Verification of WS170 HKWC using a new simplified testing protocol for floating LiDAR wind measurements

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1 Introduction

This report describes verification results of floating LiDAR wind speed measurements from the Fugro Seawatch wind LiDAR onboard buoy WS170 deployed at location C within the Hollandse Kust West wind farm zone (HKWC).

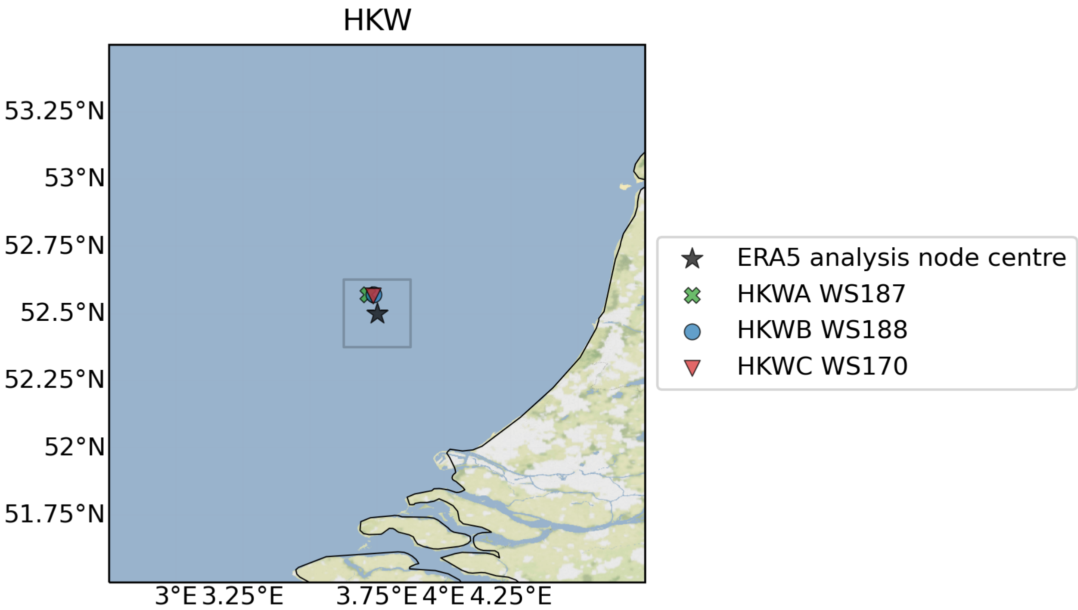

Figure 1-1: Map of HKW FLS locations relative to ERA5 0.25° node at 52.5°N, 3.75°E. The grey square depicts the boundary of the node.

The verification is conducted using a new *simplified testing protocol for floating LiDAR wind measurements* with the aim to assess its suitability for verifying the performance of floating LiDAR systems (FLS) in comparison to the Carbon Trust verification protocol.

10-min wind speed measurements observed at WS170 during August 2019 are evaluated against 'reference' floating LiDAR measurements from nearby buoy WS187 at HKWA. For comparison, evaluation results are also shown using LiDAR measurements from reference buoy WS188 at HKWB, although this is not a focus since the WS188 system and data availability was poor during the verification period. Figure 1-1 shows the relative locations of the three buoys.

2 Data

The primary data analysed are wind speeds measured by three Fugro Seawatch wind LiDARs at the following heights of 30m, 40m, 60m, 80m, 100m, 120m, 140m, 160m, 180m, 200m, 250m. The three LiDARs are onboard buoys WS187 at HKWA, WS188 at HKWB and WS170 at HKWC. The period analysed is 1-08-2019 to 31-08-

2019. Comparing the relative positions of the three buoys shows their drift during the period (Figure 2-1).

Winds and atmospheric variables from the ERA5 re-analysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) are also used to examine the winds during the measurement period and compare with each LiDAR measurement. The area covered by the ERA5 analysis node in relation to each LiDAR buoy is shown in Figure 1-1.

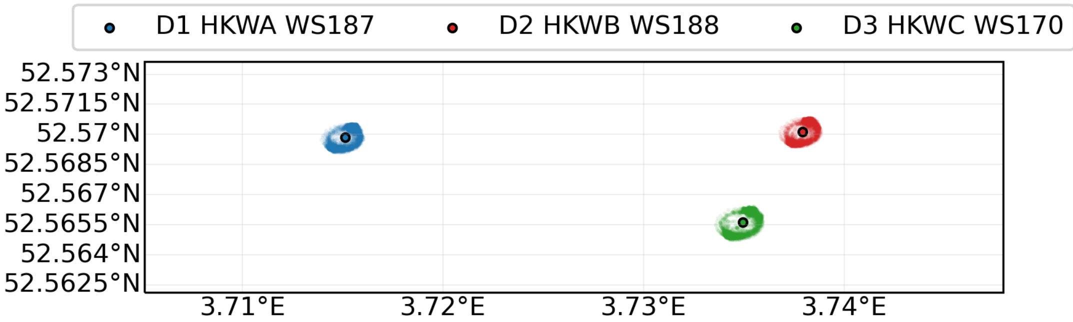

Figure 2-1: Positions of buoys WS187 (blue), WS188 (red) and WS170 (green) during August 2019. Black outlined circles indicate the mean position and shading depicts all positions recorded during the period.

3 Simplified verification method

The Simplified verification aims to simplify the data population required for a verification assessment in comparison to the binned data population criteria recommended by the Carbon Trust protocol (1) (that is, a minimum 40 data points in reference wind speed bins every 1m/s from 2 to 12 m/s, every 2 m/s from 12 to 16 m/s). The Simplified verification data population requirements are:

1. Measurement minimum duration – 14 days;
2. Minimum data points of 1440 ≥ 2m/s (after post-processing and required filtering);
3. All data ≥ 2m/s to be available for analysis.

Additionally, the Simplified verification considers the application of an upper range wind speed filter to ensure that verification results are not biased by variations in data population across the wind speed distribution. To diagnose this, a Quantile-Quantile (Q-Q) plot is used to compare the verification wind speed distributions from the reference LiDAR and evaluated LiDAR. For wind speed ranges in which there are clear deviations between the distributions, both the number of data points and data distributions across those ranges are examined to check for possible errors and decide whether an upper range filter should be applied to the data before conducting the accuracy assessment.

For the Simplified verification method, data availability is based on the Overall Post-processed Data Availability ($OPDA_{CA}$) KPI in the Carbon Trust protocol. However, to maximise the data available for a short-term campaign, the acceptable $OPDA_{CA}$ threshold is set at ≥ 90%, which is equivalent to Carbon Trust maturity stage 3. This is opposed to allowing a possible lower threshold of ≥ 85% that would be acceptable for maturity stage 2.

Once all filtering has been applied, wind speed accuracy is quantified using the same approach as the Carbon Trust protocol, applying a single-variant linear regression between the reference LiDAR and wind speeds with the y-intercept constrained to zero. The resulting slope and r-squared values from the regression are used to evaluate the FLS performance against the two following acceptance criteria (AC) as defined by the Carbon Trust protocol:

- *Minimum*: slope 0.97—1.03, $R^2 > 0.97$
- *Best practice*: slope 0.98—1.02, $R^2 > 0.98$

4 Results

4.1 Summary of winds during measurement period

As part of the measurement campaign it is now considered good practice to describe the weather conditions during the period of testing.

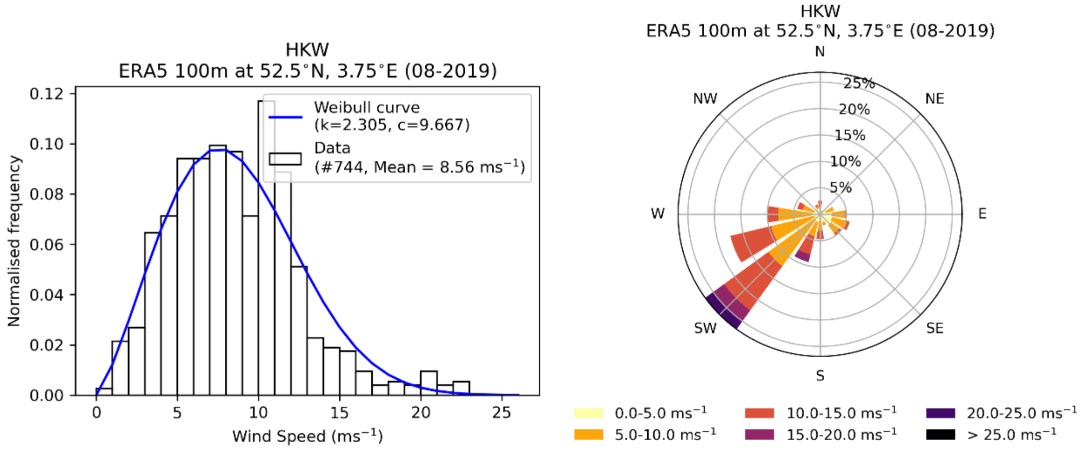

Figure 4-1: ERA5 100m wind speed and direction frequency distributions observed during August 2019. Left: wind speed frequency histogram and Weibull fit parameters. Right: wind rose showing speed and direction frequencies.

Figure 4-1 presents the frequency distributions of wind speed and direction at 100m observed by ERA5 at HKW during August 2019. The mean 100m wind speed was 8.56 m/s (7.02 m/s at 10m) and the predominant wind direction south-westerly.

The temporal variation in ERA5 winds and atmospheric variables is shown in Figure 4-2. Storms on the 10-11 August lead to the strongest winds observed during the period, exceeding 20 m/s at 100m and associated with the lowest pressure during the month of 1001.6 hPa on 10 August. The mean wind shear was modelled by ERA5 to be 0.08 and exhibited large fluctuations between very low and very high shear during a period of relatively weak easterly winds and warmer temperatures during 23-27 August. The mean 2m temperature was 18.5°C, with a minimum of 14.2°C on 13 Aug and maximum of 22.4°C on 27 August.

In terms of atmospheric stability, air-sea temperature differences generally fluctuated around zero, varying between neutral (= 0°), slightly unstable (< 0°) and slightly stable (> 0°) conditions. Stable conditions preceded the storm peak on 10 August followed by highly unstable conditions around 13 August after the storm, during the coolest period as suggested by strong negative temperature differences of more than -4°. More stable conditions occurred during the warmer period of 25-28 August coinciding with the large shear fluctuations mentioned previously.

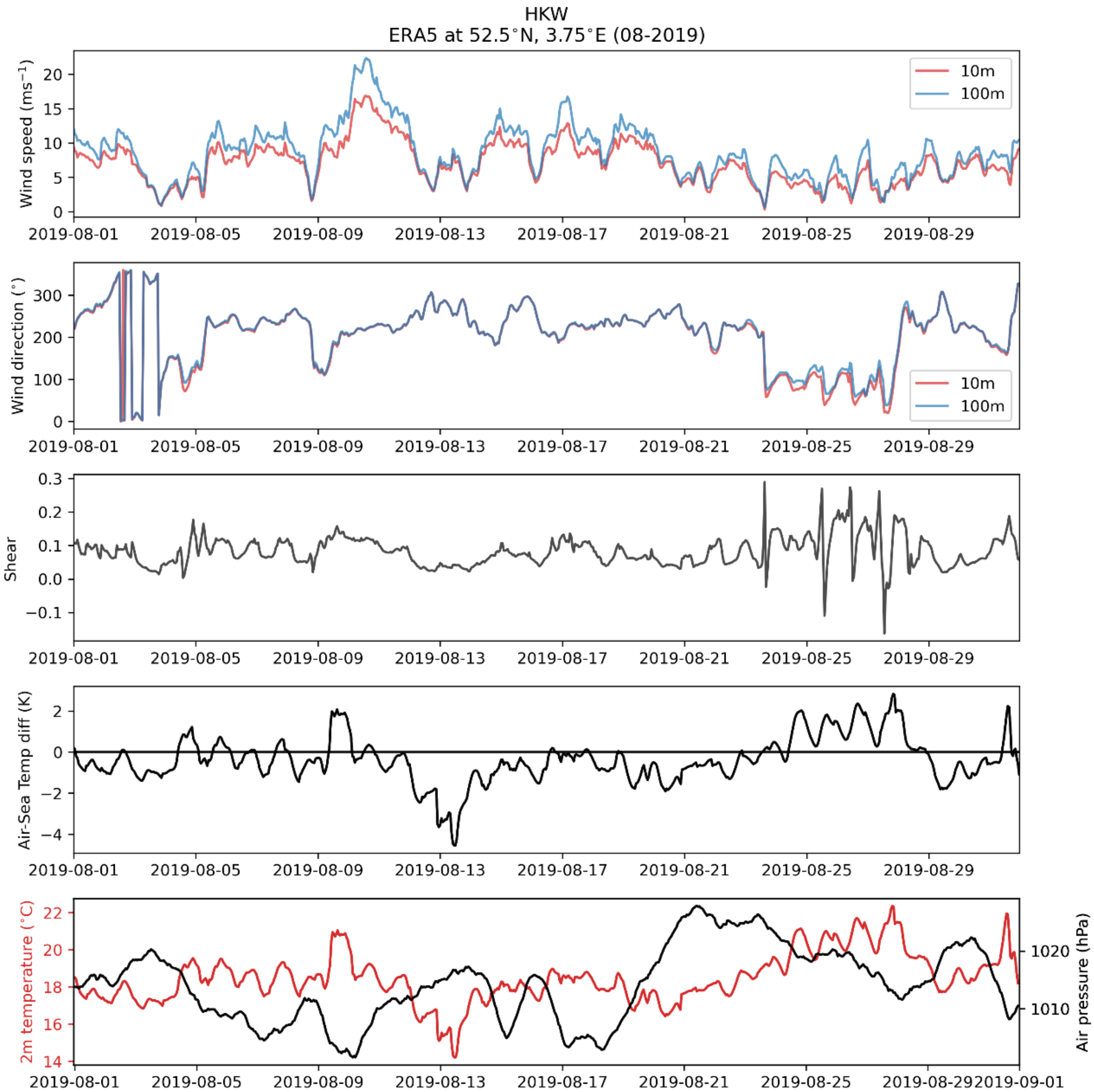

Figure 4-2: Hourly timeseries of wind speed (first panel), direction (second panel), vertical shear (i.e., power law exponent between 10m and 100m; third panel), Air-Sea temperature difference (fourth panel), 2m temperature and air pressure (fifth panel). Estimates from ERA5 reanalysis at 52.5°N 3.75°E.

The 100m wind speed estimates from ERA5 agree well with hourly mean wind speeds from each of the three FLS measurements during the period with $R^2 > 0.9$ (Figure 4-3). The wind directions are more poorly correlated but the overall bulk variations agree reasonably well with the FLS. ERA5 overestimates vertical wind shear with a mean shear exponent of 0.082 compared to 0.058 at WS187 and WS170, and 0.061 at WS188. The period with strong fluctuations in vertical wind shear during 25th to 28th August observed in ERA5 is also present in the FLS measurements, but at a larger magnitude (Figure 4-4).

Unsurprisingly, ERA5 does not always capture the variability in speed, direction and vertical shear observed by the FLS. This can be expected due to the differences between reanalysis and direct in-situ observations, which include their coarser spatial and temporal resolution. This is perhaps most noticeable in wind speeds during the storm period mentioned around the 10th and 11th of August where ERA5 captures the storm but is not able to capture the same maximum hourly mean wind speed; and in vertical wind shear during the period of strong shear variations around the 25th to 28th August where the magnitude of the shear fluctuations is underestimated by ERA5. It is worth noting that the period of strong shear variability was found to have a negligible effect on the FLS wind speed verification results presented in Section 4.

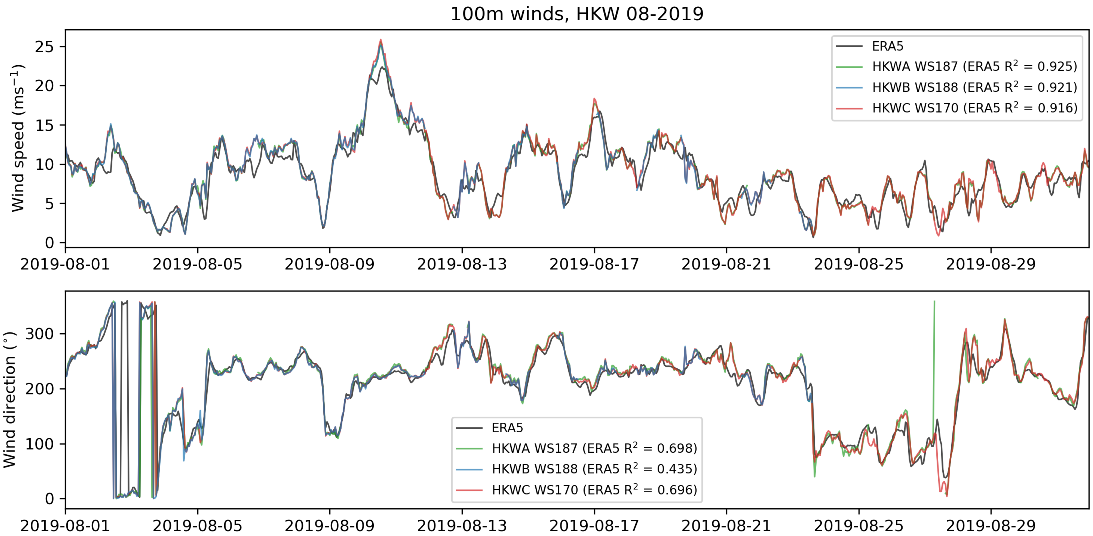

Figure 4-3: Hourly timeseries of 100m wind speed (top) and direction (bottom) from ERA5 and the three FLS (WS187, WS188 and WS170).

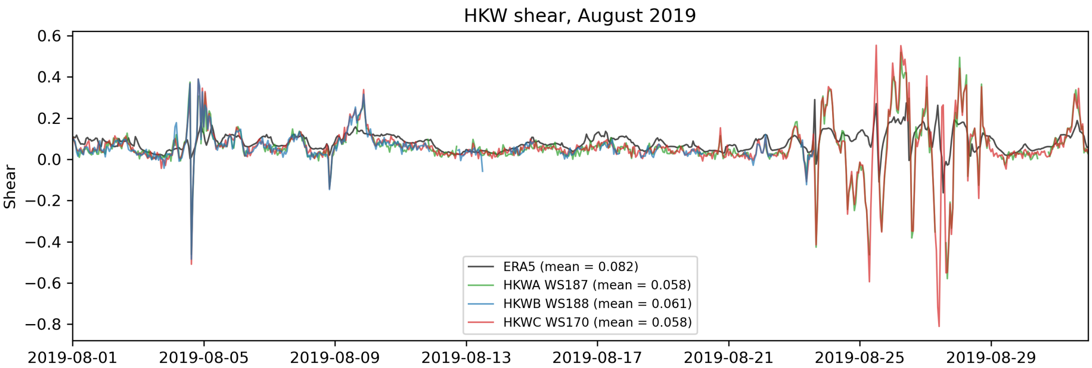

Figure 4-4: Hourly timeseries of vertical wind shear (power law exponent) estimated by ERA5 (between 10m and 100m) and the three FLS (between 30m and 100m).

Wave heights (significant wave height, H_{mo}; and maximum wave height, H_{max}) throughout the period are shown in Figure 4-5. At all three buoys, the median H_{mo} was 1.1m and median H_{max} was 1.7m (Table 4-1). Highest waves were recorded during the storm period of 10-11 August, where heights reached a maximum H_{max} of 8m at WS187 and WS188 and almost 9m at WS170.

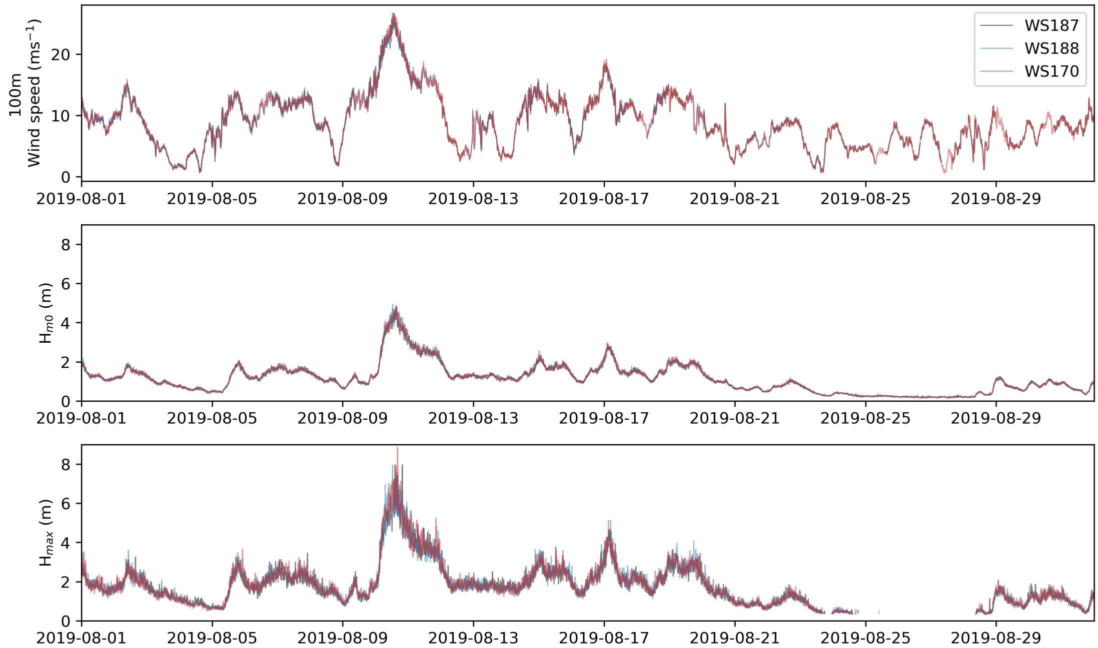

Figure 4-5: 10-min timeseries of 100m wind speed, and wave heights; H_{m0} and H_{max} for the three FLS.

	Median			Maximum		
Wave height (m)	**WS187**	**WS188**	**WS170**	**WS187**	**WS188**	**WS170**
H_{mo}	1.06	1.06	1.06	4.83	4.94	4.87
H_{max}	1.67	1.65	1.67	7.97	7.95	8.87

Table 4-1: Median and maximum wave heights observed by each FLS during August 2019.

4.2 Floating LiDAR data availability

During August 2019, data availabilities at all height levels were above 99% for WS170 and marginally above 83% for WS187 (Figure 4-6 and Appendix, Table 7-1 and Table 7-3). WS170 passes the $OPDA_{CA}$ threshold of ≥ 90%. Data availability at WS188 was lower (48—52%; Figure 4-6 and Table 7-2) due to power issues which led to sporadic measurements after 11/08/2019.

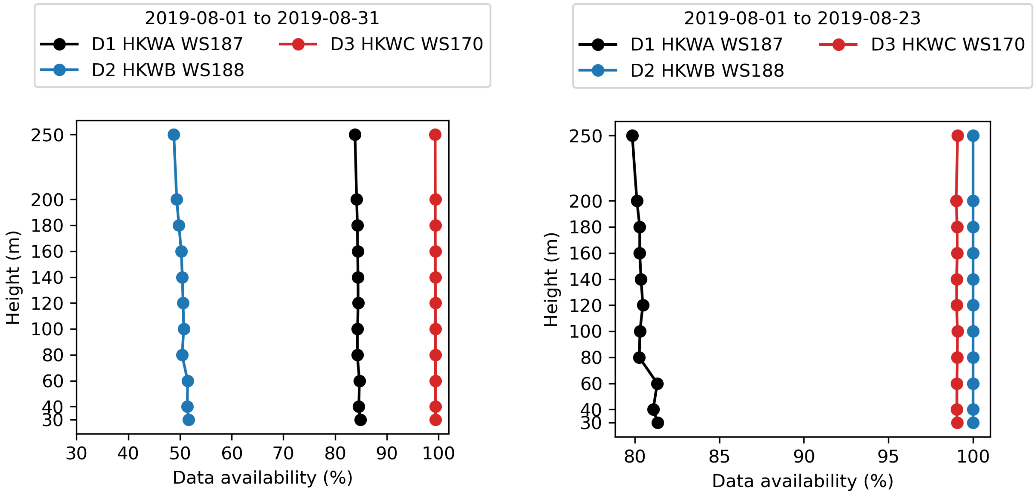

Figure 4-6: Data availability per system throughout the full analysis period of 01/08/2019 to 31/08/2019 (Period 1; left) and for the subset period of 01/08/2019 to 11/08/2019 (Period 2; right).

Given the different levels of availability for all three FLS, the verification test is split into two test periods:

Period 1: August 2019: 1/08/2019 to 31/08/2019 using all available data. The duration of Period 1 was 31 days (1/08/2019 to 31/08/2019), exceeding the minimum observation period requirement of 14 days. The number of 10-min data points ≥ 2 m/s exceeded the minimum data point threshold of 1440 at all height levels. See section 4.4.

Period 2: Subset period of 1/08/2019 to 11/08/2019 when WS188 was available. In this case only concurrent timestamps in all three systems are evaluated. The data availability for all three systems during Period 2 was > 79%. The duration of Period 2 was almost 11 days (WS188 available until 21:10 on 11/08/2019), and therefore did not reach the minimum 14-day measurement duration. However, the number of 10-min data points ≥ 2 m/s exceeded the 1440 minimum for every height level. See section 4.5.

4.3 Wind speed distributions / Q-Q

Figure 4-7 and Figure 4-8 present Q-Q plots comparing WS170 and WS187 (WS187 as reference) wind speeds at height levels 40m and 140m, respectively. While Q-Q plots were generated for all height levels, only 40m and 140m Q-Qs are shown here for brevity and to help compare distributions at two levels with different measurement accuracy, as described later.

From examining Figure 4-7 and Figure 4-8 that the wind speed distributions from both LiDARS agree well in the low to medium wind speed range (i.e. 2 to 13 m/s), including close agreements between the mean, median (50%) and interquartile range (25% and 75% percentiles) at both height levels (c.f. Table 4-2 and Table 4-3). However, at 13 m/s the distributions begin to differ with increasing variability toward higher wind speeds. At 40m, WS170 records higher wind speeds than

WS187, first at 14–16 m/s then to a larger extent at 18—25 m/s (Figure 4-7). A similar deviation pattern is also evident at 140m, except that the first deviation occurs at slightly higher wind speeds of 16—17 m/s (Figure 4-8).

Given that the wind speed distributions start to deviate at higher wind speeds, suggests an insufficient data population toward the tails of the distributions. Percentile wind speeds presented in Table 4-2and Table 4-3 confirm this, showing that at 40m, only 5% (95th percentile) of the data population exceeds wind speeds of 15 m/s in both LiDAR measurements, whereas at 140m only 5% data exceeds wind speeds of 16—17 m/s.

Importantly, these 95th percentile wind speeds are approximately where the data distributions begin to show deviations in the Q-Q plots, and is therefore further justification of the use of wind speeds ≤ 13 m/s at 40m and ≤ 16 m/s at 140m as the upper wind speed filter range for this verification.

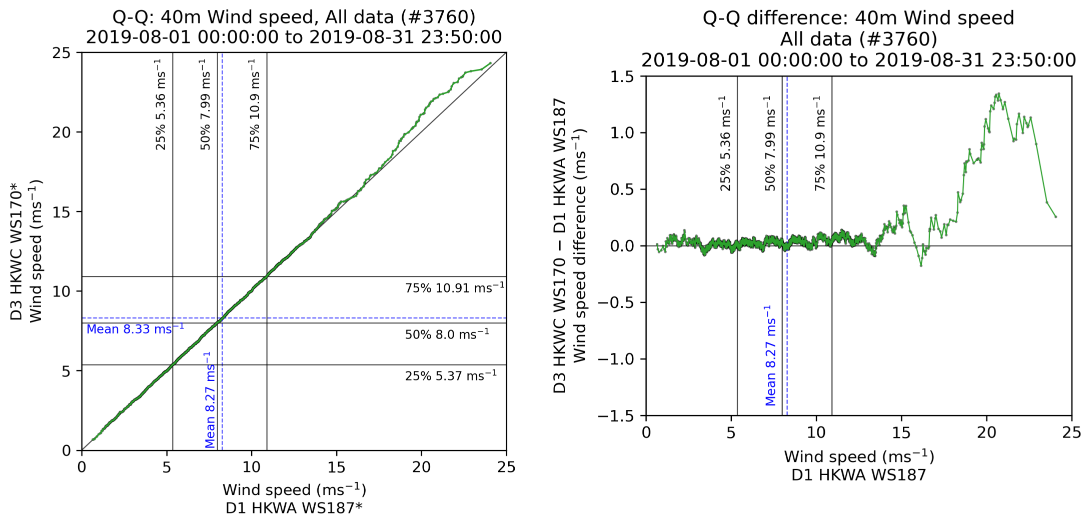

Figure 4-7: Left: Quantile-Quantile (Q-Q) plot, comparing quantiles of wind speeds measured at 40m by WS187 with WS170. Right: Difference between quantiles observed by WS170 and WS187 as a function of WS187 quantiles

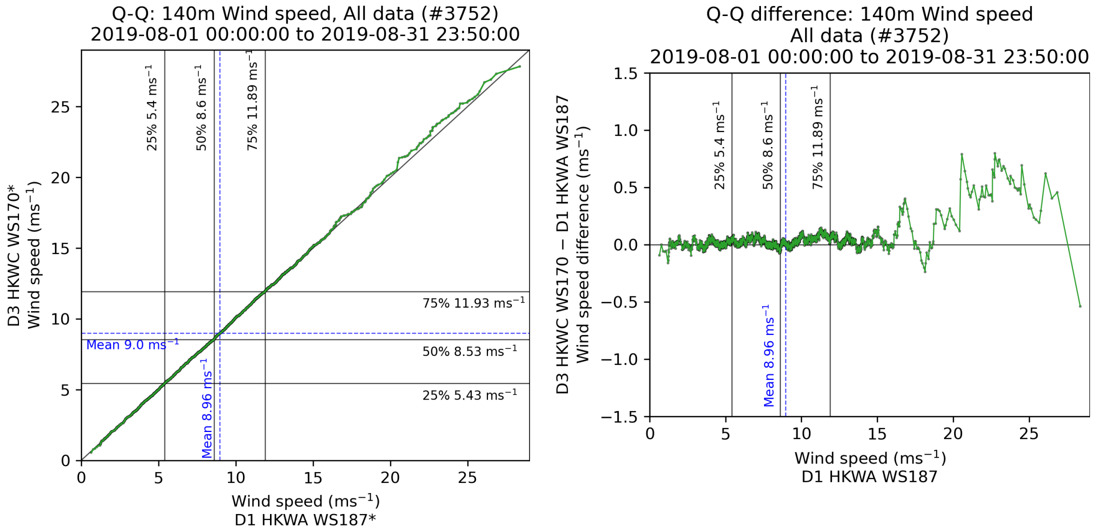

Figure 4-8: As Figure 4-7 except for wind speeds at 140m.

	Wind Speed (m/s)			
Percentile	**WS187**	**WS170**	**Difference**	**% Difference**
1	1.46	1.50	0.05	3.10
5	2.66	2.69	0.03	1.07
10	3.60	3.59	-0.01	-0.26
25	5.36	5.37	0.01	0.27
50	7.99	8.00	0.01	0.08
75	10.90	10.91	0.01	0.10
90	12.85	12.88	0.03	0.21
95	14.86	15.08	0.23	1.54
99	20.57	21.90	1.33	6.49

Table 4-2: Percentiles of observed wind speeds at 40m from WS187 and WS170.

	Wind Speed (m/s)			
Percentile	**WS187**	**WS170**	**Difference**	**% Difference**
1	1.46	1.47	0.01	0.54
5	2.61	2.61	0.00	-0.09
10	3.64	3.59	-0.06	-1.52
25	5.40	5.43	0.03	0.62
50	8.60	8.53	-0.07	-0.78
75	11.89	11.93	0.03	0.28
90	14.16	14.13	-0.03	-0.21
95	16.48	16.81	0.33	2.00
99	23.76	24.29	0.53	2.23

Table 4-3: Percentiles of observed wind speeds at 140m from WS187 and WS170.

4.4 Verification results for all heights

Following the Q-Q evaluation of WS170 wind speeds at 40m and 140m, Figure 4-9 presents scatter plots between wind speeds ≥ 2 m/s from WS187 and WS170 at these two height levels. For both heights, the highest density of points between approximately 5-10m/s are well constrained along the 1:1 line, although the overall variance in the scatter is slightly lower at 140m which leads to both a slope and R^2 closer to 1 than at 40m. However, WS170 passes Carbon Trust best-practice KPI levels at the two heights.

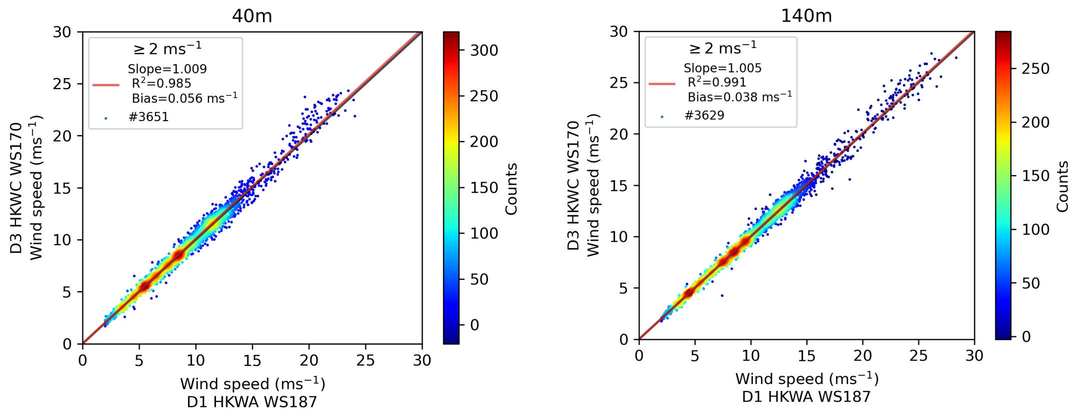

Figure 4-9: Density scatter plots between WS187 and WS170 wind speeds ≥ 2 m/s at 40m (left) and 140m (right).

The slope and R^2 are compared for the WS170 verification at 40m and 140m for different verification wind speed ranges, including those where upper filters have been applied based on the Q-Q distributions in Section 4.3 (Table 4-4). The upper-range filter application results only in very small changes in slope and R^2.

	Slope		R^2	
Verified range	**40m**	**140m**	**40m**	**140m**
≥ 2 m/s	1.009	1.005	0.985	0.991
≥ 2 m/s to upper filter	1.003	1.002	0.981	0.989
4 to 16 m/s	1.003	1.002	0.975	0.985
≥ 4 m/s to upper filter	1.004	1.002	0.972	0.985

Table 4-4: Slope and R^2 for WS170 evaluated against WS187 at 40m and 140m for various wind speed range criteria, including that based on upper filters of 13 m/s at 40m and 16 m/s at 140m found from Q-Q analysis at these heights.

The full ≥ 2 m/s verification results for all height levels are shown in Figure 4-10 and Table 4-5 per FLS comparison for August 2019. In summary, all LiDAR comparisons pass both the minimum and best practice Carbon Trust KPIs for slope and R^2.

When the data are constrained to the additional 4-16 m/s verification stated in the Carbon Trust protocol, all LiDAR comparisons pass the best practice slope KPI but not the R^2 KPIs toward lower height levels (Figure 4-11 and Table 4-6).

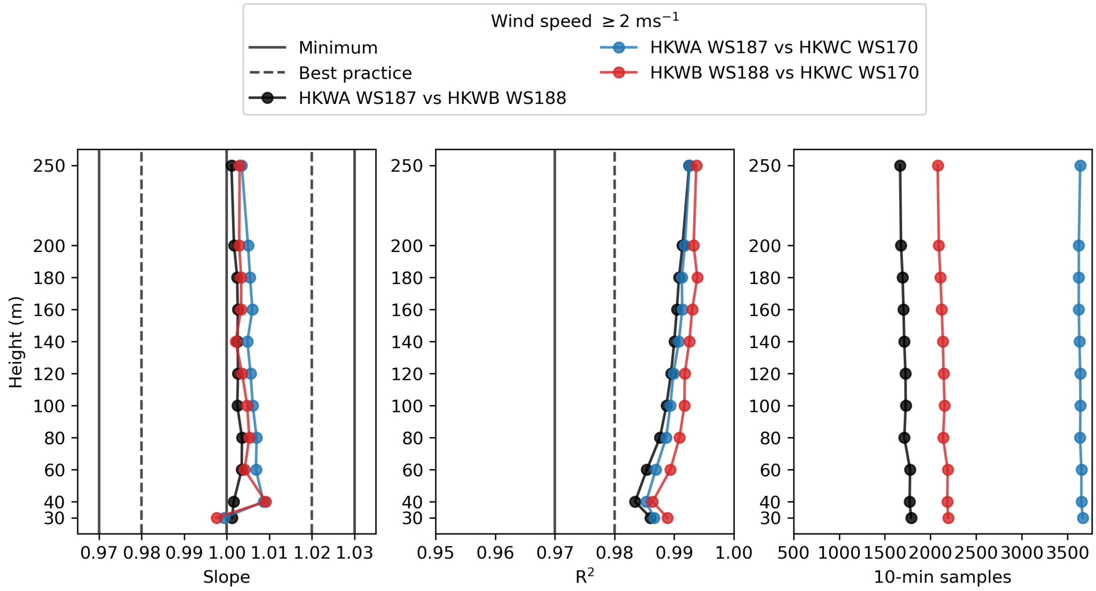

Figure 4-10: Slope, R^2 and number of samples for the ≥ 2 m/s verification.

	Slope			R^2		
Height (m)	**WS188 (WS187)**	**WS170 (WS187)**	**WS170 (WS188)**	**WS188 (WS187)**	**WS170 (WS187)**	**WS170 (WS188)**
30	1.001	0.999	0.998	0.986	0.987	0.989
40	1.002	1.009	1.009	0.983	0.985	0.986
60	1.003	1.007	1.004	0.985	0.987	0.989
80	1.004	1.007	1.005	0.988	0.989	0.991
100	1.002	1.006	1.005	0.989	0.989	0.992
120	1.003	1.006	1.004	0.989	0.990	0.992
140	1.003	1.005	1.002	0.990	0.991	0.993

	Slope			R^2		
160	1.003	1.006	1.003	0.990	0.991	0.993
180	1.002	1.005	1.003	0.991	0.991	0.994
200	1.002	1.005	1.003	0.991	0.992	0.993
250	1.001	1.004	1.003	0.993	0.993	0.994

Table 4-5: Slope and R^2 values per height level for the ≥ 2 m/s verification. The column sub-headers present the verified LiDAR system followed by the reference LiDAR system in brackets.

Results for the ≥ 2 m/s verification with the addition of upper wind speed filters applied through qualitative examination of Q-Q distributions per height level are shown in Figure 4-12. The upper wind speed thresholds applied are provided in Appendix Table 7-7.

Overall, the differences between the KPIs for the ≥ 2 m/s verification with and without the upper filter are small. The R^2 inclusive of filtering is slightly lower than the ≥ 2 m/s verification with no upper filter, but still passes the best practice KPI at all height levels except for the WS187/WS188 verification below 80m. R^2 remains higher for the ≥ 2 m/s with upper-filter verification test than the 4-16 m/s test. The reduction in R^2 indicates that the removal of higher wind speeds by the upper filter reduces the amount of variance that can be explained by the verification FLS.

In some cases the application of the upper-filter also improves the slope (i.e. closer to 1). This suggests a removal of larger differences at higher wind speeds which would corroborate with the larger deviations observed at higher wind speeds from the Q-Q analysis.

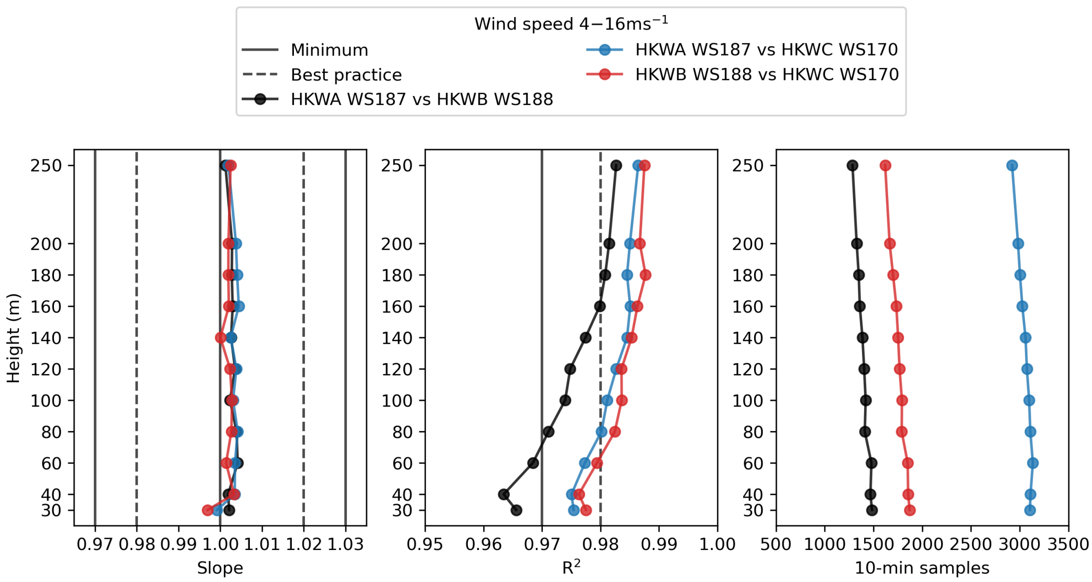

Figure 4-11: As Figure 4-10 but for the 4—16 m/s verification.

	Slope			R^2		
Height (m)	**WS188 (WS187)**	**WS170 (WS187)**	**WS170 (WS188)**	**WS188 (WS187)**	**WS170 (WS187)**	**WS170 (WS188)**
30	1.002	0.999	0.997	0.966	0.975	0.978
40	1.002	1.003	1.003	0.963	0.975	0.976
60	1.004	1.004	1.001	0.968	0.977	0.979
80	1.004	1.004	1.003	0.971	0.980	0.982
100	1.002	1.003	1.003	0.974	0.981	0.984
120	1.004	1.004	1.002	0.975	0.983	0.984
140	1.003	1.002	1.000	0.977	0.985	0.985
160	1.003	1.004	1.002	0.980	0.985	0.986
180	1.003	1.004	1.002	0.981	0.985	0.988
200	1.003	1.004	1.002	0.981	0.985	0.987
250	1.001	1.002	1.002	0.983	0.986	0.988

Table 4-6: As Table 4-5 but for the 4—16 m/s verification.

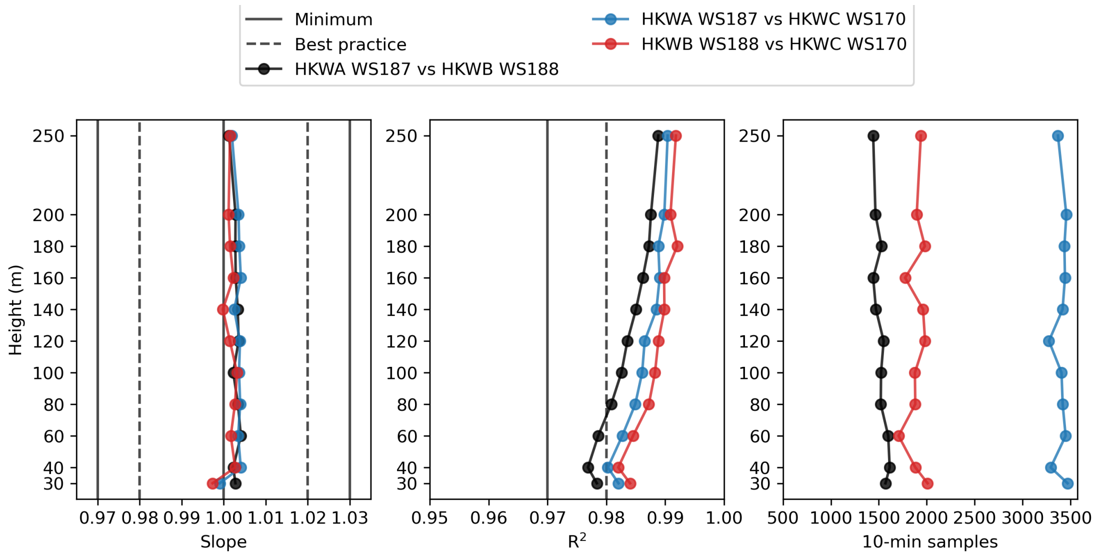

Figure 4-12: As Figure 4-10 but for the ≥ 2 m/s verification with the addition of the upper-range wind speed filter based on qualitative analysis of Q-Q distributions.

	Slope			R^2		
Height (m)	**WS188 (WS187)**	**WS170 (WS187)**	**WS170 (WS188)**	**WS188 (WS187)**	**WS170 (WS187)**	**WS170 (WS188)**
30	1.003	0.999	0.997	0.978	0.982	0.984
40	1.002	1.004	1.003	0.977	0.980	0.982
60	1.004	1.003	1.002	0.979	0.983	0.985
80	1.003	1.004	1.003	0.981	0.985	0.987
100	1.002	1.004	1.003	0.983	0.986	0.988
120	1.004	1.004	1.001	0.984	0.987	0.989
140	1.003	1.002	1.000	0.985	0.989	0.990
160	1.003	1.004	1.002	0.986	0.989	0.990
180	1.003	1.004	1.002	0.987	0.989	0.992
200	1.003	1.004	1.001	0.988	0.990	0.991
250	1.001	1.002	1.001	0.989	0.990	0.992

Table 4-7: As Table 4-5 but for the ≥ 2 m/s verification with the addition of the upper-range wind speed filter based on qualitative analysis of Q-Q distributions.

4.5 Verification results using concurrent temporal period in all systems

Figure 4-13 and Table 4-8 present the verification results for the first 11 days in August when all three FLS are subset to same period. Although there is a much smaller number of data points available, R^2 values for the ≥ 2 m/s verification are very similar to the full month period.

However, for the 4—16 m/s verification, R^2 drops lower than for the full month (Figure 4-14 and Table 4-9). This is most likely due to the reduction in number of data points which can be seen comparing each wind speed range in Figure 4-11Figure 4-10 and Figure 4-11. For some height levels, slopes are marginally closer to 1 for the 4—16 m/s verification than the ≥ 2 m/s verification.

When the upper-range filters are applied to the ≥ 2 m/s verification over the subset period, a similar pattern to the full period is observed; the effect of applying the upper-range filter is small. In general, a slight reduction in R^2 is observed and in some cases slopes become marginally closer to 1.

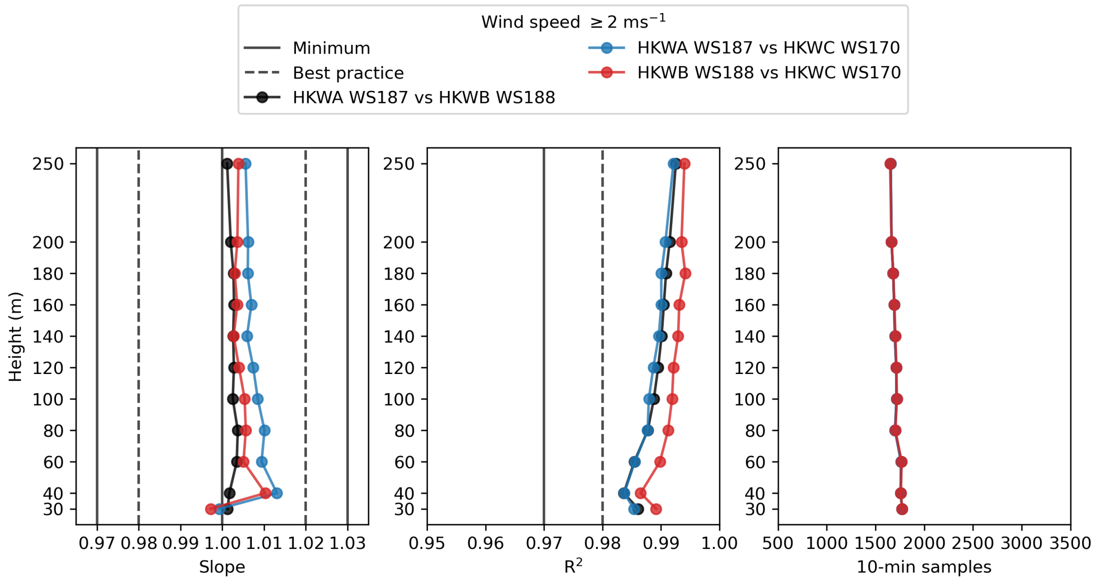

Figure 4-13 Slope, R^2 and number of samples for the ≥ 2 m/s verification applied to Period 2 (01/08/2019-11/08/2019).

	Slope			R^2		
Height (m)	**WS188 (WS187)**	**WS170 (WS187)**	**WS170 (WS188)**	**WS188 (WS187)**	**WS170 (WS187)**	**WS170 (WS188)**
30	1.001	0.999	0.997	0.986	0.985	0.989
40	1.002	1.013	1.010	0.984	0.984	0.987

	Slope			R^2		
60	1.003	1.009	1.005	0.985	0.986	0.990
80	1.004	1.010	1.006	0.988	0.988	0.991
100	1.003	1.008	1.005	0.989	0.988	0.992
120	1.003	1.007	1.004	0.990	0.989	0.992
140	1.003	1.006	1.003	0.990	0.990	0.993
160	1.003	1.007	1.004	0.990	0.990	0.993
180	1.003	1.006	1.003	0.991	0.990	0.994
200	1.002	1.006	1.004	0.991	0.991	0.994
250	1.001	1.006	1.004	0.993	0.992	0.994

Table 4-8: Slope and R^2 values per height level for the ≥ 2 m/s verification applied to Period 2 (01/08/2019-11/08/2019). The column sub-headers present the verified LiDAR system followed by the reference LiDAR system in brackets.

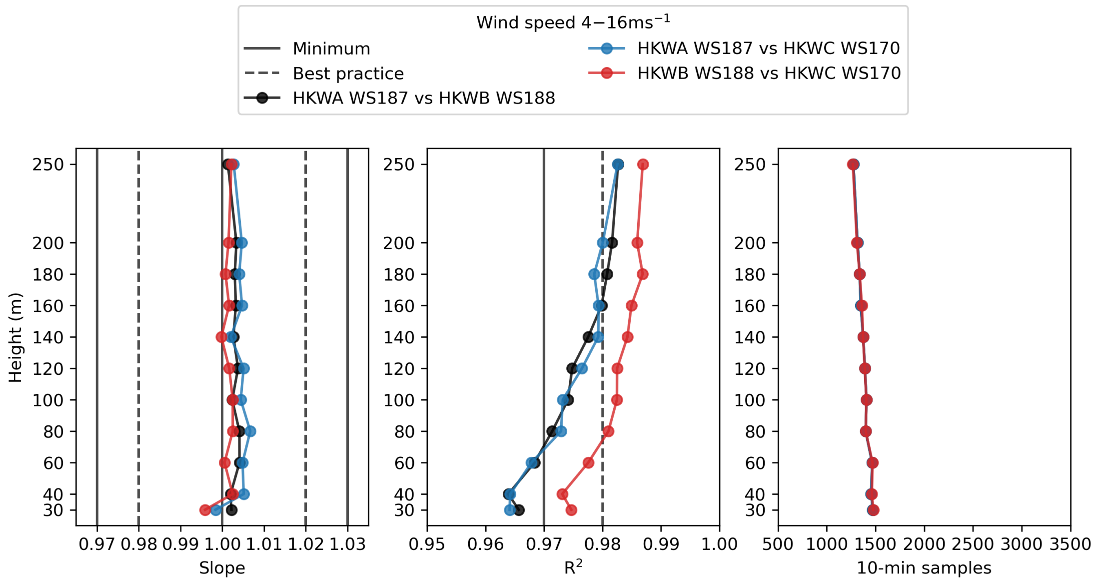

Figure 4-14: As Figure 4-13 but for the 4—16 m/s verification.

	Slope			R^2		
Height (m)	**WS188 (WS187)**	**WS170 (WS187)**	**WS170 (WS188)**	**WS188 (WS187)**	**WS170 (WS187)**	**WS170 (WS188)**

	Slope			R^2		
30	1.002	0.998	0.996	0.966	0.964	0.975
40	1.002	1.005	1.002	0.964	0.964	0.973
60	1.004	1.005	1.001	0.968	0.968	0.978
80	1.004	1.007	1.003	0.971	0.973	0.981
100	1.002	1.004	1.002	0.974	0.973	0.982
120	1.004	1.005	1.002	0.975	0.976	0.982
140	1.003	1.002	1.000	0.978	0.979	0.984
160	1.003	1.005	1.002	0.980	0.979	0.985
180	1.003	1.004	1.001	0.981	0.979	0.987
200	1.003	1.005	1.001	0.982	0.980	0.986
250	1.001	1.003	1.002	0.983	0.983	0.987

Table 4-9: As Table 4-8 but for the 4—16 m/s verification.

	Slope		R^2	
Verified range	40m	140m	40m	140m
≥ 2 m/s	1.013	1.006	0.984	0.990
≥ 2 m/s to upper filter	1.005	1.002	0.976	0.986
4 to 16 m/s	1.005	1.002	0.964	0.979
≥ 4 m/s to upper filter	1.005	1.002	0.957	0.979

Table 4-10: Slope and R^2 for WS170 evaluated against WS187 at 40m and 140m for various wind speed range criteria applied to Period 2 (01/08/2019-11/08/2019), including that based on upper filters of 13 m/s at 40m and 16 m/s at 140m found from Q-Q analysis at these heights.

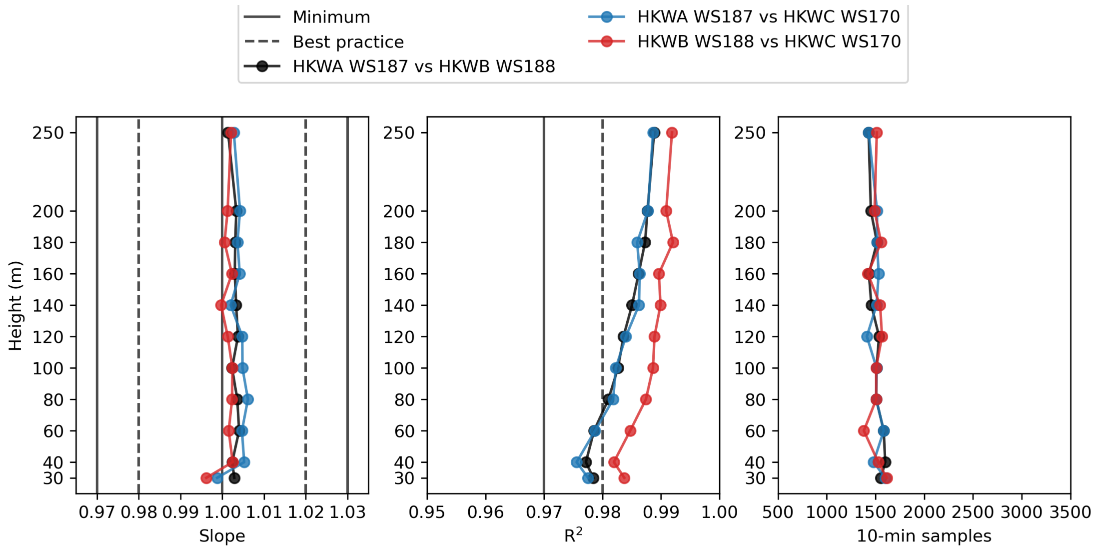

Figure 4-15: As Figure 4-13 but for the ≥ 2 m/s verification with the addition of the upper-range wind speed filter based on qualitative analysis of Q-Q distributions.

	Slope			R^2		
Height (m)	**WS188 (WS187)**	**WS170 (WS187)**	**WS170 (WS188)**	**WS188 (WS187)**	**WS170 (WS187)**	**WS170 (WS188)**
30	1.003	0.999	0.996	0.978	0.978	0.984
40	1.002	1.005	1.002	0.977	0.976	0.982
60	1.004	1.005	1.002	0.979	0.979	0.985
80	1.004	1.006	1.002	0.981	0.982	0.987
100	1.002	1.005	1.002	0.983	0.982	0.989
120	1.004	1.005	1.001	0.984	0.984	0.989
140	1.003	1.002	1.000	0.985	0.986	0.990
160	1.003	1.004	1.002	0.986	0.986	0.990
180	1.003	1.004	1.001	0.987	0.986	0.992
200	1.003	1.004	1.001	0.988	0.988	0.991
250	1.001	1.003	1.002	0.989	0.989	0.992

Table 4-11: Slope and R^2 for WS170 evaluated against WS187 at 40m and 140m for various wind speed range criteria applied to Period 2 (01/08/2019-11/08/2019), including that based on upper

While the systems pass in terms of verification, there is a clear difference in correlation between the three buoys, with WS187 and WS170 more clearly aligned during both verification periods. The closer proximity of WS188 and WS170 compared to WS187 to WS170 cannot be ruled out as a factor in the results. A systematic issue in terms of data processing cannot however be ruled out either.

In general, the systems pass at all heights apart from the lowest 2 levels (30m and 40m) within the wind speed range of 4-16m/s. It is not fully possible to investigate the reason for lower KPIs at the lower two levels, however the impact of a lower number of samples is a possible reason. In this instance there is both a lower number of samples within the chosen wind speed range as well as within each metre-per-second bin above 13m/s which most likely leads to a lower correlation when the data is thus constrained. It is not the opinion of the author that this is a systematic issue.

5 Discussion

Section 4 illustrates that the accuracy KPIs for an FLS are sensitive to the verification period, and any subsequent filtering applied. This stresses the importance of intelligently examining the data distributions and population during the observation period to understand whether the results are a function of limited data or are physically based, before making any final conclusions.

As indicated in an adjacent report describing the verification using the Carbon Trust protocol, the R^2 determined at 4—16 m/s is likely a result of an inadequate data population available within the wind speed range as opposed to a systematic physical error.

The impact of varying the length of the verification period and therefore data population on R^2 across the different verification data filters is further examined in Figure 5-1. The uncertainty in R^2 is large for verifications over short periods (< 2 days) but reduces substantially when the number of available data samples exceeds the equivalent of about 2-4 days. Importantly, for smaller data populations/shorter periods, the uncertainty and variations in R^2 between the different filtering criteria is smaller than the variation due to data population, suggesting that data population is the primary driver of R^2 variations at periods shorter than 3 days. This is around the timescale of synoptic weather variability, where a 0 to 3 day period would typically sample a specific wind regime, and thus may limit the data population to a specific wind speed range. In contrast, for data periods exceeding 2-4 days, this pattern can switch such that variations in R^2 are primarily driven by the filtering applied to the wind speed distribution for the verification tests. This feature is more apparent at 40m than 140m suggesting that this may vary depending on the height level.

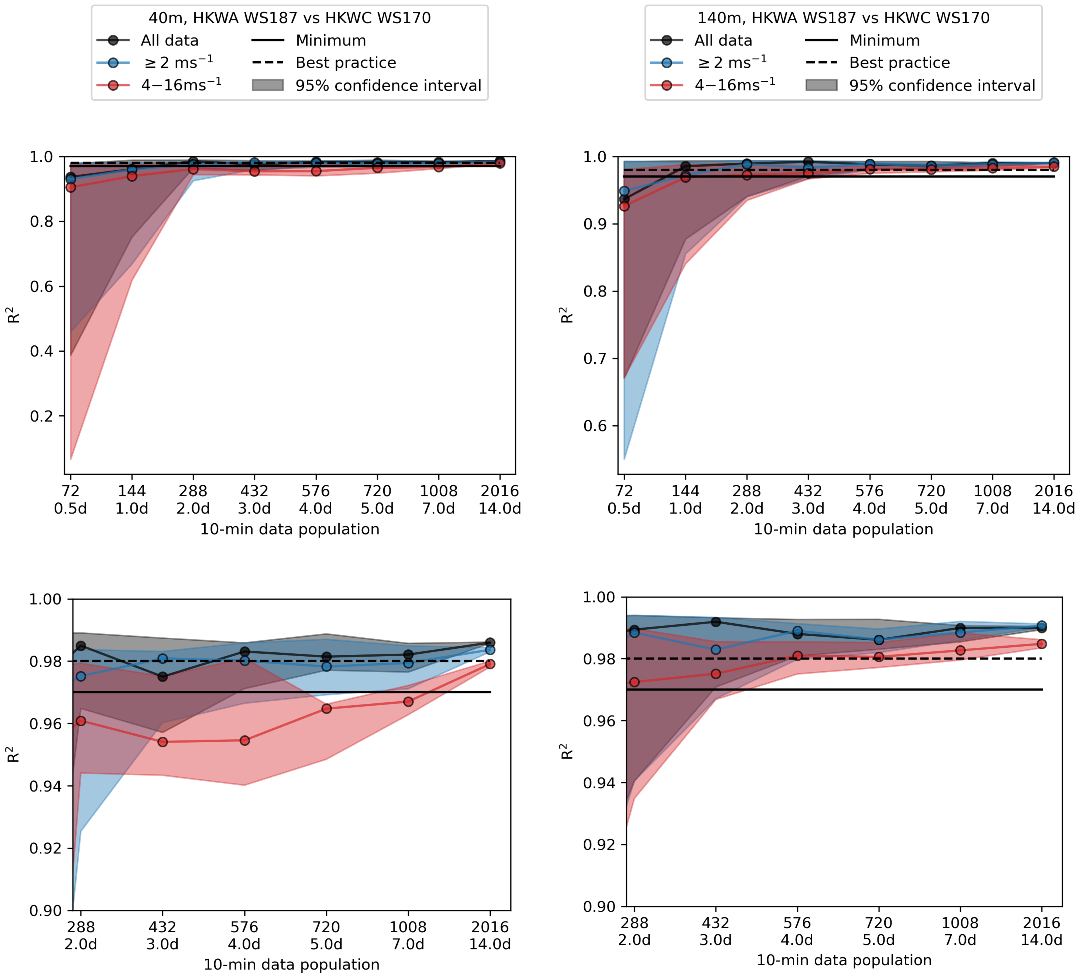

Figure 5-1: Sensitivity of R^2 for each verification criteria to data population (left: 40m, right: 140m, bottom row is zoomed in version of top row between 2d and 14d). Each line shows the median and shading shows the 90% confidence interval in R^2 per data population size, derived from block-bootstrap sampling the data timeseries at different block lengths (10-min data population). The number of blocks available from the data varies with the block length; smaller/larger block lengths contain higher/lower numbers of blocks available to calculate the uncertainty.

This is further illustrated in Figure 5-2 which examines the effect of using different campaign start dates and campaign lengths on the 40m wind speed verification. For both start dates, slope and R^2 KPIs fluctuate as more observations are acquired. After 2-4 days of data the KPIs stabilise with slopes tending towards 1.0 and R^2 increasing to above 0.97. In combination with the result shown in Figure 5-1, this analysis strongly suggests that at least 4 days of continuous data during a campaign are required before a reliable measurement of accuracy can begin to be obtained. A similar result is also found for 140m (Figure 5-3).

The timeseries analysis also highlights the potential impacts of the specific wind regime observed during a measurement campaign on data population and resulting KPIs. For the 40m verification starting on 1 August, the data population reaches the minimum 40 samples per bin requirement for the Carbon Trust verification criteria at the end of the storm on the 10-11 August. Moreover, R^2

increases to above 0.98 (best practice), whereas the slope increases further away from 1.0 (more positive). This indicates that the higher wind speeds observed during the storm have the effect of increasing the amount of variance explained by the verified FLS (increase in R^2) but introduce a bias (shown through the change in slope). Moreover, the increase in slope during 10-11 August and its subsequent very gradual reduction towards 1.0 for the remainder of the month highlights the impact of introducing higher wind speeds into the verification data population.

However, if the verification period begins on 13 August after the storms, the minimum data population for the Simplified verification is fulfilled by 25 August but not for Carbon Trust at any point during the remainder of the month. This is because there are not enough moderate to high wind speeds observed between 13-31 August to adequately populate the Carbon Trust wind speed bin criteria. However, by 25 August both KPIs both pass best practice thresholds. R^2 matches that found for the longer verification starting on 1 August and moreover, the slope is closer to 1.0. For the 140m verification starting 13 August the Carbon Trust reaches the minimum data population a day or so after the Simplified verification (Figure 5-3). This can be explained by the fact that this height level experienced higher wind speeds than at 40m enabling the moderate to high wind speed bins in the Carbon Trust to be sufficiently populated by this time.

Although the Carbon Trust data requirements would be met at all height levels in 11.6 days if the measurement campaign started on 1 August, they would not be met at all heights if the measurement campaign started on 13 August because of the absence of the higher wind speeds due to the storms (Table 5-1). In contrast the Simplified criteria data requirements would be met at all heights in 11.9 days after 13 August. This further highlights the sensitivity of these two verification approaches to the wind regime observed during sampling period available for the verification.

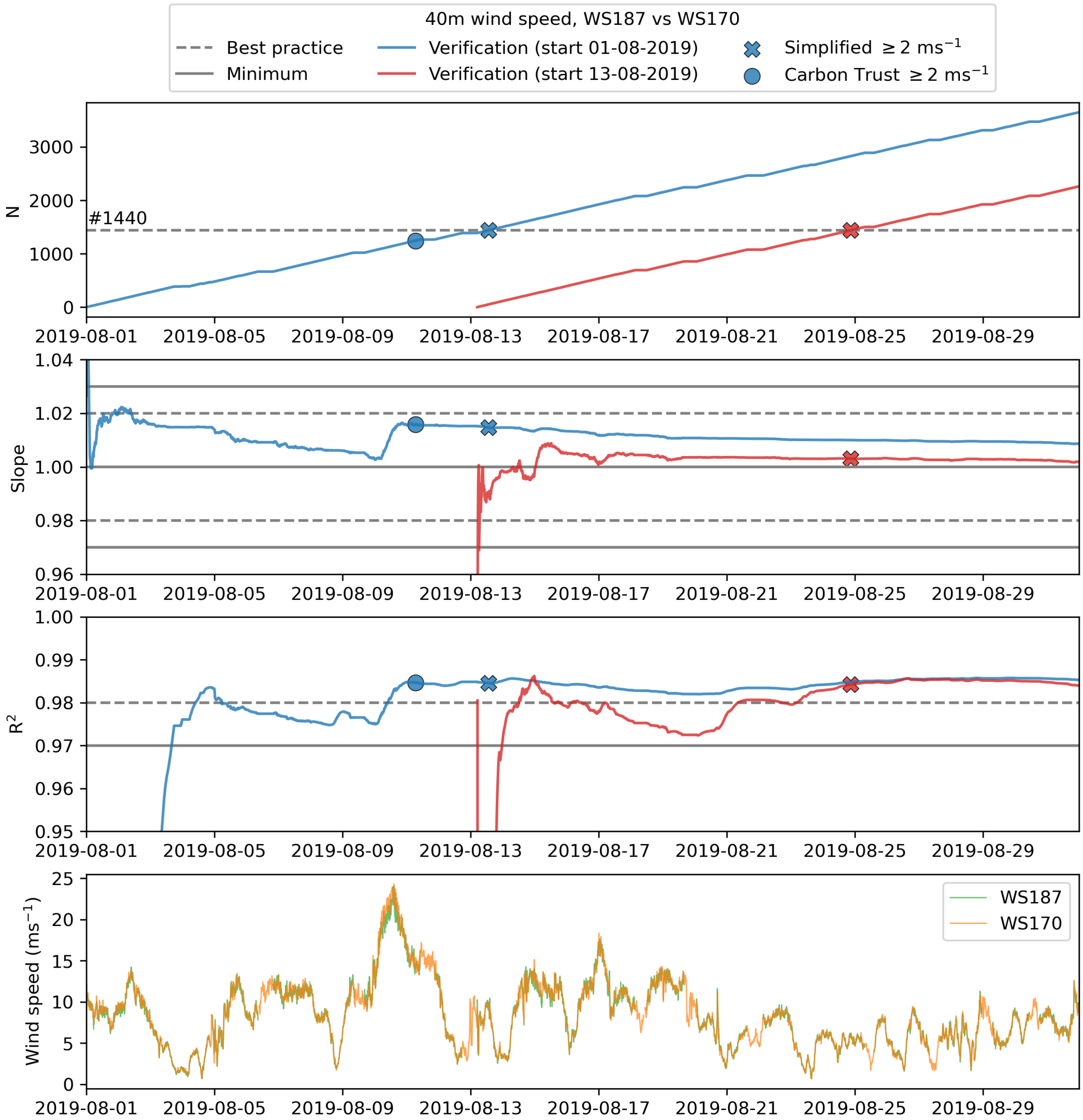

Figure 5-2: Temporal evolution in ≥ 2 m/s verification statistics at 40m for WS170 verified against WS187, showing total 10-min data points (top), regression slope (upper middle), R^2 (lower middle) and observed wind speeds (bottom) for data between two validation start dates (1 and 13 August 2019) and all 10-min timestamps throughout the period.

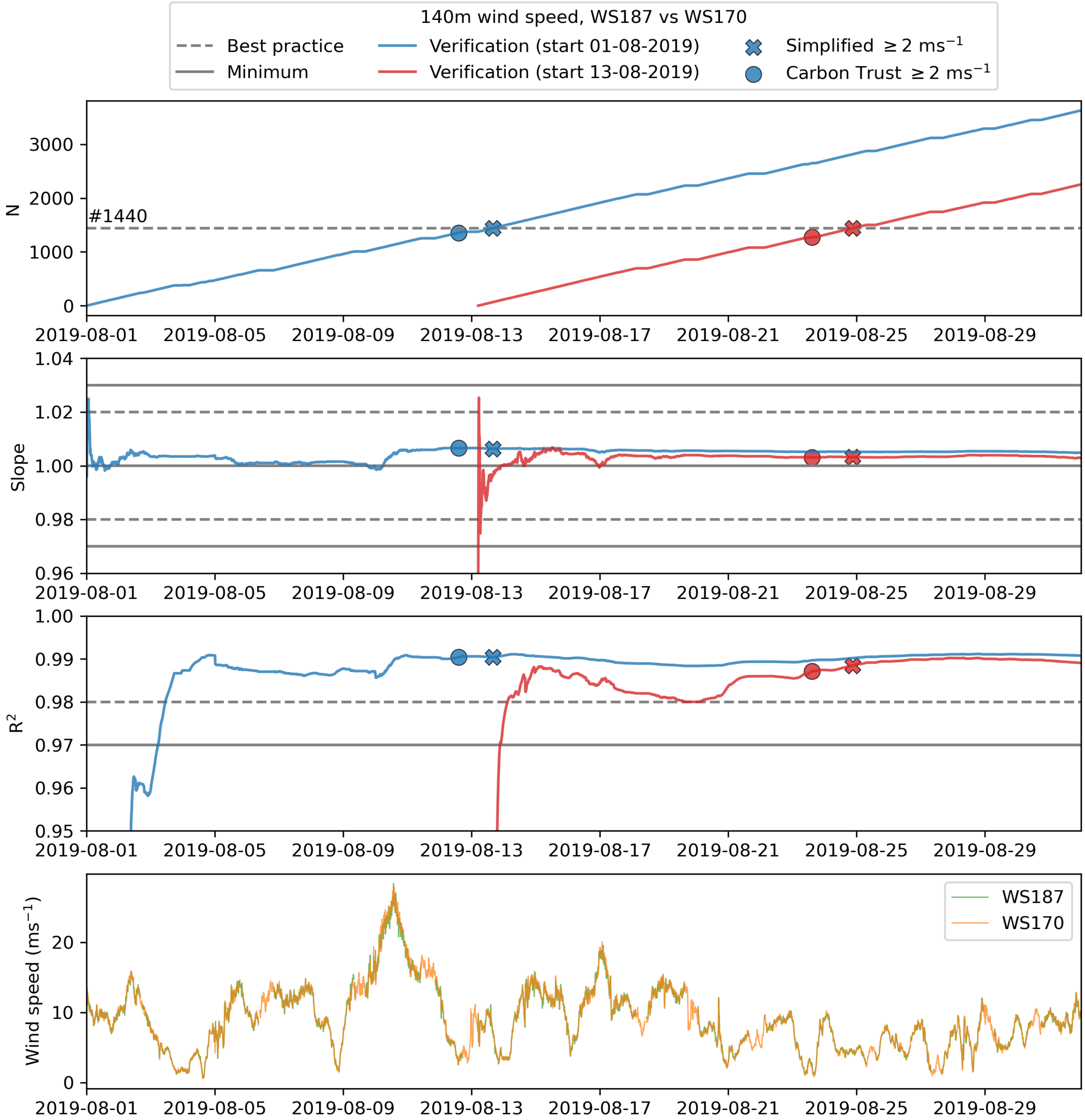

Figure 5-3: As Figure 5-2 but for the 140m verification.

	Date and time		No. of timestamps		No. of days	
Verification	**Simplified**	**CT**	**Simplified**	**CT**	**Simplified**	**CT**
≥ 2 ms^{-1} (start 01-08)	13/08/2019 16:10	12/08/2019 14:30	1826	1672	12.7	11.6
≥ 2 ms^{-1} (start 13-08)	24/08/2019 22:00	N/A	1717	N/A	11.9	N/A

Table 5-1: Time taken for Simplified and Carbon Trust protocols to reach minimum data population criteria at all measurement height levels for the WS170 verification with WS187 during August 2019.

6 Summary

This report has evaluated floating LiDAR wind speed measurements situated on three buoys located at HKW. The primary aim has been to assess a new Simplified approach for verifying floating LiDAR wind speed measurements and compare this with the already established Carbon Trust protocol.

The simplified protocol simplifies the data population criteria required for the verification assessment with an additional examination of wind speed distributions to establish whether an upper-range wind speed filter should be applied to the verification data population.

The verification was conducted by evaluating floating Fugro SeaWatch LiDAR wind speed measurements onboard buoy WS170 at HKWC with equivalent measurements from WS187 at HKWA and WS188 at HKWB during August 2019. The measurement period was characterised by mean wind speeds of 9-10 m/s and predominantly south-westerly winds at 100m. Storms with wind speeds above 20 m/s also occurred during 10-11 August.

During August 2019, the LiDAR data availability at all measurement heights was > 99% for WS170, >83% for WS187 and 48-52% for WS188. Due to the variable data availability between the systems, verification tests were conducted over two periods; the entire month of August using all available data, and the subset period of 1/08/2019 to 11/08/2019 when WS188 was fully available.

As part of the simplified verification protocol, a quantile-quantile analysis (Q-Q) was presented at measurement heights 40m and 140m for WS170 (verified against WS187) to evaluate wind speed distributions between LiDAR systems and determine whether upper-range filtering should be applied. The analysis indicated good agreement between measurements across the low to medium wind speed range (i.e. approx. 2-13 m/s) comprising at least 75% of the data population, but increased deviations between the distributions at higher wind speeds, typically towards the upper 5^{th}-10^{th} percentiles of the distribution. Upper filters of 13m/s at 40m and 16m/s at 140m were thus chosen to be appropriate in this case. Upper filters were also selected for all other height levels through qualitative analysis of Q-Q distributions (Appendix Table 7-7).

All LiDAR comparisons passed both minimum and best practice Carbon Trust KPIs for the ≥ 2 m/s verification during the full period. For the 4—16 m/s verification, all comparisons passed best practice KPI for slope but not for R^2 toward lower height levels. Results for the Simplified ≥ 2 m/s verification including the upper-range filter were similar. Slope passed best practice at all heights, but R^2 was slightly lower than the ≥ 2 m/s verification with no upper filter, although still passed best practice at all heights except below 80m for WS187 (verified against WS188).

For the subset verification period of 1/8/2019 to 11/8/2019, verification results ≥ 2m/s were also similar to the full month even though the data population was smaller. However, the LiDARs were more poorly correlated for the 4-16m/s verification due to the impact of limited data population from further filtering. WS188 and WS170 correlations did not pass at height levels below 80m. Moreover, a clear difference in correlation between the three buoys was observed, with WS187 and WS170 more clearly aligned.

Overall, these results have shown that the simplified method is a reliable verification approach both in terms of simplifying data population requirements and examining data distributions for potential discrepancies. The findings also highlight the high sensitivity of verification results to the data population and sampling period available. Periods of at least 4 days of continuous measurements are required before stable verification statistics can be attained. However, the verification data requirements (such as those required by the Carbon Trust protocol) may not be met when a measurement campaign period only observes a limited or specific wind regime, even if the verification KPIs are stable and would pass during that time. In such cases, the Simplified verification approach would remove this limitation while still enabling system accuracy to be robustly evaluated.

7 Appendix

7.1 Data availability and summary during Period 1

Height (m)	Availability (%)	Mean (m/s)	Min (m/s)	Max (m/s)
30	84.90	8.15	0.69	24.09
40	84.59	8.28	0.66	24.06
60	84.70	8.52	0.64	25.22
80	84.30	8.67	0.61	26.50
100	84.34	8.79	0.67	26.60
120	84.45	8.90	0.63	27.46
140	84.43	8.97	0.64	28.37
160	84.36	9.04	0.61	27.79
180	84.32	9.09	0.73	27.81
200	84.16	9.15	0.79	28.04
250	83.85	9.27	0.98	28.20

Table 7-1: Wind speed availability and data summary at WS187 HKWA during August 2019.

Height (m)	Availability (%)	Mean (m/s)	Min (m/s)	Max (m/s)
30	51.68	9.26	0.66	24.04
40	51.41	9.38	0.60	23.68
60	51.48	9.69	0.72	25.19
80	50.40	9.92	0.67	25.52
100	50.74	10.07	0.70	26.23
120	50.60	10.22	0.58	27.22
140	50.45	10.36	0.60	27.51
160	50.25	10.46	0.62	27.78
180	49.80	10.54	0.70	28.33
200	49.37	10.62	0.70	28.05
250	48.81	10.80	0.97	28.98

Table 7-2: Wind speed availability and data summary at WS188 HKWB during August 2019.

Height (m)	Availability (%)	Mean (m/s)	Min (m/s)	Max (m/s)
30	99.42	8.14	0.67	23.66
40	99.42	8.34	0.67	24.32
60	99.42	8.56	0.61	25.45
80	99.42	8.73	0.55	26.58
100	99.40	8.83	0.61	26.76
120	99.40	8.93	0.55	27.89
140	99.40	9.00	0.55	27.83
160	99.37	9.08	0.61	28.37
180	99.37	9.15	0.67	28.55
200	99.37	9.20	0.73	28.31
250	99.35	9.31	0.85	28.55

Table 7-3: Wind speed availability and data summary at WS170 HKWC during August 2019.

7.2 Data availability and summary during Period 2

Height (m)	Availability (%)	Mean (m/s)	Min (m/s)	Max (m/s)
30	81.36	9.24	0.75	24.09
40	81.09	9.32	0.68	24.06
60	81.33	9.63	0.72	25.22
80	80.27	9.84	0.86	26.50
100	80.31	10.01	0.67	26.60
120	80.48	10.17	0.63	27.46
140	80.37	10.31	0.64	28.37
160	80.29	10.42	0.61	27.79
180	80.30	10.51	0.73	27.81
200	80.13	10.60	0.80	28.04
250	79.85	10.77	0.98	28.20

Table 7-4: Wind speed availability and data summary at WS187 HKWA during subset period of 1/08/2019 to 11/08/2019.

Height (m)	Availability (%)	Mean (m/s)	Min (m/s)	Max (m/s)
30	100	9.26	0.66	24.04
40	100	9.38	0.60	23.68
60	100	9.69	0.72	25.19
80	100	9.92	0.67	25.52
100	100	10.07	0.70	26.23
120	100	10.22	0.58	27.22
140	100	10.36	0.60	27.51
160	100	10.46	0.62	27.78
180	100	10.54	0.70	28.33
200	100	10.62	0.70	28.05
250	100	10.80	0.97	28.98

Table 7-5: Wind speed availability and data summary at WS188 HKWB during subset period of 1/08/2019 to 11/08/2019.

Height (m)	Availability (%)	Mean (m/s)	Min (m/s)	Max (m/s)
30	99.05	9.23	0.67	23.66
40	99.04	9.44	0.67	24.32
60	99.04	9.71	0.73	25.45
80	99.07	9.95	0.73	26.58
100	99.07	10.10	0.73	26.76
120	99.03	10.24	0.55	27.89
140	99.02	10.36	0.55	27.83
160	99.06	10.48	0.61	28.37
180	99.06	10.56	0.67	28.55
200	99.00	10.64	0.73	28.31
250	99.08	10.82	0.85	28.55

Table 7-6: Wind speed availability and data summary at WS170 HKWC during subset period of 1/08/2019 to 11/08/2019.

7.3 Upper-range filters

Height (m)	WS188 (WS187)	WS170 (WS187)	WS170 (WS188)
30	13.5	14.5	15
40	15	13	13.5
60	15	15	12.5
80	15	15	15
100	15	15	15
120	16	14	17
140	15	16	17
160	15	17	15
180	17	17	19
200	16	18	17
250	16	16	19

Table 7-7: Wind speed upper-range filters (m/s) derived from qualitative examination of Q-Q deviations per height level. Filters are applied for the ≥ 2 m/s verifications inclusive of upper-filtering in Sections 4.4 and 4.5. Note that the upper-range filters shown represent the maximum wind speed included in the verification; any values greater are excluded.

8 Bibliography

1. **The Carbon Trust.** *Carbon Trust Offshore Wind Accelerator Roadmap for the Commercial Acceptance of Floating LiDAR Technology.* s.l. : The Carbon Trust, 2018.
2.