0.1 Response to Reviewer 4 Comments

Dear reviewer:

We appreciate the time and effort that you have dedicated to providing your insightful comments on our paper. We have been able to incorporate changes to reflect most of the suggestions provided by you. We have highlighted the changes within the manuscript.

Major comments:

1 **The main critical point of this manuscript is that the conclusion was based only on the values of three minutes with (no) rain during one event. However, more minutes with rain are existing (Figure 16), but only a visual comparison was provided. It is essential to validate the proposed data processing procedure by considering more rain minutes (if possible also from other rain events on different dates with different intensities) to conclude the applicability of the method in various rain conditions.**
Thank you for pointing this out. In this study, we first compared three minutes of data with different rain intensities in Section 5.1 and then applied the rain-suppressing normalization method to three-hour data in Section 5.2. We would like to investigate more data on several days with various rain intensities for this proof-of-concept study. This point is presented in the Conclusion part as "The tendency is that the more it rains, the stronger the bias and the more the rain-suppressing normalization is reducing the bias. For moderate rain intensity (we do not have a heavy rain period in our data), the range of the bias is reduced from the interval 0.1 to 0.4 ms^{-1} to 0.0 to 0.1 ms^{-1}. The suggested method in this study could also be investigated for rain events (containing heavy rain) on several days and also for pulsed Doppler lidars even though their measurement volume is quite larger than that of the continuous-wave lidars. Further investigations could also attempt to retrieve the falling velocity and the size distribution of raindrops using the fast Doppler spectra.".

2 **From the text, it is not easy to distinguish between the steps in the standard procedure of WindScanner data processing and the new proposed procedure. As this is the key point in this manuscript, a sketch showing the steps with and without rain-signal exclusion would be really helpful to understand the differences in the data processing.**
Thank you for pointing this out. We agree with this comment. We added a processing diagram block in the draft to show the spectral process steps of our proposed method. Now, Sect. 4.1 is restructured according to the suggestion. The first paragraph is about how Doppler spectra after being averaged to lower frequencies are processed. Then we show the comparison between normal Doppler spectra with only aerosol-induced Doppler

signals and the spectra with rain-induced signals. Subsequently, we proposed our rain-suppressing normalization method.

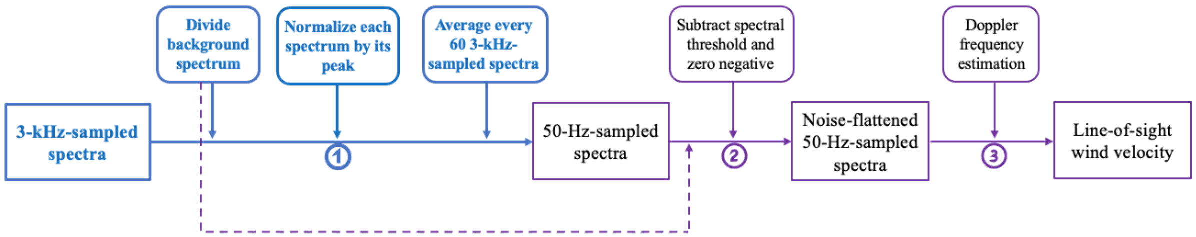


Figure 1: Processing block diagram of the rain-suppressing normalization method (the solid lines from ① to ③) to estimate wind velocity based on 3-kHz-sampled Doppler spectra. Doppler spectra at lower frequencies that do not resolve individual raindrops (like 50 Hz) are processed according to the purple path including the dashed purple line, ②, and ③.

3 **The authors provide 0.35 ms as transit time of a raindrop through the lidar beam. Which assumptions were made to calculate this time? It would be interesting to have a range of potential transit times, because different raindrop sizes exist. Depending on the size and other factors, the fall velocity of a raindrop varies as shown already in Figure 9 (b).**
Thank you for pointing this out. We agree with this comment and explained in the text like this "The shortest beam transit time can be determined based on large raindrops' maximum downfall speed of 9 ms^{-1} from the disdrometer measurement in Fig. 6b, the beam width (twice of the beam waist w_0), and the elevation angle of a lidar. For lidar #1 with a beam width of 1.12 mm and an elevation angle of 57.9°, the shortest beam transit time is 0.234 ms $= 1.12/(9 \cdot \cos(57.9°))$, while it is 0.362 ms $= 3.14/(9 \cdot \cos(15.3°))$ for lidar #3 with a beam width of 3.14 mm and an elevation angle of 15.3°. Most often, however, raindrops' transit time is longer than the aforementioned shortest time if their paths are away from the lidar focus and if they fall slower. In this study, it is reasonable to set the spectral sampling frequency to 3 kHz so that the sampling period for a spectrum (0.333 ms) is shorter than the beam transit of raindrops [see Jin et al., 2022, Fig. 5b]. Therefore, the rare instances where a raindrop resides in the beam could be identified and suppressed based on the lidar measurements.".

4 **The PDFs of the no-rain minutes were higher in case of the new procedure compared to the old one. Can the authors elaborate on the reasons for that and possible consequences? This example shows that a validation with more data is necessary to see how the data processing procedure behaves in non-rainy periods as well. This is important, because it raises the question if the proposed procedure can only be applied for measurements taken during rain or if it can be applied during dry and wet conditions.**

Thank you for this comment. Due to the fact that this minute was a few minutes before rain began, it is possible that a raindrop passed through the laser beam of lidar #1 and was detected by the lidar. After applying the proposed method, the strong rain signal was suppressed. This results in a higher peak in the blue curve than in the red, but closer to the green (the sonic data). From the results in Tables 4 and 5 as well as Fig. 10, we believe that our proposed method also works for dry conditions as the bias between the sonic anemometer and two lidars' measurements is almost the same.

Minor comments and technical corrections:

1 **L10: The authors write significant reduction. Was the reduction analyzed with a statistical test that supports the assumption of a significant reduction? If yes, please include this result in the manuscript. If not, please consider removing the word 'significant'.**
Thank you for pointing this out. We agree with this comment and removed the word "significant" in **L11**. Now the sentence is "This reduction of the bias occurs at the minute with the highest amount of rain when the measurement distance of the lidar is 103.9 m with a corresponding probe length being 9.8 m.".

2 **L11: It is not clear what should be understood by 'the measurement distance of the lidar'. Distance to what?**
Thank you for this comment. Here the measurement distance is the focus distance of a lidar. We have changed "measurement" to "focus" in **L12**. Now the new sentence is "This reduction of the bias occurs at the minute with the highest amount of rain when the focus distance of the lidar is 103.9 m with a corresponding probe length being 9.8 m.".

3 **L16-22: When starting with meteorology, examples of this application area should be mentioned first.**
Thank you for this comment. We agree and have implemented it in the manuscript. The new paragraph is "Precise determination of wind flow plays an important role in reducing loads on critical turbine components and power variations, correcting commonly used models for wind energy assessment, improving the performance of wind turbine controllers, and improving the prediction of the potential wind power extracted from the wind [Davoust et al., 2014, Jena and Rajendran, 2015, Li et al., 2018, Samadianfard et al., 2020, Guo et al., 2022]. Besides, wind velocity estimation is also useful for understanding important phenomena, i.e., atmospheric boundary layer flows and wind turbulence [Van Ulden and Holtslag, 1985, Türk and Emeis, 2010, Debnath et al., 2017]. Therefore, accurate measurements of wind velocity are crucial for many applications in meteorology and wind energy.".

4 **L42: I assume the measurements of Doppler lidars are influenced, not the instrument itself? Maybe the authors can clarify that.**

Thank you for this comment. We agree and have implemented this in the manuscript in **L42**. The new sentence is "Doppler lidars' measurements of wind velocity can be influenced by heavy rainfall because the projected speed of raindrops on the propagation direction of the lidar beam will be different from the line-of-sight wind velocity.".

5 **L43-L44: Please remove the brackets around the reference of Träumner et al.**
Thank you for pointing this out. We agree and removed the brackets around the reference to Träumner et al. The new sentence is "A synergy approach was proposed by Träumner et al. [2010], which combined radar and vertically scanning lidar measurements to estimate the vertical wind velocity and the raindrop size distribution during rain episodes.".

6 **L46: Please remove the brackets around the reference Wei et al.**
Thank you for this comment. We agree and removed the brackets. The new sentence is "Later, by using a velocity-azimuth display (VAD) scanning technique, wind speed, and rainfall speed were simultaneously retrieved in Wei et al. [2019], by fitting the two-peak spectrum with a two-component Gaussian model. The spectral peak close to 0 ms^{-1} is the Doppler signal of the vertical wind speed, which can be easily recognized in this scenario.".

7 **L54: The acronym 'cw' is not defined. Please add the information.**
Thank you for this comment. We agree with this point. The definition of CW is in **L54** "A field measurement campaign was carried out at Risø where three coherent continuous-wave (CW) Doppler lidars [Mikkelsen et al., 2017] were deployed to point towards a common focus point very close to a mast-mounted sonic anemometer at 31 m height.".

8 **L107: What does Risø in the brackets mean? Is this the type/manufacturer of the cup anemometers? Please clarify.**
Thank you for this comment. We have added the type information in **L113**. The new sentence is "There are five sonic anemometers (USA-1, Metek) on booms facing north and five cup anemometers (P2546A from WindSensor) on booms facing south, placed at 18 m, 31 m, 44 m, 57 m, and 70 m above the terrain (Fig. 3). The sampling frequency of the sonic anemometers was 50 Hz.".

9 **L108-L109: What is the manufacturer of the wind vane and the air temperature sensor? In this connection, the wording 'absolute temperature' sounds strange. Maybe 'air temperature' is more appropriate?**
Thank you for this comment. We have added the type information in **L116** and deleted the word "absolute". The new sentence is "Furthermore, the mast is instrumented with a vector wind vane (W200P from Kintech Engineering) at 41 m, and two air temperature sensors (Pt 100, developed by DTU) mounted at 18 m and 70 m, respectively.".

10 **L138-L139: It is not clear how the wake influence of the turbine was determined and why this was important for the experiment. Please clarify.**

Thank you for this comment. So far, we are uncertain about the influence of turbine wake on our proposed rain-suppressing normalization method. But, we would like to have clean data to investigate the performance of the suggested method. Therefore, we avoided the complication of turbine wakes.

11 L144: Can the authors provide a reference to the Met Office's definition?
Thank you for this comment. We agree with this point and add a reference to the definition in **L172**. The new sentence is "Moderate rain is defined as a precipitation rate between 2.6 mm and 7.6 mm per hour [Glossary of Meteorology (June 2000), last access: 21 June 2023.].".

12 L185: Please remove the brackets around the reference of Angelou et al.
Thank you for this comment. e agree and removed the brackets. The new sentence is "As concluded in Angelou et al. [2012], the optimum number of standard deviations for defining the threshold is not the same for different data sets and a number of 2.5 has been used for the three lidars in this investigation.".

13 L186: Why was the number 2.5 used for the analysis?
Thank you for this comment. We compared the velocity difference between sonic data and lidar data with different values ranging from 1.0 to 4.5. We find that 2.5 is a reasonable number for all three lidars. We added some explanation to the manuscript "After calculating velocity difference with sonic data over a short period of time, a number of 2.5 has been chosen for the three lidars in this study." in **L205**.

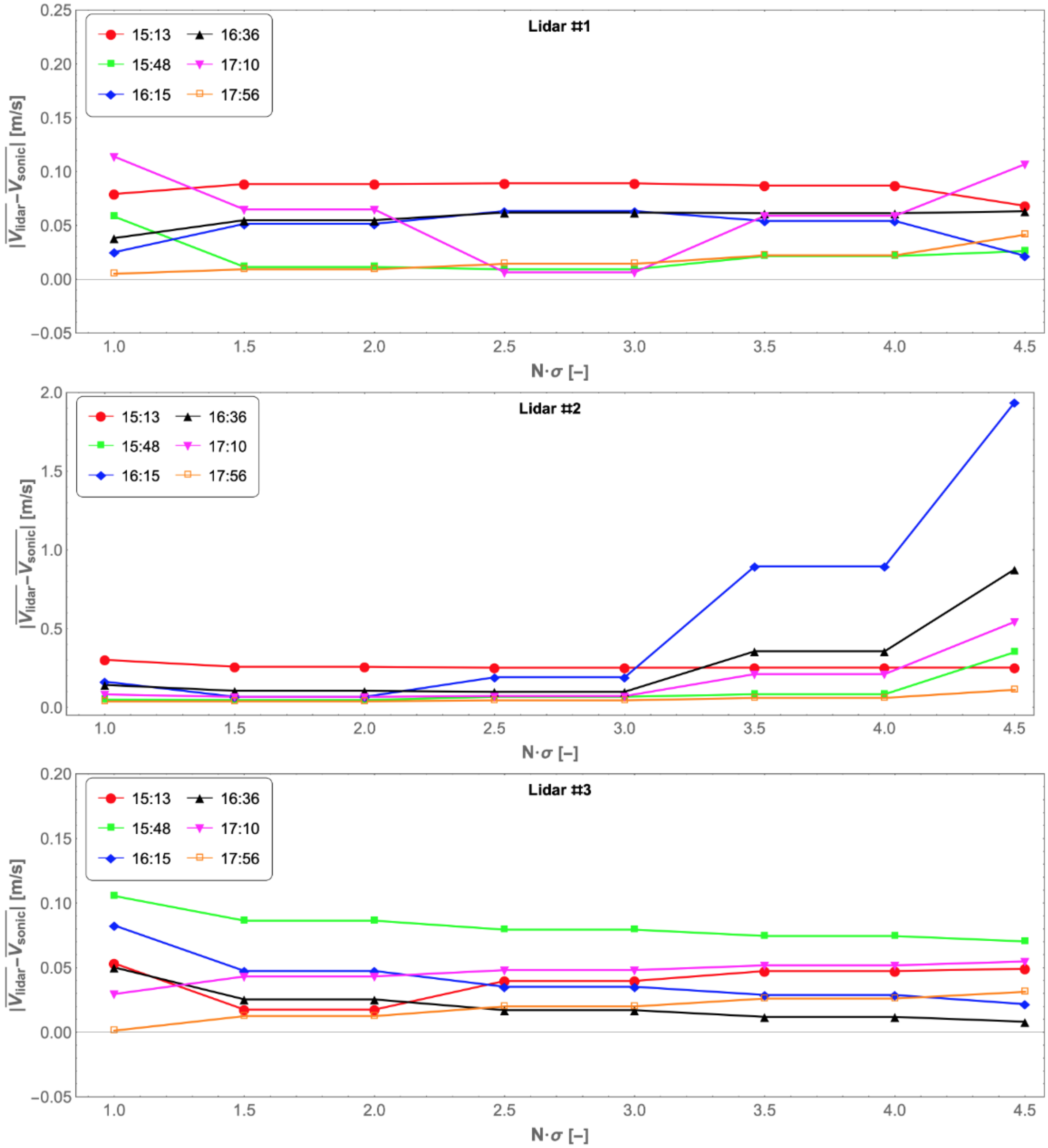


Figure 2: Mean absolute 1-minute wind velocity difference between the three lidars and the sonic anemometer as a function of different multiples of the standard deviation.

14 L195-L197: It is not clear what the authors want to express with the sentence starting with 'Consequently, the projection of . . . '. Maybe a sketch could help?

Thank you for this comment. The sketch is as follows. Because another reviewer has pointed out that there are many figures in the manuscript, we explained this point in the text instead of putting a figure: "It is worth noting that the wind direction at the minute with the highest rain intensity (15:48, UTC+1) is from 160° by the 10-minute averaged sonic data, and the two lidars' geographic beam directions are 42.6° and 299.3° (Fig. 2). Therefore, the wind is moving away from both lidars' laser beams at this minute, causing negative line-of-sight velocity. Consequently, the projection of the resultant velocity of raindrops, in the measuring configuration used here, is smaller than that of the horizontal wind speed in the beam direction.". Hope this will be accepted by you.

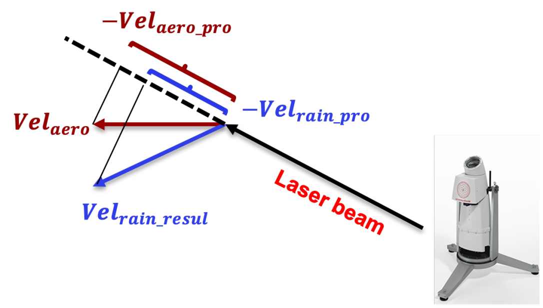


Figure 3: Illustration of velocity projection of aerosol speed Vel_{aero} and resultant raindrop speed Vel_{rain_resul} on the propagation direction of one lidar.

15 L204: '. . . in detail' instead of 'in details'.
Thank you for this comment. We agree and have implemented this in the manuscript in **L222**. The new sentence is "In the section below, we compare the radial wind velocity detected by lidars and the sonic anemometer at 31 m height in detail in light of the promising results about the effective suppression of rain Doppler signals at one moderate-rain minute (15:48, UTC+1).".

16 L208-L210: How much do raindrops influence the sonic measurements? The authors should provide some information about that in the sensor description in Chapter 2. Furthermore, what interpolation method was used?
Thank you for this comment. If the sonic measurement is influenced by raindrops, its status will be "4", indicating that this is not a valid number, and it just repeats the previous number. Therefore, we used linear interpolation to replace the repeated numbers. We added one paragraph in **L127** in Section 2.2 as "It is evident from the sonic status information that wind velocity measurements by sonic anemometers can be affected by raindrops. In those cases, the sonic anemometer would repeat the previous velocity value and the status would be "4". Thus, the linear interpolation method was used in this study to eliminate repeated velocities, which represented about 60% of the 50 Hz sonic data recorded at moderate-rain minutes.".

17 Figures in general: It would be easier to read the caption if (a), (b), . . . are written before the actual description.

Thank you for this comment. We agree and have changed all figures' captions to have (a), (b), . . . written before the description.

18 Figure 1: Can the authors add the information about the location of the disdrometer?

Thank you for pointing this out. We have removed Fig. 1 from the manuscript. But we added the location information in **L138** as "This disdrometer was about 20 m north of the met mast."

19 Figure 2: Do the red arrows indicate the location of the common focus point on the met mast? Please add some explanation about the arrows in the figure caption.

Thank you for this comment. Yes, they indicated the common focus point. We have written "Blue points marked by 1, 2, and 3 are the three CW Doppler lidars, focused at the common point 4 which is 1 m north of the sonic anemometer at a height of 31 m above the ground." in the caption.

20 Figure 6: The disdrometer shown on this photo is not a Thies LPM, but a Ott Parsivel2. Please check the manufacturer of the disdrometer which was used in this experiment.

You have raised an important point here. Yes, we put the wrong picture before. It is corrected in the manuscript now.

Figure 4: Thies Laser Precipitation Monitor(LPM) at DTU Risø campus.

21 Figure 9: Is the plotted rain intensity taken from the automatic output of the disdrometer or calculated based on a quality-controlled rain-drop-size distribution?

Thank you for this comment. The plotted rain intensity in Fig. 9 (now Fig. 6) is taken from the automatic output of the disdrometer.

22 Figure 10: It is a bit confusing using the same colours in (a), (b) and (c), although the colours in (c) describe not the same as in (a) and (b). The authors should consider using other colours or adding a legend to (c). Furthermore, the acronym 'PSD' is not described. This information should be added.

Thank you for this comment. We agree and have changed the color in panel (c). The acronym 'PSD' is defined in **L99** as Additionally, Bartlett's method is used to obtain the power spectral density (PSD) of each spectrum [Press et al., 1988, Chap. 13], which is the square of the absolute value of the FFT of the detector's time series..

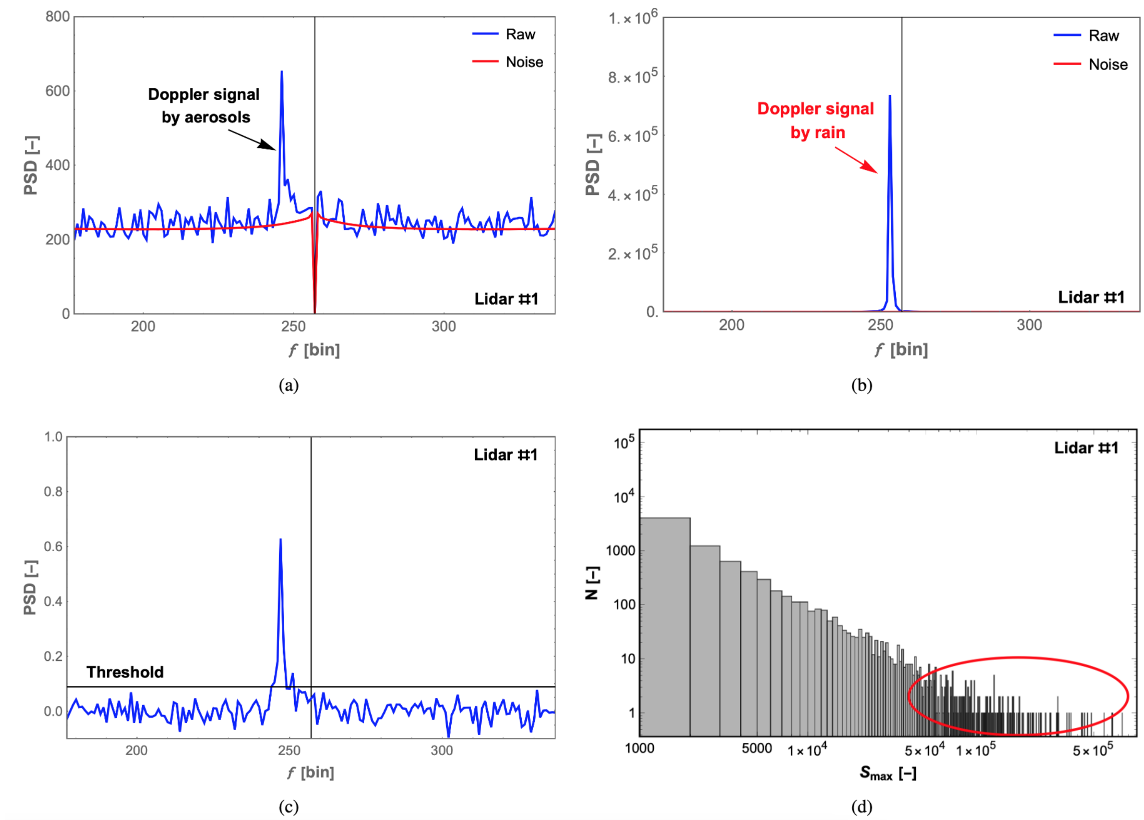


Figure 5: Examples of representative Doppler spectra measured at the moderate-rain minute (15:48, UTC+1) with the highest rain intensity. **(a)** A 3-kHz-sampled spectrum containing only wind signal (blue) and the mean background spectrum (red). **(b)** A 3-kHz-sampled spectrum containing rain signal (blue) and the mean background spectrum (red). **(c)** A noise-flattened 50-Hz-sampled spectrum and its spectral threshold. **(d)** Histogram of the maximum spectral energy S_{max} of 180000 raw spectra over the duration of the same minute with a red circle marking the strongest rain signals. The solid black line stands for the zero-Doppler shift at frequency bin 257.

23 Figure 11: Strictly speaking, the Doppler signal is caused by aerosols not by wind.

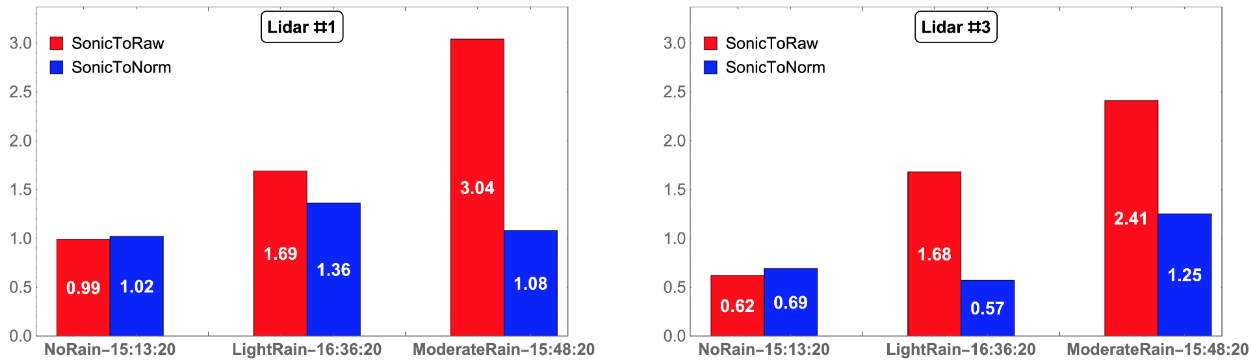
Thank you for pointing this out. We agree and have changed to "Doppler signals by aerosols" in Fig. 8 (the above figure).

24 Figure 12 and Figure 13: To the last sentence the information 'in the scatter plot' should be added to make the description clearer.

Thank you for this comment. We agree. However, we have removed the scatter plots in Fig. 12 and 13.

25 Figure 15: The figure could be simplified by plotting the bars in the same direction and the two different methods (SonicToRaw and SonicToNorm) are visualised by different colours (e.g. bright and dark). This would allow an easier comparison of the values.

Thank you for this comment. We agree and the new figure is as follows.



(a) (b)

Figure 6: Comparison of the integral value of the PDF's absolute difference between the sonic and the lidar data with (SonicToNorm) and without (SonicToRaw) rain-suppressing normalization at no-rain, light-rain ($I_{rain} = 1$ mmh^{-1}), and moderate-rain ($I_{rain} = 4$ mmh^{-1}) minutes. **(a)** Lidar #1. **(b)** Lidar #3.

26 Table 4: For 'Light-rain minute 16:36' in two cases three digits are given. Depending on the possible accuracy, please provide two or three digits for all numbers.

Thank you for pointing this out. We agree and have implemented this in Table 4.

Table 4. 1-minute averaged wind velocity based on 50 Hz data and the corresponding bias between the sonic anemometer and lidar #1 (probe length of 1.2 m) at three minutes, with (norm) and without (raw) normalization. Rain intensity at the light-rain and moderate-rain minutes are 1 mmh^{-1} and 4 mmh^{-1}.

	V_{sonic} (ms^{-1})	V_{raw} (ms^{-1})	$V_{sonic} - V_{raw}$ (ms^{-1})	V_{norm} (ms^{-1})	$V_{sonic} - V_{norm}$ (ms^{-1})
No-rain minute 15:13:20+1min	-1.01	-1.07	0.06	-1.08	0.07
Light-rain minute 16:36:20+1min	-0.38	-0.39	0.01	-0.39	0.01
Moderate-rain minute 15:48:20+1min	-0.64	-0.49	-0.15	-0.60	-0.04

27 Table 4 & 5: Are the values calculated for the same time period plotted in Figure 12 and Figure 13? The figures represent the values for a bit more than

exact one minute. The authors are asked to state exactly which time period (including seconds) was used for the values provided in the tables.
Thank you for this comment. We agree with this point. Both figures and tables are compared with the same one-minute period, for example, 15:13:20+1min for the no-rain minute. Now the tables are corrected to be consistent with the figures.

Table 4. 1-minute averaged wind velocity based on 50 Hz data and the corresponding bias between the sonic anemometer and lidar #1 (probe length of 1.2 m) at three minutes, with (norm) and without (raw) normalization. Rain intensity at the light-rain and moderate-rain minutes are 1 mmh^{-1} and 4 mmh^{-1}.

	V_{sonic} (ms^{-1})	V_{raw} (ms^{-1})	$V_{sonic} - V_{raw}$ (ms^{-1})	V_{norm} (ms^{-1})	$V_{sonic} - V_{norm}$ (ms^{-1})
No-rain minute 15:13:20+1min	-1.01	-1.07	0.06	-1.08	0.07
Light-rain minute 16:36:20+1min	-0.38	-0.39	0.01	-0.39	0.01
Moderate-rain minute 15:48:20+1min	-0.64	-0.49	-0.15	-0.60	-0.04

Table 5. 1-minute averaged wind velocity based on 50 Hz data and the corresponding bias between the sonic anemometer and lidar #3 (probe length of 9.8 m) at three minutes, with (norm) and without (raw) normalization. Rain intensity at the light-rain and moderate-rain minutes are 1 mmh^{-1} and 4 mmh^{-1}.

	V_{sonic} (ms^{-1})	V_{raw} (ms^{-1})	$V_{sonic} - V_{raw}$ (ms^{-1})	V_{norm} (ms^{-1})	$V_{sonic} - V_{norm}$ (ms^{-1})
No-rain minute 15:13:20+1min	-5.42	-5.41	-0.01	-5.45	0.03
Light-rain minute 16:36:20+1min	-3.37	-3.16	-0.21	-3.36	-0.01
Moderate-rain minute 15:48:20+1min	-3.62	-3.29	-0.33	-3.54	-0.08

28 **The authors are not consistent by using 'rain drops' and 'rain droplets'. Please harmonize the description to 'rain drops'.**
Thank you for this comment. We agree and have implemented this in the manuscript. Now we use "raindrop" throughout.

29 **The authors should check whether 'filter out' is more appropriate than 'filter away'.**
Thank you for this comment. We agree. Now we use the word "suppress" instead of "filter away" since the rain Doppler signals are still in the spectrum after normalization.

30 **Sometimes the description of the lidars is 'lidar #1/#2/#3', sometimes 'WindScanner #1/#2/#3' and sometimes 'WindScanner lidar #1/#2/#3'. To improve the reading, I suggest using the same description throughout the manuscript.**
Thank you for this comment. We agree and now use lidar #1/#2/#3 both in the text and the figures.

Bibliography

N. Angelou, F. F. Abari, J. Mann, T. Mikkelsen, and M. Sjöholm. Challenges in noise removal from doppler spectra acquired by a continuous-wave lidar. In *Proceedings of the 26th International Laser Radar Conference, Porto Heli, Greece*, pages 25–29, 2012.

S. Davoust, A. Jehu, M. Bouillet, M. Bardon, B. Vercherin, A. Scholbrock, P. Fleming, and A. Wright. Assessment and optimization of lidar measurement availability for wind turbine control. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2014.

M. Debnath, G. V. Iungo, R. Ashton, W. A. Brewer, A. Choukulkar, R. Delgado, J. K. Lundquist, W. J. Shaw, J. M. Wilczak, and D. Wolfe. Vertical profiles of the 3-d wind velocity retrieved from multiple wind lidars performing triple range-height-indicator scans. *Atmospheric Measurement Techniques*, 10(2):431–444, 2017.

Glossary of Meteorology (June 2000). Rain. `https://glossary.ametsoc.org/wiki/Rain`, last access: 21 June 2023.

F. Guo, J. Mann, A. Peña, D. Schlipf, and P. W. Cheng. The space-time structure of turbulence for lidar-assisted wind turbine control. *Renewable Energy*, 2022.

D. Jena and S. Rajendran. A review of estimation of effective wind speed based control of wind turbines. *Renewable and Sustainable Energy Reviews*, 43:1046–1062, 2015.

L. Jin, N. Angelou, J. Mann, and G. C. Larsen. Improved wind speed estimation and rain quantification with continuous-wave wind lidar. In *Journal of Physics: Conference Series*, volume 2265, page 022093. IOP Publishing, 2022.

J. Li, X. Wang, and X. B. Yu. Use of spatio-temporal calibrated wind shear model to improve accuracy of wind resource assessment. *Applied energy*, 213:469–485, 2018.

T. Mikkelsen, M. Sjöholm, N. Angelou, and J. Mann. 3d windscanner lidar measurements of wind and turbulence around wind turbines, buildings and bridges. In *IOP Conference Series: Materials Science and Engineering*, volume 276, page 012004. IOP Publishing, 2017.

W. H. Press, W. T. Vetterling, S. A. Teukolsky, and B. P. Flannery. *Numerical recipes*. Citeseer, 1988.

S. Samadianfard, S. Hashemi, K. Kargar, M. Izadyar, A. Mostafaeipour, A. Mosavi, N. Nabipour, and S. Shamshirband. Wind speed prediction using a hybrid model of the multi-layer perceptron and whale optimization algorithm. *Energy Reports*, 6:1147–1159, 2020.

K. Träumner, J. Handwerker, A. Wieser, and J. Grenzhäuser. A synergy approach to estimate properties of raindrop size distributions using a doppler lidar and cloud radar. *Journal of Atmospheric and Oceanic Technology*, 27(6):1095–1100, 2010.

M. Türk and S. Emeis. The dependence of offshore turbulence intensity on wind speed. *Journal of Wind Engineering and Industrial Aerodynamics*, 98(8-9):466–471, 2010.

A. Van Ulden and A. Holtslag. Estimation of atmospheric boundary layer parameters for diffusion applications. *Journal of Applied Meteorology and Climatology*, 24(11):1196–1207, 1985.

T. Wei, H. Xia, J. Hu, C. Wang, M. Shangguan, L. Wang, M. Jia, and X. Dou. Simultaneous wind and rainfall detection by power spectrum analysis using a vad scanning coherent doppler lidar. *Optics express*, 27(22):31235–31245, 2019.