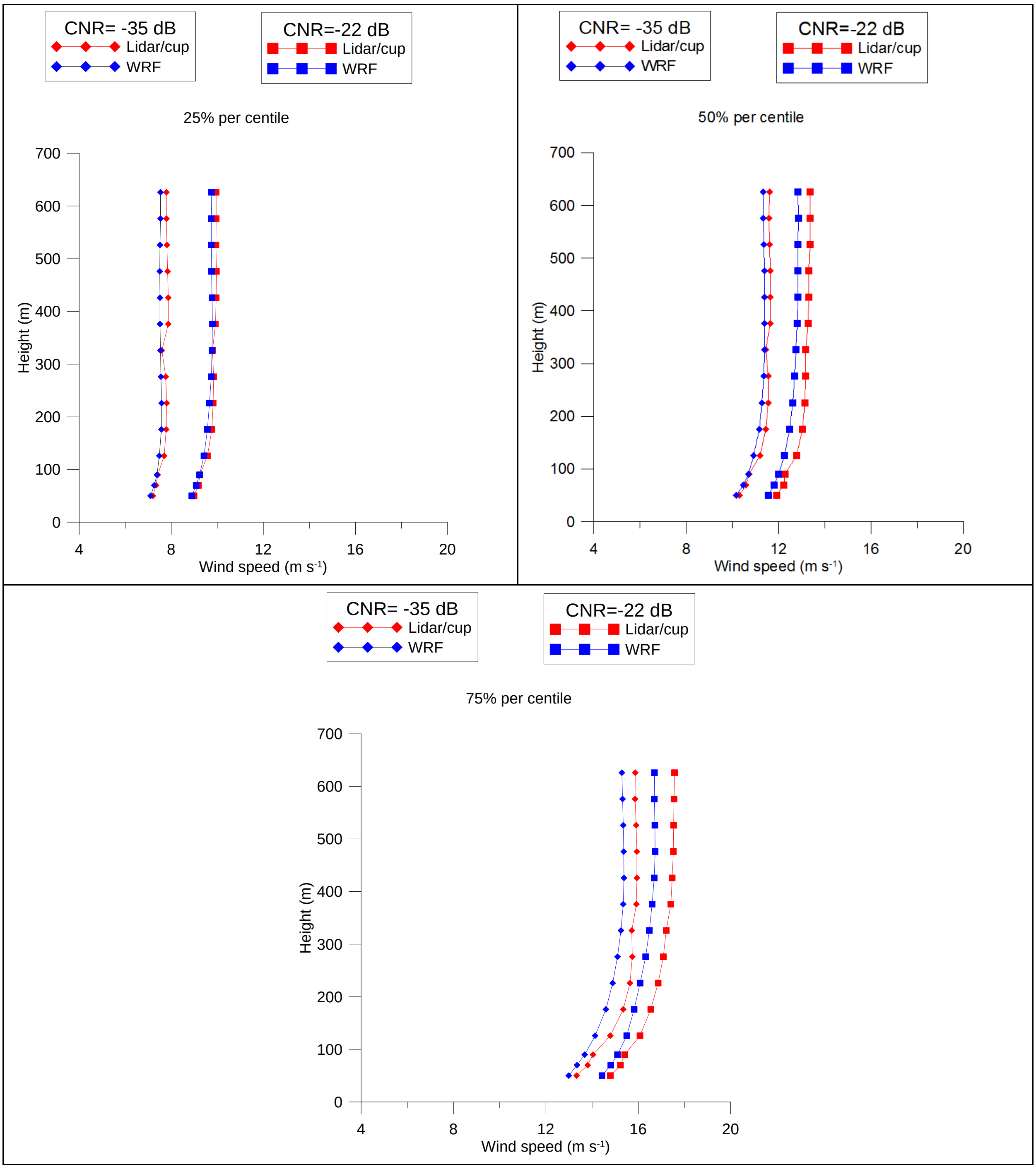

Fig. 7. Measured and modelled wind speed profiles in 25, 50 and 75 percentile

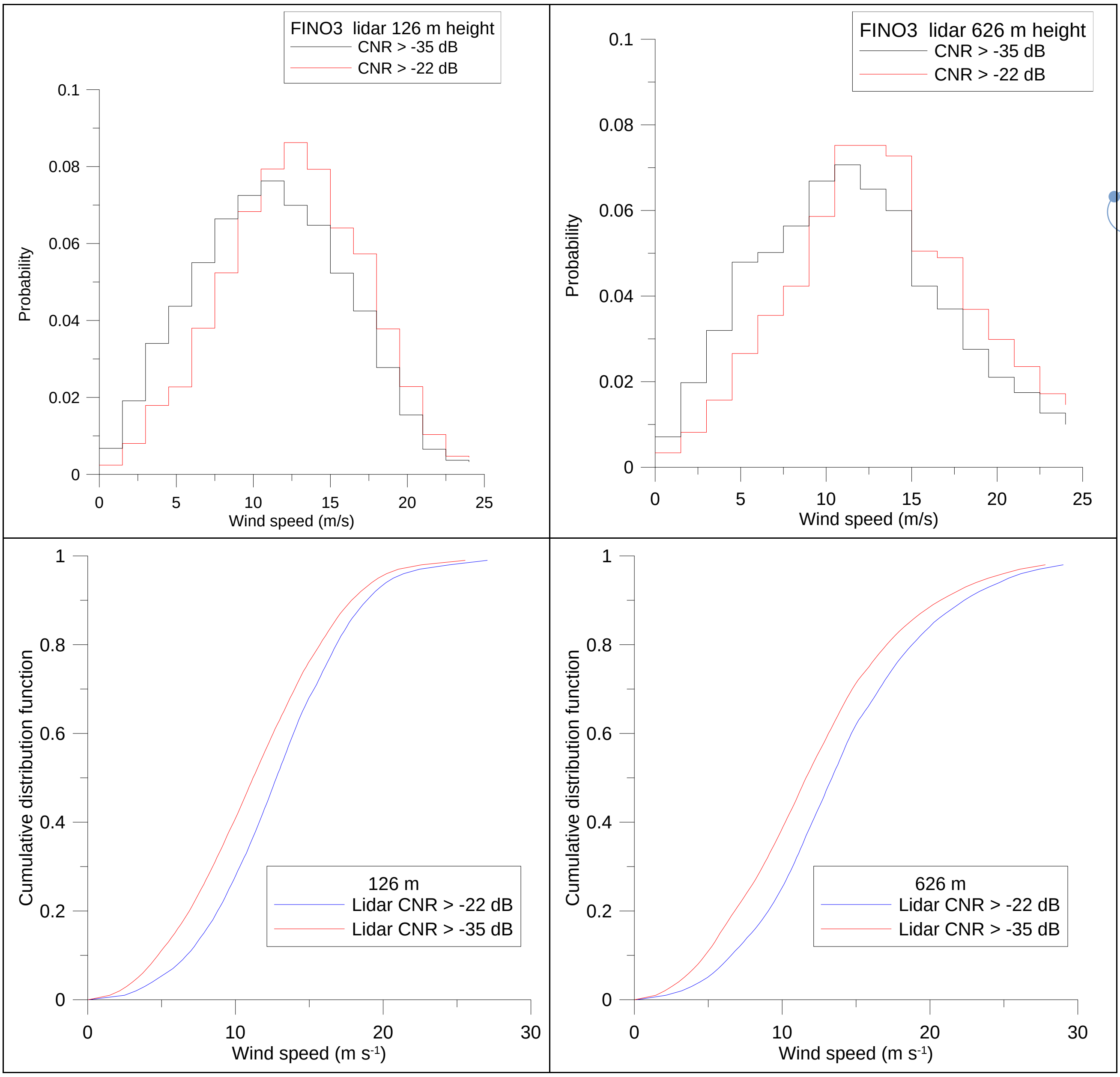

Fig. 8. Histograms and cumulative distribution of measured wind speed for different CNR at different levels (colours in both types of graphs should match)

Widening the above analysis to include the WRF model data, Fig. 9, shows that the model simulates the distributions by level and the cumulative distributions successfully with slight underestimation. The lidar data are slightly shifted towards higher wind speed values.

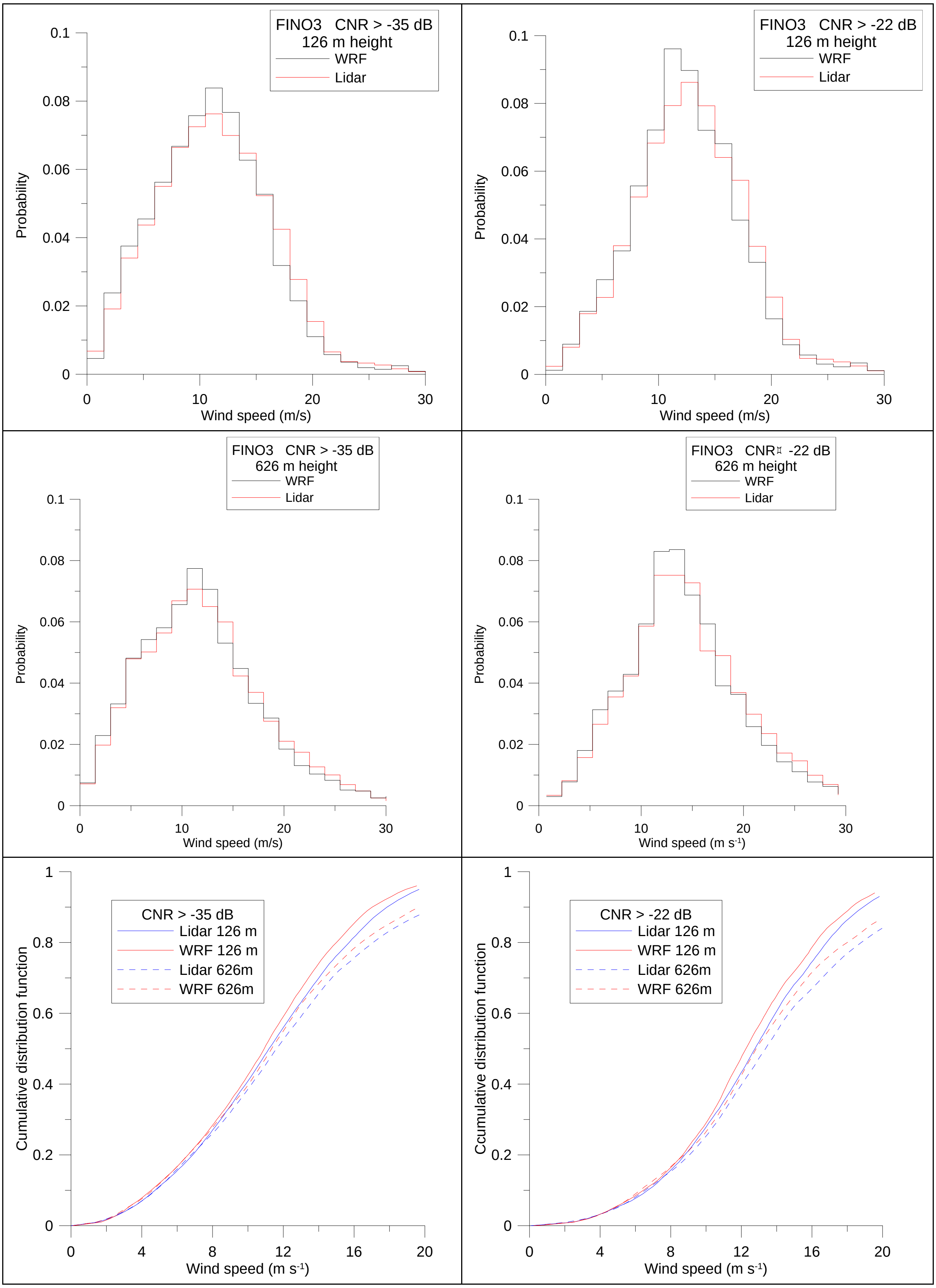

Fig. 9. Comparison of WRF and lidar data distributions for different CNR threshold value

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The choice of CNR value affects also the time-lag statistics. This is demonstrated in Figs. 10 and 11 pairing the observations and model at given time with those at time 10, 20,…60,…360,…720, …1440 minutes later (24 hours in intervals of 10 minutes corresponding to the temporal resolution of measurements and model output).

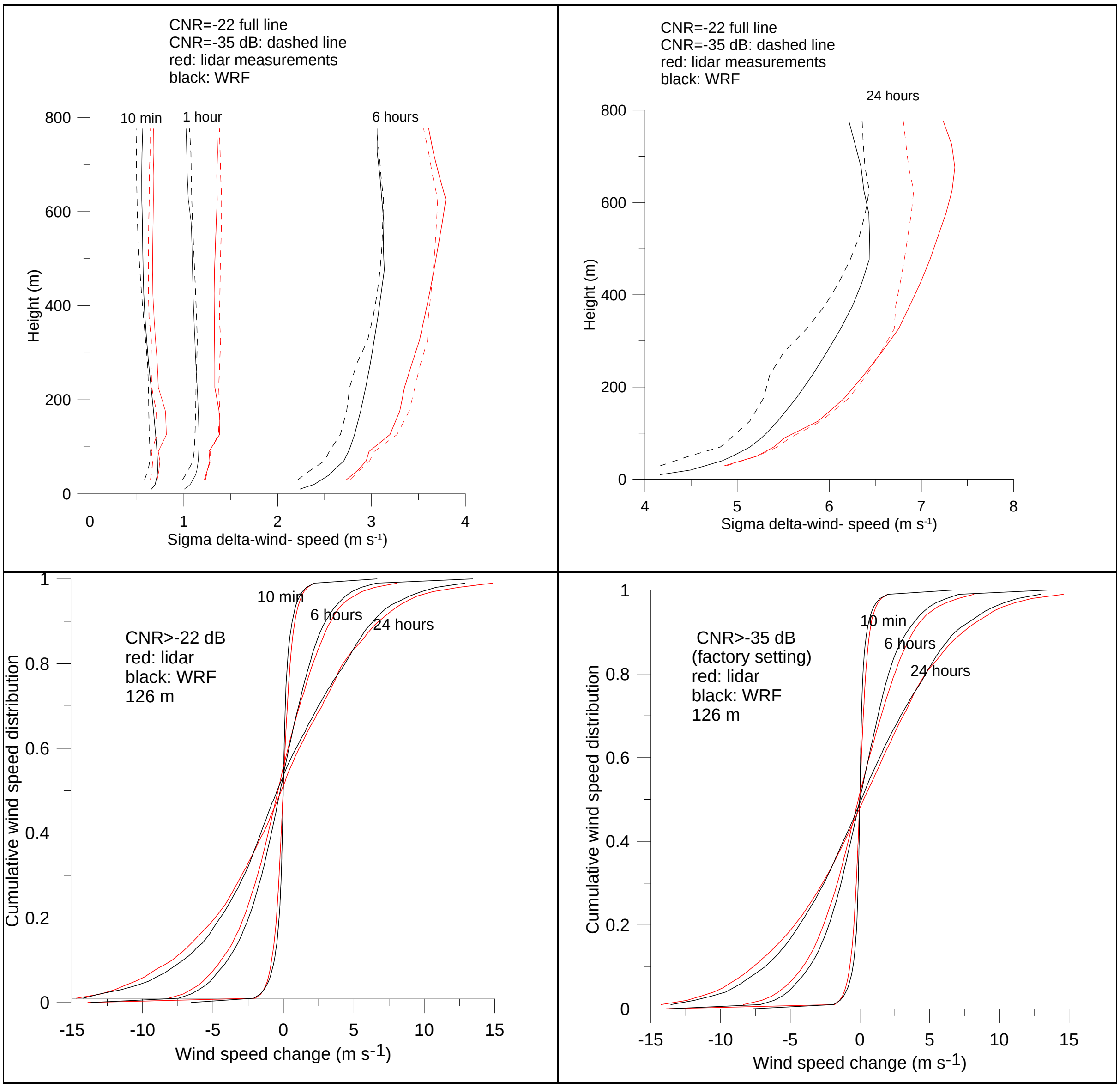

Fig. 10. Profiles of standard deviation of the change in wind speed for the pairs of time lags 10 minutes, 1 hour, 6 hours and 24 hours (upper panels) and cumulative distributions of the change in wind speed over these time lags at 126 m height for CNR -22 dB and -35 dB (lower panel)

Compared to measurements, WRF underestimates this time-lag wind speed parameter at all levels and all time lags. The model values are lower for CNR -35 dB compared to CNR -22 dB near the ground (Fig. 10, upper panels) and higher above a level different for each time lag. In the observations, the difference between profiles with different CNR is smaller and changes sign. WRF underestimates the cumulative distribution for all time lags at both CNR threshold values at 126 m. The distribution slightly widens for CNR -35 dB.

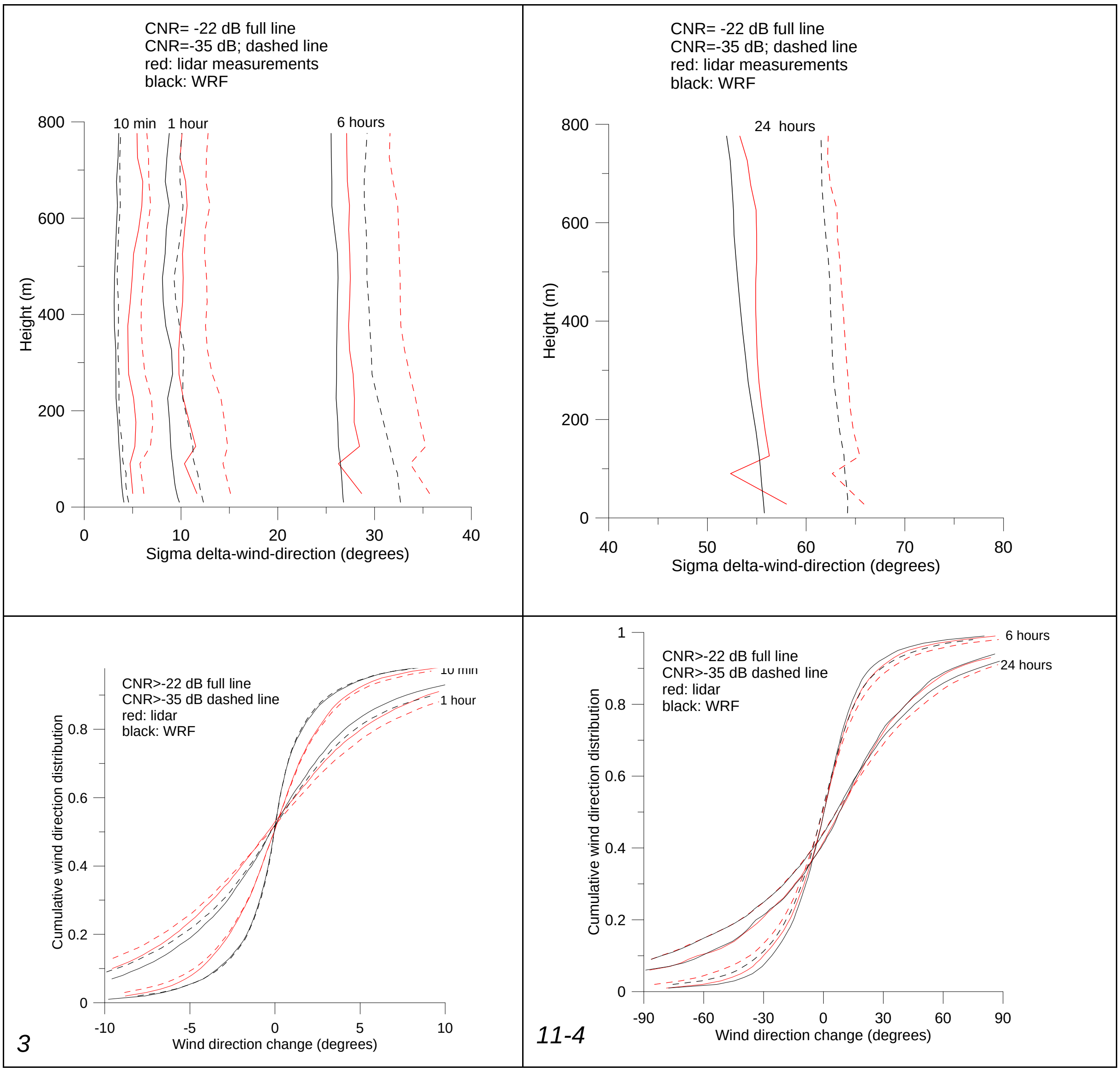

Fig. 11. Profiles of dispersion of the change in wind direction for the pairs of time legs -10 minutes, - 1 hour, – 6 hours and -24 hours (upper panels) and cumulative distributions of the change in wind direction over these time legs at 126 m height for CNR -22 dB and -35 dB (lower panel)

Compared to measurements, WRF underestimates this time-lag wind-direction parameter at all levels and all time lags. The model values are higher for CNR -35 dB compared to CNR -22 dB (Fig. 11, upper panels). WRF underestimates the cumulative distribution for all time lags at both CNR threshold values at 126 m. The cumulative distribution slightly widens for CNR -35 dB.

The outcome of the study can be summarized as:

In general, WRF underestimates the wind speed and overestimates the Weibull shape parameter at all levels, which means that the model suggests lower values and lower variability for the wind speed at all levels up to 600 m.

Thus, when comparing all WRF data to lidar data with strong CNR filter applied, the underestimation will be bigger than presented here.

Also, if high quality lidar data are assimilated into WRF, there will be shift towards higher wind speeds, which may reduce the difference between model and observations.

Conclusions

The study provides experience on the use of wind lidar measurements for model evaluations over sea, where profiles of wind up to several hundreds of metres are rarely observed for long periods.

It is important to consider the CNR when using a wind-lidar for climatological studies, as the choice of CNR threshold affects the mean wind speed. Stronger filtering (-22 dB) results in higher mean wind speed compared to weaker filtering (-35 dB).

The CNR threshold value affects also a number of other physical parameters, such as reversal height and a number of statistical measures as the Weibull distribution parameters, histograms of wind speed distribution and cumulative distribution.

In an example of marine climatology from FINO3, WRF underpredicts the wind-speed profile up to 600 m for both CNR > -22 dB and CNR > -35 dB and suggests lower than observed variabitlity of the wind speed at all levels.

The scientific report will be posted on the TOPROF website: www.toprof.eu.

References

Batchvarova E, Gryning SE, Skov H, Sørensen LL, Kirova H, Münkel C (2014) Boundary-layer and air quality study at “Station Nord” in Greenland. In: Steyn D, Mahur R (eds) Air pollution modelling and its application XXIII. Springer International Publishing, Cham, pp 525–529.

Cariou JP (2013) Pulsed lidars. In: Peña A, Hasager CB, Lange J, Anger J, Badger M, Bingöl F, Bischoff O, Cariou JP, Dunne F, Emeis S, Harris M, Hofsäss M, Karagali I, Laks J, Larsen S, Mann J, Mikkelsen T, Pao LY, Pitter M, Rettenmeier A, Sathe A, Scanzani F, Schlipf D, Simley E, Slinger C,Wagner R,Würth I (eds) Remote sensing for wind energy. DTU Wind Energy-E-Report-0029(EN), pp 104–121.

Chen F, Dudhia J (2001) Coupling an advanced land surface-hydrology model with the Penn State-NCAR. MM5 modeling system. Part I: model implementation and sensitivity. Mon Weather Rev 129:569–585.

Floors R, Vincent C-L, Gryning SE, Peña A, Batchvarova E (2013) The wind profile in the coastal boundary layer: wind lidar measurements and numerical modelling. Boundary-Layer Meteorol 147:469–491.

Frehlich R (1996) Simulation of coherent Doppler lidar performance in the weak-signal regime. J Atmos Ocean Technol 13:646–658.

Fujii Y, Yamashita J, Shikata S, Saito S (1978) Incoherent optical heterodyne detection and its application to air pollution detection. Appl Opt 17:3444–3449.

Fujii T, Fukuchi T (2005) Laser Remote Sensing. Taylor & Francis Group, Boca Raton, 912 pp

Gryning SE, Lyck E (1984) Atmospheric dispersion from elevated sources in an urban area: comparison between tracer experiments and model calculations. J Clim Appl Meteorol 23:651–660.

Gryning SE, Batchvarova E, Brümmer B, Jørgensen H, Larsen S (2007) On the extension of the wind profile over homogeneous terrain beyond the surface boundary layer. Boundary-Layer Meteorol 124:251–268.

Gryning SE, Batchvarova E, Floors R, Peña A, Brümmer B, Hahmann AN, Mikkelsen T (2014) Long-term profiles of wind and Weibull distribution parameters up to 600 m in a rural coastal and an inland suburban area. Boundary-Layer Meteorol 150:167–184.

Gryning S-E, Floors R, Pena A, Batchvarova E, Brümmer B (2016) Weibull Wind-Speed Distribution Parameters Derived from a Combination of Wind-Lidar and Tall-Mast Measurements Over Land, Coastal and Marine Sites, Boundary-Layer Meteorol, 159:329–348, DOI 10.1007/s10546-015-0113-x.

Nakanishi M, Niino H (2009) Development of an improved turbulence closure model for the atmospheric boundary layer. J Meteorol Soc Jpn 87(5):895–912.

O'Connor EJ, Illingworth AJ, Brooks IM, Westbrook CD, Hogan RJ, Davies F, Brooks BJ (2010) A method for estimating the turbulent kinetic energy dissipation rate from a vertically-pointing Doppler lidar, and independent evaluation from balloon-borne in-situ measurements. J AtmosOcean Technol 27:1652–1664.

Peña A, Gryning SE, Hahmann AN (2013) Observations of the atmospheric boundary layer height under marine upstream flow conditions at a coastal site. J Geophys Res 118:1924–1940.

Skamarock, WC, Klemp JB, Dudhia J,Gill DO, Barker DM,Duda MG,HuangXY,WangW, Powers JG(2008) A description of the advanced research. WRF version 3. NCAR/TN-475+STR, NCAR technical note, Mesoscale and Microscale Meteorology Division, National Center for Atmospheric Research, Boulder, 113 pp

Thompson G, Rasmussen RM, Manning K (2004) Explicit forecasts of winter precipitation using an improved bulk microphysics scheme, part I: description and sensitivity analysis. Mon Weather Rev 132(2):519–542

Confirmation by the host institution of the successful execution

DTU Wind Energy confirms that Ekaterina Batchvarova was present at DTU Wind Energy from 8 August till 16 August 2017 to work with Sven-Erik Gryning on long-term lidar and WRF data from a marine site (FINO3).