Energy Island North Sea

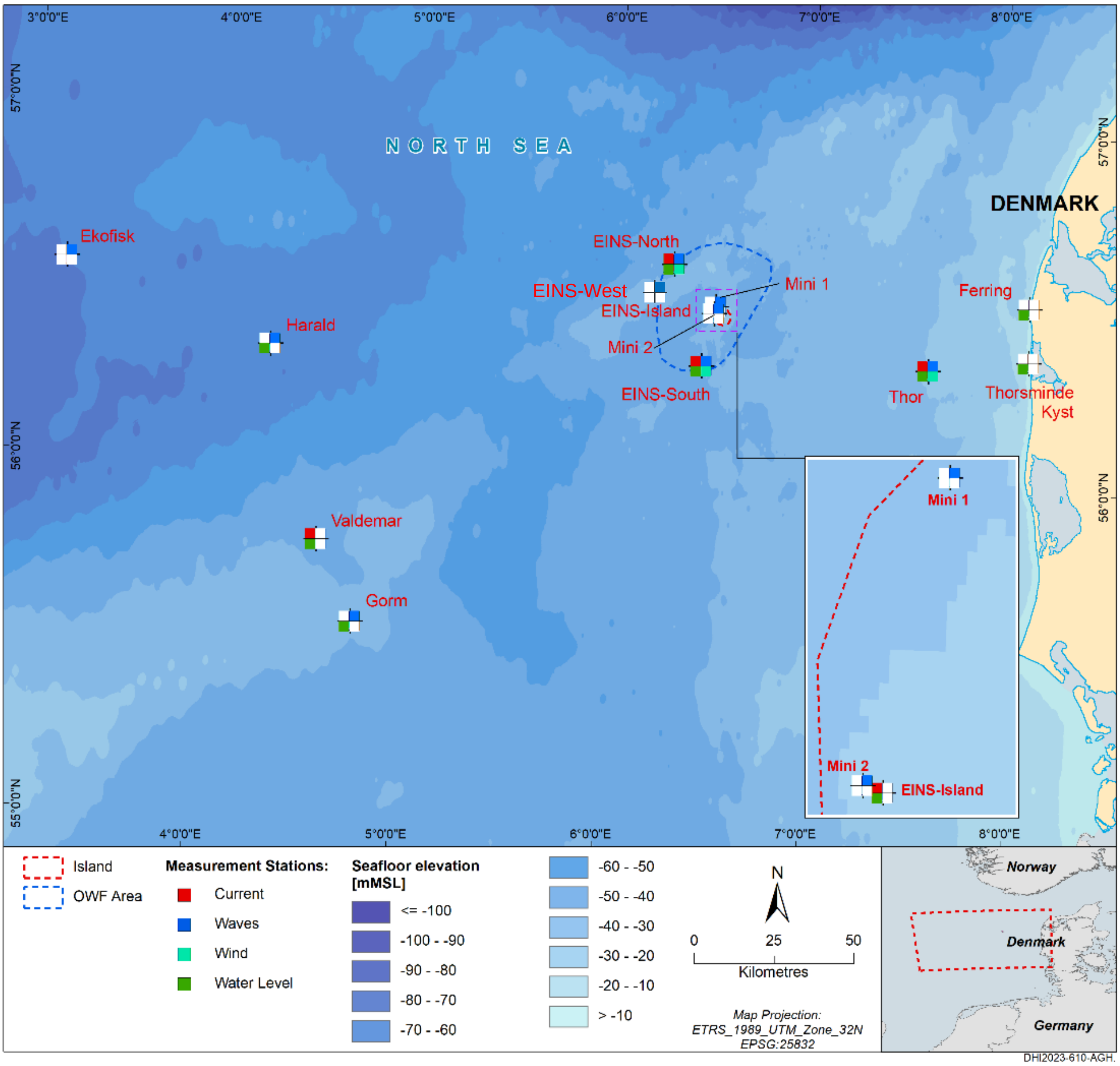
Metocean Assessment

Part D: Data Basis - Reverification

Report
IO Number: 4500087261

2024-09-19

Prepared for Energinet Eltransmission A/S



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Prepared for:	Energinet Eltransmission A/S
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Contents

Nomenclature

Variable	Abbrev.	Unit
Atmosphere		
Wind speed @ 10 m height	WS_{10}	m/s
Wind direction @ 10 m height	WD_{10}	°N (clockwise from)
Air pressure @ mean sea level	P_{MSL}	hPa
Air temperature @ 2 m height	$T_{air,2m}$	°C
Relative humidity @ 2 m height	RH_{2m}	-
Downward solar radiation flux	SR	W/m^2
Ocean		
Water level	WL	mMSL
Current speed	CS	m/s
Current direction	CD	°N (clockwise to)
Water temperature	T_{water}	°C
Water Salinity	Salinity	-
Water density	ρ_{water}	Kg/m^3
Waves		
Significant wave height	H_{m0}	m
Peak wave period	T_p	s
Mean wave period	T_{01}	s
Zero-crossing wave period	T_{02}	s
Energy wave period	T_{m10}	s
Peak wave direction	PWD	°N (clockwise from)
Mean wave direction	MWD	°N (clockwise from)
Direction standard deviation	DSD	°

Definitions	
Coordinate System	WGS84 EPSG 4326 (unless specified differently)
Direction	Clockwise from North Wind: °N coming from Current: °N going to Waves: °N coming from
Time	Times are relative to UTC
Vertical Datum	MSL (unless specified differently)

Abbreviations	
2D	2-dimensional
3D	3-dimensional
ADCP	Acoustic Doppler Current Profiler
AME	Mean Absolute difference
CC	Cross-Correlation
CFSR	Climate Forecast System Reanalysis
DEA	Danish Energy Agency
DNV	Det Norske Veritas
DNVGL	Det Norske Veritas Germanischer Lloyd
EINS	Energy Island North Sea
EV	Explained variance
FEED	Front-End Engineering Design
HD	Hydrodynamic
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
mMSL	Metres above Mean Sea Level
MSL	Mean Sea Level
OWF	Offshore Wind Farm
PR	Peak to Peak Ratio
PSU	Practical Salinity Unit
QQ	Quantile-quantile
RMSE	Root-mean-square difference
SI	Scatter Index
SW	Spectral Wave
UTC	Coordinated Universal Time
WGS84	World Geodetic System 1984

Executive Summary

Energinet Eltransmission A/S (Energinet) requested from DHI A/S (DHI) a metocean site conditions assessment to form part of the site conditions assessment and to serve as basis for the design of the Energy Island North Sea (EINS) artificial island and surrounding offshore wind farms.

The study provides detailed metocean conditions for EINS and establishes a metocean database for the artificial island and the surrounding offshore wind farm (OWF) development areas as shown in Figure 0.1.

This **reverification note** concerns measurements conducted after the issuance of the Part A (Data Basis) report, [1]. The purpose is to revalidate the hindcast models established in Part A and to assess if this will change the design conditions presented in Part B, [2]¸ and/or Part C, [3]. The Part A, B, and C reports are certified, [4], [5], [6], as are the metocean measurements, [7].

In conclusion, the revalidation of all assessed parameters (wind, water level, current, waves, water temperature and salinity) does not lead to any change in the conclusions made in Part A, nor to any of the design conditions presented in Part B or Part C.

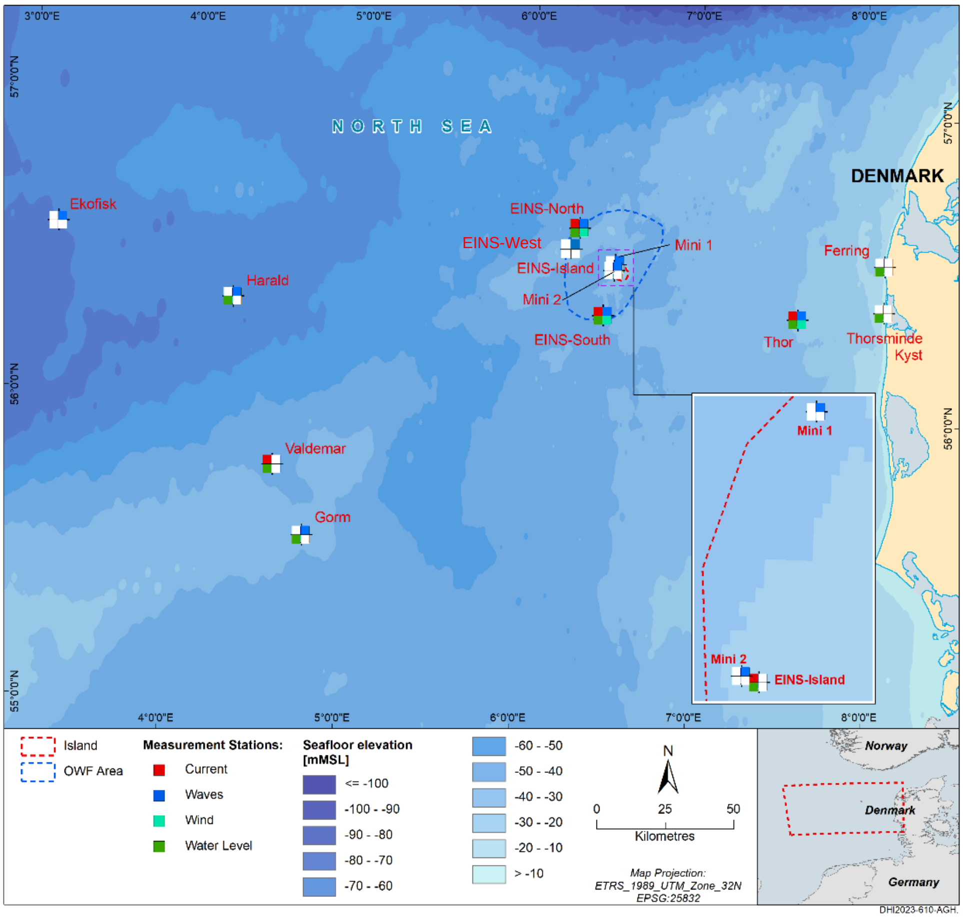

Figure 0.1 Location of the Energy Island North Sea, the related offshore wind farm development area, and measurement stations

The hindcast database (covering OWF area) entails: Waves: *EINS-SW-CFSR*, Ocean: *EINS-SW-CFSR*, Atmosphere: *Global-AT-CFSR*.

1 Introduction

This study provides detailed metocean conditions for the Energy Island North Sea (EINS) and establishes a metocean database for the island and the adjacent offshore wind farm (OWF) development area (see Figure 1.1).

Energinet Eltransmission A/S (Energinet) was instructed by the Danish Energy Agency (DEA) to initiate site investigations, including a metocean conditions assessment, to form part of the site conditions assessment and to serve as basis for the design and construction of EINS and related OWFs. The study includes an assessment of climate changes considering an 80-year lifetime.

Energinet commissioned DHI A/S (DHI) to provide this study with Scope of Work (SoW) defined in [8]. Later, the work was extended to cover also FEED level metocean conditions for the offshore wind farm area cf. scope in [9]. The study refers to the following common practices and guidelines:

- DNV-RP-C205 [10]
- IEC 61400-3-1 [11]

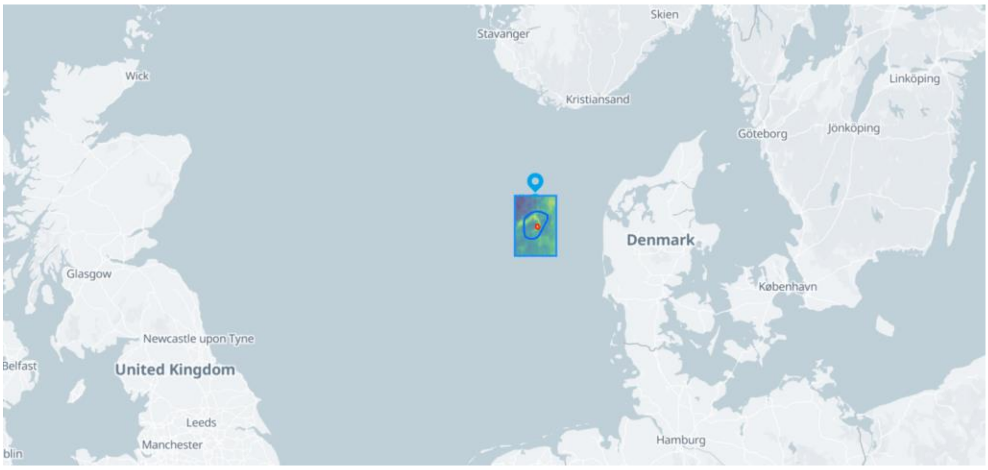

Figure 1.1 The location of the Energy Island North Sea (red), and related offshore wind farm development area (dark blue)
The hindcast database (light blue polygon) entails: Waves: *EINS-SW-CFSR*, Ocean: *EINS-SW-CFSR*, Atmosphere: *Global-AT-CFSR*.

The deliverables included time series data of hindcast metocean parameters, analyses of normal, extreme and joint metocean conditions at five (5) locations, a metocean database (see Figure 1.1), and four (4) separate reports:

- **Part A: Data Basis – Measurements and models,** [1] **(certified** [4]**)**
  Establishment of bathymetry, measurements and hindcast metocean data.

- **Part B: Data Analyses – Energy Island,** [2] **(certified** [5]**)**
  Metocean site conditions for detailed design of the energy island.

- **Part C: Data Analyses – Wind Farm Area,** [3] **certified** [6]
  FEED level metocean site conditions for the offshore wind farm area.

- **Part D: Data Basis – Reverification, (this note)**
  Revalidation of the hindcast metocean models against additional measurements.

2 Additional Measurements

This section describes the temporal coverage of the original and the additional measurements surveyed by Fugro at EINS [12] [13] and provided to DHI for revalidation of previous parts of the project by DHI.

Figure 2.1 to Figure 2.5 present the temporal coverage of the data used in Part A (2020-2022), [1], and the data received for revalidation (2022-2024), for wind, water level, current, waves, water temperature and salinity.

For waves, measurements were also received from a new buoy, 'EINS-West (Mini 3)', not previously considered. Notice that at the end of the campaign, neither the EINS-South (CP seabed) nor the EINS-South (CTD) string were found as described in [13].

Table 2.1 to Table 2.5 present details about the measurements. The following sections present validations for the new, the original, and the full period.

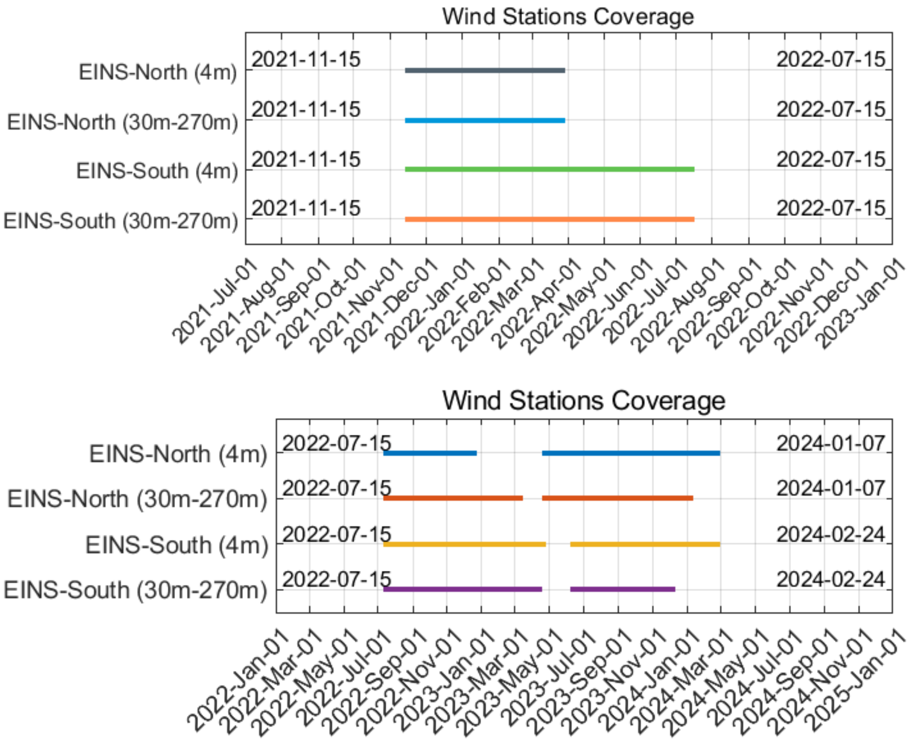

Figure 2.1 Temporal coverage period of wind measurements
Top: Original period. Bottom: New period.

Table 2.1 Details of wind measurements

Station Name	Longitude [°E]	Latitude [°N]	Measurement Height [mMSL]	Data coverage (new period)	Data coverage (full period)	Instrument	Owner / Surveyor
EINS-North	6.3007	56.6280	4 (Anemometer) 30, 40, 60, 90, 100, 120, 150, 180, 200, 240, 270 (LiDAR)	2022/11/15 – 2024/01/07	2021/11/15 – 2024/01/07	Anemometer: Gill Windsonic M LiDAR: ZephIR ZX300	Energinet / Fugro
EINS-South	6.4574	56.3444	4 (Anemometer) 30, 40, 60, 90, 100, 120, 150, 180, 200, 240, 270 (LiDAR)	2022/11/15 – 2024/02/07	2021/11/15 – 2024/02/24	Anemometer: Gill Windsonic M LiDAR: ZephIR ZX300	Energinet / Fugro

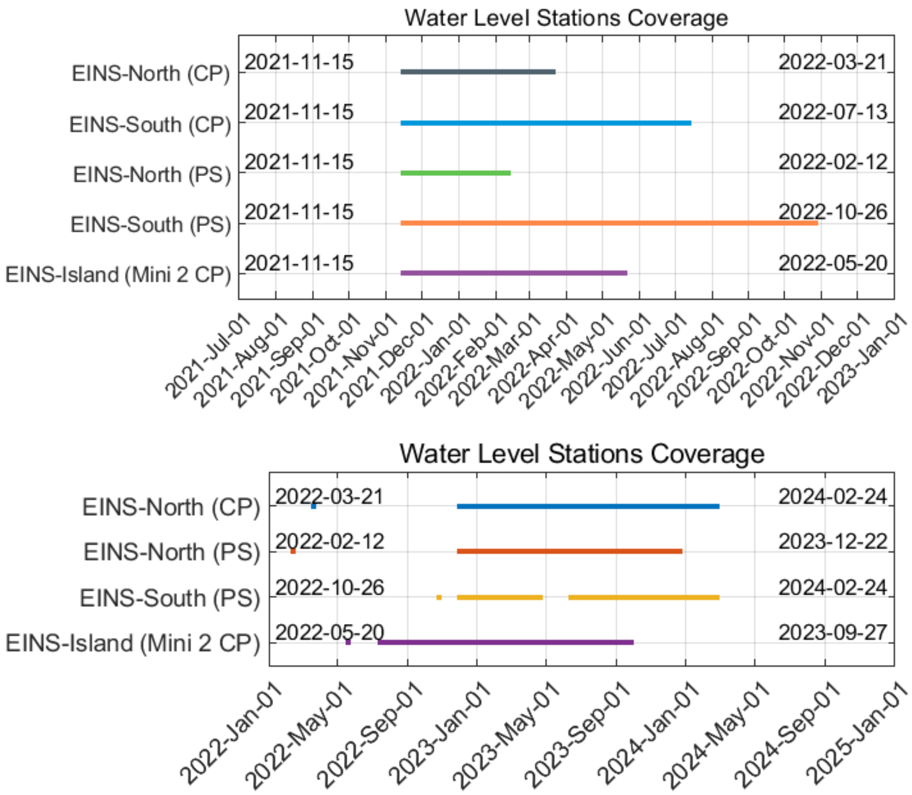

Figure 2.2 Temporal coverage of water level measurements
Top: Original period. Bottom: New period.

Table 2.2 Details of water level measurements

Station Name	Longitude [°E]	Latitude [°N]	Depth [mMSL]	Data coverage (new period)	Data coverage (full period)	Instrument	Owner / Surveyor
EINS-North (CP)	6.3008	56.6272	46.5	2021/11/22 – 2023/11/22	2021/11/22 – 2023/11/22	Nortek Signature 500 current profiler	Energinet / Fugro
EINS-North (PS)	6.3007	56.628	46.5	2022/03/21 - 2024/02/24	2022/03/21 - 2024/02/24	Thelma Biotel TBR700 pressure sensor	Energinet / Fugro
EINS-South (PS)	6,4574	56,3444	39,8	2022/02/12 - 2023-12/22	2022/02/12 - 2023-12/22	Thelma Biotel TBR700 pressure sensor	Energinet / Fugro
EINS-Island (Mini 2 CP)	6.5130	56.4925	28.9	2022/10/26 - 2024/02/24	2022/10/26 - 2024/02/24	Nortek Signature 500 current profiler	Energinet / Fugro

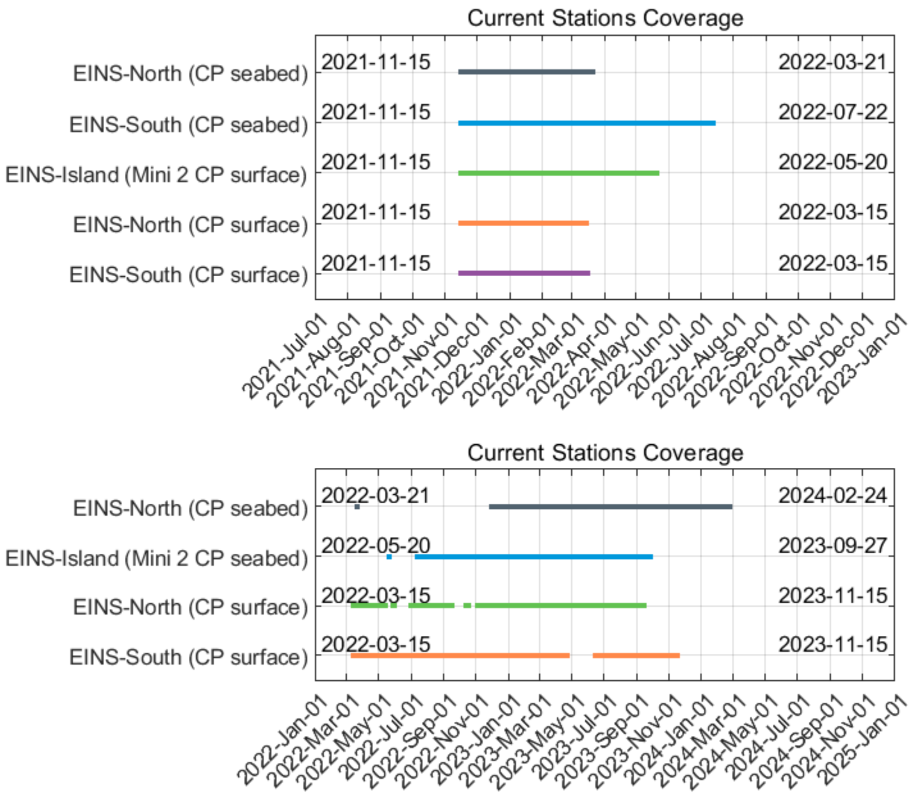

Figure 2.3 Temporal coverage of current measurements
Top: Original period. Bottom: New period.

Table 2.3 Details of current measurements

Station Name	Longitude [°E]	Latitude [°N]	Depth [mMSL]	Data coverage (new period)	Data coverage (full period)	Levels	Instrument	Owner / Surveyor
EINS-North (CP seabed)	6.3008	56.6272	46.0	2022/03/21 – 2024/02/27	2021/11/15 – 2024/02/27	1 m intervals in range 4 m to 40 mAS[1]	Nortek Signature 500 current profiler	Energinet / Fugro
EINS-Island (Mini 2 CP seabed)	6.5130	56.4925	28.0	2022/05/20 – 2023/09/27	2021/11/15-2023/09/27	1 m intervals in range 4 m to 24 mAS[1]	Nortek Signature 500	Energinet / Fugro
EINS-North (CP surface)[3]	6.3007	56.6280	46.4	2022/03/15 – 2023/11/15	2021/11/15 – 2023/11/15	1 m intervals in range 2 m to 41 mBS[2]	Nortek Aquadopp 600	Energinet / Fugro
EINS-South (CP surface)[3]	6.4574	56.3444	39.8	2022/03/15 – 2023/11/15	2021/11/15 – 2023/11/15	1 m intervals in range 2 m to 38 mBS[2]	Nortek Aquadopp 600	Energinet / Fugro

[1] mAS: meters above seabed.

[2] mBS: meters below surface.

[3] Current direction data was discarded for the whole period due to irregularities.

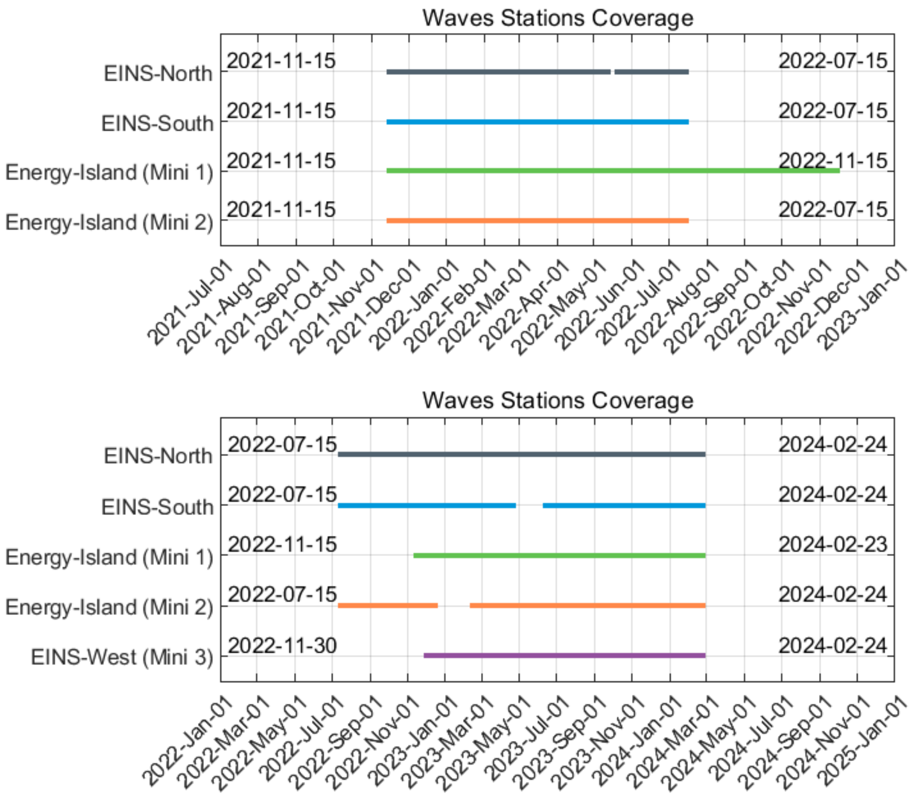

Figure 2.4 Temporal coverage of wave measurements
Top: Original period. Bottom: New period.

Table 2.4 Details of wave measurements

Station Name	Longitude [°E]	Latitude [°N]	Depth [mMSL]	Data coverage (new period)	Data coverage (full period)	Instrument	Owner / Surveyor
EINS-North	6.3007	56.628	46.4	2022/07/15 - 2024/02/24	2021/11/15 - 2024/02/24	Wavesense 3	Energinet / Fugro
EINS-South	6.4574	56.3444	39.8	2022/07/15 - 2024/02/24	2021/11/15 - 2024/02/24	Wavesense 3	Energinet / Fugro
EINS-Island (Mini 1)	6.519	56.5114	27.0	2022/11/15 - 2024/02/23	2021/11/15 - 2024/02/23	Wavesense 3	Energinet / Fugro
EINS-Island (Mini 2)	6.5108	56.4929	28.7	2022/07/15 - 2024/02/24	2021/11/15 - 2024/02/24	Wavesense 3	Energinet / Fugro
EINS-West (Mini 3)	6.4337	56.5020	45.0	2022/11/30 - 2024/02/24	2022/11/30 - 2024/02/24	Wavesense 3	Energinet / Fugro

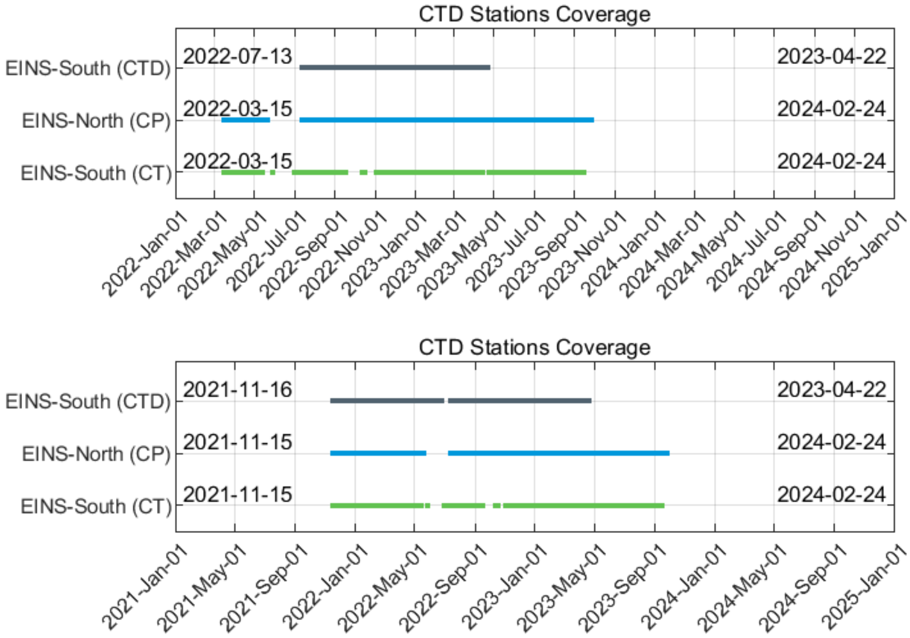

Figure 2.5 Temporal coverage of temperature and salinity measurements
Top: Original period. Bottom: New period.

Table 2.5 Details of temperature and salinity measurements

Station Name	Longitude [°E]	Latitude [°N]	Depth [mMSL]	Data coverage (new period)	Data coverage (full period)	Levels	Instrument	Owner / Surveyor
EINS-South (CTD)	6.4552	56.3449	40.0	2022/07/13 – 2023/04/22	2021/11/16 – 2023/04/22	Temperature and salinity at 10 m, 19 m 28 m and 34 m	Seabird STB CTD	Energinet / Fugro
EINS-North (CP)	6.3007	56.6280	46.4	2022/03/15 – 2024/02/24	2021/11/15 – 2024/02/24	Surface temperature	Nortek Aquadopp 600	Energinet / Fugro
EINS-South (CT)	6.4574	56.3444	39.8	2022/03/15 – 2024/02/24	2021/11/15 – 2024/02/24	Surface temperature and salinity	Seabird CT	Energinet / Fugro

2.1 Post-processing and quality control

Fugro follows the international standard recommendations ISO-19901-1:2015 for the collection and supply of oceanographic data, to verify the proper functioning of the measuring and recording systems and for data quality control procedures as stated in [12], [13]. The general data flow, post-processing and quality control applied by Fugro before the data is delivered to the client are described in the measurement plan [14].

However, DHI noticed minor differences between the original data set and the revised data set that followed with the additional measurements. Furthermore, DHI has applied in-house post-processing routines to remove (a few) outliers and spurious data.

3 Wind Revalidation

This section presents a revalidation of the hindcast CFSR wind data (see Section 3.3 of [1]) versus the measured wind speed and direction. For this revalidation, the CFSR data period was extended to February 24, 2024 (end of measurements).

Figure 3.1 to Figure 3.2 present comparisons in terms of time series, scatter plots, and wind roses of wind speed during the new, the original, and the full period of measurements, while Table 3.1 provides the validation statistics of the new and the full periods of measurements.

The validation during the new period is consistent with the validation during the original period, regarding both magnitude and direction. Hence, in conclusion, the CFSR wind has a high correlation with local measurements and no adjustment of the wind-related sections in Part A, B, and C is needed.

Table 3.1 Statistics of wind validation – new period & full period

Name	N	Mean [m/s]	Bias [m/s]	MAE [m/s]	RMSE [m/s]	SI	EV	CC	PR
EINS-North (new period)	11,595	8.84	0.01	0.98	1.34	0.15	0.90	0.95	1.05
EINS-North (full period)	16,381	9.00	0.04	0.98	1.34	0.15	0.89	0.95	1.05
EINS-South (new period)	10,119	8.76	0.09	0.96	1.30	0.15	0.90	0.95	1.05
EINS-South (full period)	15,927	8.83	0.11	0.95	1.27	0.15	0.90	0.95	1.05

EINS-North

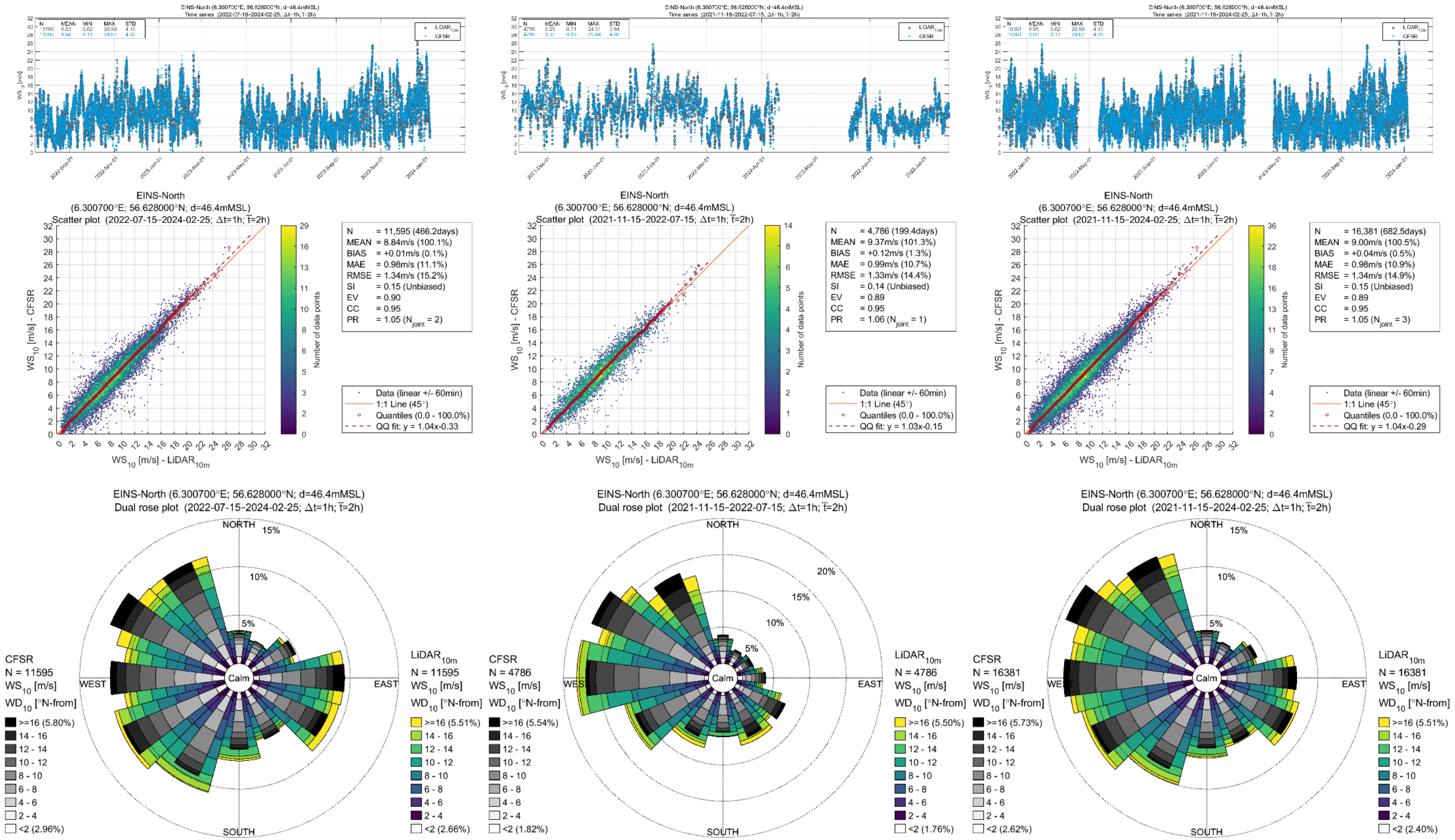

Figure 3.1 Comparison of measured and modelled wind at EINS-North
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

EINS-South

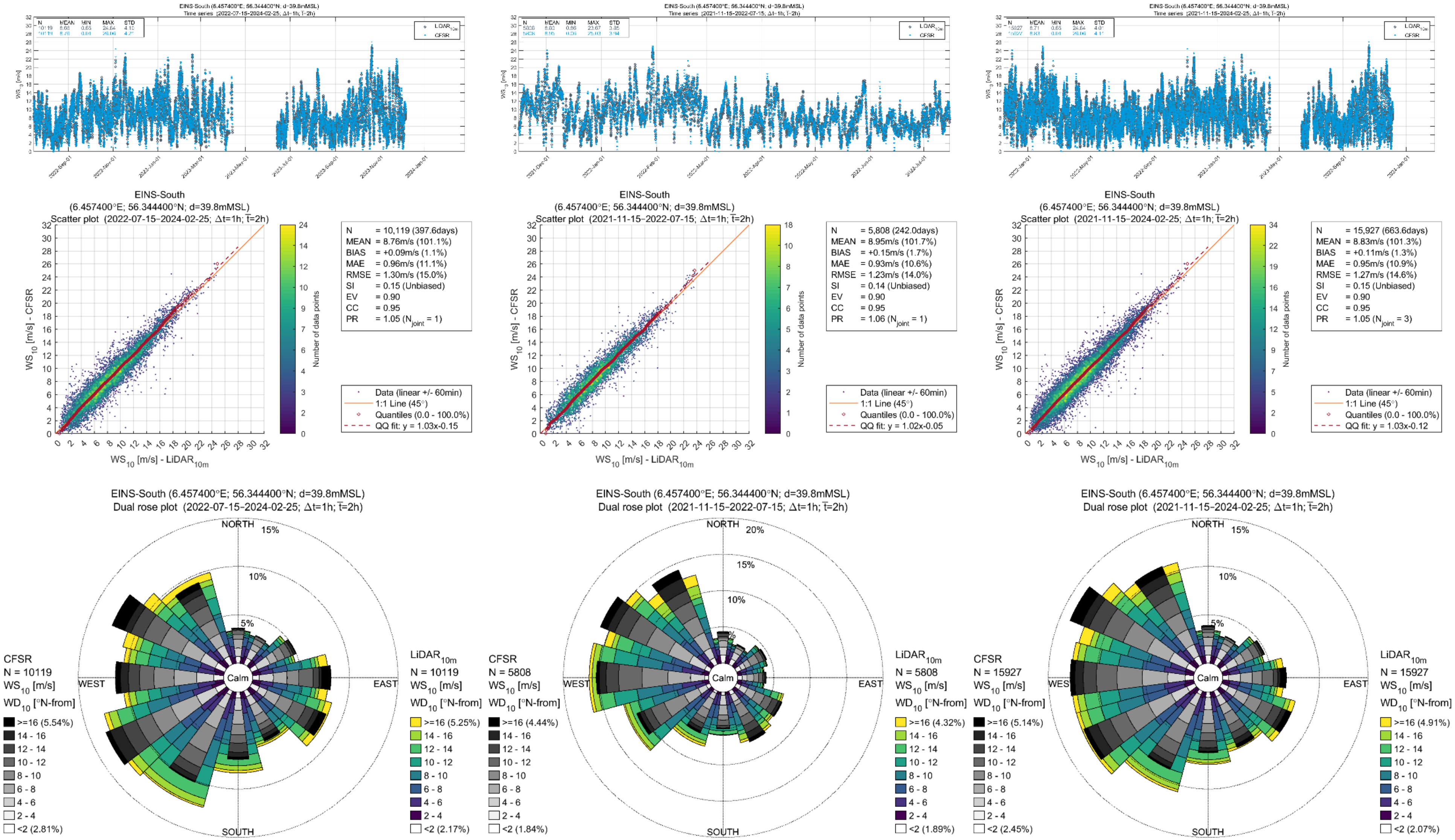

Figure 3.2 **Comparison of measured and modelled wind at EINS-South**
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

4 Water Level Revalidation

This section presents a revalidation of the modelled HD_{EINS} water levels (see Section 4.3 of [1]) versus the measured water levels. For this revalidation, the HD_{EINS} model coverage was extended to December 31, 2023.

Figure 4.1 to Figure 4.4 present comparisons in terms of time series and scatter plots of water levels during the new, the original, and the full period of measurements, while Table 4.1 provides the validation statistics for the new and full periods of measurements.

The validation during the new period is consistent with the validation during the original period, except at EINS-South (PS), where there are several extreme events (e.g., January, and March to May 2024) that are not present in the model. However, these events are not measured at the other stations suggesting uncertainties in the measurement at EINS-South (PS).

Generally, the SI increases and CC decreases slightly for all the stations when including the additional measurements. This is mainly attributed to a period of about 3 weeks during October 2023 (see scatter plots) during which the discrepancies between the measurements and the model are larger than for the rest of the measuring period for no immediate reason.

However, in conclusion, the revalidation affirms a high correlation of water level between the HD_{EINS} model and the local measurements. Therefore, no adjustments are required for the water level sections in Part A, B, and C.

Table 4.1 Statistics of water level validation – new period & full period

Name	N	Mean [m]	Bias [m]	MAE [m]	RMSE [m]	SI	EV	CC	PR
EINS-North (CP) (new period)	18,569	0.00	0.00	0.08	0.11	0.64	0.76	0.89	1.07
EINS-North (CP) (full period)	24,599	0.00	0.00	0.08	0.11	0.56	0.82	0.91	0.96
EINS-North (PS) (new period)	18,072	0.00	0.00	0.10	0.13	0.73	0.67	0.86	0.97
EINS-North (PS) (full period)	22,282	0.00	0.00	0.10	0.13	0.69	0.72	0.88	0.93
EINS-South (PS) (new period)	16,172	-0.00	-0.00	0.17	0.24	0.90	0.54	0.74	0.93
EINS-South (PS) (full period)	32,713	0.00	0.00	0.12	0.18	0.78	0.65	0.81	0.86
EINS-Island (Mini 2 CP) (new period)	21,129	-0.00	-0.01	0.08	0.10	0.57	0.80	0.90	0.87
EINS-South (Mini 2 CP) (full period)	30,057	0.00	-0.00	0.08	0.10	0.53	0.83	0.92	0.78

EINS-North (CP)

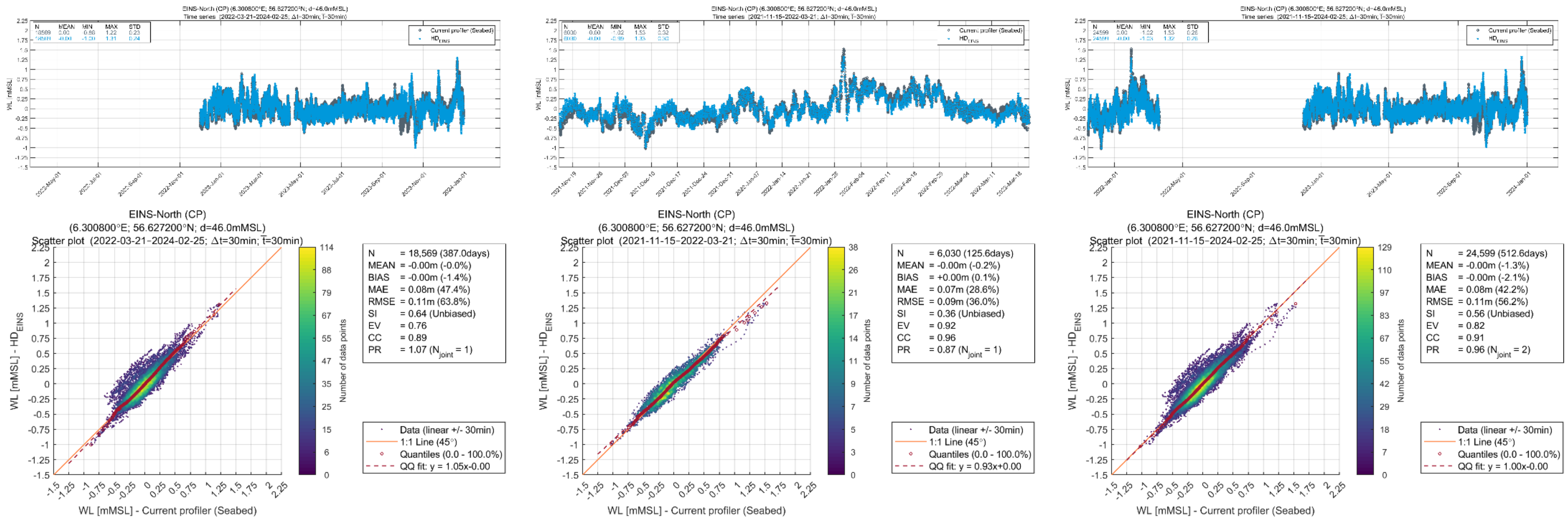

Figure 4.1 Comparison of measured and modelled water level (WL) at EINS-North (CP)
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

EINS-North (PS)

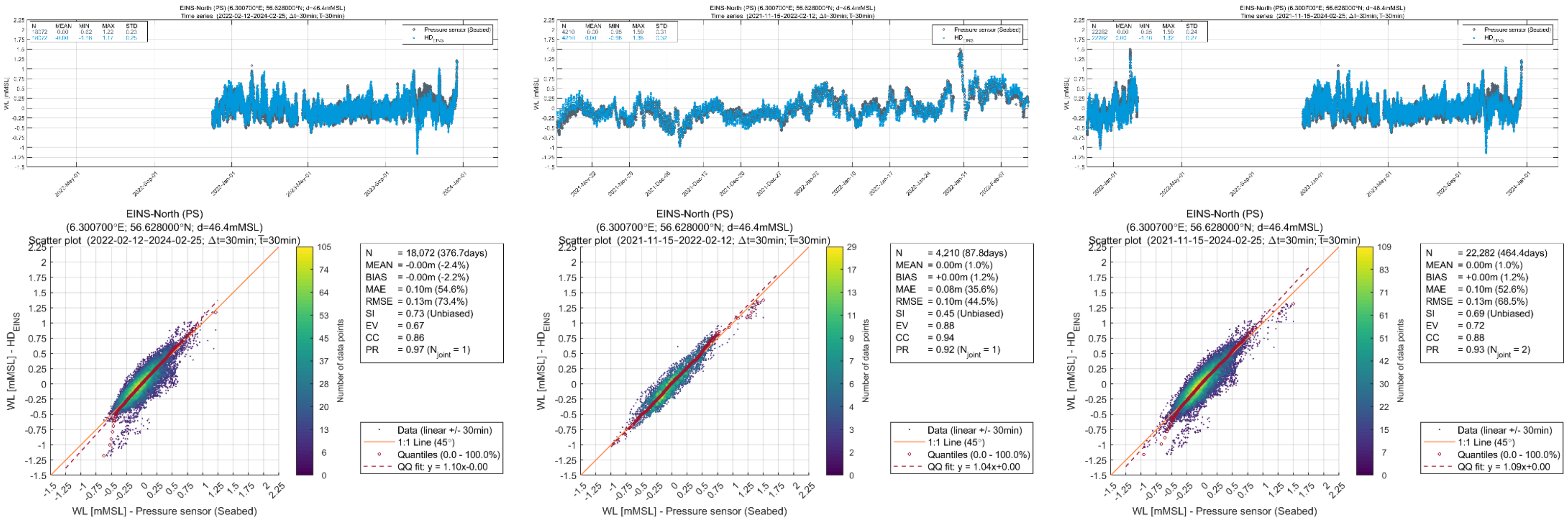

Figure 4.2 Comparison of measured and modelled water level (WL) at EINS-North (PS)
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

EINS-South (PS)

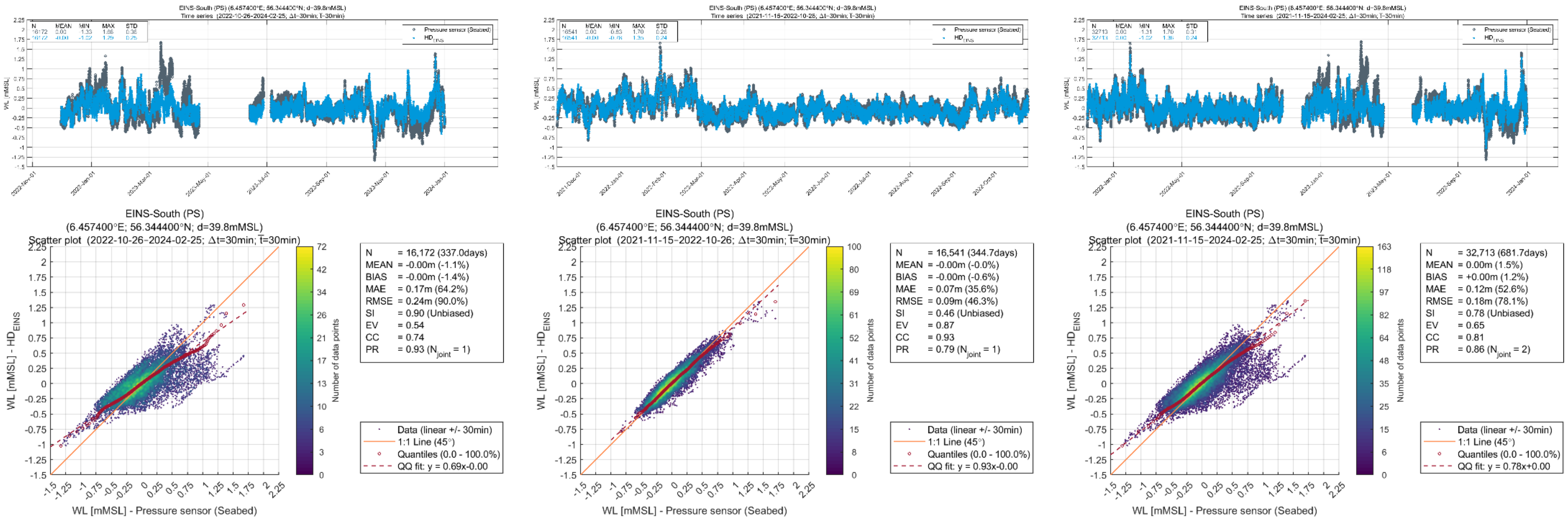

Figure 4.3 Comparison of measured and modelled water level (WL) at EINS-South (PS)
Left: New measurements, Middle: Original measurement, Right: Full period of measurements.

EINS-Island (Mini 2 CP)

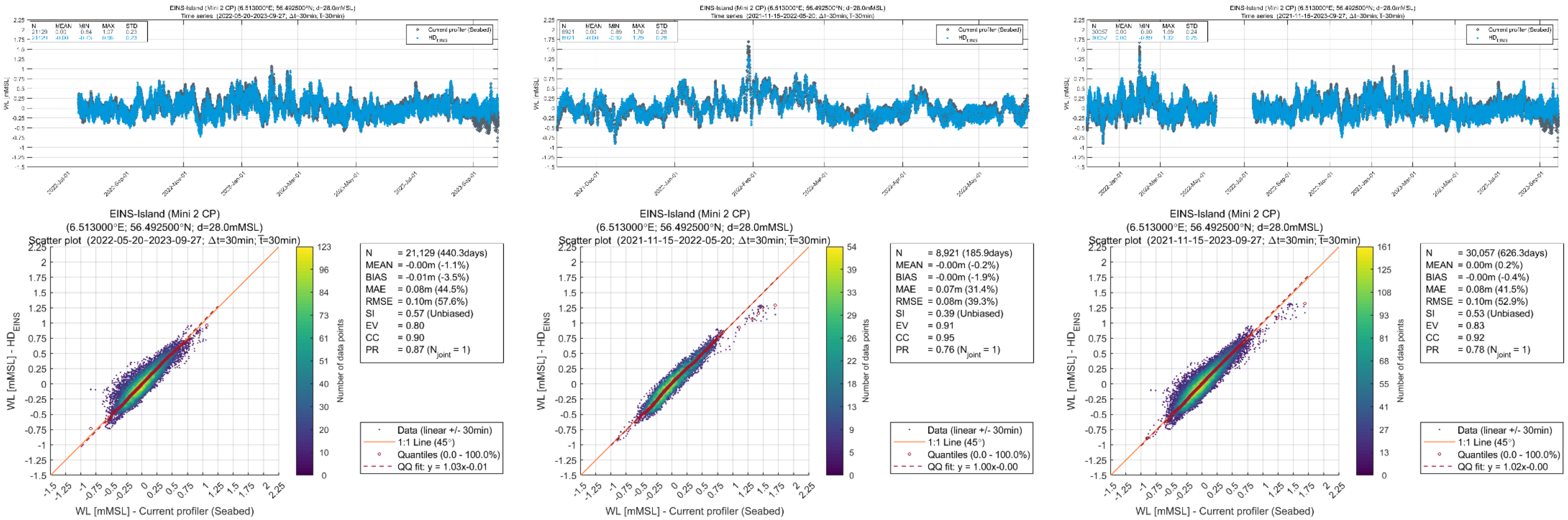

Figure 4.4 Comparison of measured and modelled water level (WL) at EINS-Island (Mini 2 CP)
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

5 Current Revalidation

This section presents a revalidation of the modelled HD_{EINS} (2D) current speed (see Section 5.3 of [1]) versus the measured current speed. For this revalidation, the HD_{EINS} model coverage was extended to December 31, 2023.

Figure 5.1 to Figure 5.4 present comparisons in terms of time series, scatter plots, and current roses of depth-averaged current during the new, the original, and the full period of measurements, while Table 5.1 provides the validation statistics for the new and the full periods of measurements.

The validation during the new period is consistent with the validation during the original period. This affirms a high correlation of current speed between the HD_{EINS} model and local measurements. Therefore, no adjustments are required for the current-related sections in Part A, B, and C.

Table 5.1 Statistics of depth-averaged current speed validation – new period & full period

Name	N	Mean [m/s]	Bias [m/s]	MAE [m/s]	RMSE [m/s]	SI	EV	CC	PR
EINS-North (CP seabed) – (new period)	18,983	0.14	-0.01	0.04	0.05	0.32	0.71	0.86	1.07
EINS-North (CP seabed) – (full period)	24,959	0.15	-0.01	0.04	0.05	0.32	0.71	0.86	1.01
EINS-Island (Mini 2 CP seabed) – (new period)	21,152	0.16	-0.02	0.05	0.07	0.39	0.35	0.69	1.19
EINS-Island (Mini 2 CP seabed) – (full period)	30,080	0.16	-0.01	0.05	0.07	0.38	0.40	0.73	1.12
EINS-North (CP surface) – (new period)	16,260	0.13	-0.03	0.06	0.07	0.41	0.50	0.72	0.77
EINS-North (CP surface) – (full period)	22,020	0.14	-0.03	0.06	0.08	0.41	0.49	0.72	0.77
EINS-South (CP surface) – (new period)	24,920	0.13	-0.02	0.05	0.07	0.43	0.45	0.70	0.90
EINS-South (CP surface) – (full period)	30,680	0.14	-0.02	0.05	0.07	0.43	0.43	0.69	0.90

EINS-North (CP seabed)

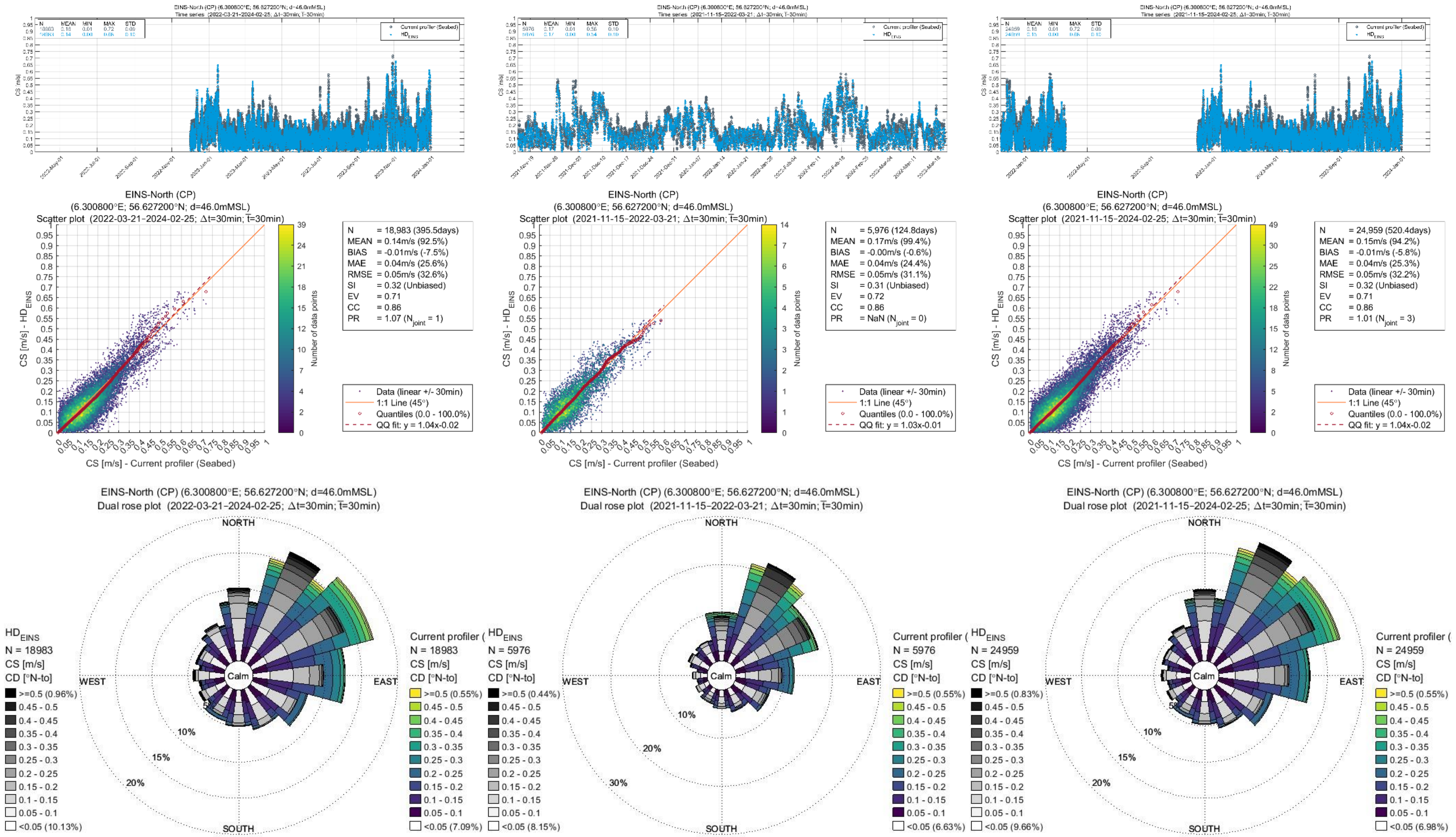

Figure 5.1 **Comparison of measured and modelled depth-averaged total current at EINS-North (CP seabed)**
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

EINS-Island (Mini 2 CP seabed)

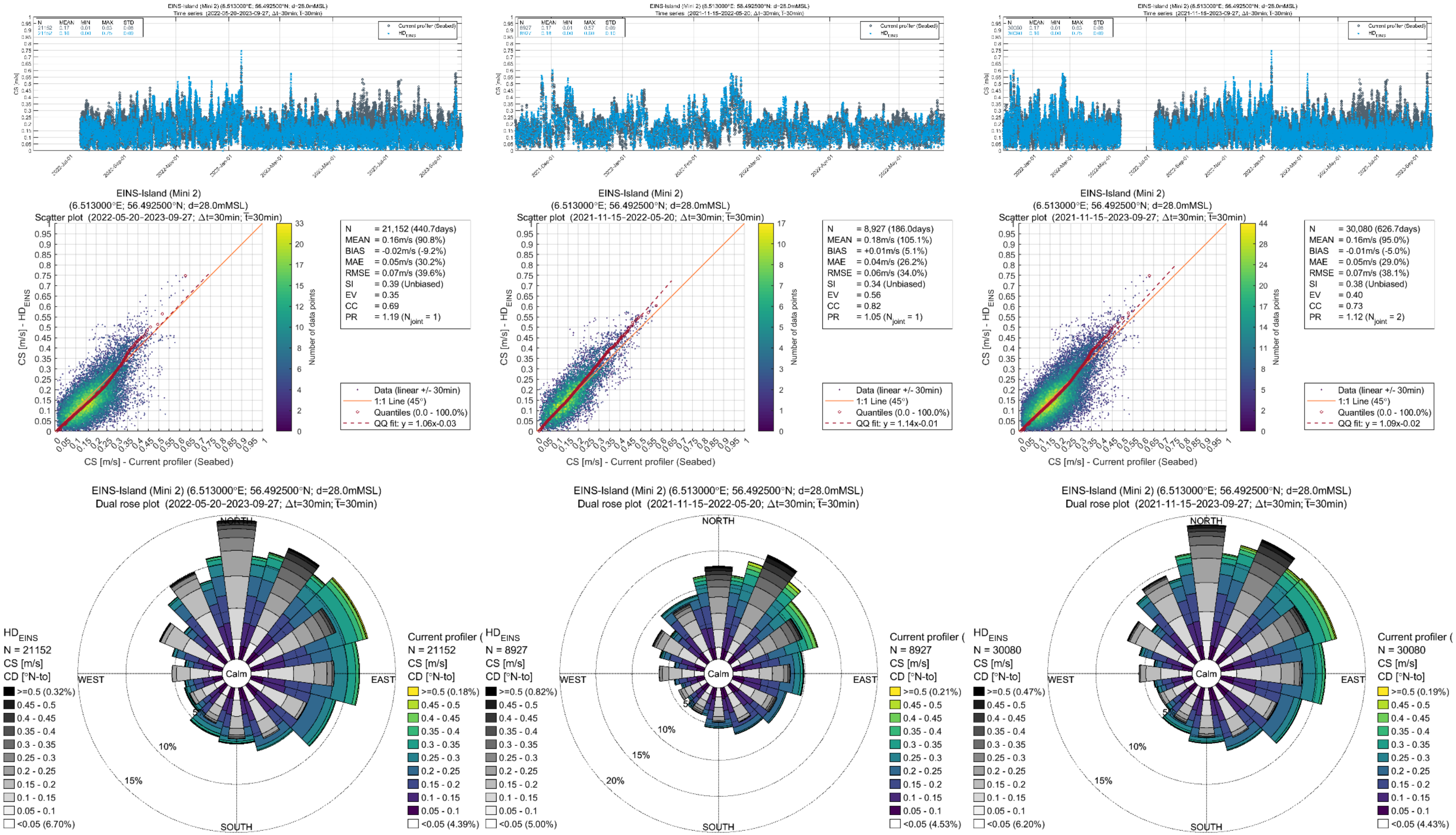

Figure 5.2 Comparison of measured and modelled depth-averaged total current at EINS-Island (Mini 2 CP seabed)
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

EINS-North (CP surface)

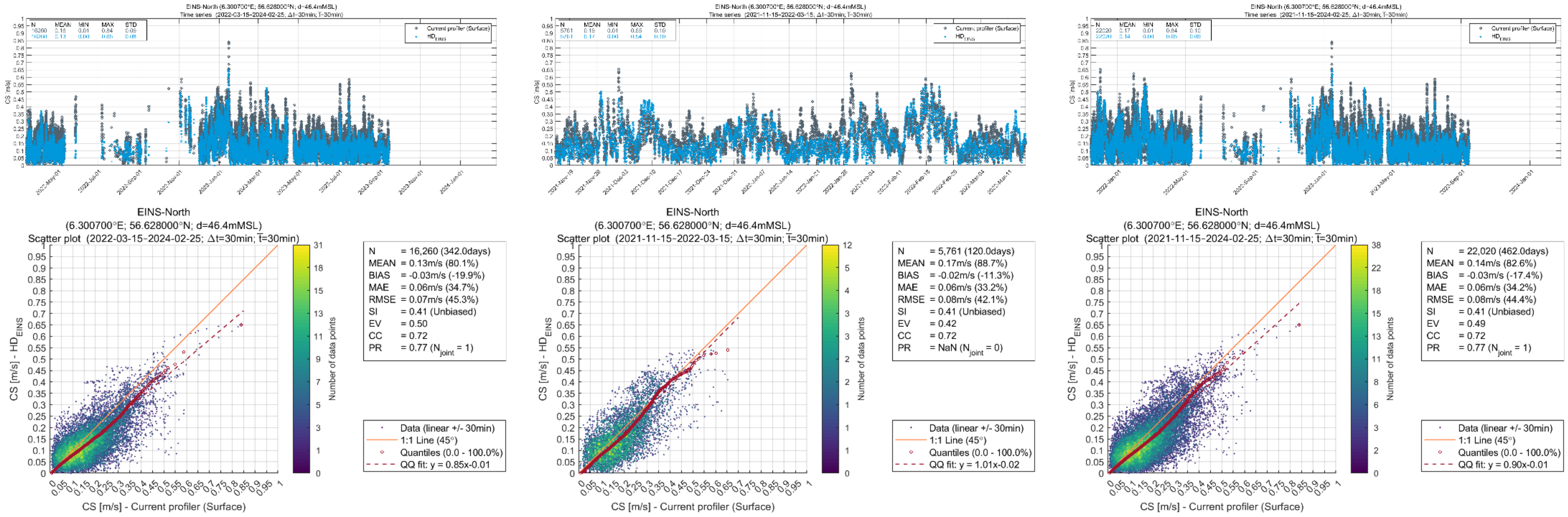

Figure 5.3 Comparison of measured and modelled depth-averaged total current at EINS-North (CP surface)
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

EINS-South (CP surface)

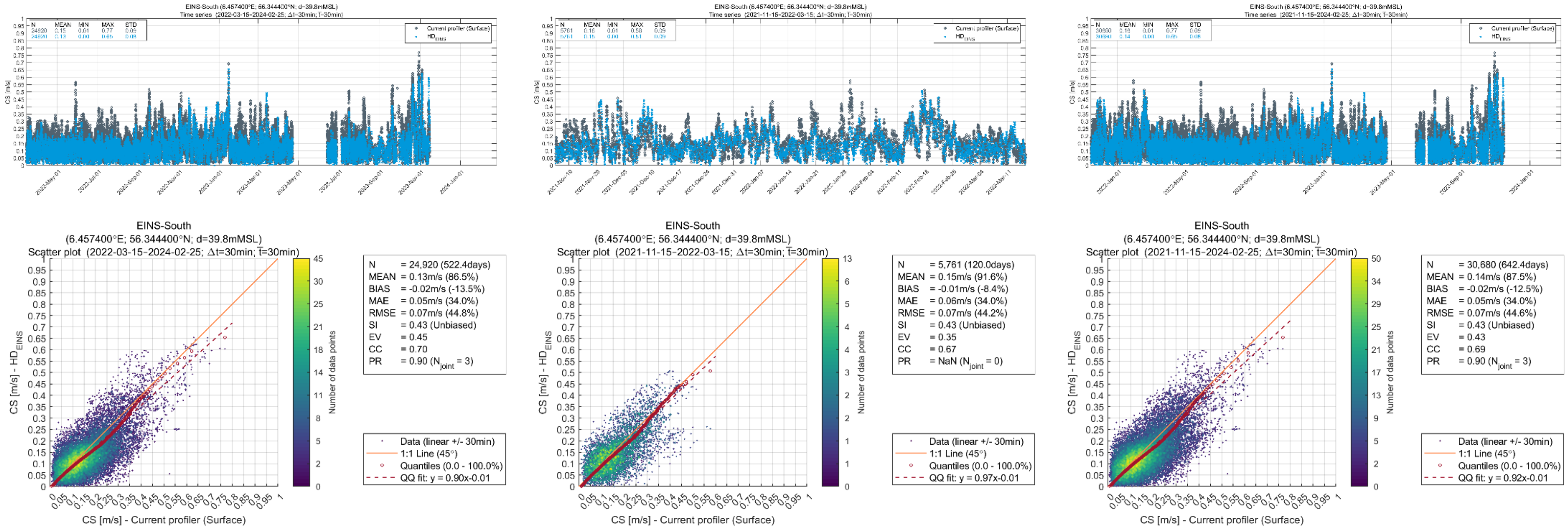

Figure 5.4 Comparison of measured and modelled depth-averaged total current at EINS-South (CP surface)
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

6 Wave Revalidation

This section presents a revalidation of the modelled SW_{EINS} waves (see Section 6.3 of [1]) versus the measured waves. For this revalidation, the SW_{EINS} model coverage was extended to December 31, 2023.

Figure 6.1 to Figure 6.9 present comparisons in terms of time series, scatter plots, and wave roses of wave parameters (H_{m0}, T_p, T_{02}, MWD) during the new, the original, and the full period of measurements, while Table 6.1 provides the validation statistics for the new and the full periods of measurements.

The validation during the new period is consistent with the validation during the original period, regarding both H_{m0}, T_p, T_{02}, and MWD. The validation results for the new dataset from EINS-West (Mini 3) show similar statistics for all variables as for the other existing stations, giving further confidence in the performance of the model. Thus, in conclusion, the SW_{EINS} model agrees well with the local measurements for the new period, and no adjustment is needed for the wave-related sections in Part A, B, and C.

Table 6.1 Statistics of significant wave height validation (H_{m0}) – new period & full period

Name	N	Mean [m]	Bias [m]	MAE [m]	RMSE [m]	SI	EV	CC	PR
EINS-North (new period)	25,227	1.99	0.04	0.17	0.25	0.12	0.96	0.98	1.08
EINS-North (full period)	36,413	2.02	0.05	0.18	0.24	0.12	0.96	0.98	1.04
EINS-South (new period)	22,787	1.98	0.06	0.17	0.25	0.12	0.96	0.98	1.07
EINS-South (full period)	34,403	1.99	0.07	0.17	0.24	0.12	0.96	0.98	1.03
EINS-Island (Mini 1) (new period)	19,692	1.96	0.08	0.19	0.26	0.13	0.95	0.98	1.09
EINS-Island (Mini 1) (full period)	37,212	1.93	0.08	0.18	0.25	0.13	0.95	0.98	1.07
EINS-Island (Mini 2) (new period)	22,685	1.83	0.04	0.16	0.22	0.12	0.96	0.98	0.99
EINS-Island (Mini 2) (full period)	34,297	1.88	0.05	0.16	0.22	0.12	0.96	0.98	0.98
EINS-West (Mini 3) (new period)	9,502	2.00	0.09	0.20	0.28	0.14	0.95	0.98	1.04

Table 6.2 Statistics of peak wave period validation (T_{p}, for H_{m0} > 1.0 m)

Name	N	Mean [s]	Bias [s]	MAE [s]	RMSE [s]	SI	EV	CC	PR
EINS-North (new period)	18,414	7.95	0.24	0.75	1.41	0.18	0.41	0.74	1.04
EINS-North (full period)	27,060	8.28	0.33	0.89	1.82	0.23	0.32	0.72	1.07
EINS-South (new period)	16,862	7.87	0.27	0.76	1.46	0.19	0.36	0.73	1.03
EINS-South (full period)	25,569	8.16	0.40	0.90	1.86	0.23	0.22	0.69	0.98
EINS-Island (Mini 1) (new period)	14,035	7.92	0.45	0.84	1.59	0.20	0.11	0.67	-
EINS-Island (Mini 1) (full period)	26,877	8.11	0.57	0.96	1.98	0.25	-0.05	0.65	1.06
EINS-Island (Mini 2) (new period)	15,703	7.65	0.19	0.69	1.21	0.16	0.54	0.79	0.98
EINS-Island (Mini 2) (full period)	24,440	8.06	0.40	0.90	1.88	0.24	0.21	0.69	1.05
EINS-West (Mini 3) (new period)	6,708	8.07	0.43	0.86	1.55	0.19	0.27	0.68	-

Table 6.3 Statistics of zero-crossing wave period validation (T_{02}, for H_{m0} > 1.0 m)

Name	N	Mean [s]	Bias [s]	MAE [s]	RMSE [s]	SI	EV	CC	PR
EINS-North (new period)	18,869	5.18	-0.40	0.45	0.55	0.07	0.83	0.93	0.94
EINS-North (full period)	27,515	5.23	-0.38	0.43	0.54	0.07	0.84	0.93	0.92
EINS-South (new period)	17,057	5.14	-0.37	0.42	0.51	0.06	0.84	0.94	0.93
EINS-South (full period)	25,764	5.18	-0.35	0.41	0.50	0.06	0.84	0.94	0.93
EINS-Island (Mini 1) (new period)	14,454	5.14	-0.29	0.38	0.46	0.06	0.82	0.94	0.99
EINS-Island (Mini 1) (full period)	27,296	5.13	-0.28	0.37	0.45	0.07	0.82	0.94	0.97
EINS-Island (Mini 2) (new period)	16,045	5.01	-0.34	0.39	0.48	0.06	0.84	0.94	0.80
EINS-Island (Mini 2) (full period)	24,782	5.09	-0.31	0.38	0.46	0.06	0.85	0.94	0.88
EINS-West (Mini 3) (new period)	6,957	5.23	-0.29	0.37	0.46	0.06	0.84	0.94	0.94

EINS-North

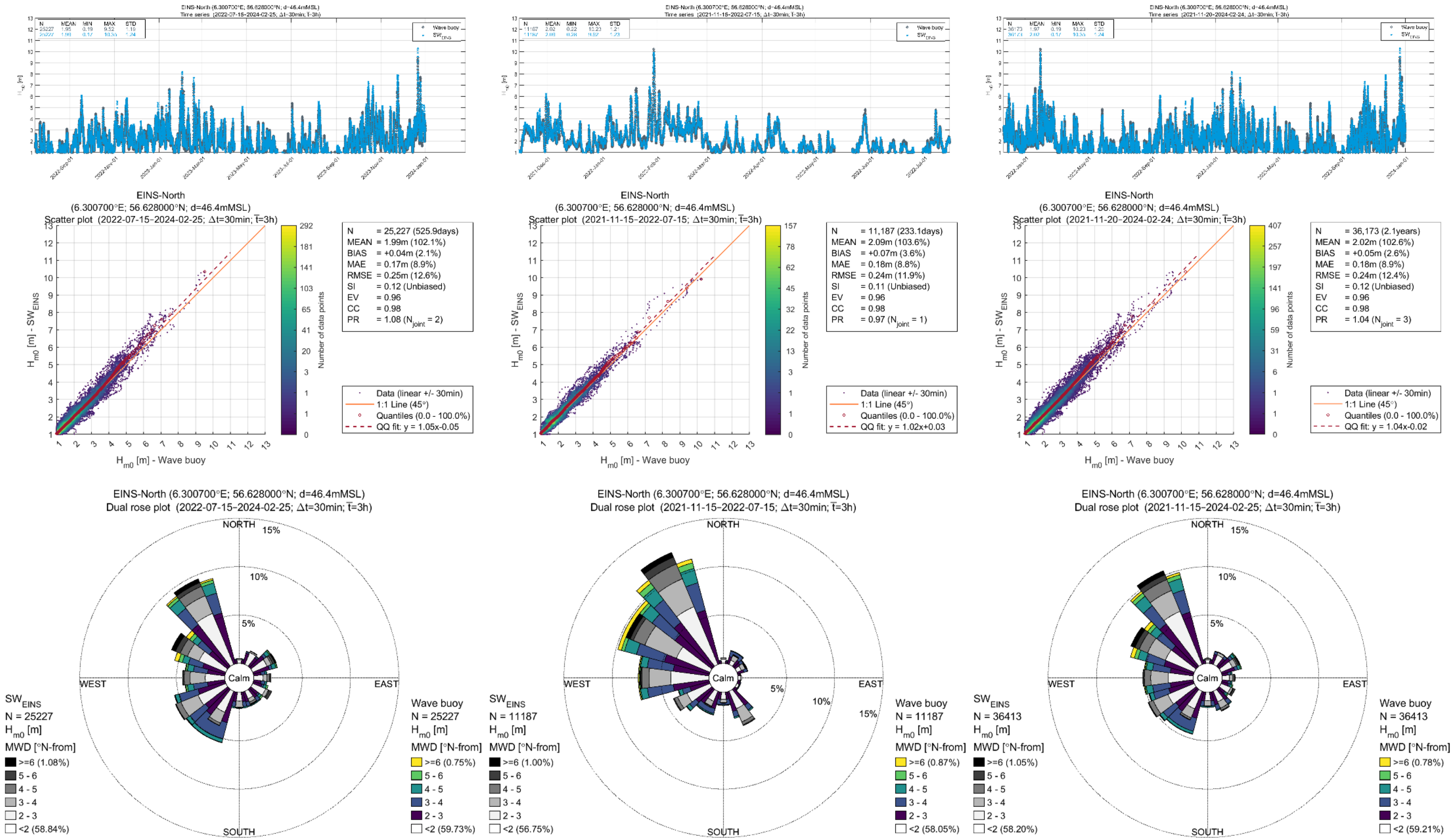

Figure 6.1 Comparison of measured and modelled H_{m0} at EINS- North
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

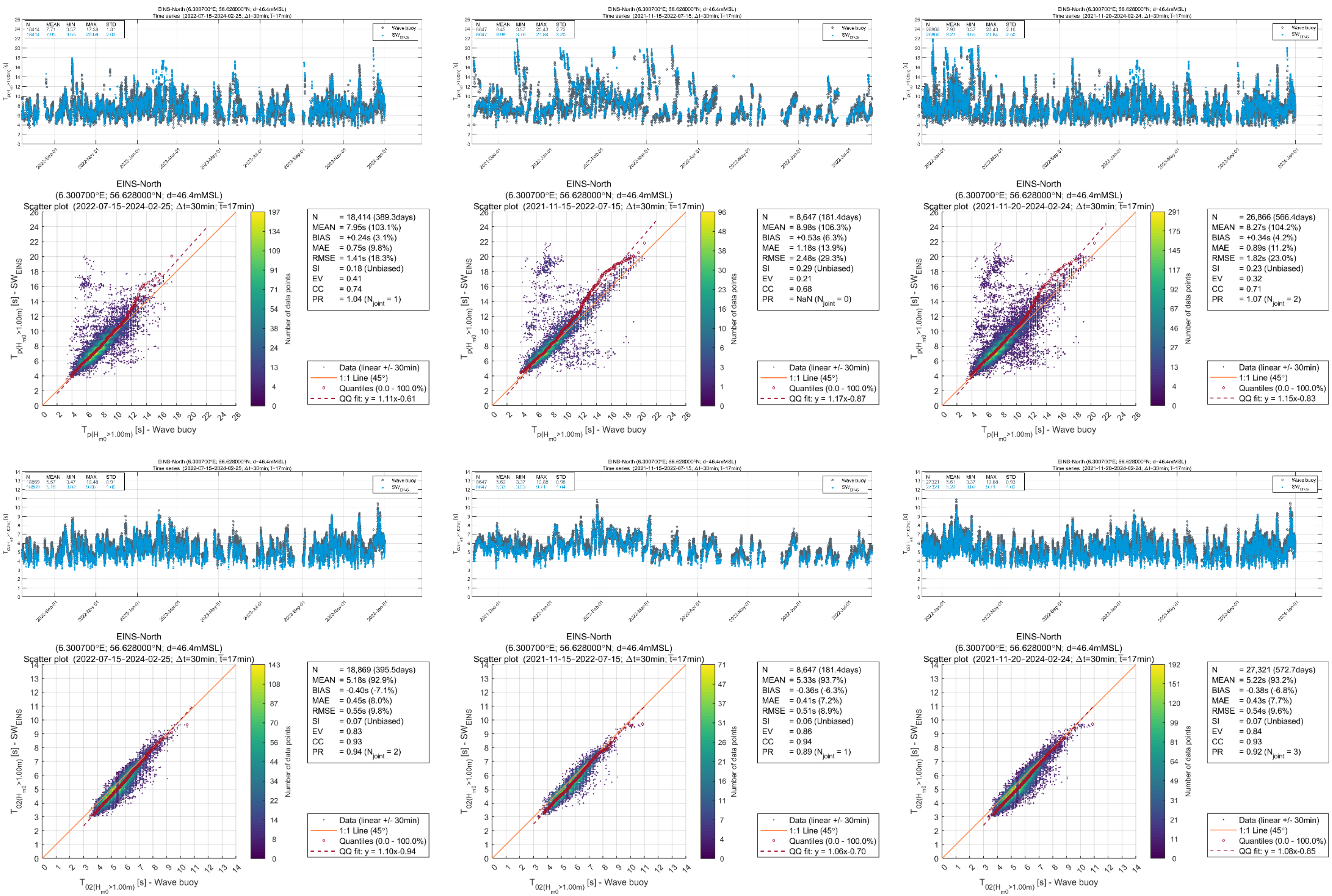

Figure 6.2 Comparison of measured and modelled T_p (upper) and T_{02} (lower) at EINS-North

Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

EINS-South

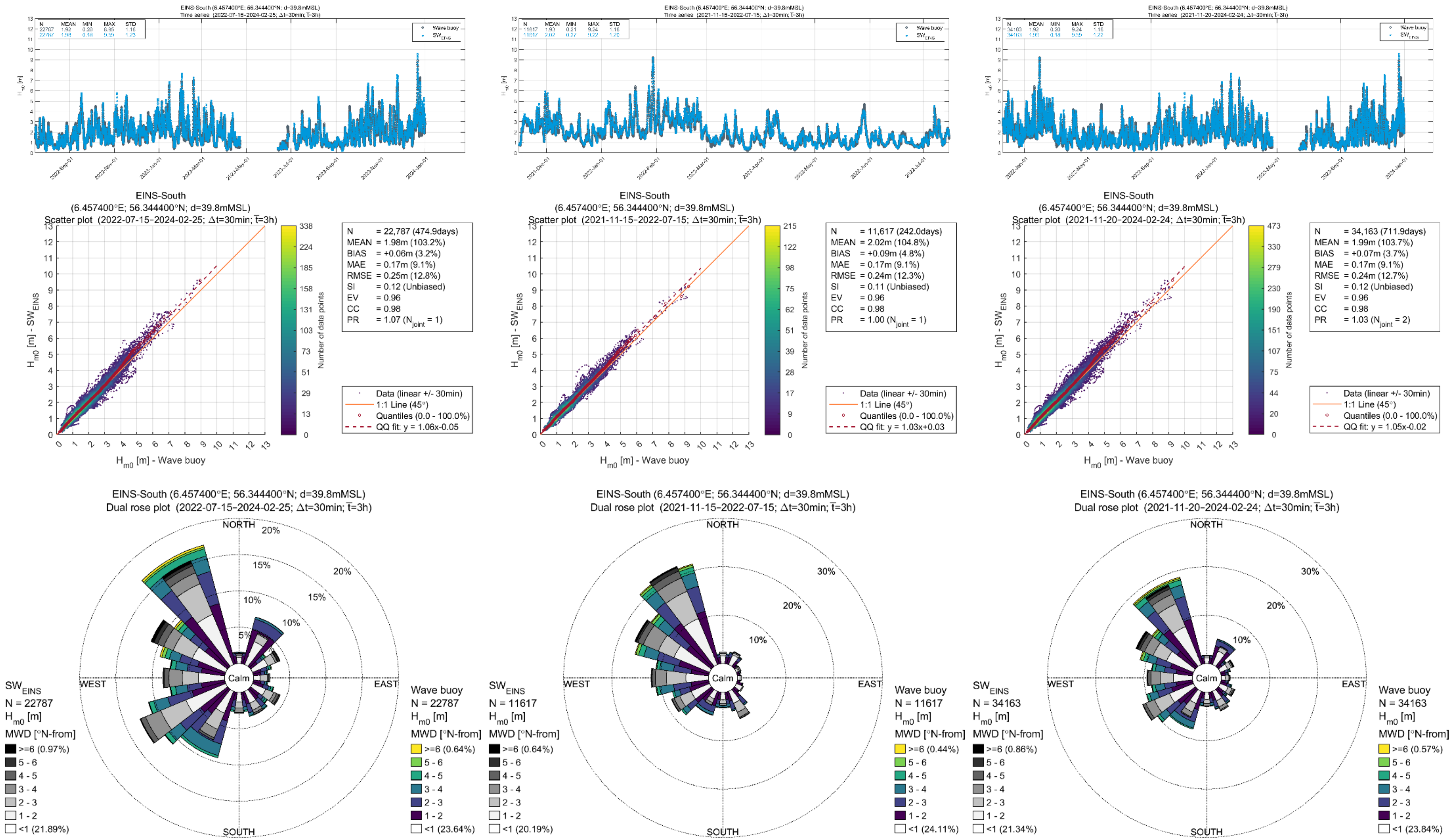

Figure 6.3 Comparison of measured and modelled H_{m0} at EINS-South

Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

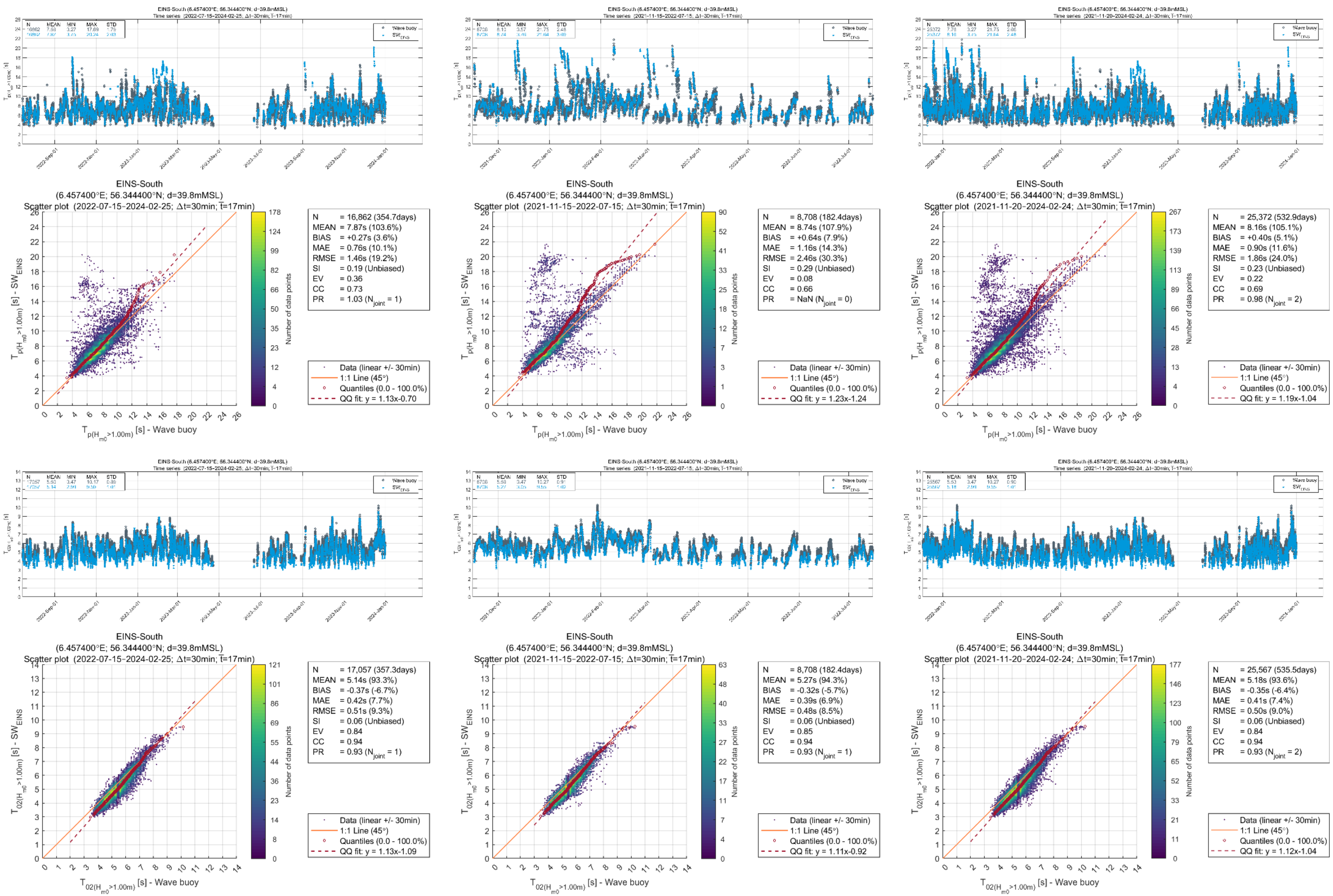

Figure 6.4 Comparison of measured and modelled T_p (upper) and T_{02} (lower) at EINS-South
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

EINS-Island (Mini 1)

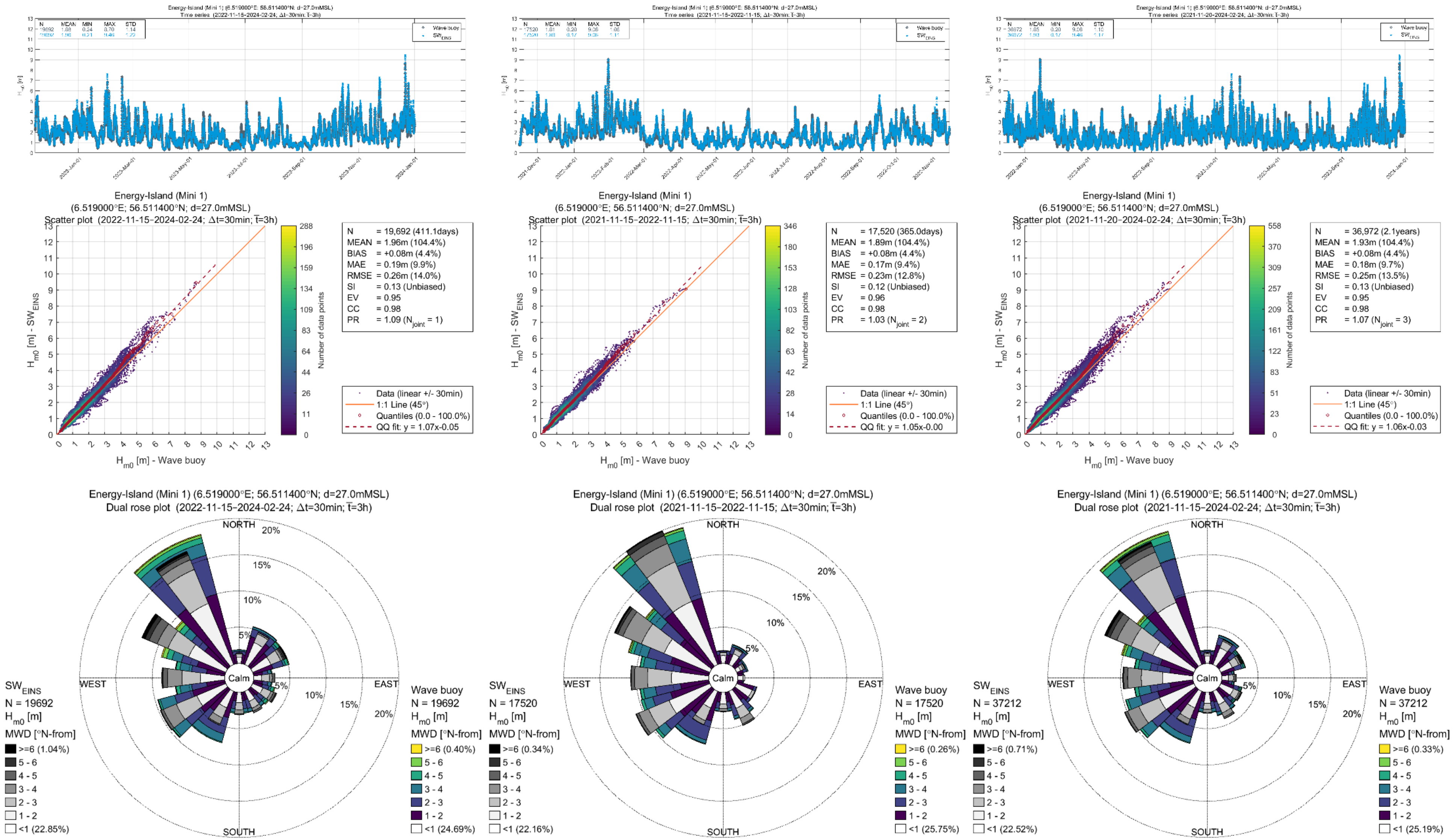

Figure 6.5 Comparison of measured and modelled H_{m0} at EINS-Island (Mini 1)
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

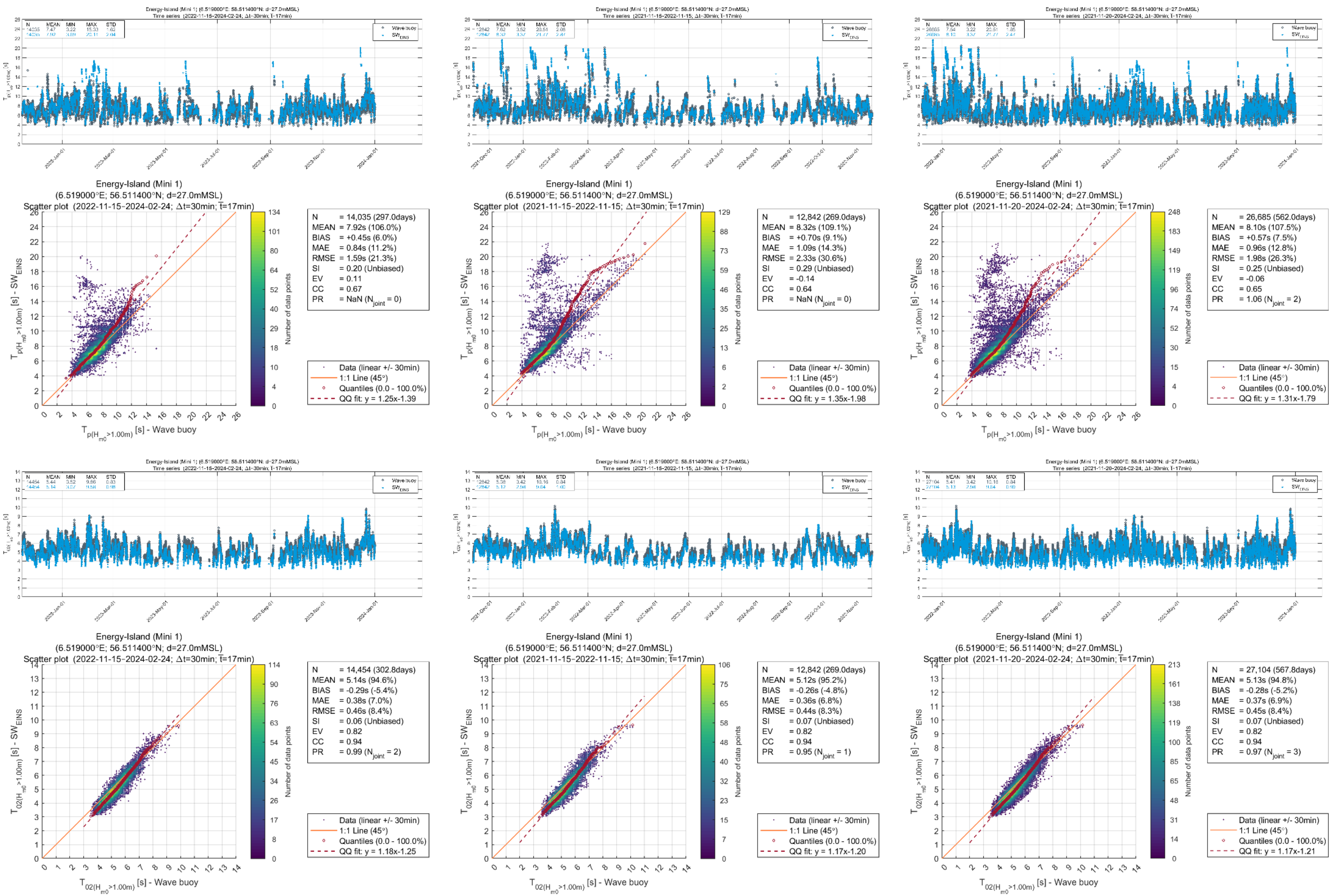

Figure 6.6 Comparison of measured and modelled T_p (upper) and T_{02} (lower) at EINS-Island (Mini 1)
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

EINS-Island (Mini 2)

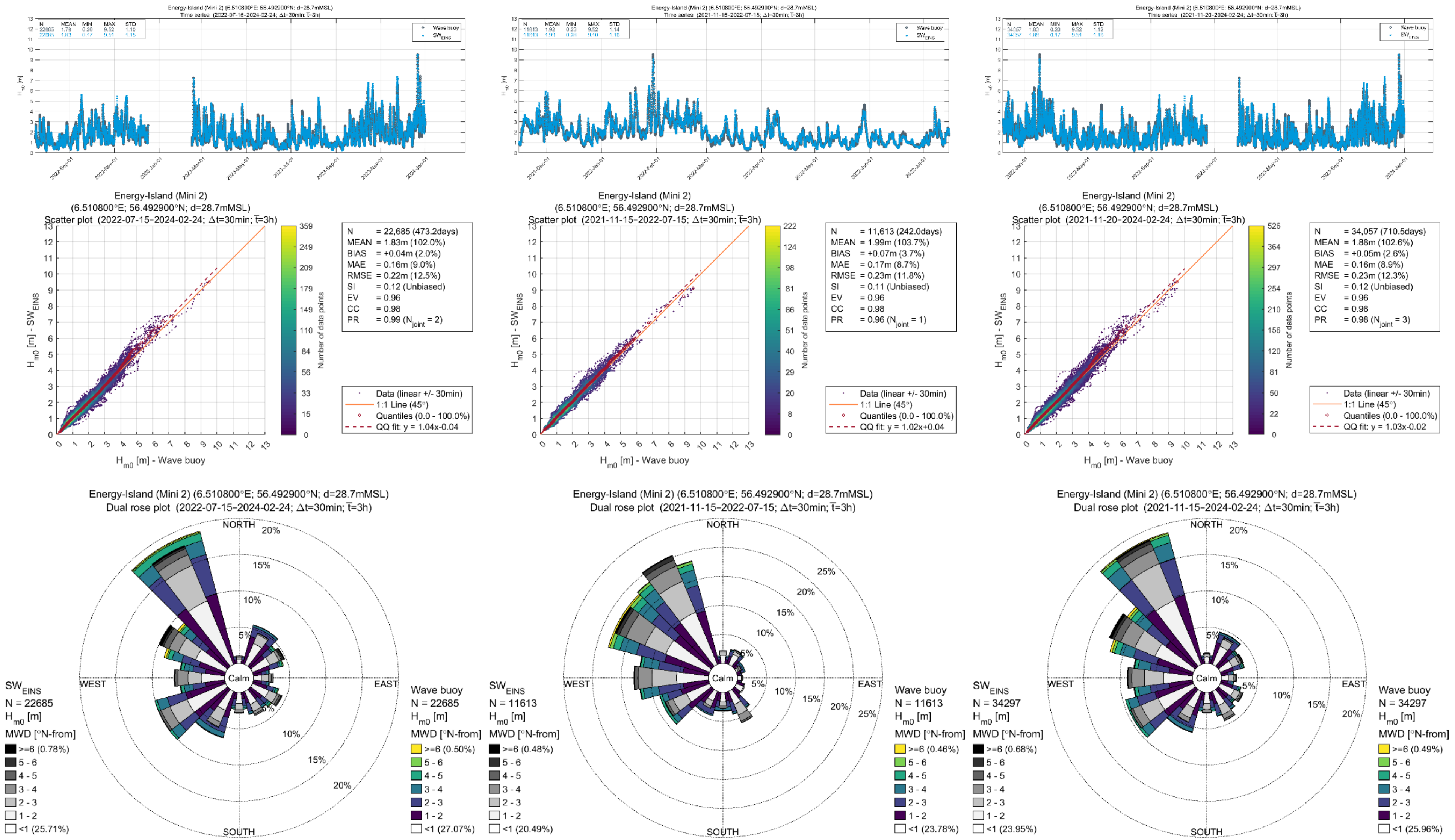

Figure 6.7 Comparison of measured and modelled H_{m0} at EINS-Island (Mini 2)
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

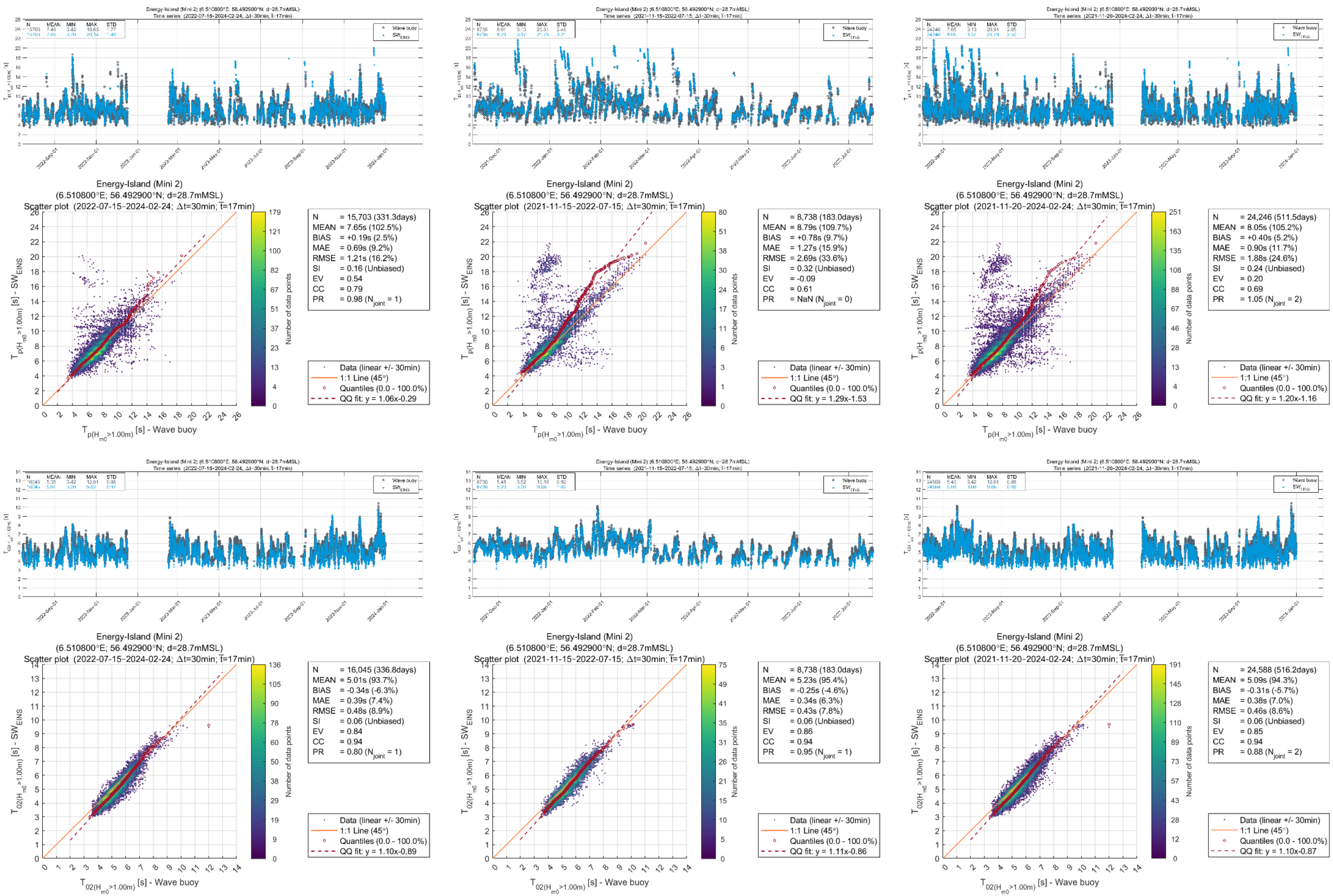

Figure 6.8 Comparison of measured and modelled T_p (upper) and T_{02} (lower) at EINS-Island (Mini 2)
Left: New measurements, Middle: Original measurements, Right: Full period of measurements.

EINS-West (Mini 3)

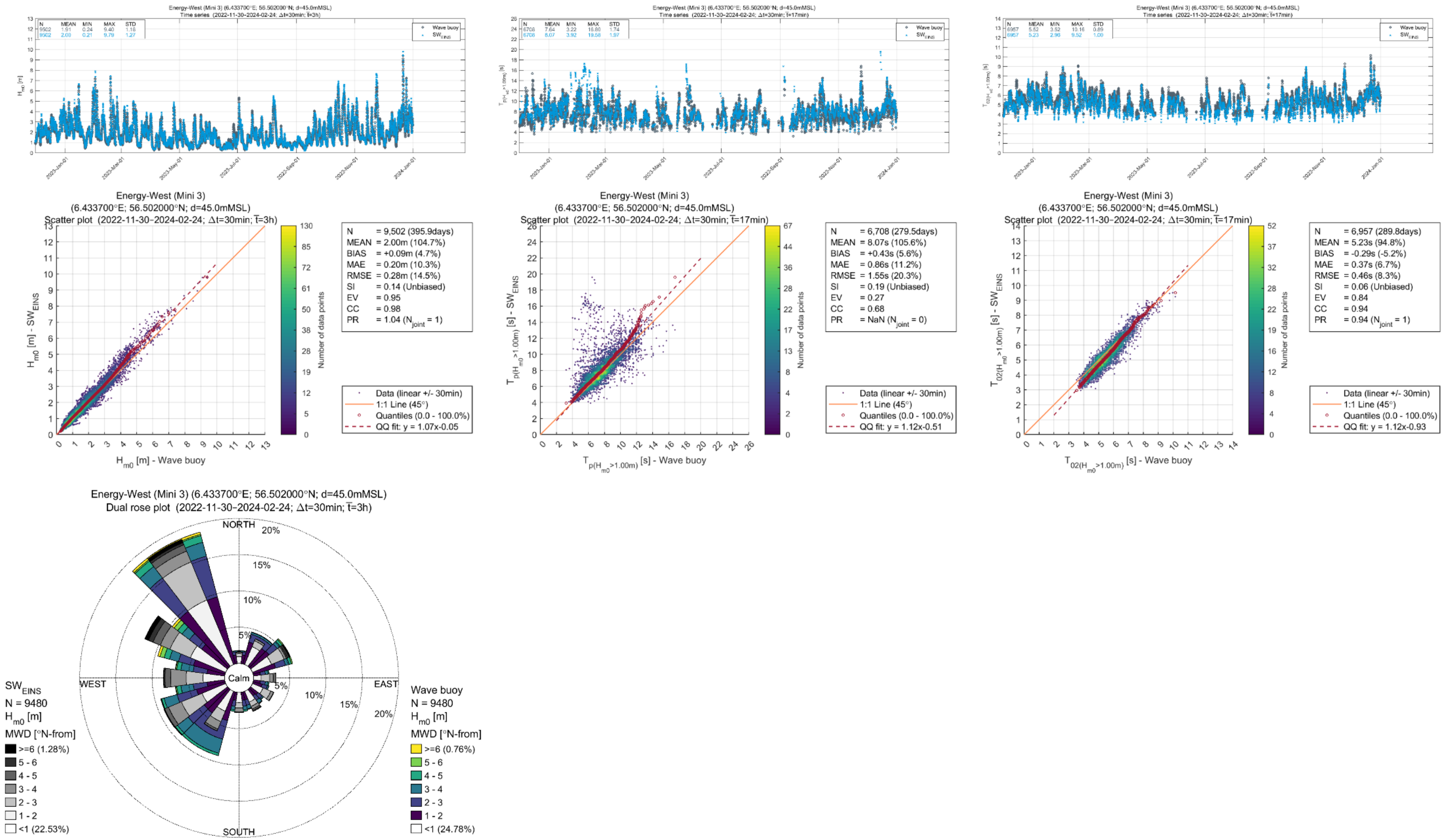

Figure 6.9 Comparison of measured and modelled waves at EINS-West (Mini 3)
Left: H_{m0}, Middle: $T_{p(Hm0>1.00m)}$ and, Right: $T_{02(Hm0>1.00m)}$.

7 Other Oceanographic Revalidation

This section presents the revalidation of other ocean conditions and parameters, i.e. water temperature and salinity. Modelled temperature and salinity parameters are adopted from the HD_{UKNS3D} model (see Section 8.1 of [1]).

Figure 7.1 to Figure 7.2 present comparisons in terms of time series plots of water temperature and salinity at two depths, 10 and 34 m below surface, during the new and the full periods of measurements.

The plots demonstrate that HD_{UKNS3D} describes the water temperature and salinity accurately at the measurement station EINS-South, and that the validation during the new period is consistent with the validation during the original period. Therefore, no adjustments are required for the water temperature- and salinity-related sections in Part A, B, and C.

EINS-South

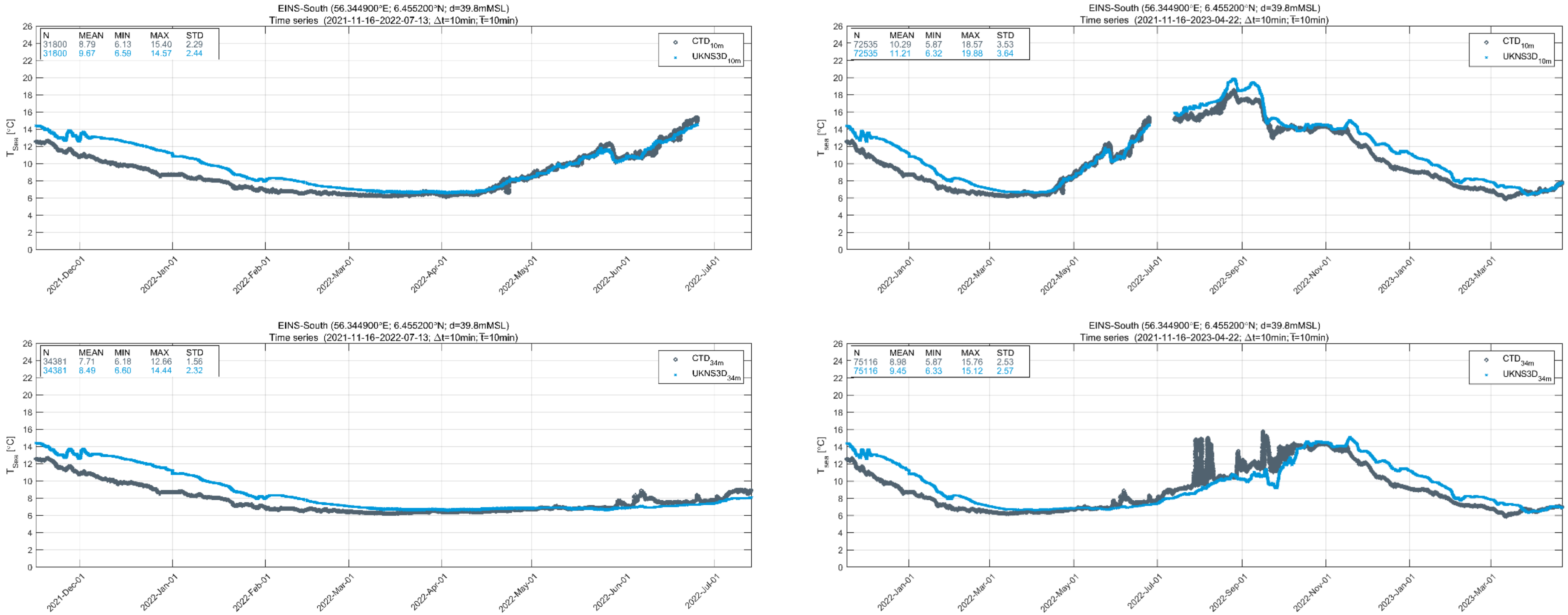

Figure 7.1 Water temperature time series comparison at 10 m (top) and 34 m (bottom) depth between measurements and HD_{UKNS3D}
Left: Original measurements, Right: Full period of measurements.

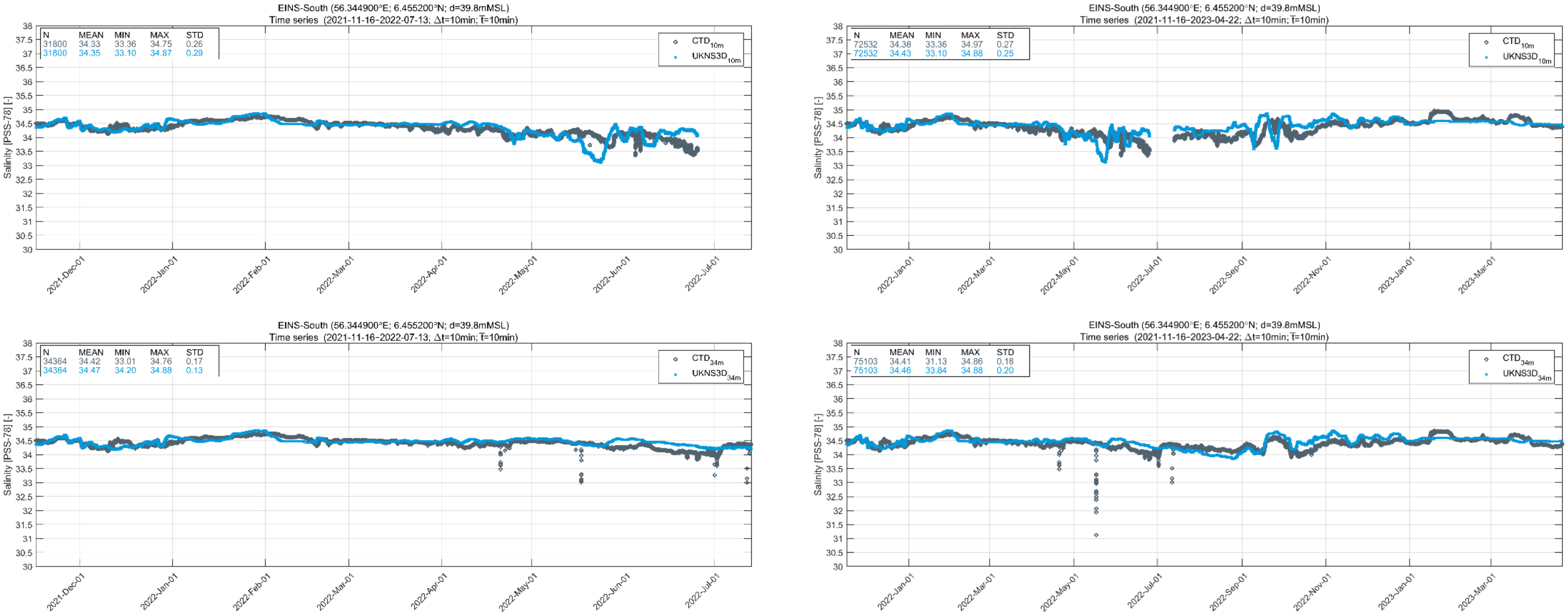

Figure 7.2 Salinity time series comparison at 10 m (top) and 34 m (bottom) depth between measurements and HD_{UKNS3D}
Left: Original measurements, Right: Full period of measurements.

8 References

[1] DHI, “Energy Island North Sea, Metocean Site Conditions Assessment, Part A: Data Basis – Measurements and Models, 2023-11-20, Rev 1.1 Final,” 2023.

[2] DHI, “Energy Island North Sea, Metocean Site Conditions Assessment, Part B: Data Analyses – Energy Island, 2023-08-09, Rev 1.2 Final,” 2023.

[3] DHI, “Energy Island North Sea, Metocean Site Conditions Assessment, Part C: Data Analyses – Wind Farm Area, 2023-11-20, Rev. 1.3 Final,” 2023.

[4] ULS, “Evaluation Report Site Conditions - Metocean Conditions Part A (Report No. R14772868-0-2, Rev. 2, 2024-07-09),” 2024a.

[5] ULS, “Evaluation Report Site Conditions - Metocean Conditions Part B (Report No.: R14772868-0-3, Rev. 2, 2024-07-09),” 2024b.

[6] ULS, “Evaluation Report Site Conditions - Metocean Conditions Part C (Report No.: R14772868-0-4, Rev. 2, 2024-07-09),” 2024c.

[7] ULS, “Evaluation Report Site Conditions - Measurement Campaign for Winds and Metiocean Conditions (Report No.: R14772868-0-5, Rev. 2, 2024-07-09),” 2024d.

[8] Energinet, “Scope of Services – North Sea Energy Island Metocean Conditions Assessment, document number: 2/05192-6, 2022-06-22,” 2022.

[9] Energinet, “Scope of Services – Site Metocean Conditions Assessment for Offshore Wind Farms, North Sea, Document number: 22/08564-1, 2022-11-08,” 2022.

[10] DNV, “DNV-RP-C205 Environmental conditions and environmental loads,” DNV AS, 2021.

[11] IEC, “61400-3-1, Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines,” 2021.

[12] Fugro, “Energy Islands – Floating LiDAR Measurements - Final Campaign Report for Lot 1, November 2021 – February 2024,” 2024.

[13] Fugro, “Energy Islands – Floating LiDAR Measurements - Final Campaign Report for Lot 2, November 2021 – February 2024,” 2024.

[14] Fugro, “SWLB measurements at Energy Islands Project Measurement Plan, All Lots,” 2022.

9 Appendix A: Model Quality Indices

To obtain an objective and quantitative measure of how well the model data compared to the observed data, several statistical parameters, so-called quality indices (QI's), are calculated.

Prior to the comparisons, the model data is synchronised to the time stamps of the observations so that both time series had equal length and overlapping time stamps. For each valid observation, measured at time t, the corresponding model value is found using linear interpolation between the model time steps before and after t. Only observed values that had model values within ± the representative sampling or averaging period of the observations are included (e.g., for 10-min observed wind speeds measured every 10 min compared to modelled values every hour, only the observed value every hour is included in the comparison).

The comparisons of the synchronised observed and modelled data are illustrated in (some of) the following figures:

- Time series plot including general statistics
- Scatter plot including quantiles, QQ-fit and QI's (density-coloured dots)
- Histogram of occurrence vs. magnitude or direction
- Histogram of bias vs. magnitude
- Histogram of bias vs. direction
- Dual rose plot (overlapping roses)
- Peak event plot including joint (coinciding) individual peaks

The quality indices are described below, and their definitions are listed in Table A.1. Most of the quality indices are based on the entire dataset, and hence the quality indices should be considered averaged measures and may not be representative of the accuracy during rare conditions.

The MEAN represents the mean of modelled data, while the bias is the mean difference between the modelled and observed data. MAE is the mean of the absolute difference, and RMSE is the root-mean-square of the difference. The MEAN, BIAS, MAE and RMSE are given as absolute values and relative to the average of the observed data in percent in the scatter plot.

The scatter index (SI) is a non-dimensional measure of the difference calculated as the unbiased root-mean-square difference relative to the mean absolute value of the observations. In open water, an SI below 0.2 is usually considered a small difference (excellent agreement) for significant wave heights. In confined areas or during calm conditions, where mean significant wave heights are generally lower, a slightly higher SI may be acceptable (the definition of SI implies that it is negatively biased (lower) for time series with high mean values compared to time series with lower mean values (and same scatter/spreading), although it is normalised).

EV is the explained variation and measures the proportion [0 - 1] to which the model accounts for the variation (dispersion) of the observations.

The correlation coefficient (CC) is a non-dimensional measure reflecting the degree to which the variation of the first variable is reflected linearly in the variation of the second variable. A value close to 0 indicates very limited or no (linear) correlation between the two data sets, while a value close to 1 indicates a very high or perfect correlation. Typically, a CC above 0.9 is considered a high correlation (good agreement) for wave heights. It is noted that CC is 1 (or -1) for any two fully linearly correlated variables, even if they are not 1:1. However, the slope and intercept of the linear relation may be different from 1 and 0, respectively, despite CC of 1 (or -1).

The QQ line slope and intercept are found from a linear fit to the data quantiles in a least-square sense. The lower and uppermost quantiles are not included on the fit. A regression line slope different from 1 may indicate a trend in the difference.

The peak ratio (PR) is the average of the Npeak highest model values divided by the average of the Npeak highest observations. The peaks are found individually for each dataset through the Peak-Over-Threshold (POT) method applying an average annual number of exceedances of 4 and an inter-event time of 36 hours. A general underestimation of the modelled peak events results in a PR below 1, while an overestimation results in a PR above 1.

An example of a peak plot is shown in Figure A.1. 'X' represents the observed peaks (x-axis), while 'Y' represents the modelled peaks (y-axis), based on the POT methodology, both represented by circles ('o') in the plot. The joint (coinciding) peaks, defined as any X and Y peaks within ±36 hours[1] of each other (i.e., less than or equal to the number of individual peaks), are represented by crosses ('x'). Hence, the joint peaks ('x') overlap with the individual peaks ('o') only if they occur at the same time exactly. Otherwise, the joint peaks ('x') represent an additional point in the plot, which may be associated with the observed and modelled individual peaks ('o') by searching in the respective X and Y-axis directions, see example with red lines in Figure A.1. It is seen that the 'X' peaks are often underneath the 1:1 line, while the 'Y' peaks are often above the 1:1 line.

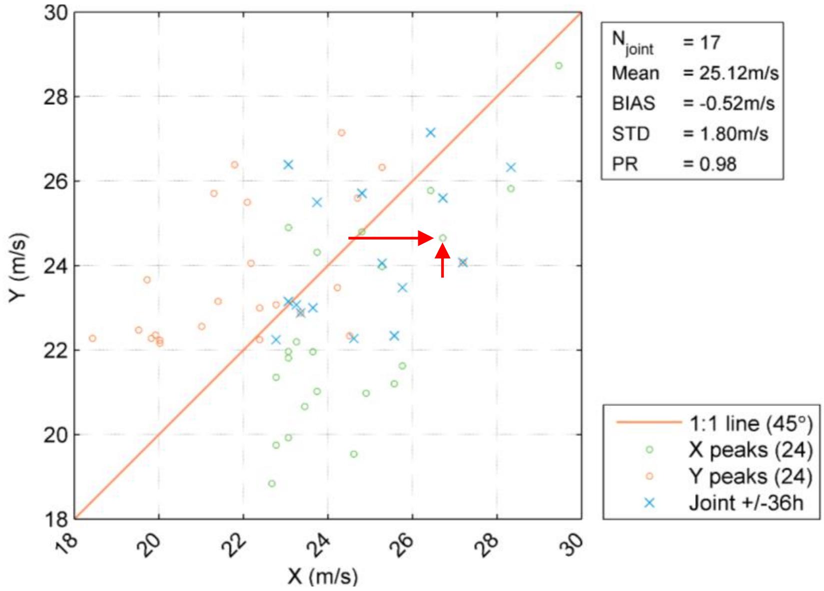

Figure A.1 Example of peak event plot (wind speed)

1 36 hours is chosen arbitrarily as representative of an average storm duration. Often the measured and modelled peaks are within 1-2 hours of each other.

Table A.1 Definitions of model quality indices (X = Observation, Y = Model)

Abbreviation	Description	Definition
N	Number of data (synchronised)	–
MEAN	Mean of Y data Mean of X data	$\frac{1}{N}\sum_{i=1}^{N} Y_i \equiv \overline{Y}$, $\frac{1}{N}\sum_{i=1}^{N} X_i \equiv \overline{X}$
STD	Standard deviation of Y data Standard deviation of X data	$\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(Y-\overline{Y})^2}$, $\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(X-\overline{X})^2}$
BIAS	Mean difference	$\frac{1}{N}\sum_{i=1}^{N}(Y-X)_i = \overline{Y}-\overline{X}$
MAE	Mean absolute difference	$\frac{1}{N}\sum_{i=1}^{N}(\lvert Y-X\rvert)_i$
RMSE	Root-mean-square difference	$\sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y-X)_i^{\;2}}$
SI	Scatter index (unbiased)	$\frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y-X-BIAS)_i^{\;2}}}{\frac{1}{N}\sum_{i=1}^{N}\lvert X_i\rvert}$
EV	Explained variance	$\frac{\sum_{i=1}^{N}(X_i-\overline{X})^2-\sum_{i=1}^{N}[(X_i-\overline{X})-(Y_i-\overline{Y})]^2}{\sum_{i=1}^{N}(X_i-\overline{X})^2}$
CC	Correlation coefficient	$\frac{\sum_{i=1}^{N}(X_i-\overline{X})(Y_i-\overline{Y})}{\sqrt{\sum_{i=1}^{N}(X_i-\overline{X})^2\sum_{i=1}^{N}(Y_i-\overline{Y})^2}}$
QQ	Quantile-Quantile (line slope and intercept)	Linear least square fit to quantiles
PR	Peak ratio (of N_{peak} highest events)	$PR = \frac{\sum_{i=1}^{N_{peak}} Y_i}{\sum_{i=1}^{N_{peak}} X_i}$