Energinet Eltransmission A/S

Lot 3 (North Sea I)

Wind Assessment Supplementary Note

REPORT

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Document information and change log.

Revision	Date	Status / Reason for Issue	Author	Checker
0	2024-10-07	For internal QC	DWH	JOG
1	2024-10-11	Issued for Client	DWH	JOG
2	2024-11-13	Implementing Client comments	JOG	DWH
3	2024-11-26	Final version to Client	JOG	DWH

Section	Summary of Changes (latest revision only)
All	Final version to Client

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Abbreviations	
AGL	Above Ground Level
ASL	Above Surface Level. This is used when a surface-following vertical reference is needed for measurements on land, whereas SWL is typically used for the same purpose at sea (although ASL could in principle be used there as well).
CRS	Coordinate Reference System
DLC	Design Load Case Table
ECD	Extreme Direction Change
ECN	Energy research Centre of the Netherlands
EDC	Extreme Direction Change
EOG	Extreme Operating Gust
ETM	Extreme Turbulence Model
EVA	Extreme Value Analysis
EWM	Extreme Wind Model
EWS	Extreme Wind Shear
FEED	Front-End Engineering Design
FLS	Floating LiDAR System, Fatigue Limit State
HAT	Highest Astronomical Tide
ibid.	From Latin ibidem (“in the same place”), it is used to save space in textual references to a quoted work, or another section in the present document, which has been mentioned in a previous reference.
IFORM	Inverse first-order reliability method
ILA	Integrated Load Analysis
LAT	Lowest Astronomical Tide
MoMM	Mean Of Monthly Means
MSL	Mean Sea Level
NaN	Not a Number
NSS	Normal Sea State
NTM	Normal Turbulence Model
NWP	Normal Wind Profile
RNA	Rotor-Nacelle Assembly
SWL	Still Water Level
WTG	Wind Turbine Generator

Subscripts	
Hub	Value at Hub height
Free	Undisturbed inflow, i.e. Free Stream
Mean	Mean value
Ref	Reference
Agg	Aggregate (i.e. composed of several parts)

Symbols	
Latin characters	
WS, V	Wind Speed
WD	Wind Direction
N	Number of independent environmental states
A	Weibull scale parameter
k	Weibull shape parameter
g	9.816 m/s^2 is the gravitational acceleration[1]
h	Height
P	Pressure
P_x	Upper *x* % quantile of a set of values; e.g. P_{90} is the 90 % quantile
TI	Turbulence Intensity
t	Timestamp, i.e. a time-coordinate
T	Temperature, Time period (two separate meanings)
R	Ideal gas constant
RelH	Relative humidity
z	Elevation (i.e. vertical coordinate) above a vertical reference.
Greek characters	
ρ	Density
μ	Mean value
σ	Standard deviation
α	Power-law wind shear exponent

[1] See: https://www.wolframalpha.com/input?i=acceleration+of+gravity+at+ringkoebing

Executive Summary

The present document gives input to the document *WTG Site Conditions Assessment* for the North Sea I Offshore Wind farm (NSI), and it is intended for this project only. It covers the analysis of wind conditions and other atmospheric conditions.

The document provides input to:

- The site-specific design of support structures (including towers) for the Wind Turbine Generators (WTGs).
- The evaluation of site suitability of the Rotor-Nacelle Assemblies (RNAs).

The results are referenced below:

Still Water Levels		**Reference**
0 mMSL = 0 mDVR90		Section 1.2 of [NSIWA]
Normal conditions parameters. Given at h_{Hub} = 150.0 mDVR90		**Reference**
Weibull Mean wind speed	Not summarised; see Table 6-1	Appendix A and Table 6-1
Omni-directional Weibull wind speed distribution parameters	Not summarised; see Table 6-1	Appendix A and Table 6-1
Wind profile for wind speed extrapolation with elevation	$WS(z) = WS_{\mathrm{Hub}} \left(\frac{z}{h_{\mathrm{Hub}}}\right)^{0.07}$ Here, z and h_{Hub} are in mMSL.	Section 6.2.1
Wind profile for load calculations, Normal Wind Profile (NWP)	$WS_{\mathrm{NWP}}(z) = WS_{\mathrm{NWP,Hub}} \left(\frac{z}{h_{\mathrm{Hub}}}\right)^{0.106}$ Here, z and h_{Hub} are in mMSL.	Section 6.2.2
Normal Turbulence Model (NTM)	Not summarised.	Section 6.3.1 of [NSIWA]
Extreme Turbulence Model (ETM)	Largest of: ➢ IEC Class IB in Table 6-5 of [NSIWA] ➢ Centre-wake *TI*(*WS*)	Section 6.3.2 of [NSIWA]
Normal ambient air temperature range	-6.0 °C ≤ *T* < 25.0 °C	Section 6.4.1 of [NSIWA]
Design temperature (lowest daily mean temperature)	1.7 °C	Section 6.4.1 of [NSIWA]
Relative humidity limit	*RelH* ≤ 100 %	Section 6.4.2 of [NSIWA]
Extreme conditions parameters (Extreme Wind speed Model, EWM). Given at h_{Hub} = 150.0 mDVR90		**Reference**
Wind profile for load calculations	$WS(z) = WS_{\mathrm{Hub}} \left(\frac{z}{h_{\mathrm{Hub}}}\right)^{0.11}$ Here, *z* and h_{Hub} are in mMSL.	Section 8.1 of [NSIWA]

Wind profile for extreme wind speed extrapolation with elevation	$WS(z) = WS_{\text{Hub}} \left(\frac{z}{h_{\text{Hub}}}\right)^{0.11}$ Here, z and h_{Hub} are in mMSL.	Section 8.1 of [NSIWA]
Mean air density	$\rho_{\text{Hub,EWM}} = 1.21\ \frac{\text{kg}}{\text{m}^3}$	Section 8.2 of [NSIWA]
Maximum 10-minute mean wind speed for a 1-year EWM	$WS_{1,\text{Hub}}$ = 34.9 m/s	Section 8.3.7 of [NSIWA]
Maximum 10-minute mean wind speed for a 5-year EWM	$WS_{1,\text{Hub}}$ = 40.2 m/s	Section 8.3.7 of [NSIWA]
Maximum 10-minute mean wind speed for a 10-year EWM	$WS_{1,\text{Hub}}$ = 42.3 m/s	Section 8.3.7 of [NSIWA]
Maximum 10-minute mean wind speed for a 25-year EWM	$WS_{1,\text{Hub}}$ = 45.4 m/s	Section 8.3.7 of [NSIWA]
Maximum 10-minute mean wind speed for a 50-year EWM	$WS_{50,\text{Hub}}$ = 48.0 m/s	Section 8.3.7 of [NSIWA]
Turbulence Intensity for use with EWM	TI_{EWM} = 11 %	Section 8.4 of [NSIWA]
Other Conditions **Given at h_{Hub} = 150.0 mDVR90**		**Reference**
Extreme ambient air temperature range, 1-hour mean:	- 9.0 °C ≤ T < 28.0 °C	Section 6.4.1 of [NSIWA]
Mean air temperature at hub height	8.6 °C	Section 6.4.1 of [NSIWA]
Highest temperature in 25 years	28.0 °C	Section 6.4.1 of [NSIWA]
Highest temperature while WTG in production	28.0 °C	Section 6.4.1 of [NSIWA]
Lowest temperature in 25 years	-9.0 °C	Section 6.4.1 of [NSIWA]
Lowest temperature while WTG in production	-9.0 °C	Section 6.4.1 of [NSIWA]

1. Introduction

Energinet Eltransmission A/S (EE, or "the Client") has appointed C2Wind ApS (C2Wind) to carry out Site Wind Conditions Assessment for the North Sea I project (Lot 3), located in the Danish North Sea. The purpose of this document is to serve as a supplement to the Site Wind Conditions Assessment carried out with 9 months of on-site floating Lidar measurements [NSIWA], updating the results after the measurement campaign gathered a full year of measurements. Thus, the present document repeats the structure of [NSIWA], but only provides content in the sections where the additional months of measurements have resulted in changes to the conclusions of the analysis.

The numbering of tables and figures in this document preserves the numbering used in [NSIWA]. Similarly, the list of references in this document does not reproduce in full that of [NSIWA], but rather lists only the documents that are cited herein. Finally, the Executive Summary clearly indicates which results can be found in [NSIWA] and which have been updated in the present document.

1.1 Geographical location

[There are no changes in this section]

1.2 General considerations

[There are no changes in this section]

2. Applied standards and guidelines

[There are no changes in this section]

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3. Overview of available data and review of data quality

[There are no changes in this section]

3.1 Available data

[There are no changes in this section]

3.2 Sensor naming convention

[There are no changes in this section]

3.3 High-level quality check filters

[There are no changes in this section]

4. Generic methods

The updated analysis uses the same approach and methods as those in [NSIWA].

4.1 Turbulence intensity detrending

[There are no changes in this section]

4.2 Method of Mean-of-Monthly-Means: Handling missing data

[There are no changes in this section]

4.3 Calculation of wind shear and extrapolating to hub height

[There are no changes in this section]

5. Selection of representative analysis points

[There are no changes in this section]

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6. Normal wind conditions

6.1 Normal conditions wind Weibull distribution and wind roses

This section has been updated with the results of a long-term correction using the full 1-year of measurements.

The wind speed distribution Weibull parameters at hub height have been derived in Appendix A for the analysis points found in Section 5 of [NSIWA]. The analysis in Appendix A consisted of an update of that in [NSIWA], namely the long-term correction of the measurements with an MCP approach, followed by spatial extrapolation to the analysis points.

The Weibull parameters describing the wind speed distribution at the analysis points are summarised in Table 6-1, while the wind rose applicable to all points is shown in Figure 6-1.

Site	Point	A	k	Mean wind speed
		[m/s]	[-]	[m/s]
A1	P1	11.71	2.25	10.38
A2	P2	11.76	2.25	10.44
A3	P3	11.80	2.25	10.48
A4	P4	11.88	2.26	10.54
A4	P5	11.83	2.26	10.50
NSI-1-LB		11.88	2.26	10.54
NSI-2-LB		11.62	2.25	10.31
NSI-3-LB		11.62	2.26	10.31

Table 6-1: Weibull parameters estimated at the analysis points and FLS locations at hub height. The mean wind speed is calculated from the fitted Weibull parameters.

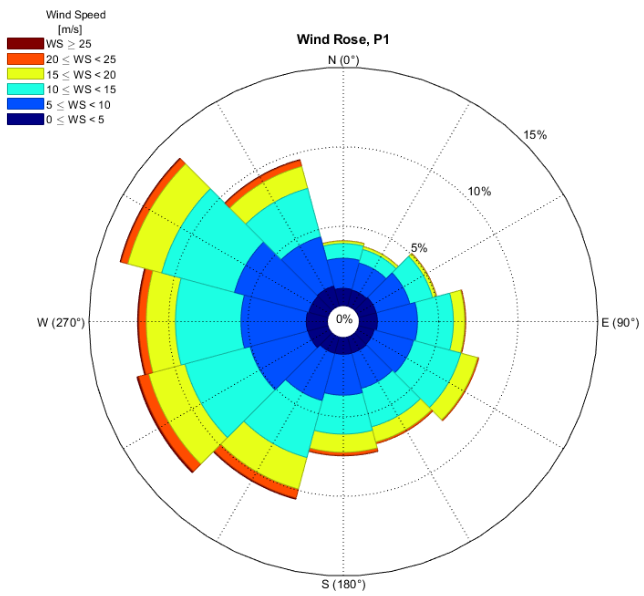

Figure 6-1: Wind rose corresponding to the long-term wind distribution at point P1, applicable to all analysis points.

For use in Fatigue Limit State (FLS) Design Load Cases (DLCs) in Integrated Load Analysis, particularly those involving Normal Sea States (NSS), joint directional occurrence frequencies for the wind speed and (Wind-Sea) wave directions are needed. These are unambiguously provided through the misalignment tables in a Marine Assessment.

For some purposes, e.g. calculation of Wind Farm Turbulence, it is necessary to use directional occurrence frequencies of wind speeds. These can be found through summing over (Wind-Sea) wave directions in the aforementioned misalignment tables provided in the project's Marine Assessment. Alternatively, and requiring that the user first justifies its applicability for that purpose, the Marine Assessment provides directional Weibull fits that can be used for input to Wind Farm Turbulence analyses.

6.2 Wind shear and wind shear profile for normal conditions

The updated datasets resulted in no changes to the discussion and conclusions in this section. The precise numerical value of the fitted wind shear exponents did change, and thus Figure 6-2 has been updated.

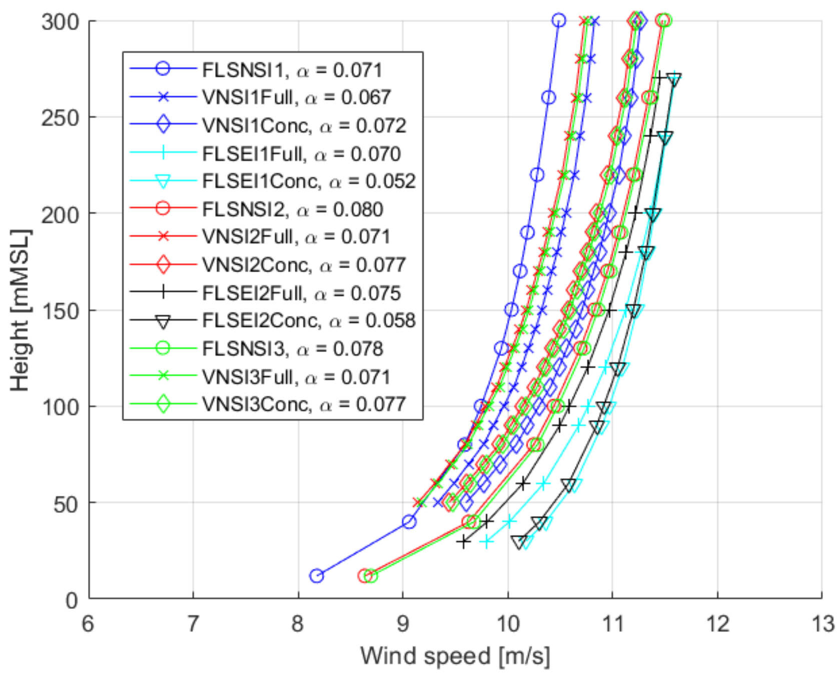

Figure 6-2: Mean wind speed profiles and fitted shear exponents to the 3 NSI FLSs, their co-located Vortex model time series, and the 2 EINS FLSs. Update to the corresponding Figure 6-2 of [NSIWA] with updated datasets.

6.2.1 Normal conditions wind climate scaling

The results in this section have been updated, now assessing wind shear with the full year of measurements at all three FLSs and selecting the most conservative (numerically larger) value among the three.

Normal conditions wind speeds shall, for all wind directions, be transformed to other heights using a shear exponent of 0.07.

$$WS(h) = WS_{Hub} \left(\frac{h}{h_{\text{Hub}}} \right)^{0.07} \qquad \text{Eq. 6-2}$$

Here, *z* and *h*$_{\text{Hub}}$ are measured in metres above Mean Sea Level (MSL), i.e. mMSL.

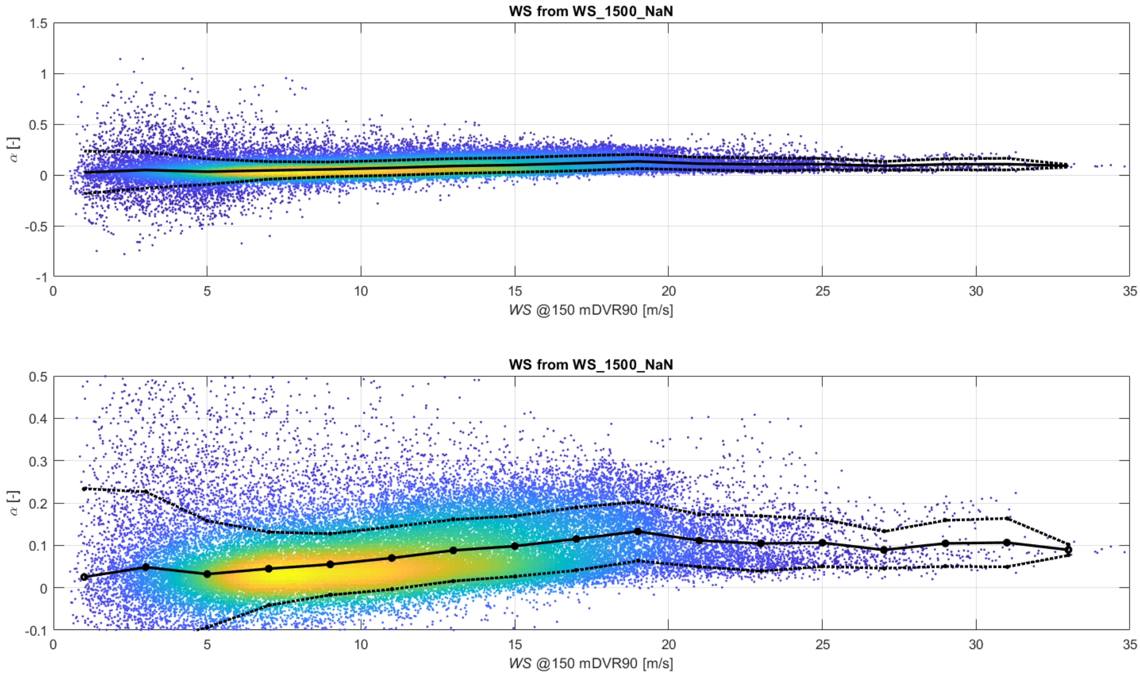

Figure 6-3: Scatter plots of wind shear exponents vs. hub height wind speed, obtained from the hub height sensor at the NSI1 FLS and fitting the wind profile across all elevations covering the rotor plane and up to 300 mMSL as listed in Section 1.2. The plots show the points coloured according to density. The upper plot shows all data, whereas the lower plot shows details for the most widespread values. The black points, joined by the fully drawn black line, show the mean-of-monthly means wind-speed binned mean values. The markers joined by dashed lines show the mean values described in the preceding sentence, plus and minus one mean-of-monthly-means wind speed binned standard deviation.

			Wind Direction [°N]												
WS bin		**Min**	-15	15	45	75	105	135	165	195	225	255	285	315	
[m/s]		**Max**	15	45	75	105	135	165	195	225	255	285	315	345	**Omni**
≤	**<**	**Centre**	**0**	**30**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**	
0	2	**1**	0.022	-0.015	0.114	0.018	-0.003	0.053	0.068	0.087	0.077	0.091	0.066	0.020	0.051
2	4	**3**	-0.048	-0.133	-0.086	0.014	0.043	0.072	0.101	0.066	0.077	0.032	0.035	0.044	0.030
4	6	**5**	-0.004	-0.055	-0.004	0.010	0.064	0.038	0.045	0.044	0.062	0.046	0.047	0.023	0.031
6	8	**7**	0.018	0.006	0.017	0.042	0.069	0.063	0.071	0.076	0.063	0.051	0.046	0.030	0.049
8	10	**9**	0.014	0.023	0.018	0.047	0.064	0.084	0.098	0.077	0.072	0.061	0.041	0.033	0.059
10	12	**11**	0.029	0.034	0.033	0.058	0.095	0.088	0.110	0.097	0.083	0.075	0.039	0.039	0.071
12	14	**13**	0.041	0.028	0.029	0.083	0.107	0.109	0.114	0.113	0.110	0.080	0.060	0.050	0.089
14	16	**15**	0.041	0.098	0.049	0.093	0.103	0.125	0.130	0.135	0.121	0.097	0.066	0.084	0.104
16	18	**17**	0.042	0.058	0.083	0.107	0.114	0.103	0.135	0.167	0.147	0.125	0.084	0.075	0.123
18	20	**19**	0.056	-	0.056	0.075	0.093	0.112	0.153	0.154	0.151	0.164	0.091	0.061	0.130
20	22	**21**	0.056	-	0.074	0.079	0.080	0.150	0.143	0.183	0.145	0.135	0.091	0.067	0.123
22	24	**23**	-	-	0.077	0.077	-	0.153	0.174	0.173	0.155	0.121	0.087	0.065	0.114
24	26	**25**	-	-	0.088	0.067	-	0.225	0.192	0.153	0.157	0.131	0.102	0.068	0.111
26	28	**27**	-	-	-	0.075	-	-	0.172	0.173	0.144	0.132	0.106	0.082	0.126
28	30	**29**	-	-	-	-	-	-	-	0.197	0.079	0.084	0.087	0.073	0.131
30	32	**31**	-	-	-	-	-	-	-	0.200	0.081	0.088	0.089	-	0.100
32	34	**33**	-	-	-	-	-	-	-	-	-	-	0.096	0.088	0.095
Mean over *WS*:			**0.008**	**-0.012**	**0.021**	**0.061**	**0.087**	**0.089**	**0.105**	**0.102**	**0.097**	**0.084**	**0.056**	**0.042**	**0.073**

Table 6-2: Mean shear exponent measured at NSI-3-LB, binned as function of wind speed and wind direction.

6.2.2 Wind shear exponent to use in load calculations requiring Normal Wind Profile

The results in this section have been updated, now assessing wind shear with the full year of measurements at all three FLSs and selecting the most conservative (numerically larger) value among the three.

WS bin [m/s]		# 10-min samples [-]	Mean shear exponent [-]	Std. dev. of shear exponent [-]	Mean absolute shear exponent [-]	Std. dev. of absolute shear exponent [-]
≤	<					
0	2	731	0.051	0.216	0.152	0.162
2	4	2869	0.030	0.211	0.134	0.166
4	6	5739	0.031	0.128	0.080	0.105
6	8	7379	0.049	0.098	0.068	0.086
8	10	7254	0.059	0.081	0.069	0.072
10	12	6897	0.071	0.082	0.081	0.073
12	14	6722	0.089	0.071	0.092	0.066
14	16	5455	0.104	0.066	0.105	0.065
16	18	3427	0.123	0.067	0.123	0.067
18	20	2217	0.130	0.063	0.130	0.063
20	22	1218	0.123	0.064	0.123	0.064
22	24	613	0.114	0.058	0.114	0.058
24	26	347	0.111	0.050	0.111	0.050
26	28	97	0.126	0.049	0.126	0.049
28	30	53	0.131	0.059	0.131	0.059
30	32	30	0.100	0.036	0.100	0.036
32	34	10	0.095	0.015	0.095	0.015

Table 6-3: Statistical shear exponent values to use as input for the selection of shear exponent to use for deriving the Normal Wind Profile (NWP); i.e. for use in the Integrated Load Analyses that require this wind profile type. The values shaded with light blue are the ones that Section 12.3 in [IEC6131] requires are used to evaluate the shear exponent to be used for Integrated Load Analysis with NWP for an IEC Class I site (0.2-0.4·V_{Ref}); as noted in the text above, this is in line with the suggestions in Section 6.4.3.1 of [IEC6131]. The values for the largest WS_{Hub}-bins have their values listed in grey text to highlight that they are found using only a few data points.

The wind shear exponent for the NWP is found as the (unweighted) mean of the values in the cells shaded light blue in Table 6- to 0.106:

$$WS_{\mathrm{NWP}}(z) = WS_{\mathrm{NWP,Hub}} \left(\frac{z}{h_{\mathrm{Hub}}}\right)^{0.106} \quad \text{Eq. 6-3}$$

Here, *z* and h_{Hub} are measured in metres above Mean Sea Level (MSL), i.e. mMSL.

This value of 0.106 is larger than the mean value from Table 6-2, but smaller than the mean value for some individual wind directional bins such as [195; 255[°N. This is expected, as the largest shear values do not occur for the most frequent wind directional bin. Also, this is acceptable since these mean shear values remain smaller than the value of 0.2 used for RNA type certification.

6.3 Free Stream Turbulence Intensity

The general discussion in this section has been updated, and the analysis of directional dependence in FLS-measured turbulence intensity has been updated with the full year of measurements. The additional months have mostly added southwesterly and westerly winds, offshore directions that change little to the overall picture and discussion in [NSIWA].

Figure 6-5 and Figure 6-6 have been updated as shown below, but the discussion and conclusion remain valid:

- While the absolute FLS-measured turbulence intensity values are likely biased compared to cup anemometer measurements applicable for deriving an NTM, their directional dependence is useful in assessing whether the FLSs see differences in the incoming flow that can be clearly attributable to land or neighbouring OWFs.
- While the plots in Figure 6-5 could seem to indicate a sector of higher turbulence for onshore directions, closer inspection reveals this is not the case. All three plots seem to reach their maxima between 30° and 70°, a direction which is neither the closest distance to shore nor which can be associated with an operational OWF for all three FLSs. Rather, the reason for all three FLSs measuring higher *TI* in those directions is likely a combination of site-specific flow features and the small number of datapoints in those directions, as seen in Figure 6-6, where the plots from Figure 6-5 have been reproduced now removing the point clouds and adding histograms to indicate the amount of data points in each directional bin. The fact that the local maximum happens at 60° for all three FLSs despite them having different upwind features clearly indicates that this is either caused by the low number of data points or a feature of the local wind climate, rather than land or OWFs. Furthermore, the fact that FLSs NSI2 & NSI3 do not see a clear increase in FLS-measured TI for directions with upstream operational OWFs, 180° and 90° respectively, also suggests that no wake added turbulence is perceptible at the site and at hub height.
- Thus, the turbulence intensity is treated omnidirectionally in the present document. Furthermore, following the analyses in Appendix C of [NSIWA], it is characterized using measurements from the top-mounted cup anemometers at

the IJmuiden met mast, extrapolated to hub height by the measured wind shear from its co-located Lidar.

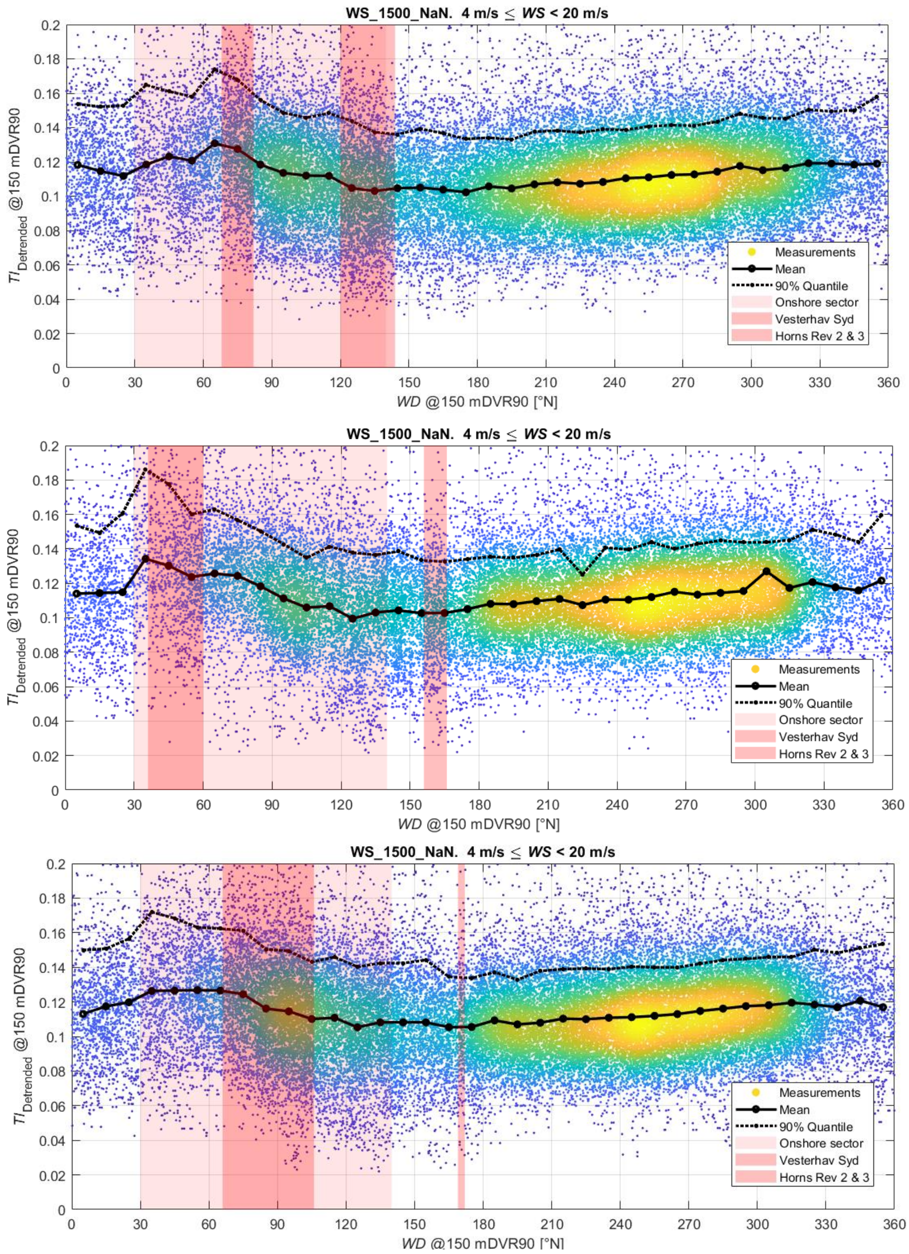

Figure 6-5: FLS-measured TI at 150 mMSL as a function of wind direction at 150 mMSL for FLSs NSI-1-LB (top), NSI-2-LB (middle) and NSI-3-LB (bottom). Binned mean values are plotted with a solid black and the 90% quantiles are plotted with a dotted black line. The light red area indicates wind directions where wind comes from land, while dark red areas indicate directions where there is an operational OWF upstream.

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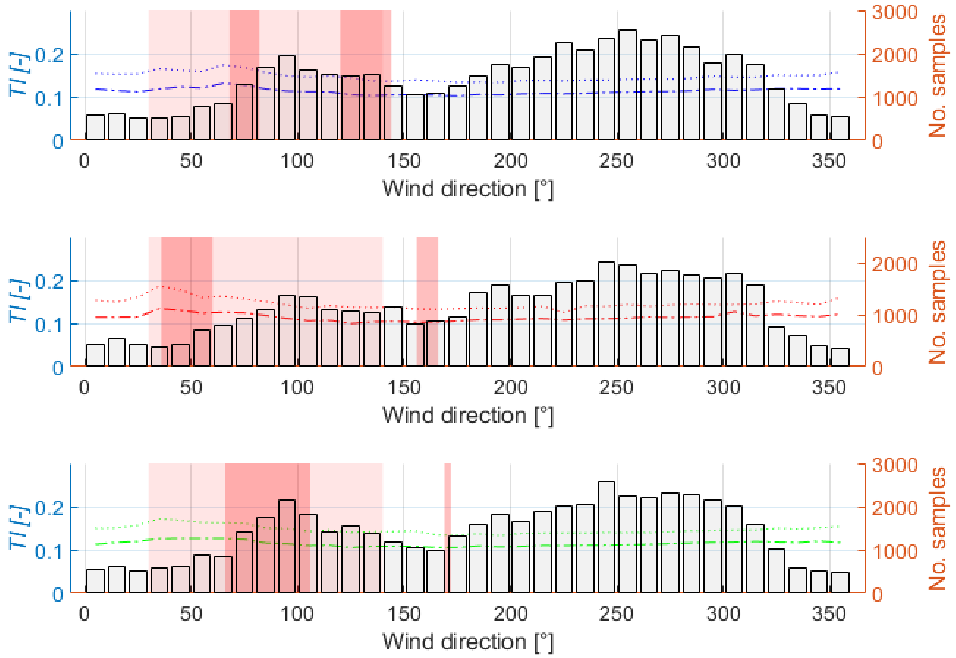

Figure 6-2: Reproduction of the plots from Figure 6-, removing the point clouds and adding histograms to indicate the amount of data points in each directional bin example.

6.3.1 Normal Turbulence Model and turbulence statistics

[There are no changes in this section]

6.3.2 IFORM analysis and discussion of ETM

[There are no changes in this section]

6.4 Other normal conditions air parameters

6.4.1 Air temperature

The comparisons between the Vortex model and the FLS measurements have been repeated with the additional data, now using NSI-1-LB instead of NSI-2-LB as used in [NSIWA] due to the error in temperature data collection at NSI-2-LB as mentioned in Appendix B.1.3. The correlation remains strong, the bias remains small, and the conclusion to use the Vortex model data to describe air temperatures remains valid, see Figure 6-8.

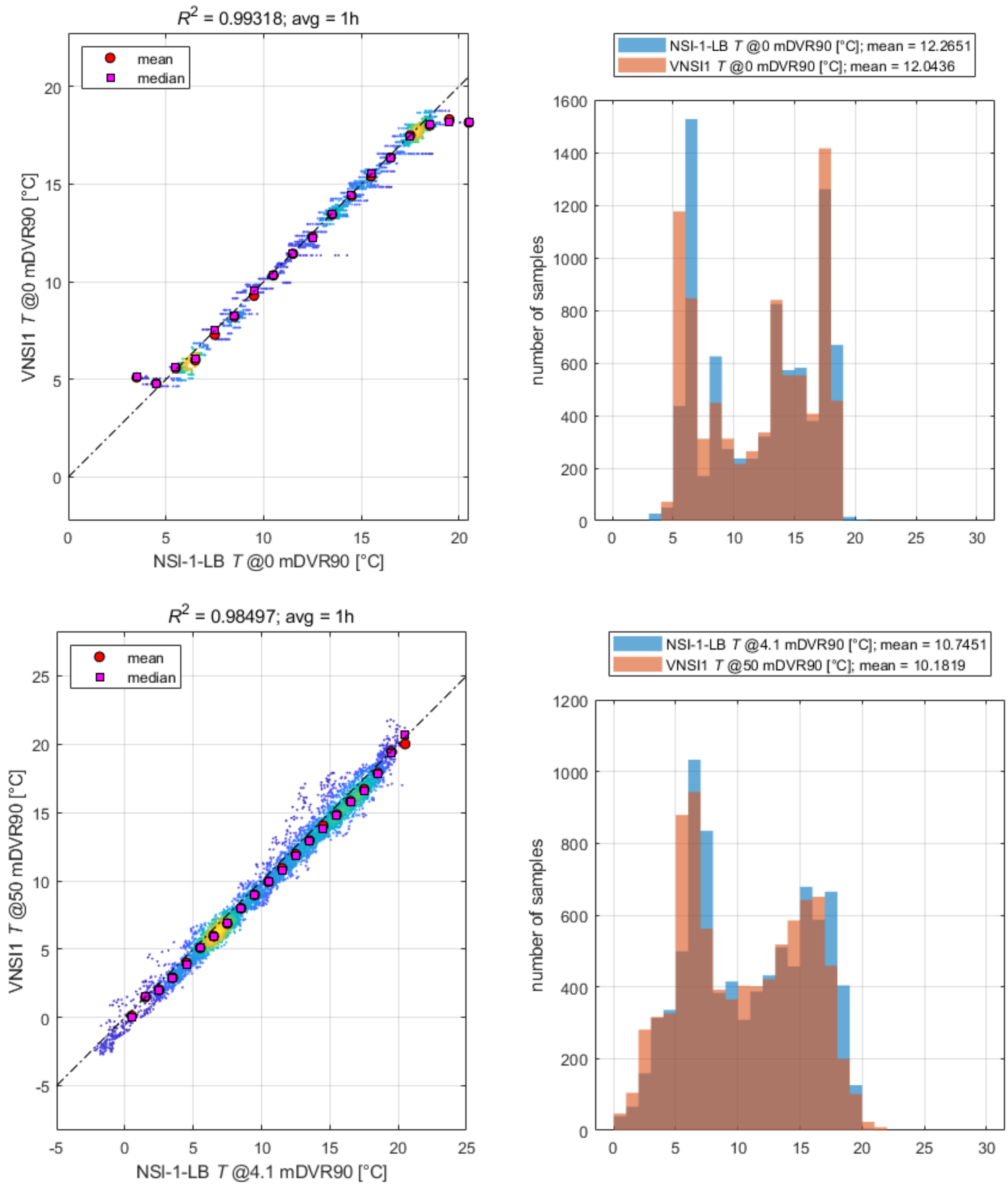

Figure 6-8: Scatter plots and histograms between temperatures measured by NSI-1-LB and from the co-located Vortex model. Top: sea surface temperature for both datasets; bottom: air temperature measured at 4.1 mSWL and modelled at 50 mMSL.

6.4.2 Air humidity

The comparisons between the Vortex model and the FLS measurements have been repeated with the additional data. The correlation remains strong and the conclusion to use the Vortex model data to describe air temperatures remains valid, see Figure 6-11.

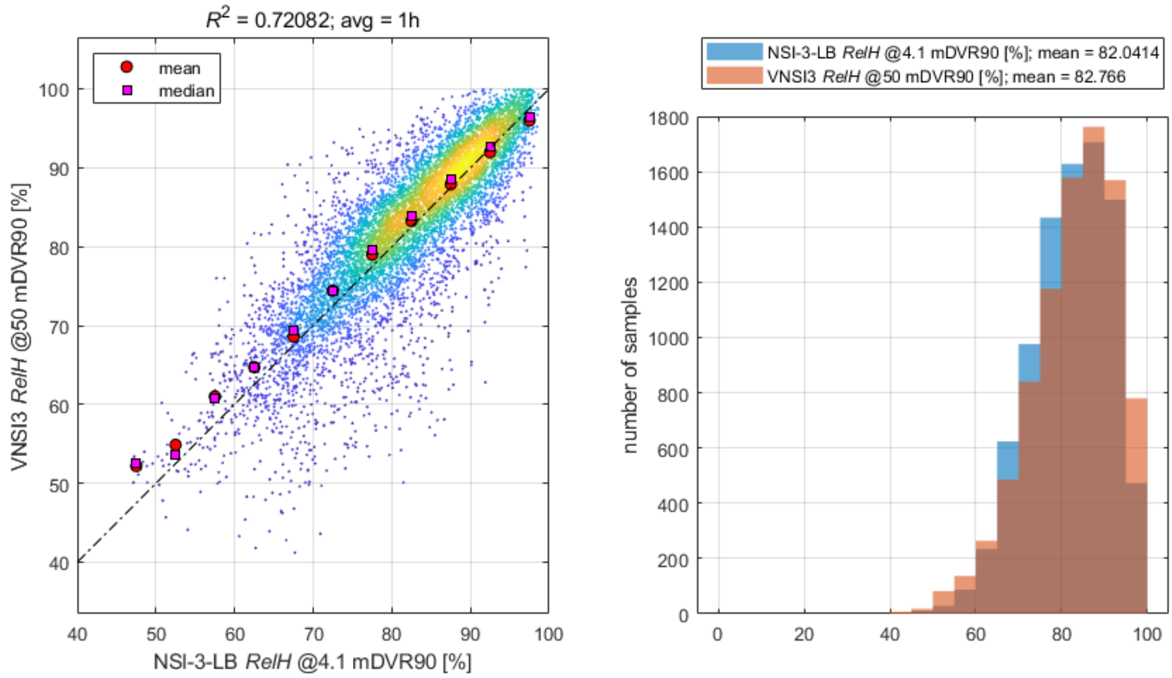

Figure 6-11: Scatter plot and histograms between relative humidity measured by NSI-LB-3 at 4.1 mSWL and from the co-located Vortex model at its lowest elevation, 50 mMSL.

6.4.3 Air pressure

The comparisons between the Vortex model and the FLS measurements have been repeated with the additional data. The correlation remains strong and the conclusion to use the Vortex model data to describe air temperatures remains valid, see Figure 6-13.

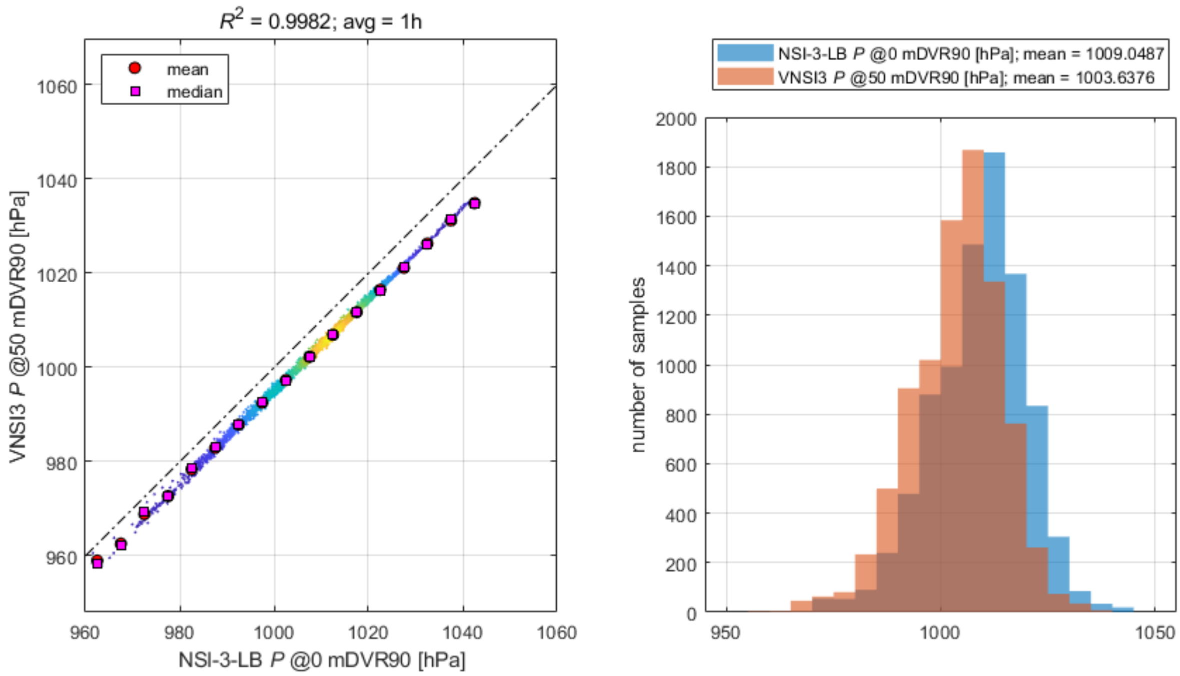

Figure 6-13: Scatter plot and histograms between atmospheric pressure measured by NSI-3-LB at 4.1 mSWL and from the co-located Vortex model at its lowest elevation, 50 mMSL.

6.4.4 Air density

The comparisons between the Vortex model and the FLS measurements have been repeated with the additional data. The correlation remains strong and the conclusion to use the Vortex model data to describe air temperatures remains valid, see Figure 6-16 and Figure 6-17.

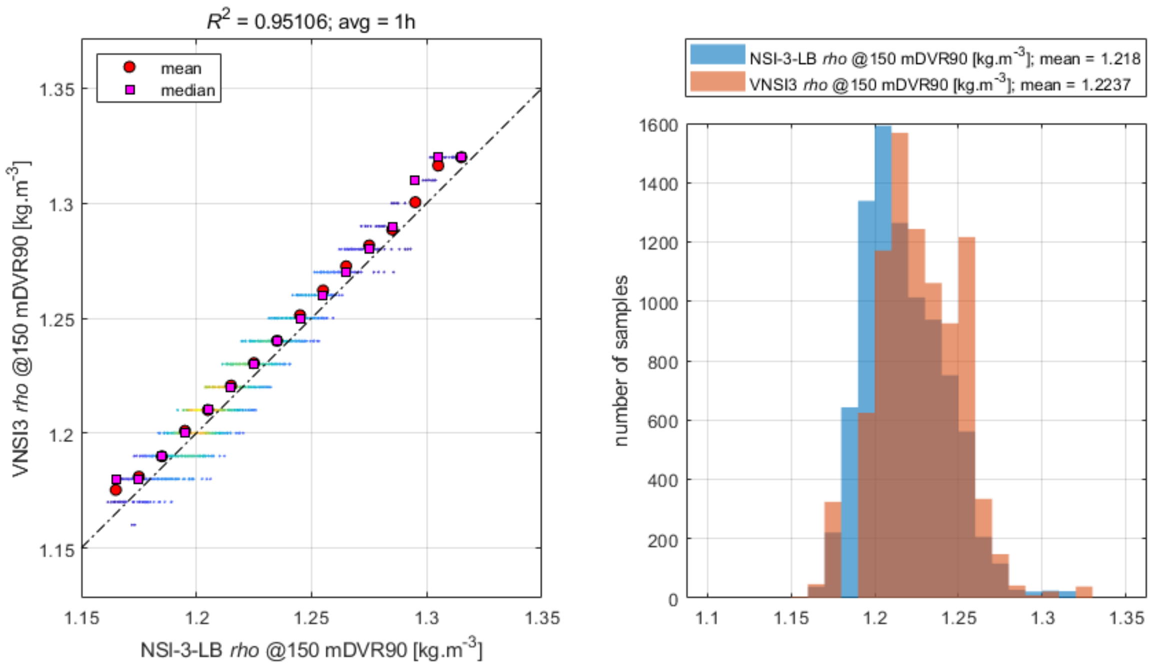

Figure 6-16: Scatter plot and histograms between air density at hub height derived from NSI-3-LB measurements as explained in the text, and modelled by the co-located Vortex model at hub height.

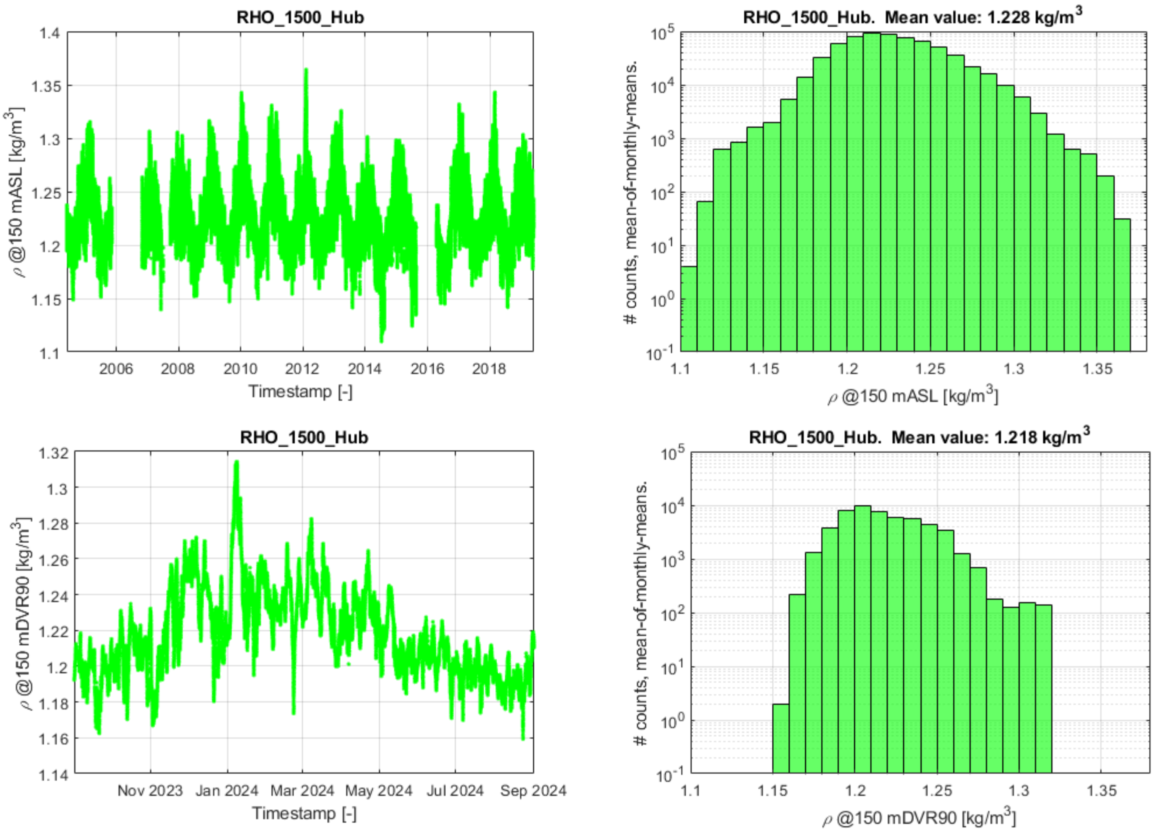

Figure 6-17: Air density at 150 mASL from the Høvsøre measurements (top) and 150 mDVR90 from the NSI-3-LB measurements (bottom). The left part of the figure shows the model time series, and the right part of the figure shows an MoMM histogram of the values with a logarithmic 2nd axis. The MoMM mean value is shown in the title above the histogram.

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7. Wind farm induced conditions and gust conditions

7.1 Operational conditions – Wake and Wind Farm Turbulence

[There are no changes in this section]

7.2 Operational conditions – Gust amplitudes

[There are no changes in this section]

7.3 Extreme wind speed conditions

[There are no changes in this section]

8. Extreme wind speed model

8.1 Wind shear for the Extreme Wind speed Model
[There are no changes in this section]

8.2 Air density for the Extreme Wind speed Model
[There are no changes in this section]

8.3 Extreme Wind speeds
[There are no changes in this section]

8.3.1 Eurocode 1 supplemented by DS 472
[There are no changes in this section]

8.3.2 The UK Health and Safety Executive method
[There are no changes in this section]

8.3.3 ISO 19901-1
[There are no changes in this section]

8.3.4 Extreme Value Analysis using the Høvsøre met mast dataset
[There are no changes in this section]

8.3.5 Estimates from X-WiWa
[There are no changes in this section]

8.3.6 Estimates from Global Atlas of Siting Parameters
[There are no changes in this section]

8.3.7 Comparison of, and conclusion on, extreme wind speed estimates
[There are no changes in this section]

8.4 Turbulence for the Extreme Wind speed Model
[There are no changes in this section]

9. Other environmental conditions

9.1 Lightning

[There are no changes in this section]

9.2 Solar radiation

[There are no changes in this section]

9.3 Earthquakes

[There are no changes in this section]

9.4 Icing on blades

[There are no changes in this section]

9.5 Precipitation

[There are no changes in this section]

9.5.1 Seasonal precipitation

[There are no changes in this section]

9.5.2 Hail

[There are no changes in this section]

10. References

[DOW30MR] **Fugro.** Danish Offshore Wind 2030 – Floating LiDAR Measurements. Monthly Reports for North Sea I. *Sharepoint folder containing 8 monthly reports for the three FLSs in NSI, covering the period 2023-09 to 2024-05.*

[IEC613] **IEC.**
IEC 61400-3-1: Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines. Edition 1.0. International Electrotechnical Commission (2019-04-05).

[IEC6131] **IEC.** IEC 61400-3-1: Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines. Edition 1.0. International Electrotechnical Commission (2019-04-05).

[NSIWA] **C2Wind.** Lot 3 (North Sea I) – Wind Assessment. Doc. no. 23072-04-06, Rev. 4. (2024-10-11).

Appendices

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C2WIND

Appendix A. Derivation of Weibull parameters

A.1 Long-term hub height wind speed at the NSI FLSs

The changes in this section relate to updating the long-term correction to use the full 1-year of measurements.

The long-term correction can be done using another available time series which better represents the distribution of the wind speed in the long-term. The following model datasets were considered as potential long-term references:

- **NORA3**: This mesoscale time series was found to have good correlation with the FLS measurements collected at NSI and Energy Island North Sea projects, but are only available until 2024-06-01, thus having only 9 concurrent months with the FLSNSI datasets. Since such a short concurrent period would exacerbate the risk of seasonal bias already present with the short measurement duration, it was decided not to use NORA3 for the long-term correction of the FLS measurements.
- **Vortex**: This mesoscale time series was found to have good correlation with the FLS measurements at NSI and is available for the period from 1994-01-01 to 2024-10-01, thus allowing for use of the full FLS measured dataset.
- **ERA5**: This reanalysis time series was found to have a good correlation with the FLS measurements at NSI and EINS and is available for the period from 1940-01-01 to 2024-06-30, thus also allowing for use of the entire measured dataset. Since ERA5 was used as input to the Vortex time series, these two datasets are not independent, and only the higher quality Vortex dataset was included in the long-term correction.
- **MERRA2**: This reanalysis time series was found to have a good correlation with the FLS measurements at NSI and EINS and is available for the period from 1980-01-01 to 2024-09-01, thus also allowing for use of the entire measured dataset.

The methodology is unchanged from that in [NSIWA] with regards MCP regression and sensitivities to averaging windows and long-term period definition. The updated MCP results are summarised in Table A-2.

Results from MCP analysis Long-term WS at NSI FLSs @ 150 mMSL [m/s]								
Location	Long-term reference	LT start 2019-09 (5 y)	LT start 2014-09 (10 y)	LT start 2009-09 (15 y)	LT start 2004-09 (20 y)	LT start 2001-09 (23 y)	LT start 1999-09 (25 y)	LT start 1994-09 (30 y)
NSI-1-LB	Vortex	10.53	10.61	10.63	10.65	10.58	10.60	10.63
NSI-1-LB	MERRA2	10.49	10.55	10.55	10.56	10.50	10.54	10.57
NSI-2-LB	Vortex	10.31	10.38	10.39	10.40	10.34	10.36	10.38
NSI-2-LB	MERRA2	10.29	10.33	10.33	10.34	10.28	10.31	10.35
NSI-3-LB	Vortex	10.31	10.39	10.39	10.41	10.34	10.36	10.38
NSI-3-LB	MERRA2	10.29	10.33	10.32	10.34	10.28	10.31	10.35
Long-term WS for NSI-1-LB		10.51	10.58	10.59	10.61	**10.54**	10.57	10.60
Long-term WS for NSI-2-LB		10.30	10.36	10.36	10.37	**10.31**	10.34	10.37
Long-term WS for NSI-3-LB		10.30	10.36	10.36	10.37	**10.31**	10.33	10.36

Table A-2: MCP results for the 150 mMSL wind speed time series at each of the FLS locations. The results selected to continue the analysis are highlighted in bold.

The resulting long-term wind speed at 150 mMSL at the NSI-1-LB, NSI-2-LB and NSI-3-LB locations are 10.54, 10.31 and 10.31 m/s, respectively. These results were obtained as the average of the MCP results regressions with the two reference datasets shown in Table A-2 for a long-term period of 23 years. The 150 mMSL wind speed and wind direction time series resulting from the MCP analysis with the Vortex time series as a long-term reference has been scaled to the long-term mean wind speed obtained at each FLS location. The decision to use the time series resulting from MCP with the Vortex dataset was taken because:

- The Vortex time series was found to have the best correlation with the FLS measurements, see for instance Figure A-1 for comparisons for NSI-1-LB. Results for the other two FLSs are consistent with this trend.
- The shape of the wind speed- and direction frequency distributions from the Vortex time series is the most similar to those of the FLS measurements, see Figure A-1 for comparisons for NSI-1-LB. Results for the other two FLSs are consistent with this trend.
- When comparing the time series resulting from the MCP with their respective short-term measurements over the concurrent period and using the fitted Weibull parameters as metric, the MCP time series obtained using the Vortex time series as long-term reference is consistently found to be the closest to the measurements, see Table A-3.

FLS	MCP time series	A FLS	A MCP time series	k FLS	k MCP time series
		[m/s]	[m/s]	[-]	[-]
NSI-1-LB	MCPVortexNSI1	13.16	13.09	2.15	2.13
	MCPERA5NSI1	13.16	13.27	2.15	2.12
	MCPMERRA2NSI1	13.16	13.28	2.15	2.09
NSI-2-LB	MCPVortexNSI2	12.94	12.88	2.20	2.18
	MCPERA5NSI2	12.94	13.03	2.20	2.17
	MCPMERRA2NSI2	12.94	13.00	2.20	2.12
NSI-3-LB	MCPVortexNSI3	12.96	12.89	2.21	2.20
	MCPERA5NSI3	12.96	13.02	2.21	2.19
	MCPMERRA2NSI3	12.96	12.97	2.21	2.13

Table A-3: Weibull parameters from the measurements of the FLSs deployed within North Sea I and MCP time series obtained when using different long-term reference time series.

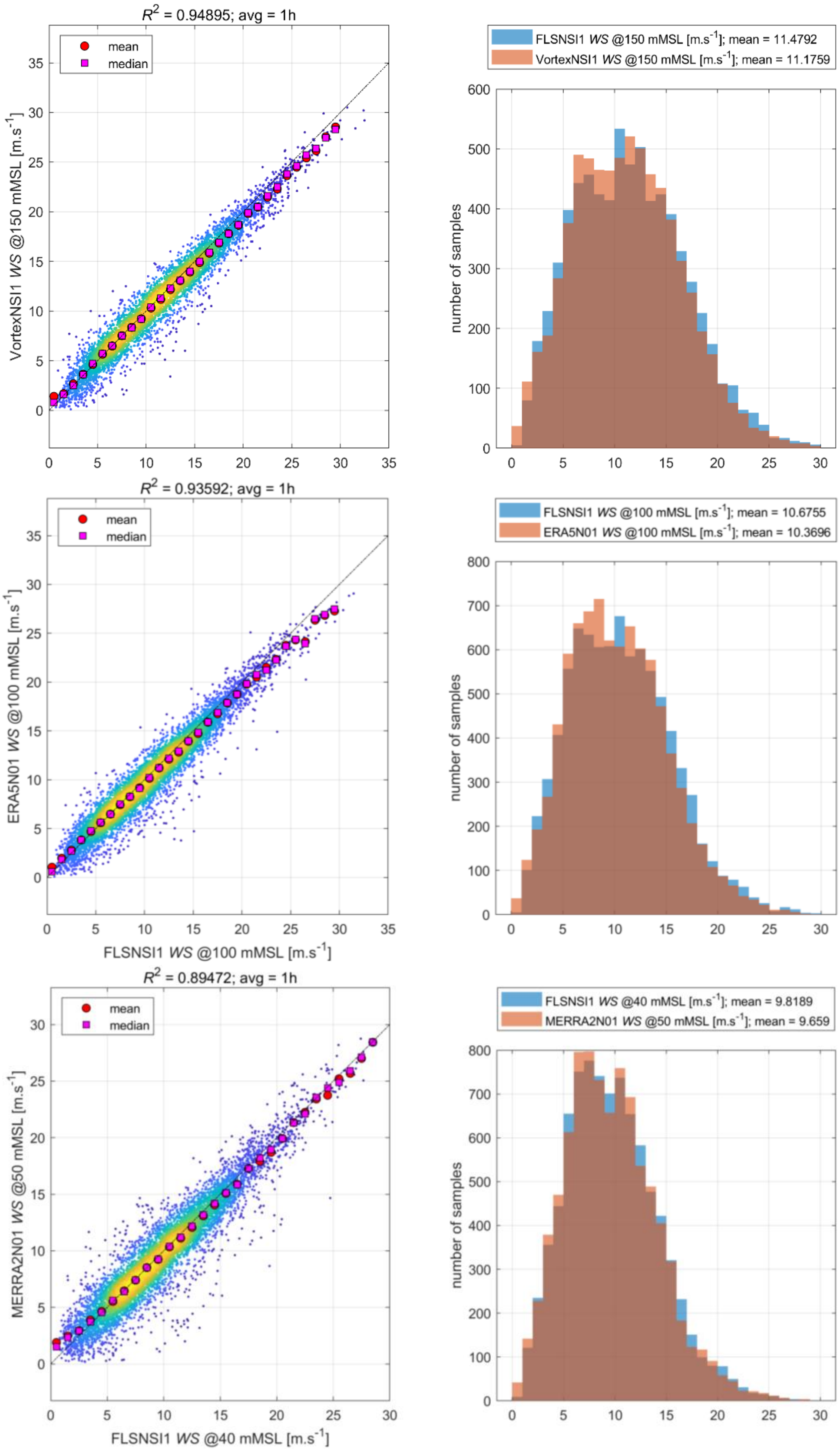

Figure A-1: Wind speed scatter plot (left) and histogram (right) of the FLS measurements and three candidate long-term reference time series (top: Vortex, middle: ERA5, bottom: MERRA2) for NSI-1-LB.

A.2 Horizontal extrapolation to the analysis points location

[There are no changes in this section]

A.3 Summary of Weibull parameters

The resulting wind speed distributions and Weibull parameters estimated at each of the analysis points and at the three FLSs are illustrated in Figure A-2 and summarised in Table A-5.

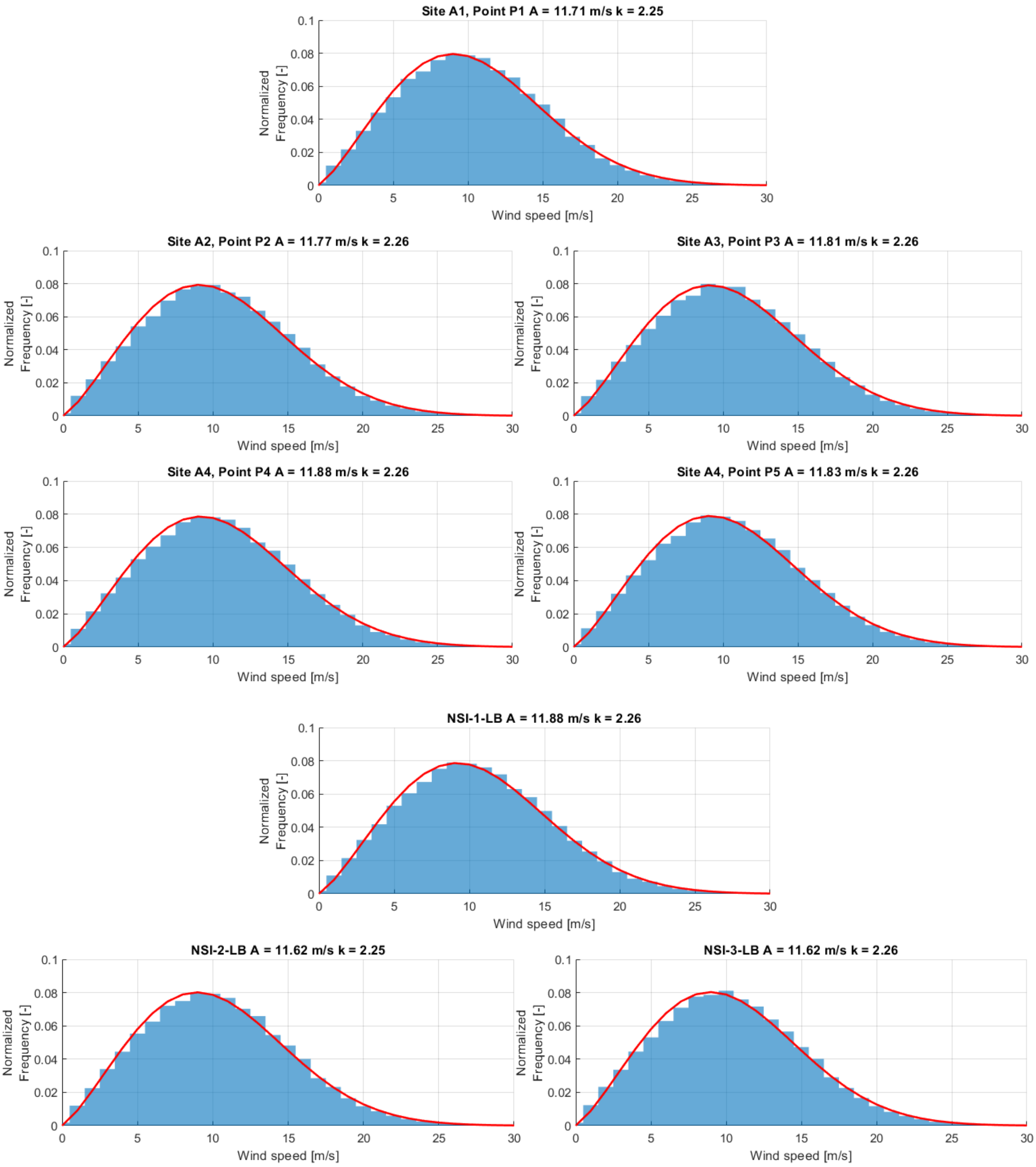

Figure A-1: Wind speed histogram of the wind climate estimated at each of the analysis points and the locations of the FLSs.

Site	Point	A	k	Mean wind speed
		[m/s]	[-]	[m/s]
A1	P1	11.71	2.25	10.38
A2	P2	11.76	2.25	10.44
A3	P3	11.80	2.25	10.48
A4	P4	11.88	2.26	10.54
A4	P5	11.83	2.26	10.50
NSI-1-LB		11.88	2.26	10.54
NSI-2-LB		11.62	2.25	10.31
NSI-3-LB		11.62	2.26	10.31

Table A-1: Weibull parameters estimated at the analysis points.

Appendix B. Description of Wind Measurement Datasets

B.1 North Sea I FLS measurement campaign

[There are no changes in this section]

B.1.1 Instrumentation setup

[There are no changes in this section]

B.1.2 Data description

The only change in this section is related to mentions of the length of the measurement campaign, which now covers the period up to 01 September 2024.

B.1.3 Data availability

The FLS measurements collected at North Sea I are available for the following periods:

- NSI-1-LB: From 2023-09-01 12:50:00 to 2024-09-01 12:40:00
- NSI-2-LB: From 2023-09-01 09:30:00 to 2024-09-01 09:20:00
- NSI-3-LB: From 2023-09-01 07:00:00 to 2024-09-01 06:50:00

The monthly data availability of all three FLSs is summarized in Table B-4. From the data in the table and a high-level analysis of the measurements, the most significant data gaps identified are:

- NSI-1-LB:
  - Wind speed- and direction from the Gill anemometer between 2023-11-24 and 2024-04-25: According to Table A-1 of the monthly reports for months 3 to 8 in [DOW30MR], this gap was due to a potential problem with the sensor or its connection due to adverse weather. The data gap was resolved with the buoy swap for the spare SWLB090 on 2024-04-25.
  - Air pressure from 2024-04-01 to 2024-04-25, see Figure B-2. According to Table A-1 of the monthly report #8 in [DOW30MR], the cause was damage to the sensor due to potential water ingress.

- NSI-2-LB:
  - Two periods with low data availability for the wind direction measurements were identified, see Figure B-3:
    - From 2024-01-30 to 2024-02-08.
    - From 2024-03-07 to 2024-05-09.

    Comparing the data gaps identified above with those listed in Table A-2 of the monthly reports for months 5 to 8 in [DOW30MR], the cause for this was a failure in the Septentrio heading source which Fugro intended to fix with data physically retrieved from the buoy – conceivably from the second position sensor – upon a service visit. C2Wind understands that this re-processing has not taken place yet, as the wind direction plot in Figure B-3 is clearly consistent with the wind direction plots in Figure 6.12 of the monthly reports for months 6 to 8 in [DOW30MR], and since the service report corresponding to the service visit on 2024-04-25 has not been available yet at the time of writing this report.

- According to monthly reports for months 10 to 12 in [DOW30MR], erroneous temperature and relative humidity measurements were recorded from June 2024 to September 2024. The root cause for this event is unknown.

➢ NSI-3-LB: No significant data gaps were identified in the measurements available at this location, see Figure B-4.

The data availability of Lidar wind speed measurements for all elevations and for the three FLSs is higher than 95%, as shown in Table B-5. Wind direction data availability is higher than 96% for all elevations at NSI-1-LB and NSI-3-LB, while it ranges between 69 and 72% for NSI-2-LB.

FLS	Year	Month	System data availability	WS @ 4 mMSL	WD @ 4 mMSL	WS @ 150 mMSL	WD @ 150 mMSL	T @ 4.1 mMSL	RelH @ 4.1 mMSL	P @ 0 mMSL
NSI-1-LB	2023	9	0.9822	0.9808	0.9808	0.9486	0.9486	0.9815	0.9815	0.9810
	2023	10	1.0000	0.9991	0.9991	0.9984	0.9984	0.9996	0.9996	0.9996
	2023	11	1.0000	0.7840	0.7840	0.9963	0.9963	0.9998	0.9998	0.9993
	2023	12	1.0000	0.0000	0.0000	0.9980	0.9980	0.9971	0.9971	0.9989
	2024	1	1.0000	0.0000	0.0000	0.9671	0.9671	0.9982	0.9982	0.9987
	2024	2	1.0000	0.0000	0.0000	0.9195	0.9195	0.9897	0.9897	0.9995
	2024	3	1.0000	0.0000	0.0000	0.9413	0.9413	0.9906	0.9906	0.9989
	2024	4	1.0000	0.1789	0.1789	0.9933	0.9933	0.9940	0.9940	0.1963
	2024	5	1.0000	0.9980	0.9980	0.9944	0.9944	0.9998	0.9998	0.9987
	2024	6	1.0000	0.9998	0.9998	0.9979	0.9979	1.0000	1.0000	0.9991
	2024	7	1.0000	0.9975	0.9975	0.9937	0.9937	0.9975	0.9975	0.9973
	2024	8	1.0000	0.9993	0.9993	0.9951	0.9951	0.9998	0.9998	0.9987
	2024	9	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178
NSI-2-LB	2023	9	0.9868	0.9856	0.9856	0.9616	0.9616	0.9863	0.9863	0.9863
	2023	10	1.0000	0.9993	0.9993	0.9973	0.9973	0.9998	0.9998	0.9998
	2023	11	1.0000	0.9993	0.9993	0.9942	0.9940	0.9998	0.9998	0.9998
	2023	12	1.0000	0.9996	0.9996	0.9944	0.9944	1.0000	1.0000	1.0000
	2024	1	1.0000	0.9561	0.9561	0.9001	0.9001	0.9991	0.9991	1.0000
	2024	2	1.0000	0.9856	0.9856	0.8932	0.5989	0.9940	0.9940	0.9986
	2024	3	1.0000	0.9996	0.9996	0.9397	0.1570	0.9993	0.9993	0.9982
	2024	4	1.0000	0.9993	0.9993	0.9907	0.0009	0.9977	0.9977	0.9998
	2024	5	1.0000	0.9962	0.9962	0.9922	0.7339	0.8533	0.8537	0.9955
	2024	6	1.0000	0.9991	0.9991	0.9949	0.9949	0.2988	0.2988	0.9993
	2024	7	1.0000	0.9964	0.9964	0.9863	0.9863	0.6503	0.6521	0.9964
	2024	8	1.0000	0.9987	0.9987	0.9957	0.9957	0.8277	0.8817	0.9982
	2024	9	0.0132	0.0132	0.0132	0.0132	0.0132	0.0044	0.0044	0.0132
NSI-3-LB	2023	9	0.9903	0.9896	0.9896	0.9609	0.9609	0.9903	0.9903	0.9903
	2023	10	1.0000	0.9991	0.9991	0.9960	0.9960	0.9996	0.9996	0.9993
	2023	11	1.0000	0.9995	0.9995	0.9972	0.9972	1.0000	1.0000	0.9998
	2023	12	1.0000	0.9993	0.9993	0.9910	0.9910	1.0000	1.0000	1.0000
	2024	1	1.0000	0.9996	0.9996	0.9630	0.9630	0.9978	0.9978	1.0000
	2024	2	1.0000	0.9995	0.9995	0.9143	0.9143	0.9947	0.9947	0.9993
	2024	3	1.0000	0.9996	0.9996	0.9559	0.9559	0.9993	0.9993	1.0000
	2024	4	1.0000	0.9993	0.9993	0.9931	0.9931	0.9986	0.9986	0.9998
	2024	5	1.0000	0.9996	0.9996	0.9931	0.9931	1.0000	1.0000	0.9987
	2024	6	1.0000	0.9995	0.9995	0.9961	0.9961	1.0000	1.0000	1.0000
	2024	7	1.0000	0.9996	0.9996	0.9953	0.9953	1.0000	1.0000	0.9982
	2024	8	1.0000	0.5809	0.5809	0.9960	0.9960	1.0000	1.0000	0.9996
	2024	9	0.0097	0.0000	0.0000	0.0097	0.0097	0.0097	0.0097	0.0097

Table B-4: Monthly data availability of wind speed and wind direction at 4 and 150 mMSL, as well as surface level air temperature, relative humidity and air pressure for the three FLSs. The data availability cells are colour coded, light green cells indicate data availability between 0.75 and 1, light yellow cells mean data availability is between 0.5 and 0.75, while light orange cells highlight data availability between 0 and 0.5.

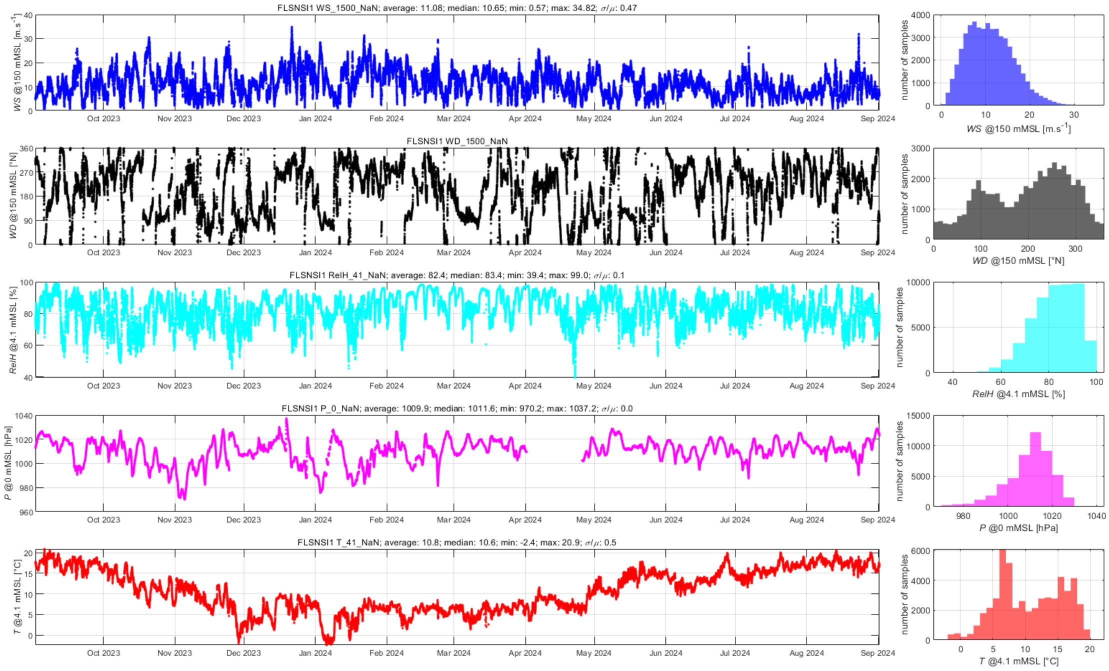

Figure B-2: Time series of wind speed and wind direction at 150 mMSL, as well as surface level air temperature, relative humidity and air pressure collected at NSI-1-LB.

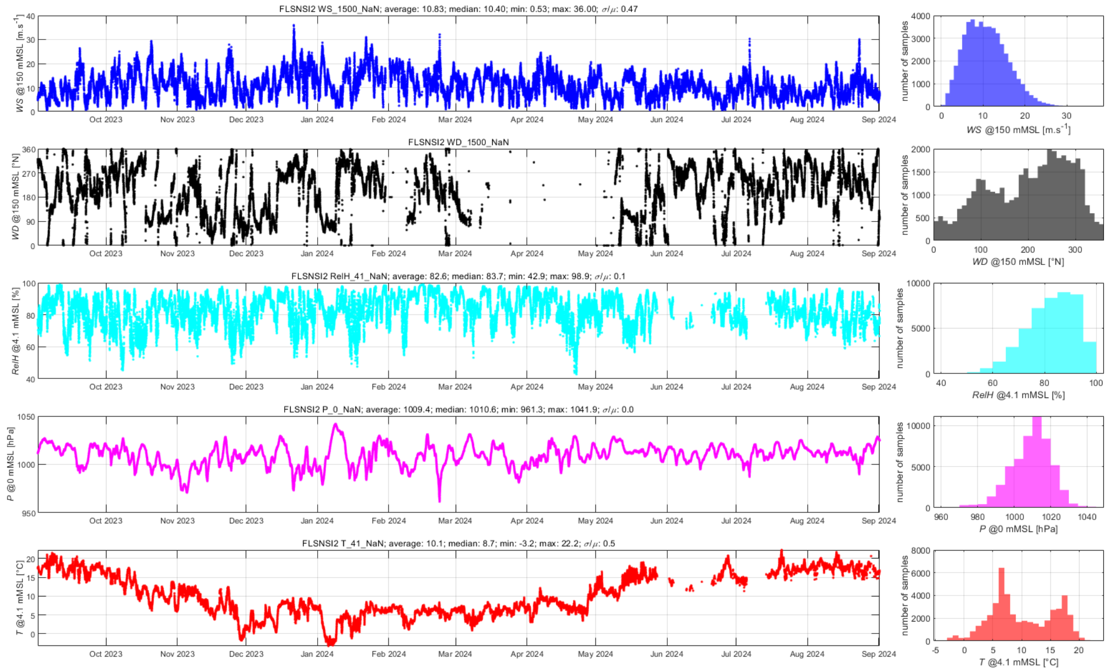

Figure B-3: Time series of wind speed and wind direction at 150 mMSL, as well as surface level air temperature, relative humidity and air pressure collected at NSI-2-LB.

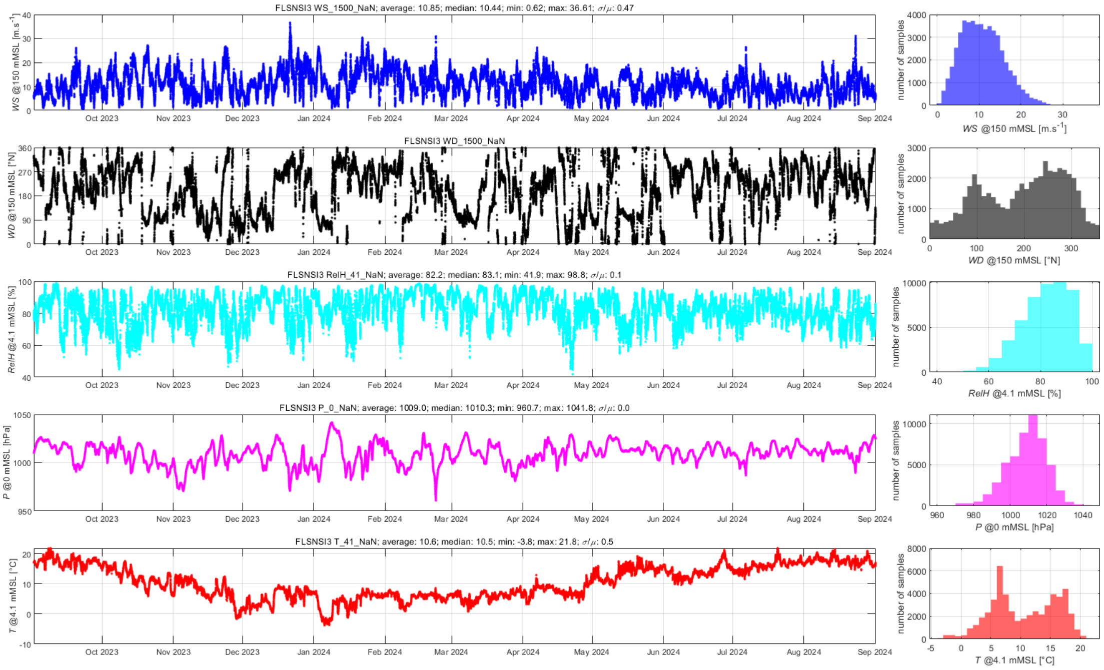

Figure B-4: Time series of wind speed and wind direction at 150 mMSL, as well as surface level air temperature, relative humidity and air pressure collected at NSI-3-LB.

NSI-1-LB		
Elevation	Availability [-]	
[mMSL]	WS	WD
12	0.9904	0.9904
40	0.9965	0.9965
80	0.9850	0.9850
100	0.9799	0.9799
130	0.9764	0.9764
150	0.9739	0.9739
170	0.9723	0.9723
190	0.9707	0.9707
220	0.9678	0.9678
260	0.9606	0.9606
300	0.9554	0.9554

NSI-2-LB		
Elevation	Availability [-]	
[mMSL]	WS	WD
12	0.9718	0.7790
40	0.9887	0.7908
80	0.9758	0.7829
100	0.9709	0.7785
130	0.9669	0.7751
150	0.9653	0.7739
170	0.9635	0.7726
190	0.9612	0.7704
220	0.9578	0.7681
260	0.9512	0.7628
300	0.9481	0.7611

NSI-3-LB		
Elevation	Availability [-]	
[mMSL]	WS	WD
12	0.9798	0.9798
40	0.9970	0.9970
80	0.9840	0.9840
100	0.9797	0.9797
130	0.9757	0.9757
150	0.9732	0.9732
170	0.9711	0.9711
190	0.9681	0.9681
220	0.9643	0.9643
260	0.9584	0.9584
300	0.9547	0.9547

Table B-5: Data availability of the LiDAR measurements collected by the three FLSs at North Sea I.

B.1.4 Data reliability and validity

[There are no changes in this section]

B.2 Energy Island FLS measurement campaign

[There are no changes in this section]

B.2.1 Instrumentation setup
[There are no changes in this section]

B.2.2 Data description
[There are no changes in this section]

B.2.3 Data availability
[There are no changes in this section]

B.2.4 Data reliability and validity
[There are no changes in this section]

Appendix C. Turbulence Intensity Conditions

[There are no changes in this section]

C.1 Note on measurement datasets

[There are no changes in this section]

C.2 Introduction

[There are no changes in this section]

C.3 Turbulence Intensity Modelling

[There are no changes in this section]

C.4 Application to North Sea I

[There are no changes in this section]