Energy Islands – Floating LiDAR Measurements

Final Campaign Report for Lot 3, November 2021 – November 2022

C75487-Lot 3-R12-001 06 | 2 May 2024
Final
ENERGINET

Document Control

Document Information

Project Title	Energy Islands – Floating LiDAR Measurements
Document Title	Final Campaign Report for Lot 3, November 2021 – November 2022
Fugro Project No.	C75487
Fugro Document No.	C75487-Lot 3-R12-001
Issue Number	06
Issue Status	Final

Client Information

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Revision History

Issue	Date	Status	Comments on Content	Prepared By	Checked By	Approved By
01	12 Mar 2024	Draft	First issue	Irene Pathirana	Arve Berg	
02	03 Apr 2024	Draft	Second updated issue	Irene Pathirana	Arve Berg	
03	12 Apr 2024	Draft	Third updated issue	Irene Pathirana	Arve Berg	
04	24 Apr 2024	Draft	4th updated issue	Irene Pathirana	Arve Berg	
05	30 Apr 2024	Draft	5th updated issue	Irene Pathirana	Arve Berg	
06	02 May 2024	Final	Final issue	Irene Pathirana	Arve Berg	Arve Berg

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Abbreviations

Abbreviation	Definition
CTD	Conductivity, temperature, depth
DD	day of month 2 digits
DGPS	Dual GPS
GNSS	Global Navigation Satellite System
GPS	Global positioning system
HAT	Highest Astronomical Tide
LAT	Lowest Astronomical Tide
LiDAR (or lidar)	Light Detection and Ranging
MM	month 2 digits
MSL	Mean Sea Level
MWL	Mean Water Level
NaN (Not a Number)	Label indicating data as invalid/missing
PEP	Project Execution Plan
PPE	Personal Protective Equipment
QHSSE	Quality, Health, Safety, Security and Environment
QA/QC	Quality Assurance / Quality Control
SI	Système International
SWLB	Seawatch Wind Lidar Buoy
SWMini	Seawatch Mini Wave Buoy
UTC	Universal Time Coordinated
WMO	World Meteorological Organization
WS	Seawatch Wavescan buoy
YYYY	year 4 digits

Conventions

Convention	Description
Time	All times are UTC
Directions	Directions are given in degrees (°) increasing clockwise from north. For wind and waves the direction is defined as incoming: 0° means wind/waves from the north, 90° from the east etc. For current velocity, the vector or flow direction is used: 0° means current flowing toward the north, 90° toward the east etc. The directions are subject to the source of heading, which is either compass - relative to magnetic north, or GNSS - relative to true north. Magnetic compass is used for wave and current direction, while GNSS is the main heading source for lidar and Gill wind directions. Compass data is available (stored in the data logger) as backup heading source for lidar wind directions. At Lot 3 the deviation between magnetic and true north is approximately +5.1°E (https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml#declination). In the monthly reports, no corrections for the magnetic declination were applied. For the final dataset (see **Table 4-1**), the magnetic deviation was applied to wave and current directions and **all** direction data are given relative to true north for all parameters. Please note, that this correction was not applied to any wave spectra data or raw data.

Executive Summary

Fugro Norway AS entered into an agreement with ENERGINET, Denmark for the project "Floating LiDAR Measurements Energy Island Offshore Wind Farm - Lot 1-4" for initially 12 months. Lots 1, 2 and 4 were extended for an additional 12 months each. The purpose of the assignment is to provide met ocean data obtained through real time measurements at the two (2) energy islands: Energioe Nordsoen and Energioe Bornholm. The results of the atmospheric and oceanographic measurements should be used for verification of the wind energy potential, as basis for derivation of metocean design parameters and as a supplement to the environmental baseline description.

For Lot 3 the following instruments were deployed: LiDAR buoy (SWLB) SW199 together with a bottom mounted Thelma water level sensor and a bottom mounted upward-looking Nortek Signature500 current profiler. The Signature500 was offline and data were downloaded at services and processed thereafter.

This final campaign report covers Lot 3 in the Baltic Sea and includes general information of the measurement campaign, configurations, post-processing, quality control, post-processed data availability and data presentations over the period 21 November 2021 to 21 November 2022. All equipment was recovered on 16 December 2022.

The data availability of WS199 for the full 12-month campaign is 97.2 % for wind, 75.3 % for currents, and >99 % for all other parameter groups.

1. Introduction

1.1 Energioe Bornholm project area

The Energioe Bornholm project area in the Baltic Sea, divided by the shallow Rønne Banke, is located approximately 20 km southwest of Bornholm (**Figure 1-1**). The water depth in the 600 km^2 in the area varies from 30 m LAT to 55 m LAT (Admiralty Chart). The area was divided into 2 lots: Lot 3 to the north of the bank and Lot 4 south of the bank. This report summarizes the measurements at Lot 3.

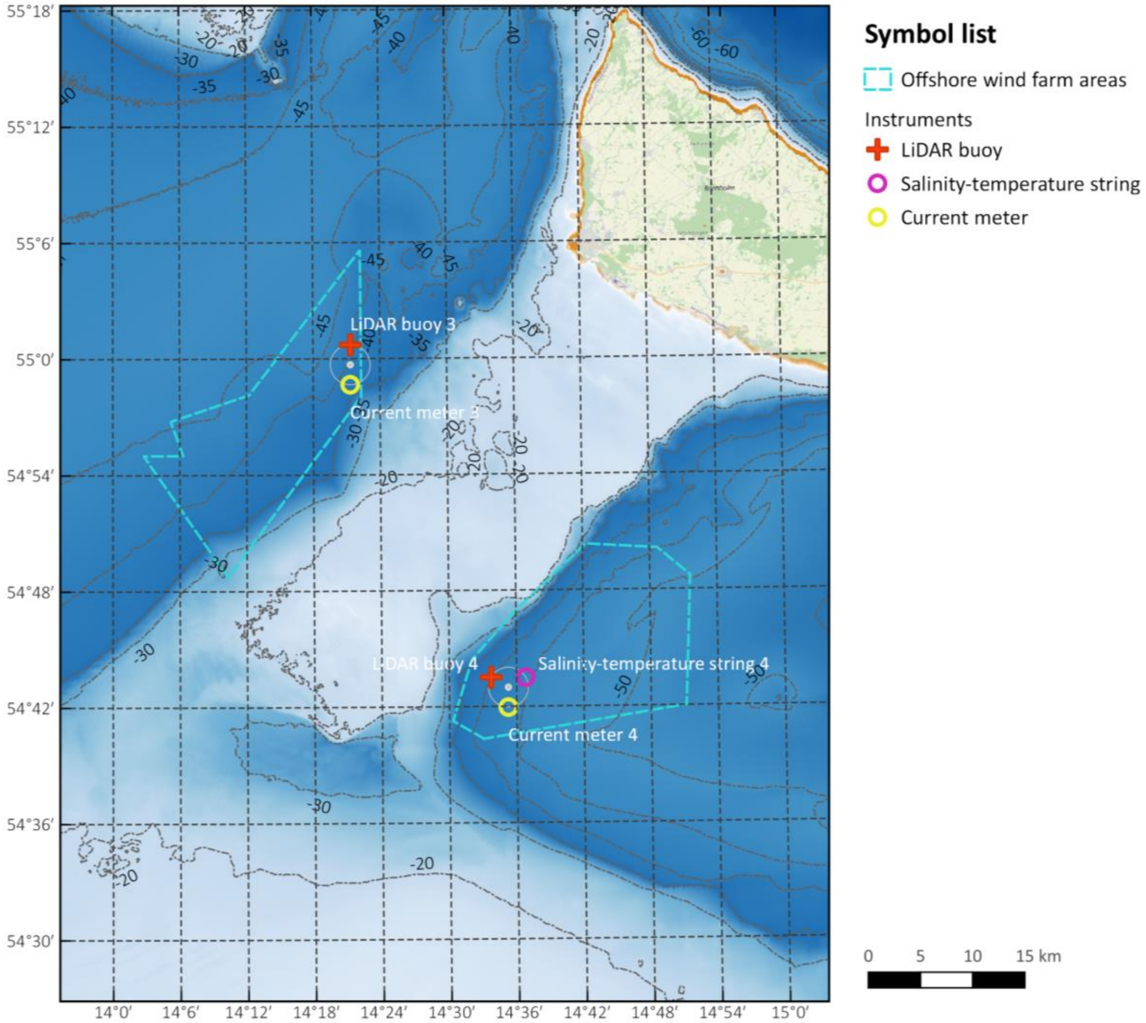


Figure 1-1 Instrument locations in the Energioe Bornholm project area

The aim of the measurement campaign is to provide a set of continuous meteorological and oceanographic (metocean) data with excellent quality and high availability. The measurement campaign will last 12 months, extended for an additional 12 months. The results of the atmospheric and oceanographic measurements are to be used for verification of wind energy potential, as basis for derivation of metocean design parameters and as a supplement to the environmental baseline description.

1.2 Lot 3 equipment, locations, and deployments

LiDAR buoy WS199 was deployed at Lot 3 on 21 November 2021 together with a bottom mounted Thelma water level sensor. A bottom mounted upward-looking Nortek Signature500 current profiler was deployed on 28 February 2022.

The LiDAR buoy provided near real-time data that was transmitted to shore every 10 minutes. The Signature500 collected data that was only stored onboard the instrument. This offline data was downloaded at service and reported thereafter.

The campaign at this lot ended on 21 November 2022. All equipment was recovered on 16 December 2022.

The positions of the bottom mooring weights are listed in **Table 1-1**. As the buoys are free to float around the mooring point within a radius of about 110 m, the actual water depth at the actual position of the buoy varies. The position of the water level sensor is assumed equal to the position of the bottom weight of the associated buoy.

Table 1-2 shows a log of the deployments at Lot 3 including start and end times of valid data.

Table 1-1 Equipment locations and water depths

Buoy	Location	Latitude [°N]	Longitude [°E]	Water Depth [m MWL]
LiDAR Buoy 3 (SWLB)	Baltic Sea/Lot 3	54.9948	14.3556	39.8
Bottom mounted ADCP	Baltic Sea/ADCP Lot 3	54.9939	14.3556	40

Table 1-2 Deployments at Lot 4

Deployment	Station	Buoy S. no.	LiDAR #	Start time (UTC)	End time (UTC)	Status
D01-SWLB	Lot 3	WS199	ZX898	2021-11-21 15:50	2022-06-20 09:20	Recovered for service
D02-SWLB	Lot 3	WS199	ZX898	2022-06-22 11:00	2022-11-21 15:50	End of campaign
D01-ADCPSWLB	ADCP Lot 3	Nortek Signature 500	-	2022-02-28 11:40	2022-06-20 10:40	Recovered for service
D02-ADCPSWLB	ADCP Lot 3	Nortek Signature 500	-	2022-06-22 12:00	2022-11-21 16:00	End of campaign

1.3 SWLB Calibration and Pre-deployment Validation

The LiDAR buoy has been pre-validated and passed Best Practice Criteria for all wind speed ranges at all heights [1].

The measurement plan [2] for this campaign includes information on calibration certificates for the other instruments.

1.4 Data collection and reports

1.4.1 SWLB data

Data from the LiDAR buoy was transmitted to shore in near real-time, quality checked monthly and reported in monthly reports. Fugro also provided motion-compensated estimates of SWLB-measured turbulence intensity in separate work packages.

Table 1-3 lists the monthly reports and the report on TI motion-compensation for this lot.

Table 1-3 List of monthly reports at Lot 3

Year 1
C75487-R-001(03)-Monthly Report Lot 3-NovDec2021
C75487-R-002(03)-Monthly Report Lot 3-Dec21Jan22
C75487-R-003(02)-Monthly Report Lot 3-JanFeb22
C75487-R-004(03)-Monthly Report Lot 3-FebMar22
C75487-R-005(03)-Monthly Report Lot 3-MarApr22
C75487-R-006(03)-Monthly Report Lot 3-AprMay22
C75487-R-007(03)-Monthly Report Lot 3-MayJun22
C75487-R-008(02)-Monthly Report Lot 3-JunJul22
C75487-R-009(02)-Monthly Report Lot 3-JulAug22
C75487-R-010(03)-Monthly Report Lot 3-AugSep22
C75487-R-011(02)-Monthly Report Lot 3-SepOct22
C75487-R-012(03)-Monthly Report Lot 3-OctNov22
C75486-R-003(03)-TI Report Lot 3 & 4 - Campaign data

1.4.2 ADCP SWLB

The instrument was deployed offline and collected data during 2 deployments. D01-ADCPSWLB is summarized in [3]. The full 12-month dataset is presented in this report.

1.4.3 Bat sensor

A bat sensor was mounted on the SWLB. The data from this instrument was downloaded during services. The raw data was provided at the end of the campaign. The locations of the bat measurements correspond to the SWLB position data.

2. Activities

2.1 Service and Maintenance Activities

LiDAR buoy WS199 was deployed at Lot 3 on 21 November 2021 at 15:50 UTC together with a bottom mounted Thelma water level sensor. A bottom mounted upward-looking Nortek Signature500 current profiler was deployed on 28 February 2022.

LiDAR buoy WS199 and the Signature500 ACDP were recovered on 20 June 2022 for servicing and refuelling and re-deployed on 22 June 2022.

The campaign at this lot ended on 21 November 2022. All equipment was recovered on 16 December 2022.

2.2 Health, Safety and Environment

No incidents were logged during the campaign.

3. Methods for Post-Processing and Availability Calculations

The general measurement setup, sensors, configurations, and measurement scheme are described in the measurement plan [2].

3.1 SWLB

3.1.1 Measurement configurations

Table 3-1 shows the measurement configuration of the SWLB at Lot 3. The data from the SWLB is averaged every 10 minutes. Definitions of wave parameters are given in **Table 3-2**.

For each instrument on a SWLB, the measurement processes are set-up individually according to the resolution needed. The measurements are stored in the onboard in-memory database. Selected measurements are averaged over 10 minutes and/or used in internal processes together with other measurements from other sensors:

- GPS position and current data (i. e. Aquadopp-produced 10-minute-averages including sea surface temperature) are delivered by these instruments every 10 minutes for storage. No further treatment of either data is done on board.
- Air pressure, air temperature, air humidity, solar irradiance, precipitation, and visibility, as well as data from the bottom mounted Thelma pressure sensor are stored in the internal memory database at their respective measurement rates. 10-minute-averages are calculated for storage every 10 minutes.
- Wave parameters are calculated onboard from raw data and stored every 10 minutes.
- Heading information (compass and DGPS) and data from the Gill sensor are continuously stored at 1 Hz and averaged for each 10-minute interval. In addition, these measurements are also made available in real time for the LiDAR processes.
- The LiDAR unit measures at 1 Hz. The LiDAR data are combined with buoy heading information to reference buoy direction to north before calculating the 10-minute-averages. Averaging over 10 minutes also serves as motion correction.

The buoys convert all measurements to physical quantities in SI units. The data are packed for transmission and storage in binary integer numbers using a proprietary compression algorithm, giving sufficient resolution while using minimal storage space. At the receiving end the data are unpacked to physical values in real numbers using the reverse conversion method. This also means that the data in transmission are encrypted.

10-minute averages transmitted via satellite form the basis of the monthly reports. Any gaps in the transmitted data or data deemed suspicious after the monthly quality checks are performed, are flagged. These gaps and issues are investigated once stored data are available. 10-minute averages stored on the datalogger form the basis of the final campaign dataset. In addition, any data downloaded during a service or at the end of the campaign (pff and raw) are used to investigate gaps in the data set that occurred during the deployment. When necessary and if available (no other instrument issues), the data can be re-processed using raw data and used to fill gaps.

Table 3-1 Configuration of measurements of the Seawatch Wind Lidar buoy at Lot 3

Instrument Type	Sensor Height [m]	Parameter Measured	Sample Height[1] [m]	Sampling Interval [s]	Averaging Period [s]	Burst Interval [s] [2]	Measurement Resolution	Trans-mitted?
Wavesense 3	0	Heave, pitch, roll, heading	0	0.5	Time series duration: 1024 s	1024	0.1m, 0.2°, 0.2° 0.5°	No
		Sea state parameters[3]	0	600	1024	1024	0.1m, 0.2°, 0.1s	Yes
ZephIR ZX300 Lidar	2	Wind speed and direction at 10 heights and the reference level at 40 m	40[4], 30, 60, 90, 100, 120 150, 180 200, 240, 270	17.4[5]	600	600	0.1m/s 1°	Yes
Gill Windsonic M	4.1	Wind speed and direction	4.1	1	600	600	0.01m/s 1°	Yes
Nortek Aquadopp 600 kHz z-cell	-1	Current speed and direction profile, water temperature (at 1m depth)	-1 -2 … -41	1	600	600	2 cm/s 1° 0.1°C	Yes
Vaisala PTB330A	0.0	Air pressure	0.0	30	60	600	0.05 hPa	Yes
Vaisala HMP155	4.1	Air temperature Air humidity	4.1	5	60	600	0.1°C 1%	Yes
MiniPWS (fog)	4.1	Visibility	4.1	600	600	1	0.6 m	Yes
Young Precipitation sensor	4.0	Precipitation	4.0	600	600	60	0.001 mm	Yes
Apogee Pyranometer	4.1	Solar Irradiance	4.1	1	600	600	1 W/m2	Yes
Septentrio DGPS	4.1	Buoy orientation	4.1	5	10	1	0.35°	No
Thelma Biotel TBR700	-42	Bottom water pressure and bottom temperature	-42	1	600	600	0.01m 0.01°C	Yes
Notes								

[1] = Height relative to actual sea surface.

[2] = A burst of measurements is the raw data time series used to calculate the average parameters. The burst interval is the time from the beginning of one burst to the beginning of the next burst, and equal to the interval between writing of raw data to disk and transmissions. Note that wave bursts overlap by 424 s.

[3] = Wave parameters as defined in **Table 3-2**

[4] = The reference level (40 m), which is not configurable.

[5] = This is the approximate time between the beginning of one sweep of the profile and the next one; the interval may vary slightly. The ZephIR sweeps one level at a time beginning at the lowest one. After the top level has been swept, it uses some time for calculations and re-focusing back to the lowest level for a new sweep. A minimum of 9 samples per height must be measured in the 10-minute interval in order to produce wind speed and direction, and derived parameters thereof. This applies after signal-noise filtering internally in the lidar is carried out.

Table 3-2 Definition of wave parameters

Parameter	Unit	Description
hm0	m	Estimate of Hs (significant wave height). Hs is the average of the one third highest waves. $hm0 = 4\sqrt{m0}$ where m0 is the zeroth order moment of the spectrum.
hm0a	m	Estimate of Hs (significant wave height) in the **a** frequency band.*
hm0b	m	Estimate of Hs (significant wave height) in the **b** frequency band.*
hmean**	m	Average height of individual waves.
hmax**	m	Height of the highest individual wave in the sample. Calculated from zero-upcrossing analysis.
hs**	m	Significant wave height, average of the one third highest waves
mdir	°N	Mean spectral wave direction. Computed from spectral analysis.
mdira	°N	Mean spectral wave direction in the **a** frequency band.*
mdirb	°N	Mean spectral wave direction in the **b** frequency band.*
sprtp	°N	Wave spreading at the spectral peak period. Computed from spectral analysis.
thhf	°N	Mean wave direction at the spectral peak period. Computed from spectral analysis.
thtp	°N	High frequency mean wave direction. This is the mean wave direction over the frequency band 0.40 – 0.45 Hz, corresponding to wave periods between 2.2 – 2.5 sec.
tm01	s	Estimate of mean wave period Tz or the average period of the individual waves. Calculated from the spectral moments. tm01 = m0/m1 where mn are the nth order spectral moments.
tm02	s	Estimate of mean wave period Tz or the average period of the individual waves. Calculated from the spectral moments. $tm02 = \sqrt{(m0/m2)}$ where mn are the nth order spectral moments.
tm02a	s	Estimate of mean wave period Tz or the average period of the individual waves in the **a** frequency band.*
tm02b	s	Estimate of mean wave period Tz or the average period of the individual waves in the **b** frequency band.*
tp	s	Period of the spectral peak
thmax**	s	Period of the highest wave. Calculated from the zero-upcrossing analysis.
tz**	s	Average period of individual waves.

Parameter	Unit	Description
ts**	s	Average period of the one third highest waves.
ui	-	Unidirectivity index, an indicator for the unidirectionality of the spectral wave components. If all mean wave directions are propagating in the same direction, ui=1

* Swell and wind sea frequency ranges:

Band "a" (Swell): 0.04 – 0.10 Hz (corresponding to wave periods between 10-25 sec, i. e. long waves)

Band "b" (Wind sea): 0.10 – 0.50 Hz (corresponding to wave periods between 2-10 sec, i. e. short waves)

** zero-upcrossing requires a certain number of "high" wave in the data series to be calculated e.g. 50. Hmax, hs, hmean, tz, ts and thmax thus are usually not calculated if significant wave height is lower than approximately 0.3 m.

3.1.2 General post-processing and data quality control

The general data flow, post-processing and quality control applied to the data before they are delivered to the client is described in the measurement plan [2].

No modifications have been applied to increase the post-processed availability or enhance the data quality. In post-processing the system integrity is maintained. Post-processing is limited to use of data from the system itself, not depending on the use of data from any external sources.

Post-processed data refers to values that have undergone the following steps:

a. Deployment period, i.e. removing values outside of those times where the system is deployed at the target position (e.g. in transit to/from shore or onshore)

b. Check that data was saved for all 10-min intervals. If not, substitutions of NaN values when all data for a 10-min time step is missing

c. Removing duplicated measurements if all measurements/parameters by one sensor are repeated from one time step to the next

d. Out of range values replaced by NaN (**Table 3-3**)

e. Applying parameter group / instrument specific quality control measures for specific groups outlined below

f. Inspection and assessment (QA/QC) by senior meteorologist/oceanographer

g. Calculate signal and system availability

The QA/QC filter ranges used for each parameter (group) are listed in **Table 3-3**.

Table 3-3 QA/QC filter ranges for each parameter

Parameter	Minimum Value	Maximum Value	Unit
Wind speed lidar	0.001	58	m/s
Wind speed Gill	0.001	35	m/s
Direction (**all**)	0	360	°N
Current speed	0	135	cm/s
Current signal strength	33	-	counts
hm0	0	18	m
hmax	0	24	m
tp	0.1	23	s
thmax	0.1	23	s
Air humidity	0.01	100	%
Air pressure	905	1100	hPa
Air temperature	-10	35	°C
Water temperature	0.1	30	°C
Water pressure	27.3	57.3	dbar
Visibility	10	6001	m
Precipitation	0	10	mm/10min
Solar irradiance	0	1000	W/m^2

3.1.3 Additional data post-processing steps

3.1.3.1 Wind speed and direction

The lidar wind dataset from 01 March 2022 until the service on 20 June 2022 was reprocessed in-house from raw 1hz lidar and Septentrio heading data.

For wind, an additional 180° ambiguity check is done on the LiDAR wind directions using Gill direction.

3.1.3.2 Turbulence intensity

The turbulence intensity (TI) supplied in the monthly and final SWLB **WindSpeedDirectionTI.csv* files is estimated from measured standard deviation with a constant factor and influenced by buoy-motion. Here TI is defined as: $(\sigma/\bar{u})$ / C where σ is the standard deviation and $\bar{u}$ is the mean of the wind speed for a 10-min period. C = 0.95 is a constant needed to convert the scan-averaged lidar measurement to the point measurements of a cup anemometer. Note that this definition frequently gives relatively high values in situations with low but variable wind speed. Note also that TI is not compensated for the motion of the buoy, which is a source of increased standard deviation in the measurements, and TI is therefore over-estimated compared to what would be obtained from a lidar on a fixed platform (*Z300 MODBUS interface, a user's guide, 19th Dec 2013, issue K, ZephIR Lidar*).

Motion-compensated estimates of SWLB-measured turbulence intensity are provided in addition to the above-mentioned dataset. Motion-compensation of turbulence intensity is described in the associated report [4].

3.1.3.3 Wave data (applied to the full campaign dataset)

Wave spectra are continuously calculated by Fugro's proprietary Neptun wave processing software while the buoys are measuring at sea. However, only the 2 Hz components of motion (SWLB: heave, pitch, roll) and the calculated wave parameters (as given in the WaveData files) are stored. Wave spectra are re-calculated in house using Neptun. Calculations of wave parameters done onboard the buoy use the measured data before storing and digitalization. Thereafter data is stored, both raw and calculated. During this storage process, the data is digitalized with a given resolution (i.e. binned). If the stored raw data or memspec files are used to re-calculate the wave parameters, there may be small differences compared to parameters calculated onboard the buoy. The resolution settings are, however, set such that the differences are insignificant.

A set of low frequency wave filters was applied to the following wave parameters (WaveData files):

a. If hmax < hm0, hmax is removed.
b. All wave parameters are removed, if hmax/hm0 > 2.3.
   The heave time series is likely contaminated by a disturbance in the form of a single large wave.
c. If tp/tm02 >2.1, tp and thtp are removed and hm0 is set equal to hm0b. If also tm02/tm02b > 2 and hm0b < 0.02, all wave parameters are removed.
d. Any tz < 1 were discarded.

All wave directions (as given in the WaveData files) were corrected for magnetic declination and are given relative to true north.

3.1.3.4 Precipitation

Precipitation is measured by a Young Precipitation Gauge that measures rain or snow precipitation without moving parts. Rain or snow collected in the catchment funnel is directed into the measuring chamber. When the maximum fill level (50 mm) is reached, the column is automatically emptied. Column level is sensed by a capacitive probe and converted to a linear voltage signal which is converted back to height in mm by the buoy's datalogger. Raw data are not stored on the instrument.

During the first half of the campaign, the buoy's datalogger processed the precipitation data into accumulated precipitation per 10 minutes. This was used in the first monthly reports. Raw measurements were not stored on the datalogger.

Mid-campaign, the processing on the datalogger was updated to store the raw column height measurements directly. Precipitation was then updated to raw precipitation ("precip_raw mm") and is reported as such. The filter limits changed to -10 mm (no precipitation) – 50 mm. Emptying of the column when the maximum fill level is reached appears as "negative precipitation", i.e., a jump from 50 mm to lower fill levels.

3.1.3.5 Currents

Only depths 2 – 39 m (top-down) were filtered on current speed, current direction, and signal strength. Current speed and direction where signal strength was below the minimum threshold was removed including any current data in depths 37-39 m. Spikes in current speed at 2 and 3 m depth were removed if the difference in speed compared to the 4 m depth bin was > 6 cm/s.

There is a drop in signal strength of the Aquadopp current meter data below 20 m depth during a large part of the campaign and a substantial amount of data below this depth is filtered out. In addition, marine growth restricted the range of valid data towards the end of the individual deployments. In the bottom half of the profile (below 23 m), any current measurements below any gaps were also removed.

The data at 001 m water depth are measured by a separate set of horizontal transducers, the z-cell. The data was included in the monthly datasets. However, the measurements deviate significantly from the neighbouring bins and appear to be subject to higher uncertainty from dynamic motion near the buoy and the sea surface. For this final dataset, the data in this 001m bin was removed as the measuring principle is different due to the deviation from the neighbouring bins.

All current directions (as given in the CurrentData files) were corrected for magnetic declination and are given relative to true north.

3.1.3.6 Water level

Water level is not measured directly but inferred from measurements of water pressure at the seabed. The Thelma water level sensor is mounted on its own mooring connected to the buoy mooring. The vertical position of the sensor relative to the mean sea level position is obtained from bathymetry data at the deployed coordinates. The pressure sensor head is free floating and assumed to be located at nominally 1-1.5 m above the seabed. This height can vary during a campaign if there are changes to the length of the rope connecting the sensor to its mooring due to either burial of the rope or manual shortening during service visits. In this campaign the nominal sensor height is 1.5 m.

The bottom mounted pressure sensor Thelma gives out an approximate value of water level as the actual pressure in dbar minus 10 dbar which is then approximately equal to the depth in metres. The air pressure measurement from the buoy is subtracted from the total measured water pressure and an adjustment for the height of the sensor above the seabed is included. The actual height of the water column above the sensor is determined using the hydrostatic equation: $h_w = (P_w - P_a)/(\rho g)$ where h_w is the height of the water column, P_w is the measured total water pressure including an adjustment for the height of the sensor above the seabed, P_a is the measured total air pressure, ρ is the average density of the water (inferred from measured salinity and density at Lot 4, here 1006 m^3/kg), and g is the normal acceleration of gravity.

Water level referenced to MSL is then obtained by removing the mean water depth.

At Lot 3, the water pressure timeseries from the Thelma pressure sensor was complete and no changes in mean sensor height were found (**Figure B-10**).

3.1.4 Availability calculations

3.1.4.1 Monthly System Availability: One-Month Average

The Floating Lidar System is ready to function according to specifications and to deliver data, taking into account all time stamped data entries in the output data files including flagged data (e.g. by NaNs or 9999s) for the given month.

Note that for the system to be considered "ready", at least one valid data point must be recorded (at any height).

The Monthly Overall System Availability is the number of those time stamped data entries relative to the maximum possible number of (here 10-minute) data entries including periods of maintenance within the respective calendar month.

3.1.4.2 Monthly Post-processed Data Availability: One-Month Average

The Monthly Post-processed Data Availability is the number of those data entries remaining after subtraction of all non-valid entries caused by including but not limited to:

- downtime (due to equipment failure, maintenance, weather, damage, malfunction, theft, or any other events)
- Lidar internal (unseen) filtering (as set by the Lidar manufacturer)
- application of quality filters based on system own parameters

These are divided by the maximum possible number of 10-minute data entries within the respective month based on the given time interval of 10-minutes.

3.1.4.3 Post-processed parameter group availability

The monthly post-processed parameter group availability is determined as follows:

a. Wind: Average of the 10-minute averaged monthly post processed data availabilities per measured elevation, speed and direction up to and including 200 m from the LiDAR but excluding 240 and 270 m. The wind data set also include near surface wind speed and direction, i. e. wind measured in mast top (4 m height) by the Gill Windsonic sensor.

b. Atmospheric pressure: main instrument (Vaisala)

c. Air temperature: main instrument (Vaisala)

d. Air humidity: main instrument (Vaisala)

e. Sea surface temperature: main instrument (Aquadopp)

f. Wave: Average of wave parameters (10-min frequency), excluding any zero-upcrossing parameters.

g. Current: Average of current speed and direction over the water column.

h. Water level: water pressure for monthly reports.

In the case of multiple (redundant) measurement instruments determining one parameter value, the availability of at least one parameter value is the determining base for the data availability.

Table 3-4 lists the parameters used in the calculations.

Table 3-4 Parameter group availability

Parameter group	Parameters
Wind	WindSpeed004m (m/s), WindSpeed030m (m/s), WindSpeed040m (m/s), WindSpeed060m (m/s), WindSpeed090m (m/s), WindSpeed100m (m/s), WindSpeed120m (m/s), WindSpeed150m (m/s), WindSpeed180m (m/s), WindSpeed200m (m/s) WindDir004m (°N), WindDir030m (°N), WindDir040m (°N), WindDir060m (°N), WindDir090m (°N), WindDir100m (°N), WindDir120m (°N), WindDir150m (°N), WindDir180m (°N), WindDir200m (°N)
Atmospheric pressure	AirPressure (hPa)
Air temperature	AirTemperature (°C)
Air humidity	AirHumidity (%)
Sea surface temperature	WaterTemp001 (°C) from Aquadopp

Wave	hm0 (m), hm0a (m), hm0b (m), mdir (°N), mdira (°N), mdirb (°N), sprtp (°N), thhf (°N), thtp (°N), tm01 (s), tm02 (s), tm02a (s), tm02b (s), tp (s)
Current	AqSpd001 (cm/s), AqSpd002 (cm/s), ..., AqSpd039 (cm/s) AqDir001 (°N), AqDir002 (°N), ..., AqDir039 (°N)
Water level	WaterPressure (dbar)

3.2 Upward-facing ADCP

3.2.1 Measurement configuration

A Nortek Signature 500 current profiler was placed on the seafloor near the SWLB on a separate mooring to measure the current profile from bottom to surface. Water depth at the deployment location was ca. 40 m. The current meter was mounted in a floating buoy resulting in a nominal depth of the transducer head at ca. 3 m above the seafloor. Antifouling patches were applied to the transducers.

Table 3-5 shows the measurement configuration of the Nortek Signature500 current meter (Serial# S102856) at Lot 3. The noise floor for the transducers of this instrument is 27 dB.

Cell size was set to 1 m with blanking distance of 0.5 m and 42 cells in total. The centre of the first valid cell is therefore nominally 4 m above the seafloor. The cells are labelled upward starting at 004m and ending at 042m.

There were 2 deployments of the ADCP in total (**Table 1-2**) with short maintenance windows for data download and battery replacements in between. The sensor configuration is given in **Table 3-5.** During deployment 2, the sensor configuration was reset to the default configuration (2 m cell size and a reduced number of pings to 48). The averaging period, blanking distance and measurement interval remained the same. In addition, the raw data in the ad2cp files is in UTC+2. This was adjusted to UTC during processing.

For this final dataset, D1 (November 2021 – June 2022) and D2 (June 2022 – December 2022) are treated separately. As a result, the processed data are delivered in 2 data files.

Table 3-5 Configuration of measurements of the upward facing ADCP

Deploy-ment	Instrument Type	Sensor Height[1] [m]	Parameter Measured	Sample Height[2] [m]	Sampling Interval	Averaging Period [s]	Measure-ment Interval [s]	Measurement Resolution
1	Nortek Signature 500	-37	Current speed and direction profile, water temperature and water pressure (at 37 m depth)	-4 -5 -6 … -37	1 Hz, 311 pings	120	600	0.9 cm/s 0.1° 0.1°C
2	Nortek Signature 500	-37	Current speed and direction profile, water temperature and water pressure (at 37 m depth)	-4 -6 -8 … -36	1 Hz, 48 pings	120	600	1 cm/s 0.1° 0.1°C

Notes

[1] = Height relative to actual sea surface.

[2] = Height relative to seafloor.

3.2.2 Seawater temperature and water level

The bottom-mounted Nortek Signature 500 also records water temperature at and pressure above the sensor head. The data from the date of deployment until the end of the campaign are nearly complete.

Seawater temperature is used without further processing except for an outlier check, with yielded no exclusions. The measurements are presented in **Section 10.2**.

For the Signature500, there is also an uncertainty in the sensor height above the sea floor similar to what is described in **Section 3.1.3.6** since it is deployed in a floating buoy. The average height for the sensor head above the seafloor is 3.15 m.

The raw water pressure measurements (**Figure B-10**) reveal a change in sensor height above the seafloor after the service visit in June 2022. During the 2nd deployment (from June 2022 onwards), the height is adjusted by comparing the mean pressure before and after the service visit. There is some uncertainty (ca. 40%) connected to this adjustment.

For air pressure, the SWLB measurements are used. Water level referenced to MSL is then calculated as described in **Section 3.1.3.6**.

3.2.3 Data 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.

Standalone ADCP processing follows the required and some recommended steps in the IOOS QUARTOD manual on in-situ current observations [5].

All current data are post-processed from raw data stored on the current meter using the manufacturer's Ocean Contour V2 [6] software and additional python scripts.

The raw data from both deployments was processed using Ocean Contour with the following quality filters:

1. Bin mapping to compensate for tilt, i.e., cell re-positioning to account for differences in the vertical bin-depth, i.e., vertical alignment.

   An excessive tilt check was not implemented.

2. Minimum signal strength of 32 dB: here noise floor (27 dB) + 5 dB.

This removes data with poor return signal quality.

3. Minimum 50 % correlation between incoming and outgoing beams.

   This also removes data with poor return signal quality.

4. Automatic sidelobe removal threshold: 95%

5. Correction for magnetic declination (+5°).

   Current directions are reported relative to true north.

6. Averaging over 1 averaging window per cell to yield 10-minute averages (default for 10-minute averages).

The processed data was exported from Ocean Contour as netcdf and combined using python scripts. The data from D2 was shifted to UTC from UTC+2. Data during the service periods was set to NaN. Current speed and current direction columns were renamed based on sensor height and cell size, upward, starting at 004 m and ending at 042 m. The Ocean Contour data mask (contained in the data files) was applied to the current speed and current directions only. Timestamps were rounded to the nearest 10 min and current speed was converted to cm/s. Bins 38m – 42m were removed by the automatic sidelobe removal (step 4). Current speed and current direction in the 37m bin still showed apparent strong influences of sidelobes and all current speeds and directions in this bin were removed.

The following IOOS QUARTOD tests were implemented:

a. Current speed [0;135] cm/s

b. Current directions [0;360°]

c. Test on extreme changes and outliers in heading, pitch, and roll

d. Vertical velocities (both up1 and up2) were checked for indications of excessive values.

   Some high vertical velocities in uppermost bins (27 – 36 m) were found, and all speed and direction data where the absolute value of the vertical velocity was greater than 17 cm/s were removed.

In April 2022, current speed spikes in the 36m bin were found and the associated current speed and direction data was removed.

Data in the near-surface bins may periodically still be affected by sidelobe energy during rougher conditions. This can appear as spikes in the current speed data. Signal strength per beam is part of the data file and can be used to do further analysis and exclusions, if deemed necessary.

The upward-facing dataset penetrates through the boundary between the Baltic water and denser North Sea overflow water (at ca. 20 m water depth during late summer), accompanied by a decrease in return signal strength above this thermocline is present in the data. The signal strength is, however, still above the minimum threshold.

3.3 Comments on top-down and bottom-up current data

During the campaign the current speed and direction measurements by the buoy-mounted, downward-facing Aquadopp 600kHz z-cell and the floater-mounted upward-facing Signature500 were compared. It was discovered that the Aquadopp-measured current directions appeared to differ by on average 30 degrees from modelled current directions while the floater-mounted upward-looking Signature agree better with modelled current directions.

Time series of depth-averaged (between 10 – 30 m) Aquadopp vs Signature current speed and directions show no constant offset but periods of agreement and periods of larger offsets for both current speeds and directions appearing to correspond to sea state.

Neither the mounting of the Aquadopp, nor magnetic influence, offsets in heading or differences in post-processing explain the differences between the Aquadopp and Signature data. The manufacturer confirmed that both instruments were set up and configured correctly and worked as intended. After checking for mounting, magnetic influence and proper processing, the main remaining issue is additional, unaccounted sources of error in the measurements, specifically motion.

In this project, the surface-buoy mounted Aquadopps experience rapid motion during both high sea states and low sea states (buoy resonance). In addition, there are effects of bubbles, turbulence, non-linear dynamics from flow around and underneath the buoy as well as reflections from the sea surface and/or air when the motion is high. These are not distinguishable in the data. In contrast, the Signatures experience less motion and less non-linear dynamics than the surface-buoy mounted Aquadopps. In addition, the Signatures have more internal QC and more post-processing options, including bin mapping that helps compensate for more motion than just averaging over a given interval.

The deviation between both instruments is strongly correlated with the prevailing sea states. When the sea is calm, both instruments measure the same and when the sea is rough, the Aquadopp measures higher current speeds than the Signature.

More details are given in two technical notes ([7], [8]).

4. Data files

Table 4-1 lists the final 12-month datafiles. This includes the full SWLB dataset, the QC'd ADCP data and the motion-compensated turbulence intensity data and reports.

Table 4-1 List of final campaign datafiles at Lot 3

Instrument	Filename
SWLB	Energinet_Lot3_SWLB_20240424 November 2021 November 2022 CurrentData.csv Energinet_Lot4_SWLB_20240303 November 2021 November 2022 MetOceanData.csv Energinet_Lot4_SWLB_20240303 November 2021 November 2022 Posdata.csv Energinet_Lot4_SWLB_20240303 November 2021 November 2022 Status.csv Energinet_Lot4_SWLB_20240424 November 2021 November 2022 WaveData.csv Energinet_Lot4_SWLB_20240303 November 2021 November 2022 WindSpeedDirectionTI.csv Energinet_Lot4_SWLB_20240303 November 2021 November 2022 WindStatus.csv
ADCP (upward)	Energinet_Lot3_Signature_20240405 November 2021 June 2022.csv Energinet_Lot3_Signature_20240405 June 2022 November 2022.csv
TI	LOT3_Deployment1_TIdata.csv LOT3_Deployment2_TIdata.csv

Appendix C lists the contents and parameters of each final post-processed datafile listed in **Table 4-1**.

Appendix D gives additional information on any raw data files supplied with this dataset.

5. Data Availabilities

5.1 Issues and gaps affecting the final dataset

Appendix A summarizes events that impact data availability and the descriptions of these gaps as far as these are ascertainable.

The lidar measurements can be influenced by adverse weather conditions (e. g. fog, rain, poor visibility) resulting in low packet counts. Measurements at each height are independent and short gaps at intermediate heights can occur.

On 01 March 2022 at 20:10, the SWLB unit stopped transmitting data. The lidar unit kept collecting data until the SWLB was recovered for service in June 2022. The lidar wind dataset from 01 March 2022 until the service on 20 June 2022 was reprocessed from raw 1hz lidar and Septentrio heading data.

There is a drop in signal strength of the Aquadopp current meter data below 20 m depth during a large part of the campaign and a substantial amount of data below this depth is filtered out. The downward looking profiler is most likely experiencing interference at the boundary between 2 water layers (Baltic water and denser North Sea overflow water), see Events 1 and 9 in **Appendix A**, and marine growth restricting the range towards the end of the individual deployments.

There is a spike in the SWLB (Aquadopp) current speed data (depths 16m and below) on 27 March 2022 (Event 8, **Appendix A**). The raw data show that the signal strength for all beams is well above the cut-off threshold. The upward-facing Signature data also show elevated current speeds at the corresponding depths, however, much lower speeds overall. The Aquadopp data are included in this dataset.

Availability of the upward facing current data is calculated per deployment and also accounting for the service intervals.

5.2 12-month Post-processed Data Availability

The final campaign post-processed data availability per parameter for the period 21 November 2021 to 21 November 2022 is presented in **Table 5-1**.

Table 5-1: SWLB 12-month post-processed data availability

Parameter	Availability [%]	Parameter	Availability [%]
WindDir004m deg	99.4	hm0 m	99.4
WindDir030m deg	99.0	hm0a m	95.9
WindDir040m deg	99.1	hm0b m	99.4
WindDir060m deg	98.9	hmax m	88.2
WindDir090m deg	96.5	hmean m	91.9
WindDir100m deg	96.3	hs m	91.9
WindDir120m deg	96.0	mdir deg	99.4
WindDir150m deg	95.7	mdira deg	99.4
WindDir180m deg	95.5	mdirb deg	99.4
WindDir200m deg	95.4	sprtp deg	99.4
WindDir240m deg	95.2	thhf deg	99.4
WindDir270m deg	95.1	thmax s	88.2
WindGust004m m/s	99.4	thtp deg	97.9
WindSpeed004m m/s	99.4	tm01 s	99.4
WindSpeed030m m/s	99.0	tm02 s	99.4
WindSpeed040m m/s	99.1	tm02a s	99.4
WindSpeed060m m/s	98.9	tm02b s	99.4
WindSpeed090m m/s	96.5	tp s	97.9
WindSpeed100m m/s	96.3	tz s	91.9
WindSpeed120m m/s	96.0	ts s	91.9
WindSpeed150m m/s	95.7	AirTemperature C	99.4
WindSpeed180m m/s	95.5	precipitation mm	99.4
WindSpeed200m m/s	95.4	solarIrradiance W/m2	99.4
WindSpeed240m m/s	95.2	thTBRtemperature degC	99.4
WindSpeed270m m/s	95.1	WaterTemp001 degC	99.4
AirHumidity %	99.4	WaterPressure dbar	99.2
AirPressure hPa	99.3	BottomTemperature degC	86.1
AqDir002 deg	90.3	AqSpd002 cm/s	90.3
AqDir003 deg	95.0	AqSpd003 cm/s	95.0
AqDir004 deg	99.4	AqSpd004 cm/s	99.4
AqDir005 deg	99.4	AqSpd005 cm/s	99.4

Parameter	Availability [%]	Parameter	Availability [%]
AqDir006 deg	99.4	AqSpd006 cm/s	99.4
AqDir007 deg	99.4	AqSpd007 cm/s	99.4
AqDir008 deg	99.4	AqSpd008 cm/s	99.4
AqDir009 deg	99.4	AqSpd009 cm/s	99.4
AqDir010 deg	99.3	AqSpd010 cm/s	99.3
AqDir011 deg	99.1	AqSpd011 cm/s	99.1
AqDir012 deg	99.0	AqSpd012 cm/s	99.0
AqDir013 deg	98.0	AqSpd013 cm/s	98.0
AqDir014 deg	96.2	AqSpd014 cm/s	96.2
AqDir015 deg	94.9	AqSpd015 cm/s	94.9
AqDir016 deg	93.6	AqSpd016 cm/s	93.6
AqDir017 deg	92.3	AqSpd017 cm/s	92.3
AqDir018 deg	90.8	AqSpd018 cm/s	90.8
AqDir019 deg	89.7	AqSpd019 cm/s	89.7
AqDir020 deg	88.7	AqSpd020 cm/s	88.7
AqDir021 deg	87.3	AqSpd021 cm/s	87.3
AqDir022 deg	85.9	AqSpd022 cm/s	85.9
AqDir023 deg	84.1	AqSpd023 cm/s	84.1
AqDir024 deg	81.8	AqSpd024 cm/s	81.8
AqDir025 deg	78.8	AqSpd025 cm/s	78.8
AqDir026 deg	75.3	AqSpd026 cm/s	75.3
AqDir027 deg	71.4	AqSpd027 cm/s	71.4
AqDir028 deg	67.4	AqSpd028 cm/s	67.4
AqDir029 deg	63.3	AqSpd029 cm/s	63.3
AqDir030 deg	59.4	AqSpd030 cm/s	59.4
AqDir031 deg	55.2	AqSpd031 cm/s	55.2
AqDir032 deg	51.3	AqSpd032 cm/s	51.3
AqDir033 deg	45.7	AqSpd033 cm/s	45.7
AqDir034 deg	40.7	AqSpd034 cm/s	40.7
AqDir035 deg	35.3	AqSpd035 cm/s	35.3
AqDir036 deg	30.9	AqSpd036 cm/s	30.9
AqDir037 deg	0.0	AqSpd037 cm/s	0.0
AqDir038 deg	0.0	AqSpd038 cm/s	0.0
AqDir039 deg	0.0	AqSpd039 cm/s	0.0

Table 5-2: Signature post-processed data availability during D1 (November 2021 – June 2022)

Parameter	Availability [%]	Parameter	Availability [%]
Speed004m_cm/s	98.2	SigDir004m_deg	98.2
Speed005m_cm/s	98.2	SigDir005m_deg	98.2
Speed006m_cm/s	98.2	SigDir006m_deg	98.2
Speed007m_cm/s	98.2	SigDir007m_deg	98.2
Speed008m_cm/s	98.2	SigDir008m_deg	98.2
Speed009m_cm/s	98.2	SigDir009m_deg	98.2
Speed010m_cm/s	98.2	SigDir010m_deg	98.2
Speed011m_cm/s	98.2	SigDir011m_deg	98.2
Speed012m_cm/s	98.2	SigDir012m_deg	98.2
Speed013m_cm/s	98.2	SigDir013m_deg	98.2
Speed014m_cm/s	98.2	SigDir014m_deg	98.2
Speed015m_cm/s	98.2	SigDir015m_deg	98.2
Speed016m_cm/s	98.2	SigDir016m_deg	98.2
Speed017m_cm/s	98.2	SigDir017m_deg	98.2
Speed018m_cm/s	98.2	SigDir018m_deg	98.2
Speed019m_cm/s	98.2	SigDir019m_deg	98.2
Speed020m_cm/s	98.2	SigDir020m_deg	98.2
Speed021m_cm/s	98.2	SigDir021m_deg	98.2
Speed022m_cm/s	98.2	SigDir022m_deg	98.2
Speed023m_cm/s	98.2	SigDir023m_deg	98.2
Speed024m_cm/s	98.2	SigDir024m_deg	98.2
Speed025m_cm/s	98.2	SigDir025m_deg	98.2
Speed026m_cm/s	98.2	SigDir026m_deg	98.2
Speed027m_cm/s	98.2	SigDir027m_deg	98.2
Speed028m_cm/s	98.2	SigDir028m_deg	98.2
Speed029m_cm/s	98.2	SigDir029m_deg	98.2
Speed030m_cm/s	98.2	SigDir030m_deg	98.2
Speed031m_cm/s	98.2	SigDir031m_deg	98.2
Speed032m_cm/s	98.2	SigDir032m_deg	98.2
Speed033m_cm/s	98.2	SigDir033m_deg	98.2
Speed034m_cm/s	98.1	SigDir034m_deg	98.1
Speed035m_cm/s	98.1	SigDir035m_deg	98.1
Speed036m_cm/s	96.7	SigDir036m_deg	96.7
Speed037m_cm/s	0.0	SigDir037m_deg	0.0

Table 5-3: Signature post-processed data availability during D2 (June 2022 – December 2022)

Parameter	Availability [%]	Parameter	Availability [%]
Speed004m_cm/s	99.8	SigDir004m_deg	99.8
Speed006m_cm/s	100.0	SigDir006m_deg	100.0
Speed008m_cm/s	100.0	SigDir008m_deg	100.0
Speed010m_cm/s	100.0	SigDir010m_deg	100.0
Speed012m_cm/s	100.0	SigDir012m_deg	100.0
Speed014m_cm/s	100.0	SigDir014m_deg	100.0
Speed016m_cm/s	100.0	SigDir016m_deg	100.0
Speed018m_cm/s	100.0	SigDir018m_deg	100.0
Speed020m_cm/s	100.0	SigDir020m_deg	100.0
Speed022m_cm/s	100.0	SigDir022m_deg	100.0
Speed024m_cm/s	100.0	SigDir024m_deg	100.0
Speed026m_cm/s	100.0	SigDir026m_deg	100.0
Speed028m_cm/s	100.0	SigDir028m_deg	100.0
Speed030m_cm/s	100.0	SigDir030m_deg	100.0
Speed032m_cm/s	100.0	SigDir032m_deg	100.0
Speed034m_cm/s	100.0	SigDir034m_deg	100.0

5.3 12-month post-processed parameter group availability

The monthly post processed data availability per main parameter group as reported in the monthly reports is compared to the final monthly post-processed group availability and shown in **Table 5-4** through **Table 5-6**. The final, overall, 12-month post-processed parameter group availability for the final dataset is shown in the last row (row "F").

Any gaps due to satellite transmission/reception issues are filled.

The floating lidar system performed well and without disruptions during all 12 months of the campaign leading to a virtually complete dataset.

The wave data of the first 12 months of the campaign were not filtered with the low frequency wave filter. This was added for the final dataset resulting in slightly lower availability for those months.

The SWLB current dataset has been subjected to stricter QC than during the monthly checks resulting in overall lower current data availability.

Table 5-4: Post-processed parameter group availability (wind, waves, currents) in % for the SWLB data per month: monthly reports and final dataset.

#	Reporting Period	Monthly Wind	Final Wind	Monthly Wave	Final Wave	Monthly Current	Final Current
1	NovDec2021	96.6	97.1	99.8	100.0	96.9	80.6
2	Dec2021Jan2022	95.1	95.4	100	100.0	94.6	76.5
3	JanFeb2022	97.8	98.2	100	100.0	70.4	67.1
4	FebMar2022	94.3	94.4	99.7	99.4	68.7	66.7
5	MarApr2022	98.5	98.5	99.6	99.4	88.4	83.6
6	AprMay2022	99.0	99.0	99.3	98.8	99.7	91.9
7	MayJun2022	95.6	95.7	95.3	94.9	94.8	87.2
8	JunJuly2022	96.8	96.9	96.9	96.6	90.9	83.7
9	JulyAug2022	99.0	99.0	99.5	99.0	95.4	88.7
10	AugSep2022	98.3	98.3	99.9	99.7	91.9	84.4
11	SepOct2022	99.5	99.5	99.9	99.7	61.5	55.4
12	OctNov2022	94.0	94.0	99.8	99.5	42.2	37.4
F	**Nov2021 – Nov2022**	-	**97.2**	-	**98.9**	-	**75.3**

Table 5-5: Post-processed parameter group availability (met parameters) in % for the SWLB data per month: monthly reports and final dataset.

#	Reporting Period	Monthly Atm. Pressure	Final Atm. Pressure	Monthly Air temp.	Final Air temp.	Monthly Air humidity	Final Air humidity
1	NovDec2021	99.1	100.0	99.8	100.0	99.8	100.0
2	Dec2021Jan2022	99.6	100.0	99.6	99.6	99.6	99.6
3	JanFeb2022	99.7	100.0	99.9	99.9	99.9	99.9
4	FebMar2022	98.5	100.0	99.8	99.8	99.8	99.8
5	MarApr2022	97.0	99.6	100.0	100.0	100.0	100.0
6	AprMay2022	97.5	99.9	100.0	100.0	100.0	100.0
7	MayJun2022	93.0	95.5	95.8	95.9	95.8	95.9
8	JunJuly2022	95.4	97.3	97.2	97.3	97.2	97.3
9	JulyAug2022	96.5	99.6	100.0	100.0	100.0	100.0
10	AugSep2022	97.2	99.8	100.0	100.0	100.0	100.0
11	SepOct2022	98.1	99.8	100.0	100.0	100.0	100.0
12	OctNov2022	99.1	100.0	100.0	100.0	100.0	100.0
F	**Nov2021 – Nov2022**	-	**99.3**	-	**99.4**	-	**99.4**

Table 5-6: Post-processed parameter group availability (sea surface temperature, water pressure) in % for the SWLB data per month: monthly reports and final dataset.

#	Reporting Period	Monthly Sea surf. Temp.	Final Sea surf. Temp.	Monthly Water pressure	Final Water pressure
1	NovDec2021	98.4	100.0	99.7	100.0
2	Dec2021Jan2022	94.4	100.0	100.0	100.0
3	JanFeb2022	82.1	100.0	99.9	100.0
4	FebMar2022	99.9	100.0	99.9	100.0
5	MarApr2022	100.0	100.0	100.0	100.0
6	AprMay2022	100.0	100.0	100.0	100.0
7	MayJun2022	95.8	95.9	95.8	95.9
8	JunJuly2022	97.2	97.2	94.9	95.0
9	JulyAug2022	100.0	100.0	99.5	99.5
10	AugSep2022	100.0	100.0	100.0	100.0
11	SepOct2022	100.0	100.0	100.0	100.0
12	OctNov2022	100.0	100.0	100.0	100.0
F	**Nov2021 – Nov2022**	-	**99.4**	-	**99.2**

Table 5-7: Post-processed parameter group availability (sea surface temperature, water pressure, current data) in % from the upward-facing for the final dataset per deployment.

#	Reporting Period	Final Sea surf. Temp.	Final Water pressure	Final Current
F	**Nov2021 – Jun2022**	**98.2**	**98.2**	**95.3**
F	**Jun2022 – Dec2022**	**100.0**	**100.0**	**100.0**

6. Uncertainty assessment of the Lidar wind data

The pre-deployment validation of WS199 took place between 2021-09-30 and 2021-10-19 [1] and contains an uncertainty estimation considering the following components: 1. Reference/anemometer uncertainty, 2. Mean deviation of the remote sensor measurements and the reference measurements, 3. Standard uncertainty of the measurement of the remote sensing device, 4. Mounting uncertainty of the remote sensor at the verification test, 5. Uncertainty due to non-homogenous flow, and 6. Uncertainty due to separation distance.

The uncertainty estimation for the FLS verifications was done according to the IEC bin definition. The IEC database requirement for the lidar verification of 180 hours between 4 m/s and 16 m/s was met for each comparison height. The additional IEC database requirement of a minimum of 3 data pairs in each 0.5 m/s wind speed bin was fulfilled for each comparison height.

The maximum 10-minute averaged wind speeds at the reference lidar varied between 20.5 m/s at the lowest comparison level (40 m) and 24.9 m/s at the highest level (250 m). The air temperatures ranged from 2.6 °C to 17.3 °C. The significant wave heights observed were up to 3.35 m. The maximum wave heights observed cover a range up to 4.96 m. The tidal or water levels observed at Mausund, north of Frøya during the measurement campaign varied between 125.3 cm and 123.2 cm over MSL.

For WS199, the overall uncertainty during the pre-deployment validation trial varied between 1.67 % - 2.84 % for wind speeds between 2-16 m/s and 40 - 120 m height.

7. Results: Buoy position

Figure 7-1 shows the position of the buoy throughout the campaign, the nominal anchor position reported in **Table 1-1**, and the Signature500 anchor position. There were no drifts of position changes.

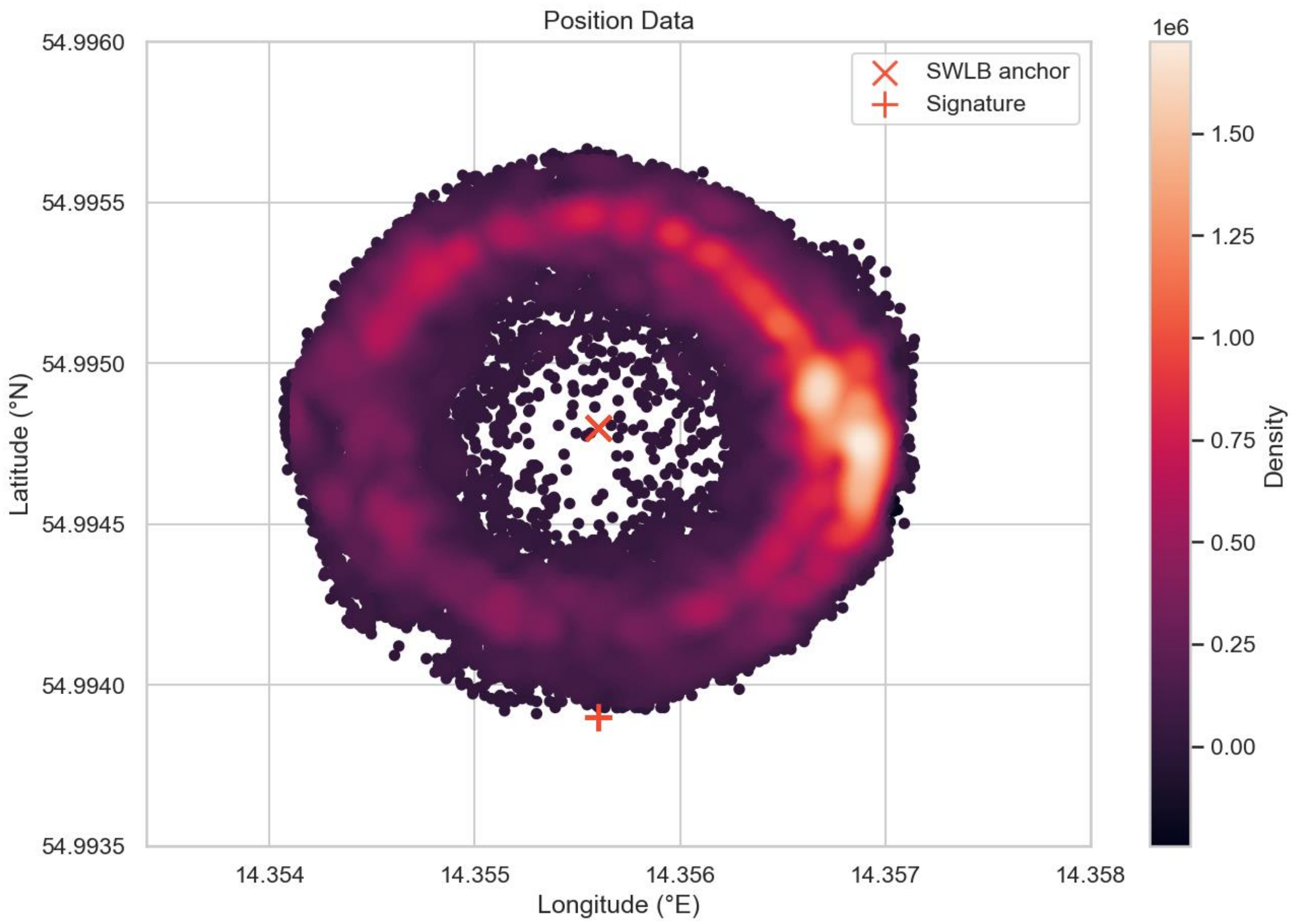


Figure 7-1: Full campaign SWLB and Signature500 position data.

8. Results: Wind

The floating lidar system performed well during all 12 months of the campaign leading to a virtually complete wind dataset. Measurements were taken between 04 m and 270 m height.

Timeseries of wind speed and direction are presented in **Appendix B**.

Table 8-1 summarizes statistics for wind speed over the full campaign. **Figure 8-1** shows wind roses at 4 heights (04, 90, 150, and 240 m) for all 12 months of data and **Figure 8-2** presents the wind speed profile for the full campaign.

The highest wind speeds during the campaign were measured in February 2022. High wind speeds (> 30 m/s) were also measured in January and April 2022. The dominant wind direction was from the west.

Table 8-1: 12-month summary statistics (standard deviation, minimum, mean and maximum): wind speed

Instrument / Parameter	Height [m]	Standard Deviation [m/s]	Minimum [m/s]	Mean [m/s]	Maximum [m/s]
Gill Windsonic 10min wind speed (WindSpeed004m m/s)	4	4.2	0.4	8.9	28.9
ZephIR Lidar 10min wind speed	30	3.3	0.0	7.1	20.8
	40	3.8	0.5	8.3	26.0
	60	3.9	0.5	8.5	26.9
	90	4.1	0.5	8.9	27.3
	100	4.4	0.5	9.4	28.9
	120	4.5	0.5	9.5	29.2
	150	4.7	0.5	9.6	30.0
	180	4.9	0.5	9.8	31.7
	200	5.0	0.5	10.0	32.9
	240	5.1	0.4	10.1	33.5
	270	5.3	0.5	10.2	33.3

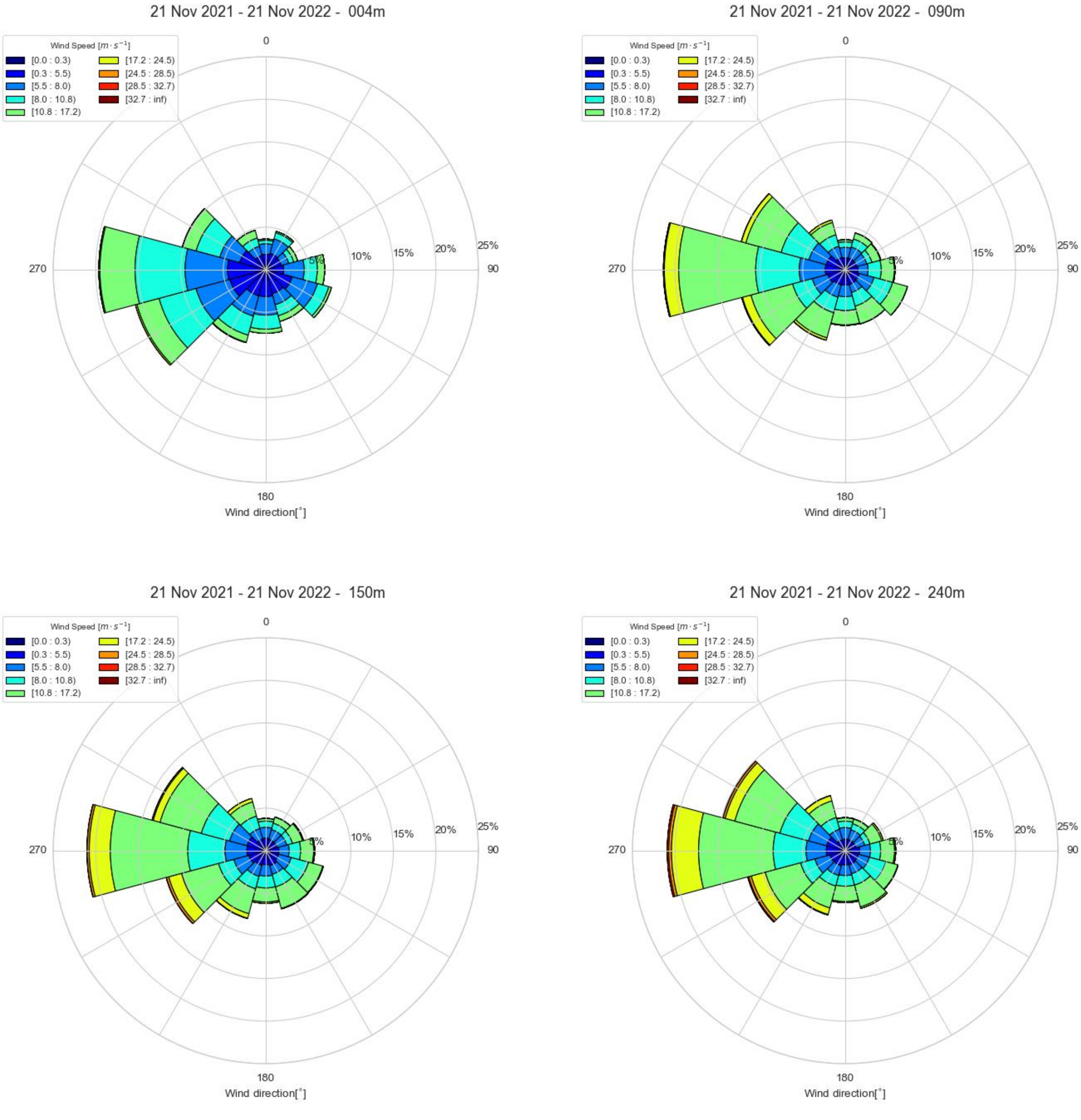


Figure 8-1 Wind roses at 04 m, 90 m, 150 m, and 240 m height for the full 12 months

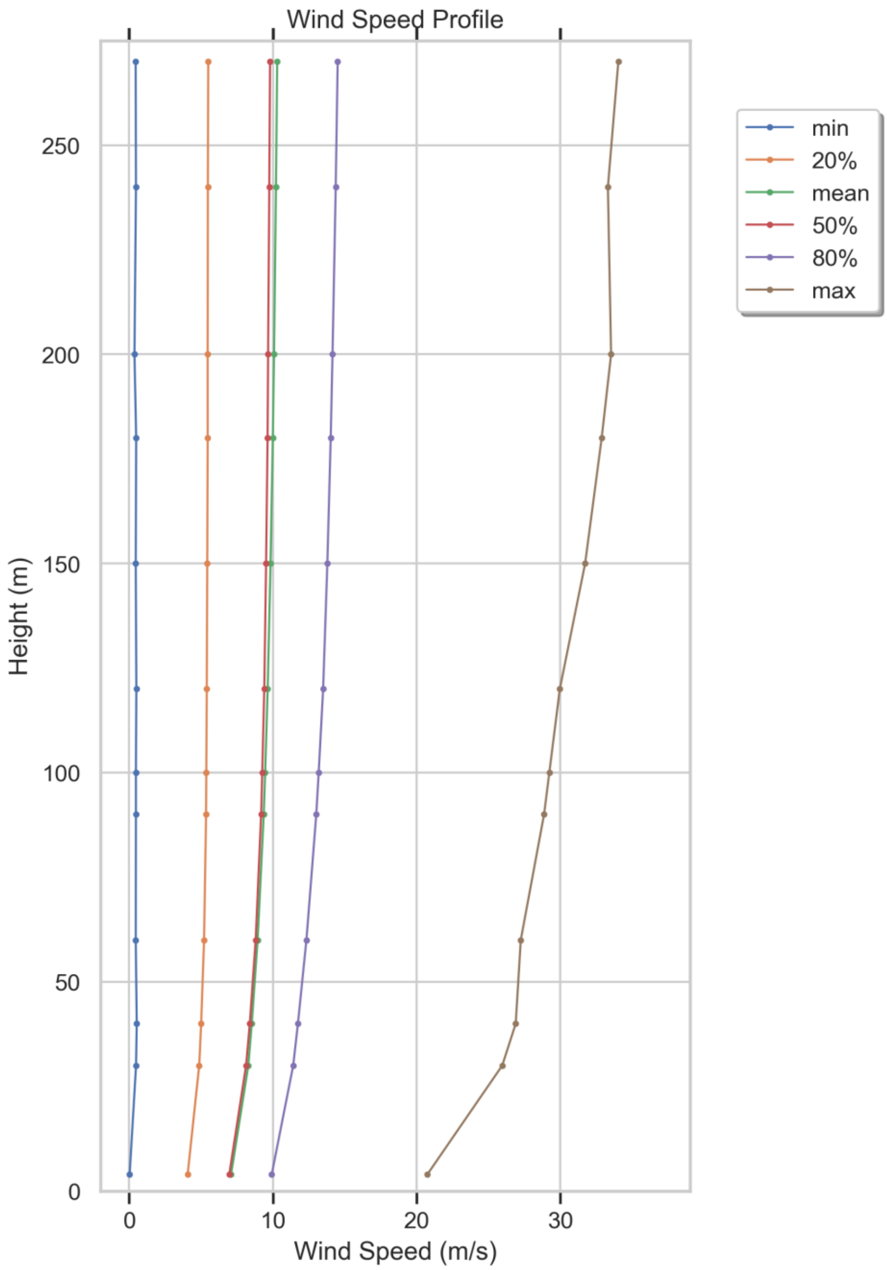


Figure 8-2 12-month wind speed profile

9. Results: Waves

The floating lidar system performed well and without disruptions during all 12 months of the campaign leading to a virtually complete wave dataset.

Timeseries of wave height, period and direction are presented in **Appendix B.2**.

Table 9-1 summarizes statistics for wave heights and periods over the full campaign. **Figure 9-1** shows a wave rose for wave height and direction for all 12 months of data. **Figure 9-2** shows examples of directional wave spectra for 3 high wave events during the campaign.

All wave directions (as given in the WaveData files) were corrected for magnetic declination and are given relative to true north.

The highest wave heights during the campaign were measured at the end of January 2022. High wave heights (hmax > 6 m) were also measured in December 2021, January, February, and April 2022. The dominant wave directions are from west.

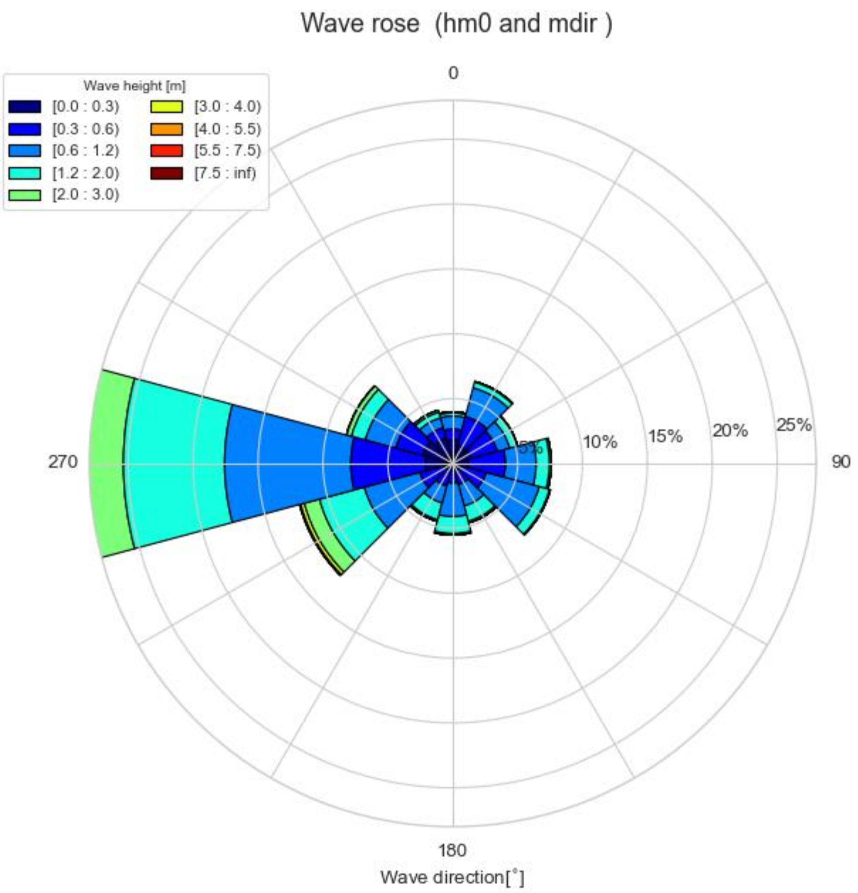
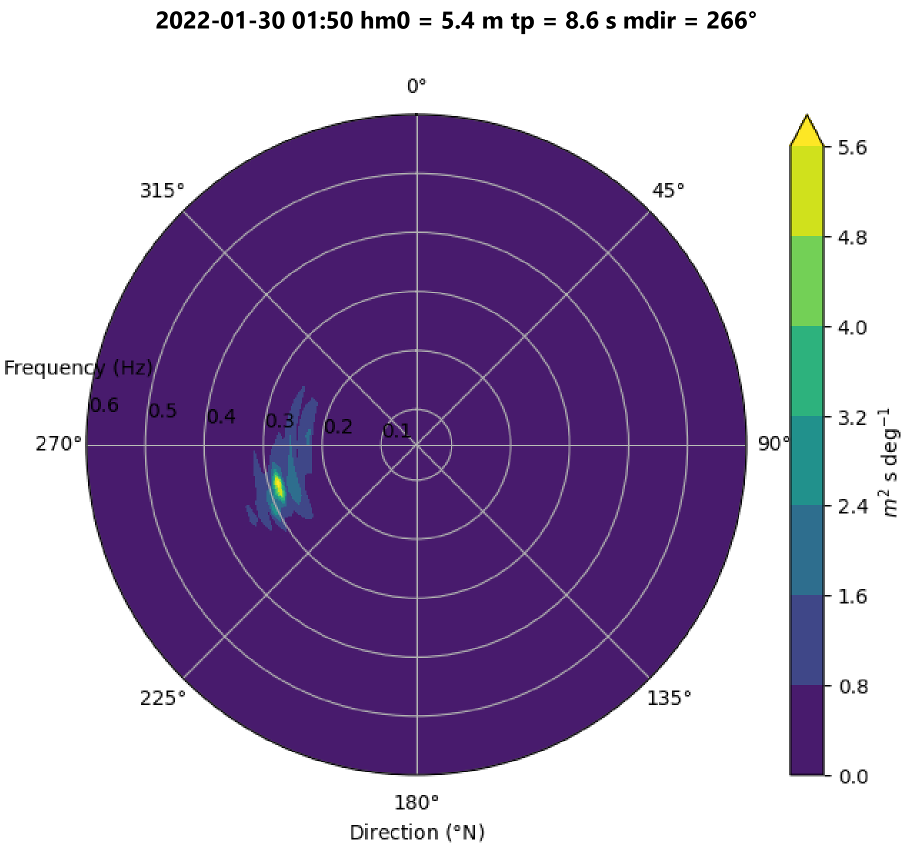


Figure 9-1 12-month waverose with wave direction relative to true north (°N)

Table 9-1: 12-month summary statistics (standard deviation, minimum, mean and maximum): wave parameters

Parameter	Unit	Height [m]	Standard deviation	Minimum	Mean	Maximum
hm0 m	m	0	0.7	0.1	0.9	5.4
hmax m	m	0	1.0	0.3	1.6	9.8
thmax s	s	0	1.1	2.4	4.4	14.3
tm01 s	s	0	0.8	2.3	3.8	7.7
tm02 s	s	0	0.7	2.3	3.6	7.3
tp s	s	0	1.2	2.0	4.5	9.8



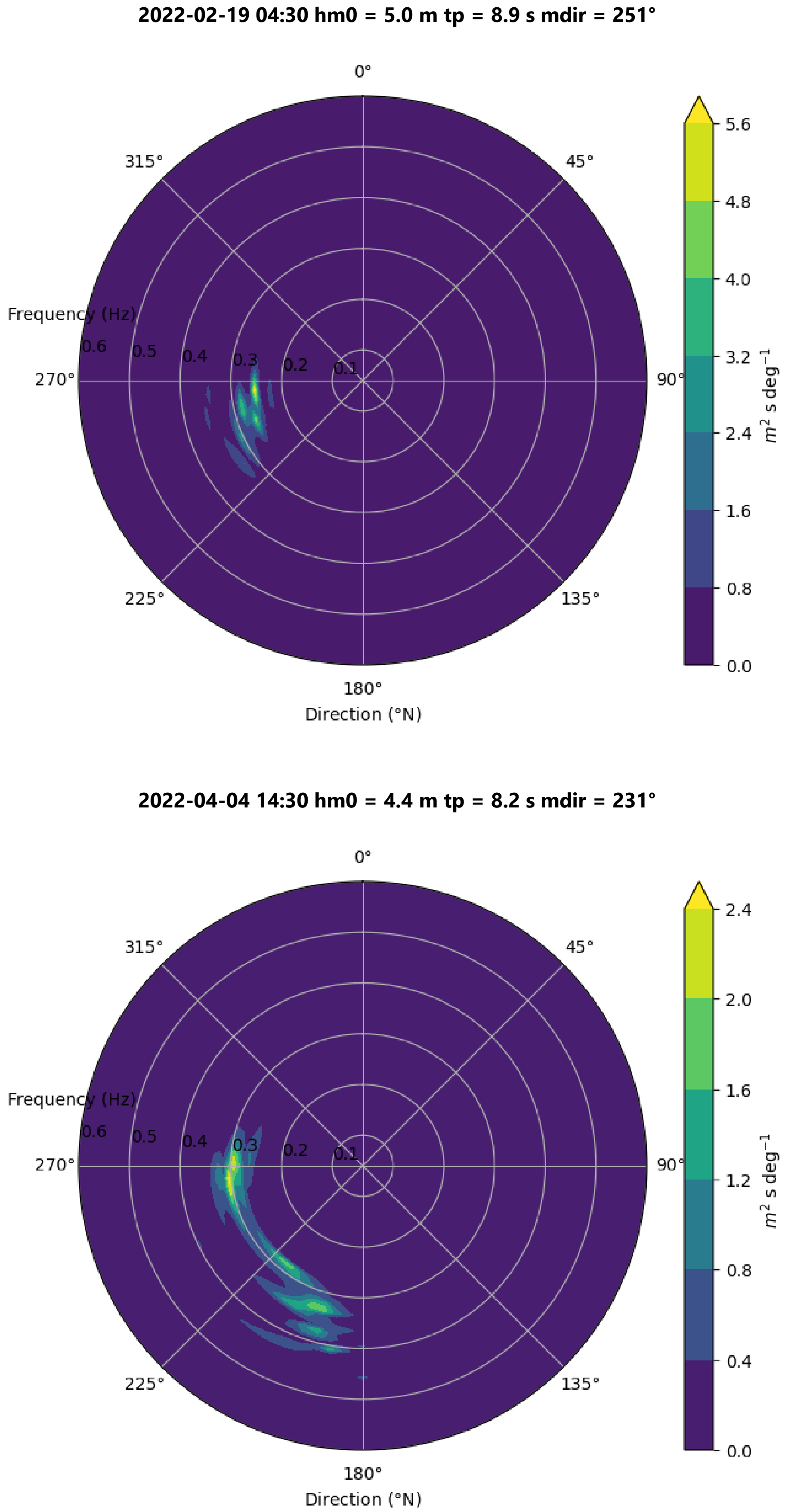


Figure 9-2 Directional wave spectra (MEM spectra m^2/s) from 3 wave events: 2022-01-30, 2022-02-19, and 2022-04-04.

10. Results Metocean

10.1 Met

Timeseries of all atmospheric parameters are presented in **Appendix B.3**.

Please note that for precipitation, a jump from 50 mm to lower fill levels indicates emptying of the column when the maximum fill level is reached.

Table 10-1 summarizes statistics for the main atmospheric parameters over the full campaign.

Between 21 November 2021 and 21 November 2022, the air temperature varied between -4.5 and 26.1 °C. The air pressure varied between 968.8 and 1048.9 hPa.

The lowest air temperatures were measured in December 2021. The highest air temperatures were recorded in August 2022. The lowest air pressures were measured in February 2022. The highest air pressures were recorded in March 2022.

Table 10-1: 12-month summary statistics (standard deviation, minimum, mean and maximum): met parameters

Parameter	Unit	Height [m]	Standard deviation	Minimum	Mean	Maximum
AirHumidity %	% R.H.	4	10.1	38.1	81.6	99.2
AirPressure hPa	hPa	0.5	10.9	968.8	1015.3	1048.9
AirTemperature C	°C	4	6.1	-4.5	10.2	26.1

10.2 Sea water temperatures

Table 10-2 summarizes statistics for water temperature from all sensors over the full campaign. **Figure 10-1** shows 6-monthly timeseries of all seawater temperature data from all sensors.

Between 21 November 2021 and 21 November 2022, the sea surface temperature varied between 3.8 and 25.1 °C. The water temperature near the seafloor varied between 4.1 and 15.9 °C.

Table 10-2: 12-month summary statistics (standard deviation, minimum, mean and maximum): sea water temperatures

Parameter	Unit	Height [m]	Standard deviation	Minimum	Mean	Maximum
Sea surface temperature (Aquadopp)	°C	-1	5.9	3.8	11.0	25.1
Signature	°C	-37	3.9	4.1	9.8	15.9
Bottom Water Temperature (Thelma)	°C	-39	3.9	4.1	9.4	15.9

Figure 10-1 Timeseries of all seawater temperature data from all sensors for all depths per 6 months intervals

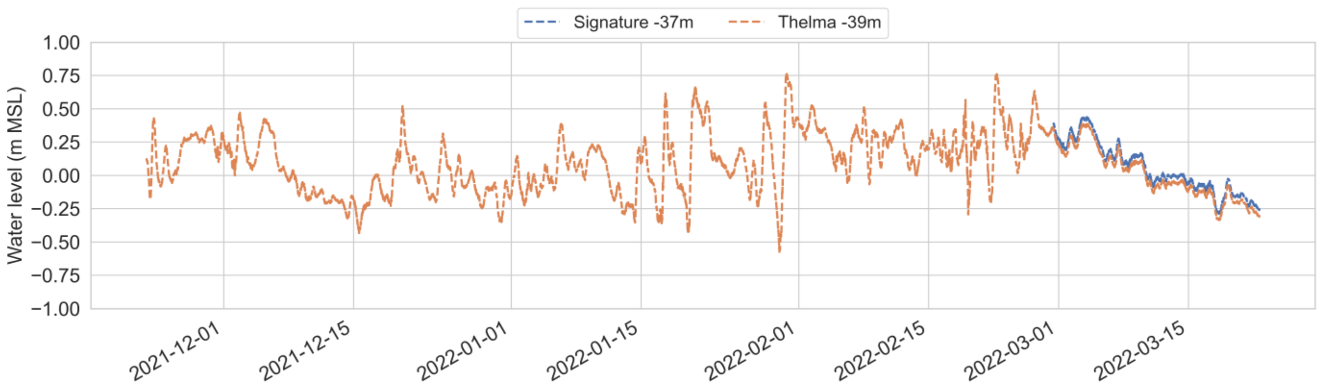
10.3 Water level

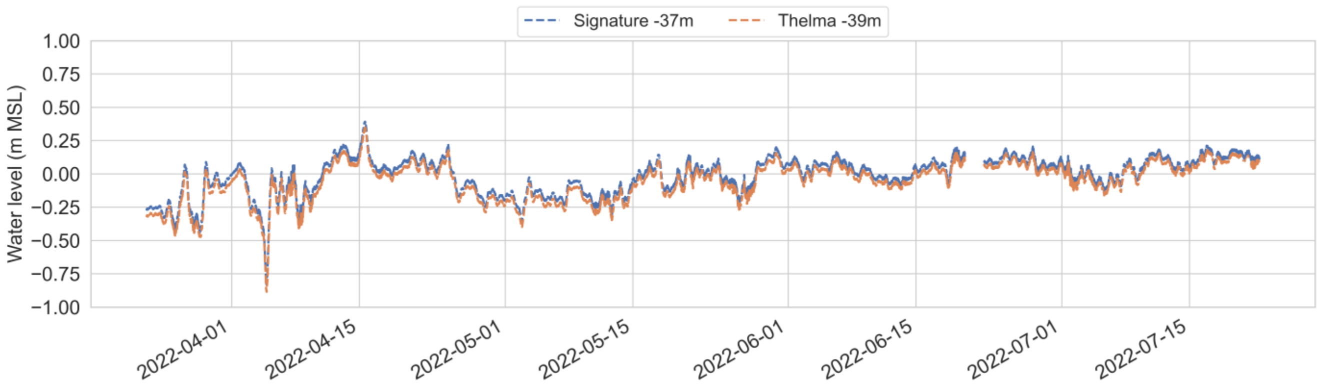
Table 10-3 summarizes statistics for water pressure and water level (ref. MSL) from the Thelma bottom unit and the Signature500 over the full campaign. **Figure 10-2** shows 6-monthly timeseries of all water level data from all sensors. Given the uncertainties in the sensor heights, the water levels calculated from both the Thelma pressure gauge and the pressure sensor of the Signature500 agree well.

Between 21 November 2021 and 21 November 2022, the water pressure varied between 37.7 and 39.7 dbar. Water level varied between -0.9 and 0.8 m.

Table 10-3: 12-month summary statistics (standard deviation, minimum, mean and maximum): water pressure and water level (ref. MSL)

Parameter	Unit	Height [m]	Standard deviation	Minimum	Mean	Maximum
Water pressure (Thelma)	dbar	-39	0.2	37.7	38.9	39.7
Water level MSL (Thelma)	m	0	0.18	-0.89	0.00	0.76
Water pressure (Signature500)	dbar	-37	0.5	36.0	37.7	38.5
Water level MSL (Signature500)	m	0	0.14	-0.83	0.00	0.44





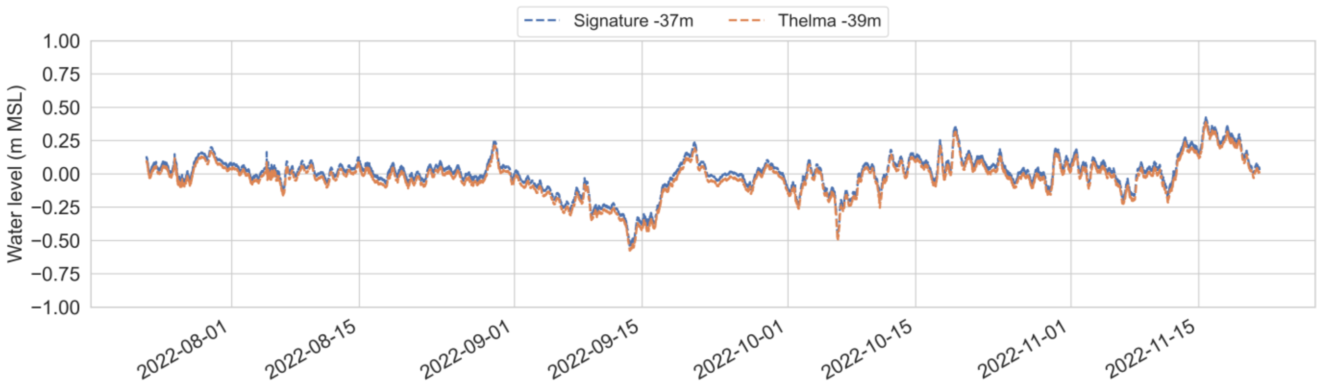


Figure 10-2 Timeseries of water level (ref. MSL) per 6 months intervals

11. Results Currents

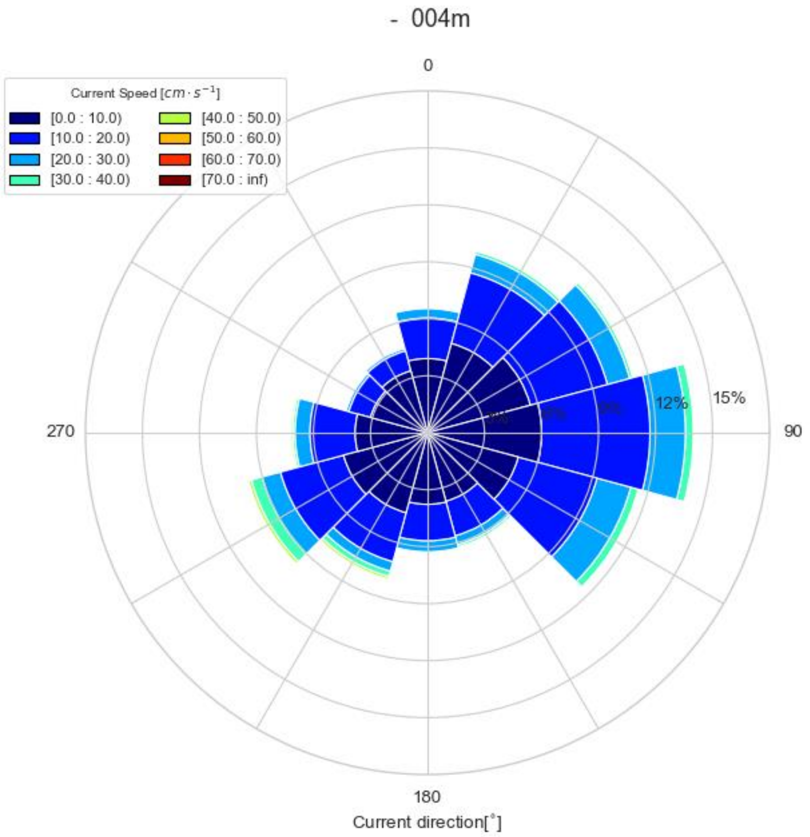
11.1 SWLB Aquadopp

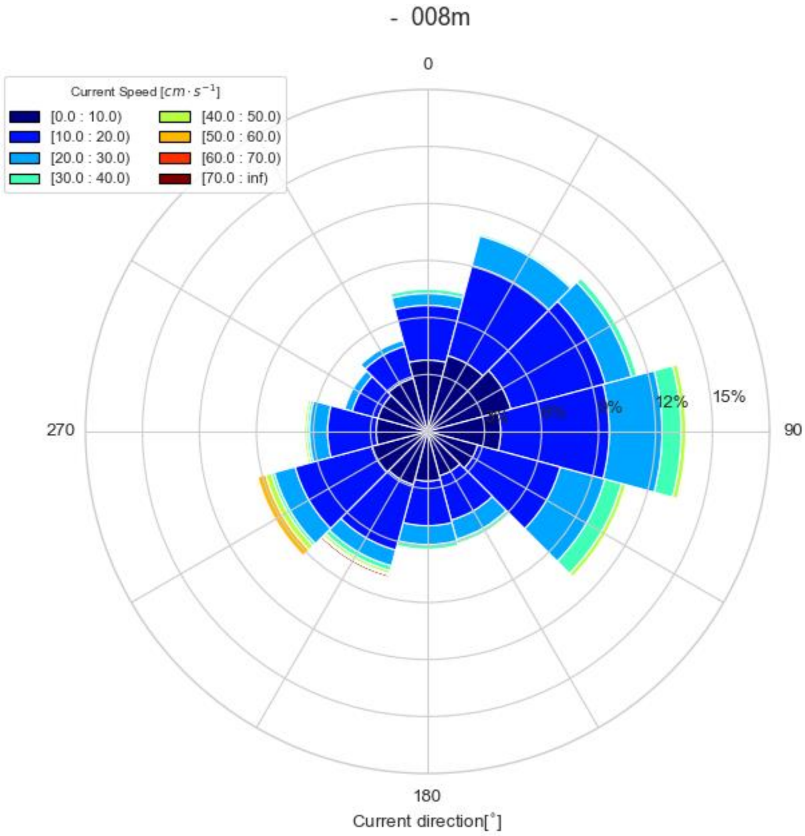
Heatmaps of current speed and direction are presented in **Appendix B.4**.

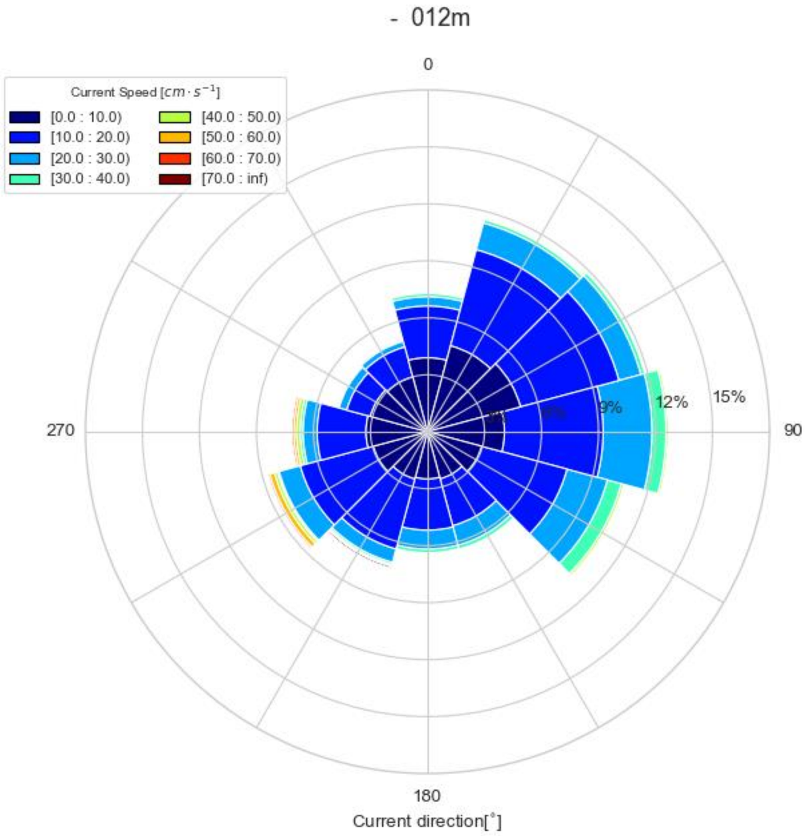
Table 11-1 summarizes statistics for current speed over the full campaign. **Figure 11-1** shows current roses at 4 depths (04, 08, 12, and 20 m) for all 12 months of data and **Figure 11-2** shows the current speed profile for the full campaign.

The timeseries show that the highest current speeds (> 100 cm/s) during the campaign were measured at the end of November 2022. This event is also present in the upward-looking ADCP data, however, with much lower speeds.

All current directions (as given in the CurrentData files) were corrected for magnetic declination and are given relative to true north.




- 008m
0
Current Speed [$cm \cdot s^{-1}$]
[0.0 : 10.0)
[10.0 : 20.0)
[20.0 : 30.0)
[30.0 : 40.0)
[40.0 : 50.0)
[50.0 : 60.0)
[60.0 : 70.0)
[70.0 : inf)
12%
15%
270
90
180
Current direction[°]


- 012m
0
Current Speed [$cm \cdot s^{-1}$]
[0.0 : 10.0)
[10.0 : 20.0)
[20.0 : 30.0)
[30.0 : 40.0)
[40.0 : 50.0)
[50.0 : 60.0)
[60.0 : 70.0)
[70.0 : inf)
9%
12%
15%
270
90
180
Current direction[°]

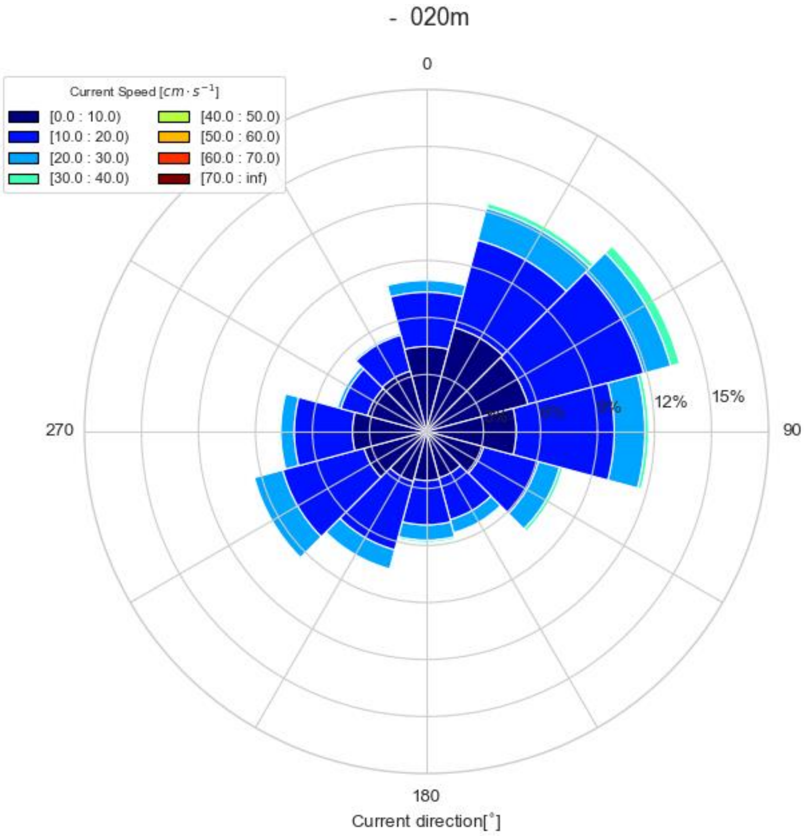


Figure 11-1 Current roses (top-down) at 04 m, 08 m, 12 m, and 20 m depth for the full 12 months

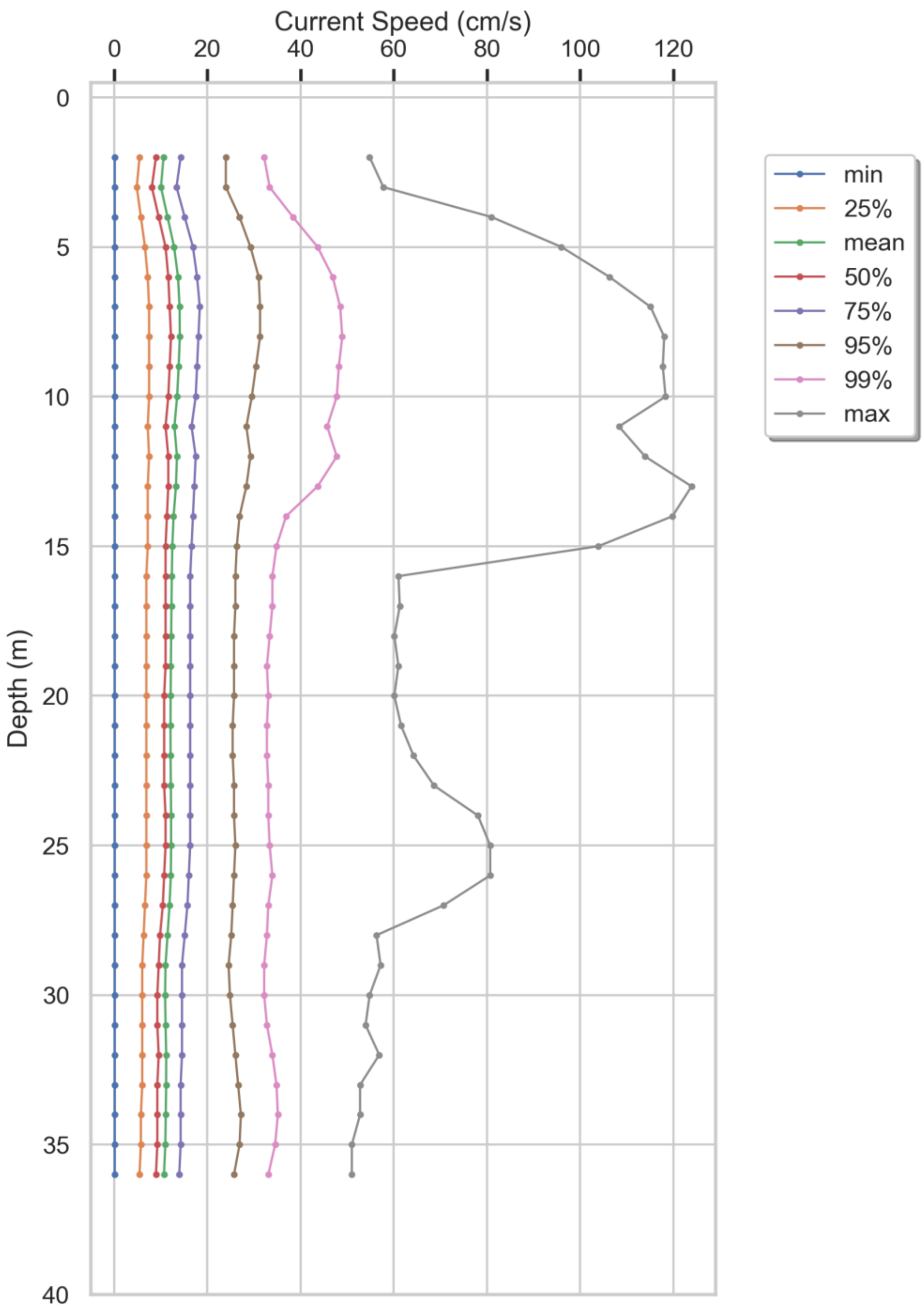


Figure 11-2 12-month current speed profile

Table 11-1: 12-month summary statistics (standard deviation, minimum, mean and maximum): current speed

Parameter	Unit	Height [m]	Standard deviation	Minimum	Mean	Maximum
AqSpd002	cm/s	-2	6.8	0.2	10.6	54.8
AqSpd003	cm/s	-3	7.2	0.2	10.1	57.8
AqSpd004	cm/s	-4	8.1	0.2	11.5	81.0
AqSpd005	cm/s	-5	8.8	0.2	12.9	96.0
AqSpd006	cm/s	-6	9.4	0.2	13.7	106.3
AqSpd007	cm/s	-7	9.6	0.2	14.1	115.1
AqSpd008	cm/s	-8	9.6	0.2	14.1	118.0
AqSpd009	cm/s	-9	9.4	0.2	13.9	117.8
AqSpd010	cm/s	-10	9.2	0.2	13.5	118.3
AqSpd011	cm/s	-11	8.8	0.2	13.0	108.3
AqSpd012	cm/s	-12	9.1	0.2	13.5	113.9
AqSpd013	cm/s	-13	8.9	0.2	13.3	123.9
AqSpd014	cm/s	-14	8.0	0.2	12.8	119.8
AqSpd015	cm/s	-15	7.4	0.2	12.5	103.9
AqSpd016	cm/s	-16	7.3	0.2	12.4	61.0
AqSpd017	cm/s	-17	7.3	0.2	12.3	61.3
AqSpd018	cm/s	-18	7.2	0.2	12.3	60.1
AqSpd019	cm/s	-19	7.2	0.2	12.2	61.0
AqSpd020	cm/s	-20	7.2	0.2	12.1	60.1
AqSpd021	cm/s	-21	7.1	0.2	12.1	61.6
AqSpd022	cm/s	-22	7.1	0.2	12.1	64.3
AqSpd023	cm/s	-23	7.2	0.2	12.2	68.7
AqSpd024	cm/s	-24	7.3	0.2	12.2	78.1
AqSpd025	cm/s	-25	7.3	0.2	12.2	80.7
AqSpd026	cm/s	-26	7.2	0.2	12.2	80.7
AqSpd027	cm/s	-27	7.1	0.2	11.9	70.7
AqSpd028	cm/s	-28	7.1	0.2	11.5	56.3
AqSpd029	cm/s	-29	7.0	0.2	11.0	57.2
AqSpd030	cm/s	-30	7.0	0.2	11.0	54.8
AqSpd031	cm/s	-31	7.1	0.2	11.1	54.0
AqSpd032	cm/s	-32	7.3	0.2	11.2	56.9
AqSpd033	cm/s	-33	7.4	0.2	11.2	52.8
AqSpd034	cm/s	-34	7.5	0.2	11.1	52.8
AqSpd035	cm/s	-35	7.5	0.2	11.0	51.0
AqSpd036	cm/s	-36	7.2	0.2	10.7	51.0

Parameter	Unit	Height [m]	Standard deviation	Minimum	Mean	Maximum
AqSpd037	cm/s	-37	-	-	-	-
AqSpd038	cm/s	-38	-	-	-	-

11.2 Upward-facing Signature

Heatmaps of 6-monthly current speed and direction are presented in **Appendix B.5**.

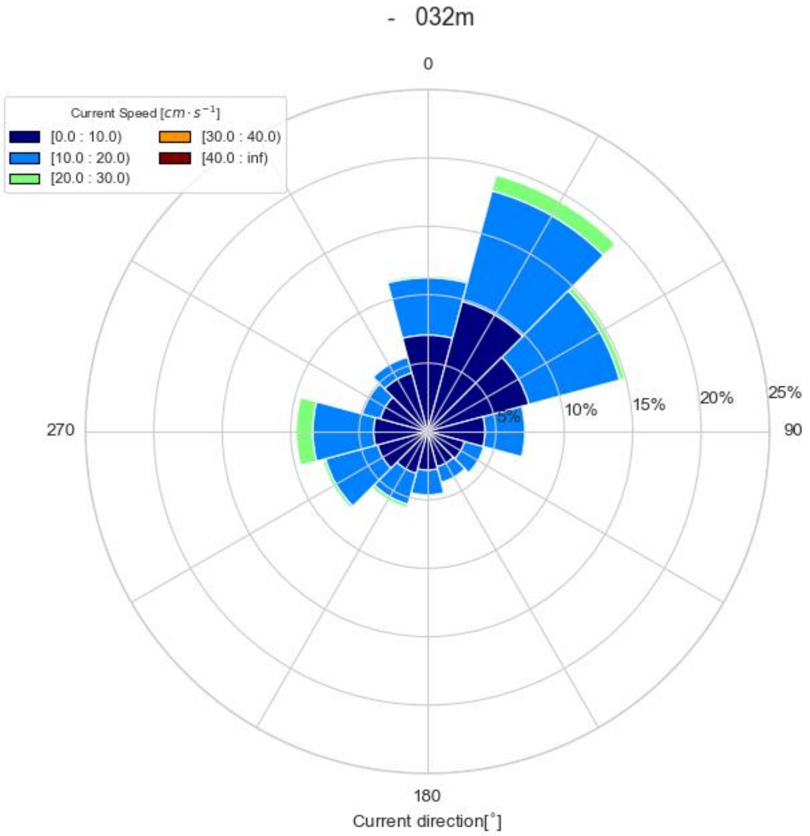
Current roses at 4 depths above the seafloor (32, 20, 14, and 06 m) are shown in **Figure 11-3** for D1 (February 2022 – June 2022) and in **Figure 11-4** for D2 (June 2022 – December 2022). **Figure 11-5** shows the current speed profile for D1, and **Figure 11-6** the profile for D2.

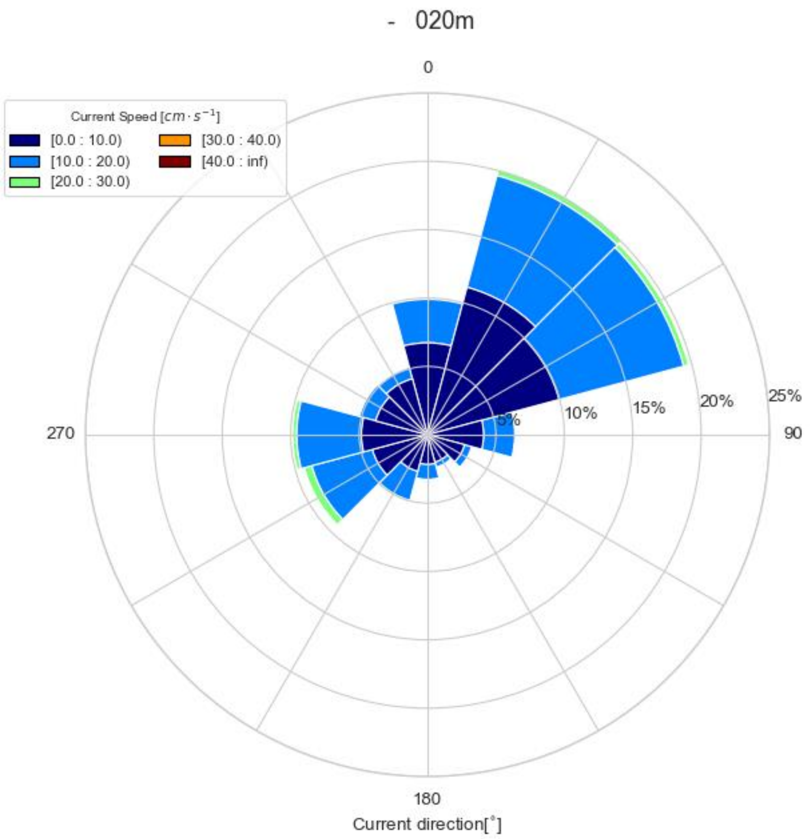
Table 11-2 and **Table 11-3** summarizes statistics for current speed over D1 and D2, respectively.

The highest current speeds during D1 were measured in April 2022 (near surface) and May 2022 (mid-water column). During D2, the highest current speeds were measured in November 2022. The mean current speeds are generally low (ca. 10 cm/s).

The upward-facing dataset penetrates through the boundary between the Baltic water and denser North Sea overflow water (at ca. 20 m water depth during late summer). However, a decrease in return signal strength above this thermocline is present in the data.

All current directions were corrected for magnetic declination and are given relative to true north.


- 032m
0
Current Speed [cm·s⁻¹]
[0.0 : 10.0)
[10.0 : 20.0)
[20.0 : 30.0)
[30.0 : 40.0)
[40.0 : inf)
5%
10%
15%
20%
25%
90
270
180
Current direction[°]


- 020m
0
Current Speed [cm·s⁻¹]
[0.0 : 10.0)
[10.0 : 20.0)
[20.0 : 30.0)
[30.0 : 40.0)
[40.0 : inf)
5%
10%
15%
20%
25%
90
270
180
Current direction[°]

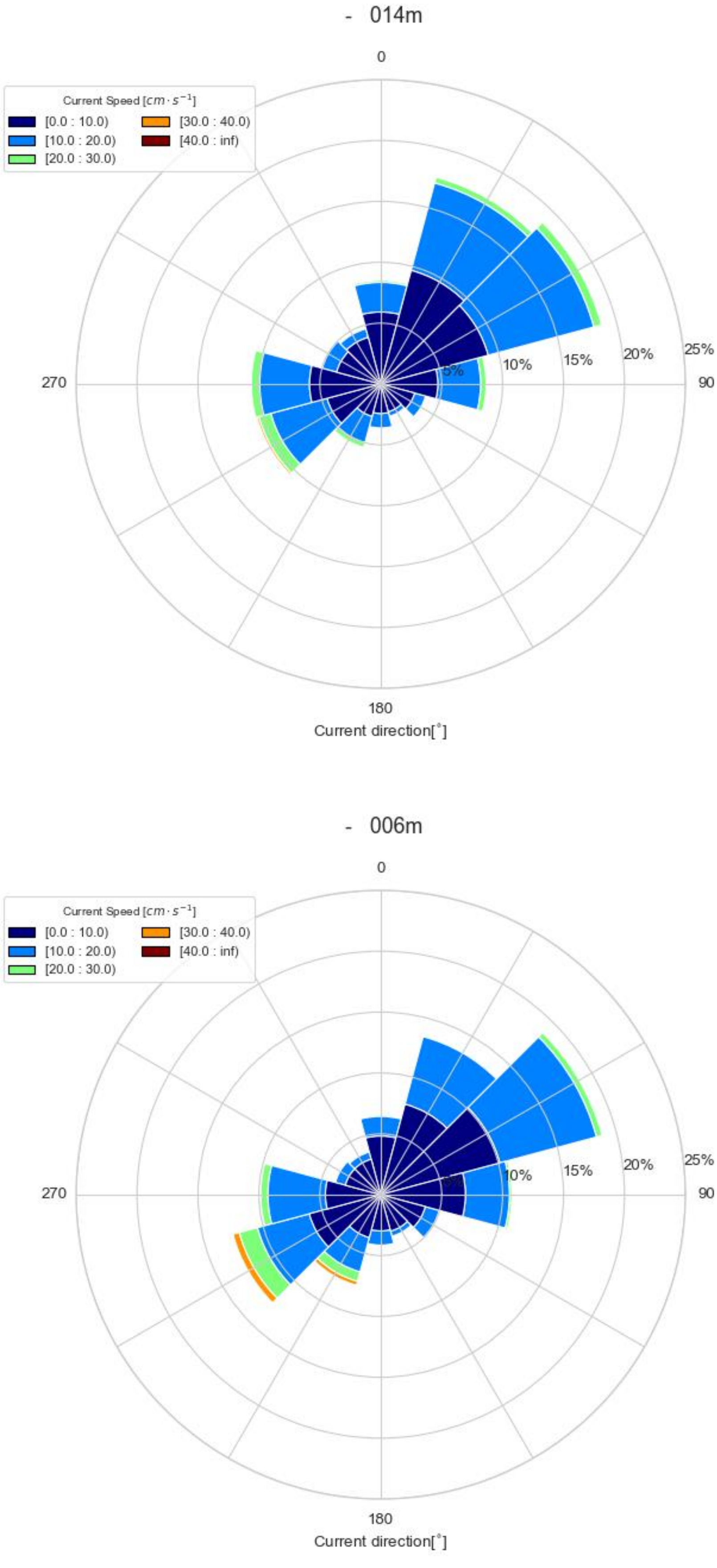
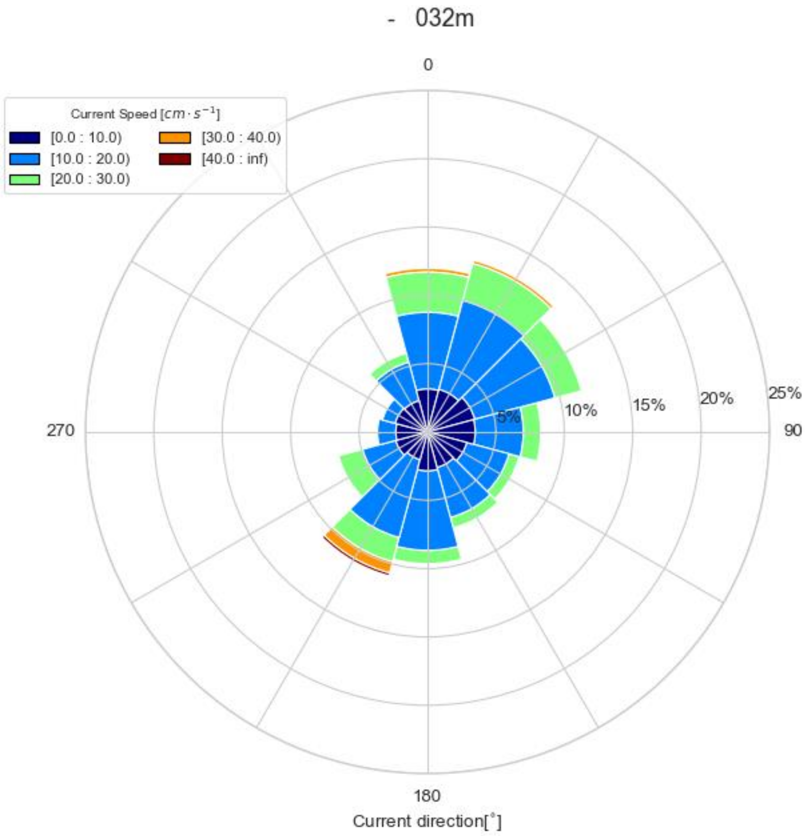
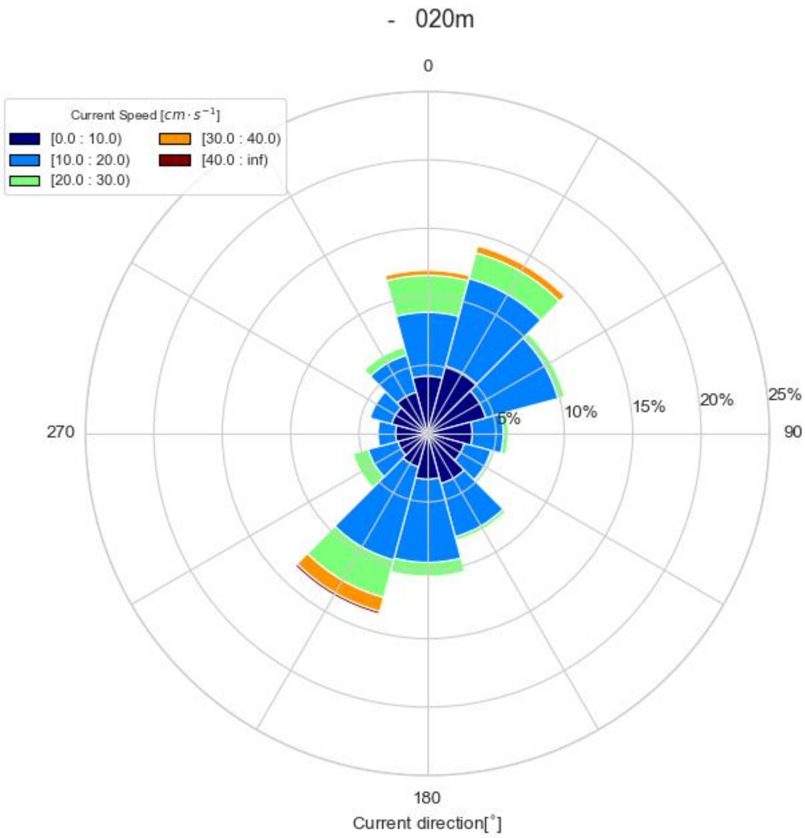
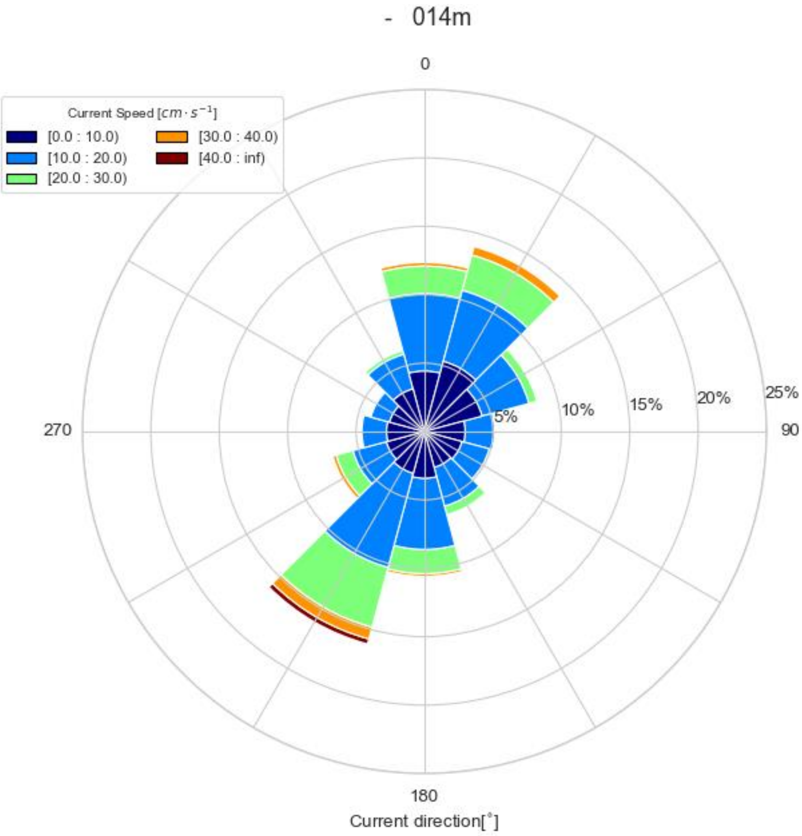


Figure 11-3 Current roses (bottom-up) at 32 m, 20 m, 14 m, and 06 m above the seafloor during D1 (November 2021 – June 2022).


- 032m
0
Current Speed [cm·s⁻¹]
[0.0 : 10.0)
[10.0 : 20.0)
[20.0 : 30.0)
[30.0 : 40.0)
[40.0 : inf)
5%
10%
15%
20%
25%
90
270
180
Current direction[°]


- 020m
0
Current Speed [cm·s⁻¹]
[0.0 : 10.0)
[10.0 : 20.0)
[20.0 : 30.0)
[30.0 : 40.0)
[40.0 : inf)
5%
10%
15%
20%
25%
90
270
180
Current direction[°]



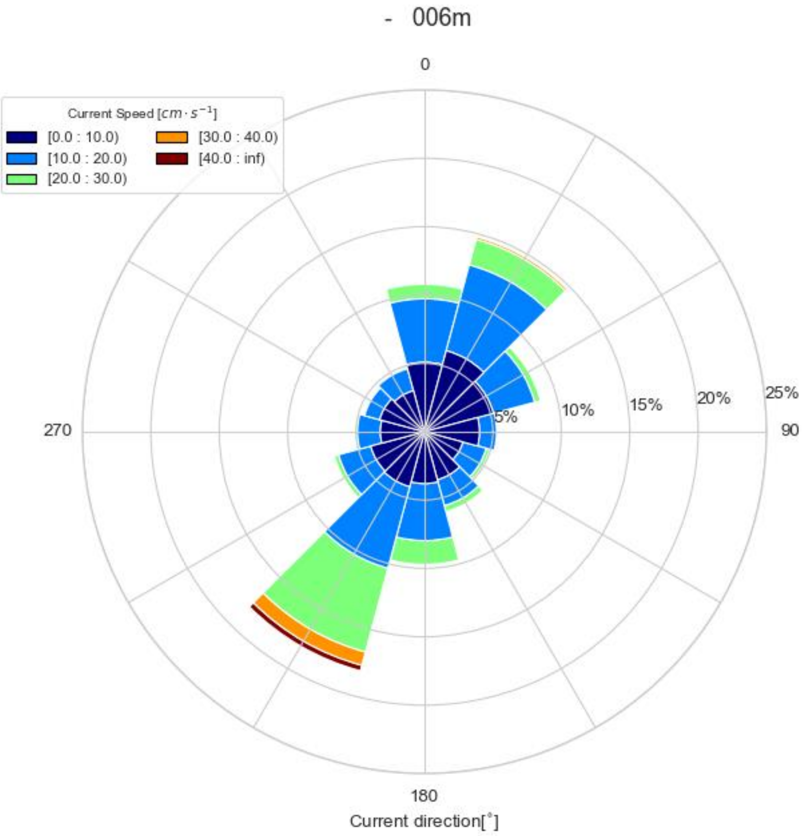


Figure 11-4 Current roses (bottom-up) at 32 m, 20 m, 14 m, and 06 m above the seafloor during D2 (June 2022 – December 2022).

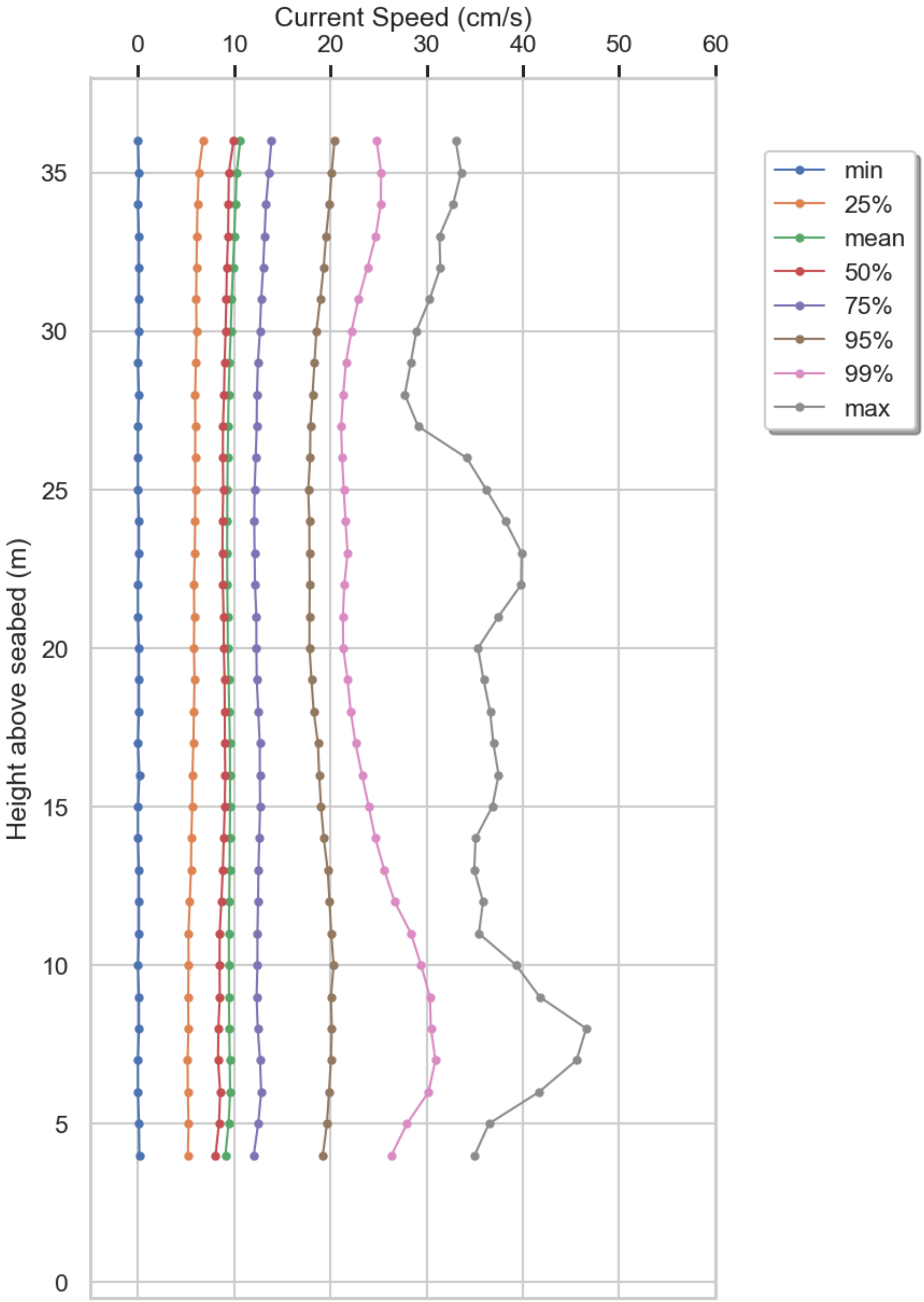


Figure 11-5 Current speed profile during D1 (November 2021 – June 2022). Note that depth is given relative to the seafloor.

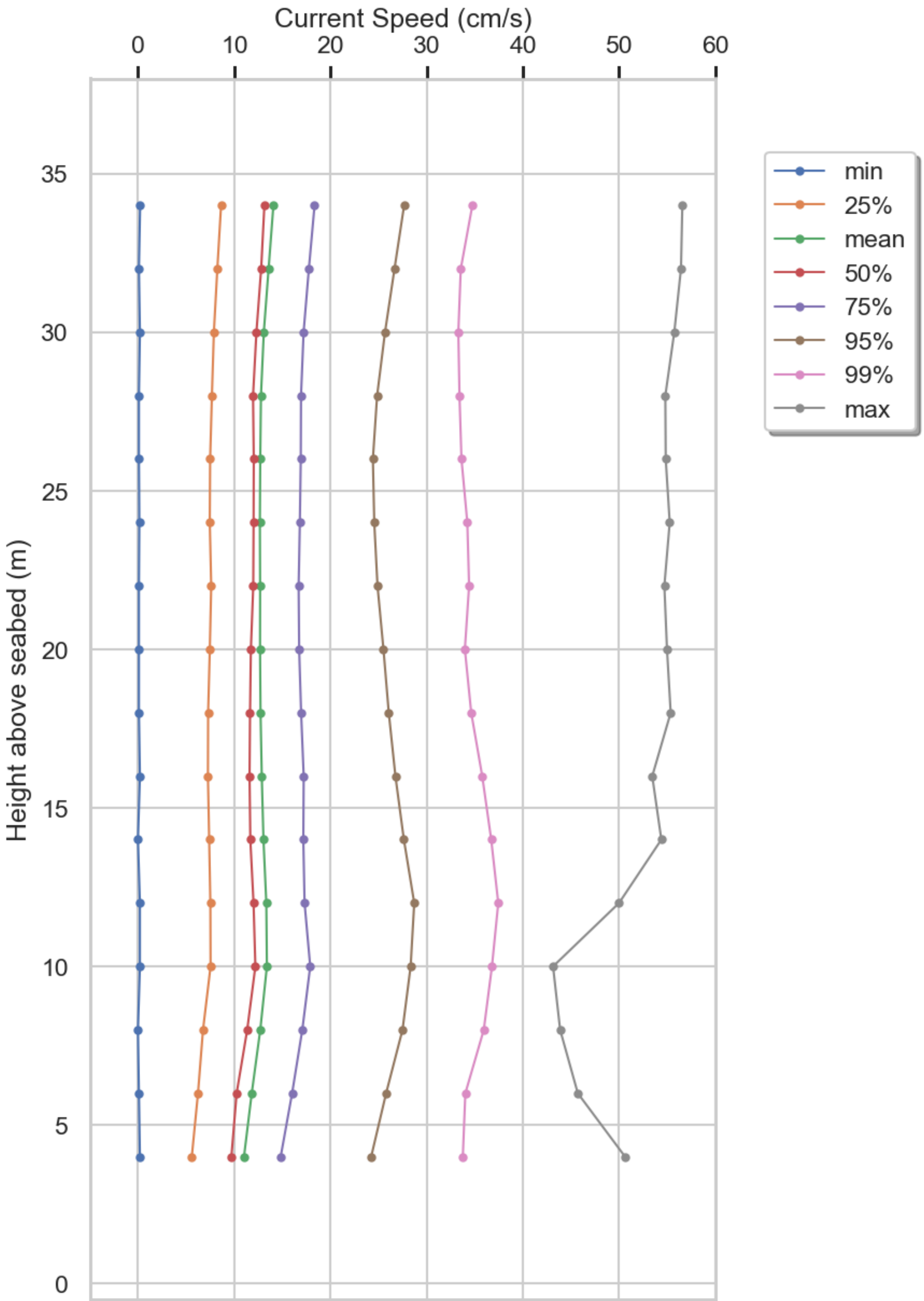


Figure 11-6 Current speed profile during D2 (June 2022 – December 2022). Note that depth is given relative to the seafloor.

Table 11-2: Current speed summary statistics (standard deviation, minimum, mean and maximum) over D1 (November 2021 – June 2022).

Parameter	Unit	Height [m]*	Standard deviation	Minimum	Mean	Maximum
Speed004m	cm/s	-4	5.4	0.1	9.1	35.0
Speed005m	cm/s	-5	5.6	0.1	9.4	36.5
Speed006m	cm/s	-6	6.0	0.0	9.6	41.7
Speed007m	cm/s	-7	6.1	0.0	9.5	45.6
Speed008m	cm/s	-8	6.0	0.1	9.5	46.6
Speed009m	cm/s	-9	5.8	0.1	9.5	41.7
Speed010m	cm/s	-10	5.7	0.0	9.5	39.3
Speed011m	cm/s	-11	5.6	0.1	9.4	35.4
Speed012m	cm/s	-12	5.5	0.1	9.5	35.9
Speed013m	cm/s	-13	5.4	0.1	9.5	34.9
Speed014m	cm/s	-14	5.3	0.0	9.5	35.1
Speed015m	cm/s	-15	5.2	0.0	9.6	36.8
Speed016m	cm/s	-16	5.1	0.1	9.6	37.5
Speed017m	cm/s	-17	5.0	0.0	9.6	36.9
Speed018m	cm/s	-18	4.8	0.1	9.5	36.6
Speed019m	cm/s	-19	4.7	0.1	9.4	35.9
Speed020m	cm/s	-20	4.7	0.1	9.3	35.3
Speed021m	cm/s	-21	4.7	0.0	9.3	37.5
Speed022m	cm/s	-22	4.7	0.0	9.3	39.8
Speed023m	cm/s	-23	4.7	0.1	9.3	39.9
Speed024m	cm/s	-24	4.7	0.1	9.3	38.2
Speed025m	cm/s	-25	4.6	0.0	9.3	36.2
Speed026m	cm/s	-26	4.6	0.0	9.3	34.2
Speed027m	cm/s	-27	4.7	0.0	9.4	29.1
Speed028m	cm/s	-28	4.7	0.1	9.4	27.7
Speed029m	cm/s	-29	4.8	0.0	9.5	28.3
Speed030m	cm/s	-30	4.9	0.1	9.6	28.9
Speed031m	cm/s	-31	5.0	0.1	9.7	30.3
Speed032m	cm/s	-32	5.1	0.1	9.9	31.4
Speed033m	cm/s	-33	5.2	0.1	10.0	31.3
Speed034m	cm/s	-34	5.3	0.0	10.1	32.7
Speed035m	cm/s	-35	5.4	0.1	10.3	33.6
Speed036m	cm/s	-36	5.3	0.0	10.6	33.0

* Height above the seafloor

Table 11-3: Current speed summary statistics (standard deviation, minimum, mean and maximum) over D2 (June 2022 – December 2022).

Parameter	Unit	Height [m]*	Standard deviation	Minimum	Mean	Maximum
Speed004m	cm/s	-4	7.1	0.2	11.0	50.6
Speed006m	cm/s	-6	7.4	0.1	11.8	45.7
Speed008m	cm/s	-8	7.7	0.0	12.7	43.9
Speed010m	cm/s	-10	7.8	0.2	13.4	43.1
Speed012m	cm/s	-12	7.9	0.2	13.3	50.0
Speed014m	cm/s	-14	7.7	0.0	13.0	54.4
Speed016m	cm/s	-16	7.6	0.2	12.9	53.4
Speed018m	cm/s	-18	7.3	0.1	12.7	55.4
Speed020m	cm/s	-20	7.1	0.1	12.7	55.0
Speed022m	cm/s	-22	7.0	0.1	12.7	54.7
Speed024m	cm/s	-24	7.0	0.1	12.7	55.3
Speed026m	cm/s	-26	6.9	0.1	12.7	54.8
Speed028m	cm/s	-28	6.9	0.1	12.8	54.8
Speed030m	cm/s	-30	7.1	0.2	13.1	55.7
Speed032m	cm/s	-32	7.3	0.1	13.6	56.4
Speed034m	cm/s	-34	7.5	0.2	14.1	56.6

* Height above the seafloor

12. References

[1] DNVGL, "WS199 Independent performance verification of Seawatch Wind Lidar Buoy at Frøya, Norway. FUGRO NORWAY AS. 10281716-R-11, Rev. A. 2021-11-03".

[2] Fugro, "SWLB measurements at Energy Islands Project Measurement Plan, All Lots," Fugro, 2022.

[3] Fugro, "Signature500 (offline) data report Lot 3, Feb 2022 – June 2022," Fugro, 2022.

[4] Fugro, "Motion correction of turbulence intensity. WP4: Baltic Sea campaign data," C75486-TI1-R-03 04, 20 March 2024.

[5] U.S. Integrated Ocean Observing System, "Manual for Real-Time Quality Control of In-Situ Current Observations Version 2.1 A Guide to Quality Control and Quality Assurance of Acoustic Doppler Current Profiler Observations.," 2019.

[6] Ocean Contour Acoustic Doppler Data Processing Package V 2.1.5, Ocean Illumination Ltd. 2016-2018, 2022.

[7] Fugro, "Technical Note – Deviations between downward-looking and upward-looking current measurements," C75486-TN-001 01, 21 June 2023.

[8] Fugro, "Nortek Aquadopp – Error assessment and correction, Comparison of measurements from two collocated ADCPs," C75 01, 11 August 2023.

Appendix A

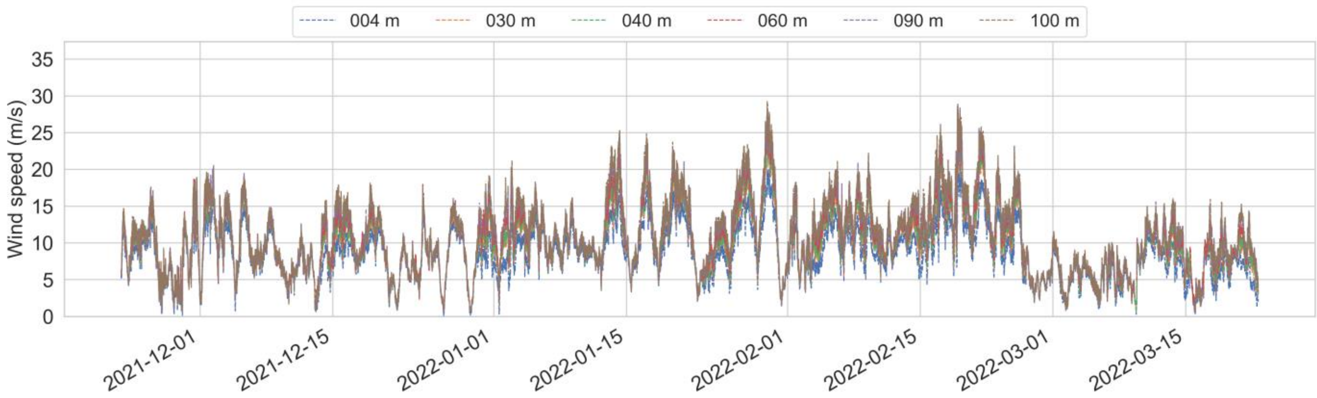
Event logs

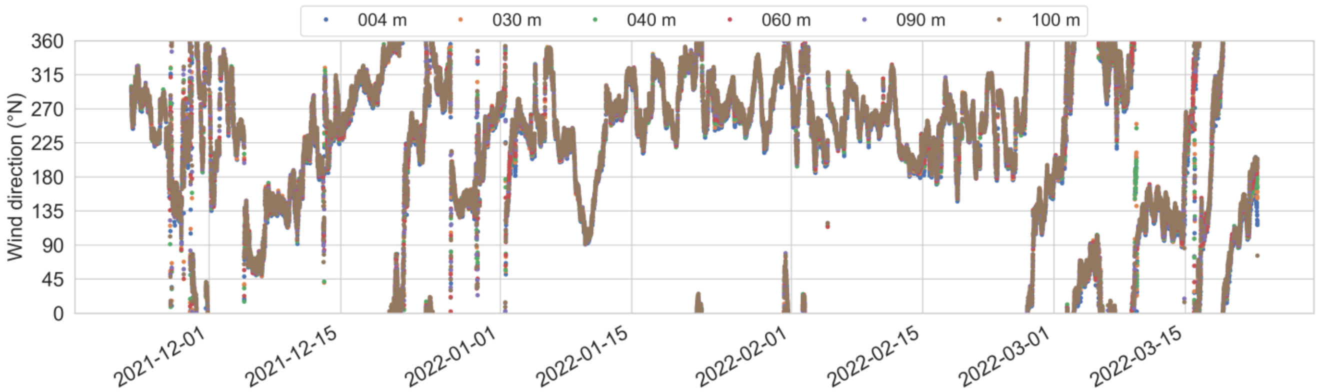
Issue number	Start time	End time	Instru-ment	Parameter	Description
1	2022-01-21	2022-11-21	Aquadopp	Current speed and direction below 23 m	There is a substantial drop in signal strength of the Aquadopp current meter data below 23 m depth and a large amount of data below this depth is filtered out. The downward looking profiler is most likely experiencing interference at the boundary between 2 water layers (Baltic water and denser North Sea overflow water). This assumption is corroborated by a higher water temperature near the seafloor than at the sea surface.
2	2022-01-22 23:30	2022-01-23 02:40	Lidar	Lidar parameters at intermediate heights	Lidar data partially missing due to low visibility/fog
3	2022-01-23 10:30	2022-01-23 12:30	Lidar	Lidar parameters at intermediate heights	Lidar data partially missing due to low visibility/fog
4	2022-01-23 22:10	2022-01-24 09:00	Lidar	Lidar parameters at intermediate heights	Lidar data partially missing due to low visibility/fog
5	2022-02-09 04:50	2022-02-09 08:10	Lidar	Lidar parameters at intermediate heights	Lidar data partially missing due to low visibility/fog
6	2022-02-11 06:10	2022-02-11 08:50	Lidar	Lidar parameters at intermediate heights	Lidar data partially missing due to low visibility/fog
7	2022-03-01 20:10	2022-06-20 09:20	Lidar	All lidar data	Lidar stopped transmitting data but is still drawing full power. Likely a communication fault between lidar and datalogger. Lidar data was stored, reprocessed and added to this dataset.
8	2022-03-27 05:50	2022-03-27 05:50	Aquadopp	Current speed, depths 16 m and below	Spike, to be investigated once raw data are available.
9	2022-05-21	2022-11-21	Aquadopp	Current speed profiles	Profiles appear to be flat. To be compared to bottom-up profiles from Signature500.
10	2022-06-20	2022-06-22	SWLB	All SWLB data	WS199 was recovered for service, data download and refuelling. WS199 was redeployed on 22nd June 2022.

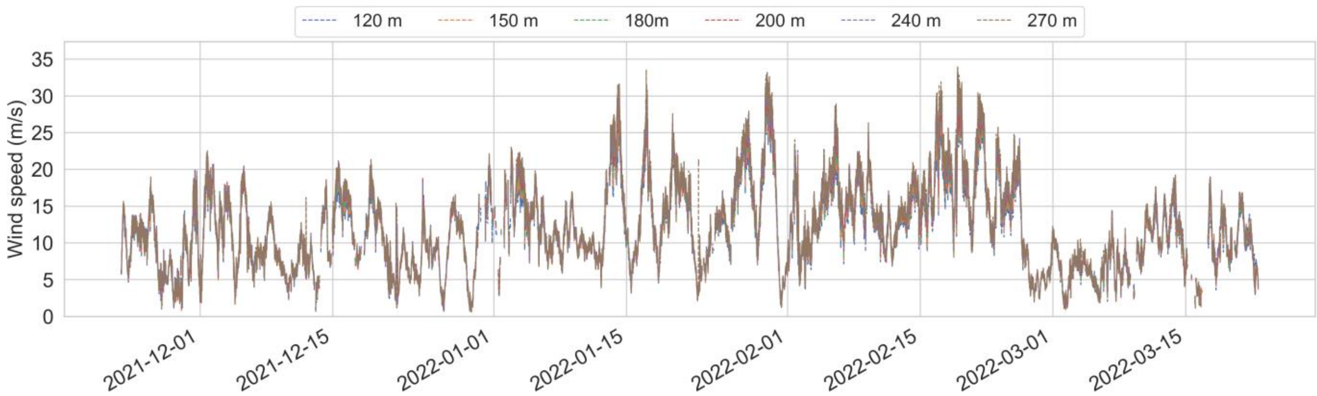
Appendix B

Data presentation

B.1 Wind data


004 m
030 m
040 m
060 m
090 m
100 m
Wind speed (m/s)
0
5
10
15
20
25
30
35
2021-12-01
2021-12-15
2022-01-01
2022-01-15
2022-02-01
2022-02-15
2022-03-01
2022-03-15


004 m
030 m
040 m
060 m
090 m
100 m
Wind direction (°N)
0
45
90
135
180
225
270
315
360
2021-12-01
2021-12-15
2022-01-01
2022-01-15
2022-02-01
2022-02-15
2022-03-01
2022-03-15


120 m
150 m
180m
200 m
240 m
270 m
Wind speed (m/s)
0
5
10
15
20
25
30
35
2021-12-01
2021-12-15
2022-01-01
2022-01-15
2022-02-01
2022-02-15
2022-03-01
2022-03-15

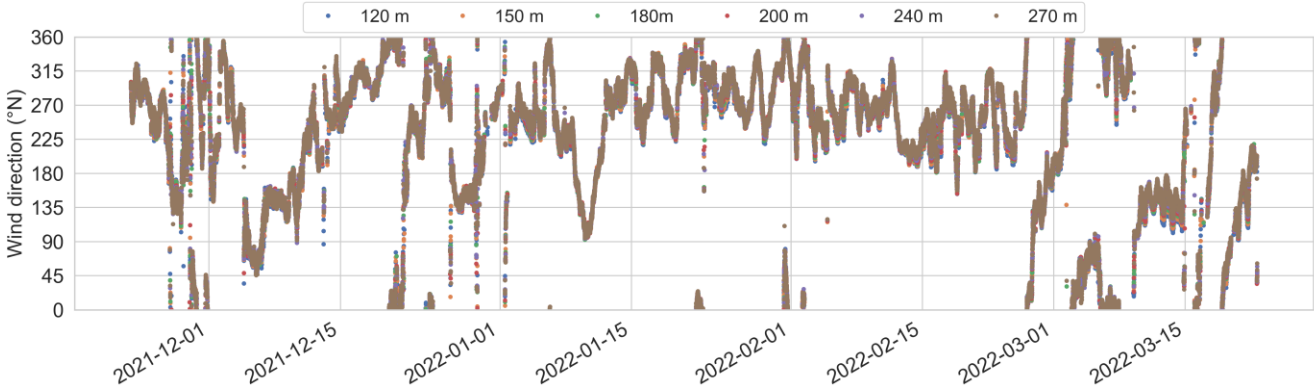
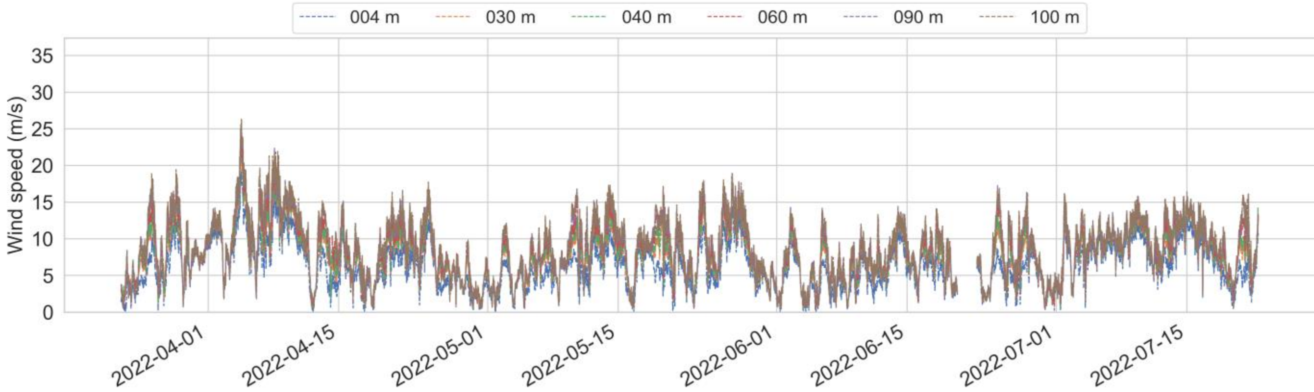
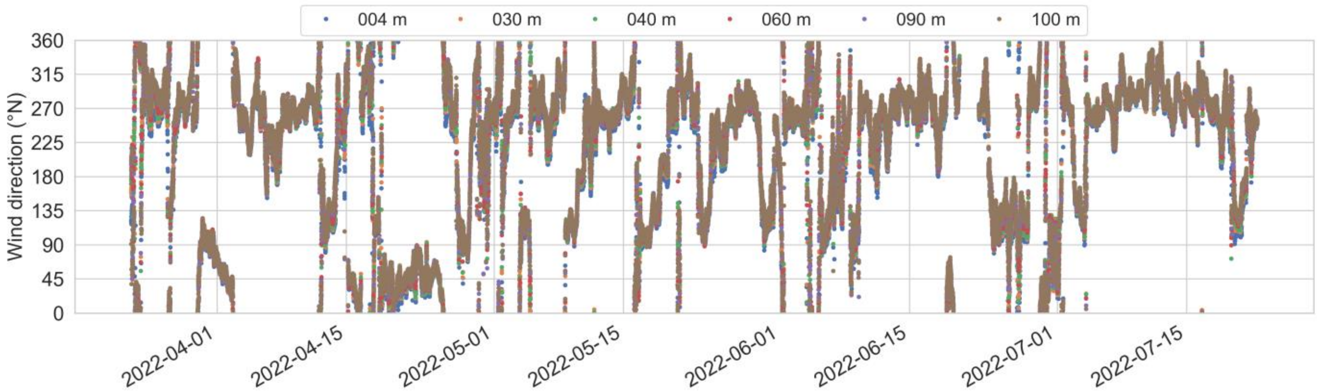


Figure B-1 Timeseries of wind speed and direction from November 2021 until March 2022. Please note that the y-axis for wind direction spans from 0° (bottom line) to 360° (top line).





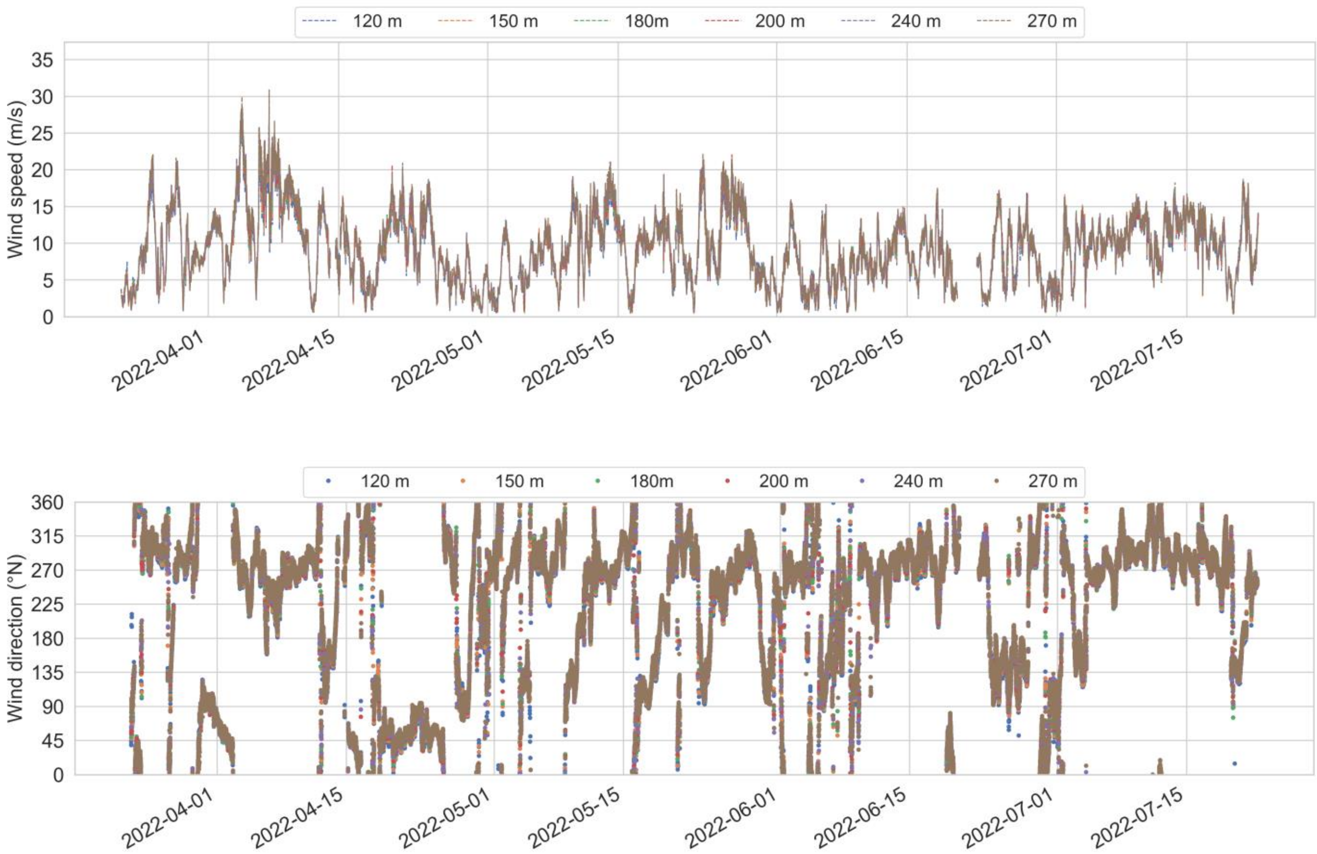
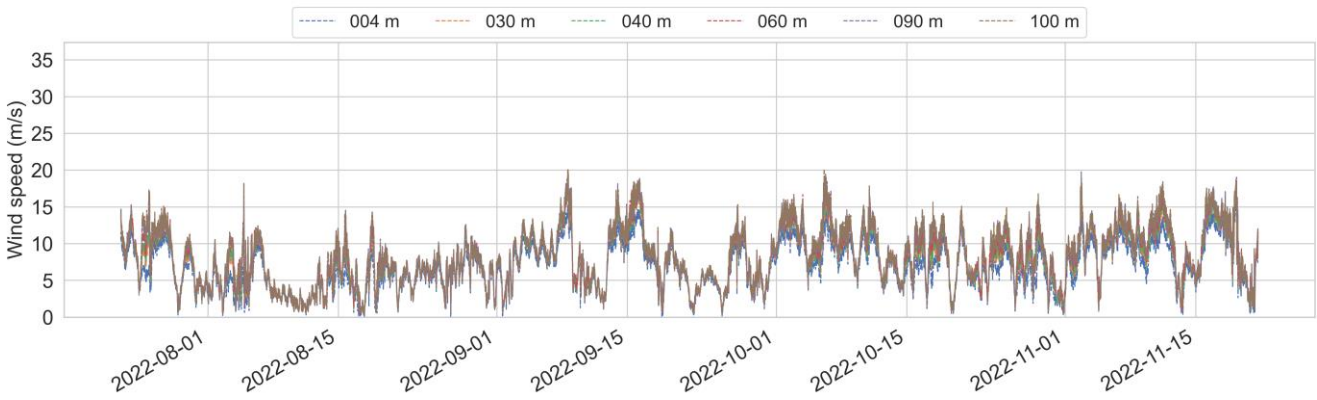


Figure B-2 Timeseries of wind speed and direction from March 2022 until July 2022. Please note that the y-axis for wind direction spans from 0° (bottom line) to 360° (top line).



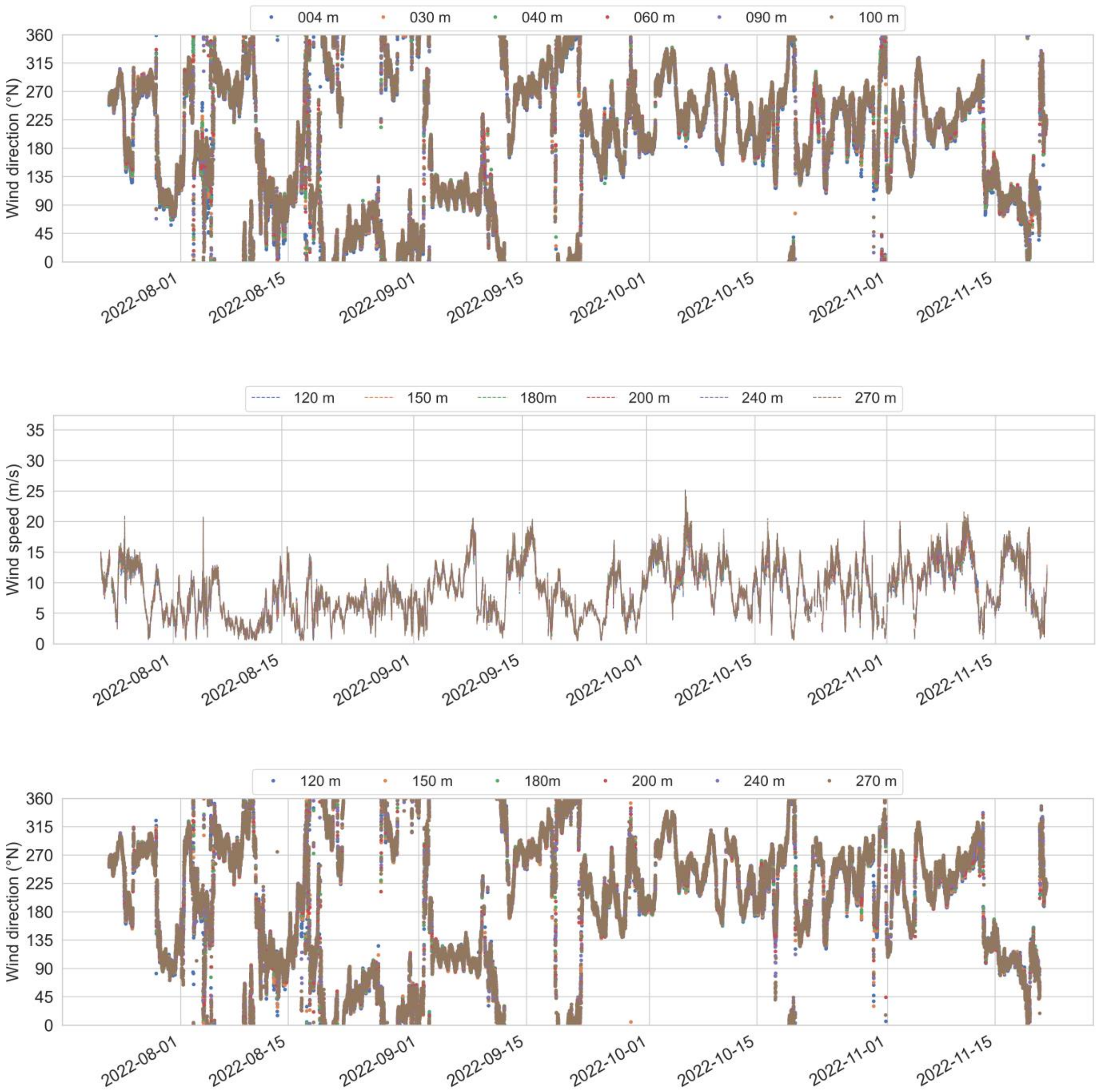


Figure B-3 Timeseries of wind speed and direction from July 2022 until November 2022. Please note that the y-axis for wind direction spans from 0° (bottom line) to 360° (top line).

B.2 Wave data

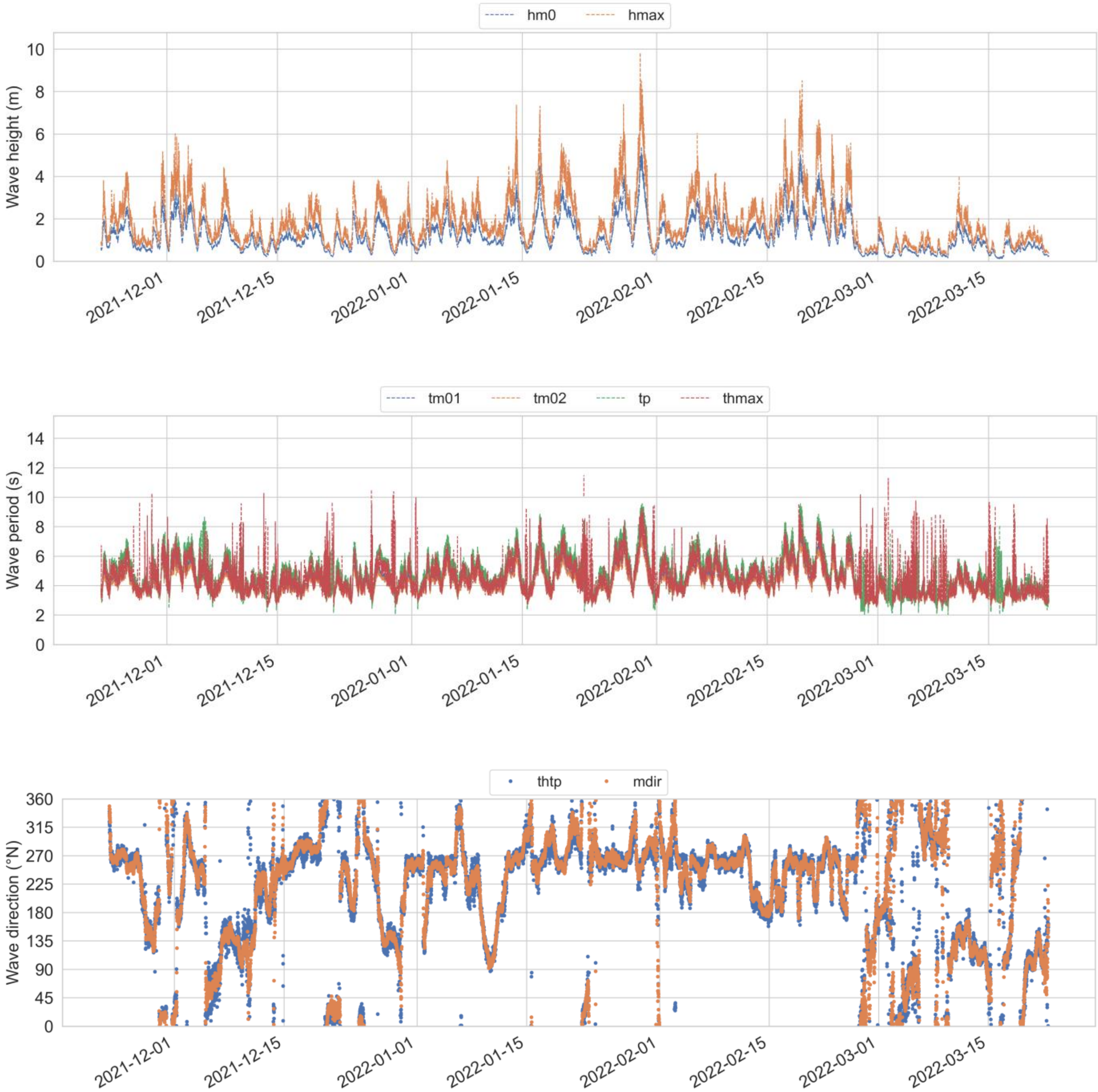


Figure B-4 Timeseries of wave heights, wave periods, and wave direction from November 2021 until March 2022. Please note that the y-axis for wave direction spans from 0° (bottom line) to 360° (top line).

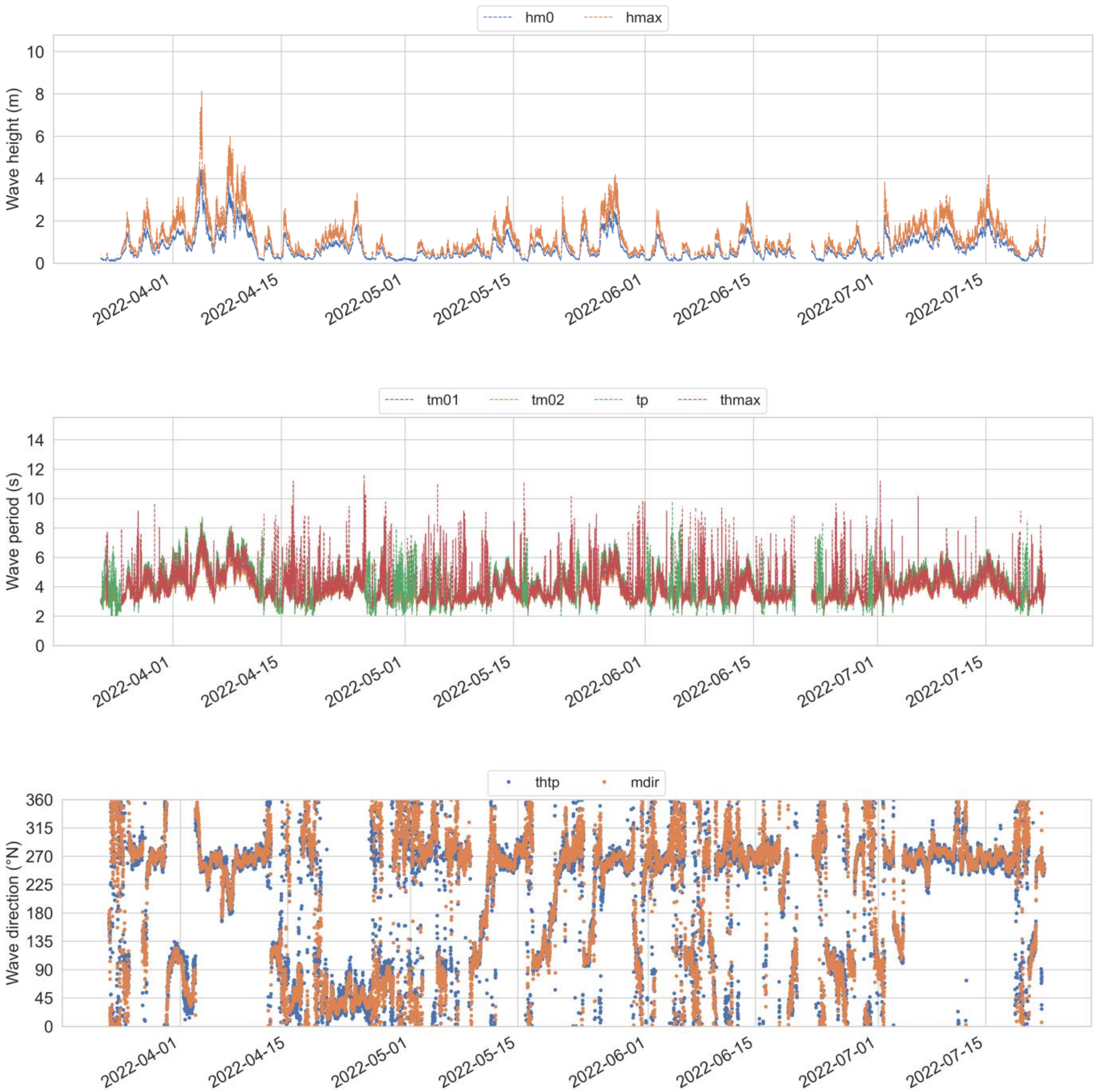


Figure B-5 Timeseries of wave heights, wave periods, and wave direction from March 2022 until July 2022. Please note that the y-axis for wave direction spans from 0° (bottom line) to 360° (top line).

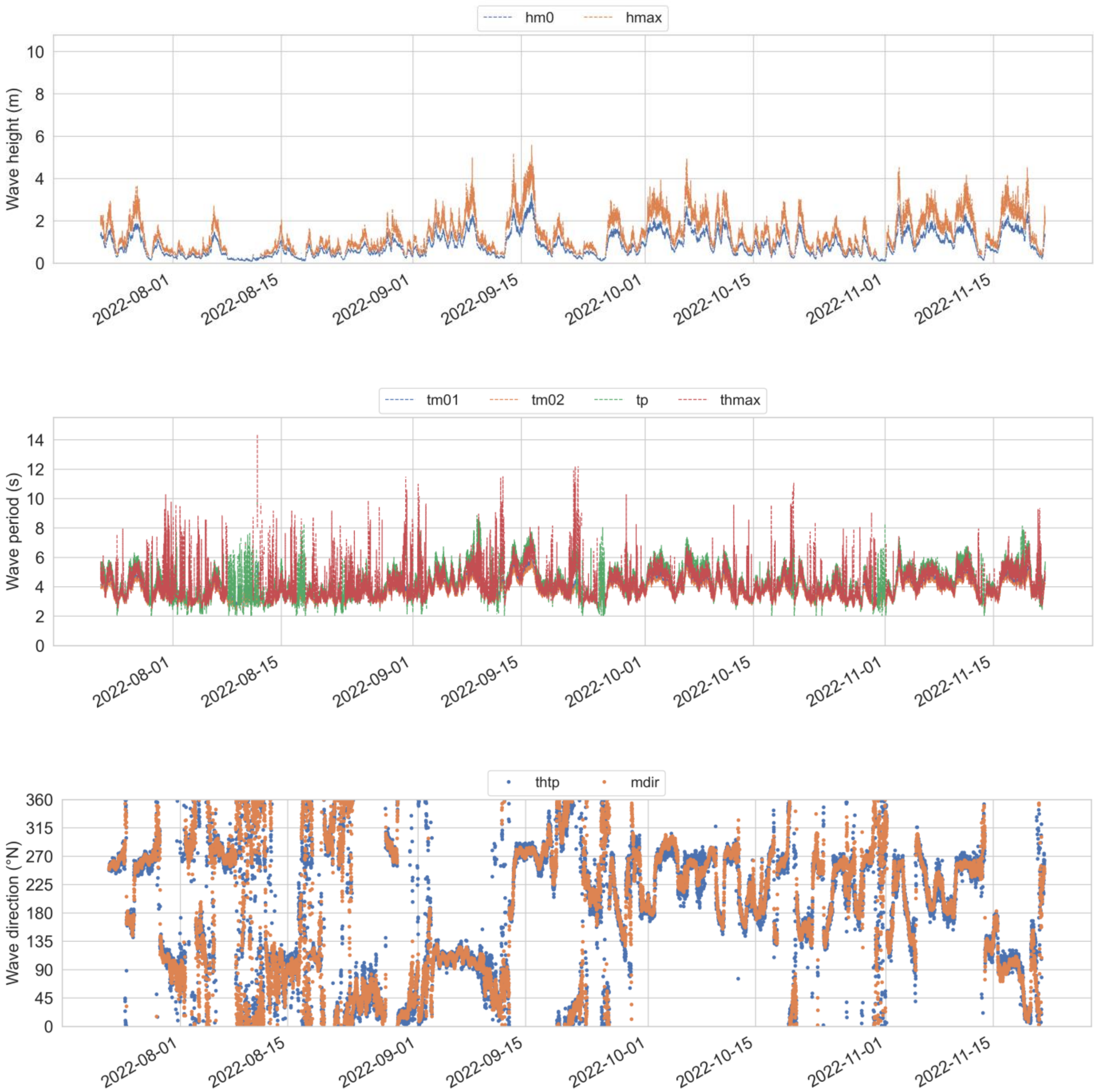
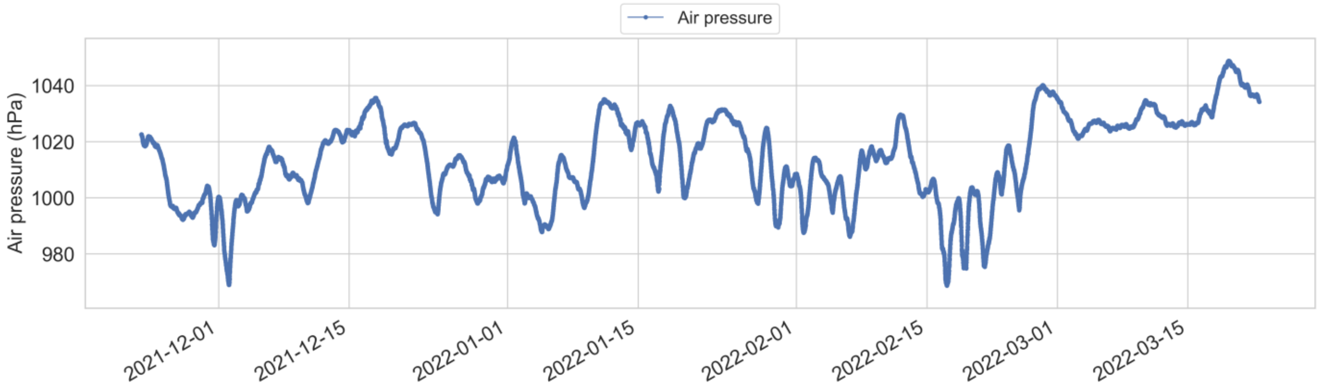
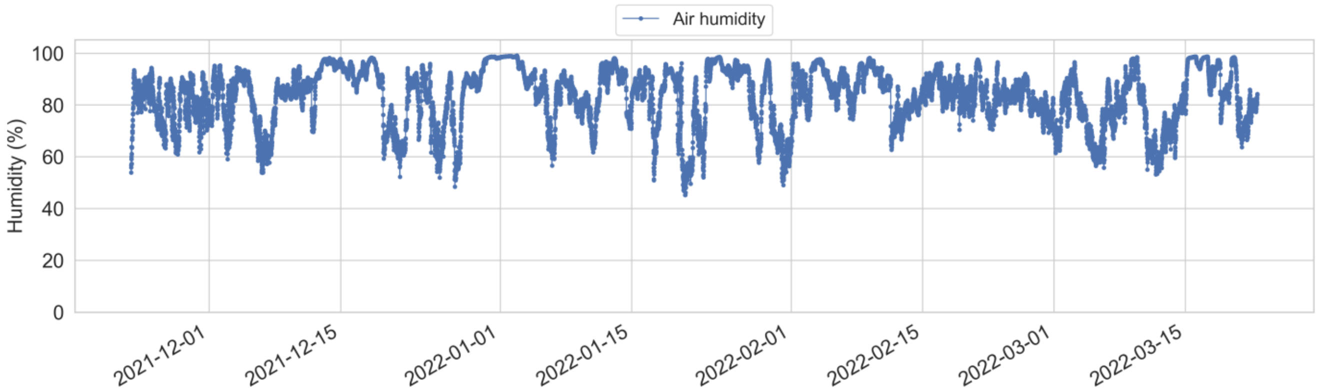
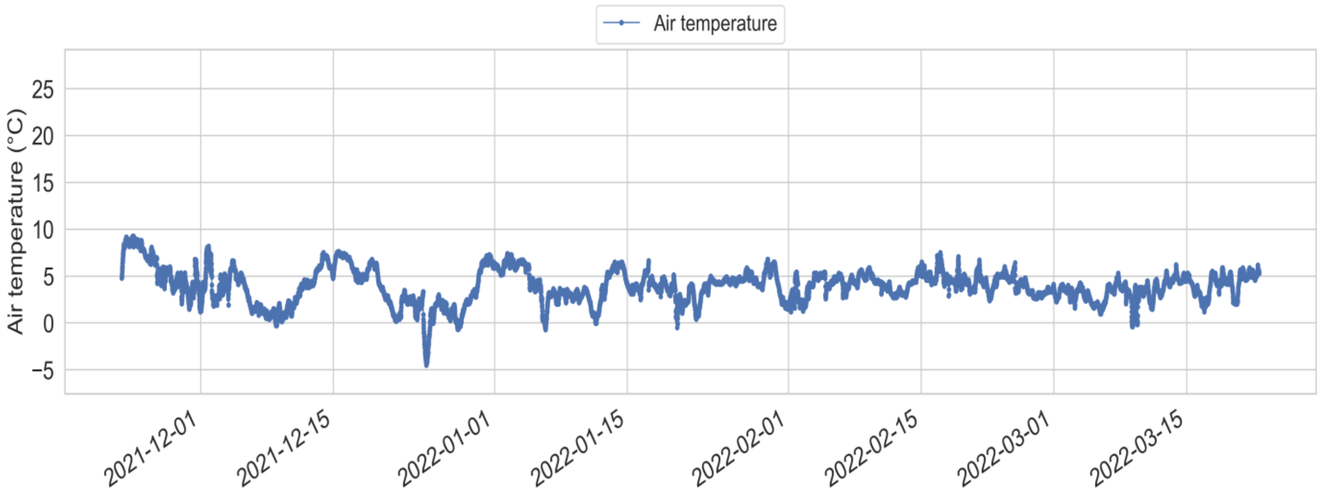


Figure B-6 Timeseries of wave heights, wave periods, and wave direction from July 2022 until November 2022. Please note that the y-axis for wave direction spans from 0° (bottom line) to 360° (top line).

B.3 Metocean data







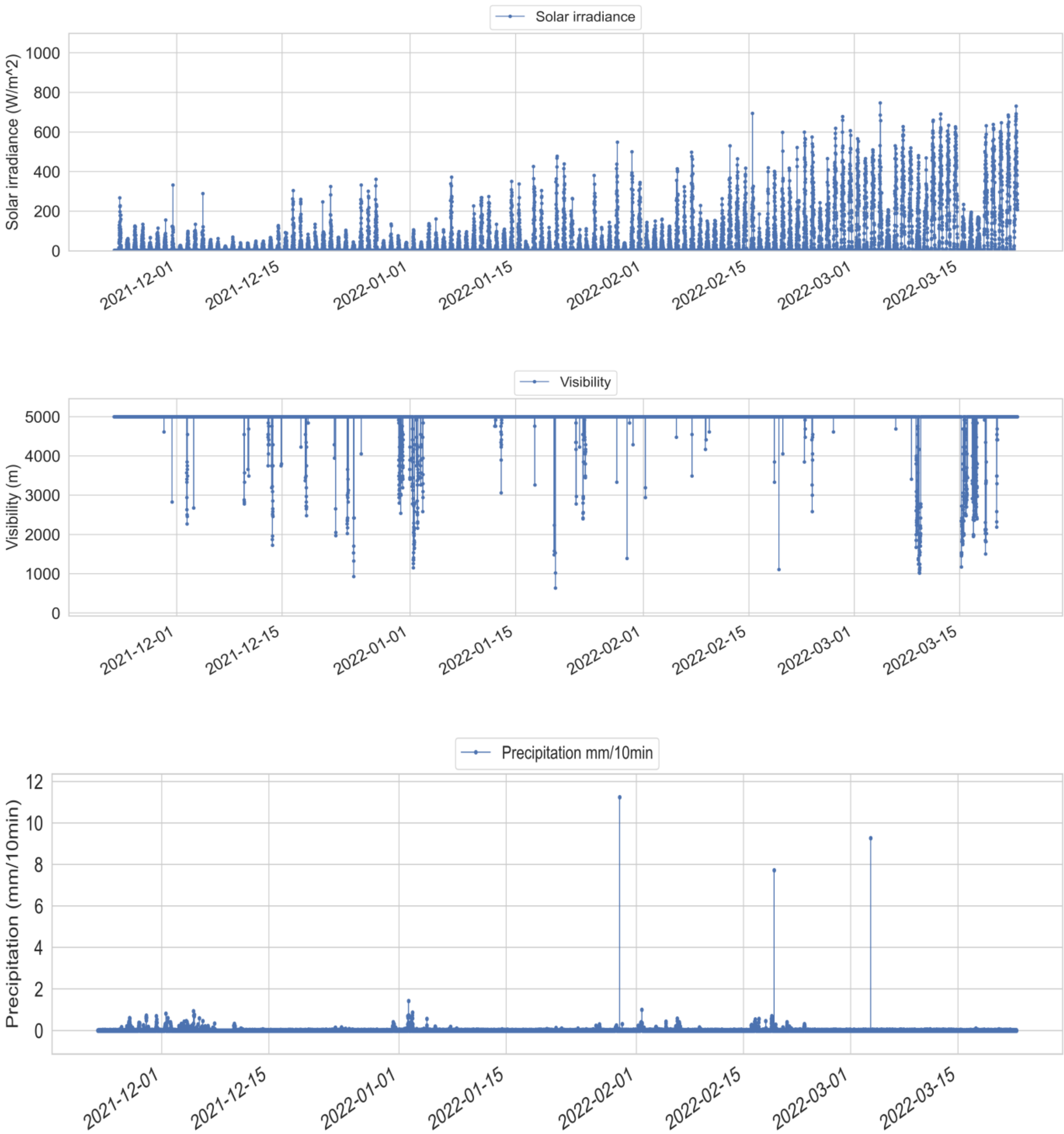
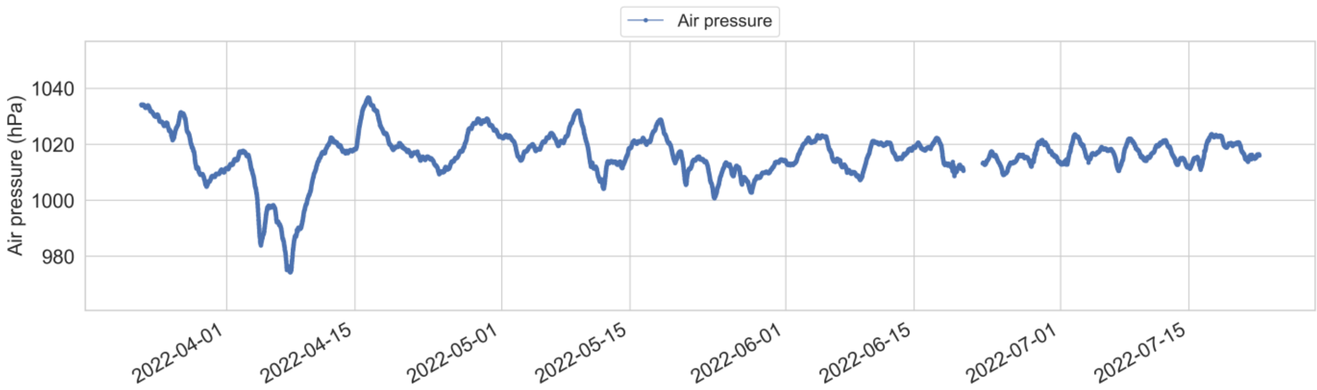
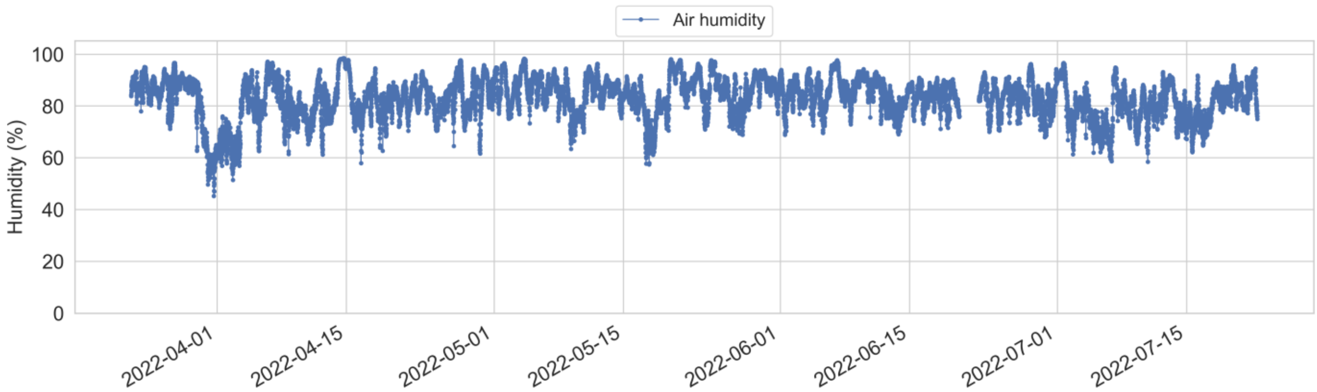
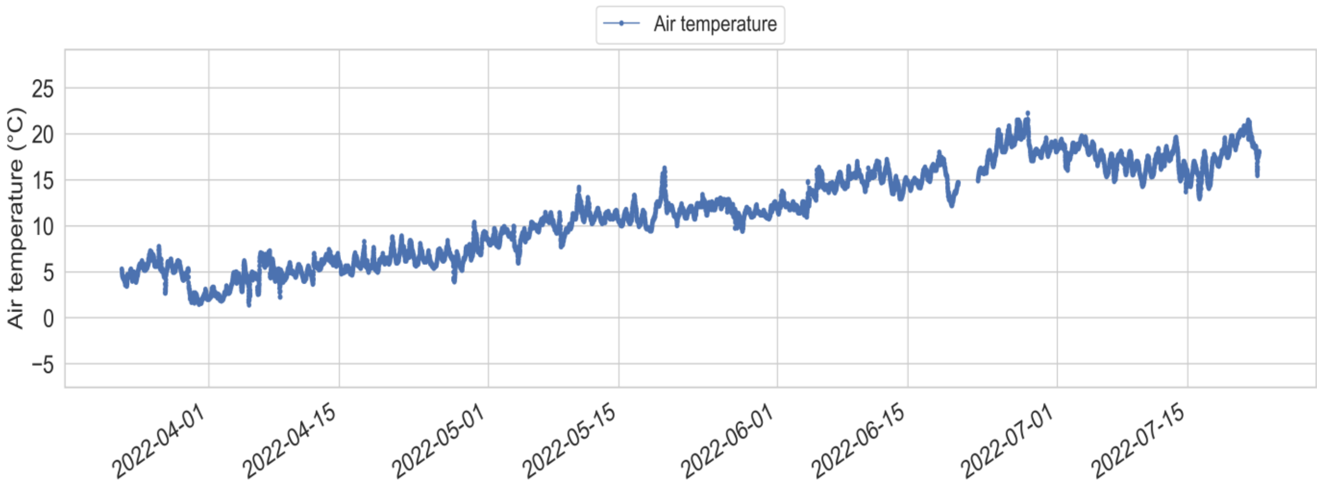


Figure B-7 Timeseries of air pressure, air humidity, air temperature, solar irradiance, visibility, and precipitation from November 2021 until March 2022


Air pressure
Air pressure (hPa)
1040
1020
1000
980
2022-04-01
2022-04-15
2022-05-01
2022-05-15
2022-06-01
2022-06-15
2022-07-01
2022-07-15


Air humidity
Humidity (%)
100
80
60
40
20
0
2022-04-01
2022-04-15
2022-05-01
2022-05-15
2022-06-01
2022-06-15
2022-07-01
2022-07-15


Air temperature
Air temperature (°C)
25
20
15
10
5
0
−5
2022-04-01
2022-04-15
2022-05-01
2022-05-15
2022-06-01
2022-06-15
2022-07-01
2022-07-15

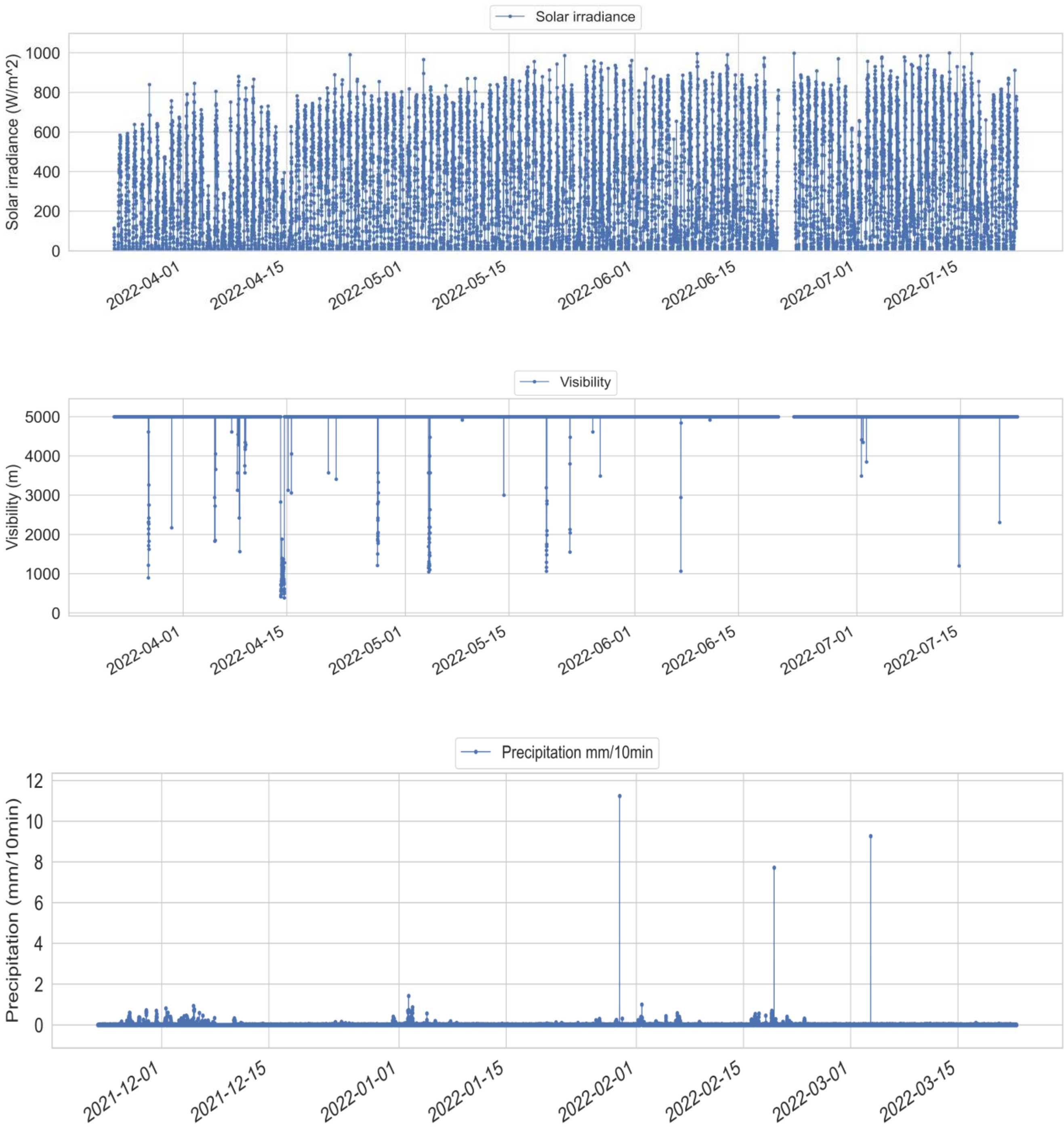
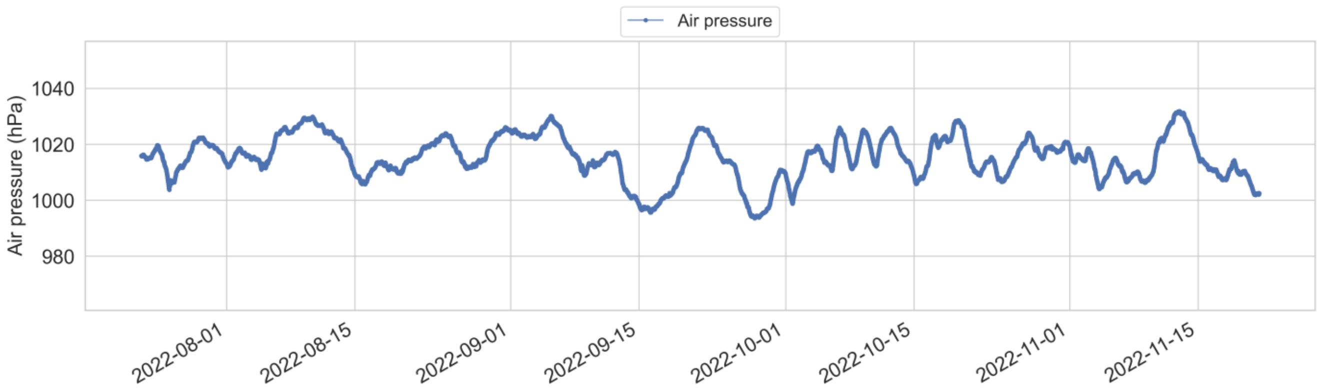
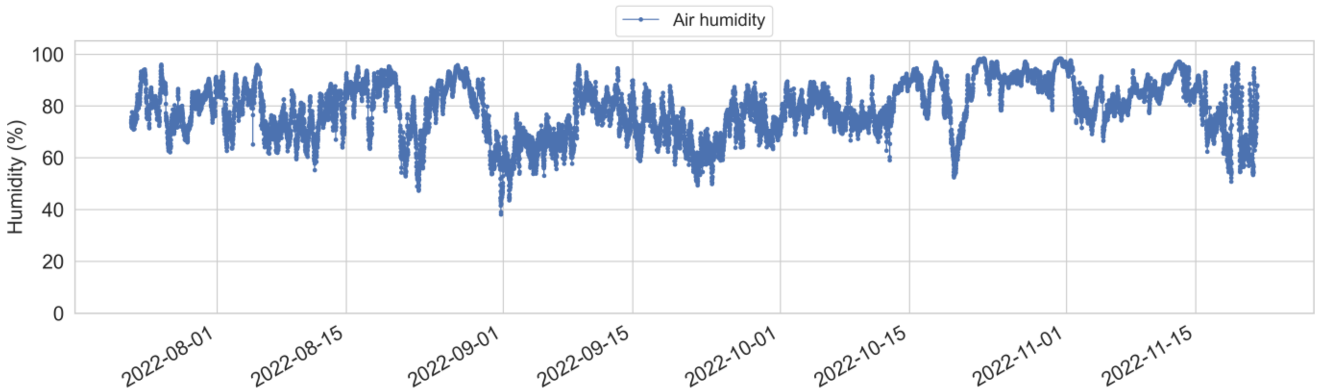
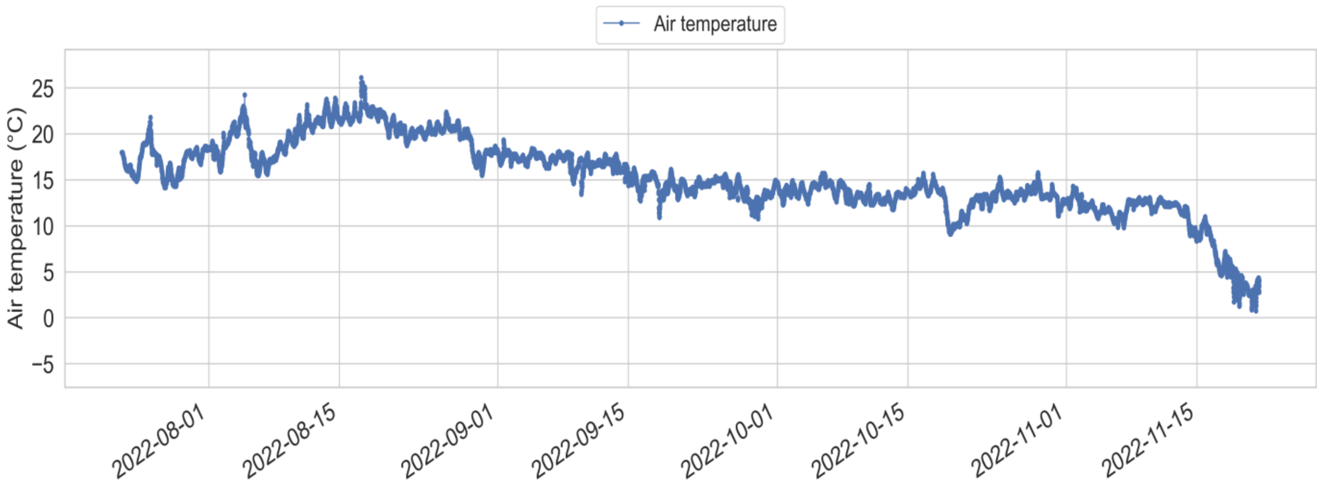


Figure B-8 Timeseries of air pressure, air humidity, air temperature, solar irradiance, visibility, and precipitation from March 2022 until July 2022


Air pressure
Air pressure (hPa)
1040
1020
1000
980
2022-08-01
2022-08-15
2022-09-01
2022-09-15
2022-10-01
2022-10-15
2022-11-01
2022-11-15


Air humidity
Humidity (%)
100
80
60
40
20
0
2022-08-01
2022-08-15
2022-09-01
2022-09-15
2022-10-01
2022-10-15
2022-11-01
2022-11-15


Air temperature
Air temperature (°C)
25
20
15
10
5
0
−5
2022-08-01
2022-08-15
2022-09-01
2022-09-15
2022-10-01
2022-10-15
2022-11-01
2022-11-15

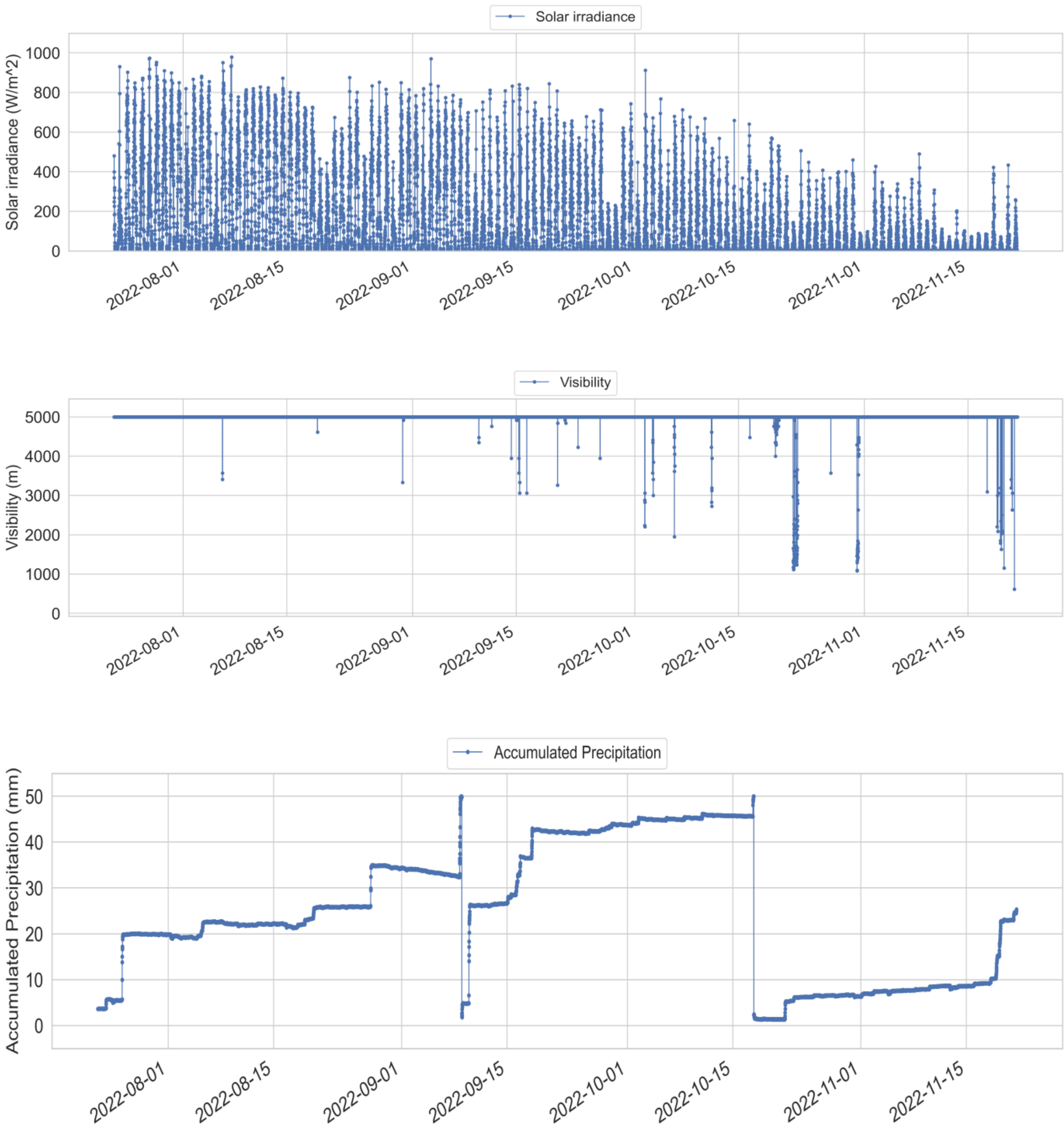


Figure B-9 Timeseries of air pressure, air humidity, air temperature, solar irradiance, visibility, and precipitation from July 2022 until November 2022. Please note that for precipitation, a jump from 50 mm to lower fill levels indicates emptying of the column when the maximum fill level is reached.

Figure B-10 Timeseries of water pressure in 6-monthly intervals

B.4 Current data (top-down)

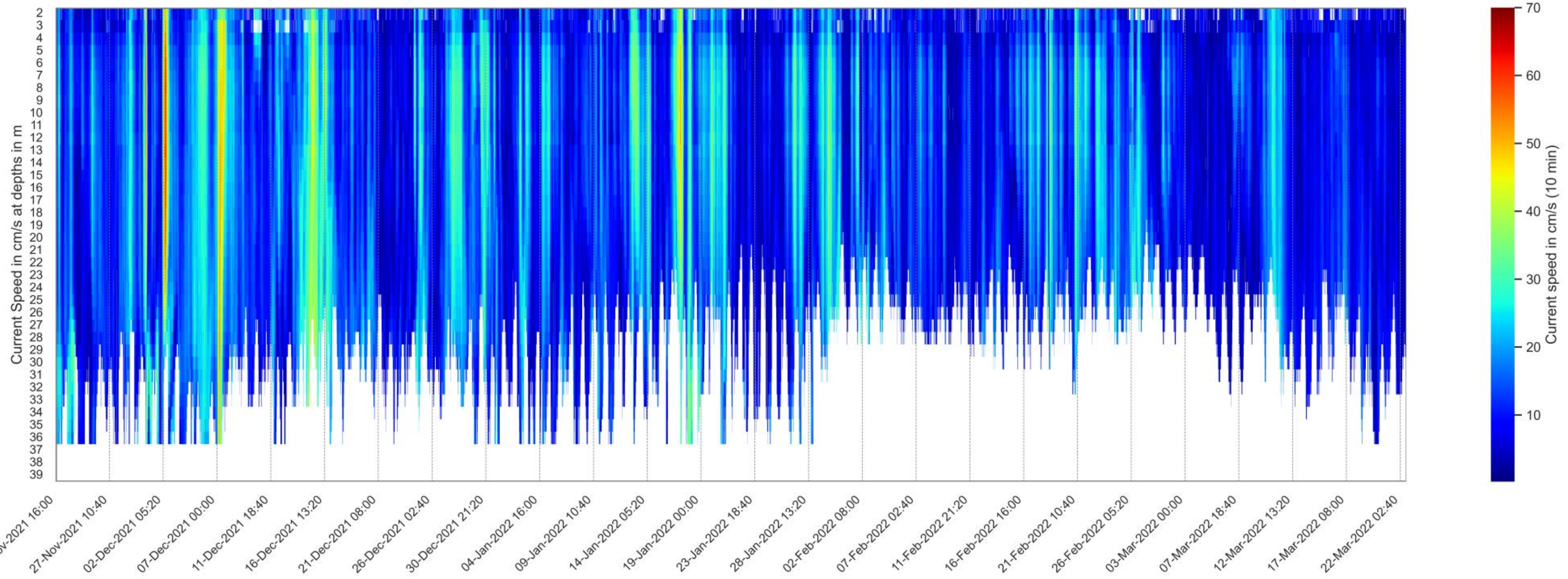


Figure B-11 Heatmap of SWLB (Aquadopp)-measured top-down current speed from November 2021 until March 2022.

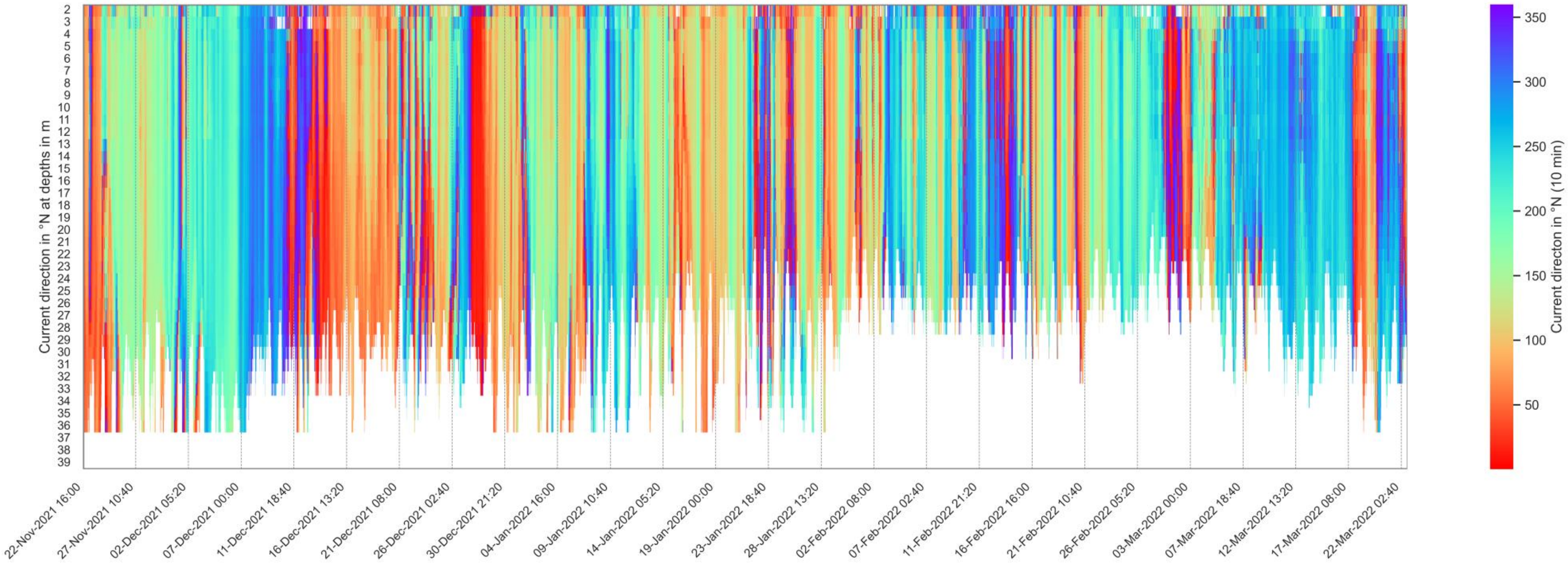


Figure B-12 Heatmap of SWLB (Aquadopp)-measured top-down current direction from November 2021 until March 2022.

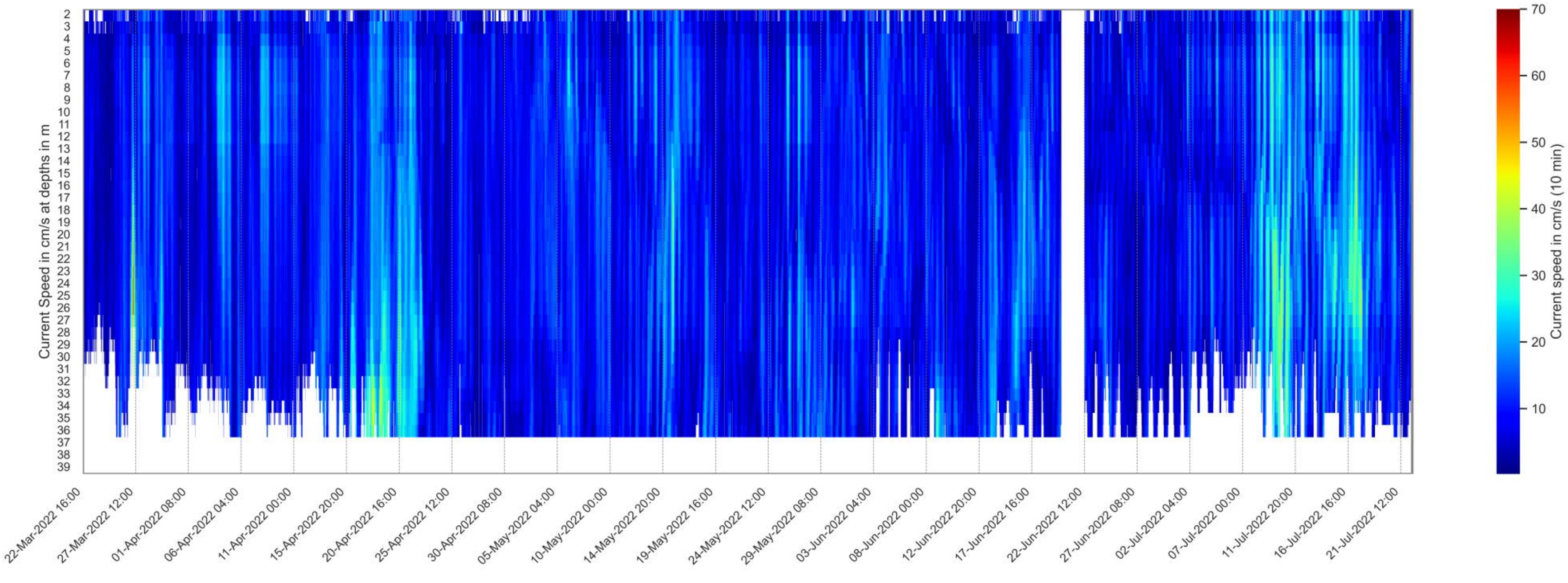


Figure B-13 Heatmap of SWLB (Aquadopp)-measured top-down current speed from March 2022 until July 2022.

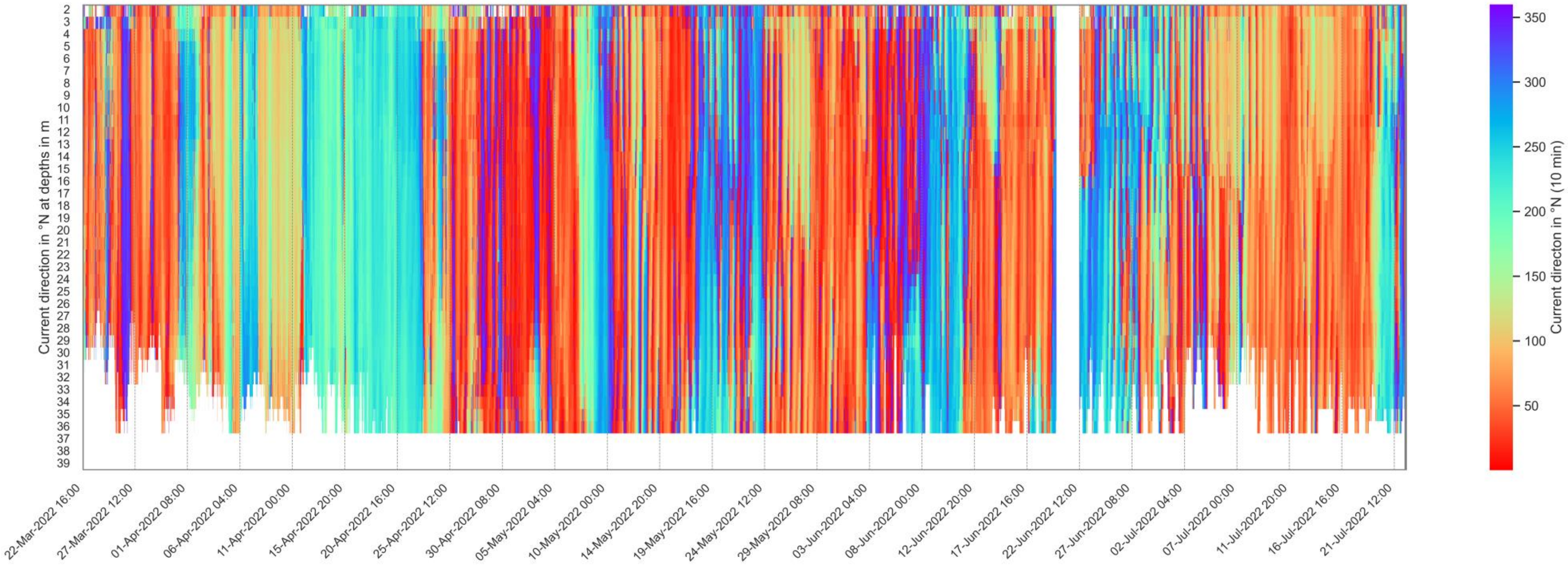


Figure B-14 Heatmap of SWLB (Aquadopp)-measured top-down current direction from March 2022 until July 2022.

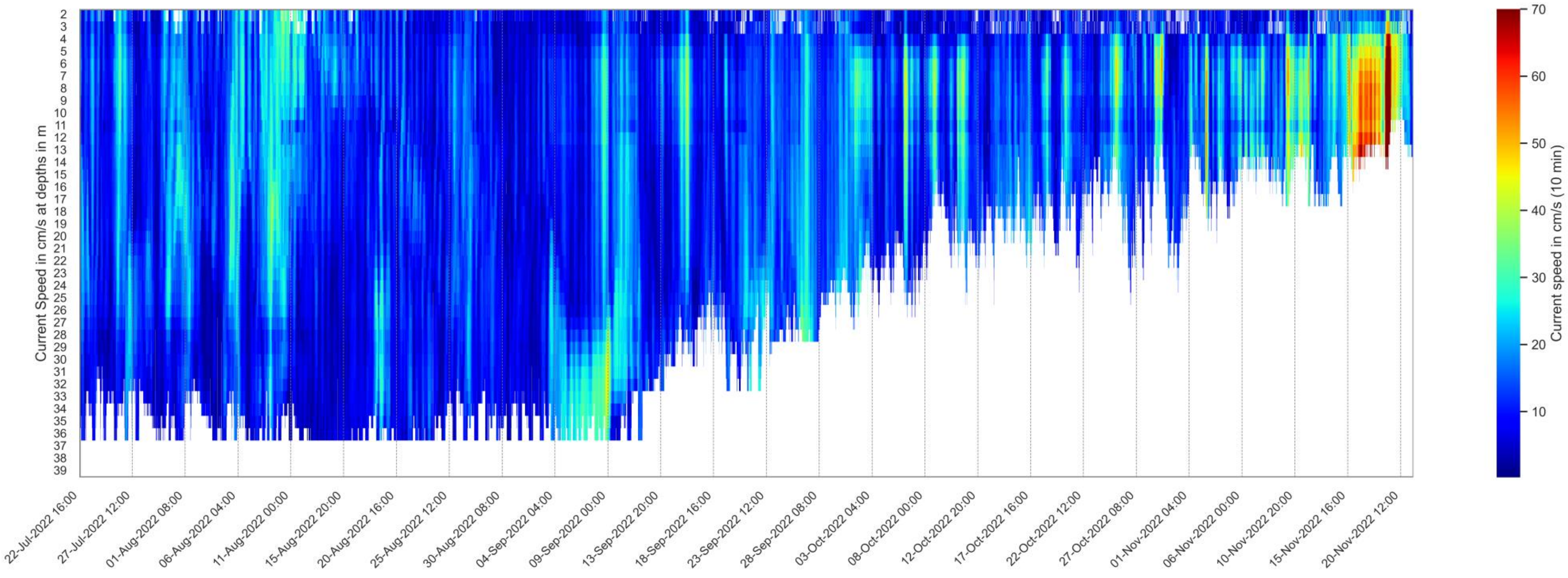


Figure B-15 Heatmap of SWLB (Aquadopp)-measured top-down current speed from July 2022 until November 2022.

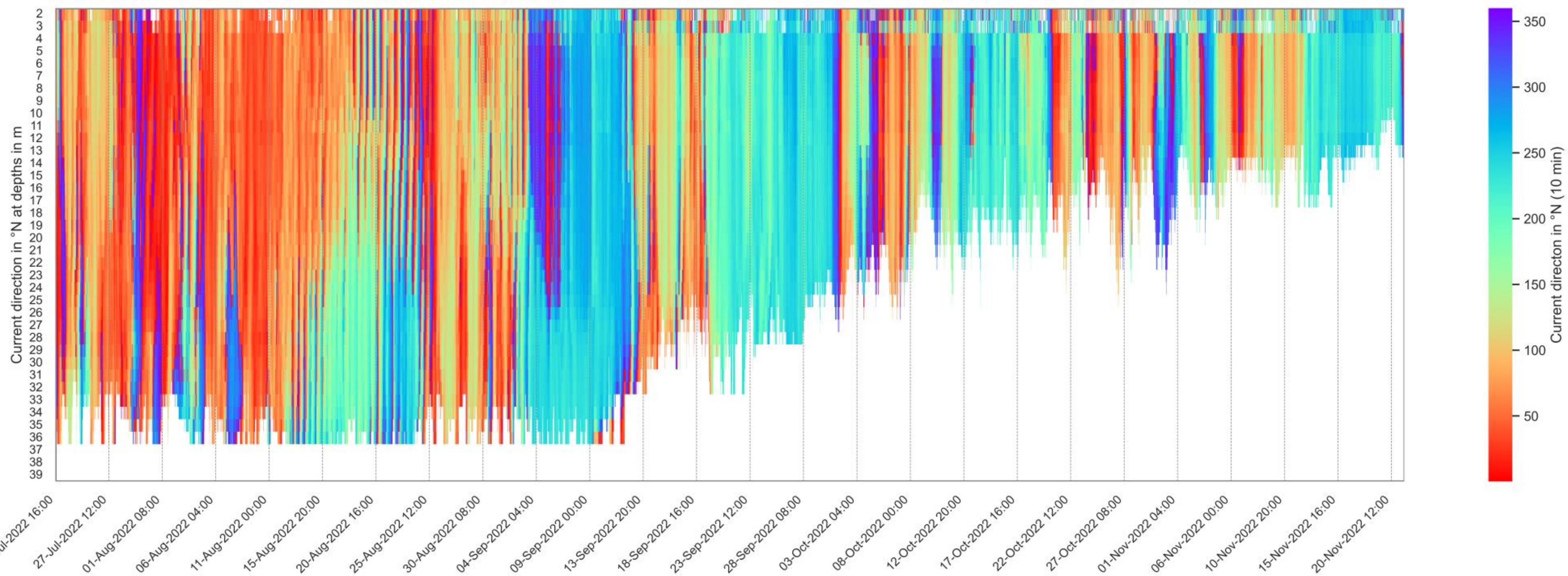


Figure B-16 Heatmap of SWLB (Aquadopp)-measured top-down current direction from July 2022 until November 2022.

B.5 Current data (upward)

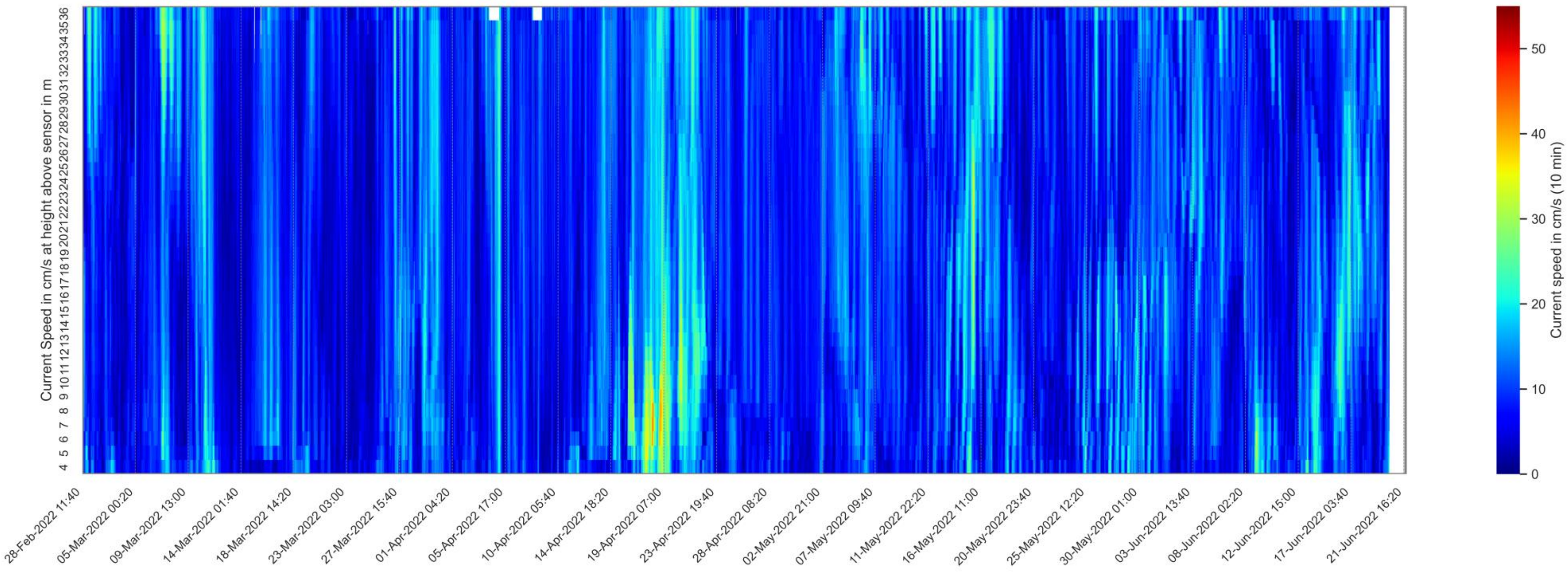


Figure B-17 Heatmap of offline (Signature)-measured bottom-up current speed from February 2022 until June 2022 (D1).

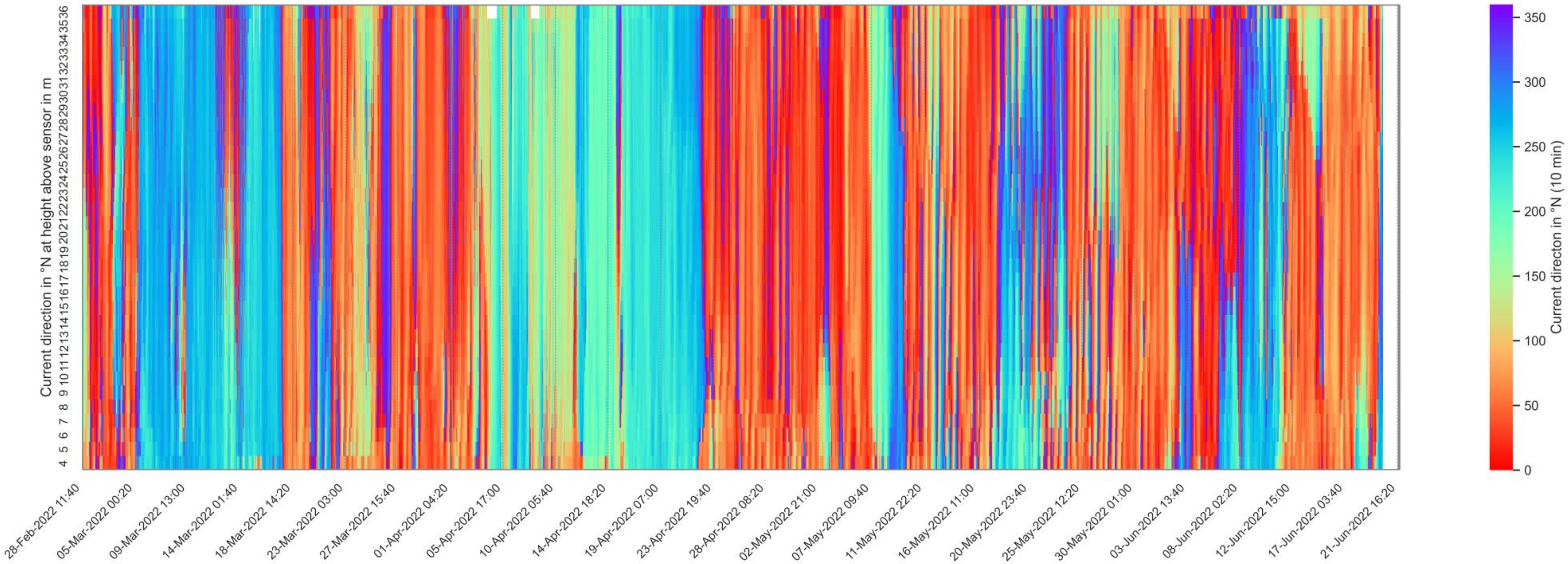


Figure B-18 Heatmap of offline (Signature)-measured bottom-up current direction from February 2022 until June 2022 (D1).

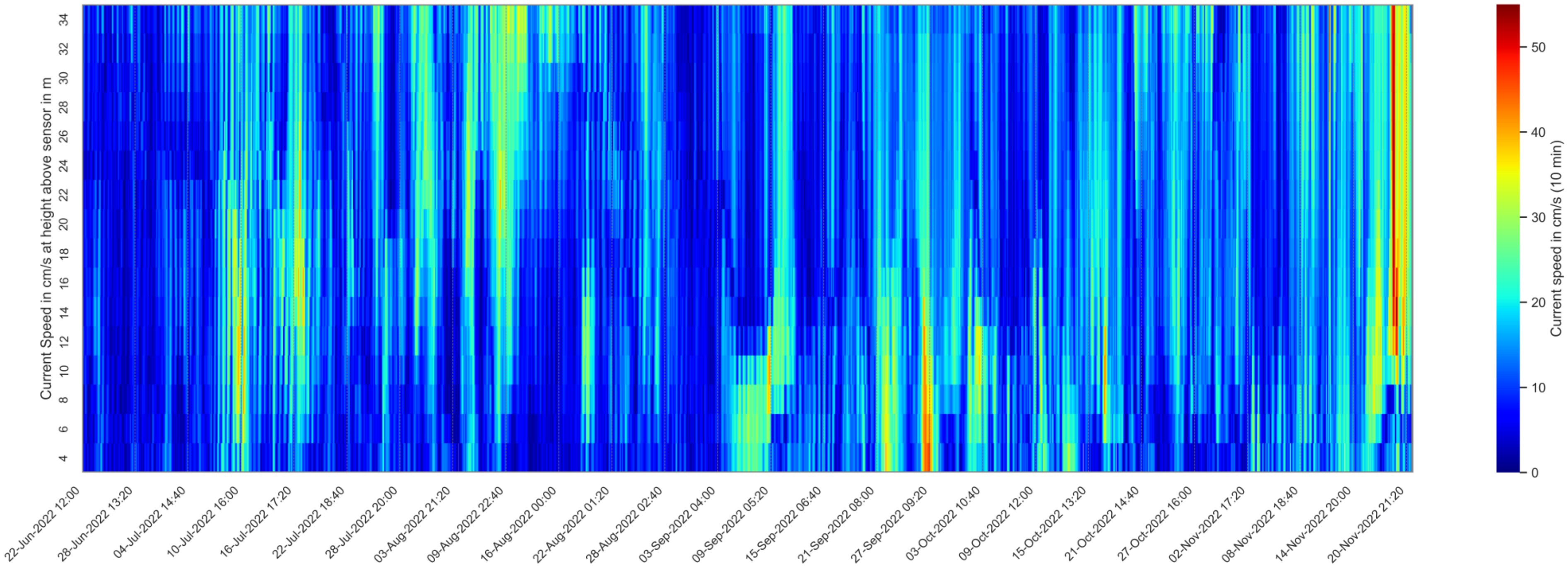


Figure B-19 Heatmap of offline (Signature)-measured bottom-up current speed from June 2022 until November 2022 (D2).

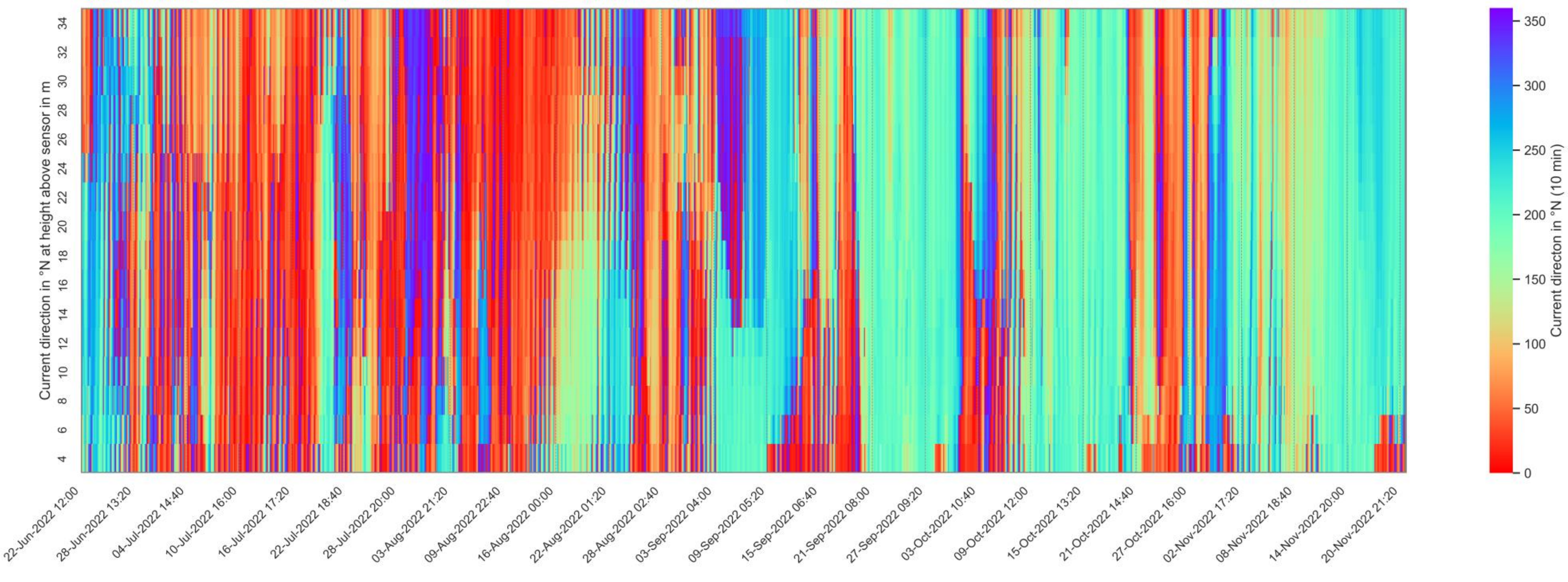


Figure B-20 Heatmap of offline (Signature)-measured bottom-up current direction from June 2022 until November 2022 (D2).

Appendix C

Final post-processed file contents

C.1 Energinet_Lot3_SWLB_20240424 November 2021 November 2022 CurrentData.csv

Parameter	Unit	Description
AqDir00xx deg	°N	Aquadopp current direction
AqSpd00xx cm/s	cm/s	Aquadopp current speed
AqAmpxx int	int	Aquadopp signal strength
where xx = 001, … , 041 m corresponding to measurement depth		

C.2 Energinet_Lot3_SWLB_20240303 November 2021 November 2022 MetOceanData.csv

Parameter	Unit	Description
AirHumidity %	%	Air humidity, Vaisala HMP155
AirPressure hPa	hPa	Air pressure, Vaisala PTB330
AirTemperature C	°C	Air temperature, Vaisala HMP155
AirPressure_lidar hPa	hPa	Air pressure from lidar met station
AirTemp_lidar C	°C	Air temperature from lidar met station
thSNR dB	dB	Thelma bottom sensor signal strength
thTBRtemperature degC	°C	Thelma modem (keelweight) surface water temperature
thTilt deg	°	Thelma bottom sensor tilt
BottomTemperature degC	°C	Thelma bottom sensor water temperature (near seafloor)
WaterPressure dbar	dbar	Thelma bottom sensor water pressure
precip_raw mm	mm	Accumulated precipitation
solarIrradiance W/m2	W/m2	Solar irradiance
pws_visibility m	m	Visibility in m
pws_WMOcode int	int	Visibility decoded
precipitation mm/10min	mm/10min	Precipitation
WaterTemp001 degC	°C	Aquadopp sea surface temperature
precipitation mm	mm	Accumulated precipitation

C.3 Energinet_Lot3_SWLB_20240303 November 2021 November 2022 Posdata.csv

Parameter	Unit	Description
irLatitude deg	°N	Latitude (position) from the Iridium modem
irLongitude deg	°E	Longitude (position) from the Iridium modem
spLatitude deg	°N	Latitude (position) from the Septentrio DGPS
spLongitude deg	°E	Latitude (position) from the Septentrio DGPS

C.4 Energinet_Lot3_SWLB_20240303 November 2021 November 2022 Status.csv

Parameter	Unit	Description
fcCurrentz A	A	Current produced by fuel cell z**
fcErrorz int	int	Error number from fuel cell z**
fcFuelRemz l	l	Remaining fuel connected to cell z**
fcOpTimez h	h	Operational time of fuel cell z**
fcULFz V	V	Fan voltage of fuel cell z**
leadAhCharged Ah	Ah	Net battery charging by solar panels during last hour
leadAhDischarged Ah	Ah	Energy drawn from batteries during last hour
leadBatteryVoltage V	V	Voltage in the lead acid batteries
lithiumAhDischarged Ah	Ah	Discharge of the lithium batteries during last hour
lithiumBattVoltage V	V	Battery voltage in the lithium batteries
pmuCardNo no	int	Card no in use in the power management unit, 1 or 2
sysUptime unknown	s	Time (in seconds) since last reboot of the buoy
thTBRid unknown	int	ID number of the water level sensor at bottom
** z= 1,2,3,4 = number of fuel cell		

C.5 Energinet_Lot3_SWLB_20240424 November 2021 November 2022 WaveData.csv

Parameter	Unit	Description
hm0 m	m	Significant wave height
hm0a m	m	Significant wave height, a-band**
hm0b m	m	Significant wave height, b-band**
hmax m	m	Average height of individual waves***
hmean m	m	Height of the highest individual wave***
hs m	m	Significant wave height, average of the one third highest waves***
mdir deg	°N	Mean spectral wave direction
mdira deg	°N	Mean spectral wave direction, a-band**
mdirb deg	°N	Mean spectral wave direction, b-band**
sprtp deg	°N	Wave spreading at the spectral peak period
thhf deg	°N	Mean wave direction at the spectral peak period
thmax s	s	High frequency mean wave direction
thtp deg	°N	Estimate of mean wave period tz, calculated from spectral moments tm01 = m0/m1
tm01 s	s	Estimate of mean wave period tz, calculated from spectral moments $tm02 = \sqrt{(m0/m2)}$
tm02 s	s	Estimate of tm02 in a-band**
tm02a s	s	Estimate of tm02 in b-band**
tm02b s	s	Period of spectral peak
tp s	s	Period of the highest wave***
tz s	s	Average period of individual waves***
ts s	s	Average period of the one third highest waves***

** Swell and wind sea frequency ranges:

Band “a” (Swell): 0.04 – 0.10 Hz (corresponding to wave periods between 10-25 sec, i. e. long waves)

Band “b” (Wind sea): 0.10 – 0.50 Hz (corresponding to wave periods between 2-10 sec, i. e. short waves)

*** zero-upcrossing requires a certain number of "high" wave in the data series to be calculated e.g. 50. Both hmax and thmax thus are usually not calculated if significant wave height is lower than approximately 0.3 m.

C.6 Energinet_Lot3_SWLB_20240303 November 2021 November 2022 WindSpeedDirectionTI.csv

Parameter	Unit	Description
VerticalWindSpeedxx m/s	m/s	Vertical lidar wind speed 10 min average calculated on buoy
WindDir004m deg	°N	Ultrasonic anemometer wind direction
WindGust004m m/s	m/s	Ultrasonic anemometer wind speed
WindSpeed004m m/s	m/s	Ultrasonic anemometer wind gust speed
WindDirxx deg	°N	Lidar wind direction 10 min average calculated on buoy
WindSpeedxx m/s	m/s	Horizontal lidar wind speed 10 min average calculated on buoy
windMax_horxx m/s	m/s	Maximum horizontal wind speed in 10 min interval
windMin_horxx m/s	m/s	Minimum horizontal wind speed in 10 min interval
turbulence(TI)xx	-	Turbulence intensity*, calculated on buoy
StandardDeviationxx m/s	m/s	Standard Deviation of wind speed in 10 min interval using lidar data

where xx = 30m, … , 270m corresponding to measurement height

* Turbulence Intensity (TI) is defined as: $(\sigma/\bar{u}) / C$ where σ is the standard deviation and $\bar{u}$ is the mean of the wind speed for a 10-min period. C = 0.95 is a constant needed to convert the scan-averaged lidar measurement to the point measurements of a cup anemometer. Note that this definition frequently gives relatively high values in situations with low but variable wind speed. Note also that TI is not compensated for the motion of the buoy, which is a source of increased standard deviation in the measurements, and TI is therefore over-estimated compared to what would be obtained from a lidar on a fixed platform. Methods for motion compensation are being developed and corrected data may be calculated in the future. (Z300 MODBUS interface, a user's guide, 19th Dec 2013, issue K, ZephIR Lidar)

C.7 Energinet_Lot3_SWLB_20240303 November 2021 November 2022 WindStatus.csv

Parameter	Unit	Description
liBattteryVoltage unknown	V	Lidar battery voltage
liPODHumidity unknown	%	Lidar pod humidity
liRain unknown	int	Lidar rain count
liMirrorTemp unknown	°C	Lidar mirror temperature
liStatusFlagHi unknown	int	Lidar status flag high bits
liStatusFlagLow unknown	int	Lidar status flag low bits
liInfoFlagHi unknown	int	Lidar info flag high bits
liInfoFlagLow unknown	int	Lidar info flag low bits

liInfoFlag	int	Lidar status flag combined
liStatusFlag	int	Lidar info flag combined
liInfoFlagText	-	Lidar status flag translated to text
liStatusFlagText	-	Lidar info flag translated to text
liPacketCountxx	-	Number of samples for the averaging period
where xx = 30m, … , 270m corresponding to measurement height		

C.8 Energinet_Lot3_Signature_20240405 November 2021 June 2022.csv

Column header	Unit	Description
Speed004m_cm/s, …, Speed037m_cm/s	cm/s	10-min averaged current speed
SigDir004m_deg, …, SigDir037m_deg	°N	10-min averaged current direction
DataMask_0, …, DataMask_33[1]	int	Data selection mask: non-zero indicates bad data value
BinMapAmp_BeamX_0, …, BinMapAmp_BeamX_33[1]	dB	Beam amplitude (signal-to-noise ration) where X corresponds to beam number 1 through 4
BinMapCor_Beam1_0, …, BinMapCor_Beam1_33[1]	%	Beam correlation (outgoing vs. incoming) where X corresponds to beam number 1 through 4
BinMapVel_East_0, …, BinMapVel_East_33[1]	cm/s	East velocity
BinMapVel_North_0, …, BinMapVel_North_33[1]	cm/s	North velocity
BinMapVel_Up1_0, …, BinMapVel_Up1_33[1]	cm/s	Vertical velocity
BinMapVel_Up2_0, …, BinMapVel_Up2_33[1]	cm/s	Vertical velocity
SpeedOfSound	m/s	Speed of sound during data collection at transducer head
WaterTemperature	°C	Seawater temperature at transducer head
Pressure	dbar	Water pressure measured at transducer head
Heading	°N	Heading
Pitch	°N	Pitch
Roll	°N	Roll
Altimeter_LE	dbar	Altimeter pressure - Leading Edge
Altimeter_AST	dbar	Altimeter pressure - Acoustic Surface Tracking
Altimeter_Pressure	dbar	Altimeter pressure
AltimeterQuality_LE	int	Altimeter Leading Edge quality parameter
AltimeterQuality_AST	int	Altimeter Acoustic Surface Tracking quality parameter

ASTPressureOffset	s	Acoustic Surface Tracking pressure offset
AltimeterStatus	int	Altimeter status
[1] where 0 corresponds to 004m and 33 to 037m		

C.9 Energinet_Lot3_Signature_20240405 June 2022 November 2022.csv

Column header	Unit	Description
Speed004m_cm/s, Speed006m_cm/s, …, Speed034m_cm/s	cm/s	10-min averaged current speed
SigDir004m_deg, SigDir006m_deg, …, SigDir034m_deg	°N	10-min averaged current direction
DataMask_0, …, DataMask_15[1]	int	Data selection mask: non-zero indicates bad data value
BinMapAmp_BeamX_0, …, BinMapAmp_BeamX_15[1]	dB	Beam amplitude (signal-to-noise ration) where X corresponds to beam number 1 through 4
BinMapCor_Beam1_0, …, BinMapCor_Beam1_15[1]	%	Beam correlation (outgoing vs. incoming) where X corresponds to beam number 1 through 4
BinMapVel_East_0, …, BinMapVel_East_15[1]	cm/s	East velocity
BinMapVel_North_0, …, BinMapVel_North_15[1]	cm/s	North velocity
BinMapVel_Up1_0, …, BinMapVel_Up1_15[1]	cm/s	Vertical velocity
BinMapVel_Up2_0, …, BinMapVel_Up2_15[1]	cm/s	Vertical velocity
SpeedOfSound	m/s	Speed of sound during data collection at transducer head
WaterTemperature	°C	Seawater temperature at transducer head
Pressure	dbar	Water pressure measured at transducer head
Heading	°N	Heading
Pitch	°N	Pitch
Roll	°N	Roll
[1] where 0 corresponds to 004m and 15 to 034m		

Appendix D

File formats and contents of the raw data files

Energy Islands – Floating LiDAR Measurements

File formats and contents of the raw data files

C75487-RawData-README-001 01 | 2 May 2024
Final
ENERGINET

Document Control

Document Information

Project Title	Energy Islands – Floating LiDAR Measurements
Document Title	File formats and contents of the raw data files
Fugro Project No.	C75486
Fugro Document No.	C75487-RawData-README-001
Issue Number	01
Issue Status	Final

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Revision History

Issue	Date	Status	Comments on Content	Prepared By	Checked By	Approved By
01	24 Apr 2024	Draft	First complete issue	Irene Pathirana	Arve Berg	
02	05 May 2024	Final	Final issue	Irene Pathirana	Arve Berg	Arve Berg

Contents

1. ZX Lidars *.zph

There are two types of data produced by the ZX 300:

- Unaveraged 1 Hz data (wind*.zph)
- Averaged "10 minute" data (Wind10*.zph)

Each day has an associated file of each type resulting in two data files per day. Both data types are contained on the ZX 300's internal storage and can be accessed by the user. Data is compressed by the ZX 300 to save storage space and bandwidth during transmission.

The unaveraged 1 Hz data is used by the SWLB datalogger unit to determine wind speed and direction using the SWLB heading.

The averaged 10-minute data is **not used by the SWLB system**. It is not heading corrected and is only provided for completeness. The user should only use the 1 Hz *.zph data and the QC'd SWLB 10-minute data.

2. Nortek Aquadopp *.prf

The .prf file is the output from the AquaPro software, in binary format.

3. Nortek Signature500 raw data

The .ad2cp file contains all 1 Hz raw current measurements collected by the Signature 500. In addition a configuration file (*.cfg), a deployment setup file (*.deploy) and an internally averaged 10-min file (*.avgd.ad2cp) are supplied. The *.avgd.ad2cp is not used for any post-processing.

4. Thelma Biotel water level sensor *.bin

Data from both the bottom sensor and the top receiver modem are written to file by the SWLB datalogger into daily "thelma-YYYY-MM-DD.bin" files, where YYYY = year, MM = month, DD = day, readable with a text editor.

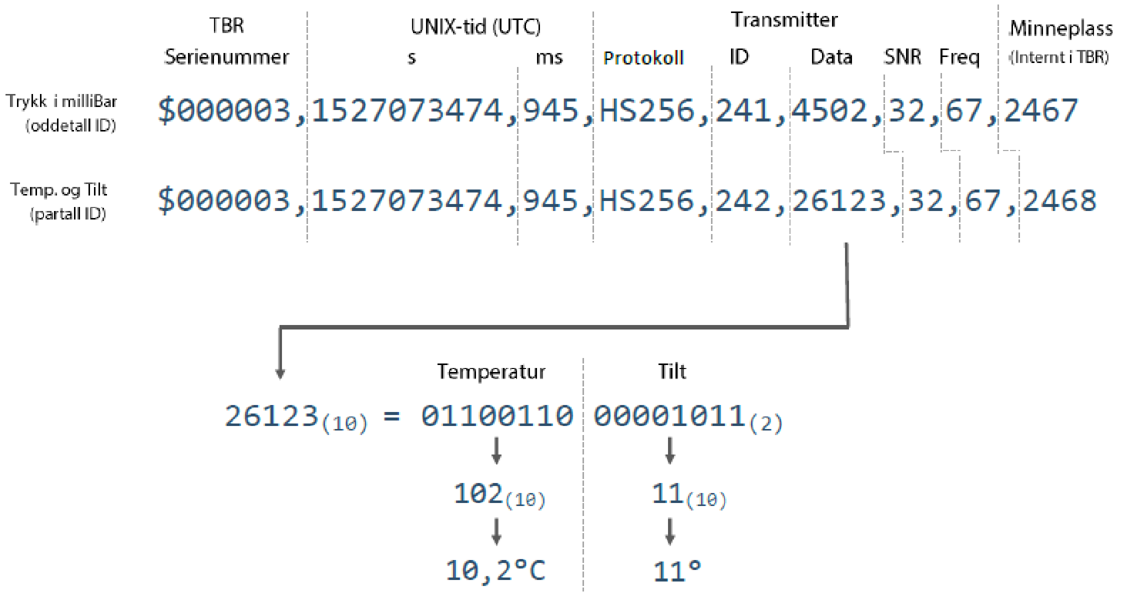
4.1 Tag detections

Bottom sensor data									
1554076846	000924	1554076840	432	HS256	21	3316	38	67	116543
GENITIME	SERIAL	UNIXTIME	MILLIS	PROTO	TAGID	DATA	SNR	FREQ	FLASHENTRY
int	int	int	int	int	int	int	int	int	int
Real time data	TBR serial number	UTC UNIX timestamp (automatically reset to 1. Jan. 2000 when power is off)	millisecond timestamp	code type	tag ID	data	Signal to Noise Ratio	TBR listening frequency - kHz	code running entry number in flash memory
Top Modem data									
1554076801	000924	1554076800	TBR Sensor	132	9	15	67	116542	
int	int	int	int	int	int	int	int	int	
Real time data	TBR serial number	UTC UNIX timestamp (automatically reset to 1. Jan. 2000 when power is off)	code type	Modem Temperature data	Average noise level	Peak noise level	TBR listening frequency - kHz	code running entry number in flash memory	

4.2 Decoding bottom sensor data

Odd TAGID X = total pressure in milliBar

Even TAGID X+1 = bottom temperature and tilt



4.3 Decode top modem data

Temperature = (data -50)/10 -> °C

5. Fugro Wavesense 3 *chpr* (*enh*)

chpr.csv files contain Wavesense 3 compass, heave, pitch, roll raw data from the SWLB buoys as basis to determine the wave parameters. The sensor sampling rate is set to 2Hz.

enh.csv files contain Wavesense 3 east, north, heave raw data from the SWLB buoys as basis to determine the wave parameters. The sensor sampling rate is set to 2Hz.

Compass direction is given in degrees, pitch and roll in radians, heave elevations, east and north positions are given in m.

For each row the timestamp in the first column given represents the start of the sampling of all the time series in that row.

The index in the parameter name, given by [0],[1],...,[2048] is the sample number for the parameter.

Note that there is a 20-minute difference in the timestamps between the raw *chpr* (*enh*) data and the processed, QC'd 10-minute averaged wave data.

6. MEM wave spectra

The directional wave spectra are estimated from the directional Fourier components using the Burg Maximum Entropy method (MEM) [1] . The wave spectra were postprocessed to using the raw compass, heave, pitch and roll data (lidar buoys) or east, north and heave data (wave buoy). There is a 20 min offset between the data in the memspec files and the timeseries.

Spectra are stamped like the time series, rounded back to the beginning of the measuring interval. Parameter records from real rime processing are stamped at the time of recording, which is rounded forward to the end of the recording interval.

Calculations of wave parameters done onboard the buoy use the measured data before storing and digitalization. Thereafter data is stored, both raw and calculated. During this storage process, the data is digitalized with a given resolution (i.e. binned). If the stored raw data or memspec files are used to re-calculate the wave parameters, there may be small differences compared to parameters calculated onboard the buoy. The resolution settings are, however, set such that the differences are insignificant (better than the accuracy).

6.1 Spectra for SW Mini wave buoy

fmin = 0.04; fmax = 1.0; df = 0.01; units = Hz

dirmin =0; dirmax = 360; ddir = 5; units = degrees.

6.2 Spectra for lidar buoy

fmin = 0.04; fmax = 0.6; df = 0.01; units = Hz

dirmin =0; dirmax = 360; ddir = 5; units = degrees.

7. Memspec* file format

The file contains the 2-dimensional directional spectral density S(f, ϴ) [m^2 s deg^{-1}] in addition to other spectral parameters. The directional spectrum is estimated from the directional Fourier components using the Burg Maximum Entropy method (MEM) [1].

The MEMspec data file is a sequential text file containing a sequence of records for each recorded wave time series:

1. ISSUE TIME: The date and time when the analysis was produced.
2. START TIME: The time of the first measurement in the time series of Heave, Pitch, Roll and Compass heading data
3. END TIME: The time of the end of the time series of Heave, Pitch, Roll and Compass heading data
4. LOCATION: Text identifying the location and buoy.
5. direction: Unit for direction data.
6. frequency: Unit for frequency
7. matrix rows: Number of rows (frequencies) in the spectrum matrix.
8. Hm0 m: Spectral estimate of significant wave height in meters for this time series.
9. Tp s: Peak period = $1/f_{Peak}$ where f_{Peak} is the frequency of the maximum spectral energy density within the (omni-directional) wave spectrum S(f).
10. Mdir deg: Mean wave direction in degrees for this time series.
11. spectral density: Unit for spectral density (m^2 s = m^2 Hz-1).
12. a1: a_1(f) = Fourier coefficients a_1 of the directional distribution at frequency f = fmin, ..., fmax.
13. b1: b_1(f) = Fourier coefficients b_1 of the directional distribution at frequency f = fmin, ..., fmax.

14. a2: $a_2(f)$ = Fourier coefficients a_2 of the directional distribution at frequency f = fmin, ..., fmax.
15. b2: $b_2(f)$ = Fourier coefficients b_2 of the directional distribution at frequency f = fmin, ..., fmax.
16. hspec: Omnidirectional spectral energy density S(f) for each frequency f.
17. Directions in degrees for each column in the following directional spectrum matrix.
18. – 18 + <matrix rows> -1: The directional wave spectrum. There is one record for each frequency, f, of the directional spectrum, containing f and then S(f, Θ), for Θ = ΔΘ, ..., 360°.

Then follows the next spectrum data block beginning with "ISSUE TIME".

8. Seabird CTD raw data

Each SBE 37-IMP-ODO MicroCAT (SBE37SMP-RS485 instrument stores the raw data in *.hex and '.xmlcon files. Each instruments' raw data files (SBE37SMP-RS485_*_DATE.hex and SBE37SMP-RS485_*_DATE.xmlcon) were converted to SBE37SMP-RS485_*_DATE.cnv files (readable with text editors) for each depth, where * indicates the serial numbers for the sensors at the different depths and DATE the filedate.

9. References

[1] A. Lygre and H. E. Krogstad. Maximum entropy estimation of the directional distribution in ocean wave spectra. J. Phys. Oceanogr., 16, 1986.