Danish Offshore Wind 2030 – Floating LiDAR Measurements

Final Campaign Report for Kattegat, July 2023 – July 2024

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Abbreviations

Abbreviation	Definition
ADCP	Acoustic Doppler Current Profiler
D1, D2	D1: The campaign period by first deployment D2: The campaign period by second deployment (after service)
FLS	Floating Lidar System
GNSS	Global Navigation Satellite System
IEC	International Electrotechnical Commission
LAT	Lowest Astronomical Tide
LiDAR (or lidar)	Light Detection and Ranging
MSL	Mean Sea Level
MWL	Mean Water Level
NaN (Not a Number)	Label indicating data as invalid/missing
QA/QC	Quality Assurance / Quality Control
SI	Système International
SWLB	Seawatch Wind Lidar Buoy
TI	Turbulent Intensity
UTC	Universal Time Coordinated
WMO	World Meteorological Organization
WS	Seawatch Wavescan buoy (Prefix for some type of Lidar buoy)

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. The deviation between magnetic and true north is approximately 4.5°(E) for KG-1-LB and KG-1-CP station.[1] This deviation applies to magnetic compass heading data, and wave and current directions have been corrected accordingly. Thus, 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.

[1] https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml#declination

Executive Summary

Fugro Norway AS entered into an agreement with ENERGINET, Denmark for the project "Danish Offshore Wind 2030 – Lot1-3" for 12 months.

The measurements from the metocean surveys will be used as input to various environmental, metocean, and other studies and analyses to support the project development and design process, including energy yield calculations, site assessment, selection and design of foundation, grid connections, cable corridors, etc.

Lot 1 consists of Kattegat and Hesselø South with one Lidar buoy and one bottom mounted current profiler on the bottom at each location. The two primary buoys allocated for Lot 1 are WS199 and SWLB059. Both buoys were first deployed on 21 July 2023 at Kattegat and Hesselø South, respectively. On 23 March 2024, WS190 was deployed at Hesselø South replacing SWLB059.

The LiDAR buoys are online with processed data being transmitted every ten minutes. Unprocessed data from the buoys and the bottom current profilers were downloaded at service and processed thereafter.

This final campaign report covers Lot 1, Kattegat and includes general information of the measurement campaign, configurations, post-processing, quality control, post-processed data availability and data presentations over the period from 21 July 2023 to 21 July 2024. All equipment was recovered on 3 August 2024 from Kattegat.

The data availability of WS199 for the full 12-month campaign is 96.6 % for wind (lower than 200m) and 97.8 % for waves, 90.3 % for currents (down to 17m, top down) and >98 % for all other parameter groups except water pressure (87% after post-process). The data availability of KG-1-CP current profiler is 99.0 %.

1. Introduction

1.1 Kattegat and Hesselø South project area

The Kattegat project area is located 20 km east of the Djursland peninsular, protruding into Kattegat Sea. The water depth in the more than 120 km^2 area is between 17 and 38 m. The approximate distance to Grenå Port is 20 km. The Hesselø South project area is located 40 km northwest off the north coast of Zealand and nearly 50 km east of the Djursland peninsular. The water depth in the 160 km^2 area is between 14 m and 32 m. The approximate distance to Hundested Port is 45 km.

Deployment locations are given in Figure 1.1 and exact positions and water depths for the different buoy locations are given in Table 1.1.

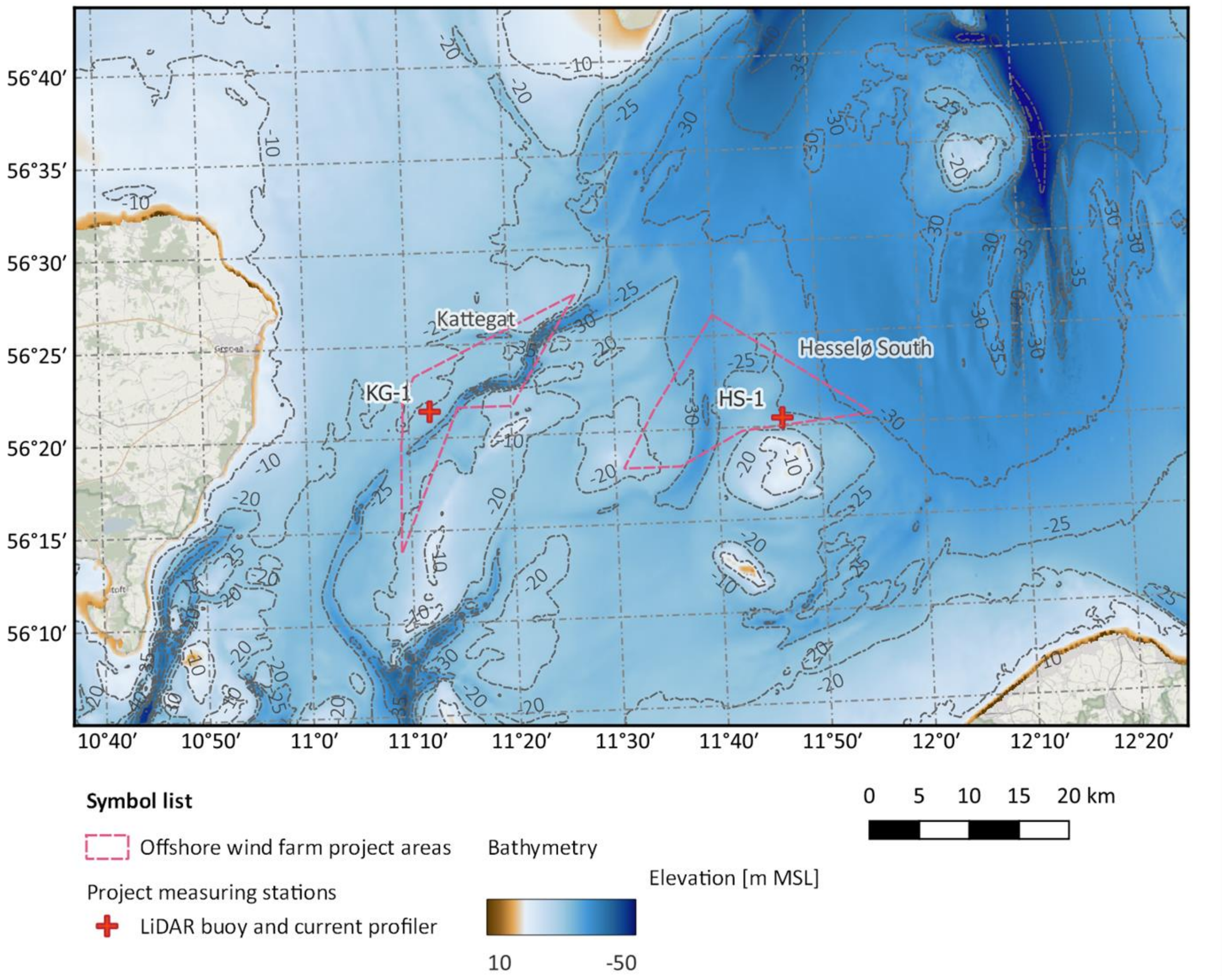


Figure 1.1: Instrument locations in the Kattegat and Hesselø project area

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 lasted 12 months.

Table 1.1: Buoy locations and water depths

Station	Area	As laid location (WGS84)		Depth [m]	Type
		Latitude[°N]	Longitude[°E]		
HS-1-LB	Hesselø South	56.3340	11.7723	22.6	LiDAR buoy
HS-1-CP	Hesselø South	56.3342	11.7722	22.6	Current profiler*
KG-1-LB	Kattegat	56.3506	11.2010	20.8	LiDAR buoy
KG-1-CP	Kattegat	56.3503	11.2011	20.7	Current profiler*

Note
*Indicates offline instruments

1.2 Deployments Kattegat

Wind LiDAR buoy WS199 was deployed at Kattegat on 21 July 2023 at 11:10 UTC together with a bottom mounted water level sensor and a bottom mounted upward-looking current profiler.

The LiDAR buoy provides near real-time data that is transmitted to shore every 10 minutes. This report gives an overview of this transmitted data and the data downloaded from instrument and the buoy, data availability and activities during the campaign. Unprocessed data from the buoy and the bottom current profiler were only downloaded at service.

The positions of the bottom mooring weights are listed in Table 1.1. As the buoy is free to float around the mooring point within a radius of about 110 m, the water depth varies slightly with the position of the buoy.

Table 1.2 shows a log of the deployments at Kattegat.

Table 1.2: Deployments at Kattegat

Station	ID	LiDAR #	D#	Start time (UTC)	End time (UTC)	Status
KG-1-LB	WS199	ZX1741	D1	2023-07-21 11:10	(2024-02-18 08:30)	Recovered, end of campaign
			D2	(2024-02-22 13:25)	2024-07-21 11:10*	
KG-1-CP	104507	-	D1	2023-07-21 11:16	2024-02-22 15:35	
	104510	-	D2	2024-02-22 15:54	2024-07-21 11:16*	

Note
*12-month campaign ended respectively. WS199 was recovered 08:30 UTC, 3 August 2024 and 104510 current profiler was recovered 09:30UTC, 3 August 2024

1.3 SWLB Calibration and Pre-deployment Validation

The LiDAR buoy WS199 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 KG-1-LB SWLB data

Data from the LiDAR buoy was transmitted to shore in near real-time, quality checked monthly and reported in monthly reports. Table 1.3 lists the monthly reports for this project area.

Table 1.3: List of monthly reports at Kattegat

Time period	Monthly report
21 July 2023 – 21 August 2023	C75516-R-KG-M01(07)
21 August 2023 – 21 September 2023	C75516-R-KG-M02(04)
21 September 2023 – 21 October 2023	C75516-R-KG-M03(03)
21 October 2023 – 21 November 2023	C75516-R-KG-M04(03)
21 November 2023 – 21 December 2023	C75516-R-KG-M05(02)
21 December 2023 – 21 January 2024	C75516-R-KG-M06(01)
21 January 2024 – 21 February 2024	C75516-R-KG-M07(01)
21 February 2024 – 21 March 2024	C75516-R-KG-M08(01)
21 March 2024 – 21 April 2024	C75516-R-KG-M09(01)
21 April 2024 – 21 May 2024	C75516-R-KG-M10(01)
21 May 2024 – 21 June 2024	C75516-R-KG-M11(02)
21 June 2024 – 21 July 2024	C75516-R-KG-M12(02)

The raw data of buoy mounted current profiler (Aquadopp 400 kHz) was also collected after the campaign and was used for this final 12-month report.

1.4.2 KG-1-CP ADCP data

The bottom mounted instrument (Signature500) was deployed offline and collected data during the 12 months campaign period. The full 12-month dataset is presented in this report.

2. Activities

2.1 Service and Maintenance Activities

LiDAR buoy WS199 was deployed at KG-1-LB at 11:10 UTC, 21 July 2023. A bottom mounted upward-looking Nortek Signature500 current profiler was deployed at KG-1-CP at 11:16 UTC, 21 July 2023.

In February 2024, WS199 was serviced onshore and redeployed on 22 February 2024 and the identically configured bottom mounted current profiler (serial number: 104510) was also deployed at KG-1-CP on the same day, replacing the one deployed before (serial number: 104507)

All equipment was recovered on 3 August 2024.

2.2 Health, Safety and Environment

No incidents were logged during the campaign.

2.3 Weather Events

Bottom mounted Thelma pressure transmitter showed irregular patterns in pressure and abrupt changes in temperatures during 23 December 2023 and few times in January 2024. Compared to the pressure data from bottom mounted Signature instrument, it is regarded that Thelma pressure data on these periods is less reliable than that from Signature.

2.4 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.

This subsection summarizes events that impact data availability and the descriptions of these gaps and their respective rectifications.

2.4.1 Lidar supply power outage

The lidar stopped measuring wind from 20:10, 24 January 2024 to 19:00, 26 January 2024 due to abrupt input power outage. The root cause was fault reading of temperature input to lidar heater which drew input power abruptly.

2.4.2 Current profiler degradation and 2-beam process

In general, there are multiple reasons why either Aquadopp or Signature current profiler data are filtered out. For example, the data can be rejected by low signal strength due to the degradation of the performance like physical interference by obstacle or by marine growth and due to the site-specific condition like water purity. Sidelobe rejection is one of post-processing filter applied, with which the current data near surface from a certain depth onwards farther is filtered away.

Two-beam process can be accepted by the manufacturer of the current profiler, which employs the assumption that the vertical velocity is negligible. In the final dataset, the two-beam process applied the buoy mounted Aquadopp current profiler measurement during D1 of KG-1-LB, 21 July 2023 to 18 February 2024. The process only used beam number 2 and 3.

2.4.3 Precipitation gauge measurement

The precipitation sensor may have been damaged in the second deployment period (D2) and have measured inaccurate values this period thus the measured value is provided solely for reference use only.

3. Post-Processing and Availability

3.1 Measurement Configurations

3.1.1 SWLB

The general measurement setup, sensors, configurations, and measurement scheme are described in the measurement plan [2]. Table 3.1 shows the measurement configuration of the SWLB. 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:

- GNSS 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.
- 10-minute-averaged data of air pressure, air temperature, humidity, precipitation, visibility, and sea surface temperature as well as of the bottom mounted Thelma pressure sensor is calculated for storage every 10 minutes.
- Wave parameters are calculated onboard from motion data and stored every 10 minutes based on 2048 samples in a 1024 second burst.
- Heading information (compass and GNSS) is 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 11 different levels in a conical sweep during averagely 17 seconds. The LiDAR data are combined with buoy heading information to reference buoy direction to north before calculating the 10-minute-averages.

The buoy converts 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.

Table 3.1: Configuration of measurements of the Seawatch Wind Lidar buoy

Instrument Type	Sensor Height [m]	Parameter Measured	Sample Height[1] [m]	Samp-ling Interval [s]	Averaging Period [s]	Burst Inter-val [s] [2]	Measure-ment 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 ZX300M Lidar	2	Wind speed and direction at 10 heights and the reference level at 40 m	40[4], 12, 80, 100, 130, 150, 170, 190, 220, 260, 300	17.4[5]	600	600	0.1m/s 1°	Yes
Gill Windsonic M (Ancillary anemometer)	4.1	Wind speed and direction	4.1	1	600	600	0.01m/s 1°	Yes
Nortek Aquadopp 400 kHz	-1	Current speed and direction profile, water temperature (at 1m depth)	-2 … -bottom[6]	1	590	600	2 cm/s 1° 0.1°C	Yes
Thelma Biotel TBR700	-2	Surface water temperature	-2	1	600	600	0.01°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
Septentrio GNSS	4.1	Buoy orientation	4.1	5	10	1	0.35°	No
Thelma Biotel TBR700	2m above seabed	Bottom water pressure and bottom temperature	2m above seabed	1	600	600	0.01m 0.01°C	Yes

Instrument Type	Sensor Height [m]	Parameter Measured	Sample Height[1] [m]	Samp-ling Interval [s]	Averaging Period [s]	Burst Inter-val [s] [2]	Measure-ment Resolution	Trans-mitted ?

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, which is not configurable and referred to as 40.0 Ref.

[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.

[6] = Bottom depths are 19m in monthly dataset but 17m in the final dataset due to sidelobe rejection in post-processing.

Table 3.2: Definitions 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	°	Mean spectral wave direction. Computed from spectral analysis.
mdira	°	Mean spectral wave direction in the a frequency band.*
mdirb	°	Mean spectral wave direction in the b frequency band.*
sprtp	°	Wave spreading at the spectral peak period. Computed from spectral analysis.
thhf	°	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.
thtp	°	Mean wave direction at the spectral peak period. Computed from spectral analysis.
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.*

Parameter	Unit	Description
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.
ts**†	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. 25. Hmax, hs, hmean, tz, ts and thmax thus are usually not calculated if significant wave height is lower than approximately 0.3 m.

† The parameters can only be provided from Neptun re-analysis

3.1.2 Bottom mounted current profiler

A Nortek Signature 500 current profiler was placed on the seabed at KG-1-CP on a separate mooring to measure the current profile from bottom to surface. Figure 3.1 presents the conceptual drawing of the instrument.

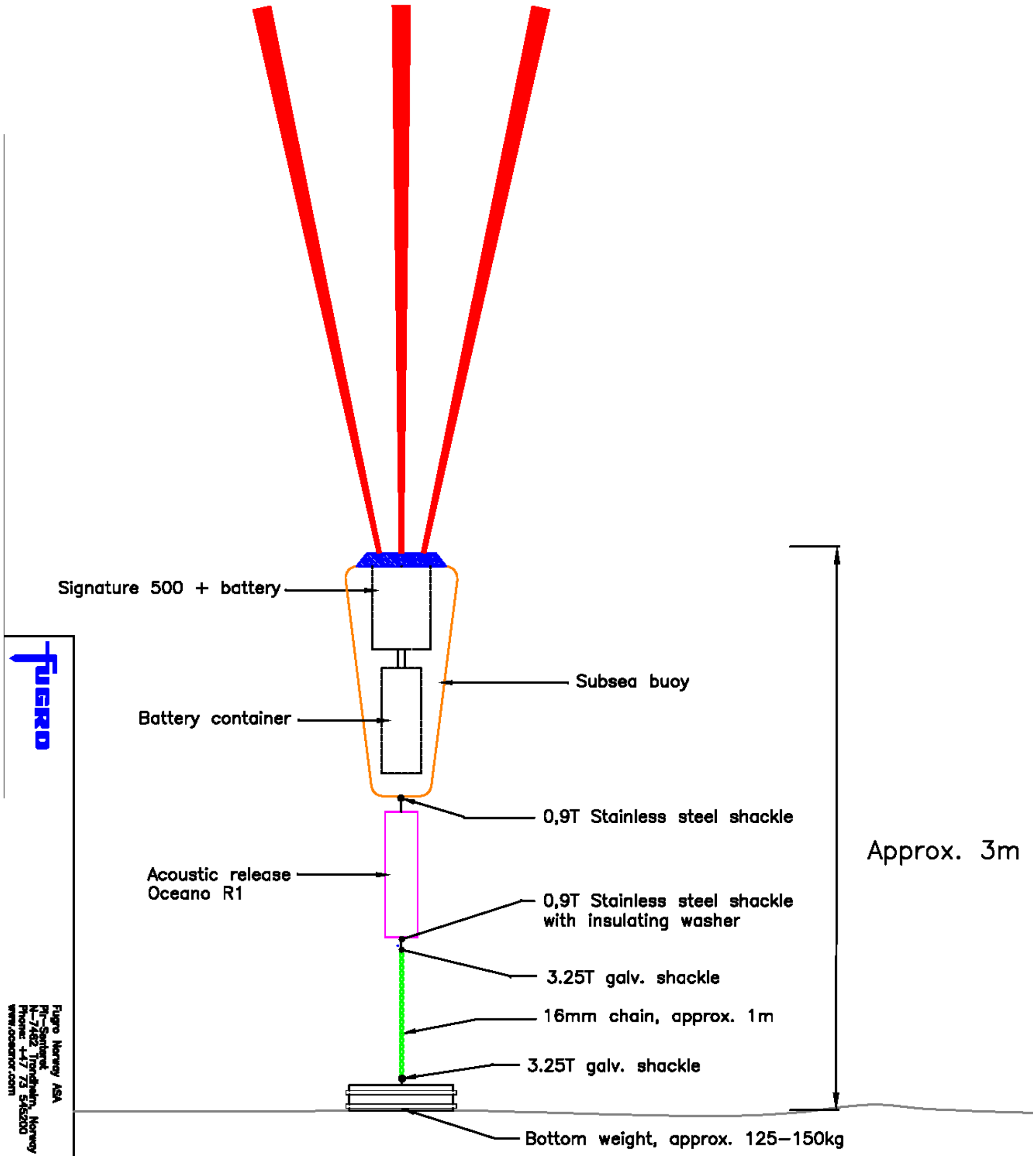


Figure 3.1: Bottom mounted current profiler (Nortek Signature500)

Table 3.4 shows the measurement configuration of the Nortek Signature500 current profiler (Serial# 104507 and 104510) at KG-1-CP. The noise floor for these both instruments is 27 dB. Table 3.3 describes the height or depths for measurement bins of current profiler instruments.

Table 3.3: Measurement height or depth bin setting for current profilers

	Bottom mounted current profiler	Buoy mounted current profiler
Instrumnet type	Nortek Signature 500	Nortek Aquadopp 400kHz
Cell size (m)	1	1
Blanking distance (m)	0.5	0.5

	Bottom mounted current profiler	Buoy mounted current profiler
First cell depth or height	4m above seabed	2m beneath water surface
Depth or height bins	4, 5, 6, …18m above seabed	3,….,17m beneath water surface
Sensor heights	3m above seabed	2m beneath water surface

The bottom-mounted current profiler also records water temperature at seabed and pressure above the sensor head. There is an uncertainty in the sensor height above the sea floor since it is deployed on a floating buoy. The nominal height of bottom sensor is 3 m above sea floor.

Table 3.4: Configuration of measurements of the upward facing ADCP

Instrument Type	Sensor Height[1] [m]	Parameter Measured	Sample Height[1] [m]	Sampling Interval	Averaging Period [s]	Measure-ment Interval [s]	Measure-ment Resolution
Nortek Signature 500	3m above seabed	Current speed and direction profile, water temperature and water pressure	4, 5, 6, …, 18	1 Hz, 359 pings	180	600	0.9 cm/s 0.1° 0.1°C

Notes

[1] = Height relative to seafloor.

3.2 SWLB Post-processing

3.2.1 General post-processing and quality control

The general data flow, post-processing and quality control applied to the data is described in the measurement plan [2]. 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 3.5)

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 3.5.

Table 3.5: 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	7*	-	dB
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	23	-	dbar

Parameter	Minimum Value	Maximum Value	Unit
Visibility	10	5000	m
Precipitation	0	10	mm/10min

Note
*Final post-processing. This number is equivalent to 16-17 counts (0.4-0.45 dB: 1 count)

3.2.1.1 Wind speed and direction

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

3.2.1.2 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*).

3.2.1.3 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.

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

3.2.1.4 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.

3.2.1.5 Currents

Only depths 3 – 17 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 deeper layers.

It is often desirable to neglect data that is near the free surface, e.g. sea bottom or water surface, due to the possibility of sidelobe interference. Assuming the instrument is installed not too slanted and very closed to the surface, the fraction of 0.95 applied to reject sidelobe effect. The surface is detected by finding the peak in the acoustic return. Note that if the profiler is pointing downward from the free surface, then the peak in amplitude is used to locate the bottom. [3]

Both a gradual decrease in signal strength with respect to the distance increase from the instrument head and sidelobe rejection of the current profiler data near the free surface result in a substantial amount of data is filtered out at farther layer bins. In addition, marine growth restricted the range of valid data towards the end of the individual deployments.

The data at 2m water depth from Aquadopp instrument is 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 2m 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.

3.2.1.6 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 pressure sensor head is free floating and assumed to be located at nominally 1.5-2 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 2 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 approximate equal to the depth in metres. However, to get the proper height of the water column above the sensor, the air pressure measurement from the buoy must be subtracted from the total measured water pressure as simplified in the following:

$$h_w = \frac{P_w - P_a}{\rho g}$$

where h_w is the height of the water column, P_w is the measured total water pressure, P_a is the measured total air pressure, ρ is the density of the water (inferred from measured salinity and temperature), and g is the acceleration of gravity. Since the gravity changes with respect to latitude slightly, the conversion from pressure to depth in this project will employ the formula by UNESCO (1983) (Ref. [4] and [5])

3.2.2 Project specific post-processing criteria

This section outlines any deviations or additions from the general post-processing steps.

3.2.2.1 High thmax filter

At calm seas zero-upcrossing analysis could miss small wave amplitude which may lead to over-estimate tz or thmax values. To disregard these values, the suggested rule can apply to the derived wave statistics:

- thmax/tm02 < 3, Otherwise set thmax, hmax, tz missing

3.2.2.2 Buoy mounted current profiler raw data process setting

For the first 6 month period from 21 July 2023 to 18 February 2024, one beam (Beam 1) out of three from Aquadopp instrument was rejected due to the degradation of that specific beam on the assumption that the vertical current velocity is negligible.

The following settings are also used:

- Low SNR threshold : 7 dB , equivalent to 16-17 counts (noise floor 10 count)
- Sidelobe rejection : 95%, Bottom

3.3 Upward-facing ADCP

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.

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.

3.3.1 Ocean Contour raw data post-process

All raw data from all 2 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.
2. Minimum signal strength filter, which removes data with poor return signal quality.
3. Minimum correlation check between incoming and outgoing beams, which removes data with poor return signal quality.
4. Automatic sidelobe removal threshold
5. Correction for magnetic declination. 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. 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 4 m and ending at 26 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 19m – 26m were removed by the automatic sidelobe removal (step 4). Current speed and current direction in the 18m bin still showed apparent strong influences of sidelobes and some of current speeds and directions in this bin were removed.

The following settings are also used for Ocean Contour data process:

- Bin mapping applied
- Low SNR threshold : 30 dB (noise floor 27 dB)
- Minimum correlation : 50%

- Sidelobe rejection : 95%, Surface
- Correction for magnetic declination : +4.5°

3.3.2 IOOS Qartod tests

Standalone ADCP processing follows the required and some recommended steps in the IOOS QARTOD manual on in-situ current observations [7]. The following IOOS QARTOD 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 (around 18m) were found, and all speed and direction data where the absolute value of the vertical velocity was greater than 20 cm/s were 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.

4. Data files

Table 4.1 summarizes the contents of each delivered datafile following the post-processing steps outlined in the measurement plan [2].

Table 4.1: Post-processed SWLB data by files

File	Signals
CurrentData	The file contains 10-minute average data calculated on the buoy from the current profiler. All timestamps are set at the end of the averaging period. For all current speed and direction signals AqSpd(d) and AqDir(d), where d = 3,4,5, ..., 17m, the data are checked for out-of-bounds values and signal strength. For timestamps and depths where the speed is outside the accepted range, the speed and direction are set to NaN.
MetOceanData	The file contains 10-minute average data calculated on the buoy from the meteorological and oceanographic sensors. All timestamps are set at the end of the averaging period. Parameters: Air and Water Temperatures, Air Pressure, Humidity from all available sensors, precipitation, visibility, solar irradiance, water pressure, depth, and water level. All data with values outside the accepted range are replaced by NaNs.
PosData	The file contains 10-minute average position data from all available sources. All timestamps are set at the end of the averaging period.
Status	The file contains hourly buoy status data. Parameters: fuel, voltage, battery, error codes.
WaveData	The file contains the wave data at 10-min frequency based on 17 min sampling. Parameters: hm0, hm0a, hm0b, hmax, mdir, mdira, mdirb, sprtp, thhf, thmax. Thtp, tm01, tm02, tm02a, tm02b, tp, tz All data with values outside the accepted range are replaced by NaNs.
WindSpeedDirectionTI	The file contains 10-minute averaged wind speed and direction measurements as well as turbulence intensity calculated on the buoy. The signals are all timestamped with the end of the averaging period. All wind measurements must have wind speed and direction values. For timestamps where either the wind speed or direction is outside this range, the speed and direction are set to NaN. To correct for 180 degrees ambiguities in the lidar wind directions, an additional correction with 10-minute average directions from the ancillary anemometer as ground truth has been used. The correction is done automatically using an algorithm checking each height for ambiguous wind directions and flipping it 180 degrees if necessary.
WindStatus	This file contains status information from the lidar unit. Parameters: Packet count, mirror temperature, rain count, battery voltage, POD humidity, status flags, info flags

Table 4.2 lists the final 12-month datafiles. This includes the full SWLB dataset and the QC'd ADCP data.

Table 4.2 List of final campaign datafiles at Kattegat

Instrument	Filename
SWLB 12-month dataset	**KG-1-LB_12M_CurrentData.csv** **KG-1-LB_12M_MetOceanData.csv** **KG-1-LB_12M_Posdata.csv** **KG-1-LB_12M_Status.csv** **KG-1-LB_12M_WaveData.csv** **KG-1-LB_12M_WindSpeedDirectionTI.csv** **KG-1-LB_12M_WindStatus.csv**
SWLB monthly dataset*	KG-1-LB_MXX_CurrentData.csv KG-1-LB_MXX _MetOceanData.csv KG-1-LB_MXX_Posdata.csv KG-1-LB_MXX_Status.csv KG-1-LB_MXX_WaveData.csv KG-1-LB_MXX_WindSpeedDirectionTI.csv KG-1-LB_MXX_WindStatus.csv
Neptun monthly dataset (Re-analysed)*†	KG-1-LB_MXX_chpr_WS199_....csv KG-1-LB_MXX_memfile_WS199_....txt KG-1-LB_MXX_wavepar_WS199_....txt
ADCP (upward)	**KG-1-CP_D1_CurrentData_20230721_20240222.csv** **KG-1-CP_D2_CurrentData_20240222_20240721.csv**
Water Level & Pressure	**KG-1-LB_CP_12M_WaterLevel.csv**

Note
* XX = 01 to 12
†Suffices in file name denote the running monthly periods for respective datafiles.

Appendix C lists the contents and parameters of each final post-processed datafile listed in Table 4.2. Appendix D gives additional information on any raw data files supplied with this dataset.

5. Data Availabilities

5.1 Availability Calculations

5.1.1 System availability

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 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 month or a defined period.

5.1.2 Post-processed data availability

The 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 or a defined period based on the given time interval of 10-minutes.

5.1.3 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 heights above 200 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 ancillary anemometer.

b. Atmospheric pressure: main instrument (Vaisala) or ancillary instrument (ZX Lidar)

c. Air temperature: main instrument (Vaisala) or ancillary instrument (ZX Lidar)

d. Air humidity: main instrument (Vaisala)

e. Sea surface temperature: main instrument (Aquadopp) and auxiliary instrument (Thelma)

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

g. Current: Average of current speed and direction over the water column, from 3m depth to the depth 19m (17m in the final dataset due to sidelobe rejection (See Section 3.2.1.5))

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 5.1 lists the parameters used in the calculations.

Table 5.1: Parameter group availability (Updates in final dataset in bold)

<table>
<tr><th>Parameter group</th><th>Parameters at monthly deliverable</th><th>Parameters at final dataset</th></tr>
<tr><td>Wind</td><td colspan="2">WindSpeed004m m/s, WindSpeed012m m/s, WindSpeed040m m/s, WindSpeed080m m/s, WindSpeed100m m/s, WindSpeed130m m/s, WindSpeed150m m/s, WindSpeed170m m/s, WindSpeed190m m/s
WindDir004m deg, WindDir012m deg, WindDir040m deg, WindDir080m deg, WindDir100m deg, WindDir130m deg, WindDir150m deg, WindDir170m deg, WindDir190m deg</td></tr>
<tr><td>Atmospheric pressure</td><td colspan="2">AirPressure hPa or AirPressure_lidar hPa</td></tr>
<tr><td>Air temperature</td><td colspan="2">AirTemperature C or AirTemp_lidar C</td></tr>
<tr><td>Air humidity</td><td colspan="2">AirHumidity %</td></tr>
<tr><td>Sea surface temperature</td><td colspan="2">WaterTemp001 degC (Aquadopp) or thTBRtemperature degC (Thelma)</td></tr>
<tr><td>Wave</td><td colspan="2">hm0 m, hm0a m, hm0b m, mdir deg, mdira deg, mdirb deg, sprtp deg, thhf deg, thtp deg, tm01 s, tm02 s, tm02a s, tm02b s, tp s</td></tr>
<tr><td>Current</td><td>AqSpd003 cm/s, AqSpd004 cm/s, ..., AqSpd019 cm/s,
AqDir003 deg, AqDir004 deg, ..., AqDir019 deg</td><td>AqSpd003 cm/s, AqSpd004 cm/s, ..., AqSpd017 cm/s,
AqDir003 deg, AqDir004 deg, ..., AqDir017 deg</td></tr>
<tr><td>Water level</td><td>WaterPressure dbar</td><td>WaterPressure dbar or Pressure (from Bottom mounted ADCP)</td></tr>
<tr><td>Current (Bottom mounted ADCP)</td><td>-</td><td>currSp004 cm/s, currSp005 cm/s, ..., currSp018 cm/s
currDir018 cm/s, currDir005 deg, ..., currDir018 deg</td></tr>
</table>

The final report is based on the 10-minute averages transmitted via satellite and the downloaded data after recovery of the buoys. Any gaps in the transmitted data or any data deemed suspicious after the monthly quality checks were performed, were 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. The data downloaded during a service and 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.

5.2 12-month Post-processed Data Availability

The final campaign post-processed data availability per parameter from 21 July 2023 to 21 July 2024 is presented in Table 5.2.

Table 5.2: SWLB 12-month post-processed data availability

Parameter	Availability [%]	Parameter	Availability [%]
WindDir004m deg	98.7	hm0 m	98.8
WindDir012m deg	97.8	hm0a m	95.5
WindDir040m deg	98.1	hm0b m	98.8
WindDir080m deg	96.6	hmax m	82.2
WindDir100m deg	96.1	hmean m	86.8
WindDir130m deg	95.7	hs m	86.8
WindDir150m deg	95.5	mdir deg	98.8
WindDir170m deg	95.4	mdira deg	98.8
WindDir190m deg	95.3	mdirb deg	98.8
WindDir220m deg	95.1	sprtp deg	98.8
WindDir260m deg	94.9	thhf deg	98.8
WindDir300m deg	94.8	thmax s	82.2
WindGust004m m/s	98.7	thtp deg	98.8
WindSpeed004m m/s	98.7	tm01 s	98.8
WindSpeed012m m/s	97.8	tm02 s	98.8
WindSpeed040m m/s	98.1	tm02a s	98.8
WindSpeed080m m/s	96.6	tm02b s	98.8
WindSpeed100m m/s	96.1	tp s	98.8
WindSpeed130m m/s	95.7	tz s	82.2
WindSpeed150m m/s	95.5	ts s	86.8
WindSpeed170m m/s	95.4	thTBRtemperature degC	98.8
WindSpeed190m m/s	95.3	BottomTemperature degC	90.4

Parameter	Availability [%]	Parameter	Availability [%]
WindSpeed220m m/s	95.1	WaterPressure dbar	98.6
WindSpeed260m m/s	94.9	(accumulated) precipitation mm	98.8
WindSpeed300m m/s	94.8	pws_visibility m	98.8
AirHumidity %	98.7	WaterTemp001 degC	98.7
AirPressure hPa	98.7	AirPressure_lidar hPa	98.2
AirTemperature C	98.7	AirTemp_lidar C	98.2
AqDir003 deg	98.6	AqSpd003 cm/s	98.6
AqDir004 deg	98.2	AqSpd004 cm/s	98.2
AqDir005 deg	98.0	AqSpd005 cm/s	98.0
AqDir006 deg	97.9	AqSpd006 cm/s	97.9
AqDir007 deg	97.7	AqSpd007 cm/s	97.7
AqDir008 deg	97.2	AqSpd008 cm/s	97.2
AqDir009 deg	95.5	AqSpd009 cm/s	95.5
AqDir010 deg	91.8	AqSpd010 cm/s	91.8
AqDir011 deg	88.9	AqSpd011 cm/s	88.9
AqDir012 deg	86.0	AqSpd012 cm/s	86.0
AqDir013 deg	83.7	AqSpd013 cm/s	83.7
AqDir014 deg	81.8	AqSpd014 cm/s	81.8
AqDir015 deg	80.1	AqSpd015 cm/s	80.1
AqDir016 deg	78.1	AqSpd016 cm/s	78.1
AqDir017 deg	72.6	AqSpd017 cm/s	72.6

Table 5.3: Signature post-processed data availability during D1 (21 July 2023 – 21 February 2024)

Parameter	Availability [%]	Parameter	Availability [%]
currSp004 cm/s	92.9	currDir004m deg	92.9
currSp005 cm/s	97.7	currDir005m deg	97.7
currSp006 cm/s	98.8	currDir006m deg	98.8
currSp007 cm/s	99.6	currDir007m deg	99.6
currSp008 cm/s	99.8	currDir008m deg	99.8
currSp009 cm/s	99.8	currDir009m deg	99.8
currSp010 cm/s	100.0	currDir010m deg	100.0
currSp011 cm/s	100.0	currDir011m deg	100.0
currSp012 cm/s	100.0	currDir012m deg	100.0
currSp013 cm/s	100.0	currDir013m deg	100.0
currSp014 cm/s	100.0	currDir014m deg	100.0
currSp015 cm/s	100.0	currDir015m deg	100.0

Parameter	Availability [%]	Parameter	Availability [%]
currSp016 cm/s	100.0	currDir016m deg	100.0
currSp017 cm/s	99.9	currDir017m deg	99.9
currSp018 cm/s	97.2	currDir018m deg	97.2

Table 5.4: Signature post-processed data availability during D2 (22 February 2024 – 21 July 2024)

Parameter	Availability [%]	Parameter	Availability [%]
currSp004 cm/s	96.7	currDir004m deg	96.7
currSp005 cm/s	98.2	currDir005m deg	98.2
currSp006 cm/s	98.8	currDir006m deg	98.8
currSp007 cm/s	99.0	currDir007m deg	99.0
currSp008 cm/s	99.1	currDir008m deg	99.1
currSp009 cm/s	99.2	currDir009m deg	99.2
currSp010 cm/s	99.2	currDir010m deg	99.2
currSp011 cm/s	99.2	currDir011m deg	99.2
currSp012 cm/s	99.2	currDir012m deg	99.2
currSp013 cm/s	99.2	currDir013m deg	99.2
currSp014 cm/s	99.2	currDir014m deg	99.2
currSp015 cm/s	99.2	currDir015m deg	99.2
currSp016 cm/s	99.2	currDir016m deg	99.2
currSp017 cm/s	99.1	currDir017m deg	99.1
currSp018 cm/s	98.7	currDir018m deg	98.7

5.3 12-month post-processed parameter group availability

The monthly post processed data availability (denoted as “draft”) per main parameter group as reported in the monthly reports is compared to the final monthly post-processed group availability (denoted as “final”) and shown in Table 5.5 through Table 5.6.

The SWLB current dataset has been subjected to stricter QC than during the monthly checks resulting in overall lower current data availability. There was a gain in data availability of water pressure by the quick replacement of the identically configured bottom mounted ADCP which have reduced the downtime significantly at Month 7, which may have incurred for battery replacement offshore.

Table 5.5: Post-processed parameter group availability (wind, met) in % for data per month: monthly reports and final dataset

#	Period (KG-1-LB / KG-1-CP)	Wind		Atm. Pressure		Air temp.		Air humidity		Sea surf. Temp.	
		Draft	Final	Draft	Final	Draft	Final	Draft	Final	Draft	Final
1	JulyAug2023	99.5	99.5	99.8	99.8	100.0	100.0	100.0	100.0	100.0	100.0
2	AugSep2023	98.7	98.8	99.9	99.9	99.9	99.9	99.9	99.9	100.0	100.0
3	SepOct2023	99.7	99.6	**100.0**	**99.9**	100.0	100.0	100.0	100.0	100.0	100.0
4	OctNov2023	99.9	99.9	99.8	100.0	100.0	100.0	100.0	100.0	100.0	100
5	NovDec2023	98.2	98.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
6	Dec2023Jan2024	97.6	97.6	100.0	100	99.9	100.0	99.9	99.9	100.0	100
7	JanFeb2024	79.0	79.0	89.9	89.9	89.5	89.5	89.5	89.5	89.9	89.9
8	FebMar2024	90.6	90.6	96.1	96.1	96.1	96.1	96.1	96.1	96.2	96.2
9	MarApr2024	97.9	97.9	99.9	99.9	99.8	99.8	99.8	99.8	100.0	100.0
10	AprMay2024	98.7	98.7	99.8	99.8	99.9	99.9	99.9	99.9	100.0	100.0
11	MayJune2024	99.7	99.7	99.8	99.8	100.0	100.0	100.0	100.0	100.0	100.0
12	JunJul2024	99.5	99.5	99.7	99.7	99.7	99.7	99.7	99.7	99.8	99.8

Table 5.6: Post-processed parameter group availability (waves, currents and ADCP) in % for data per month: monthly reports and final dataset

#	Period (KG-1-LB / KG-1-CP)	Wave		Current		Water pressure		Current (Bottom mounted)	
		Draft	Final	Draft	Final	Draft	Final	Draft	Final
1	JulyAug2023	99.8	99.7	100.0	96.9	99.9	100	-	99.3
2	AugSep2023	99.9	99.7	100.0	93.2	99.9	100	-	99.5
3	SepOct2023	100.0	99.9	99.9	95.0	99.5	100	-	98.0
4	OctNov2023	100.0	100.0	100.0	95.8	100	100	-	99.0
5	NovDec2023	100.0	100.0	100.0	89.2	100.0	100	-	99.2
6	Dec2023Jan2024	99.9	99.9	100	73.8	98.9	100	-	99.0
7	JanFeb2024	89.8	89.8	89.9	63.2	89.9	100	-	99.2
8	FebMar2024	95.7	95.7	96.2	89.0	95.8	100.0	-	99.3
9	MarApr2024	99.6	99.6	100.0	91.5	99.9	100	-	99.5
10	AprMay2024	99.5	99.5	100.0	95.8	100.0	100	-	99.9
11	MayJune2024	99.9	99.9	100.0	98.9	100.0	100	-	99.9
12	JunJul2024	98.9	98.9	99.8	95.1	99.7	100	-	99.9

6. Uncertainty assessment of the Lidar wind data

The pre-deployment validation between 12 May 2023 and 28 May 2023 [1] 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 24.1 m/s at the lowest comparison level (40 m) and 29.0 m/s at the highest level (250 m) during the pre-deployment validation. The air temperatures ranged from 1.2 °C to 18.7 °C. The significant wave heights observed were up to 3.65 m. The maximum wave heights observed cover a range up to 6.45 m. The tidal or water levels observed at Mausund, north of Frøya during the measurement campaign varied between -115.2 cm and 85.5 cm over MSL.

For WS199, the overall uncertainty during the pre-deployment validation trial varied between 1.34 % - 2.09 % for wind speeds between 4-16 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 SWLB anchor and bottom mounted ADCP anchor as-laid positions reported in Table 1.1. There were no drifts of position changes.

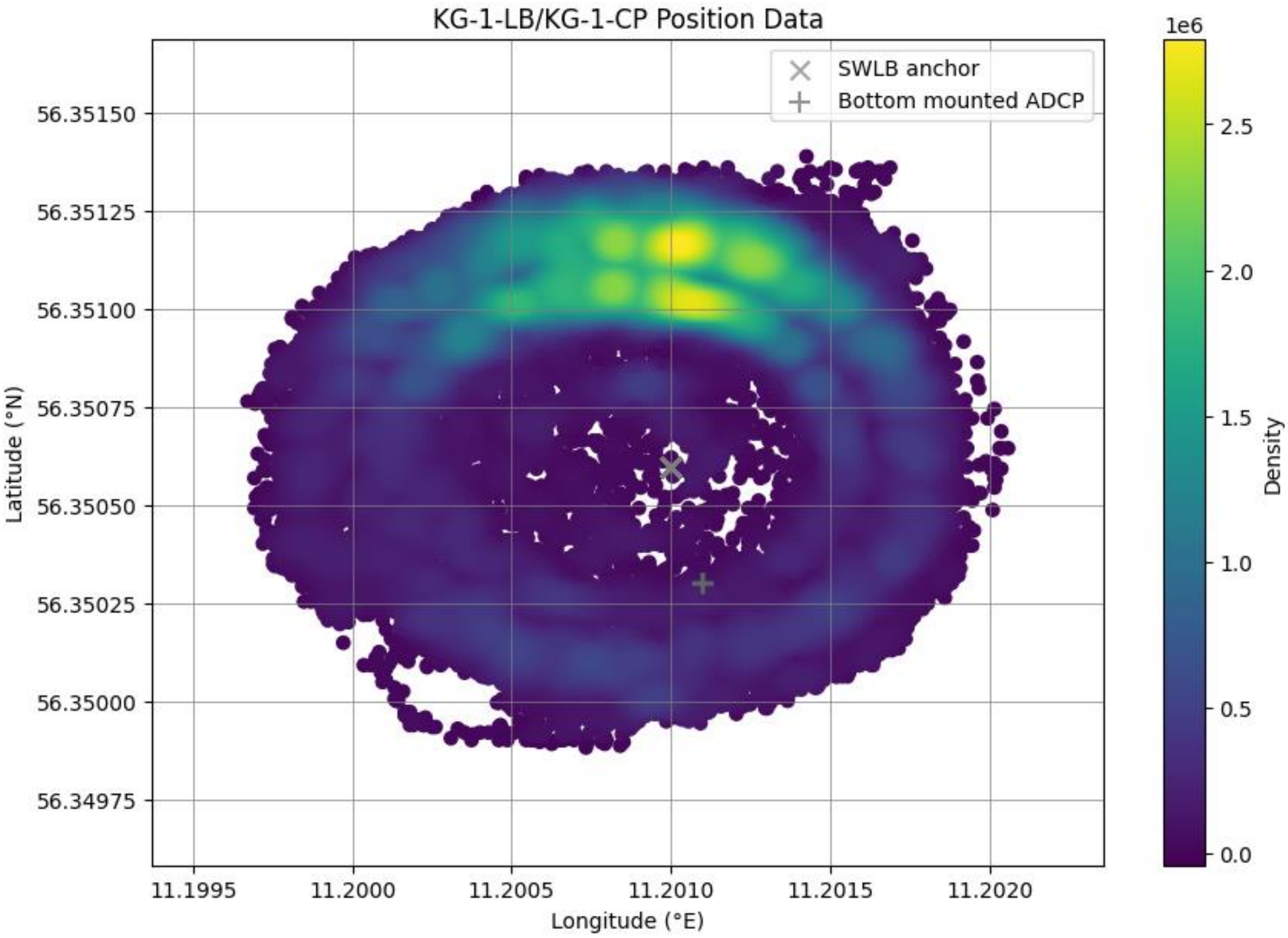


Figure 7.1: Full campaign SWLB and bottom mounted ADCP position data.

8. Results: Wind

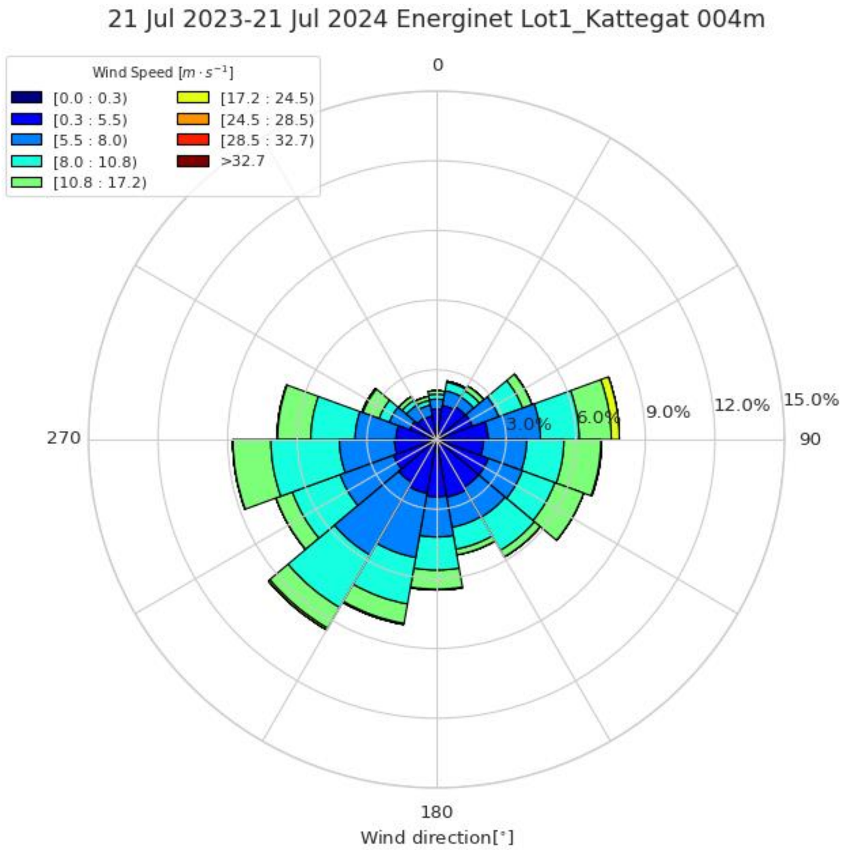
The floating lidar system performed well without disruptions during all 12 months of the campaign. Timeseries of wind speed and direction are presented in Appendix B.

Table 8.1 summarizes statistics for wind speed over the full campaign. Figure 8.2 shows wind roses at 4 heights (4, 100, 170, and 260 m) for all 12 months of data and Figure 8.3 presents the wind speed profile for the full campaign.

The highest wind speeds during the campaign were measured in February 2024. High wind speeds (> 30 m/s) were also measured in September 2023, December 2023 and January 2024. The dominant wind direction was from the west, the southwest and the southeast.

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	3.4	0.1	7.2	22.1
ZephIR Lidar 10min wind speed	12	3.6	0.6	7.8	24.4
	40	4.0	0.5	8.8	27.8
	80	4.4	0.5	9.4	29.8
	100	4.5	0.6	9.6	30.6
	130	4.7	0.5	9.8	31.4
	150	4.8	0.5	10.0	32.0
	170	4.9	0.5	10.1	32.5
	190	5.0	0.5	10.2	33.1
	220	5.1	0.5	10.3	33.8
	260	5.2	0.5	10.5	34.3
	300	5.4	0.6	10.6	34.9



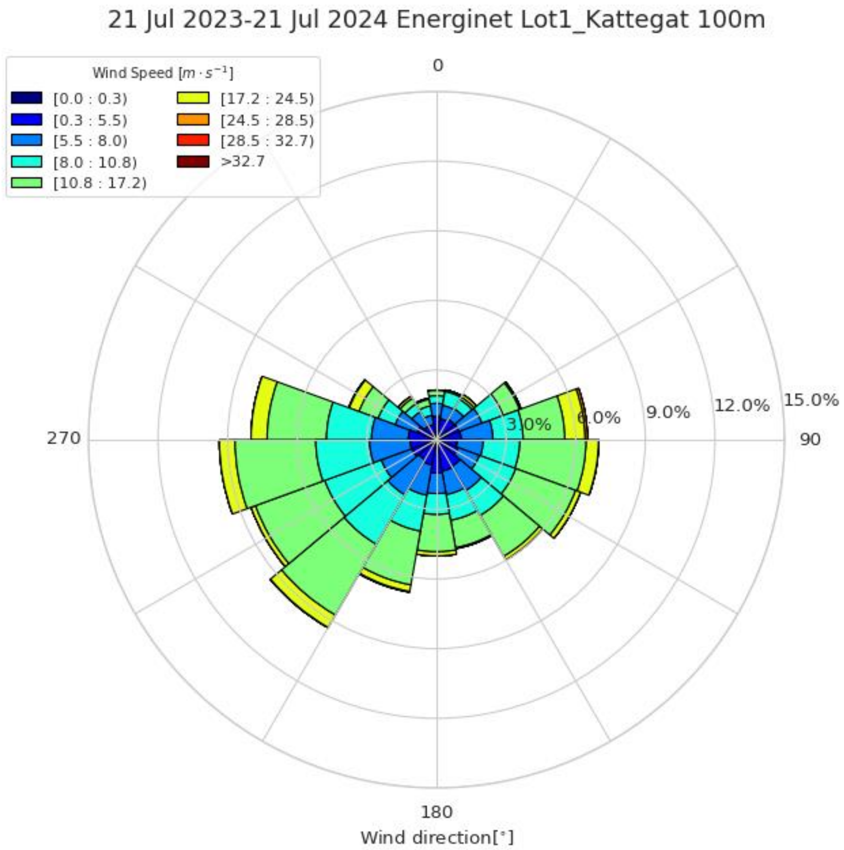
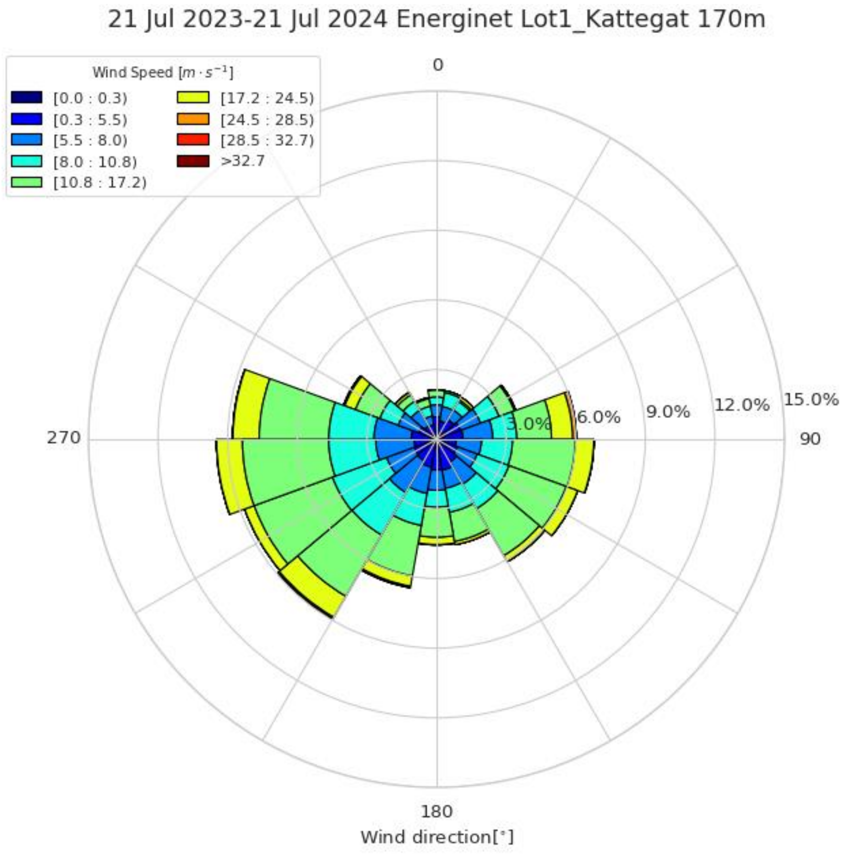


Figure 8.1 : Wind roses at 4 m and 100 m height for the full 12 months



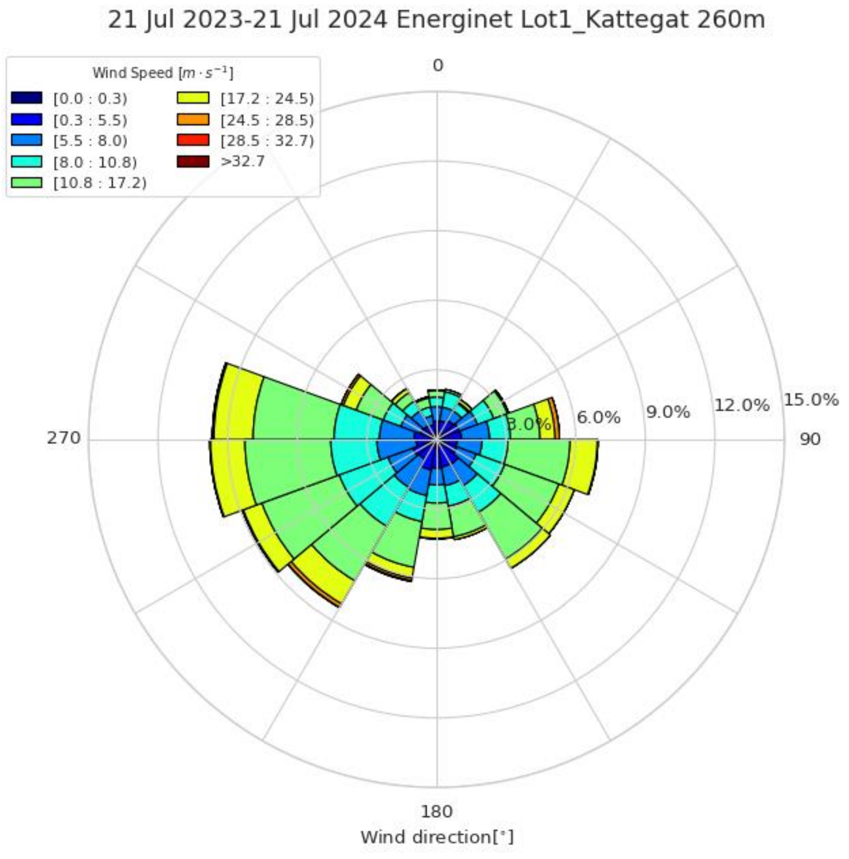


Figure 8.2 : Wind roses at 170 m, and 260 m height for the full 12 months

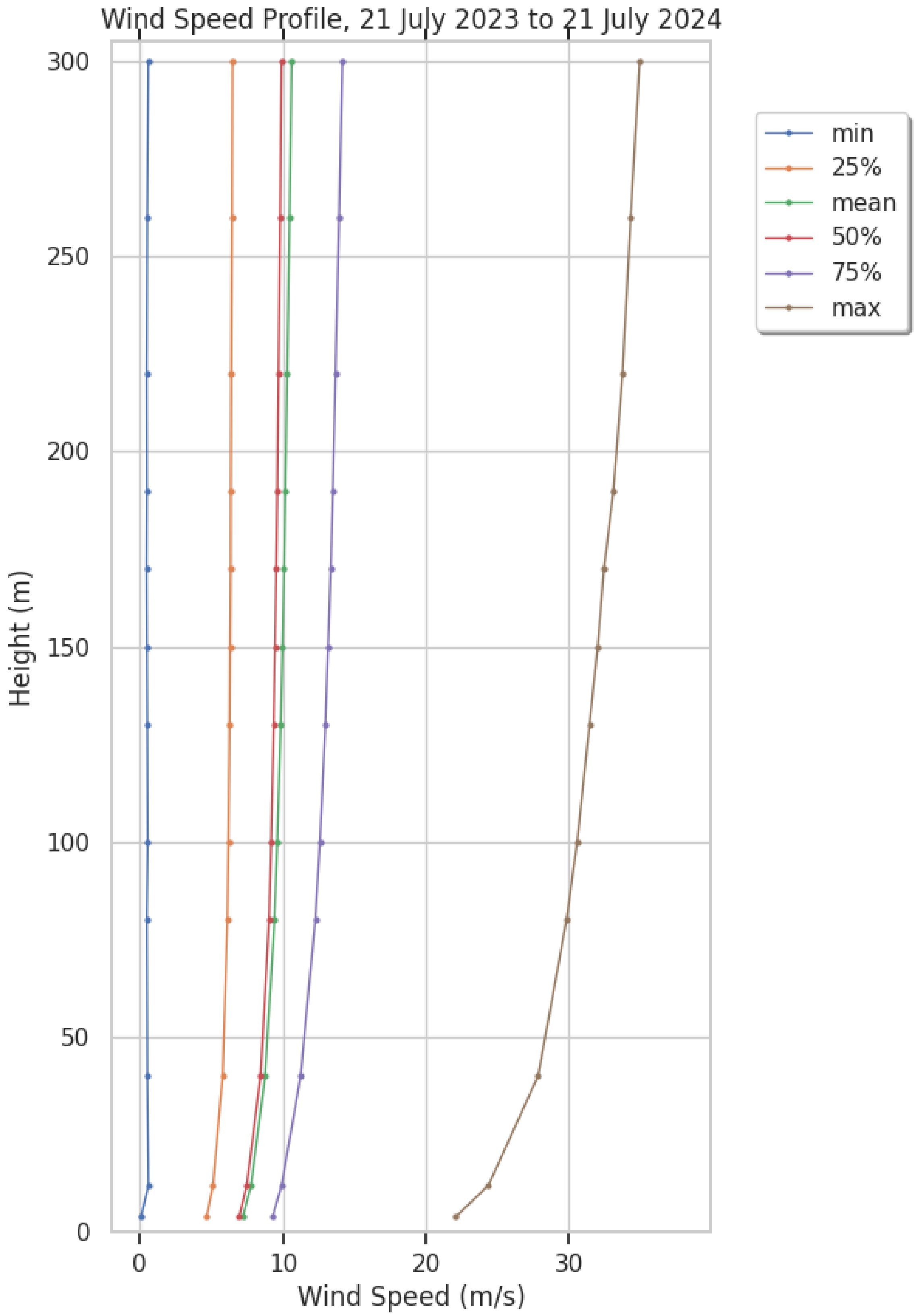


Figure 8.3 : 12-month wind speed profile

9. Results: Waves

This chapter includes the results of wave measurement from the SWLB. 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 mean direction for all 12 months of data. Figure 9.4 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 (hmax > 6 m) during the campaign were measured in January 2024. The dominant wave directions are from the southwest and the northeast.

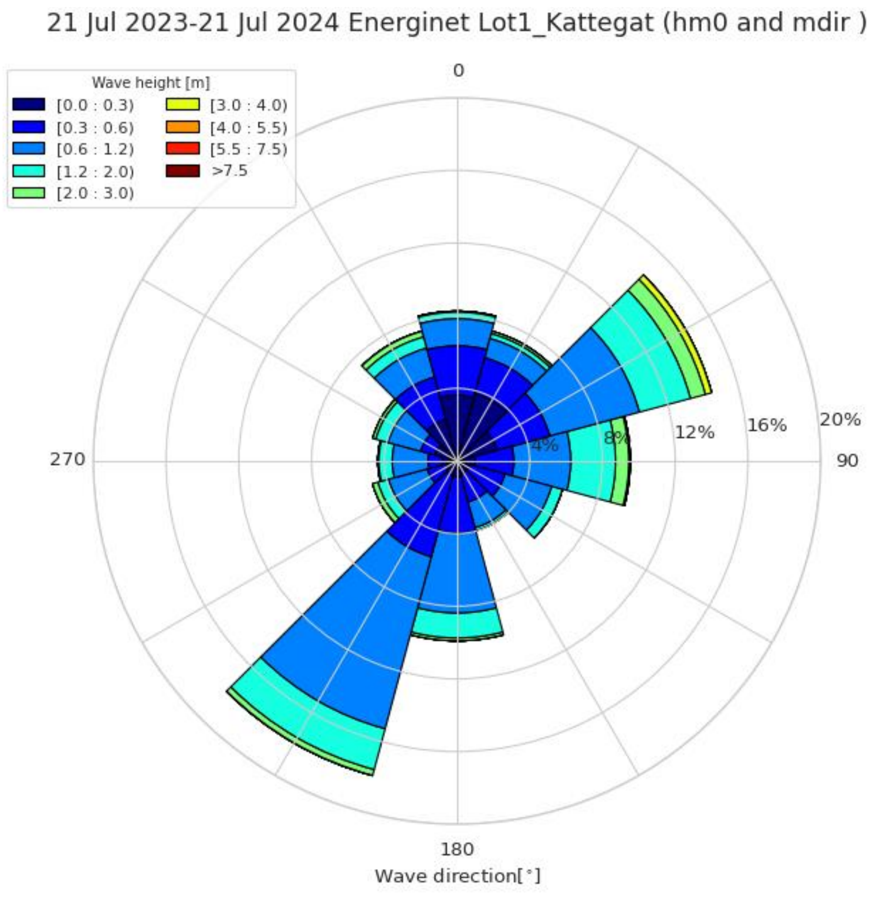


Figure 9.1: 12-month waverose

Table 9.1: 12-month summary statistics (standard deviation, minimum, mean and maximum): wave parameters

Parameter	Unit	Standard deviation	Minimum	Mean	Maximum
hm0 m	m	0.5	0.1	0.8	3.8
hmax m	m	0.8	0.3	1.4	6.7
thmax s	s	0.9	2.4	3.9	10.5
tm01 s	s	0.7	2.1	3.4	6.6
tm02 s	s	0.6	2.1	3.3	6.3
tp s	s	0.5	0.1	0.8	3.8

Notes
*The height of instrument (Wavesense) is 0m with respect to MWL

2023-10-20 22:40 hm0 = 3.8 m tp = 7.3 s mdir = 71°

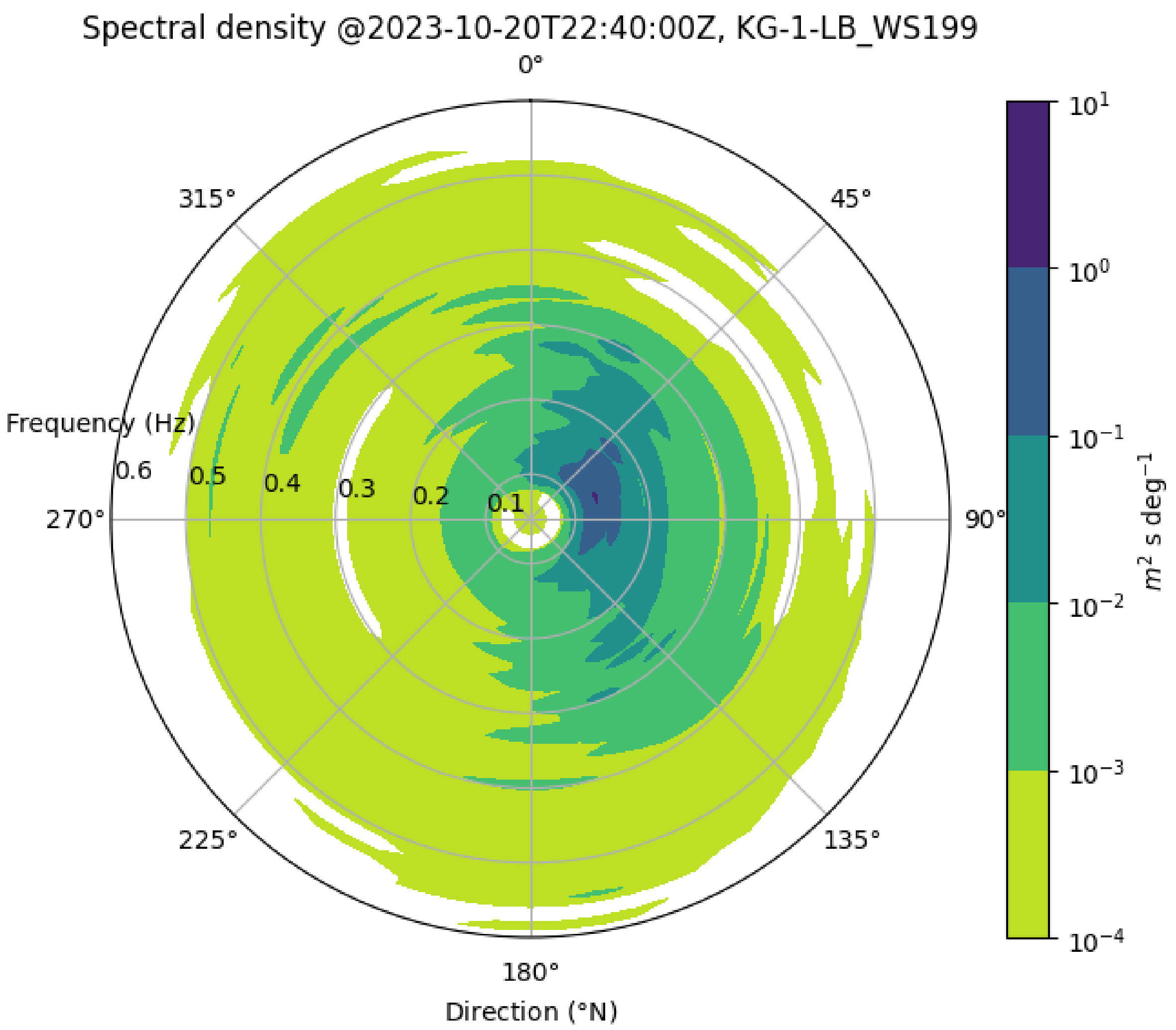


Figure 9.2: Directional wave spectra (MEM spectra m2/s) from a wave event dated on 20 October 2023

2024-01-03 18:50 hm0 = 3.7 m tp = 7.4 s mdir = 68°

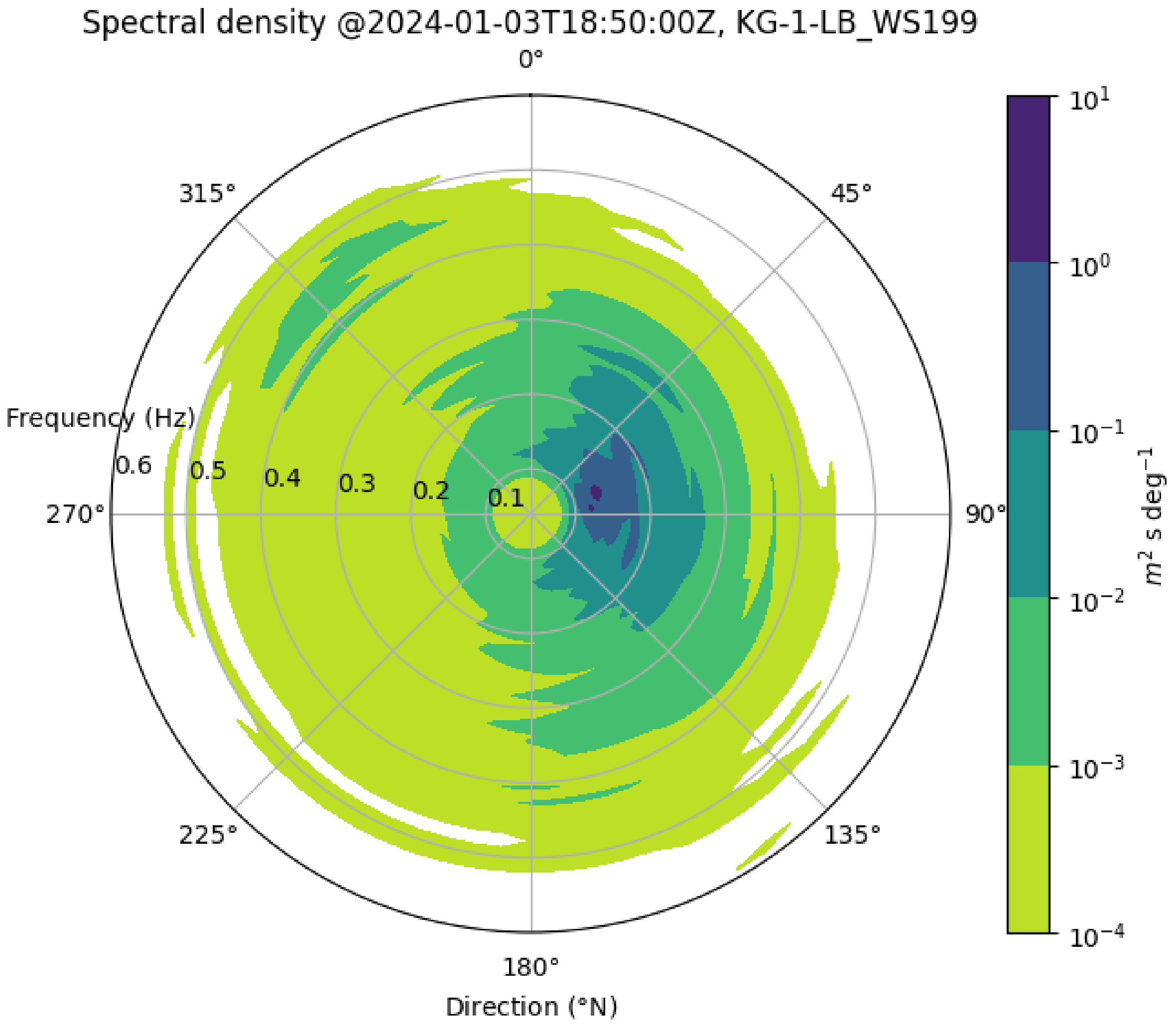


Figure 9.3: Directional wave spectra (MEM spectra m2/s) from a wave event dated on 3 January 2024

2024-02-23 04:40 hm0 = 3.3 m tp = 6.4 s mdir = 192°

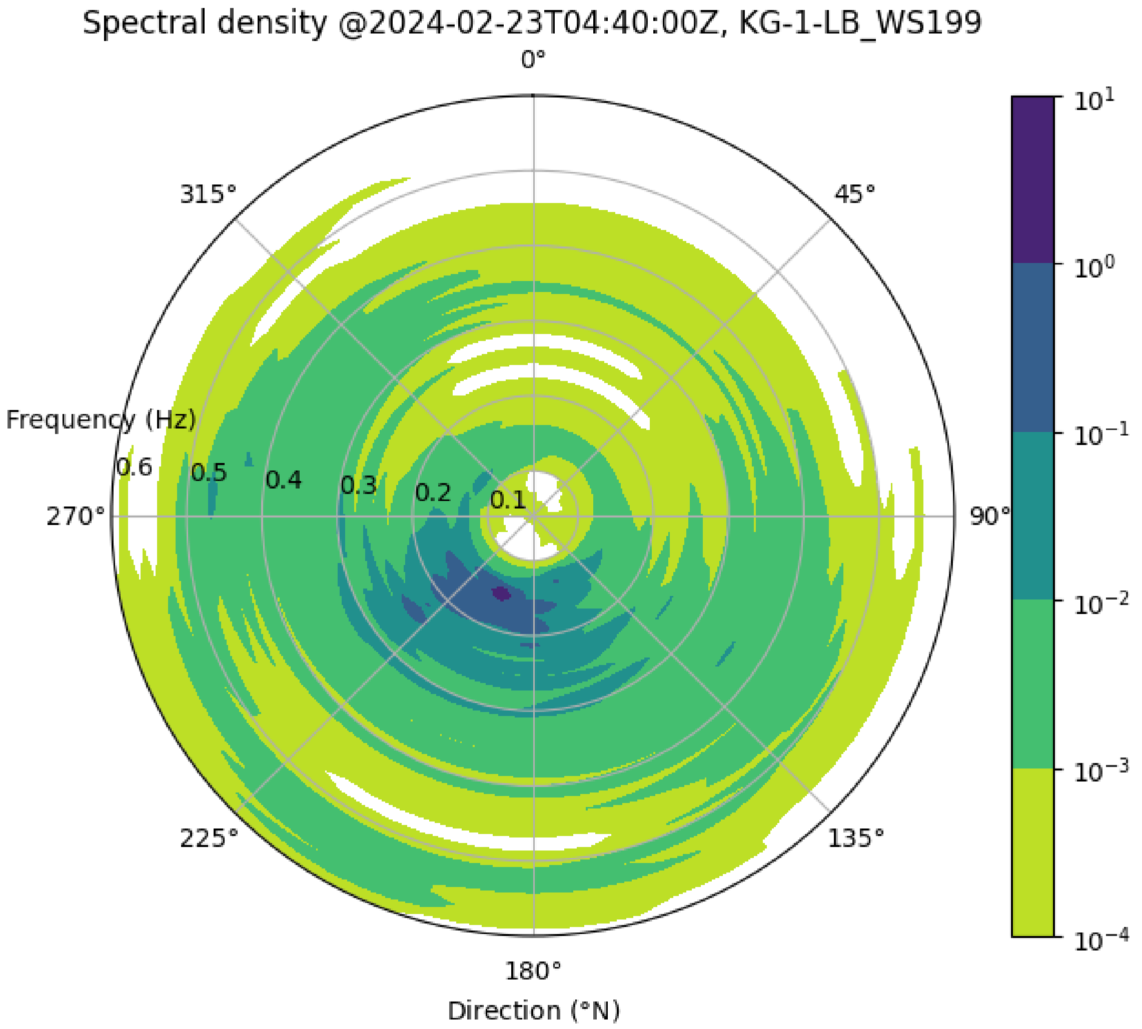


Figure 9.4: Directional wave spectra (MEM spectra m^2/s) from a wave event dated on 23 February 2024

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. The lowest air temperatures and air pressures were measured in January 2024. The highest air temperatures were measured in June 2024. The highest air pressures were measured in January 2024.

Table 10.1: 12-month summary statistics of met parameters from 21 July 2023 to 21 July 2024

Parameter	Unit	Height [m]	Standard deviation	Minimum	Mean	Maximum
AirHumidity %	% R.H.	4	9.4	36.4	83.2	99.2
AirPressure hPa (PTB330)	hPa	0.5	10.7	962.2	1009.2	1040.9
AirTemperature C (HMP155)	°C	4	6.0	-5.6	9.9	22.8

10.2 Sea water temperatures

Table 10.2 summarizes statistics for water temperature from all sensors over the full campaign. Figure 10.2 shows 3-monthly timeseries of all seawater temperature data from all sensors.

The water column appears well-mixed during the spring and fall seasons and relatively highly stratified during the summer and winter seasons.

Table 10.2: 12-month summary statistics of sea water temperatures from 21 July 2023 to 21 July 2024

Parameter	Unit	Height [m]	Standard deviation	Minimum	Mean	Maximum
Sea surface temperature (Aquadopp)	°C	-1	5.7	1.9	10.9	20.7
Sea surface temperature (Thelma)	°C	-2	5.7	1.3	10.8	19.7
Bottom Water Temperature (Thelma)	°C	2m above seabed	3.7	3.8	9.6	18.1

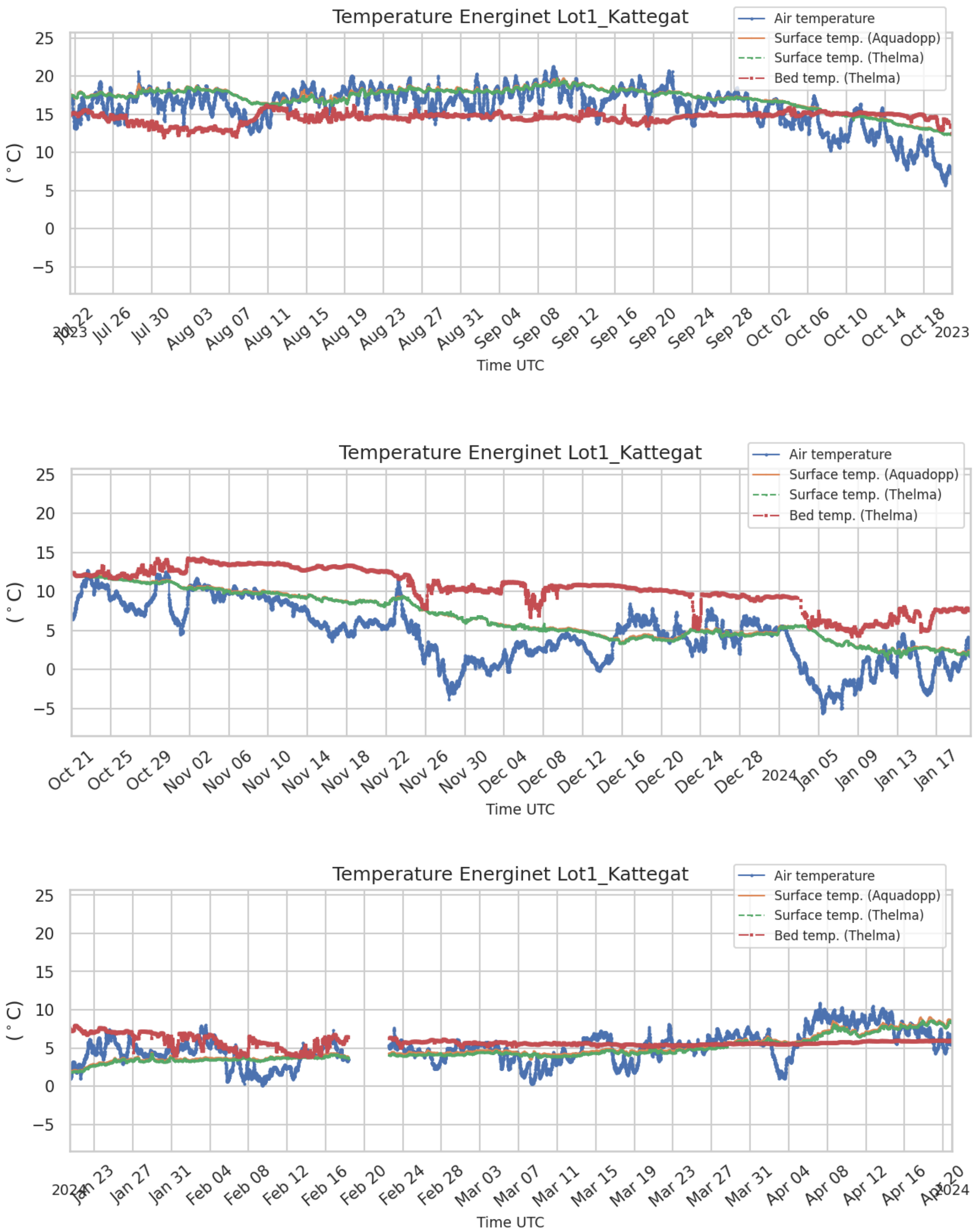


Figure 10.1: Timeseries of all seawater temperature data from all sensors per 3 months intervals (1-3/4)

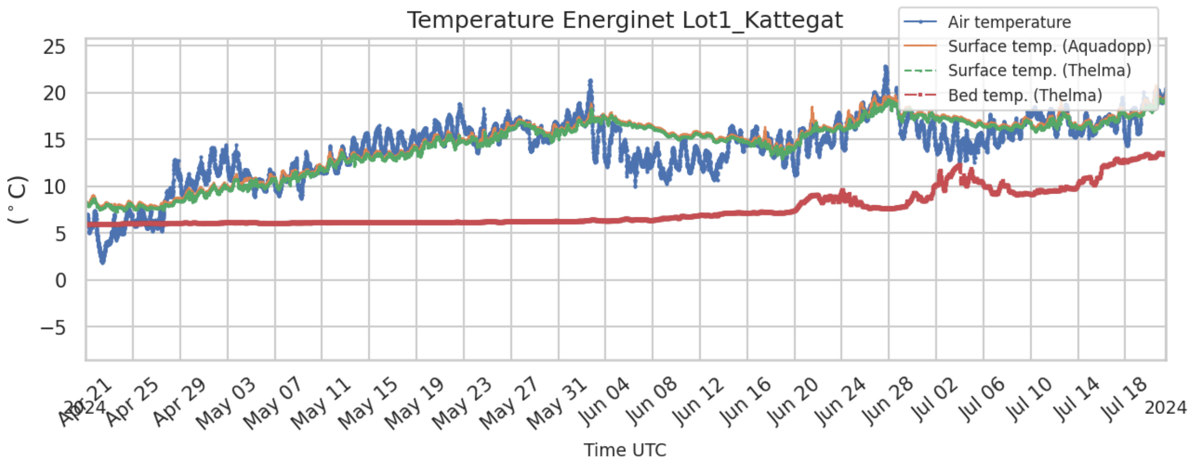


Figure 10.2: Timeseries of all seawater temperature data from all sensors per 3 months intervals (4/4)

10.3 Water level

Table 10.3 summarizes statistics for water pressure from the Thelma bottom unit and the Signature500 over the full campaign. Figure 10.4 shows 3-monthly timeseries of water pressure from both sensors. Given the uncertainties in the sensor heights depending on as-laid locations, two different sensor heights were used for Signature500, which are 2.85m and 3.5m for D1 and D2 period, respectively. The sensor height of Thelma bottom transmitter is assumed to be 2m. These heights were estimated by a sanity check with two different deployment of Signature instrument and by a validation with other source (Ref. [8]).

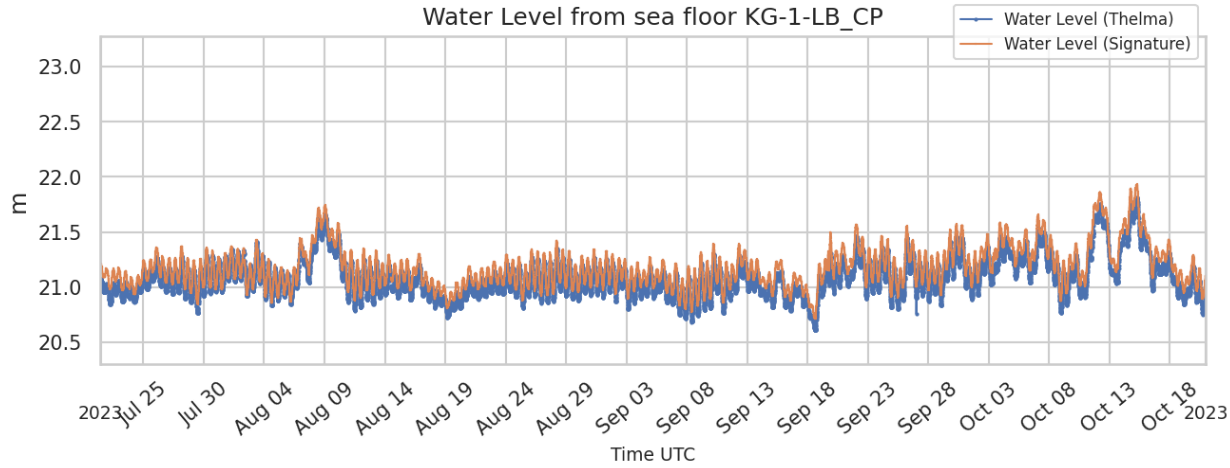
From Thelma sensors, there are two periods where the measurement values did not agree with those by Signature instrument., which were from 19 December 2023 until redeployment dated on 22 February 2024 and from April 2024 to the end of campaign. There are still uncertainties in the root cause of these disagreement, however, most likely these were caused by malfunctioning of the Thelma bottom unit. Thus, the Signature data should be considered more reliable than the Thelma data.

Table 10.3: 12-month summary statistics of water pressure

Parameter	Unit	Sensor Height [m]*	Standard deviation	Minimum†	Mean	Maximum
Water pressure (Thelma)	dbar	2m above seabed	0.5	20.7	21.7	23.0
Water pressure (Signature500)	dbar	2.85m above seabed	0.2	20.8	21.5	22.6
Water level (Thelma)	m	2m above seabed	0.5	20.5	21.4	23.0
Water level (Signature500)	m	2.85m above seabed	0.2	20.6	21.2	22.6

Parameter	Unit	Sensor Height [m]*	Standard deviation	Minimum†	Mean	Maximum

Notes
*The heights of Signature500 pressure sensor were assumed to have been 2.85m for D1 (21 July 2023 to 22 February 2024) and 3.5m for D2 (22 February 2024 to 21 July 2024)
†Validated with the water depth (20.7m) to LAT reference from European Marine Observation and Data Network (EMODnet). (https://emodnet.ec.europa.eu/en/bathymetry)
‡The upper bound of 23 dbar applied.



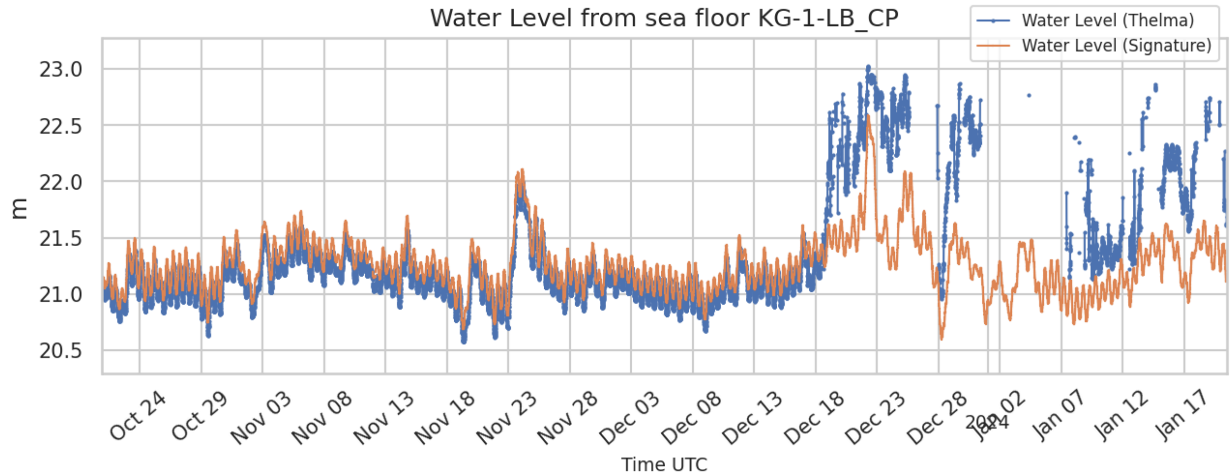
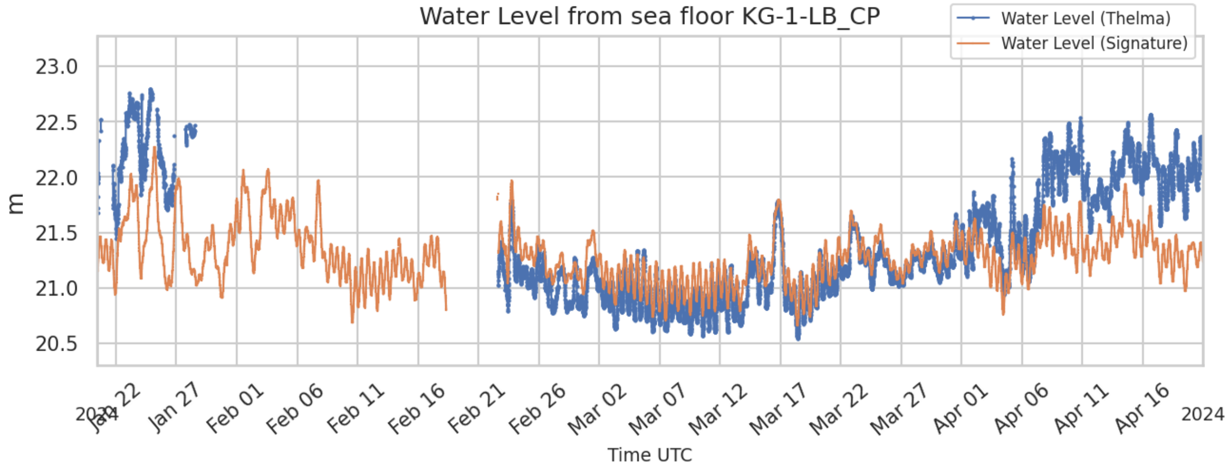


Figure 10.3: Timeseries of water level per 3 months intervals (1-2/4)



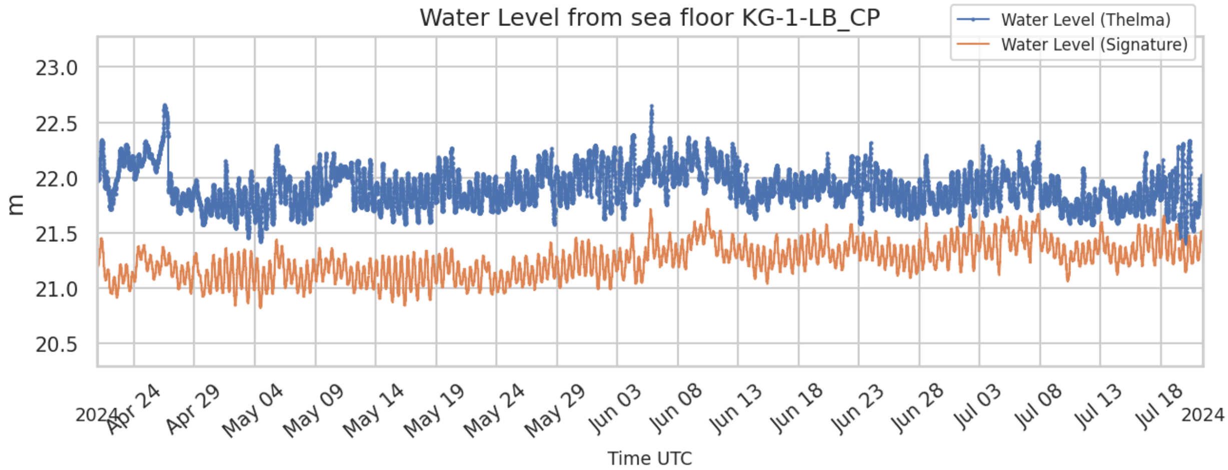


Figure 10.4: Timeseries of water level per 3 months intervals (3-4/4)

11. Results Currents

11.1 SWLB Aquadopp

Heatmaps of 3-monthly current speed and direction are presented in Appendix B.4.

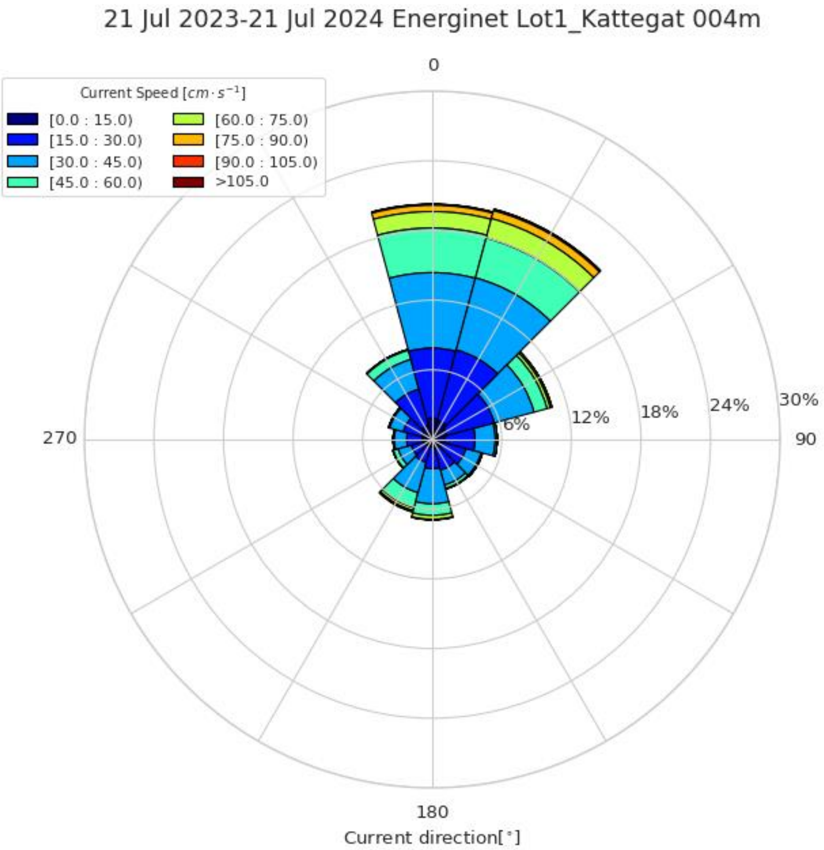
Table 11.1 summarizes statistics for current speed over the full campaign. Figure 11.2 shows current roses at 4 depths below the sea surface (4, 8, 12, and 16 m) for all 12 months of data and Figure 11.3 shows the current speed profile for the full campaign.

The highest current speeds during the campaign were measured in December 2023. The mean current speeds are around 20-40 cm/s for all depth bins.

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

Table 11.1: 12-month summary statistics (standard deviation, minimum, mean and maximum): current speed

Parameter	Unit	Height [m]	Standard deviation	Minimum	Mean	Maximum
AqSpd003	cm/s	-3	18.1	0.0	39.1	121.9
AqSpd004	cm/s	-4	16.3	0.2	32.7	117.3
AqSpd005	cm/s	-5	16.0	0.1	32.3	119.7
AqSpd006	cm/s	-6	15.9	0.0	32.7	119.8
AqSpd007	cm/s	-7	15.8	0.0	32.2	121.3
AqSpd008	cm/s	-8	15.6	0.1	31.5	119.7
AqSpd009	cm/s	-9	15.7	0.0	31.0	120.7
AqSpd010	cm/s	-10	15.7	0.1	30.5	119.4
AqSpd011	cm/s	-11	15.8	0.0	28.9	122.0
AqSpd012	cm/s	-12	16.8	0.1	30.9	121.9
AqSpd013	cm/s	-13	16.8	0.1	28.1	122.9
AqSpd014	cm/s	-14	16.6	0.0	27.0	120.5
AqSpd015	cm/s	-15	16.2	0.0	26.0	114.5
AqSpd016	cm/s	-16	15.6	0.0	24.6	109.3
AqSpd017	cm/s	-17	14.5	0.0	22.6	97.3



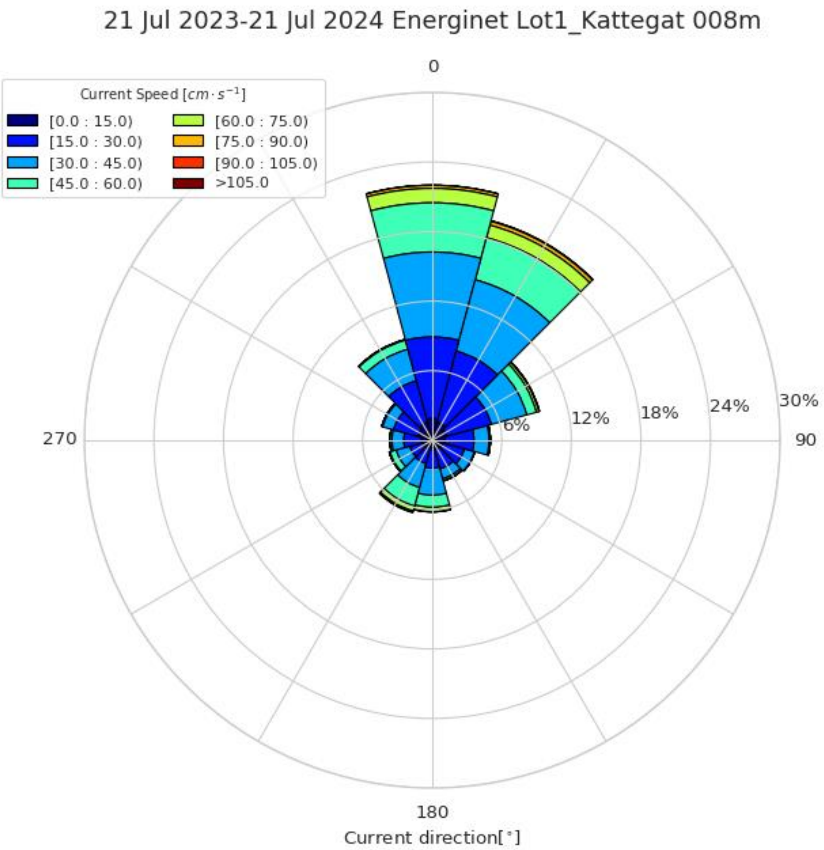
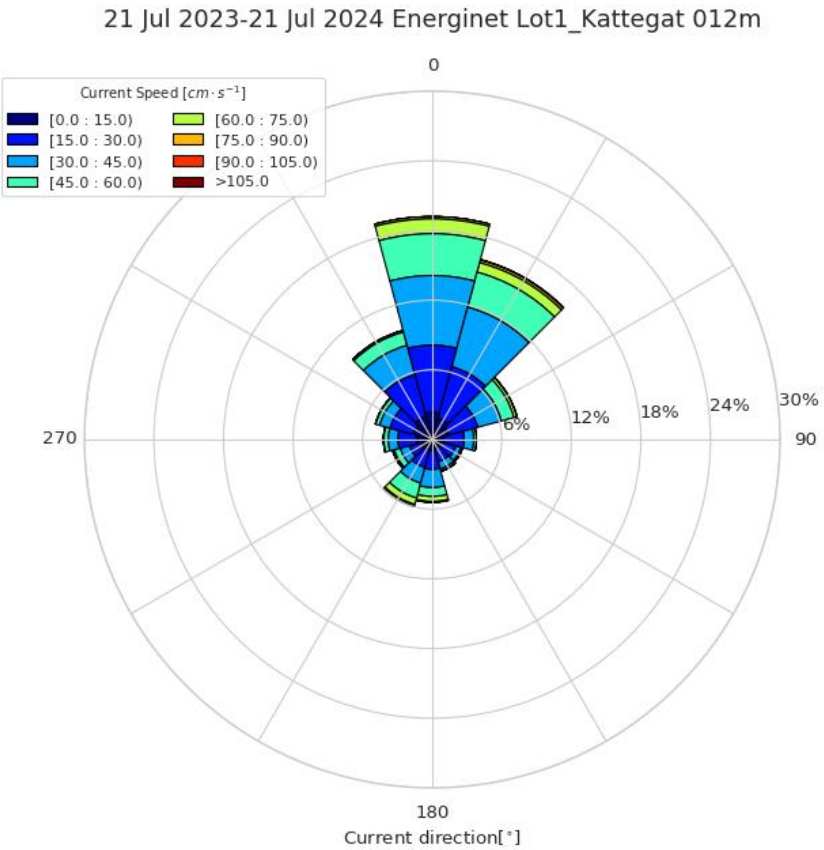


Figure 11.1 Current roses (top-down) at 04 m and 08 m depth for the full 12 months



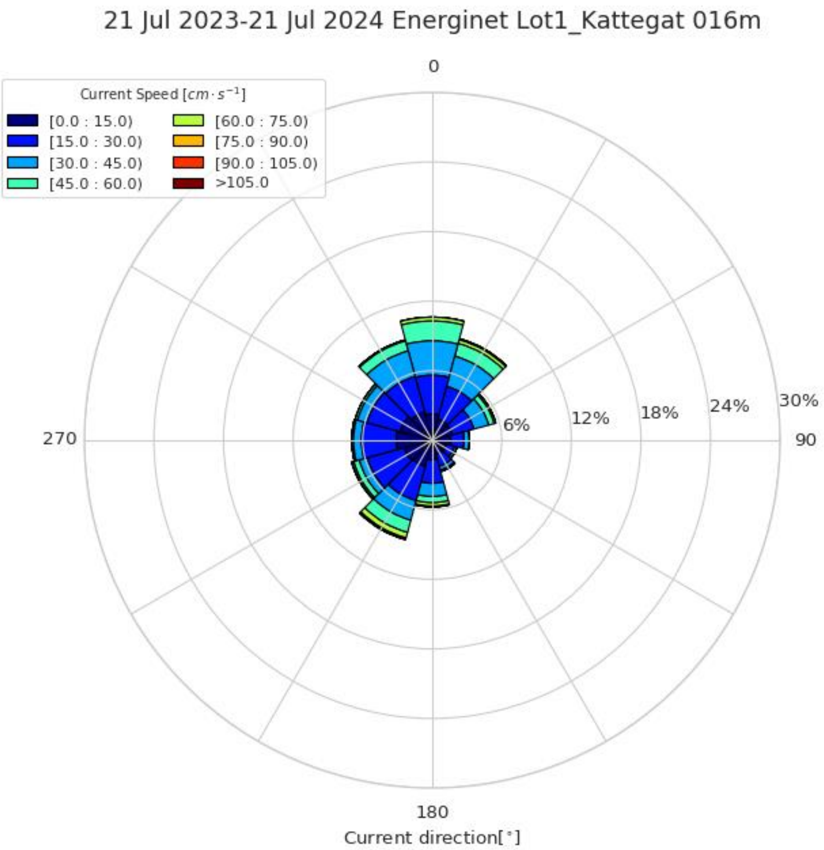


Figure 11.2 Current roses (top-down) at 12 m and 16 m depth for the full 12 months

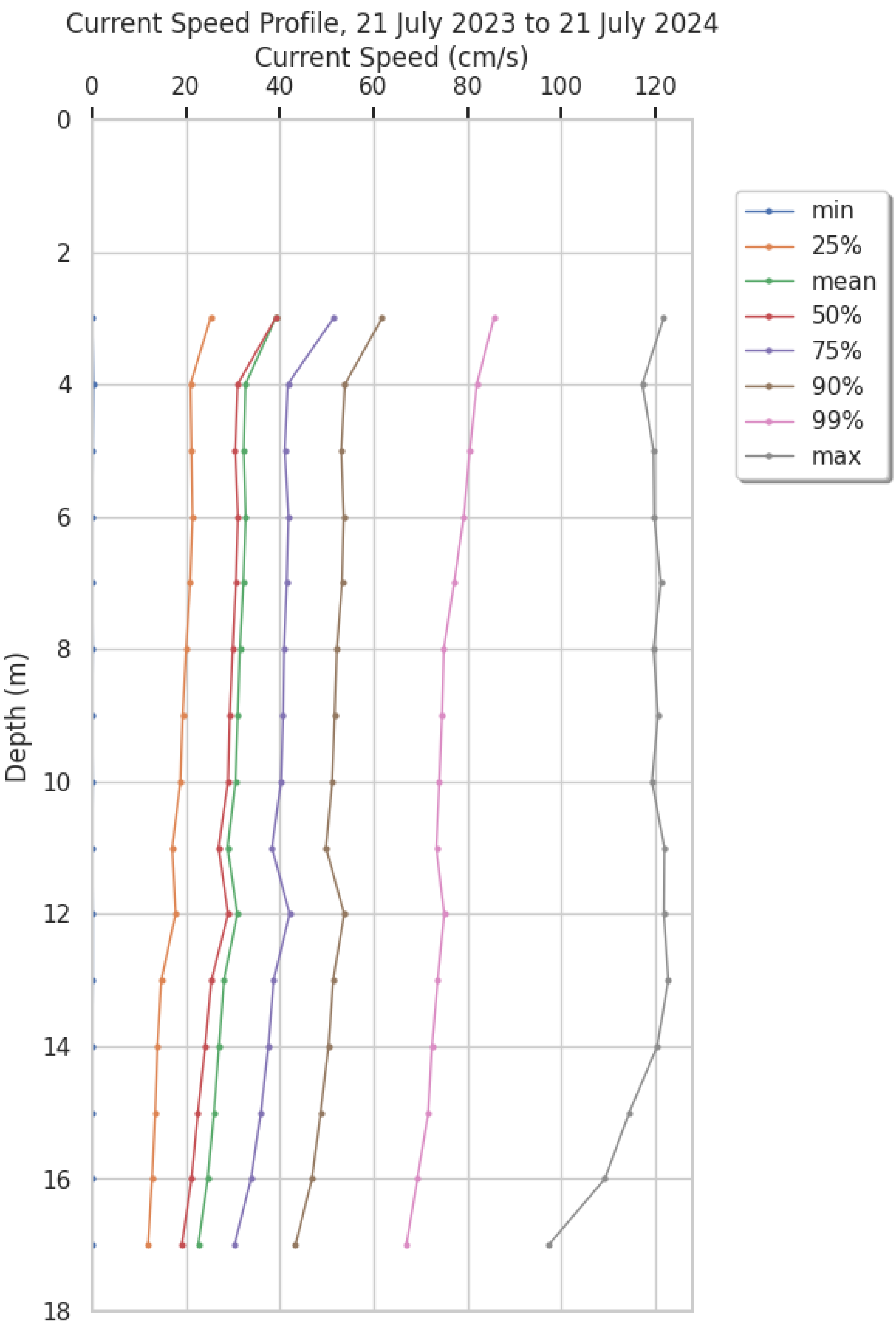


Figure 11.3: 12-month current speed profile

11.2 Upward-facing Signature

Heatmaps of 3-monthly current speed and direction are presented in Appendix B.5.

Current roses at 4 depths above the seafloor (17, 13, 9, and 5 m) are shown in Table 11.2 for D1 (July 2023 – February 2024), in Table 11.3 for D2 (February 2024 – July 2024). Figure 11.8 and Figure 11.9 show the current speed profile for D1 and D2, respectively. Table 11.2 and Table 11.3 summarize statistics for current speed over D1 and D2, respectively.

The highest current speeds during D1 were measured in October 2023 at the nearest bin to bottom, and in September 2023 at the nearest bin to surface, while the highest current speeds during D2 were measured in February 2024 at both bins. The mean current speeds are in range 15-30 cm/s for all depth bins.

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

Table 11.2: Current speed summary statistics over D1 (July 2023 – February 2024).

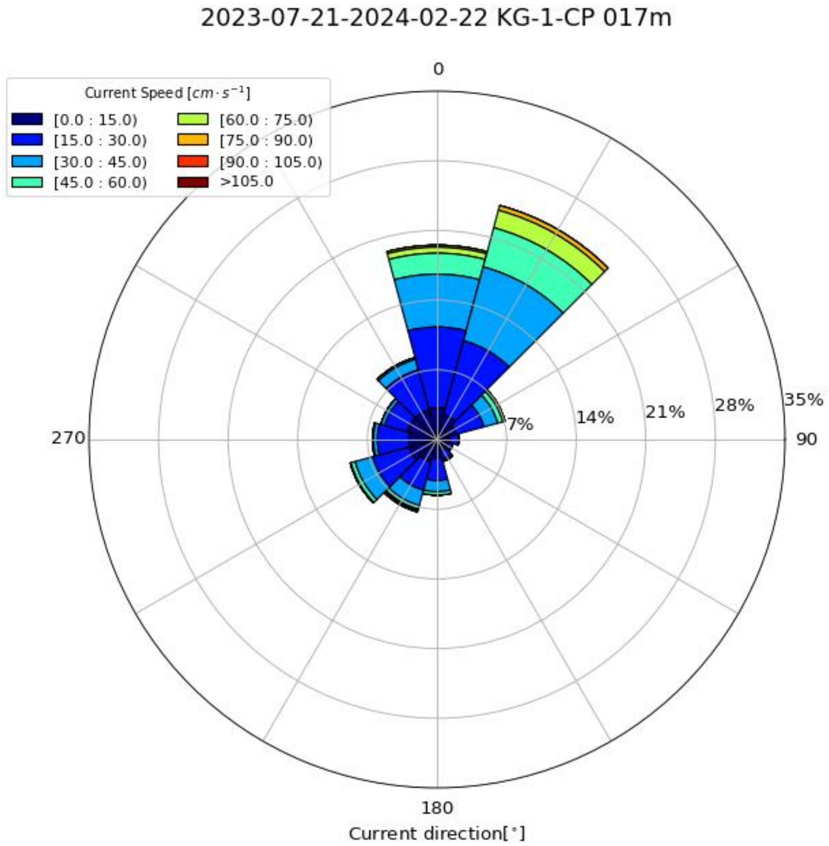
Parameter	Unit	Height [m]*	Standard deviation	Minimum	Mean	Maximum
currSp018 cm/s	cm/s	18	15.6	0.1	24.8	95.6
currSp017 cm/s	cm/s	17	15.7	0.2	25.9	94.4
currSp016 cm/s	cm/s	16	15.5	0.1	25.5	94.0
currSp015 cm/s	cm/s	15	15.2	0.1	25.1	93.0
currSp014 cm/s	cm/s	14	14.8	0.3	24.7	92.1
currSp013 cm/s	cm/s	13	14.3	0.1	24.3	86.1
currSp012 cm/s	cm/s	12	13.8	0.3	24.2	87.0
currSp011 cm/s	cm/s	11	13.4	0.0	24.1	87.8
currSp010 cm/s	cm/s	10	13.1	0.3	24.3	87.7
currSp009 cm/s	cm/s	9	13.0	0.2	24.5	88.4
currSp008 cm/s	cm/s	8	12.9	0.1	24.7	88.5
currSp007 cm/s	cm/s	7	13.1	0.1	24.8	88.7
currSp006 cm/s	cm/s	6	13.2	0.1	24.9	88.4
currSp005 cm/s	cm/s	5	12.9	0.2	24.7	86.9
currSp004 cm/s	cm/s	4	12.3	0.0	23.8	85.6

Note
* Height above the seafloor

Table 11.3: Current speed summary statistics over D2 (February 2024 – July 2024).

Parameter	Unit	Height [m]*	Standard deviation	Minimum	Mean	Maximum
currSp018 cm/s	cm/s	18	17.1	0.3	27.7	141.2
currSp017 cm/s	cm/s	17	17.1	0.2	29.7	112.5
currSp016 cm/s	cm/s	16	16.7	0.3	29.2	110.6
currSp015 cm/s	cm/s	15	16.0	0.1	28.2	108.6
currSp014 cm/s	cm/s	14	15.1	0.1	27.0	103.1
currSp013 cm/s	cm/s	13	14.1	0.4	25.7	100.9
currSp012 cm/s	cm/s	12	13.3	0.2	24.5	98.2
currSp011 cm/s	cm/s	11	12.6	0.2	23.5	92.9
currSp010 cm/s	cm/s	10	12.0	0.1	22.4	87.8
currSp009 cm/s	cm/s	9	11.6	0.1	21.6	81.6
currSp008 cm/s	cm/s	8	11.4	0.3	20.5	73.2
currSp007 cm/s	cm/s	7	11.4	0.1	19.4	71.5
currSp006 cm/s	cm/s	6	11.3	0.1	18.7	70.1
currSp005 cm/s	cm/s	5	10.5	0.1	18.2	74.2
currSp004 cm/s	cm/s	4	9.5	0.2	17.3	70.4

Note
* Height above the seafloor



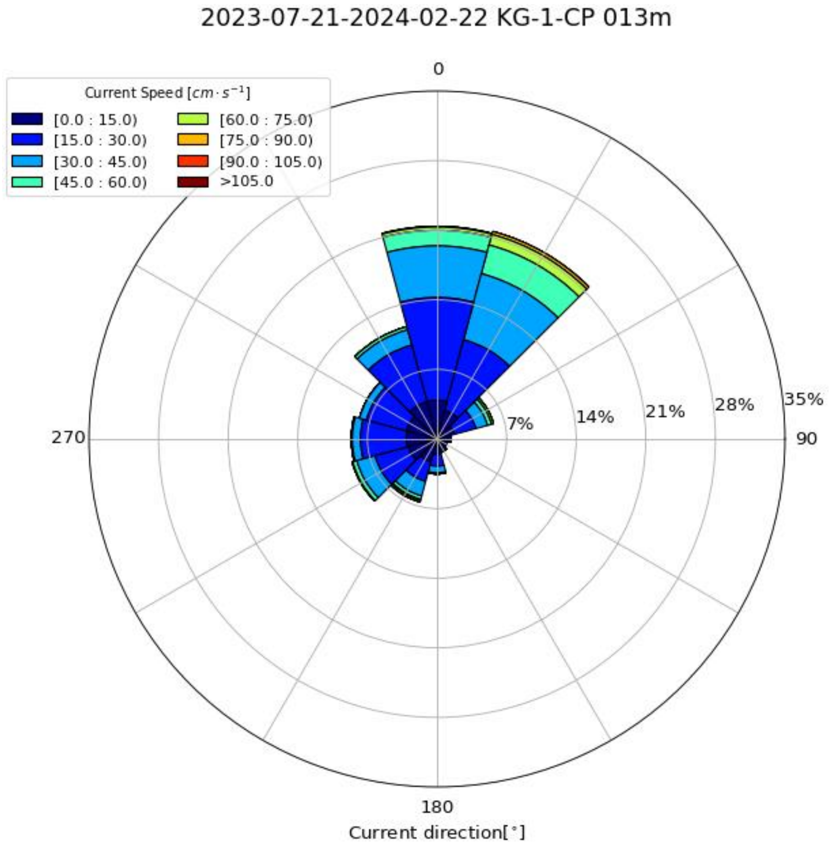
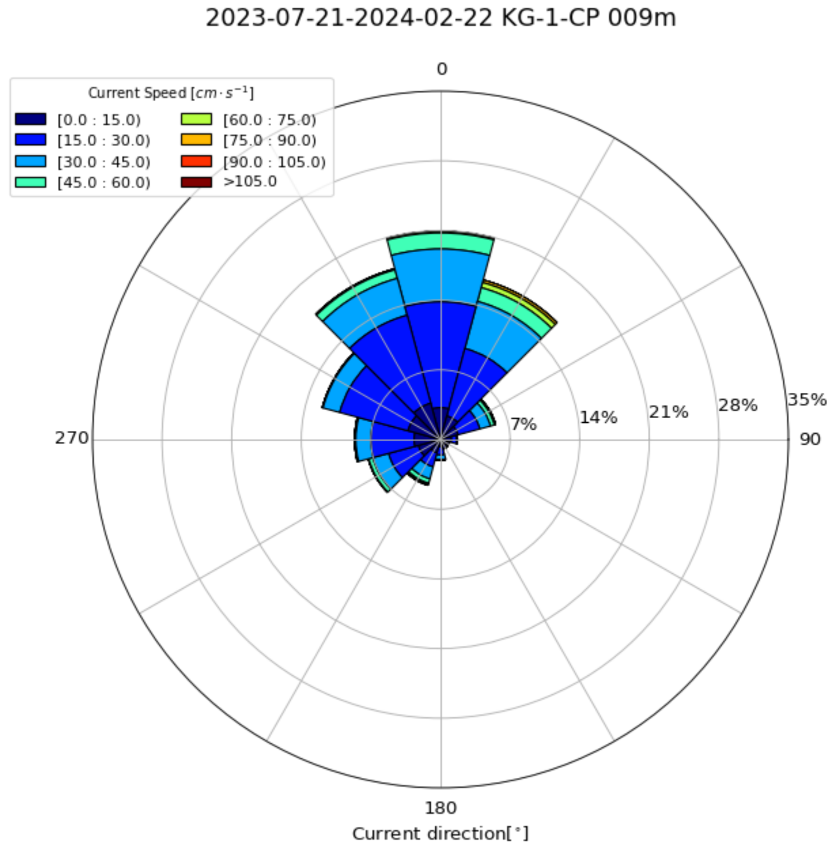


Figure 11.4: Current speed profile during D1 (1/2) (21 July 2023 – 18 February 2024). Note that heights are given relative to the seafloor.



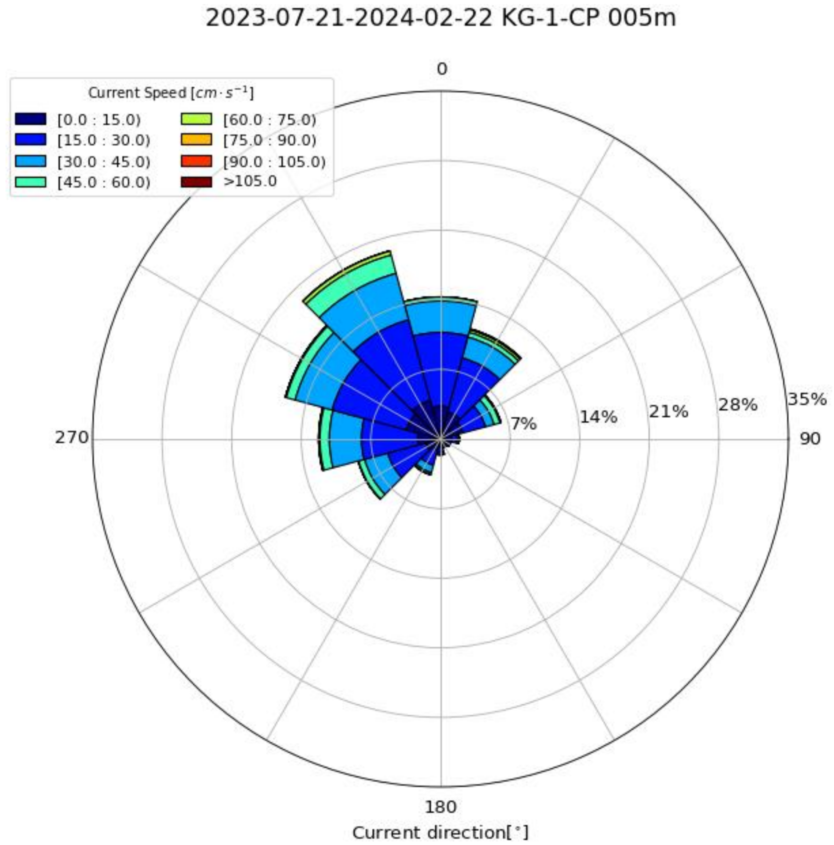
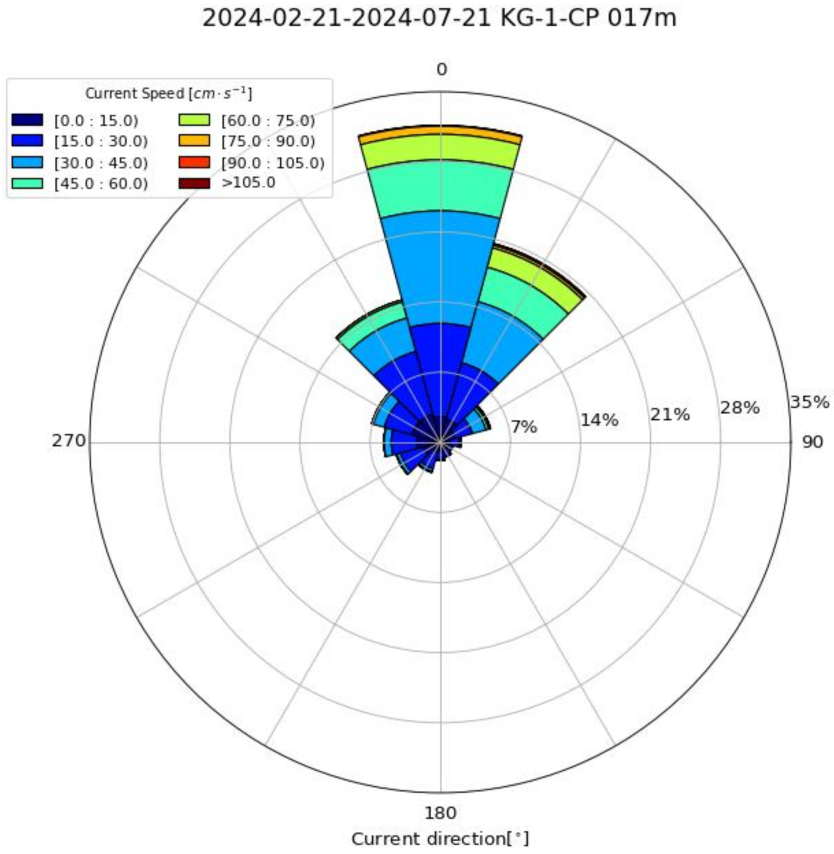


Figure 11.5: Current speed profile during D1 (2/2) (21 July 2023 – 18 February 2024). Note that heights are given relative to the seafloor.



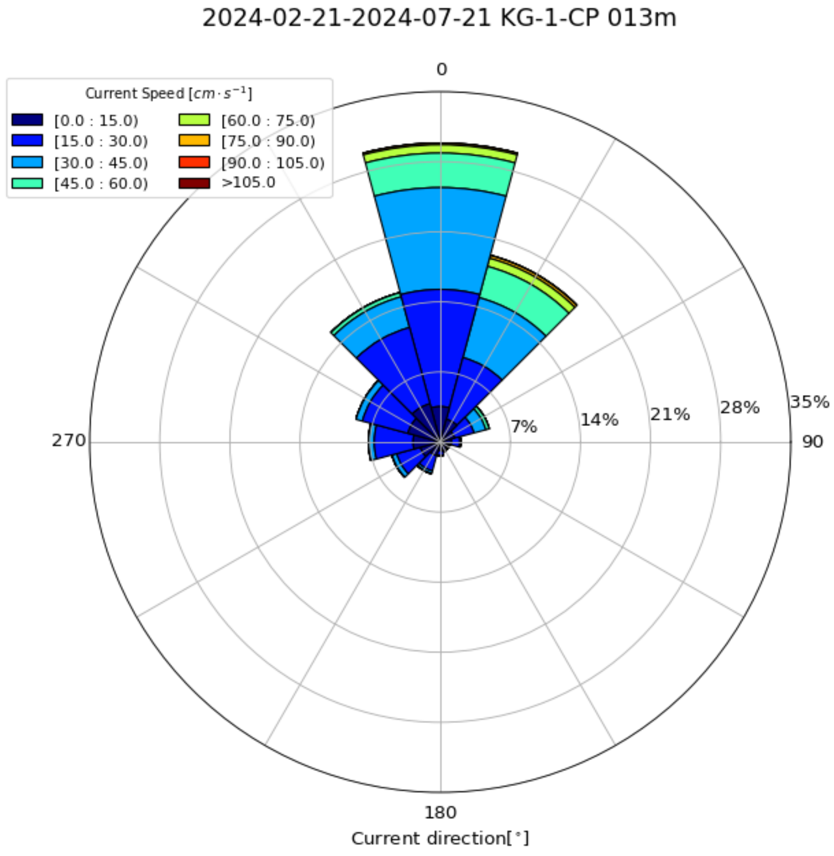
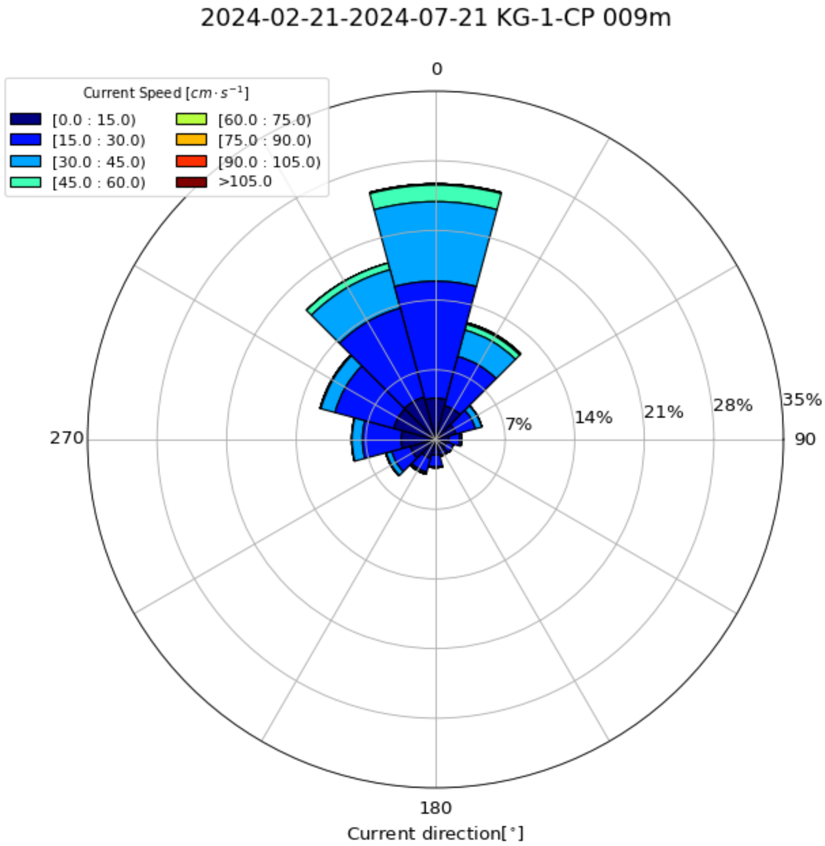


Figure 11.6: Current speed profile during D2 (1/2) (22 February 2024 – 21 July 2024). Note that heights are given relative to the seafloor.



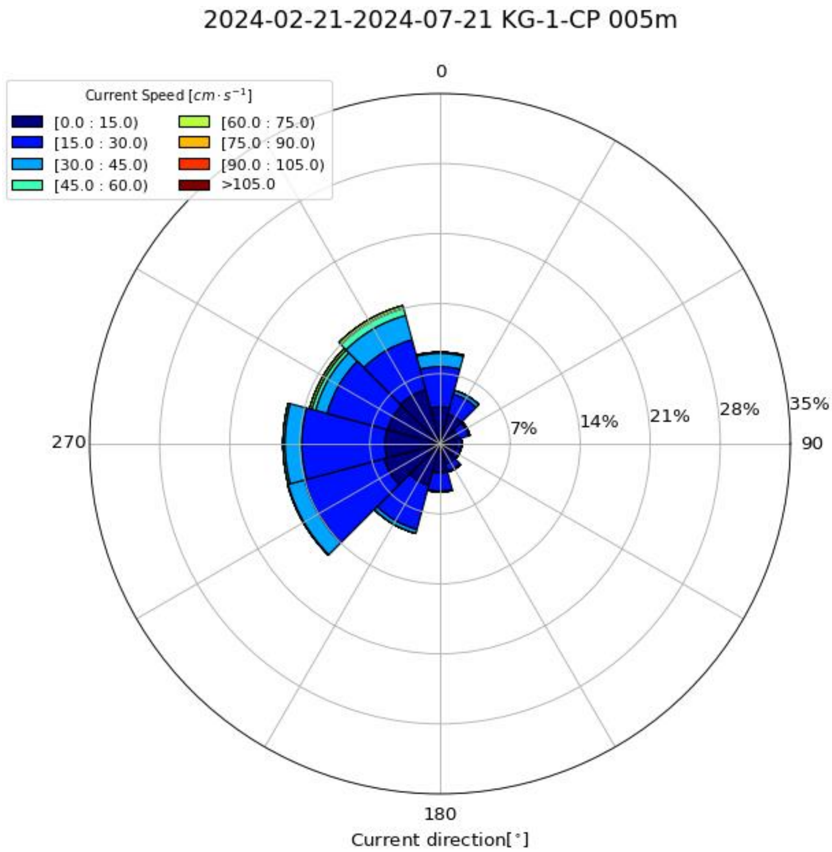


Figure 11.7: Current speed profile during D2 (2/2) (22 February 2024 – 21 July 2024). Note that heights are given relative to the seafloor.

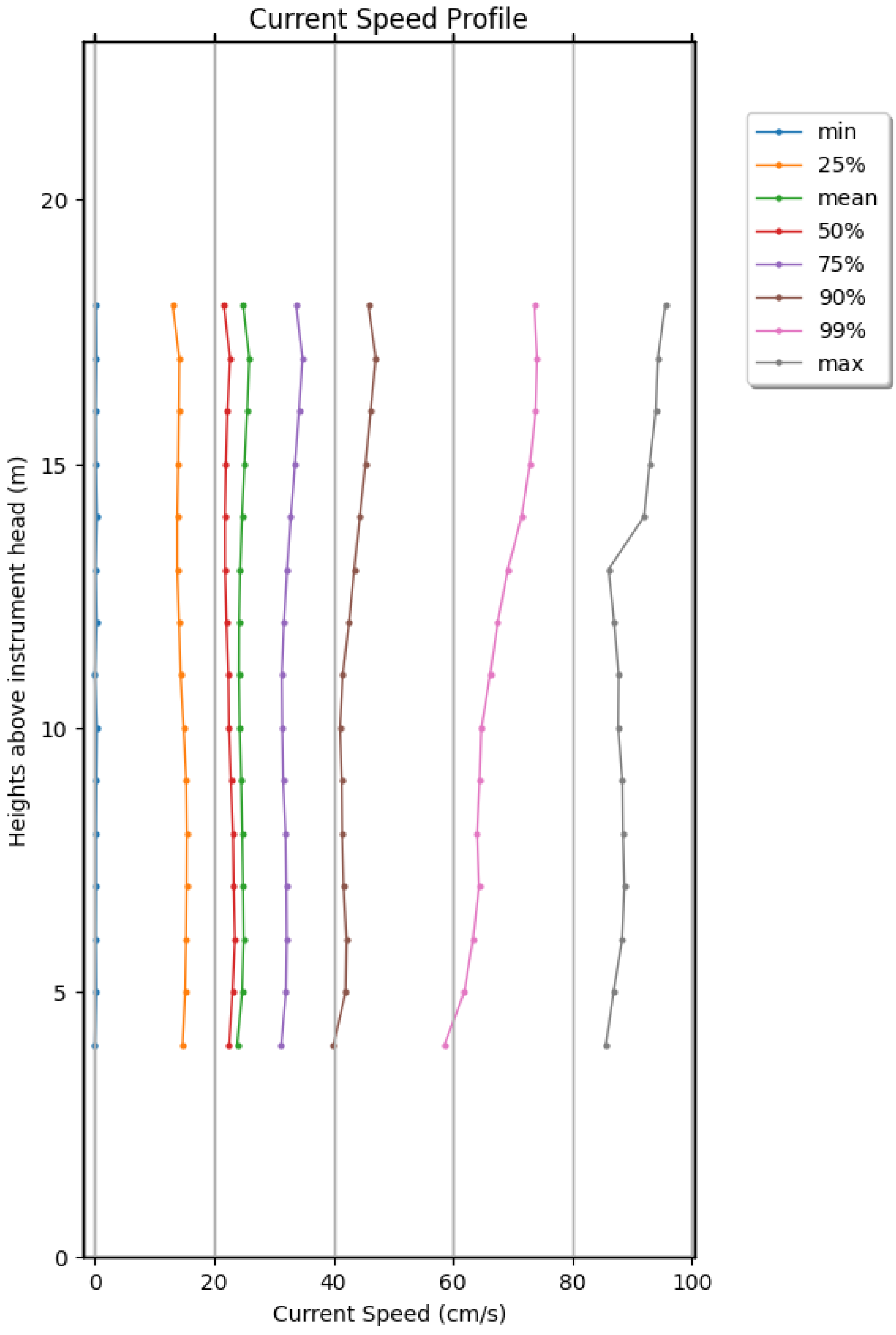


Figure 11.8: KG-1-CP current speed profile for D1 (July 2023 to February 2024)

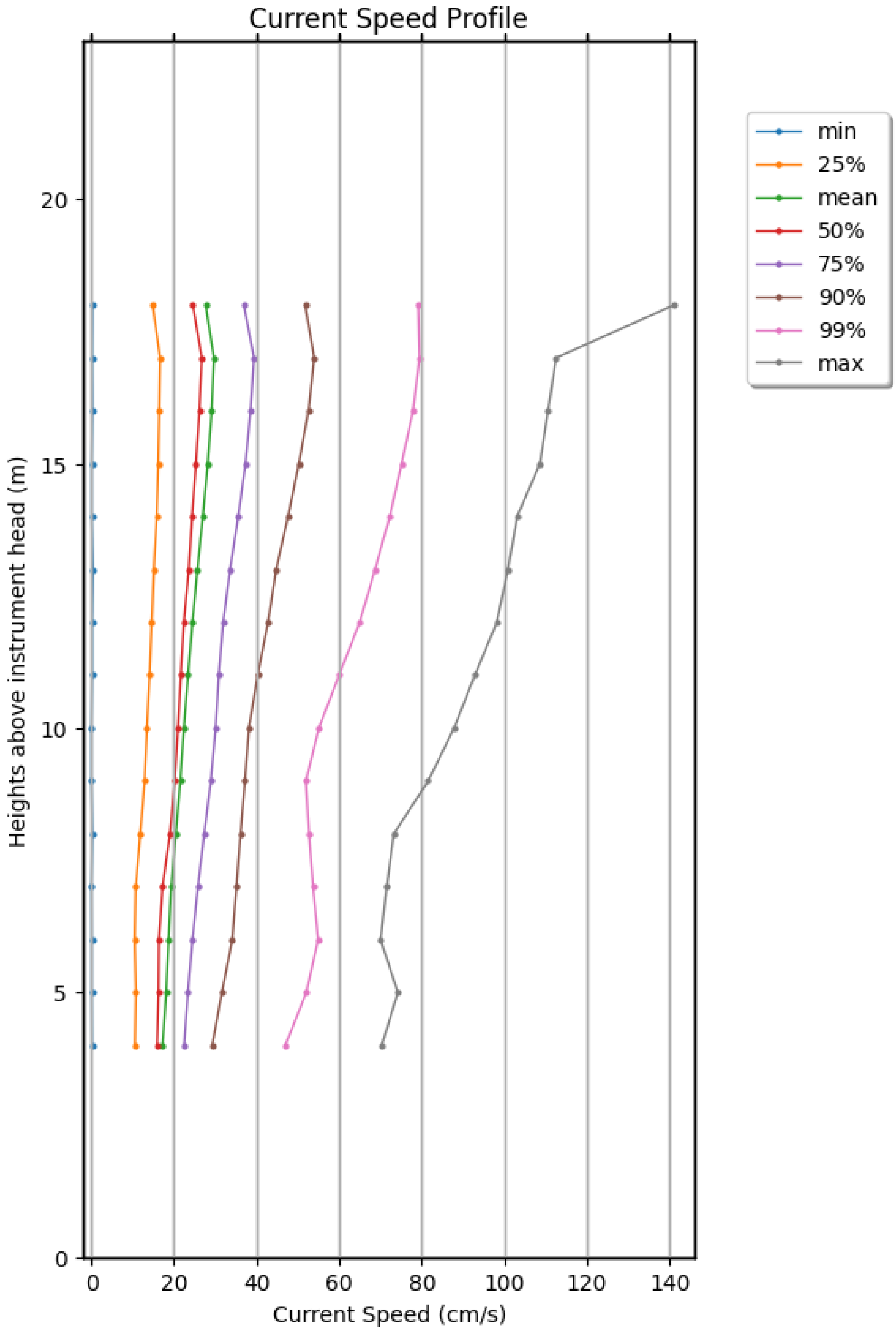


Figure 11.9: KG-1-CP current speed profile for D2 (February 2024 to July 2024)

12. References

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[3] Nortek, *Surge Help Guide*, "*Current Data Quality Control*".

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

[7] 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.

[8] European Commision, *European Marine Observation and Data Network (EMODnet), (https://emodnet.ec.europa.eu/geoviewer/)*.

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

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

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

Appendix A

Event Logs

Issue number	Start time	End time	Instrument	Parameter	Description
1	2023-07-21	2024-07-21	Aquadopp	Current speed and direction below 17 m	There are either a substantial drop in signal strength of the Aquadopp current profiler or sidelobe rejection by pos-process software below 17 m depth and a large amount of data below this depth is filtered out.
2	10/09/2023 04:10	10/09/2023 05:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
3	19/09/2023 17:00	19/09/2023 19:00	Thelma	Bottom temperature	Values out of bounds
4	20/10/2023 20:40	20/10/2023 22:30	Thelma	Bottom temperature	Values out of bounds
5	02/01/2024 15:30	02/01/2024 17:40	Thelma	Bottom temperature	Values out of bounds
6	02/01/2024 18:50	02/01/2024 21:00	Thelma	Water pressure	Values out of bounds
7	03/01/2024 09:10	03/01/2024 11:20	Thelma	Bottom temperature	Values out of bounds
8	03/01/2024 17:50	03/01/2024 19:30	Thelma	Bottom temperature	Values out of bounds
9	11/01/2024 05:20	11/01/2024 06:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
10	17/01/2024 04:30	17/01/2024 06:40	Thelma	Bottom temperature	Values out of bounds
11	24/01/2024 20:10	24/01/2024 21:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
12	24/01/2024 21:10	24/01/2024 22:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
13	24/01/2024 22:10	24/01/2024 23:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
14	24/01/2024 23:10	25/01/2024 00:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
15	25/01/2024 00:10	25/01/2024 01:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
16	25/01/2024 01:10	25/01/2024 02:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
17	25/01/2024 02:10	25/01/2024 03:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
18	25/01/2024 03:10	25/01/2024 04:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
19	25/01/2024 04:10	25/01/2024 05:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
202	25/01/2024 05:10	25/01/2024 06:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog

Issue number	Start time	End time	Instrument	Parameter	Description
21	25/01/2024 06:10	25/01/2024 07:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
22	25/01/2024 07:10	25/01/2024 08:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
23	25/01/2024 08:10	25/01/2024 09:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
24	25/01/2024 09:10	25/01/2024 10:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
25	25/01/2024 10:10	25/01/2024 11:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
26	25/01/2024 11:10	25/01/2024 12:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
27	25/01/2024 12:10	25/01/2024 13:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
28	25/01/2024 13:10	25/01/2024 14:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
29	25/01/2024 14:10	25/01/2024 15:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
30	25/01/2024 15:10	25/01/2024 16:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
31	25/01/2024 16:10	25/01/2024 17:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
32	25/01/2024 17:10	25/01/2024 18:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
33	25/01/2024 18:10	25/01/2024 19:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
34	25/01/2024 19:10	25/01/2024 20:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
35	25/01/2024 20:10	25/01/2024 21:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
36	25/01/2024 21:10	25/01/2024 22:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
37	25/01/2024 22:10	25/01/2024 23:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
38	25/01/2024 23:10	26/01/2024 00:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
39	26/01/2024 00:10	26/01/2024 01:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
40	26/01/2024 01:10	26/01/2024 02:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
41	26/01/2024 02:10	26/01/2024 03:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
42	26/01/2024 03:10	26/01/2024 04:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog

Issue number	Start time	End time	Instrument	Parameter	Description
43	26/01/2024 04:10	26/01/2024 05:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
44	26/01/2024 05:10	26/01/2024 06:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
45	26/01/2024 06:10	26/01/2024 07:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
46	26/01/2024 07:10	26/01/2024 08:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
47	26/01/2024 08:10	26/01/2024 09:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
48	26/01/2024 09:10	26/01/2024 10:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
49	26/01/2024 10:10	26/01/2024 11:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
50	26/01/2024 11:10	26/01/2024 12:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
51	26/01/2024 12:10	26/01/2024 13:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
52	26/01/2024 13:10	26/01/2024 14:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
53	26/01/2024 14:10	26/01/2024 15:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
54	26/01/2024 15:10	26/01/2024 16:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
55	26/01/2024 16:10	26/01/2024 17:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
56	26/01/2024 17:10	26/01/2024 18:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
57	26/01/2024 18:10	26/01/2024 19:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog
58	29/01/2024 23:20	30/01/2024 00:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
59	30/01/2024 01:20	30/01/2024 02:00	Lidar	100-300m	Lidar data partially missing due to low visibility/fog
60	30/01/2024 03:10	30/01/2024 03:50	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
61	30/01/2024 04:20	30/01/2024 05:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
62	30/01/2024 05:10	30/01/2024 06:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
63	30/01/2024 06:10	30/01/2024 07:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
64	30/01/2024 07:10	30/01/2024 07:50	Lidar	80-300m	Lidar data partially missing due to low visibility/fog

Issue number	Start time	End time	Instrument	Parameter	Description
65	30/01/2024 10:10	30/01/2024 11:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
66	30/01/2024 11:20	30/01/2024 12:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
67	15/02/2024 00:10	15/02/2024 00:50	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
68	15/02/2024 07:20	15/02/2024 08:00	Lidar	12m 80-300m	Lidar data partially missing due to low visibility/fog
69	15/02/2024 08:10	15/02/2024 09:00	Lidar	12m 80-300m	Lidar data partially missing due to low visibility/fog
70	15/02/2024 13:20	15/02/2024 14:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
71	16/02/2024 00:10	16/02/2024 01:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
72	16/02/2024 02:10	16/02/2024 03:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
73	16/02/2024 06:10	16/02/2024 07:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
74	18/02/2024 08:40	22/02/2024 13:30	SWLB	All parameters	SWLB serviced onshore and redeployed
75	01/03/2024 21:10	01/03/2024 22:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
76	01/03/2024 22:10	01/03/2024 22:50	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
77	02/03/2024 01:10	02/03/2024 02:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
78	02/03/2024 13:10	02/03/2024 14:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
79	02/03/2024 18:10	02/03/2024 19:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
80	02/03/2024 20:10	02/03/2024 21:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
81	02/03/2024 21:10	02/03/2024 22:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
82	08/03/2024 05:10	08/03/2024 06:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
83	08/03/2024 06:10	08/03/2024 07:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
84	08/03/2024 07:10	08/03/2024 08:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
85	08/03/2024 08:20	08/03/2024 09:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
86	08/03/2024 12:20	08/03/2024 13:00	Lidar	100-300m	Lidar data partially missing due to low visibility/fog

Issue number	Start time	End time	Instrument	Parameter	Description
87	13/03/2024 07:10	13/03/2024 08:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
88	20/03/2024 19:10	20/03/2024 20:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
89	20/03/2024 20:20	20/03/2024 21:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
90	01/04/2024 08:10	01/04/2024 08:50	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
91	05/05/2024 06:10	05/05/2024 07:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
92	05/05/2024 08:10	05/05/2024 09:00	Lidar	80-300m	Lidar data partially missing due to low visibility/fog
93	05/05/2024 11:10	05/05/2024 12:00	Lidar	130-300m	Lidar data partially missing due to low visibility/fog
94	19/07/2024 10:20	19/07/2024 11:00	Lidar	All parameters	Lidar data partially missing due to low visibility/fog

Note
Gaps less than or equal to consecutive 30 minutes were excluded from lidar data gap. For other parameters, gaps less than consecutive 100 minutes were excluded.

Appendix B

Data presentation

B.1 Wind data

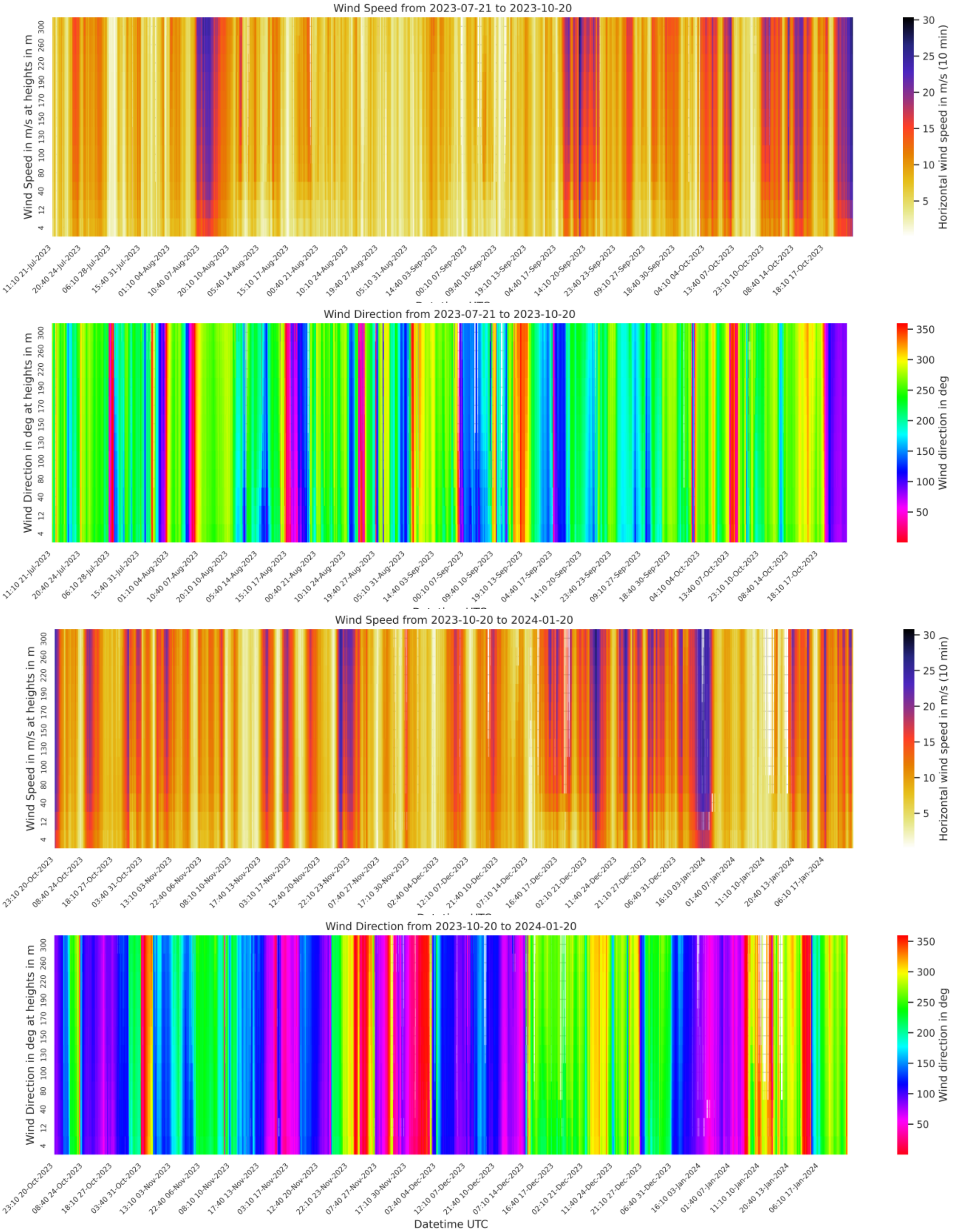


Figure B.1: Heatmaps of wind speed and direction from 21 July 2023 to 21 January 2024

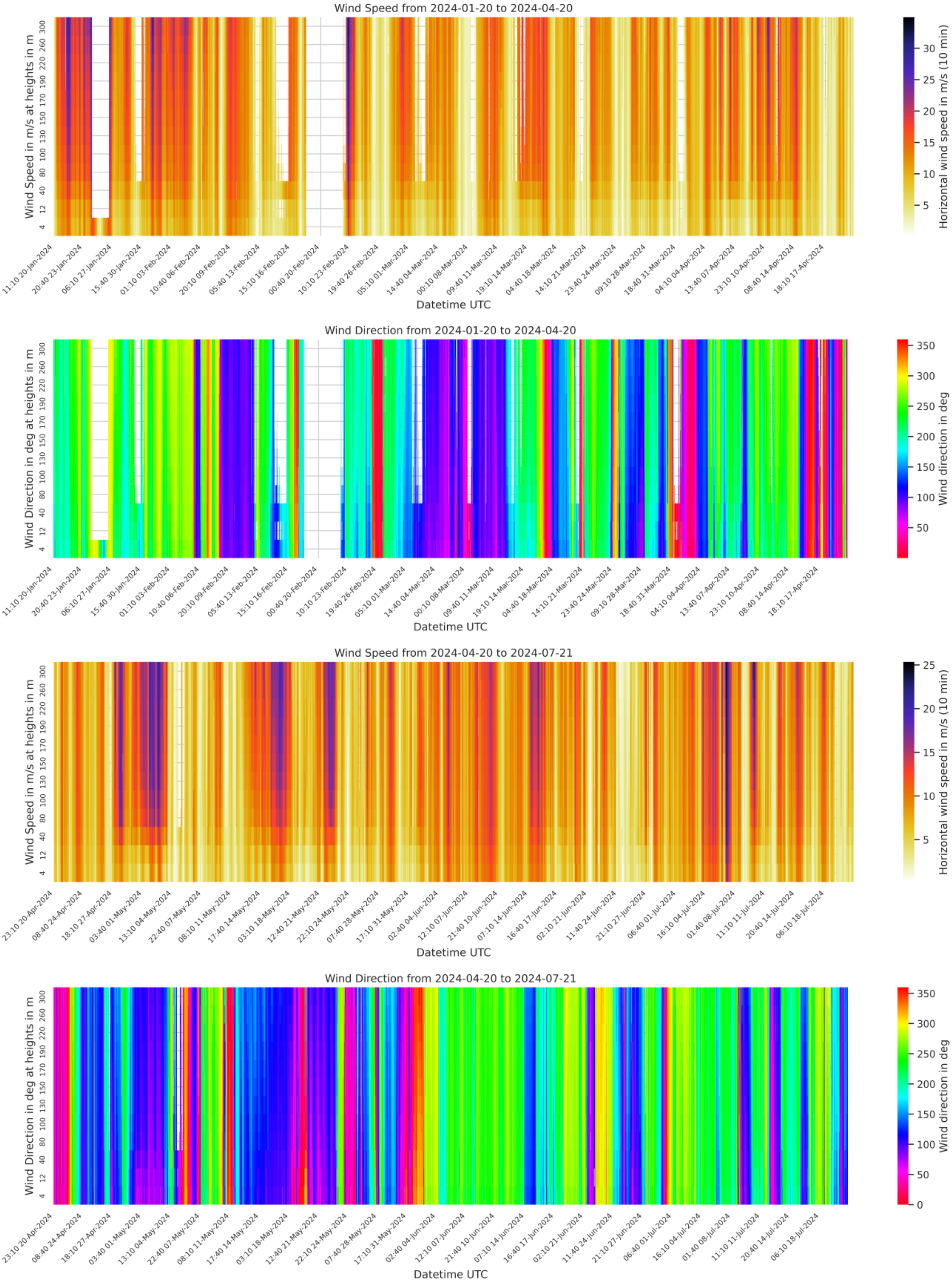


Figure B.2: Heatmaps of wind speed and direction from 21 January 2024 to 21 July 2024

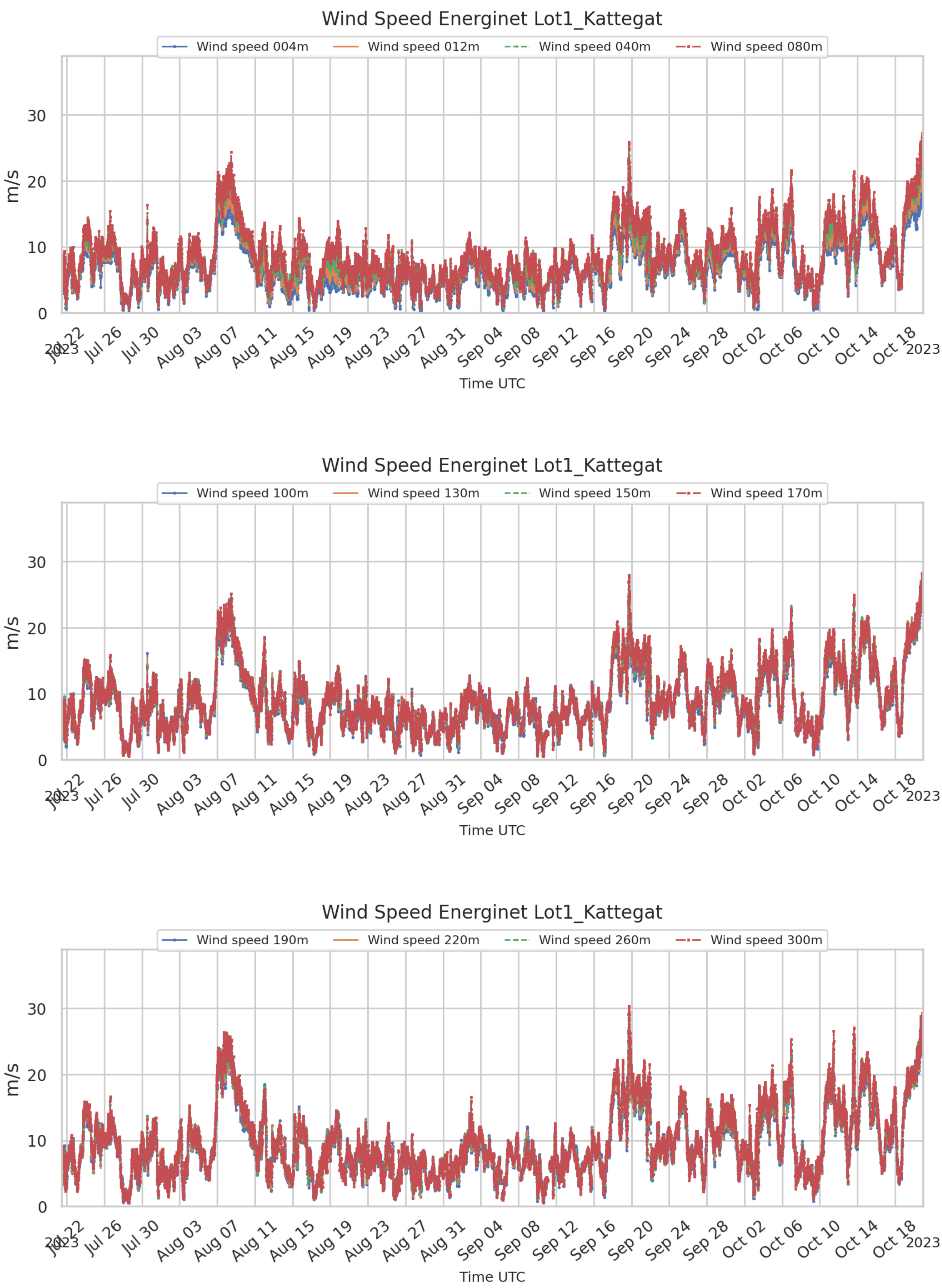


Figure B.3: Timeseries of wind speed from 21 July 2023 to 21 October 2023

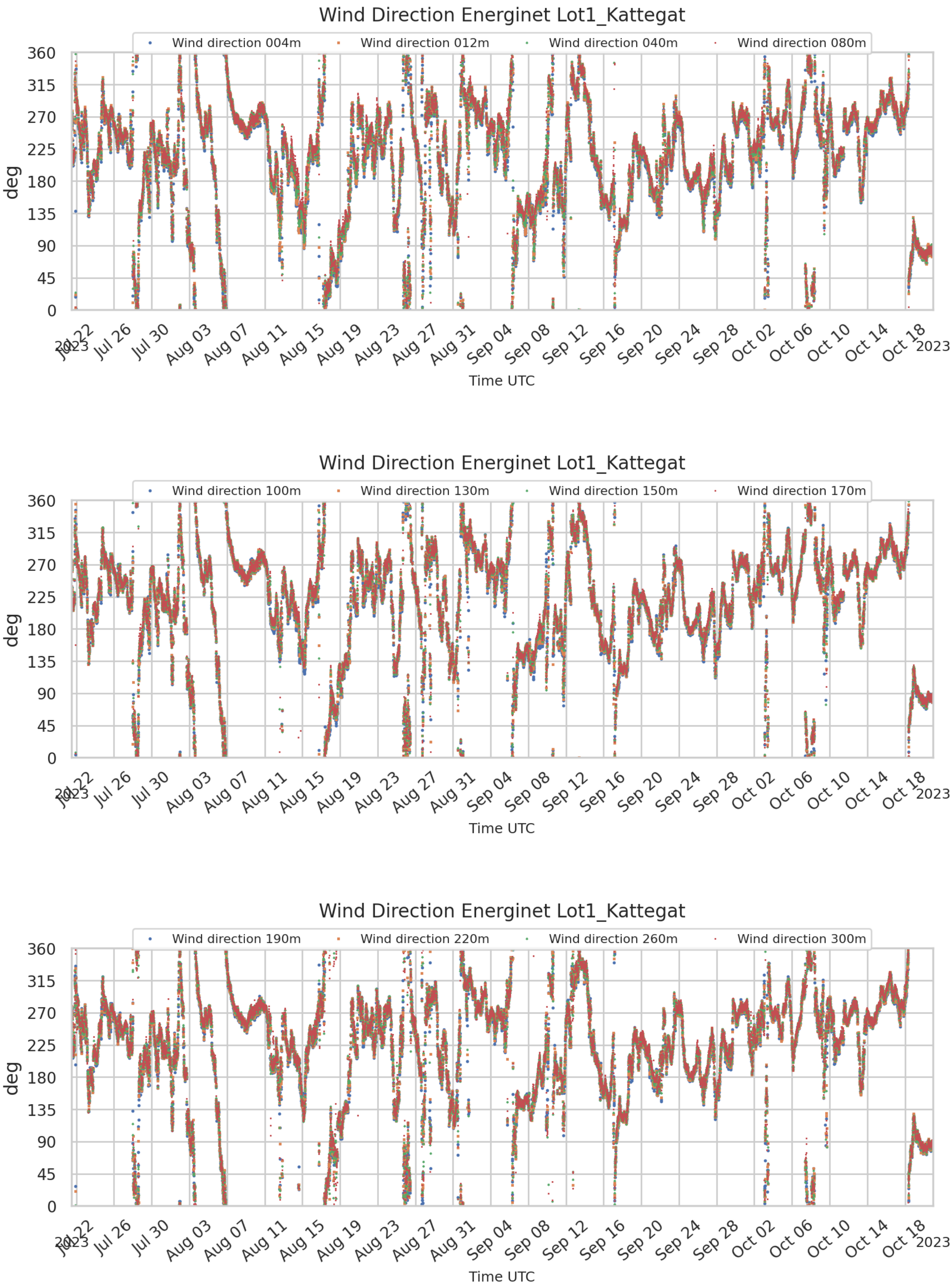


Figure B.4: Timeseries of wind direction from 21 July 2023 to 21 October 2023

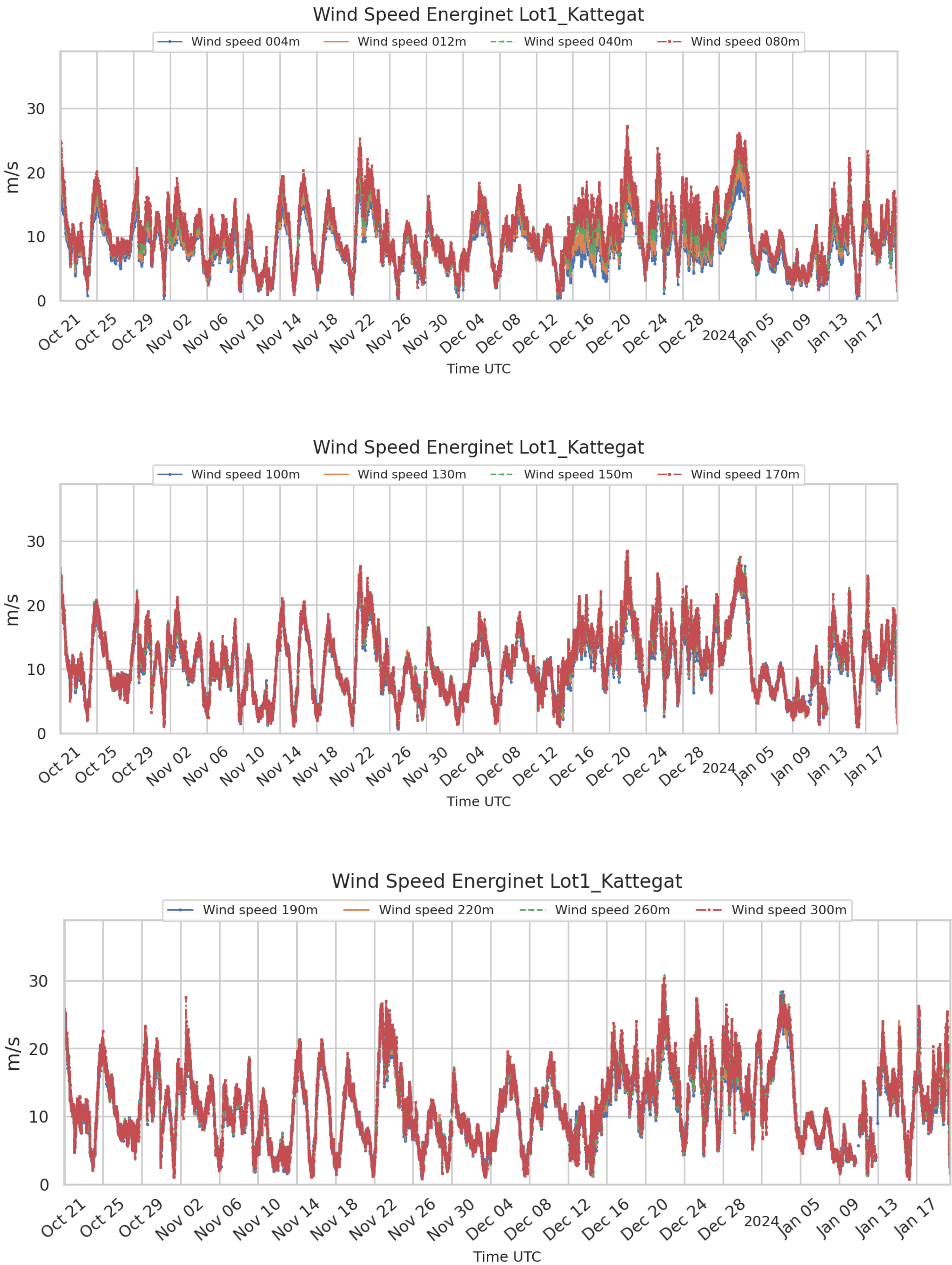


Figure B.5: Timeseries of wind speed from 21 October 2023 to 21 January 2024

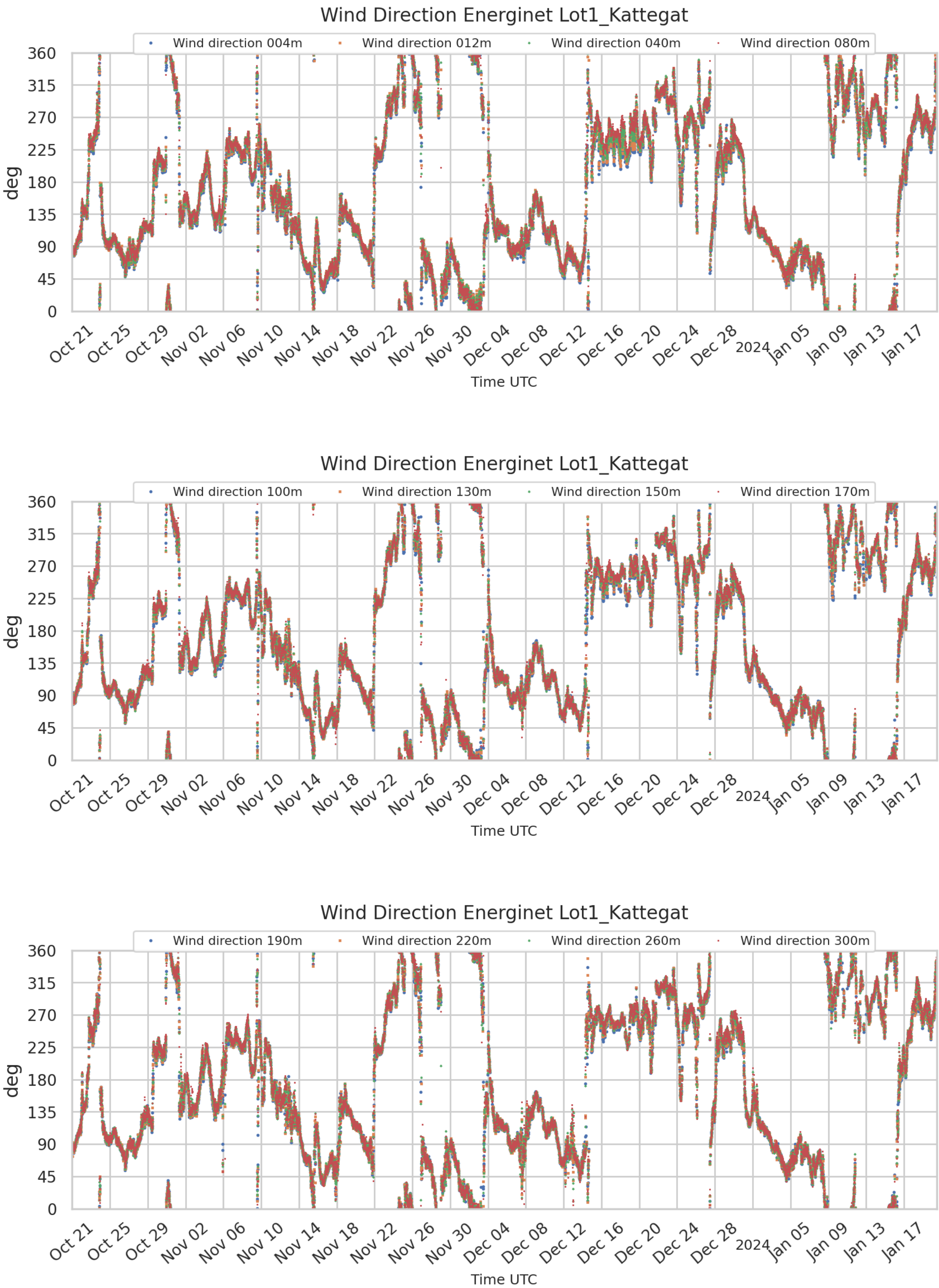


Figure B.6: Timeseries of wind direction from 21 October 2023 to 21 January 2024

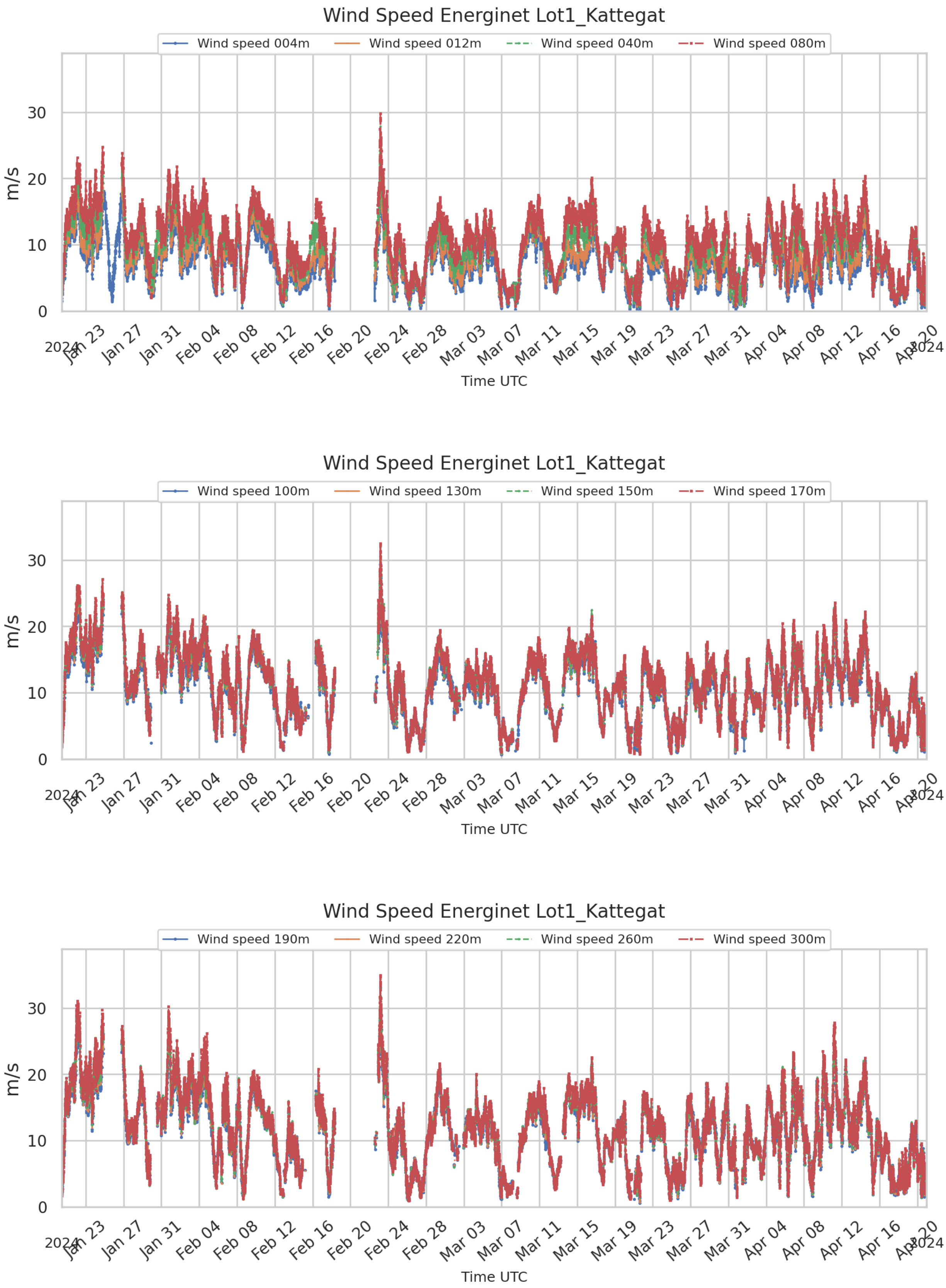
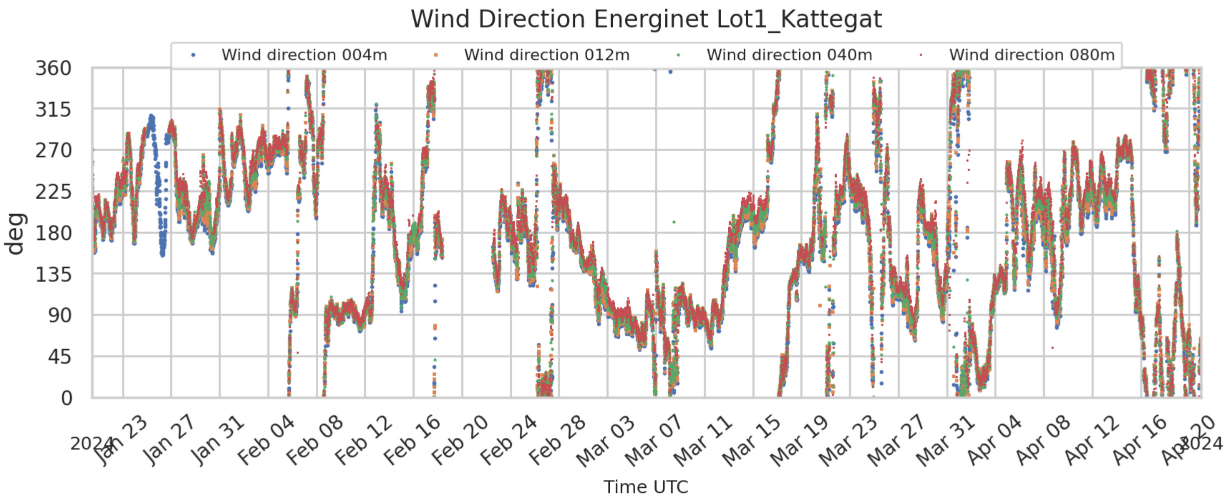
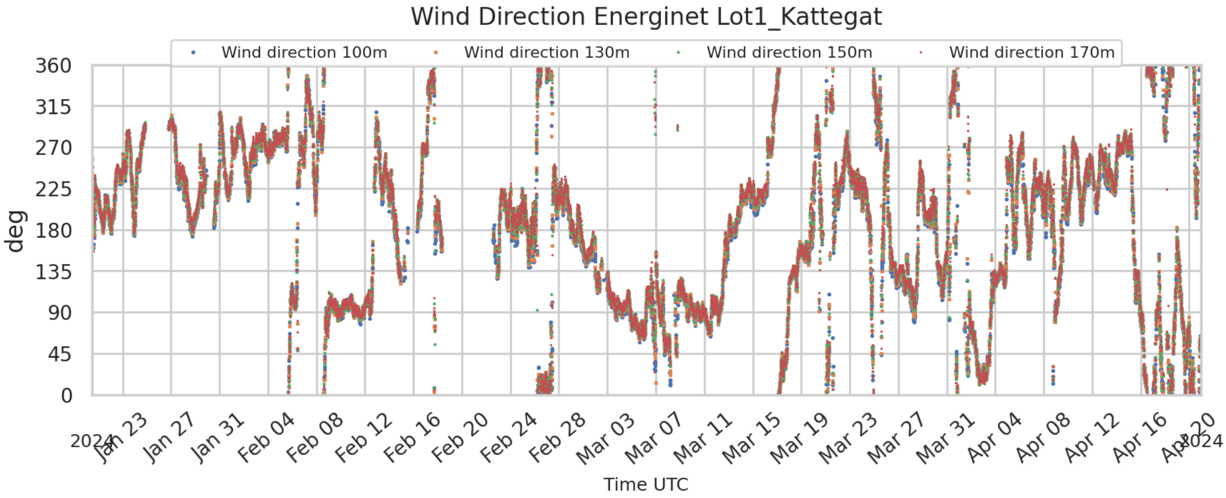


Figure B.7: Timeseries of wind speed from 21 January 2024 to 21 April 2024





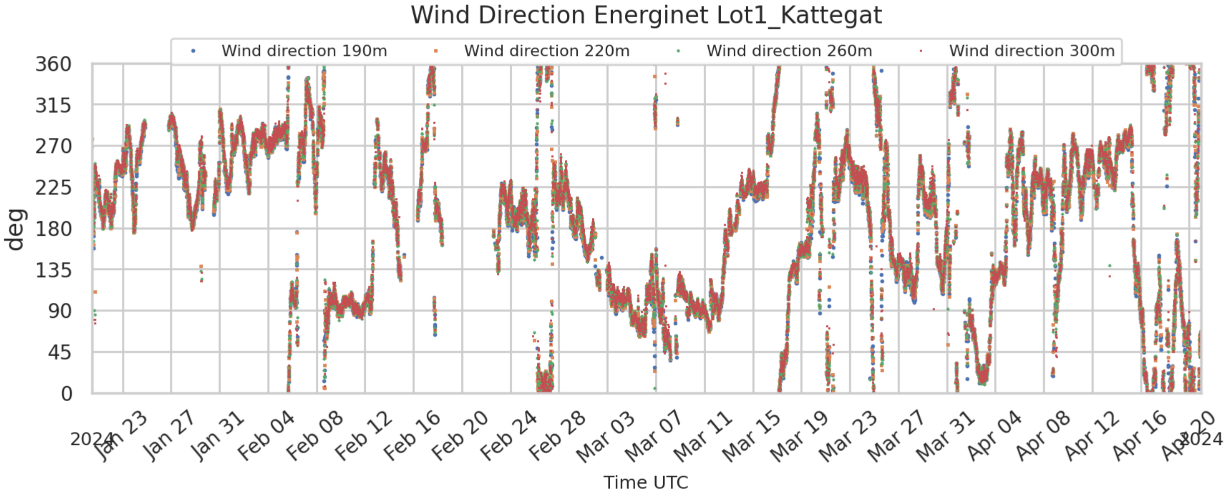


Figure B.8: Timeseries of wind direction from 21 January 2024 to 21 April 2024

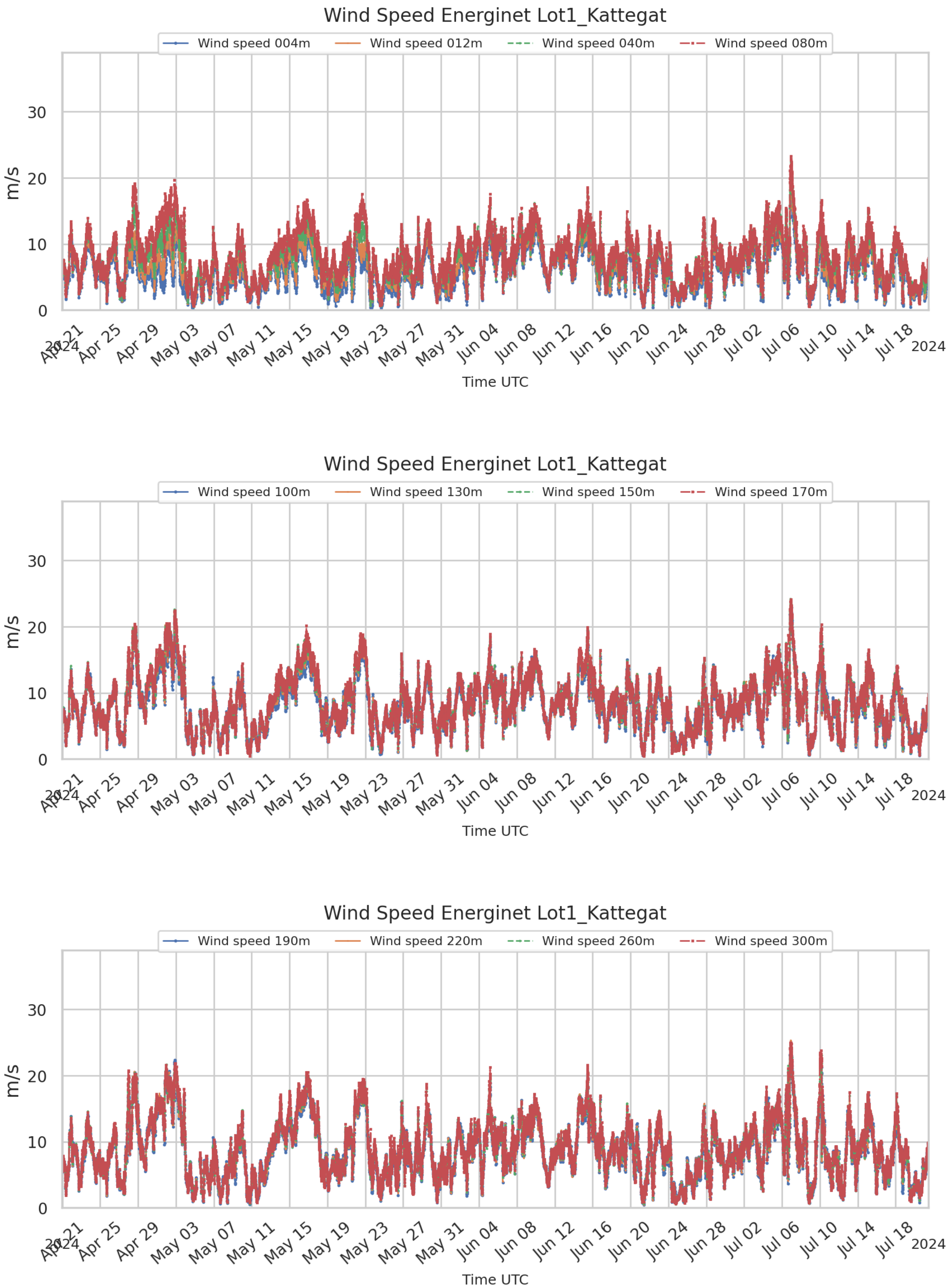
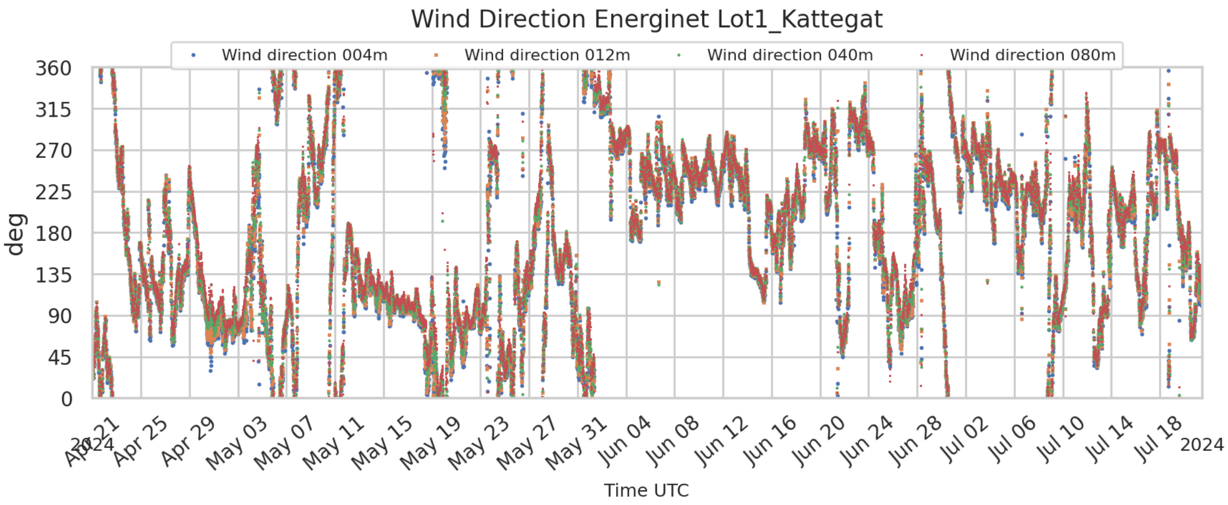
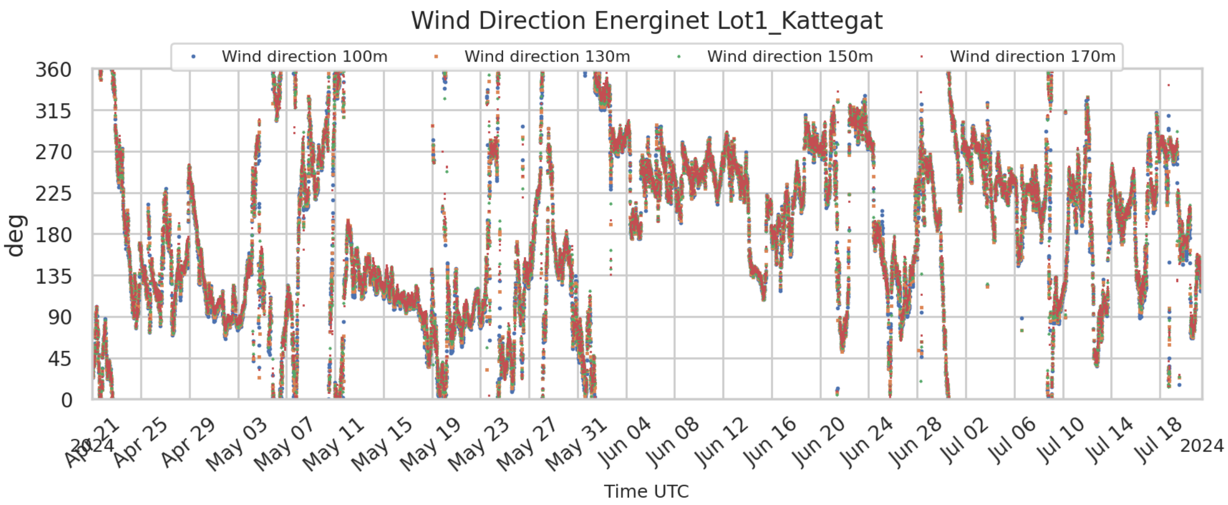


Figure B.9: Timeseries of wind speed from 21 April 2024 to 21 July 2024





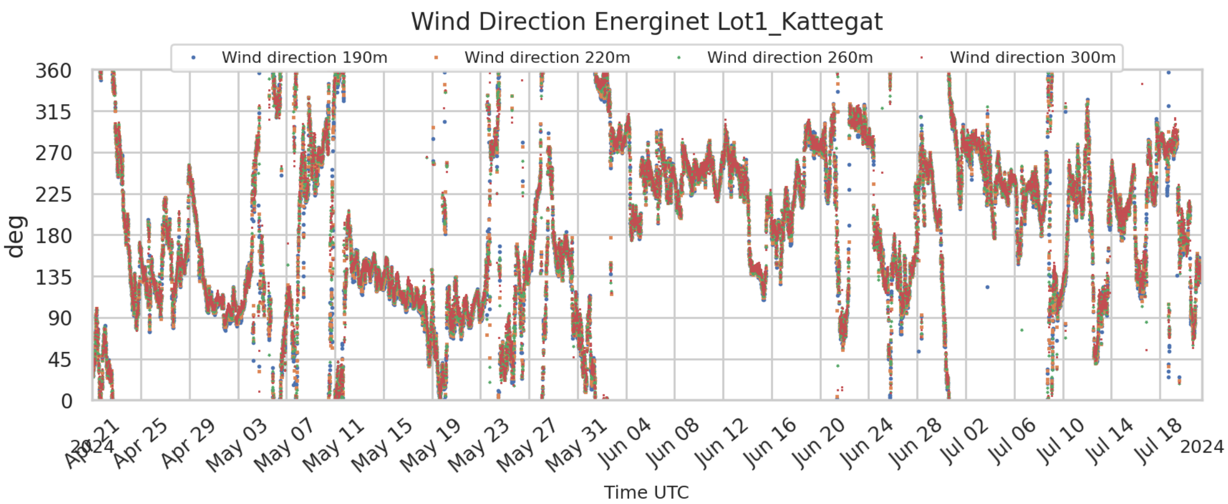


Figure B.10: Timeseries of wind direction from 21 April 2024 to 21 July 2024

B.2 Wave data

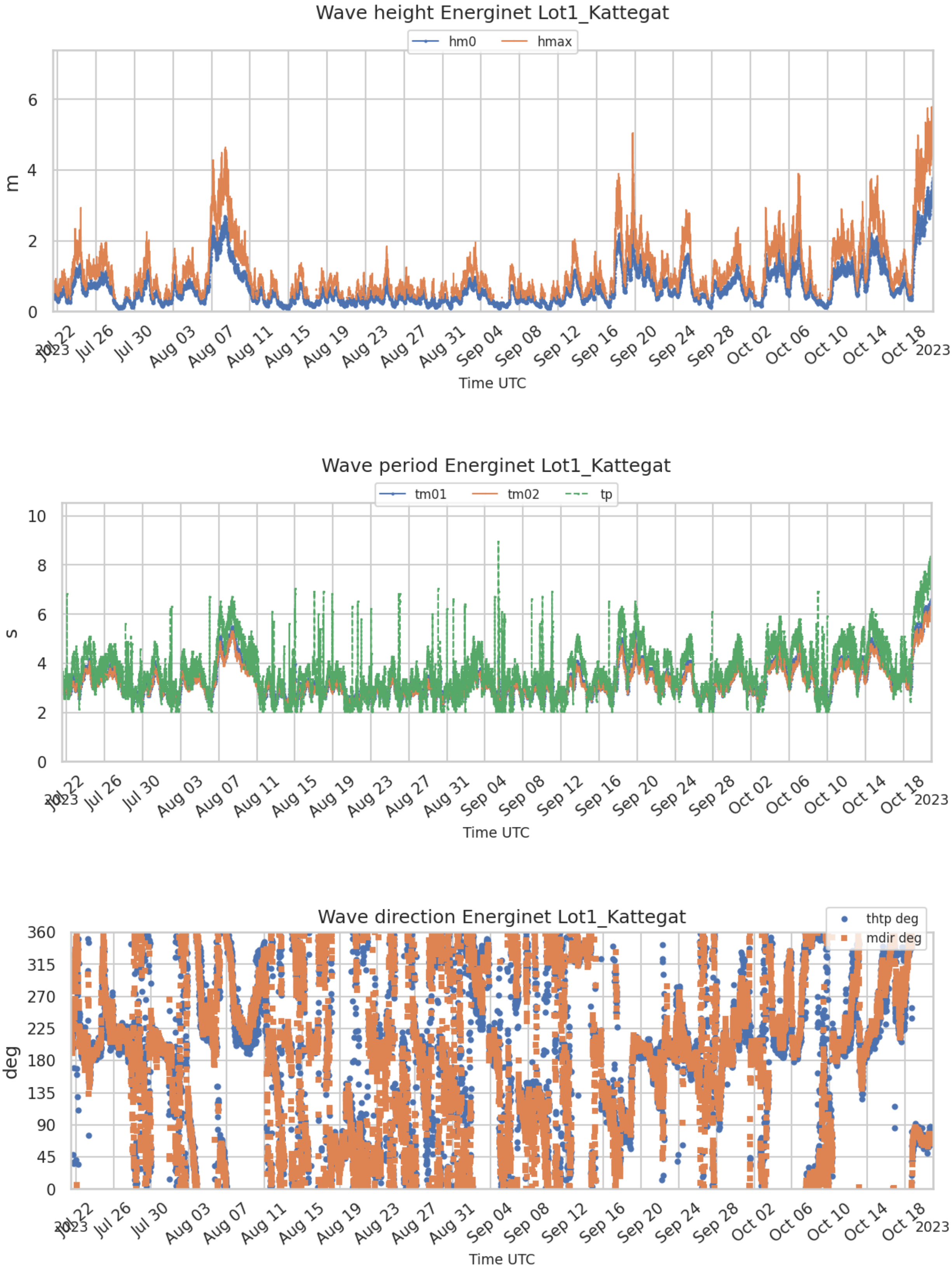
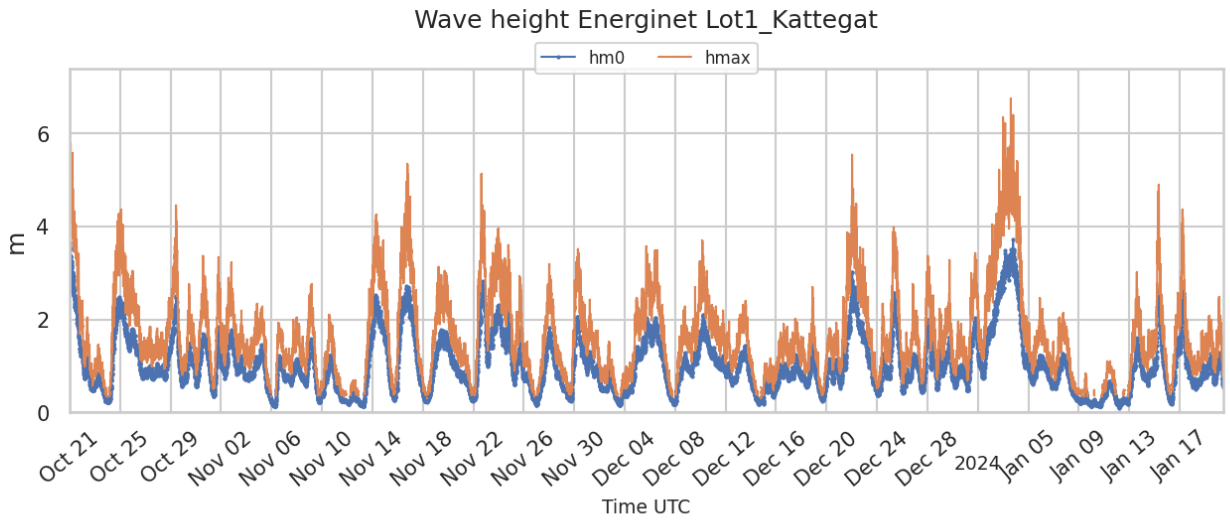
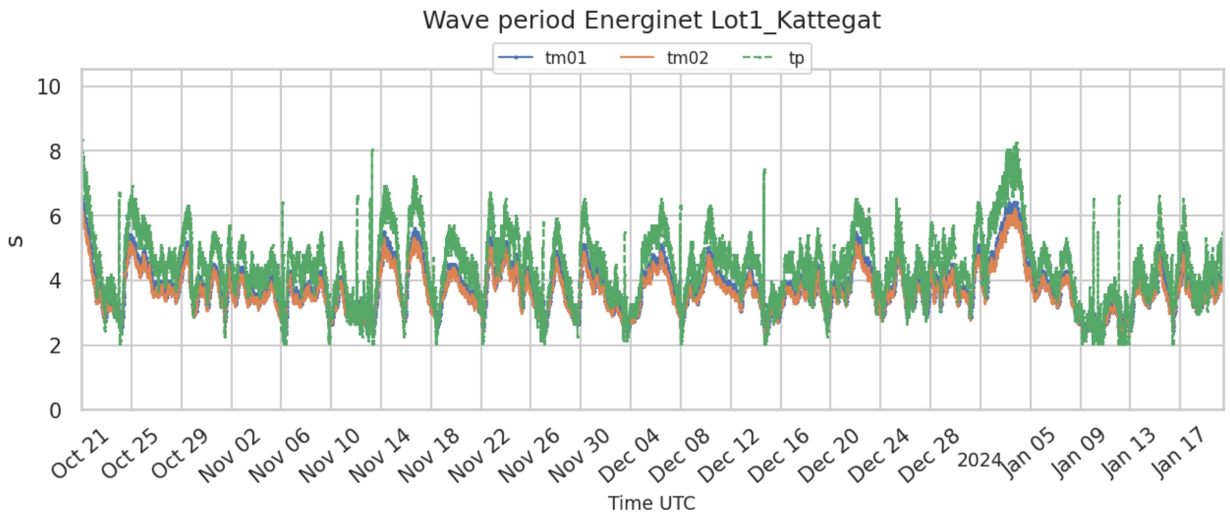


Figure B.11: Timeseries of wave heights, wave periods, and wave direction from 21 July 2023 to 21 October 2023





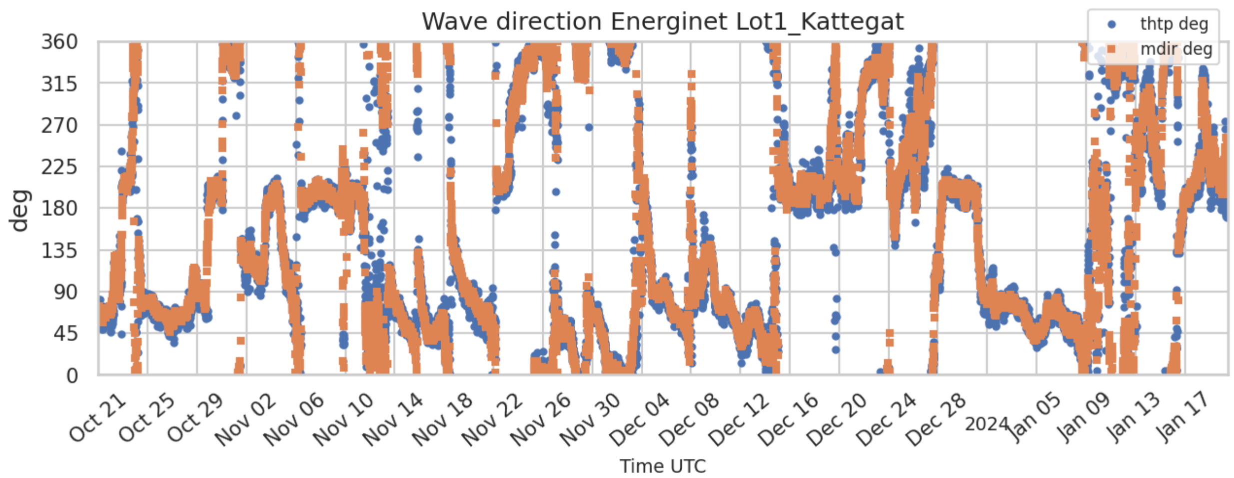


Figure B.12: Timeseries of wave heights, wave periods, and wave direction from 21 October 2023 to 21 January 2024

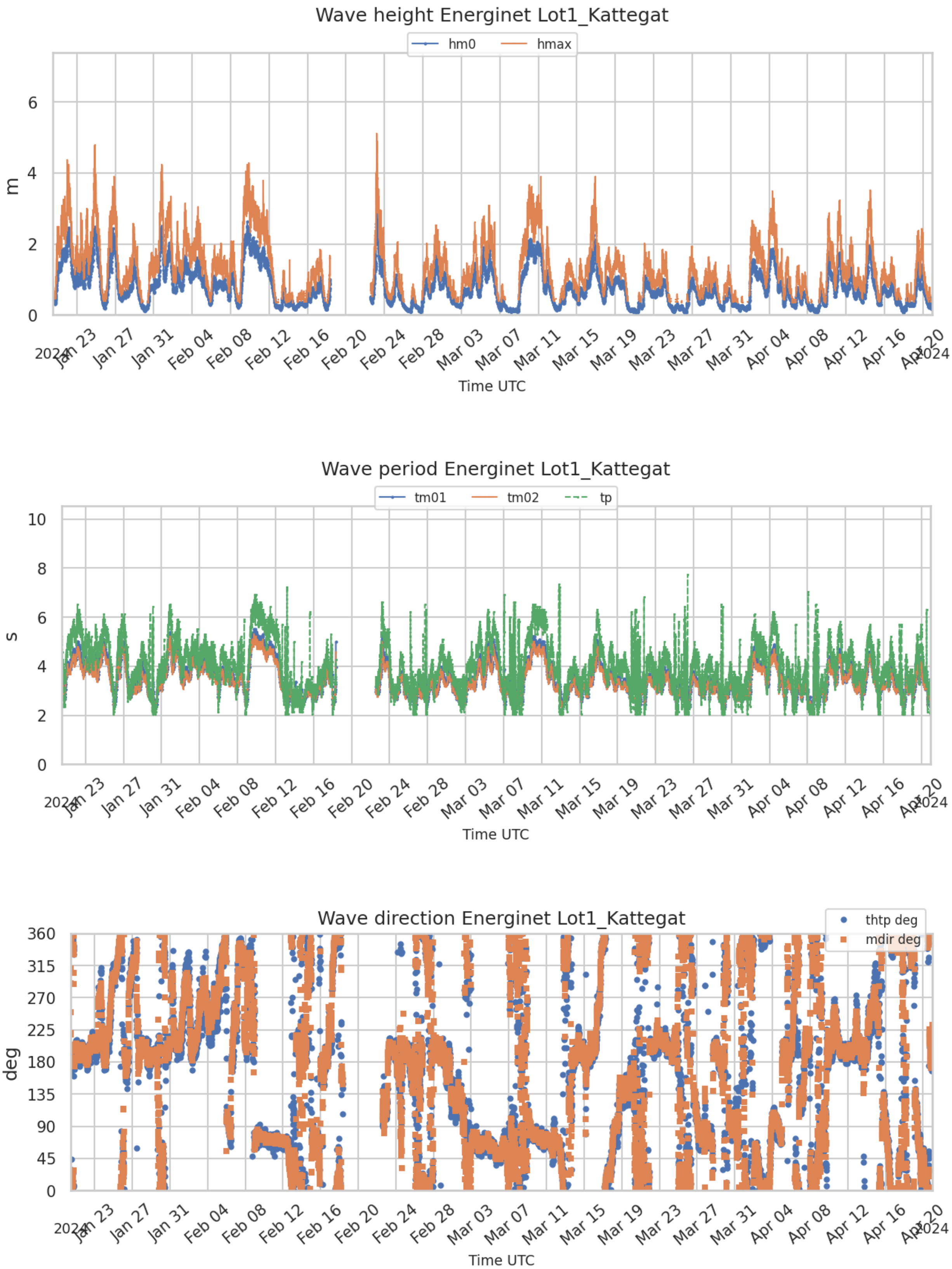
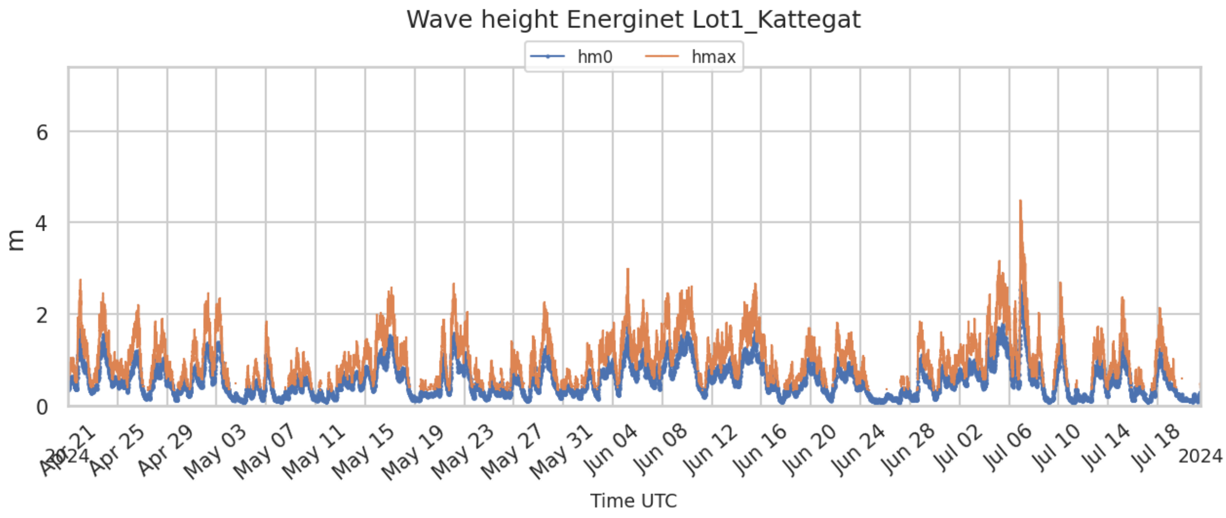
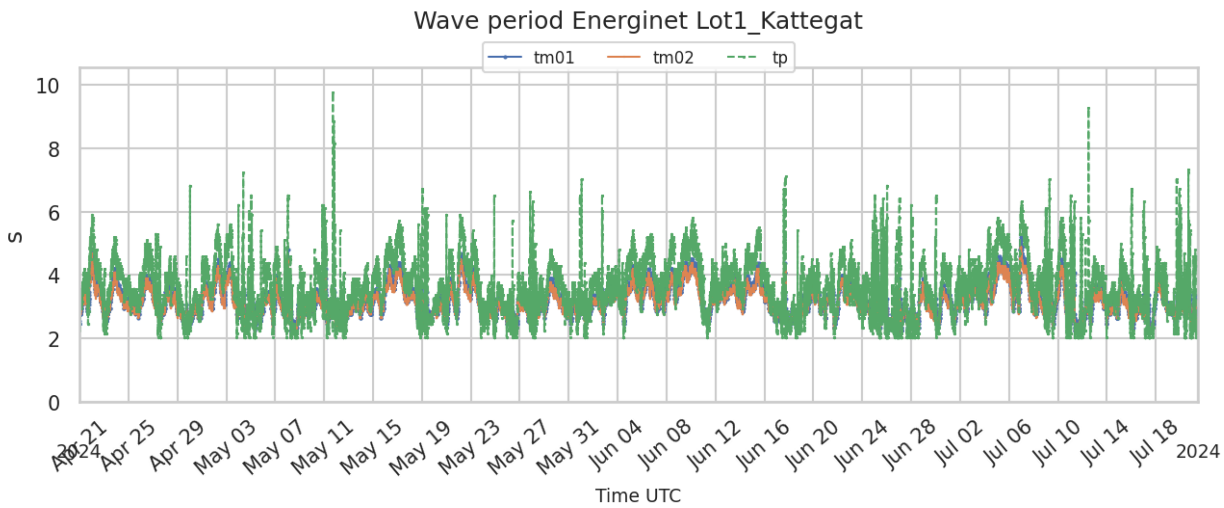


Figure B.13: Timeseries of wave heights, wave periods, and wave direction from 21 January 2024 to 21 April 2024





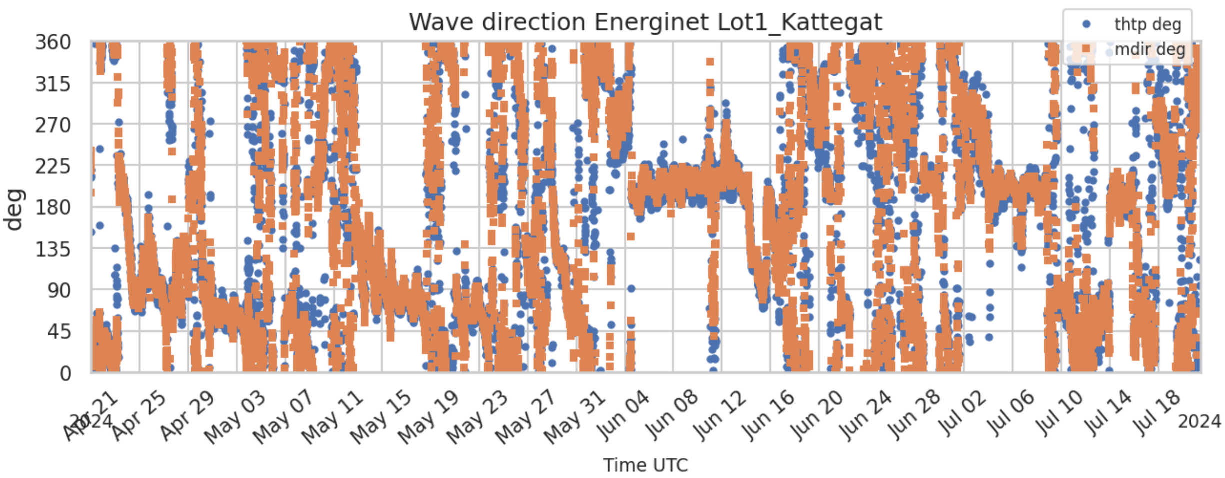


Figure B.14: Timeseries of wave heights, wave periods, and wave direction from 21 April 2024 to 21 July 2024

B.3 Metocean data

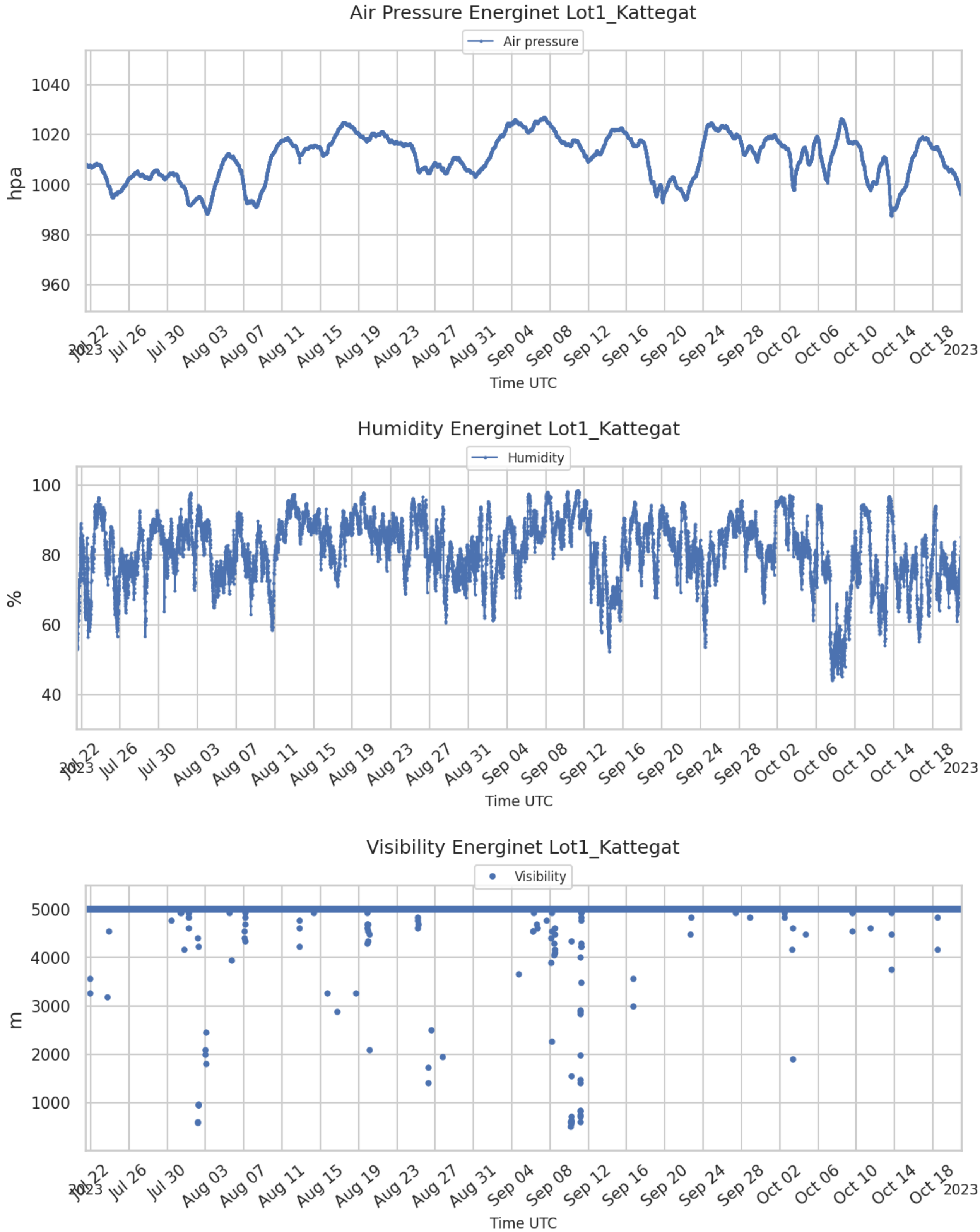


Figure B.15: Timeseries of air pressure, humidity and visibility from 21 July 2023 to 21 October 2023

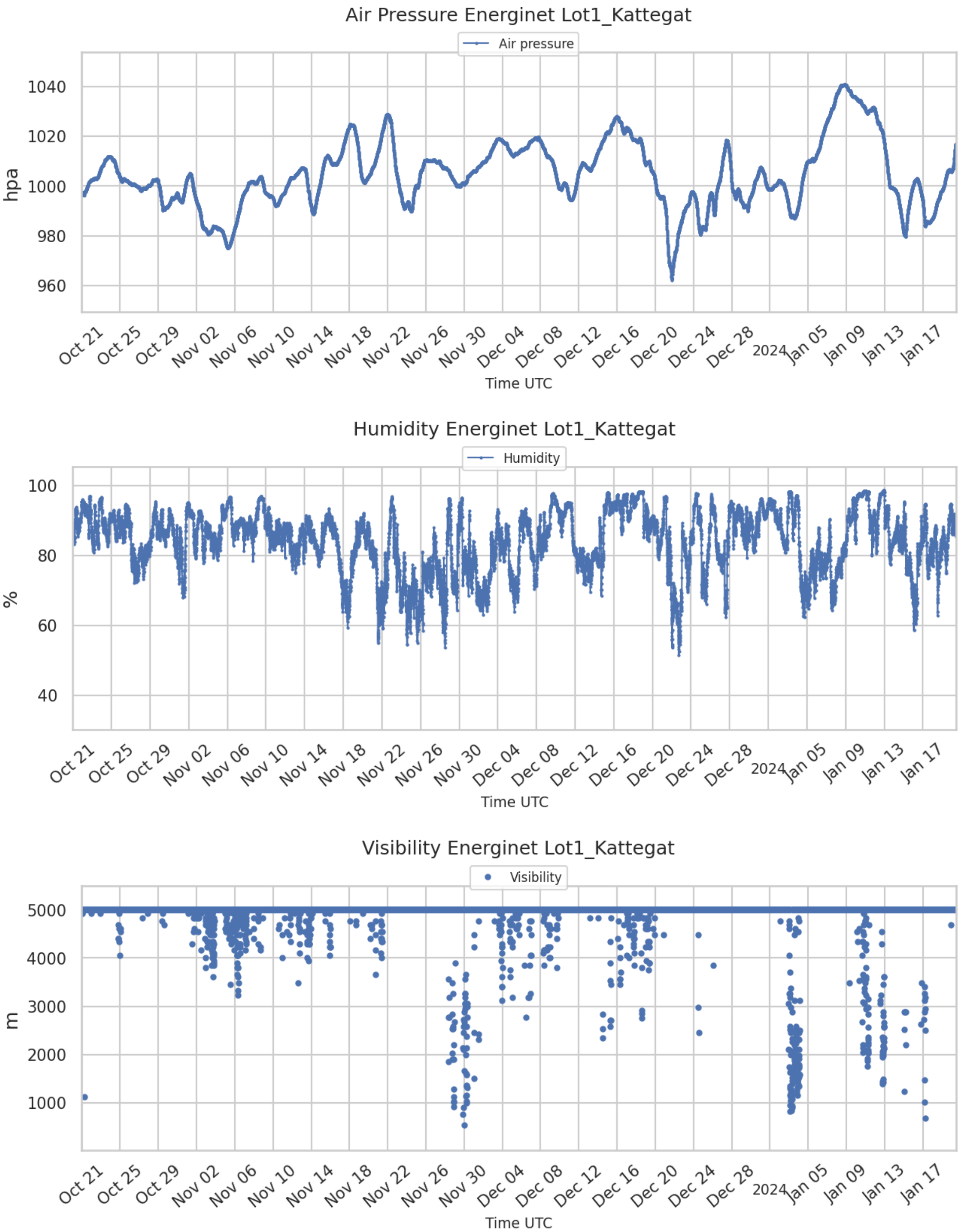


Figure B.16: Timeseries of air pressure, humidity and visibility from 21 October 2023 to 21 January 2024

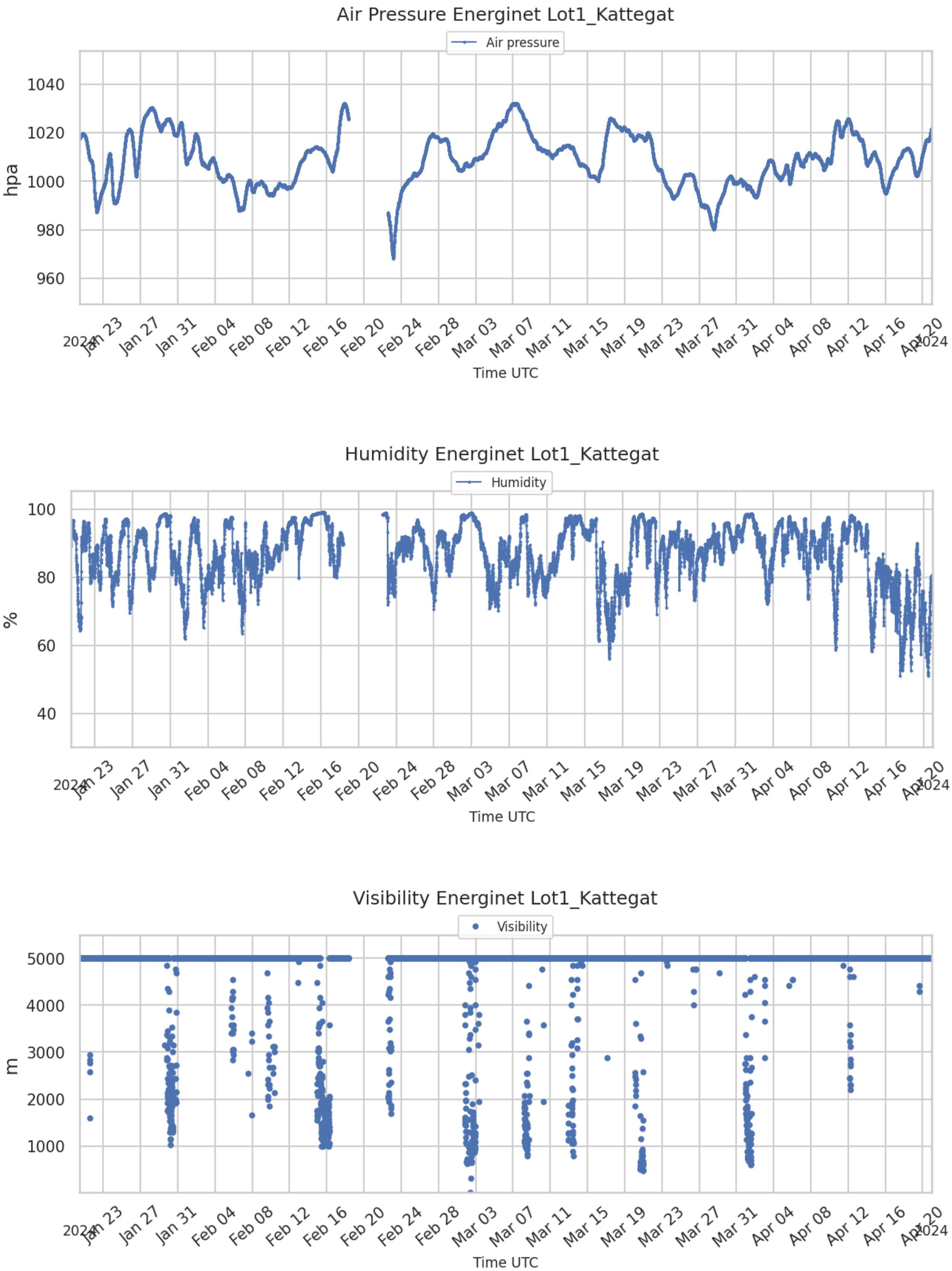


Figure B.17: Timeseries of air pressure, humidity and visibility from 21 January 2024 to 21 April 2024

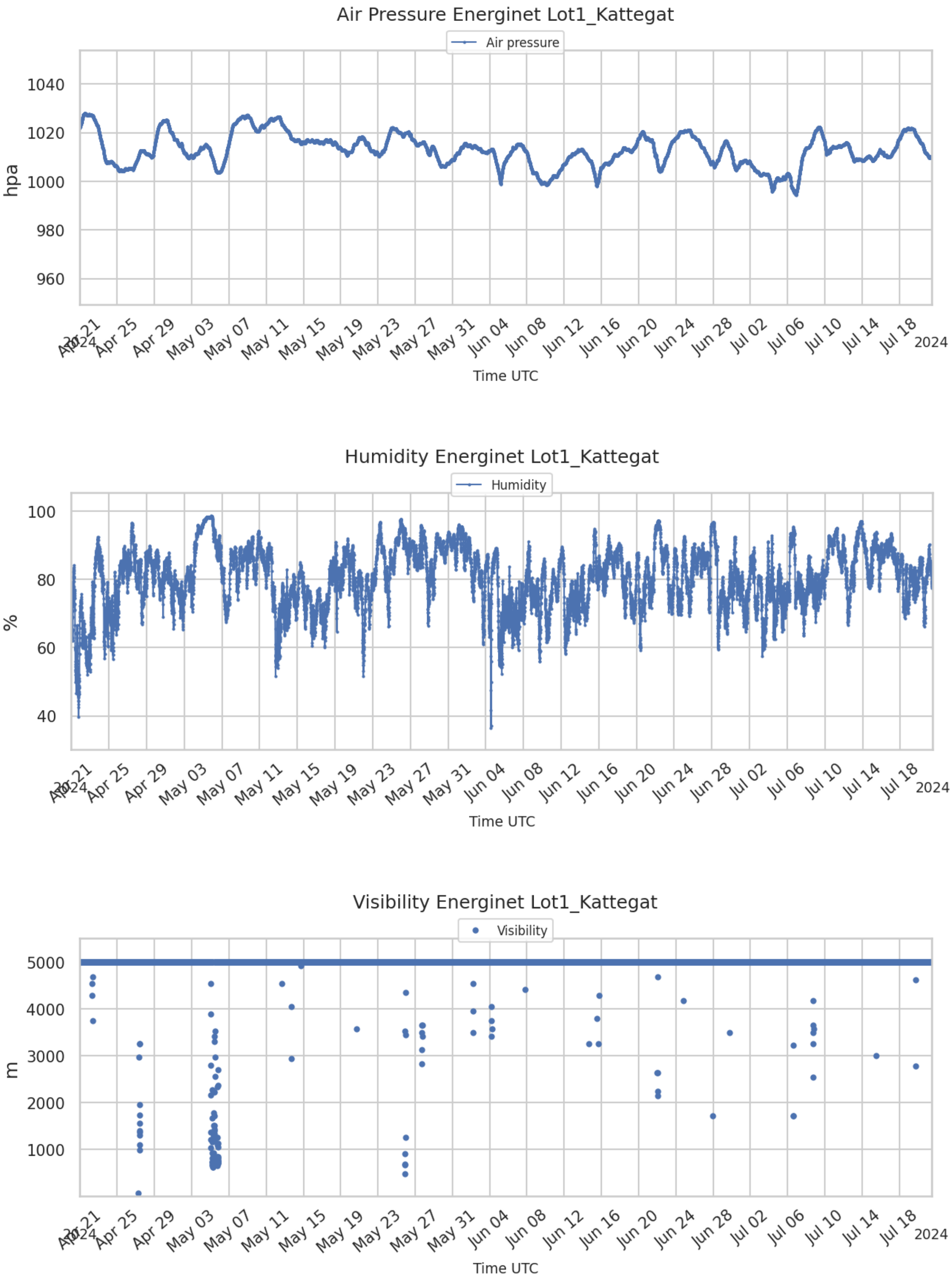


Figure B.18: Timeseries of air pressure, humidity and visibility from 21 April 2024 to 21 July 2024

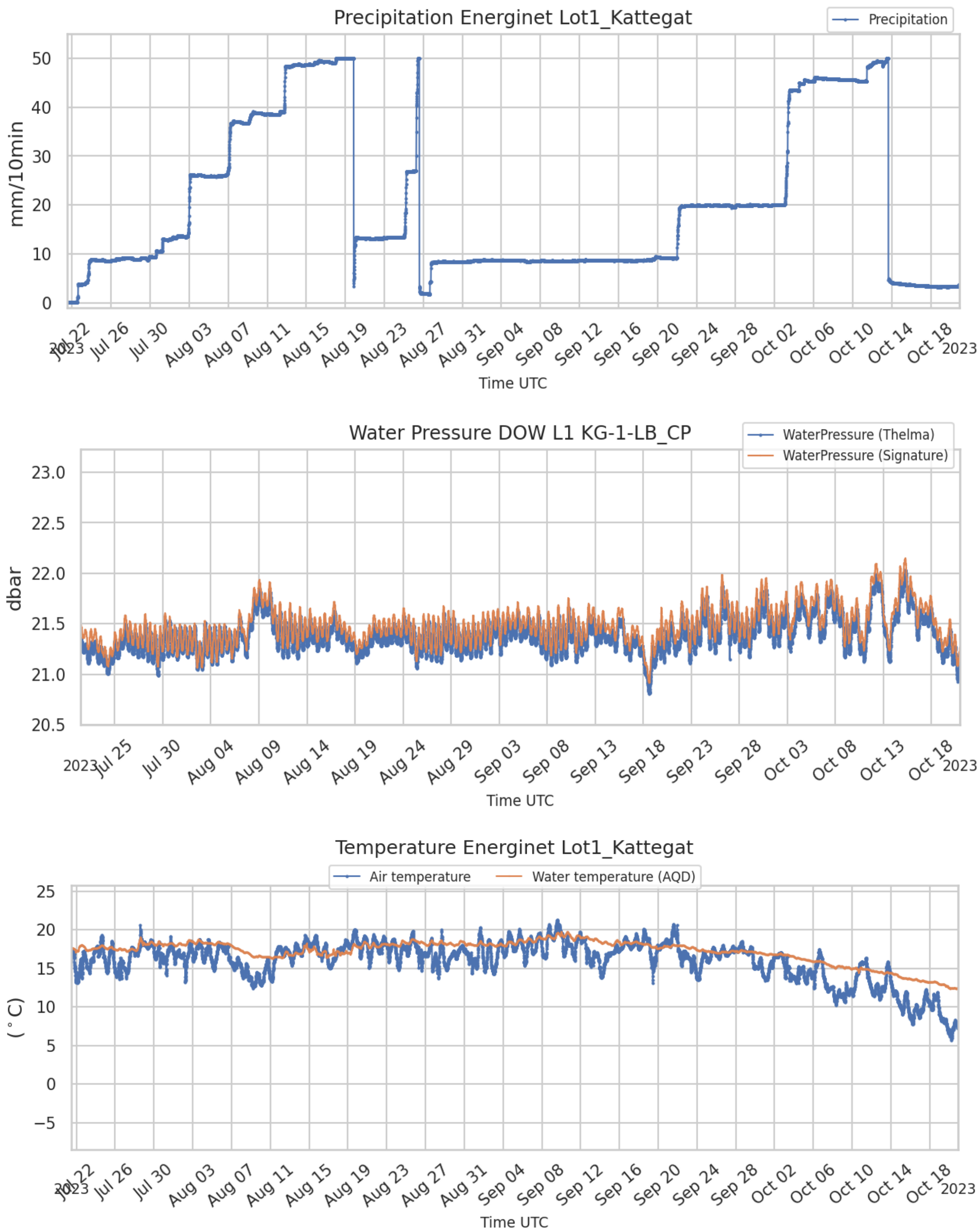


Figure B.19: Timeseries of accumulated precipitation, water pressure, air temperature and surface water temperature from 21 July 2023 to 21 October 2023

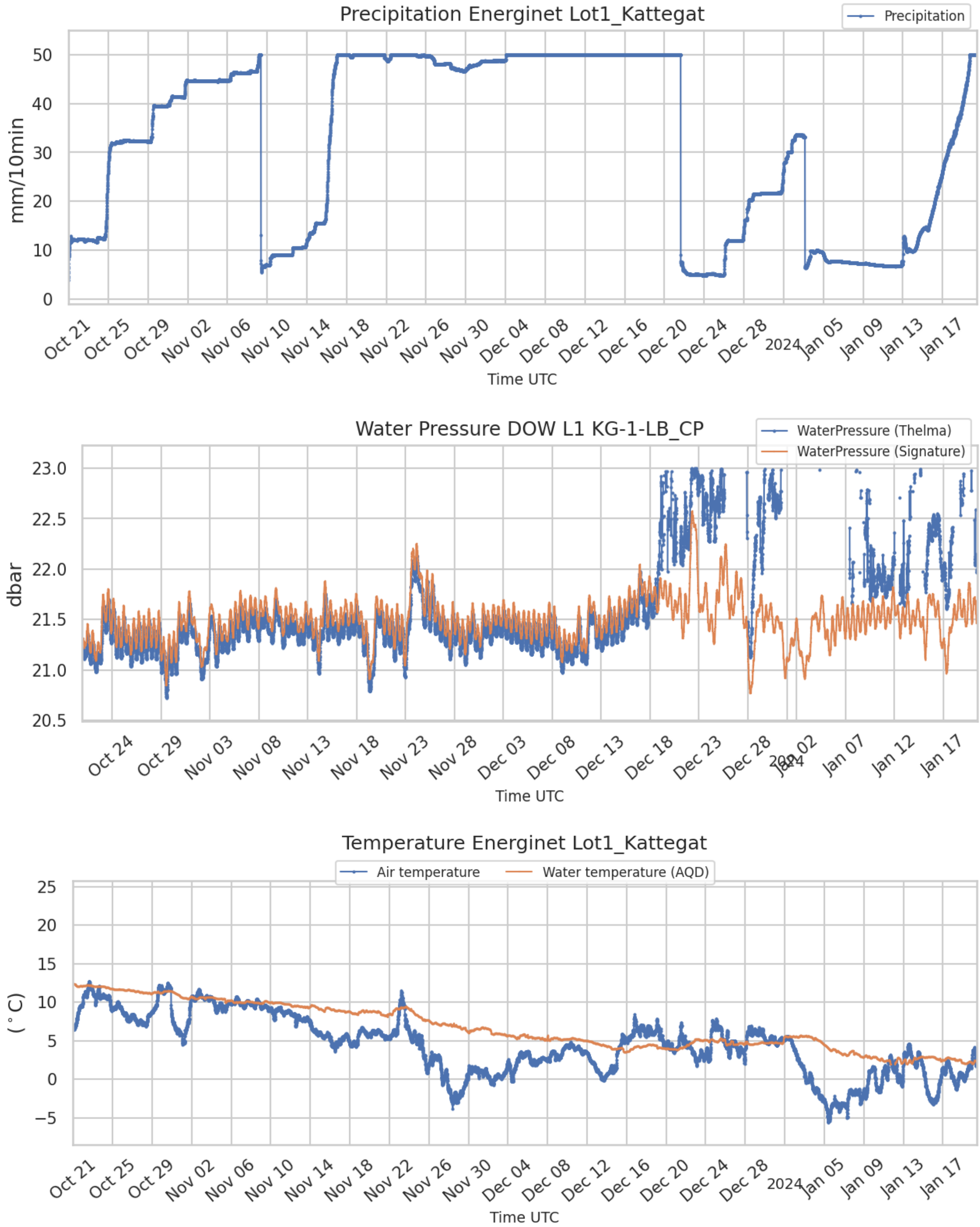


Figure B.20: Timeseries of accumulated precipitation, water pressure, air temperature and surface water temperature from 21 October 2023 to 21 January 2024

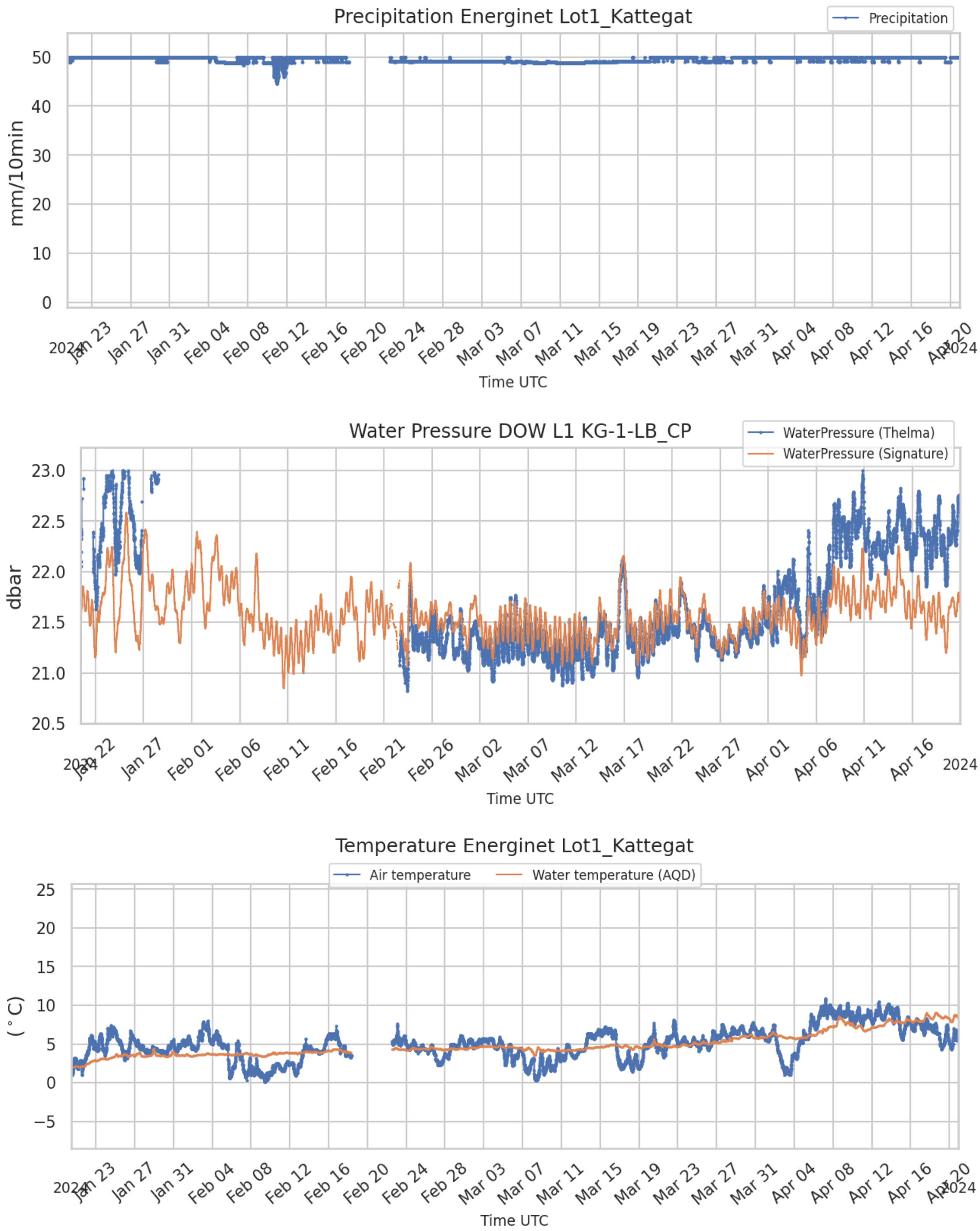


Figure B.21: Timeseries of accumulated precipitation, water pressure, air temperature and surface water temperature from 21 January 2024 to 21 April 2024

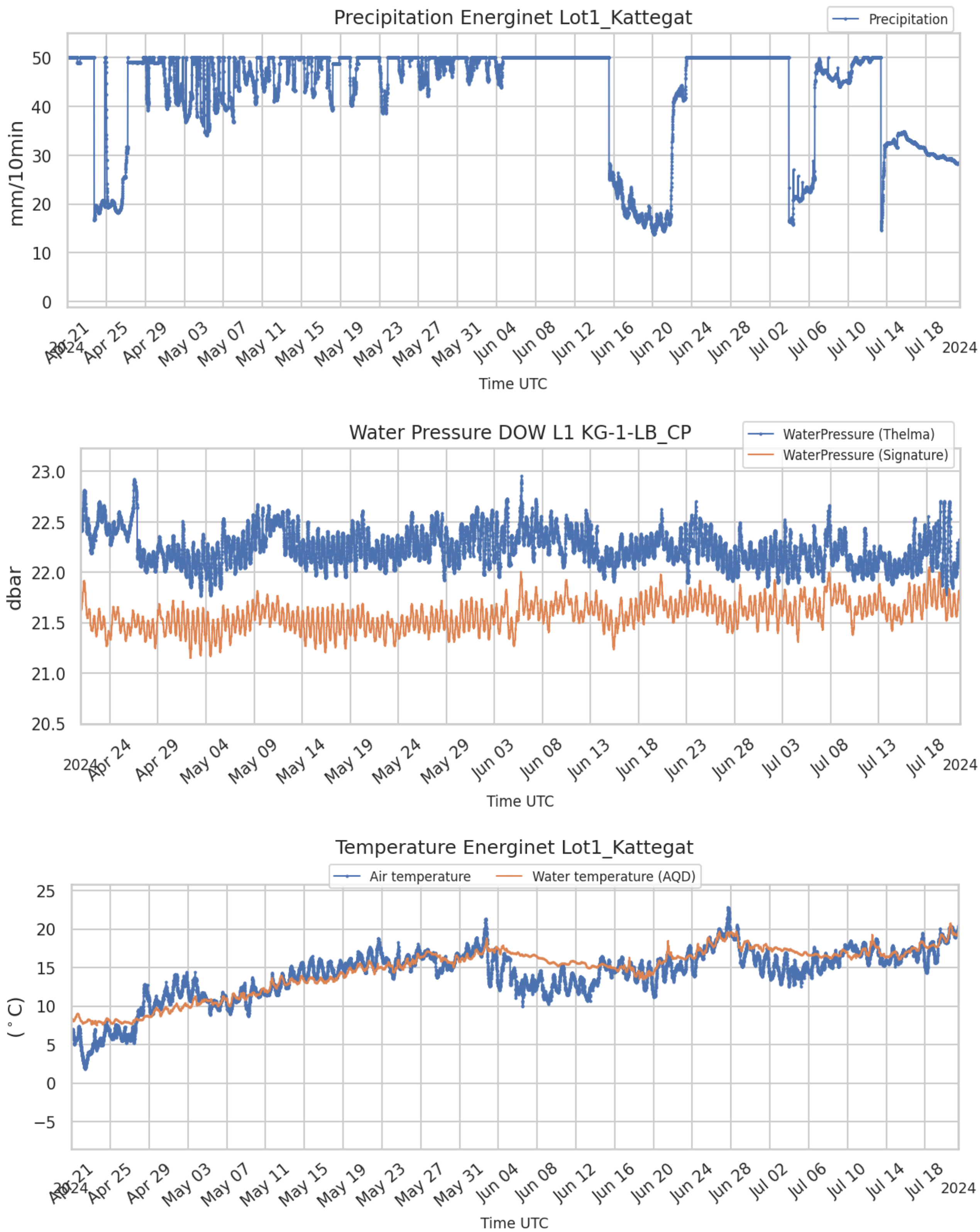


Figure B.22: Timeseries of accumulated precipitation, water pressure, air temperature and surface water temperature from 21 April 2024 to 21 July 2024

B.4 Current data (top-down)

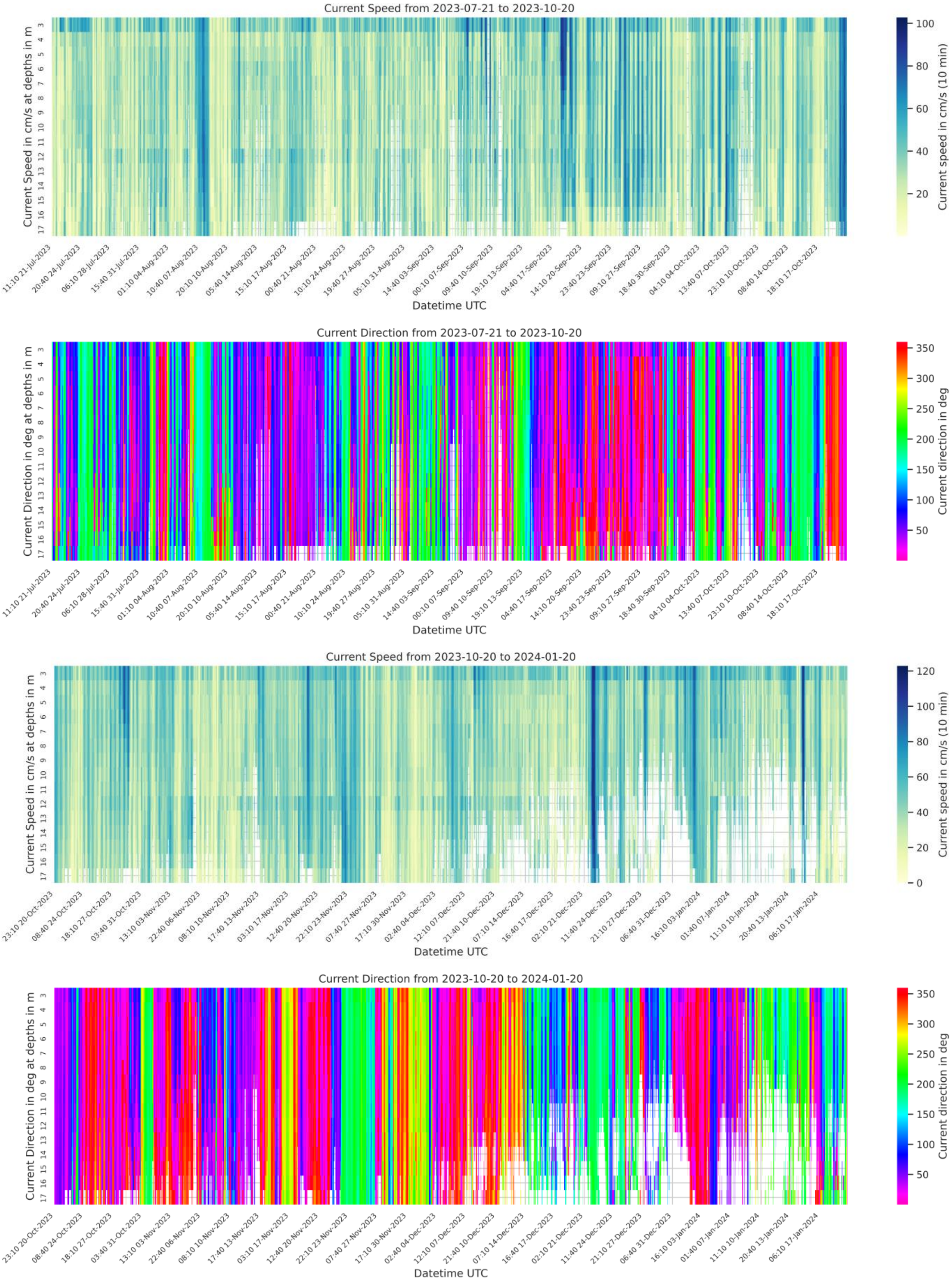


Figure B.23: Heatmaps of wind speed and direction from 21 July 2023 to 21 January 2024

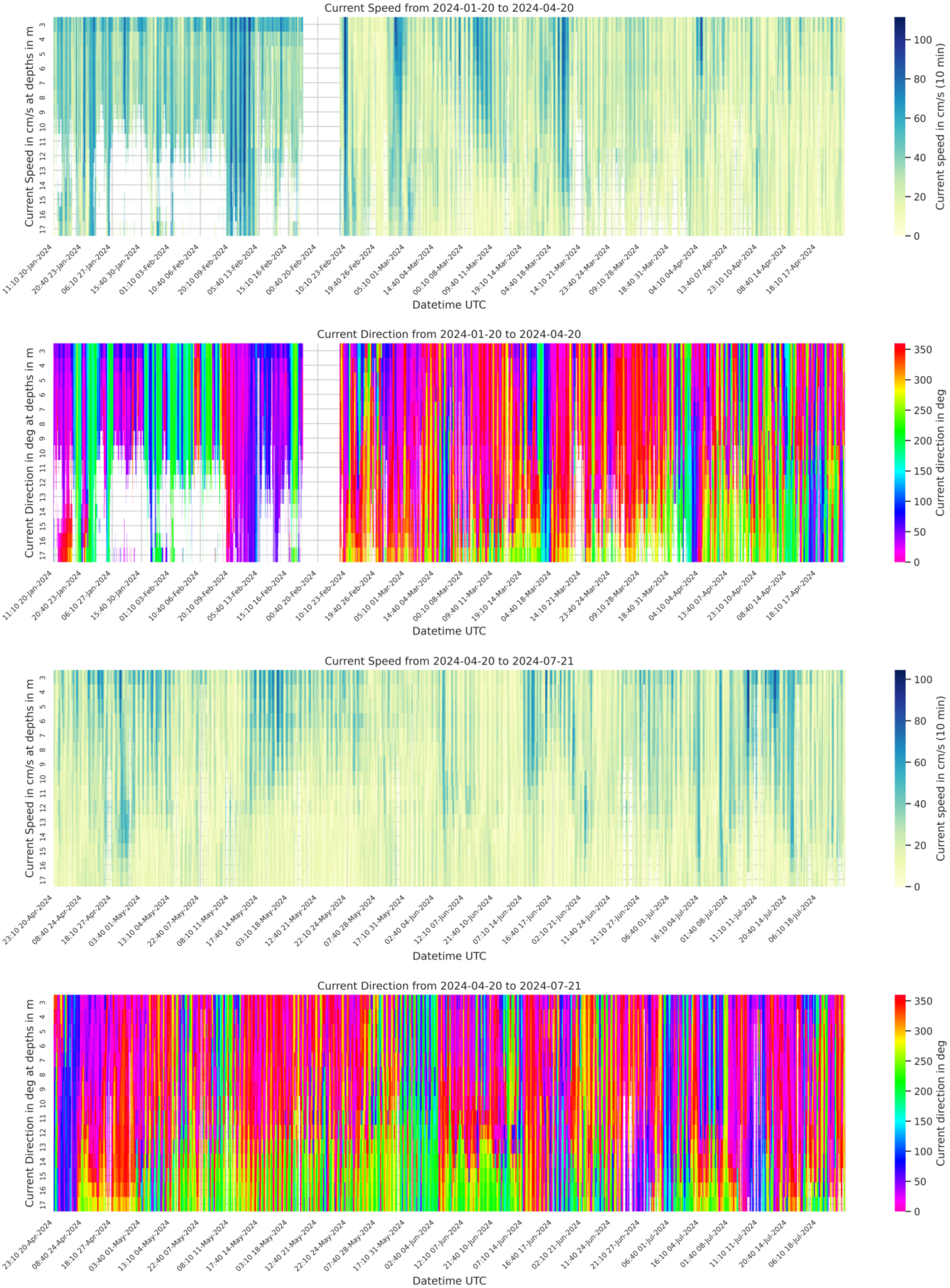


Figure B.24: Heatmaps of wind speed and direction from 21 January 2024 to 21 July 2024

B.5 Current data (upward)

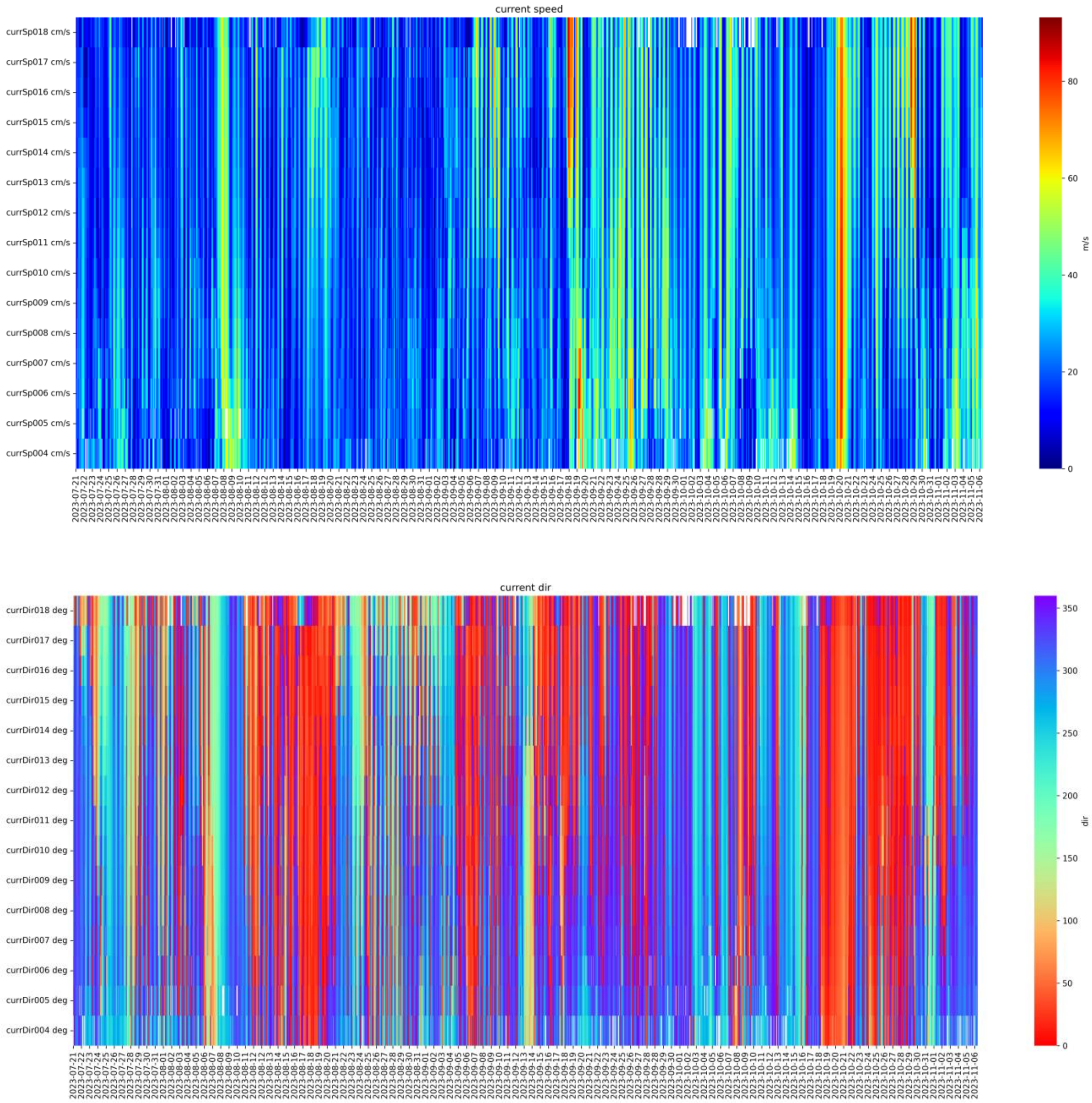
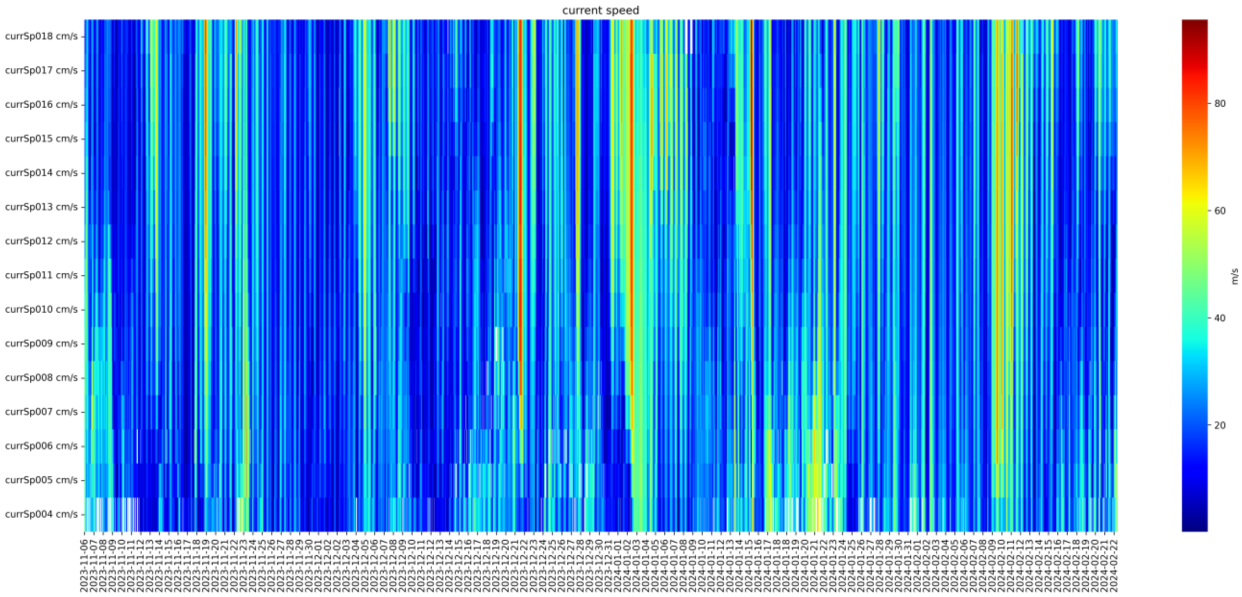


Figure B.25: Heatmap of offline (Signature)-measured bottom-up current speed and direction from 21 July 2023 until 22 February 2024 (D1) (1/2).



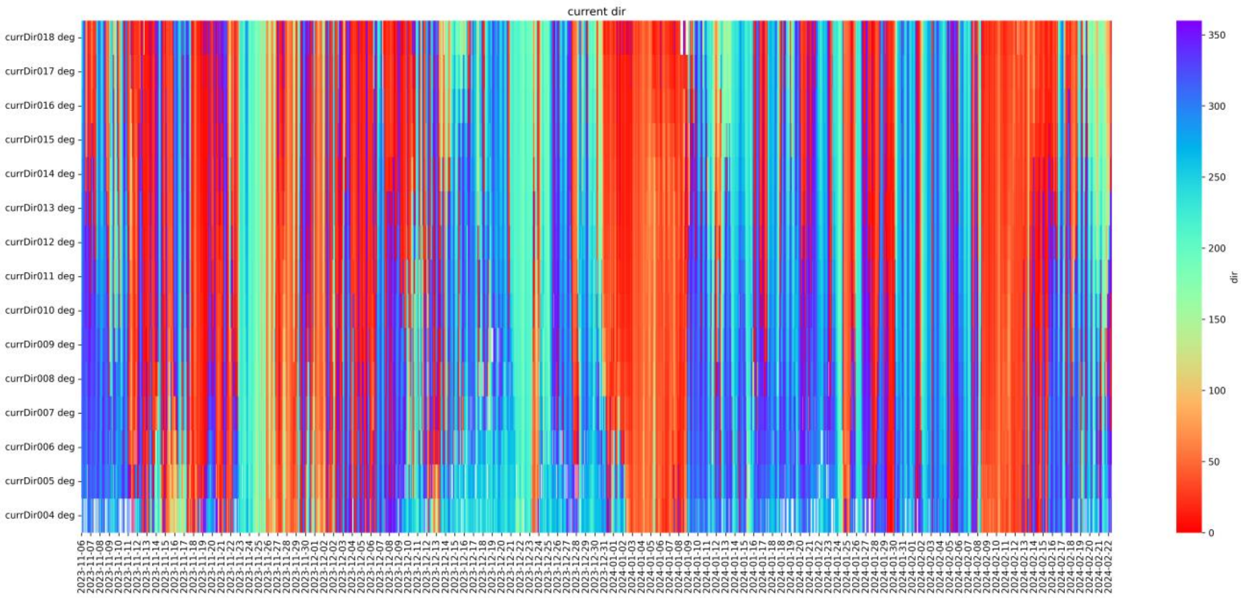


Figure B.26: Heatmap of offline (Signature)-measured bottom-up current speed and direction from 21 July 2023 until 22 February 2024 (D1) (2/2).

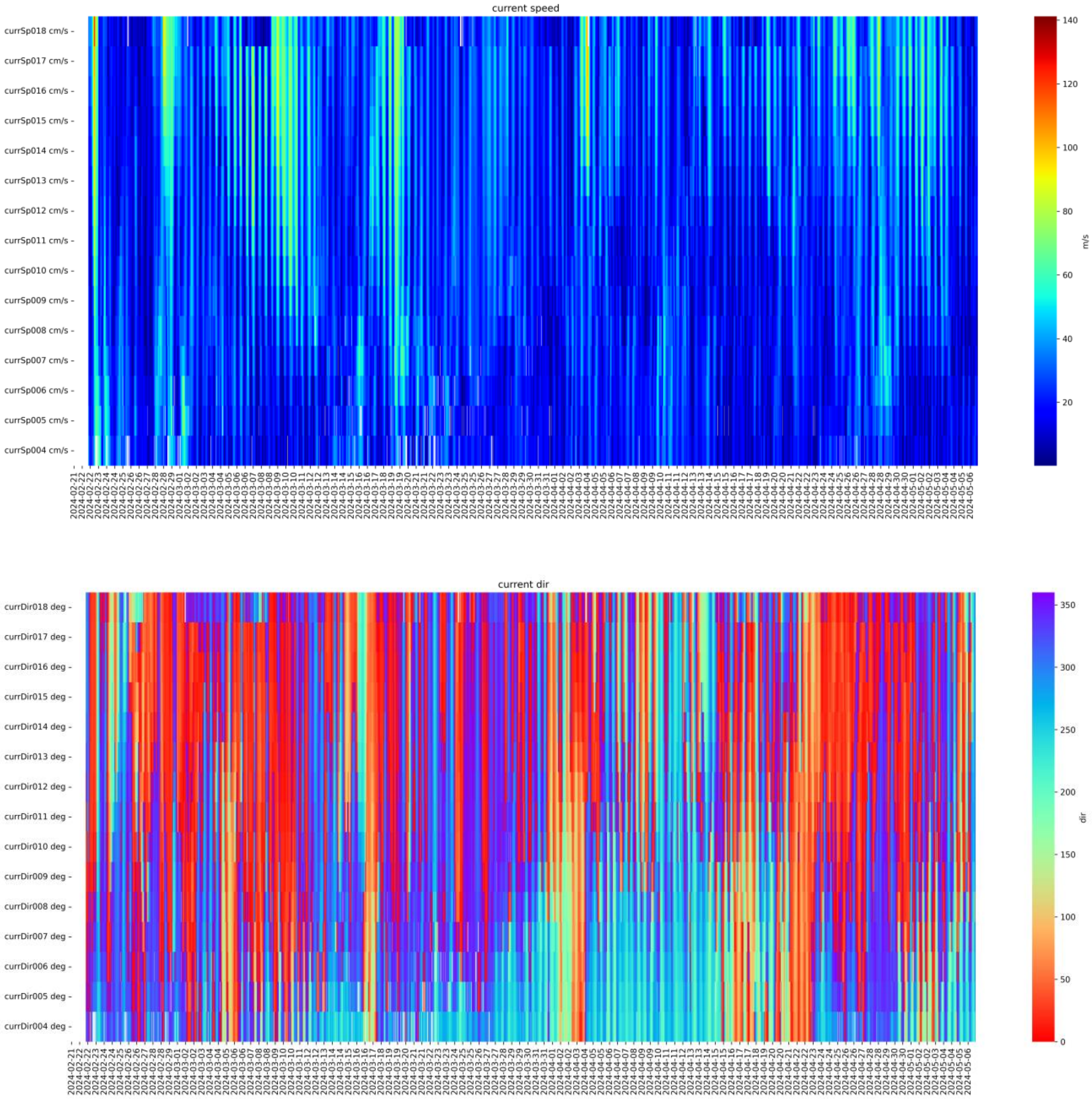


Figure B.27: Heatmap of offline (Signature)-measured bottom-up current speed and direction from 22 February 2024 until 21 July 2024 (D2) (1/2).

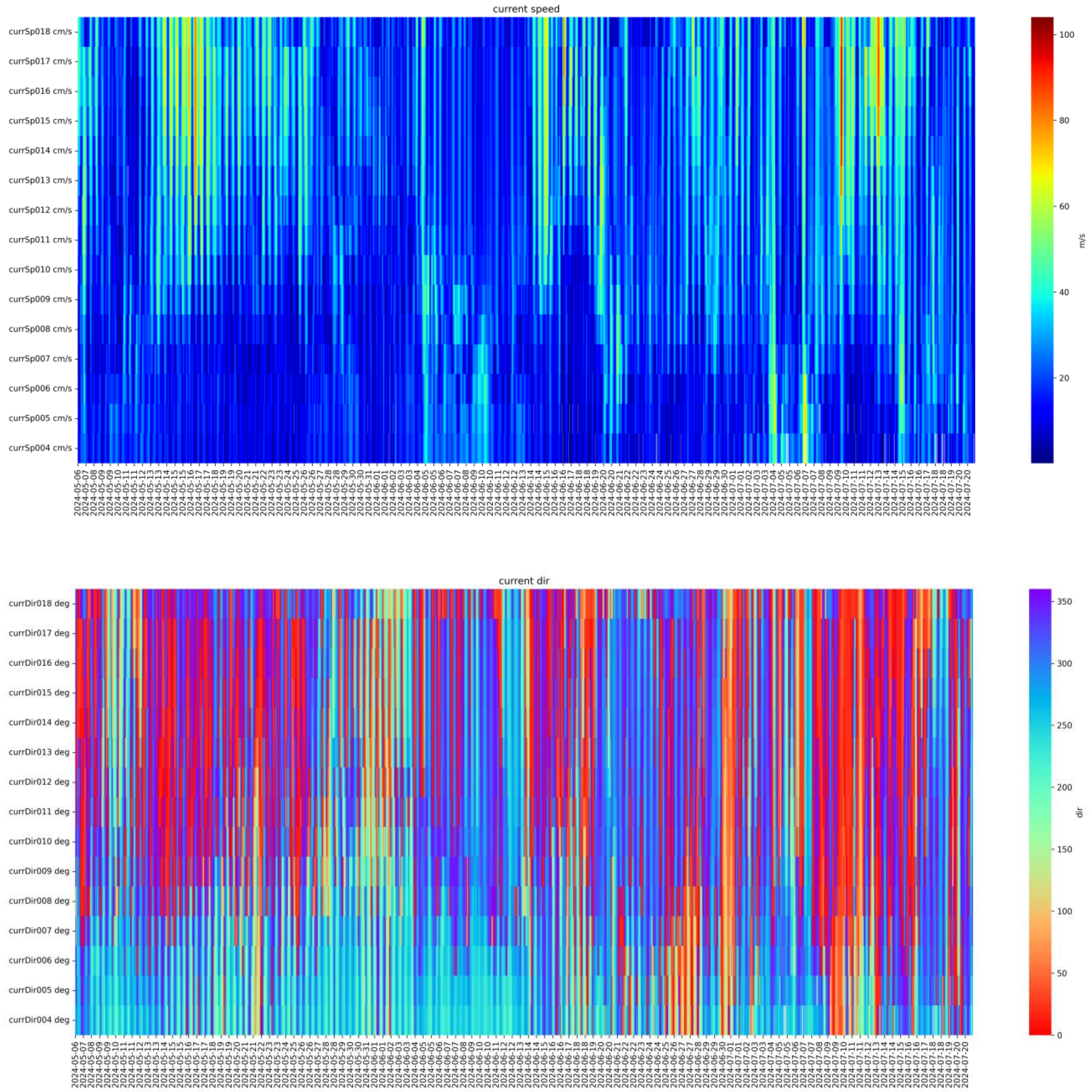


Figure B.28: Heatmap of offline (Signature)-measured bottom-up current speed and direction from 22 February 2024 until 21 July 2024 (D2) (2/2).

Appendix C

Final post-processed file contents

C.1 KG-1-LB_12M_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, ... , 017 m corresponding to measurement depth		

C.2 KG-1-LB_12M_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
pws_visibility m	m	Visibility in m
pws_WMOcode int	int	Visibility decoded
WaterTemp001 degC	°C	Aquadopp sea surface temperature
precipitation mm	mm	Accumulated precipitation

C.3 KG-1-LB_12M_Posdata.csv

Parameter	Unit	Description
spLatitude deg	°N	Latitude (position) from the Septentrio GNSS
spLongitude deg	°E	Latitude (position) from the Septentrio GNSS

C.4 KG-1-LB_12M_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**

Parameter	Unit	Description
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 KG-1-LB_12M_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	Height of the highest individual wave***
hmean m	m	Average height of individual waves***
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	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.
thmax s	s	Period of the highest wave***
thtp deg	°N	Mean wave direction at the spectral peak period
tm01 s	s	Estimate of mean wave period tz, calculated from spectral moments tm01 = m0/m1
tm02 s	s	Estimate of mean wave period tz, calculated from spectral moments $tm02 = \sqrt{(m0/m2)}$
tm02a s	s	Estimate of tm02 in a-band**
tm02b s	s	Estimate of tm02 in b-band**
tp s	s	Period of spectral peak
tz s	s	Average period of individual waves***

Parameter	Unit	Description
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 KG-1-LB_12M_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 = 12m, … , 300m corresponding to measurement height
* Turbulence Intensity (TI) is defined as: (σ/u¯) / C where σ is the standard deviation and 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 KG-1-LB_12M_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

Parameter	Unit	Description
liInfoFlagLow unknown	int	Lidar info flag low bits
liPacketCountxx	-	Number of samples for the averaging period
where xx = 12m, ... , 300m corresponding to measurement height		

C.8 KG-1-CP_D1_CurrentData_20230721_20240222.csv

Column header	Unit	Description
currSp004m_cm/s, ..., currSp018m_cm/s	cm/s	10-min averaged current speed
currDir004m_deg, ..., currDir018m_deg	°N	10-min averaged current direction
DataMask_1, ..., DataMask_15[1]	int	Data selection mask: non-zero indicates bad data value
BinMapAmp_BeamX_1, ..., BinMapAmp_BeamX_15[1]	dB	Beam amplitude (signal-to-noise ration) where X corresponds to beam number 1 through 4
BinMapCor_Beam1_1, ..., BinMapCor_Beam1_15[1]	%	Beam correlation (outgoing vs. incoming) where X corresponds to beam number 1 through 4
BinMapVel_East_1, ..., BinMapVel_East_15[1]	cm/s	East velocity
BinMapVel_North_1, ..., BinMapVel_North_15[1]	cm/s	North velocity
BinMapVel_Up1_1, ..., BinMapVel_Up1_15[1]	cm/s	Vertical velocity
BinMapVel_Up2_1, ..., 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 018m		

C.9 KG-1-CP_D2_CurrentData_20240222_20240721.csv

Column header	Unit	Description
currSp004m_cm/s, ..., currSp018m_cm/s	cm/s	10-min averaged current speed
currDir004m_deg, ..., currDir018m_deg	°N	10-min averaged current direction
DataMask_1, ..., DataMask_15[1]	int	Data selection mask: non-zero indicates bad data value
BinMapAmp_BeamX_1, ..., BinMapAmp_BeamX_15[1]	dB	Beam amplitude (signal-to-noise ration) where X corresponds to beam number 1 through 4

Column header	Unit	Description
BinMapCor_Beam1_1, ..., BinMapCor_Beam1_15[1]	%	Beam correlation (outgoing vs. incoming) where X corresponds to beam number 1 through 4
BinMapVel_East_1, ..., BinMapVel_East_15[1]	cm/s	East velocity
BinMapVel_North_1, ..., BinMapVel_North_15[1]	cm/s	North velocity
BinMapVel_Up1_1, ..., BinMapVel_Up1_15[1]	cm/s	Vertical velocity
BinMapVel_Up2_1, ..., 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 018m

C.10 KG-1-LB_CP_12M_WaterLevel.csv

Column header	Unit	Description
WaterPressure dbar	dbar	Water pressure measured from Thelma pressure transmitter
Pressure	dbar	Water pressure measured from Signature500
WaterLevel_th m	m	Water level calculated from Thelma measured pressure data
WaterLevel_sig m	m	Water level calculated from Signature measured pressure data

Appendix D

File formats and contents of the raw data files