OCEAN CURRENTS AND WATER MASS PROPERTIES INSIDE THE ANHOLT OFFSHORE WIND FARM (KATTEGAT, DENMARK)

Technical Report from DCE – Danish Centre for Environment and Energy No. 341 2025

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Christian Mohn
Marie Maar
Janus Larsen

Aarhus University, Department of Ecoscience

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Abstract:	This study investigates the complex and still insufficiently understood interactions between ocean currents and offshore wind farms (OWFs), with a focus on local-scale hydrodynamic effects near individual wind turbine foundations. Despite growing interest in the environmental impacts of OWFs, empirical field data on local-scale current dynamics within wind farms remain sparse. This technical report describes the results from a field campaign, which was conducted within the Anholt OWF in the Kattegat over a 9-day period in August 2024.
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Contents

Preface

This report contributes to the project "Environmental mapping and screening of the offshore wind potential in Denmark" initiated in 2022 by the Danish Energy Agency. The project aims to support the long-term planning of offshore wind farms by providing a comprehensive overview of the combined offshore wind potential in Denmark. It is funded under the Finance Act 2022 through the programme "Investeringer i et fortsat grønnere Danmark" (Investing in the continuing greening of Denmark). The project is carried out by NIRAS, Danish Centre for Environment and Energy (DCE) - Aarhus University and DTU Wind.

The overall project consists of four tasks defined by the Danish Energy Agency (https://ens.dk/energikilder/planlaegning-af-fremtidens-havvindmoelleparker):

1. Sensitivity mapping of nature, environmental, wind and hydrodynamic conditions.

2. Technical fine-screening and assessment of the overall offshore wind potential based on the sensitivity mapping and relevant technical parameters.

3. Assessment of potential cumulative effects from large-scale offshore wind development in Denmark and neighboring countries.

4. Assessment of barriers and potentials in relation to coexistence.

This technical report addresses one component of Task 1: sensitivity mapping. Specifically, the report provides detailed information on the hydrodynamic conditions and water mass properties within the Anholt offshore wind farm, based on 9 days of data on ocean currents, acoustic backscatter, temperature, and salinity collected from two locations—upstream and downstream of a single monopile structure. The report also presents possible applications of such measurements for use in hydrodynamic models to assess the interaction between monopile structures with the surrounding ocean. A synthesis of all topics under Task 1 will be published in 2025.

The project management teams at both AU and NIRAS have contributed to the description of the background for the report and the relation to other activities in the preface. The report and the work contained within are solely the responsibility of the authors.

Sammenfatning

I dette studie undersøger vi de komplekse og stadig utilstrækkeligt forståede interaktioner mellem havstrømme og havvindmølleparker (OWFs), med særligt fokus på hydrodynamiske effekter i nærheden af et enkelt vindmøllefundament. På trods af en stigende interesse for havvindmølleparkers miljøpåvirkning, findes der stadig kun begrænsede feltdata for strømforhold i lokal skala. Denne tekniske rapport præsenterer resultaterne fra en feltkampagne, der blev gennemført i Anholt Havvindmøllepark i Kattegat over en 9-dages periode i august 2024. Kampagnen anvendte højopløselige målinger af strømhastighed, akustisk backscatter, temperatur og salinitet ved hjælp af Acoustic Doppler Current Profilers (ADCP'er) og CT-sensorer (konduktivitet og temperatur), placeret både opstrøms og nedstrøms for et møllefundament. Undersøgelsen er motiveret af behovet for at kalibrere og validere hydrodynamiske modeller, som simulerer strømforhold, turbulens og lagdeling i OWF-miljøer. Målingerne viste, at vindpåvirkning i høj grad var den dominerende drivkraft bag de observerede variationer i vandmassernes egenskaber og strømforhold, hvilket gjorde det vanskeligt at isolere virkninger, der specifikt skyldes møllen. Dog viste data fra nedstrøms stationen tydelige tegn på et vedvarende grænselag nær havbunden samt øget akustisk backscatter, hvilket indikerer øget turbulens eller sedimenttransport. Selvom måleperioden var relativt kort, blev et bredt spektrum af fysiske processer registreret (vind og tidevandsdrevne strømninger og variationer i temperatur og salinitet), hvilket understreger værdien af lokale datasæt til validering og forbedring af numeriske modeller. Set fra et modelleringsperspektiv viste sammenligninger med resultater fra en hydrodynamisk model (FlexSem) god overensstemmelse mellem simulerede og målte strømforhold – især når modellerne inkluderede en parameterisering af modstand fra monopælen. Vi konkluderer, at kortvarige feltkampagner, selvom de er informative, ikke er tilstrækkelige til at beskrive den fulde variation i OWFs påvirkninger. Derfor anbefaler vi længerevarende overvågning, brug af tættere netværk af ADCP’er samt supplerende målinger fra skib ved hjælp af skibsbaseret (VM) ADCP’er og CTD-systemer (ledningsevne, temperatur og dybde).

Summary

This study investigates the complex and still insufficiently understood interactions between ocean currents and offshore wind farms (OWFs), with a focus on local-scale hydrodynamic effects near individual wind turbine foundations. Despite growing interest in the environmental impacts of OWFs, empirical field data on local-scale current dynamics within wind farms remain sparse. This technical report describes the results from a field campaign, which was conducted within the Anholt OWF in the Kattegat over a 9-day period in August 2024. The field campaign employed high-resolution measurements of current velocity, acoustic backscatter, temperature, and salinity using Acoustic Doppler Current Profilers (ADCPs) and CT (Conductivity, Temperature) sensors placed upstream and downstream of an OWF monopile. The study was motivated by the need to calibrate and validate hydrodynamic models that simulate flow dynamics, vertical mixing, and stratification in OWF environments. The measurements showed that wind forcing dominated the observed variations in water mass properties and currents, complicating efforts to isolate turbine-induced effects. However, data collected downstream of the monopile revealed notable a persistent near-bottom shear layer, alongside enhanced acoustic backscatter suggesting enhanced turbulence or sediment transport. Despite the brief sampling time window, the observations captured a broad range of physical processes (e.g., wind and tide driven currents and episodic variations in the temperature and salinity record), demonstrating the potential of such local area datasets for validating and refining numerical models. From a modelling perspective, comparisons with results from a hydrodynamic flume model (FlexSem) showed good agreement between simulated and measured flow characteristics, particularly when incorporating monopile drag parameterizations. We conclude that short-term campaigns, while informative, are insufficient for capturing the full variability of OWF impacts. Therefore, we recommend longer-term monitoring, the deployment of denser ADCP arrays, and complementary ship-based surveys using vessel mounted (VM) ADCPs and CTD (Conductivity, Temperature, Depth) systems.

1 Introduction and background

Increasing demand for sustainable offshore wind energy production requires new installations and the expansion of the current offshore energy infrastructure in Danish and European waters. Such installations add new knowledge gaps and unknowns to our understanding of small-scale to larger scale interactions of water currents and offshore energy structures. We investigated the small-scale and short-term variability of ocean currents and water mass properties (T, S) to develop a better understanding of mixing processes and ocean dynamics in the vicinity of an individual turbine and to investigate the potential of such measurements to be included in hydrodynamic models.

The wind wake effect of offshore wind farms has been reported to affect the hydrodynamical conditions in the surrounding ocean with knock-on effects on biogeochemical cycling and marine primary production. This is especially important in seasonally stratified shelf seas, where water density can strongly vary with depth. However, until recently only little is known about the ecosystem response to OWF wind wakes (Daewel et al. 2022; Dorrell et al. 2022). Recent modelling studies have suggested that large-scale development of offshore wind can affect hydrodynamics - not only within the parks, but also regionally (Cazenave et al. 2016; Christiansen et al. 2022; Daewel et al. 2022). Cazenave et al. (2016) and Daewel et al. (2022) reported enhanced vertical mixing and decreased seasonal stratification near offshore wind turbines in the North Sea. These local phenomena have been suggested to propagate well beyond the OWF and to introduce additional small-scale variability into the surrounding ocean (Cazenave et al. 2016; Christiansen et al. 2022).

Possible processes in the water column include development and propagation of downstream wakes and enhanced vertical mixing. This can lead to changes in stratification, altering the vertical and horizontal distribution of temperature, salinity nutrients, oxygen and suspended matter, as well as sedimentary organic carbon with possible consequences for biology and ecology (Daewel et al. 2022; Heinatz and Scheffold 2023). The magnitude of this mixing and the spatial scale of downstream wakes and other phenomena, in addition to natural background processes, have yet to be fully quantified in the field. In-situ field studies might help us estimate the scale and magnitude of these local-scale processes and improve the predictive skill and capacity of hydrodynamic models. To assess local-scale processes and flow phenomena, a pilot field study was conceived as part of the project 'Strategisk screening og vurdering af havvindspotentialet' (Strategic screening and assessment of the offshore wind potential) funded by the Danish Energy Agency. Continuous measurements of ocean currents, acoustic backscatter and water mass properties (T, S) were conducted inside the Anholt OWF (Kattegat, Denmark) over a period of 9 days to obtain time series of water currents and water mass properties at high temporal and vertical resolution.

2 Methods

2.1 Study area

Data were collected inside the Anholt OWF (Kattegat, Denmark). It is currently one of the largest OWFs world-wide (111 wind turbines, 400 MW total capacity) and is located between Djursland, at the east coast of Jutland, and the island of Anholt in the Kattegat (Figure 1). Water currents at the Anholt site are characterized by a dominant northward current with highest magnitudes of 0.4 m/s and little variability throughout the year based on an assessment of CMEMS data (Copernicus Marine Monitoring Service) prior to the field campaign. This setting made the Anholt OWF the most suitable site to investigate possible interactions between OWF structures and the surrounding water currents, when compared to more variable conditions and weaker currents at other OWF sites in inner Danish waters.

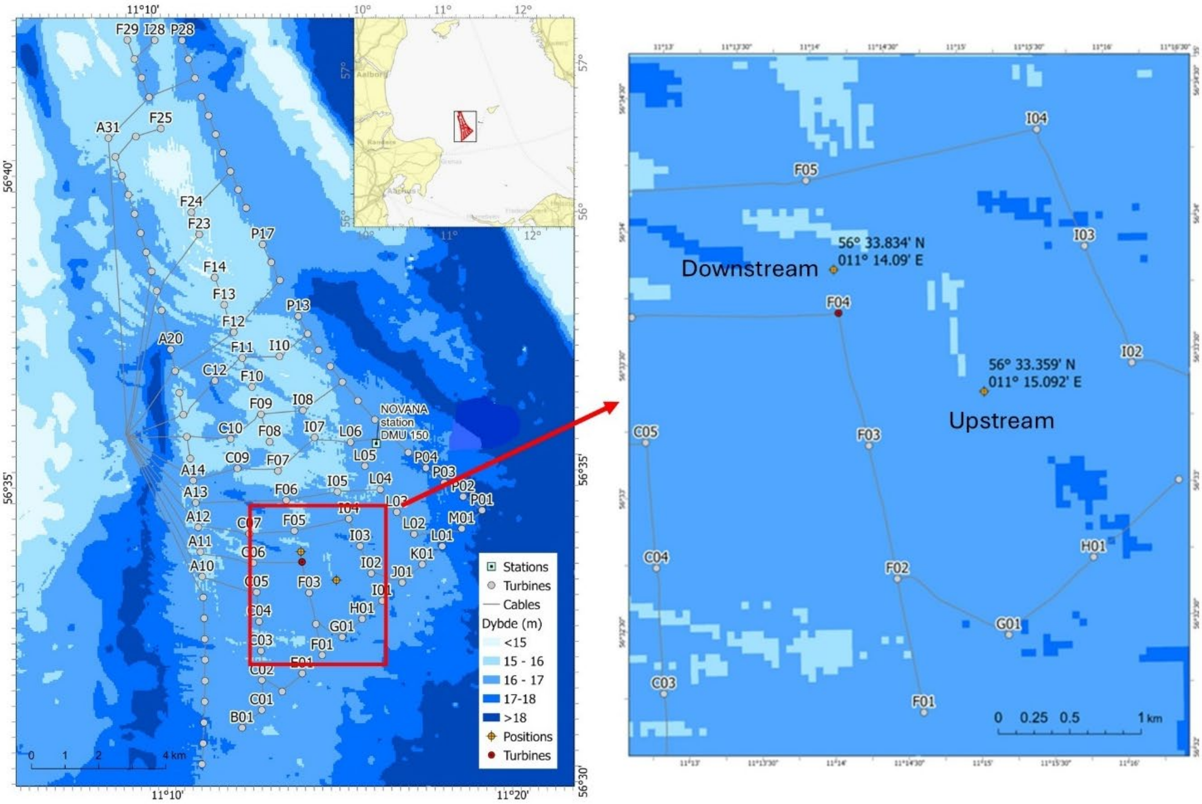


Figure 1. The wider Anholt OWF area is shown on the left panel. The permanent NOVANA monitoring station DMU150 is located inside the OWF but not discussed in the report. Locations of ADCP moorings upstream and downstream of monopile F04 inside the Anholt OWF are shown on the right panel.

2.2 Survey design and sampling techniques

The placement of the measurement stations was guided by several practical and methodological constraints. Firstly, to capture realistic flow dynamics and stratification conditions, it was essential that both stations were located inside the wind farm, rather than outside, where background conditions might differ significantly. Secondly, a mandatory safety distance of at least 200 meters from submarine power cables limited the options for instrument deployment, particularly in terms of aligning stations directly upstream and downstream of a single monopile. Thirdly, while the upstream station was not perfectly in line with the downstream station, it was selected to be as close to quasi-undisturbed conditions as possible within the wind farm layout, and to serve as a reference for assessing the impact of the downstream monopile. We acknowledge that this setup may include some influence from neighboring structures, but it reflects a balance between scientific objectives, safety regulations, and logistical feasibility in a complex operational environment.

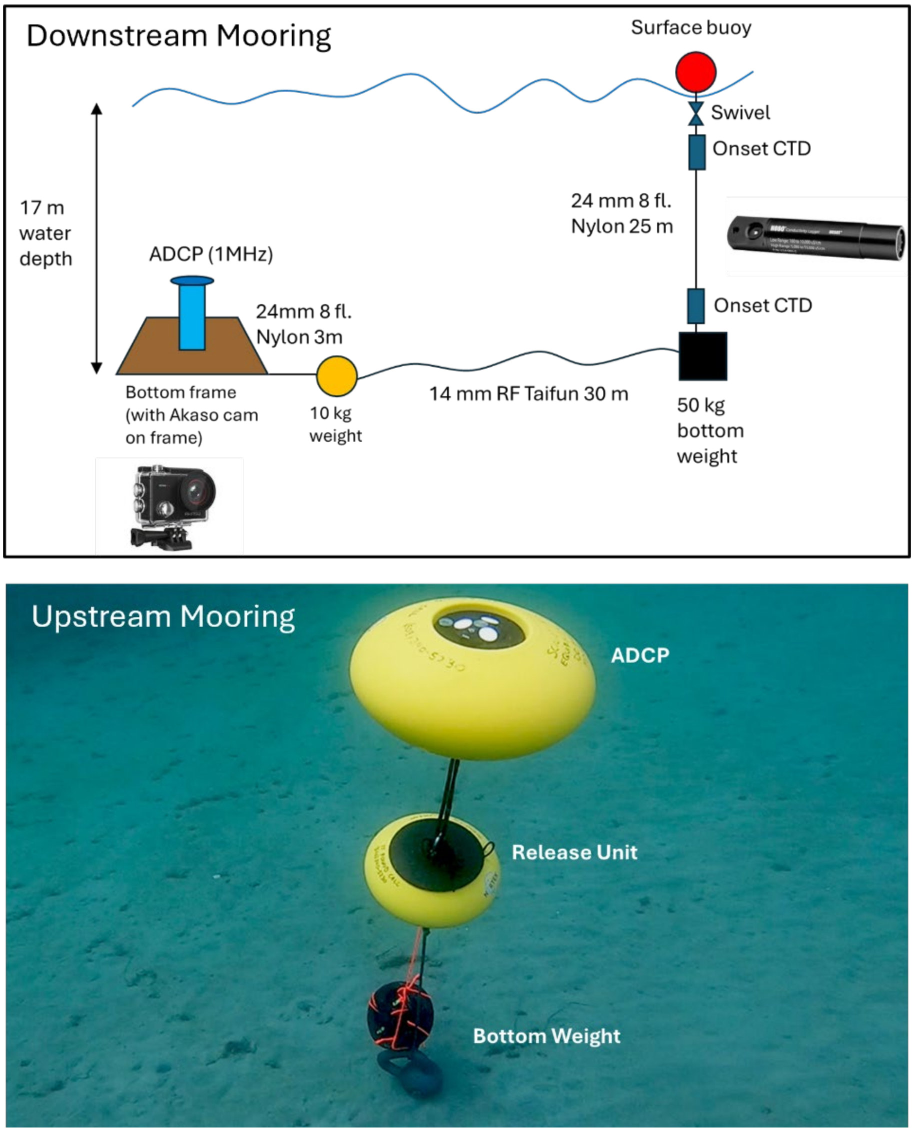


Figure 2. Mooring design and setup for deployments of bottom mounted ADCP systems upstream and downstream of an OWF monopile in the Anholt OWF (Picture of Upstream mooring shows the Nortek ECO system, https://www.nortekgroup.com/info /eco)

Two ADCPs were deployed to measure ocean currents in the water column upstream and downstream of an offshore wind turbine foundation in the Anholt OWF over a period of 9 days (turbine number F04; Figure 1). In addition, the downstream ADCP also measured acoustic backscatter (e.g. planktonic material, sediment). The ADCPs were deployed on 19 August, 2024, and recovered on 28 August, 2024 (see section 3.3 for a detailed summary of the mooring timelines and setup). ADCP data were post-processed using Nortek software provided with each instrument. Major processing steps include correcting magnetic declination and ensemble averaging. CT (Conductivity, Temperature) loggers were calibrated before deployment and outliers in the final data were removed. Post-processing of CT data also included removal of data recorded prior and after mooring deployment, as well as calculation of salinity.

The upstream mooring was set at a distance of approximately 400 m outside of the nearest monopile (and sea cables) using a Nortek ECO ADCP system. The Nortek ECO is a shallow-water current profiler that detects its own deployment depth and uses that information to split the water column above into three equal depth layers (https://www.nortekgroup.com/info/eco). It is equipped with built-in GNSS (Global Navigation Satellite System), temperature, pressure and tilt sensors. It is mounted in a top buoy and is connected to a timer release and a bottom weight. During recovery, the vessel waited at the deployment site for the submerged buoy to swim up at the pre-defined release time (Figure 2; Upstream Mooring).

The downstream mooring was deployed 200 meters away from an OWF monopile (and sea cables). Here, we used an upward-facing 1 MHz Nortek Aquadopp ADCP, which was mounted inside a bottom frame (deployment depth 16 m). Additional measurements included temperature and salinity records from two Onset HOBO conductivity loggers mounted at two different water depths (6 m and 15 m water depth respectively; Figure 2; Downstream Mooring). The two different mooring designs were applied to achieve high vertical resolution profiling at the downstream side, which was essential for capturing the small-scale, short-term downstream variability near the monopile.

Wind data at the nearest weather station *Anholt Havn* was obtained from DMI (Danish Meteorological Institute; https://www.dmi.dk/frie-data). The station Anholt Havn is located approximately 25 km northeast of the Anholt OWF.

The following tables provide an overview of instrument settings, sampling depths and sampled time intervals.

Upstream mooring:

Instrument Type	Nortek ECO ADCP, upward facing
Deployment period (local time, GMT+2)	8/19/2024, 1:00:00 PM to: 8/28/2024, 4:06:00 PM
Total Water Depth (m)	17
Instrument Depth (m)	12.8 (± 0.3)
Upper Layer Depth (m) 6.78 m	6.78
Middle Layer Depth (m)	8.91
Lower Layer Depth (m)	11.04
Temperature, Pressure	At instrument depth
Time (ensemble) interval	2 minutes

Downstream mooring:

Instrument Type	Nortek Aquadopp 1 MHz ADCP, upward facing
Deployment period (local time, GMT+2)	8/19/2024, 1:00:00 PM to: 8/28/2024, 4:06:00 PM
Total Water Depth (m)	17
Instrument Depth (m)	16.0 (± 0.15)
Bin Size (m)	0.25
Number of Bins	64
Blanking distance (m)	0.25
Temperature, Pressure	At instrument depth
Time (ensemble) interval	2 minutes
Instrument Type	HOBO Saltwater Conductivity/Salinity Data Logger, U24-002-C
Deployment period (local time, GMT+2)	8/19/2024, 1:00:00 PM to: 8/28/2024, 4:06:00 PM
Instrument Depths (m)	6, 15
Temperature, Conductivity	At instrument depths
Time interval	5 minutes

3 Results

3.1 Wind conditions

The wind conditions during the sampling period were dominated by wind from southerly directions, with wind speeds varying between 3 m/s and 25 m/s (Figure 3). Wind speeds greater than 15 m/s were recorded during two notable periods: from 22 August at 13:00 to 23 August at 23:00, and again from 24 August at 22:00 to 26 August at 15:00. During these periods, high wind speeds contributed to enhanced mixing and flow intensification in the sampling area. Between these events, wind conditions were moderate with an average wind speed of 8 m/s.

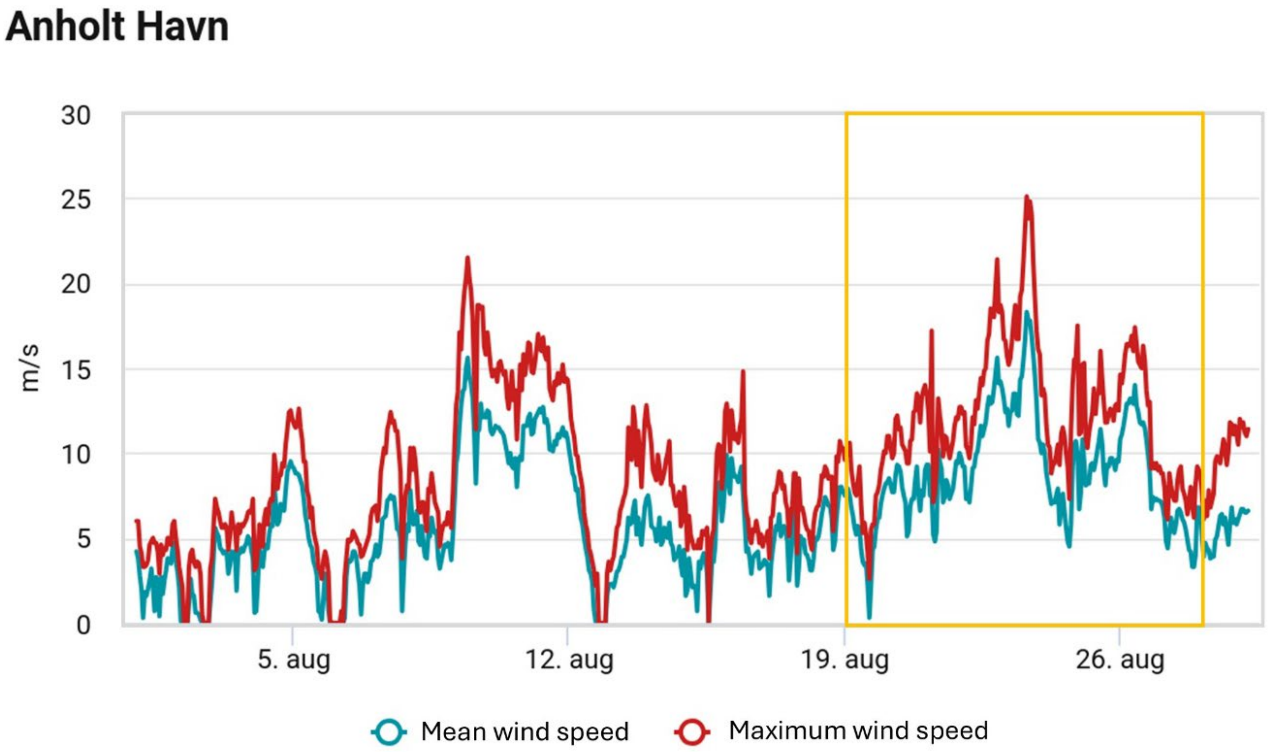


Figure 3. Wind conditions at station Anholt Havn (DMI) in August 2024. The orange rectangle highlights the wind conditions during the sampling period.

3.2 ADCP and CT measurements in the OWF

3.2.1 ADCP surveys

Instantaneous horizontal currents were estimated using the time-averaged 2-minute ensembles of the horizontal velocity components, u (positive east, m/s) and v (positive north, m/s). The resulting time series are presented as stick plots at three distinct depth levels. Data are shown every 40 minutes for clarity (every 20th data point), along with hourly mean and maximum wind speeds, as shown in Figure 4. Corresponding rose diagrams, using all ADCP data at 2-minute ensemble intervals, are presented in Figure 5.

In general, currents at both locations showed uniform direction and magnitude from the surface down to 11 meters, with minimal vertical shear observed throughout most of the sampling period. The predominant flow direction was northward, with a brief flow reversal occurring only once during the observation period (Figures 4 and 5). Variations in current magnitude were largely influenced by wind forcing, modulated by semi-diurnal tidal oscillations. The strongest instantaneous currents, reaching up to 0.86 m/s, were observed during a 2-day period of maximum wind speeds of 25 m/s (Figure 4), while the average current velocity over the 9-day sampling period was 0.32 m/s. The rose diagrams in Figure 5 illustrate the predominantly northward orientation of currents in the near-surface layers (6.75 m, 9 m, 11 m) at both sampling sites, however, with a noticeable tendency for westward veering of near-surface currents at the downstream site (see Figure 5 for clarity).

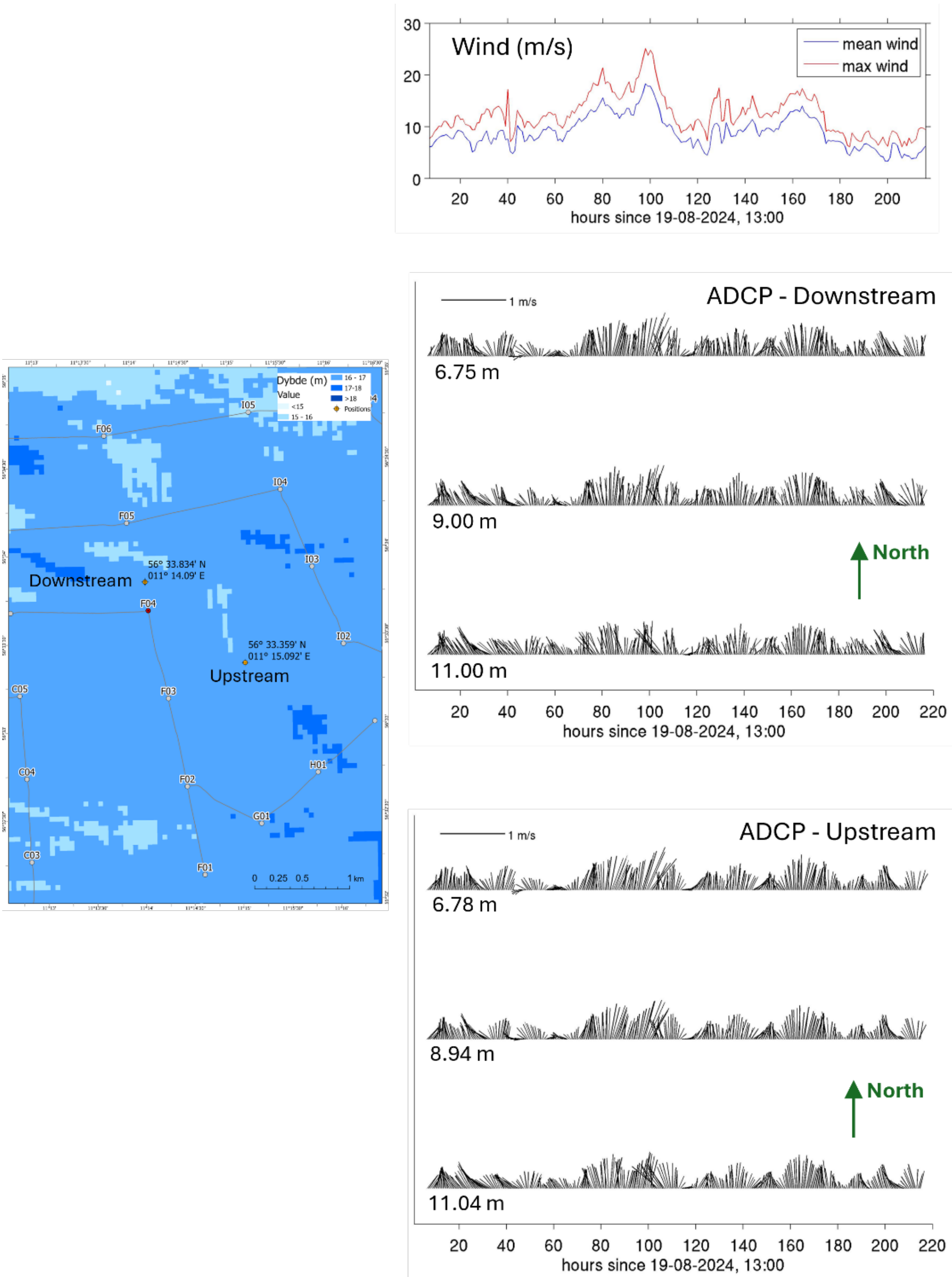
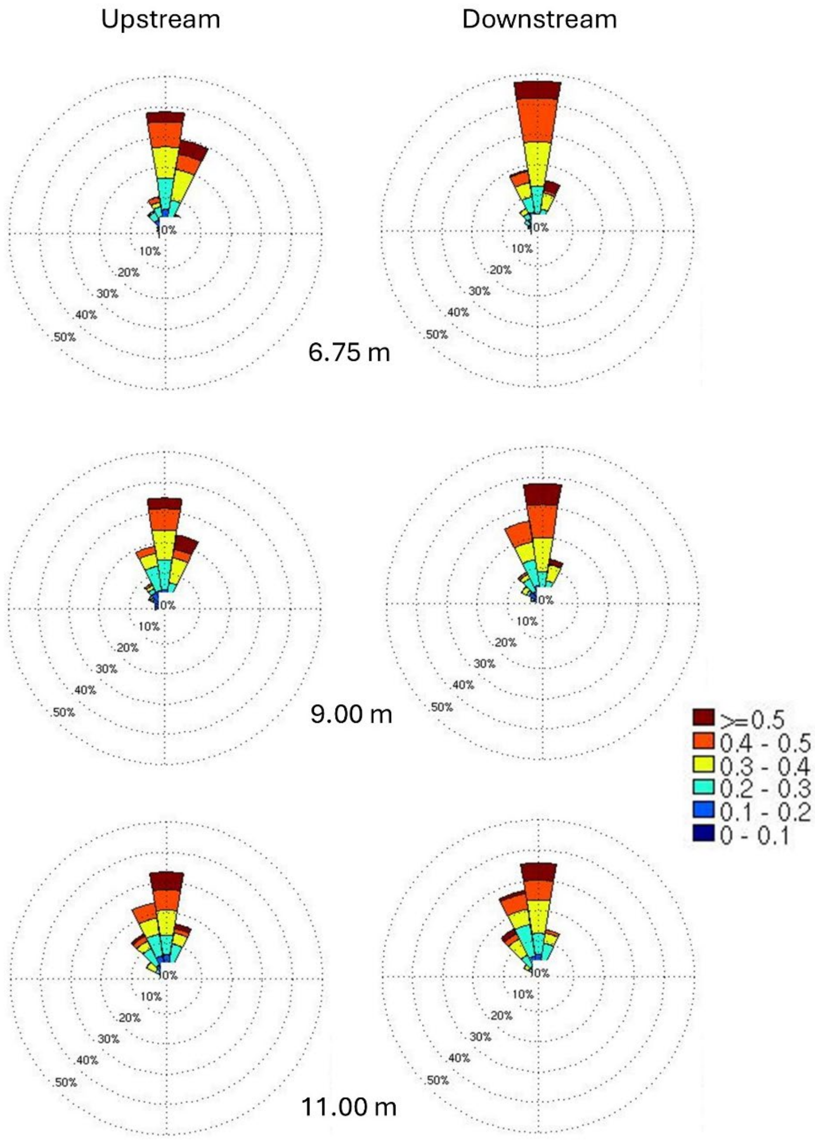


Figure 4. Time series of mean and maximum wind speeds (top, data from DMI; https://www.dmi.dk/friedata/observationer), along with stick plots of ADCP currents (every 20th data point is shown corresponding to 40-minute intervals) at three depth layers measured by the ADCPs on the upstream (lower panel) and downstream side (middle panel) of monopile F04´.

Figure 5. Rose diagrams of instantaneous ADCP currents at three upstream and downstream sampling depths. Colours indicate current velocity (m/s), percentage values representing the fraction of records in each velocity band



3.2.2 Temperature and salinity measurements

Temperature time series were collected at both ADCP survey sites from the ADCP's built-in temperature sensors at each instrument deployment depth. In addition, temperature and salinity time series were obtained at two specific water depths (6 m, 15 m) at the Anholt OWF downstream site. These measurements were obtained using HOBO saltwater loggers, which were positioned on a rope 20 meters away from the ADCP lander and anchored with a bottom weight for stability.

Across all monitoring locations and depths, the temperature data showed a gradual temperature decrease of approximately 1°C over the course of the survey period (Figure 6). At the upstream site (Figure 6, blue curve), a strong and sudden temperature decrease was recorded at 13 meters depth, where the temperature dropped from 19°C to 15°C in response to the onset of the peak wind event between August 22 at 13:00 and August 23 at 23:00. This sudden decrease suggests strong wind-induced vertical mixing throughout the entire water column. Post-storm temperature values reached pre-storm values within a few hours after the end of the mixing period.

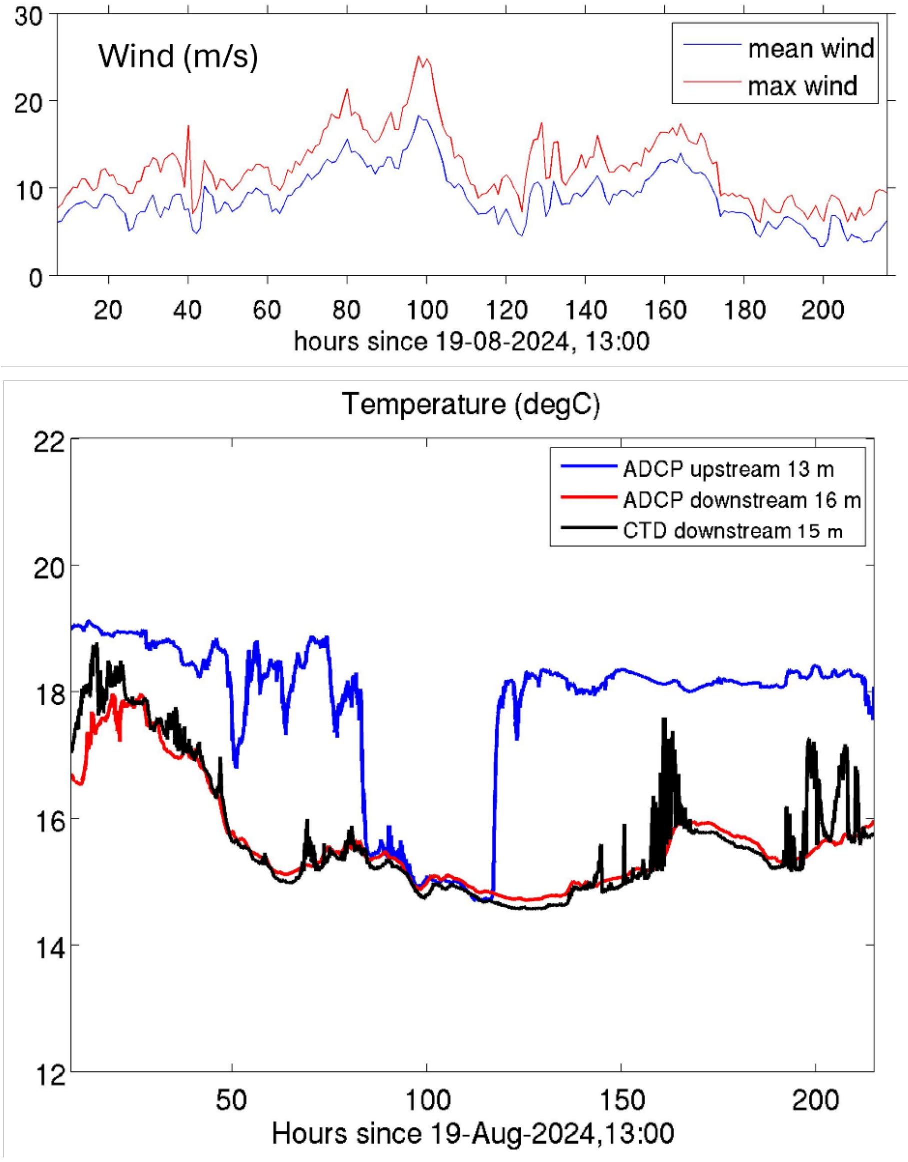
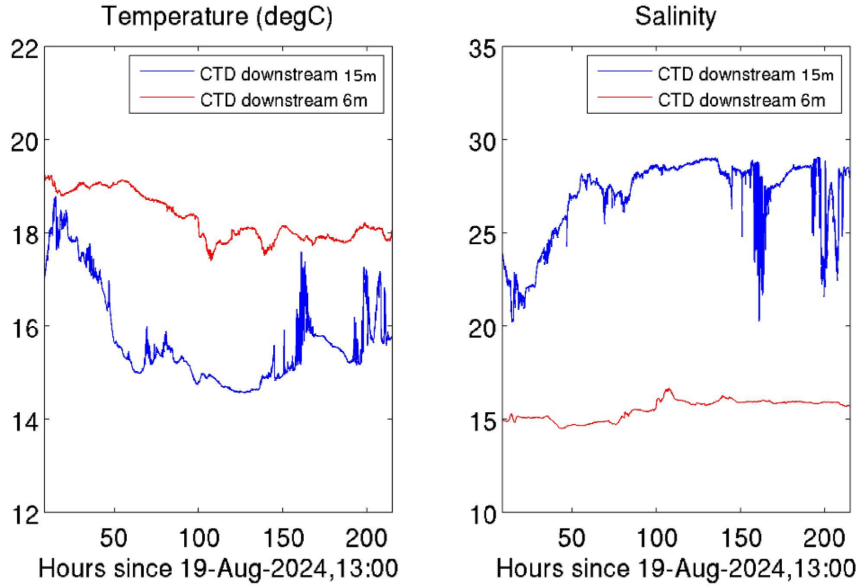


Figure 6. Time series of near-bottom temperature records at the upstream and downstream deployment sites. Please note that the downstream HOBO CT data were collected at some distance (approx. 20 m) from the downstream ADCP position.

A similar mixing event, though with a slower response, was observed at the downstream site at the onset of the storm period (Figure 6, black and red curves). At 15 m and 16 m depth temperatures dropped by 3°C over the course of the storm event (Figure 6). Unlike at the upstream site, however, temperature values at the downstream site (at both 15 m 16 m water depth) did not return to their pre-storm levels after the storm event had finished. Post-storm maximum temperatures in the deeper layers remained below 16°C, indicating that the storm-induced mixing had a longer-lasting effect on the thermal structure, preventing full recovery to pre-storm conditions.

Figure 7. Time series of near-bottom and near-surface temperature records at the downstream deployment sites from HOBO CT measurements. Please note that the downstream HOBO CT data were collected at some distance (approx. 20 m) from the downstream ADCP position



CT measurements at the downstream site reveal a post-storm increase in the difference between near-surface and near-bottom values for both temperature and salinity. The temperature difference increased from about 1.5 °C before the storm to as high as 3 °C afterward. Similarly, salinity differences increased from 6 to 12, primarily caused by an increase in bottom salinity from 21 to 27, resulting in significantly stronger stratification (Figure 7). Additionally, the CT temperature and salinity data showed episodic (lasting several hours) mixing or advection events that led to occasional and short-lived warming and freshening in the near-bottom layers (Figure 7). In summary, The CT data indicates a different response to wind-driven mixing between the upstream and downstream sampling sites, with a longer lasting effect on the thermal structure of the water column at the downstream site.

3.2.3 A high-resolution ADCP survey at the downstream OWF site

The time series of ADCP measurements at the downstream site of the monopile are presented in Figure 8 and 9 for the horizontal velocity components u (eastward positive), v (northward positive) and relative acoustic backscatter. The velocity components, measured in meters per second (m/s), and relative acoustic backscatter, measured in decibels (dB), were recorded in 0.25-meter depth intervals within the upper 16 meters of the water column at 2-minute intervals between August 19 and August 28, 2024. During the entire sampling period, the velocity field in the upper 13 meters was dominated by relatively steady northward currents, with maximum velocities reaching 0.8 m/s (Figure 8 a, b; Figure 9). These currents were mainly influenced by wind forcing and modulated by semidiurnal tidal fluctuations. The flow in this upper layer showed near-barotropic characteristics, indicating minimal variation in current velocity and direction with depth. However, as depth increased towards the seafloor, the currents weakened considerably and changed direction towards the Northwest. The strongest current velocities were recorded during periods of peak wind activity, which also coincided with enhanced mixing and increased acoustic backscatter intensity, indicative of greater particle suspension or turbulence (Figure 8 c). Notably, the near-bottom shear in the velocity field, which developed between 13 and 16 m water depth, remained a consistent and stable feature throughout the sampling period (Figure 9).

Figure 8. Time series of vertical profiles of the u (East-West, eastward positive) and v (North-South, northward positive) velocity components (a, b) and relative acoustic backscatter (rbs) as measured by the 1 MHz Nortek Aquadopp profiling ADCP at the OWF downstream site. The vertical bin size is 0.25 m and the original temporal resolution is 2 minutes (40 minute intervals are shown here).

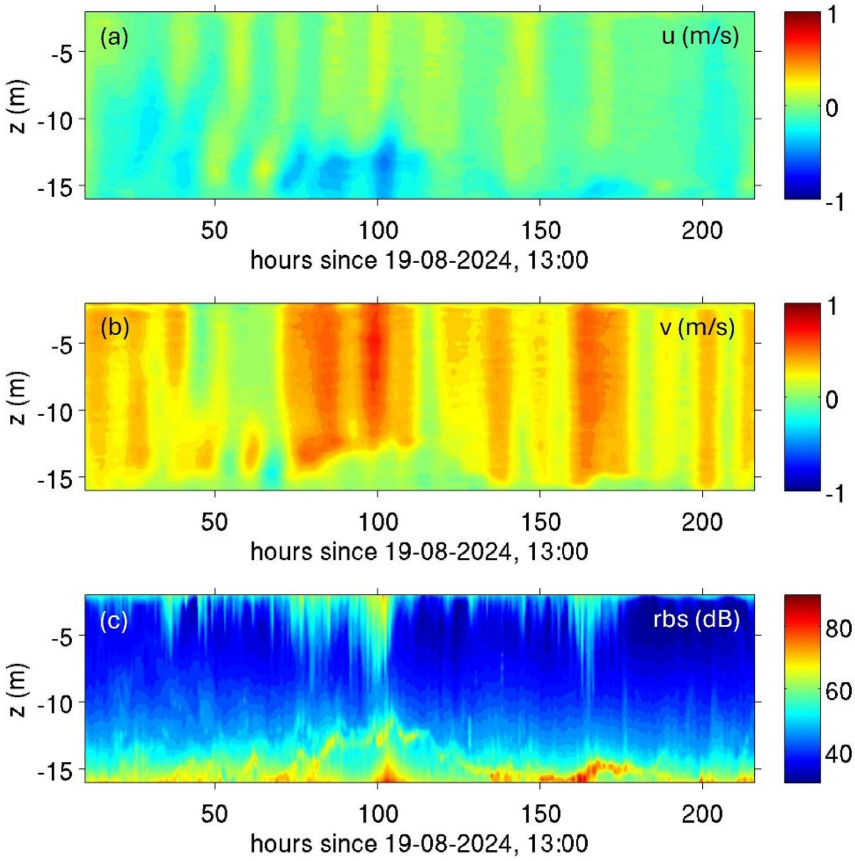
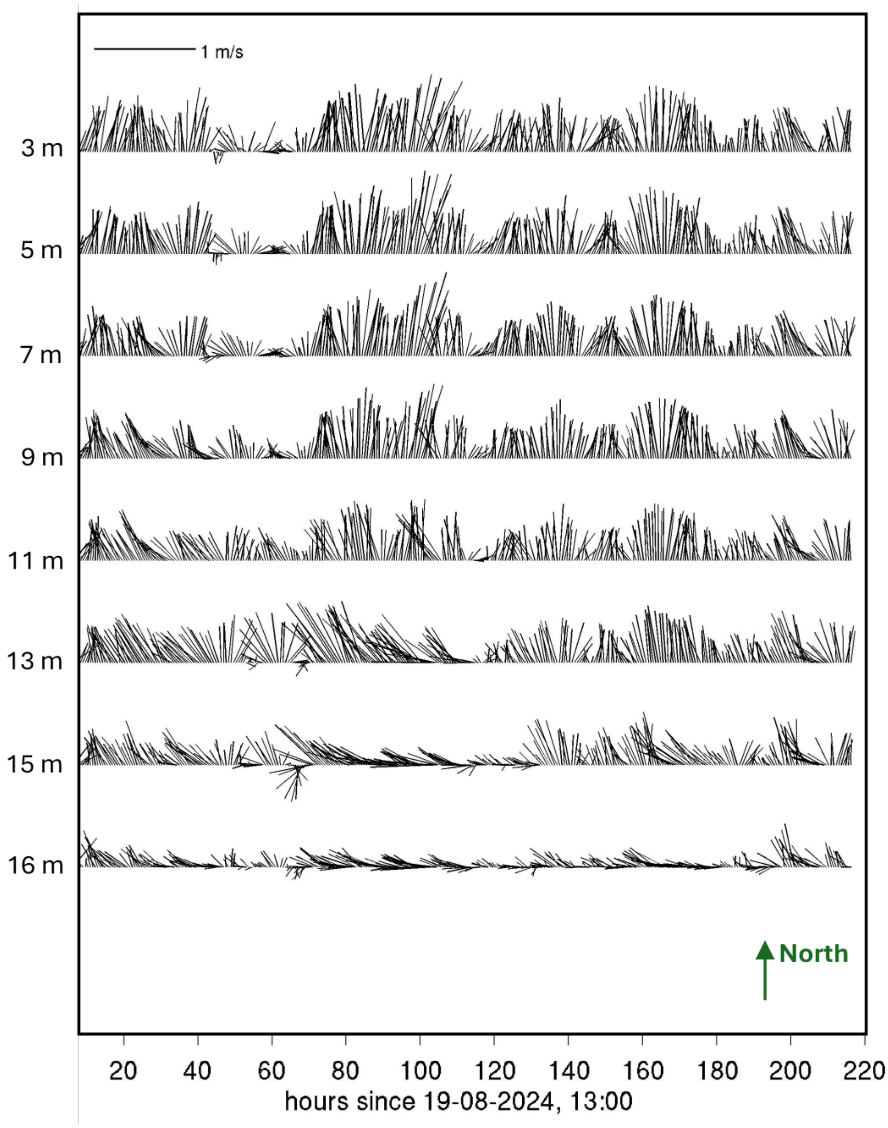


Figure 9. Stick plots of instantaneous ADCP currents (every 20th data point is shown corresponding to 40-minute intervals) at selected water depths sampled by the 1 MHz Nortek Aquadopp ADCP at the OWF downstream site.



4 Summary and key results

- Response to wind-driven mixing events caused episodic changes in temperature and salinity, but without recovery to pre-storm conditions at the downstream site.
- Current measurements showed predominantly northward flow with little vertical variation at both the upstream and downstream site.
- A consistent and stable near-bottom shear layer was detected at the downstream site with enhanced backscatter intensity and changes in current magnitude and direction in the bottom-most layer.

Upstream mooring site	**Downstream mooring site**
Barotropic currents, generally northward in the upper 13 m, mainly influenced by wind forcing and semi-diurnal tides.	• Barotropic currents, generally northward in the upper 13 m, mainly influenced by wind forcing and semi-diurnal tides. • Decrease of current speed and change to westward directions at depths > 13 m. • Development of a consistent and stable shear layer throughout the sampling period at water depths > 13 m.
Minimum current speeds: • 0.049 m/s (6.75 m) • 0.047 m/s (9.00 m) • 0.042 m/s (11.00 m)	Minimum current speeds: • 0.057 m/s (6.75 m) • 0.100 m/s (9.00 m) • 0.068 m/s (11.00 m)
Maximum current speeds: • 0.76 m/s (6.75 m) • 0.73 m/s (9.00 m) • 0.64 m/s (11.00 m)	Maximum current speeds: • 0.75 m/s (6.75 m) • 0.69 m/s (9.00 m) • 0.58 m/s (11.00 m)
Enhanced vertical mixing during the mid-sampling period storm event. Post-storm temperatures reached pre-storm levels within a few hours after the end of the storm period.	Strong vertical mixing during the mid-sampling period storm event. Post-storm maximum temperatures in the deeper layers remained constantly lower than pre-storm values.

5 Model simulations and performance assessment using high-resolution ADCP data in an OWF context

To evaluate possible applications of high-resolution ADCP measurements in an OWF context (as conducted in the Anholt OWF) in a high-resolution hydrodynamic model, we assessed performance and parameterization in a single OWF monopile test model configuration. We use the FlexSem model, a modular framework for dynamic marine modelling developed at Aarhus University, Department of Ecoscience, Denmark (Larsen et al., 2020). The model employs an unstructured computational mesh, capable of handling complex topographies and coastlines, as well as varying levels of model complexity from simple box models to detailed topography and high-resolution (HD) 3D models. The system is user-friendly, allowing users to set up new models and incorporate customized partial differential equations via an XML-formatted setup file without the need for writing or compiling code. Written in standard C++, it is freely available under the GNU public license at: http://marweb.bios.au.dk/FlexSem/. The modelling framework includes modules for full Navier-Stokes hydrodynamics, simplified hydrodynamics (HDLite), pelagic biogeochemistry and/or sediment transport, benthic biogeochemistry, surface heat modelling, surface exchanges, light penetration, and agent-based modelling (ABM). Modules can be run fully coupled (2-way) or in offline mode (1-way), where hydrodynamics are stored in a file and loaded during the simulation.

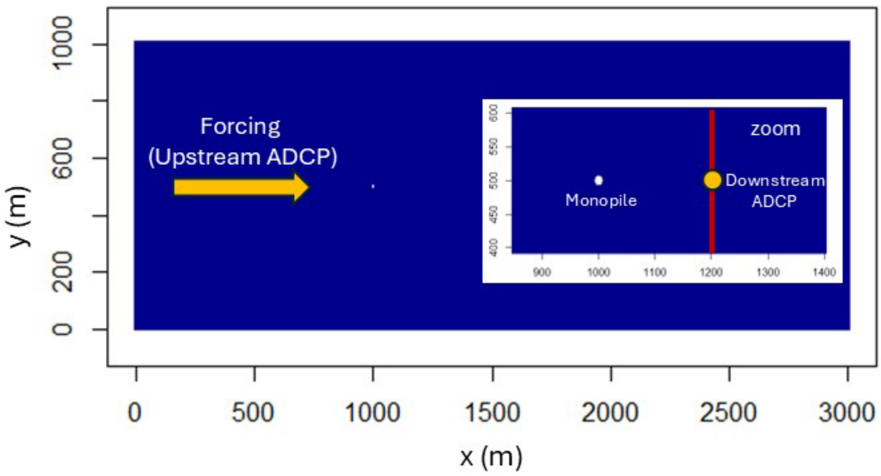


Figure 10. Flume orientation and FlexSem model configuration. In the resolved monopile setup, a monopile is positioned at flume locations x=1000 m and y=500 m. In the parameterised monopile setup, the monopile is replaced with a parameterization of the monopile drag effect at the same x-y flume coordinates. The parameterization is described in detail in Maar et al. (2025). On the left (upstream) open boundary the model is directly forced with velocity data recorded by the Anholt OWF upstream ADCP in August 2024. The model results are validated against velocity measurements from the Anholt OWF downstream ADCP.

The computational mesh of this proof-of-concept test model simulates a flume-like channel with a length of 3000 m in the x-direction and a width of 1000 m in the y-direction. We use the high-resolution 3-D FlexSem kernel. The horizontal resolution varies between 2 m in the central monopile model area to 20 m on the gradient open boundary to the right. The water depth in the flume is maintained at a constant 17 m, matching the actual water depths within the Anholt OWF sampling area. The model performance of two different test setups is compared: one with a physical obstacle representing an OWF monopile, 7.5 m in diameter, centered at x = 1000 m and y = 500 m, and another setup without a physically resolved monopile, but incorporating a parameterization of the monopile drag effect (for a monopile of the same diameter) as described in Maar et al. (2025), based on the method introduced by Rennau et al. (2012). The flume model setup is shown in Figure 10. Since this was a proof-of-concept study, we based the monopile diameter on typical dimensions for turbines at seabed level in the 3.6 to 8 MW range, corresponding to a diameter of approximately 6 to 8 meters (Energinet.dk, 2015).

Each model simulation was directly forced on the left (upstream) open boundary by measured time-series of horizontal current velocity profiles recorded by the Anholt OWF upstream ADCP. The model time step was 1 second and the model simulation period was chosen slightly shorter than the sampling period to reduce computation time (21 August 2024 13:00 to 27 August 13:00). The observed ADCP velocity profiles were interpolated from the ADCP depth bins to the model depth layers using linear interpolation. Given the flume's orientation, the measured ADCP v-velocity was used as the along-channel velocity (in the x-direction), while the ADCP u-velocity was used as the cross-channel velocity (in the y-direction). The model results from each simulation were written into output files at a one-hour time interval and compared with corresponding time-series data recorded at the Anholt OWF downstream ADCP sampling site (Figure 10).

Figure 11 presents a comparison of the along-channel velocity from simulations with both a resolved and parameterised monopile at different time steps, representing different forcing and wind conditions during the Anholt OWF sampling period. Both model simulations show a similar performance and response to different background (upstream) forcing conditions. The evolution, magnitude, and spatial extent of the simulated downstream wakes are in close agreement, with both models predicting a decrease in along-channel flow current speeds downstream of the monopile. The horizontal extent of this shadow zone of reduced current velocities is confined to the immediate vicinity of the monopile within a few turbine diameters, extending at distances well under 200 m from the monopile area.

In Figure 12, the time series of downstream currents from the Anholt OWF downstream ADCP are compared with currents from FlexSem model simulations at the downstream ADCP location. Two key results emerge from this comparison. First, the simulations with monopile parameterization accurately reproduce the results from the model simulations with a resolved monopile. Secondly, both model simulations align well with the downstream ADCP measurements, even though the near-bottom shear layer exists, but is less pronounced in the model simulations. This proof-of-concept study demonstrates that the physical effects of monopiles can be effectively modelled with sufficient resolution to treat the monopile as a physical obstacle in the water. However, this method comes with a significant computational cost, particularly for larger areas like the North Sea and Inner Danish Waters with a large increase in future offshore wind energy capacity and the number of monopiles. Alternatively, wind turbine drag can be parameterised by incorporating monopile drag (Rennau et al., 2012; Maar et al., 2025). This approach is computationally more efficient, as it does not require high spatial resolution. However, the parameterization is ocean-state dependent and not yet well validated at coarser resolutions, as direct measurements of these effects are challenging, expensive, and relatively scarce (Christiansen et al. 2023). This study demonstrates that direct measurements are important, but require a sampling design, which can resolve the relevant spatial and temporal scales of possible turbine wake effects.

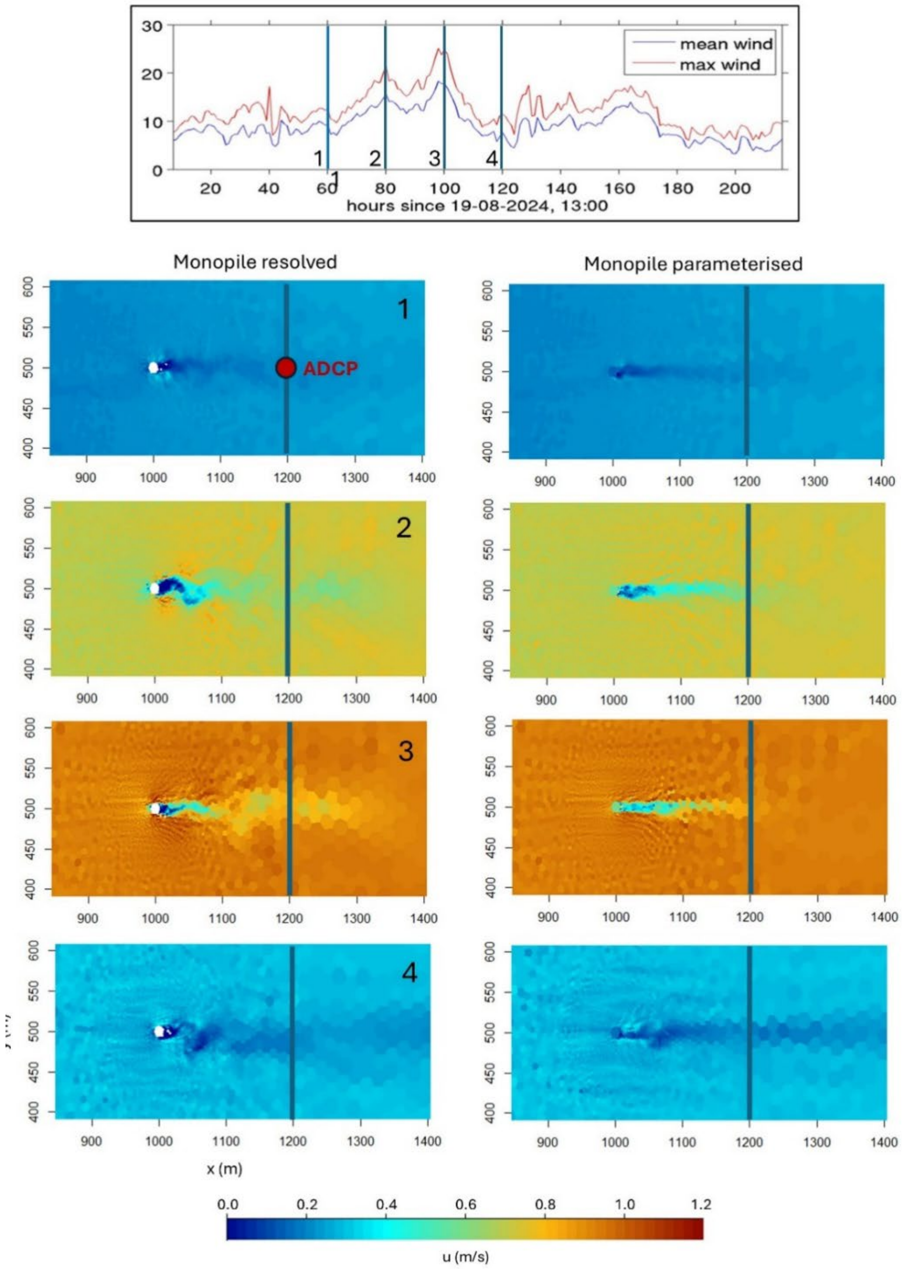
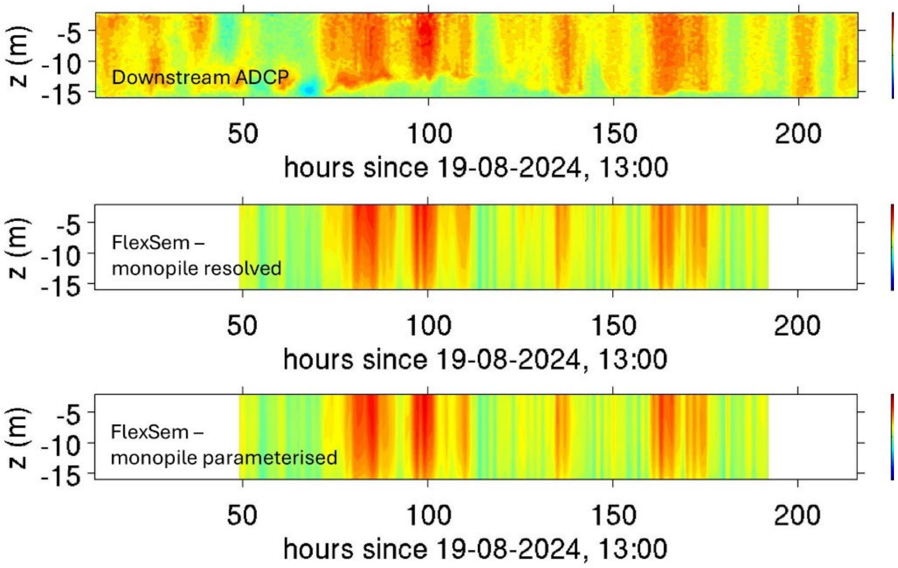


Figure 11. Along-channel velocity (m/s) at four instantaneous time steps representing different wind and current conditions during the Anholt OWF sampling period. The left column displays model results from the resolved monopile flume setup, while the right column shows corresponding results from the parameterised monopile model setup. The blue vertical lines in each subplot represent the 200 m downstream distance from the monopile. The position of the Anholt OWF downstream ADCP is indicated. Please note that the model resolution varies from 2 m at x=1000 m, y = 500 m to 20 m at the open boundaries

Figure 12. Time series of along-channel velocity (m/s) vs depth at the downstream ADCP position showing currents from the downstream ADCP (top), from the FlexSem model simulations with the monopile resolved (middle) and from the FlexSem model simulations with a monopile drag parameterization



6 Conclusions and Outlook

6.1 Modelling OWF interactions

Hydrodynamic and ecosystem model simulations can help to investigate potential interactions between wind farms and the marine environment by considering a variety of factors, including:

- Structure drag from wind turbine foundations: The flow of water past vertical cylinders, such as wind turbine foundations, can create turbulent mixing that affects both current velocities, and stratification (Dorrell et al. 2022; Christiansen et al. 2023).

- Atmospheric wakes generated by wind turbines: The extraction of kinetic energy from the wind field by wind turbines creates atmospheric wakes on the leeward side of offshore wind farms, affecting wind speeds near the sea surface boundary. This reduction in wind speed and associated wind stress can lead to changes in residual circulation, vertical momentum fluxes, wave formation, horizontal surface velocity, turbulence within the surface mixed layer, and stratification (e.g., Akhtar et al. 2021; Christiansen et al. 2022 and references therein).

Previous and recent studies have shown the capacity of modern modelling frameworks using unstructured grids to simulate these processes and their effects on various aspects of the marine environment at different spatial and temporal scales, including:

- Hydrodynamics: Model studies have reported changes in horizontal and vertical current velocities, sea surface elevation, and the formation of consistent upwelling and downwelling patterns (Christiansen et al. 2022; Daewel et al. 2022).

- Stratification: Changes in the strength and spatial distribution of the density stratification, including the potential for erosion of stratification in areas with enhanced mixing, have been highlighted in a number of investigations using different model approaches (Cazenave et al. 2016; Dorrell et al. 2022).

- Biogeochemical implications: Models can evaluate the impacts of changes in hydrodynamics and stratification on nutrient availability, primary production, bottom oxygen concentrations, and overall ecosystem functioning (van der Molen et al. 2014; Daewel et al. 2022).

6.2 The benefit of OWF marine environmental monitoring

Our measurements provide a brief snapshot of environmental conditions, capturing specific short-term changes in water mass properties and hydrodynamic conditions observed during the study period. Despite the relatively short sampling period of 9 days, the ADCP data offer a detailed view of the full spectrum of oceanic motions during this time, encompassing tidal and wind-driven currents. Such local-scale data inside an OWF are critical for driving and validating local-scale hydrodynamic models aimed at simulating conditions inside OWFs and OWF induced changes in currents and stratification. Such high-resolution datasets are often challenging to obtain from publicly accessible marine data sources like the Copernicus Marine Service or the Danish NOVANA monitoring program. Additionally, the ADCP data offer the advantage of using acoustic backscatter to estimate sediment transport and particle dispersion.

Thus, localized OWF-scale monitoring may contribute to enhancing the ability for improving model simulations of flow dynamics and mixing within OWFs, providing valuable insights into potential interactions with surrounding marine environmental and physical conditions. Such measurements also have the potential to refine model parameterizations and processes including turbine induced turbulence, mixing, and sediment transport. An accurate assessment of these physical processes also permits an evaluation of biological and sedimentary processes, including organic matter production, transport, sediment deposition and erosion.

Earlier modelling efforts, such as those by Broström et al. (2008), demonstrated that upwelling and downwelling dipoles caused by interactions between turbine structures and flow are linked to increased vertical velocities and altered mixing and stratification patterns. Supporting these findings, Floeter et al. (2022) presented empirical data confirming the presence of such dipoles. Their research identified significant changes in the depth and intensity of the mixed layer, as well as in the stratification dynamics within the wind wake zones of OWFs in the summer-stratified waters of the southern North Sea.

Understanding and modelling the vertical mixing and wake formation caused by OWFs and individual turbines alike are crucial, but challenging, due to the complexity of turbulence processes and the lack of detailed measurements for model parameterization. Rennau et al. (2012) adapted a two-equation turbulence closure scheme to capture enhanced mixing but indicated that wind farm installations at the time of the study minimally affected regional stratification. However, they cautioned that extensive future development could lead to significant impacts, such as reduced bottom salinity. They also highlighted limitations of these schemes, known for being overly dissipative in stratified flows, leading to unrealistic pycnocline representations in model simulations. Similarly, Cazenave et al. (2016) applied an oceanographic model to study the unstratified Irish Sea and used local grid refinement to resolve turbine wakes. While their results aligned qualitatively with observed sediment plumes, they did not modify turbulence closure schemes to address wake-induced turbulence. These findings underscore the need for advancements in physical process understanding and the development of improved turbulence models to accurately predict wake-associated mixing in stratified environments supported by high-resolution measurements of turbulence and stratification.

The results from our high-resolution FlexSem flume proof-of-concept model demonstrated good agreement between a configuration with an existing monopile, a setup featuring the monopile drag parameterization (but without the monopile), and measurements of the currents downstream of the monopile, obtained from inside the Anholt offshore wind farm. Field studies such as the one reported from the Anholt offshore wind farm could thus be used to test model parameterizations but require additional high-quality measurements of currents and stratification relatively close (<<200 m) to the monopile over several months.

To better understand turbine wake effects from field measurements, longer time series and the deployment of larger ADCP arrays are therefore recommended for capturing detailed spatial and temporal dynamics in future setups. Ship-based measurements of currents and stratification using VM-ADCPs and profiling CTDs should also be considered. Experimental strategies could also include simultaneous measurements inside and outside OWFs.

The main objective of the field sampling campaign was to obtain detailed insights into hydrodynamic and environmental conditions downstream of the monopile, where fine-scale variations in flow patterns were expected to be most pronounced. As a result, a more comprehensive measurement setup was implemented on the downstream side. This included a greater focus on spatial (vertical) and temporal resolution. Due to uncertain weather conditions and logistical constraints, the upstream measurement setup was designed to be more streamlined and easier to deploy. In contrast, the downstream setup was more elaborate to capture fine-scale variations in flow and other parameters. However, based on the insights gained from this study, we would recommend maintaining a more detailed downstream focus while considering additional upstream measurements in future studies if resources and conditions permit.

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OCEAN CURRENTS AND WATER MASS PROPERTIES INSIDE THE ANHOLT OFF-SHORE WIND FARM (KATTEGAT, DENMARK)

This study investigates the complex and still insufficiently understood interactions between ocean currents and offshore wind farms (OWFs), with a focus on local-scale hydrodynamic effects near individual wind turbine foundations. Despite growing interest in the environmental impacts of OWFs, empirical field data on local-scale current dynamics within wind farms remain sparse. This technical report describes the results from a field campaign, which was conducted within the Anholt OWF in the Kattegat over a 9-day period in August 2024.

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