Hywind Tampen glider monitoring

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Summary

Two autonomous surface gliders, Sailbuoys, were used to monitor the pelagic ecosystem around the Hywind Tampen floating wind farm in May 2023 collecting active acoustic data over a 4-weeks period to assess possible influence of the farm on pelagic fish and zooplankton. Sampling transects were run perpendicular to the main environmental gradient (bathymetry) in two areas: an area within or downstream of the wind farm, and an upstream area, considered a control. The upstream area was expected to show natural variability, while the downstream area would reflect the wind farm's potential influence. Three main scattering features were observed in the upper water column (0-150m): 1) weak sound scattering layers likely composed of zooplankton, consistent across times of the day, 2) strong scattering layers, likely a mixture of zooplankton and fish, moving to the upper water column at night and 3) fish schools. The different groups showed varied vertical behaviours and distributions in the area around the farm, but no systematic pattern was detected based on the distance from the farm. Moreover, no differences larger than the average natural variability were found between the upstream and downstream areas at the level of the farm, in terms of biomass density and vertical distribution. Both approaches support the conclusion of a negligible effect of the wind farm on pelagic fish aggregations or lower trophic levels production. Despite no observed patterns, it should be noted that 7 turbines were installed in 2022 and the remaining (4) in May 2024, during the survey. The longer installations are in the water, the more advanced the biofouling process will be, supporting a more complex "reef" ecosystem. Continued monitoring at later stages will be required to assess the influence on the pelagic of an established benthic "reef" ecosystem on the installations.

Approvals

Project manager	Quality control reporting
Virginie Ramasco	Virginie Ramasco

Content

1 Abbreviations and symbols

AI: Aggregation index, estimating if organisms are vertically distributed uniformly across the water column or in patches

AW: Atlantic water mass

CM: Centre of mass, the average depth of animals in the water column weighted for their density (S_V)

CAW: winter-cooled Atlantic water mass

DVM: Diel vertical migrations

I: Inertia, the vertical dispersion of animals around the average depth (CM)

SB: Sailbuoy

S_V: Volume backscattering strength, this can be considered as an index of biomass density

SW: Surface water mass

2 Introduction

The Hywind Tampen survey is a follow-up project of the successful Sailbuoy survey in Hywind Scotland in July 2021, which investigated the potential reef effects of the wind farm on pelagic fauna.

At Hywind Scotland, large spatial and temporal variability was found in the abundance and distribution of fish and zooplankton during the 4-weeks sampling campaign during the summer. A peak in biomass density was found close to the farm during a certain period, suggesting the presence of a "reef-effect" only at certain times. However, the study was based on the use of one autonomous surface glider only, therefore spatial and temporal variability were partially confounded. In addition, distance to the farm was partially confounded with one of the main environmental gradients, bathymetry. For these reasons, a smaller effect of the farm on the pelagic ecosystem could have gone unnoticed, but no large nor consistent effect was measured during this campaign.

The goals of the current study at Tampen were to:

- Provide baseline data on the distribution and abundance of pelagic zooplankton and fish inside and outside the wind farm
- Investigate potential effects of the wind farm on the abundance and distribution of pelagic fish and zooplankton

Based on the former experience at Hywind Scotland, the number of Sailbuoys was increased to 2, sailing in parallel upstream and downstream of the farm to monitor the potential effect of the installations on the water masses flowing through the farm.

3 Materials & Methods

3.1 Study area

Hywind Tampen is located on a slope at depths ranging from 250 to 300 m depth, with a shallow plateau located to the south-west and a deep basin to the north-east between the two oil extraction platforms Snorre and Gullfaks (Figure 1). The dominating current flows from the north-west to the south-east, along isobath lines, with only minor deviations in direction (Equinor, 2019).

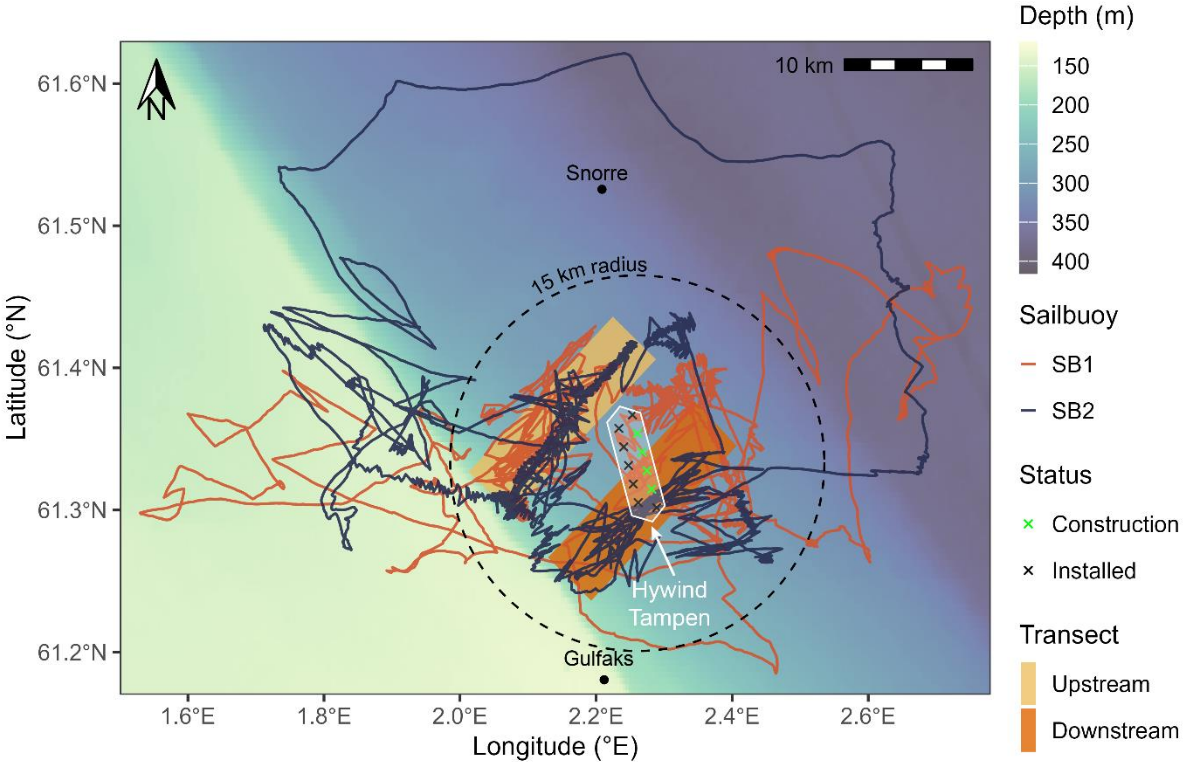

Figure 1 Map of the May 2023 survey showing the location of the sailbuoys (red and blue lines), the Hywind Tampen wind farm (white polygon), with wind turbines installed (black crosses) and under construction at the time of the survey (green crosses), and the areas of interest for sampling (orange polygons, upstream and downstream of the farm based on the main SE current direction). The dashed circle indicates the 15 km radius around the centre of the farm – the area in which we focused the data analyses.

3.2 Sailbuoy survey

3.2.1 Survey design

Two autonomous uncrewed surface vehicles – Sailbuoy (Offshore Sensing AS)– were used for monitoring the pelagic ecosystem inside and outside of the floating wind farm of Hywind (Figure 2). The Sailbuoys were deployed by Akvaplan-niva during the offshore cruise survey on 4th May 2023 and remained on site for 26 days, collecting a total of 800 GB of acoustic data and sailing ca. 3000 km (1620 nmi). At the end of the survey on 30th May 2023, the Sailbuoys left the wind farm to sail towards Bergen, where they were recovered by Redningsselskapet's ship RS *163 Kristian Gerhard Jebsen II* on 5th June 2023.

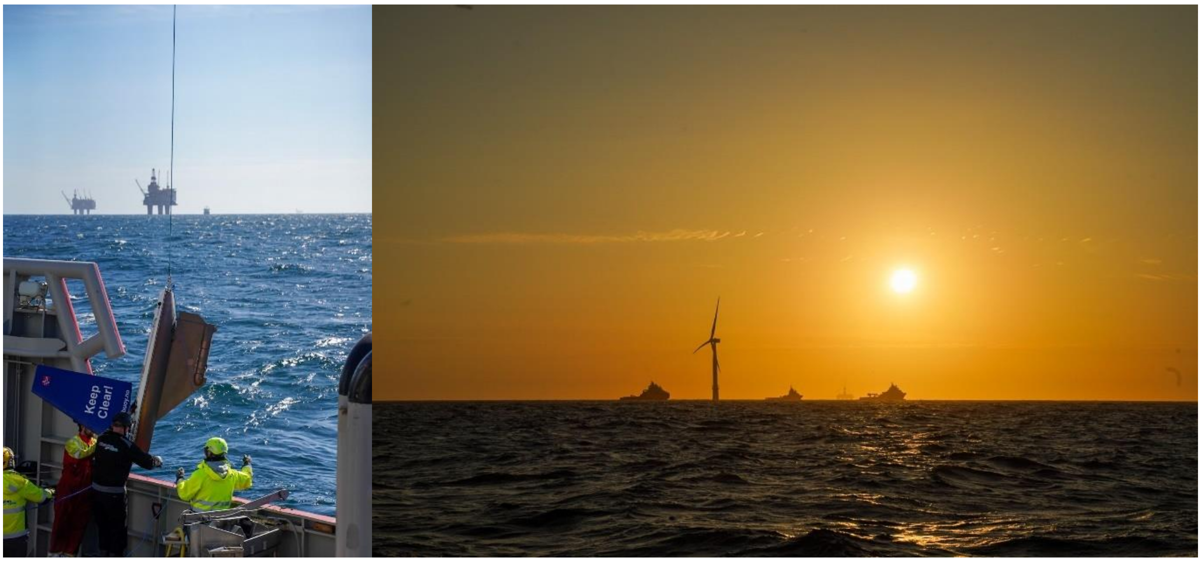

Figure 2 (left) Sailbuoy Echo 1 being deployed during the offshore cruise on 4 May 2023, and (right) a floating offshore wind turbine being constructed at Hywind Tampen (photos: Rosalyn Fredriksen).

The study design consisted of the Sailbuoy running transects perpendicular to the main environmental gradient (bathymetry) in two different areas. An *upstream transect area* was located to the north-west of the wind farm, upstream of the farm based on the main south-east current direction (Figure 1). Here we assumed the wind farm to have little influence on the distribution and abundance of pelagic fish and zooplankton along the entire length of the transect, as water masses in this area have generally not passed by the farm. This was therefore considered a control area, where variability along the transects would mainly be related to natural environmental variability. A second transect, the *downstream transect area,* was located within or downstream of the wind farm. The extent of the potential influence of the farm along this transect was unknown a priori but was expected to be highest towards the centred of the transect, which is either within or right downstream of the farm, and not at the edges of the transect. Using this rationale, **a potential effect of the farm would be inferred if the difference between the two transects was larger at the centre, where waters have likely passed through the farm, rather than at the edges, where only natural variability should be present**.

The different transect areas were not surveyed continuously by the same glider, as the choice was dependent on weather conditions and currents. The upstream transect was first surveyed by Sailbuoy Echo 1 until 15 May 2023 and then by Sailbuoy Echo 2 because of more favourable wind conditions and positioning of Sailbuoy Echo 2 at the time.

Only seven of the eleven planned floating wind turbines were installed during the survey. The remaining four turbines were being installed at the time of the study. A minimum of three vessels were required to anchor the floating wind turbine (e.g., Figure 2). Because of the wind turbine constructions, the Sailbuoy pilots regularly contacted the construction field coordinator to achieve the best possible survey of the planned transects, considering various limitations.

3.2.2 Environmental analyses

The Sailbuoys were equipped with a temperature and conductivity sensor (NBOSI CT sensor, Neil Brown) from which salinity was calculated, a fluorometer (ECO triplet, Seabird Scientific) measuring turbidity (optical backscatter at 700 nm), chlorophyll a – a proxy for phytoplankton biomass, and phycocyanin – pigment indicative of the presence of cyanobacteria, and an oxygen sensor (AADI Optode, Aanderaa) giving the oxygen concentration and saturation.

We also used conductivity, temperature, and depth casts (CTD) collected by Akvaplan-niva's offshore cruise to document the water column properties at the time of deployment.

3.2.3 Hydroacoustic analyses

3.2.3.1 Data processing

In addition to the environmental sensors, both Sailbuoy had an echosounder (WBT Mini, Kongsberg Discovery) operated in broadband mode, recording acoustic backscatter between 185-255 kHz (ES200-7CDK-Split transducer, 200 kHz nominal frequency) mounted on the keel at 50 cm below the ocean's surface. Data was recorded from the surface down to 160 m depth, pulse length was set to 2.048 ms, transmitted power to 150 W, and the chirp rate was 0.5 Hz, i.e., one chirp every two seconds. The echosounder was calibrated using the standard sphere method with 25 mm and 38.1 mm tungsten (WC-Co) spheres (Demer et al., 2015). We used the average temperature and salinity profiles to derive the sound speed profile of the water column and calibrate *in situ* backscatter levels.

The effective detection range of the echosounder, i.e., the depth range at which acoustic data are of good quality, was ca. 115 and 150 m depth at a -80 dB re 1 m^{-1} level for Sailbuoy Echo 1 and Echo 2 and below 160 m depth at -65 dB re 1 m^{-1} for both Sailbuoys. The low -80 dB re 1 m^{-1} threshold was used to detect zooplankton aggregations, while the -65 dB re 1 m-1 threshold only selected strong scatterers, e.g., fish with swimbladder. Hence, we could detect zooplankton aggregations in the upper 110 m of the water column and fish in the upper 160 m full.

The echosounder was set to turn on for 15 min every 30 min, i.e., 15 min of recording at the start of the hour (10:00 – 10:15) and 15 min just after the half-hour (10:30 – 10:45). This duty cycle was the highest sampling rate achievable without power loss and data processing.

Acoustic data from the Sailbuoy were scrutinised, cleaned, and edited using Echoview 13.1 (Echoview Software Pty Ltd.). We removed background noise (minimum 10 dB signal-to-noise ratio) and attenuated signal due to surface bubbles using Echoview's algorithms (De Robertis & Higginbottom, 2007). We did not observe acoustic interference in the acoustic data. After cleaning the data, the echograms were echo-integrated in cells of 1 min per 2 m depth using pulse-compressed data from which we calculated the mean volume backscattering strength (S_V), an index of biomass density in the water, between 185-255 kHz.

The echo-integration was done on the echograms with no S_V threshold to integrate all scattering from the water column and at a -65 dB re 1 m^{-1} threshold to focus on strong scatters like fish with swimbladder. These two datasets were further used to classify acoustic data.

3.2.3.2 Acoustic classification

We classified each echo-integration cell (1 min per 2 m depth) into four groups (Figure 3):

- Strong scatterer – most likely composed of fish with swimbladder
- Mixed scattering layer
- Weak scattering layer – most likely composed of zooplankton
- Empty water

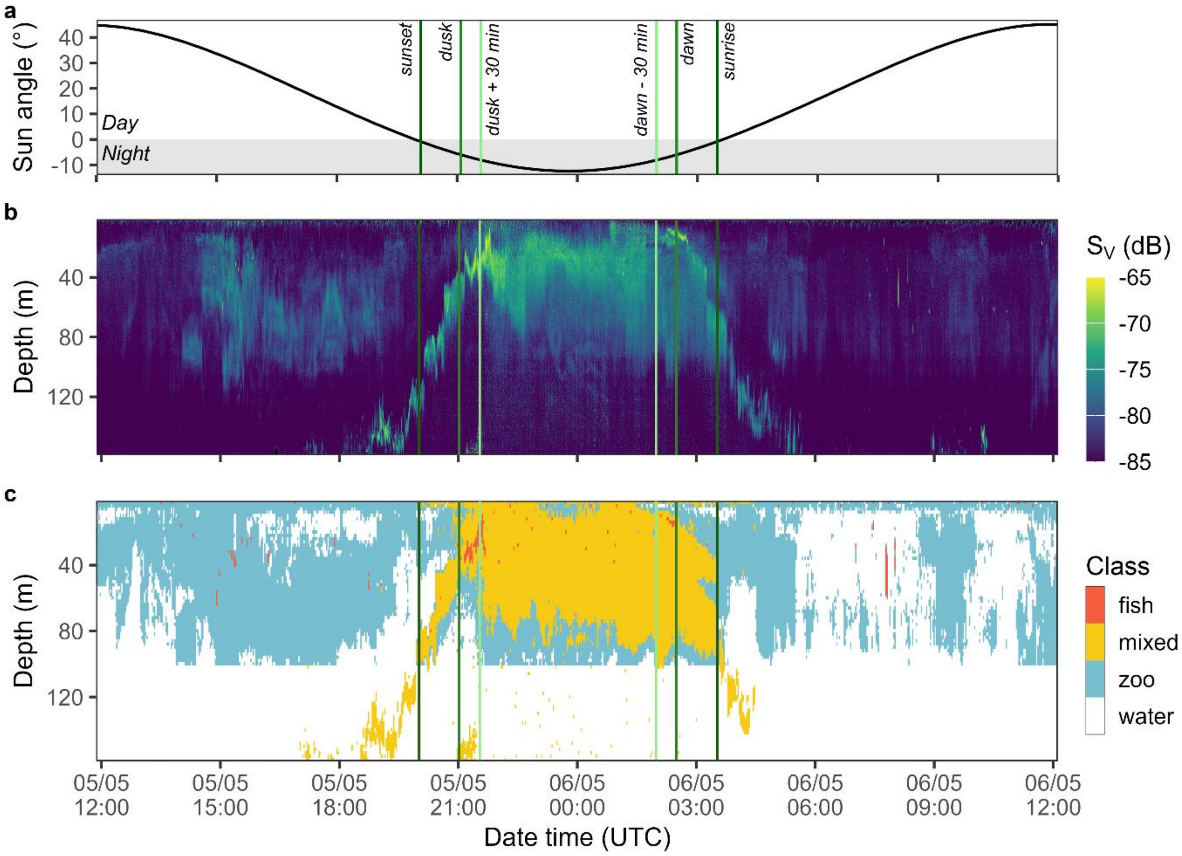

*Figure 3 (**a**) Sun angle in relation to the horizon (0 °) for the location of SB Echo 2 on the 5 and 6 May 2023. (**b**) Volume backscattering strength (S_V) echogram and (**c**) classified echogram. The vertical bars indicate the sunrise and sunset (dark green), dawn and dusk (green), and dawn and dusk ± 30 min (light green) and were used for acoustic classification.*

Each class was identified using the criteria listed in Table 1. Because of the diel vertical migrations (DVM) of the organisms, we included the time of day in the classification.

Table 1 Summary of the criteria used for classifying acoustic data (e.g., Figure 3).

Class	Definition	S_V (dB re 1 m-1)	Depth
Fish	Strong scatterer	$S_V > -65$	0-100 m
Mixed layer	Layer performing diel vertical migrations (DVM)	$-80 < S_V < -65$	Day: > 100 m Night: < 100 m
Zooplankton layer	Weak scatterer	$-85 < S_V < -80$	0-100 m
Water	Empty water	$S_V < -85$	0-160 m

3.2.3.3 Echo metrics

To investigate changes in the depth distribution, organisation, and density of organisms in the water column, we calculated several echo metrics for each group (e.g., fish, mixed layer, and zooplankton layer) and cell. Echo metrics included mean S_V, which describes the mean density of animals in the water column, as an index of biomass density, the centre of mass (CM) representing the average depth of the animals in the water column weighted for their density (S_v), inertia (I) indicating the vertical dispersion of animals around the average depth (CM), and the aggregation index (AI) estimating whether the organisms are vertically distributed uniformly across the water column or in patches (Table 2; Urmy et al., 2012). All calculations were done in the linear domain. We then ran a running average of 5 min to smooth the echo metrics over time.

Table 2 Definitions of echo metrics variables and their usage.

Symbol	Name	Quantity	Usage	Unit
S_V	Volume backscattering strength	Density	Density of organisms within a volume of water	dB re 1 m^{-1}
CM	Centre of mass	Depth	Average depth of the organisms weighted by their biomass (Sv) in the water column	m
I	Inertia	Vertical dispersion	Dispersion of organisms around the CM	m^{-2}
AI	Aggregation index	Vertical patchiness	Patchiness of organisms in the water column	m^{-1}

3.2.3.4 Potential effects analyses

Pelagic fish can actively aggregate around offshore infrastructure for multiple reasons, among which protection, generating a reef-effect in the vicinity of installations. Planktonic organisms on the other hand, will be mainly affected by the presence of a wind farm if the waters in which they are passively drifting passes through the farm. This can affect production of lower trophic levels through the increase or decrease of nutrients and mixing, and in turn affect the density of animals higher up in the trophic chain.

To investigate the potential effects of the wind farm on the density and distribution of both fish and zooplankton, we therefore conducted two different types of analyses:

1. Spatial mapping and distance analyses for mapping potential aggregations (reef-effect) in all directions around the farm, independently of environmental variability
2. Transect analyses for documenting potential effects downstream of the farm partially controlling for environmental variability

We used spatial kriging to visualise spatial changes in the density and vertical distribution of fish schools, the zooplankton layer, and the mixed layer. Kriging is a geostatistical modelling tool for spatial interpolation used to predict values of a variable at unmeasured locations based on the values measured at neighbouring points and the distance to those. Differently from simpler methods, kriging can also account for spatial distribution properties and is well suited for variables that are not uniformly distributed, such as pelagic animals (Petitgas et al., 2017). The kriging was performed on a grid with a cell resolution of 0.25 km^2 (500 m x 500 m). This analysis was based on data collected within a 15 km radius of the wind farm) – the area where the sample density was highest – when the sailbuoys were not stationary for kriging (Figure 4). We used the S_V for biomass density mapping and the centre of mass (CM) to map the average depth in the water column of each group (see Table 2). The outputs from the spatial kriging were used to make maps.

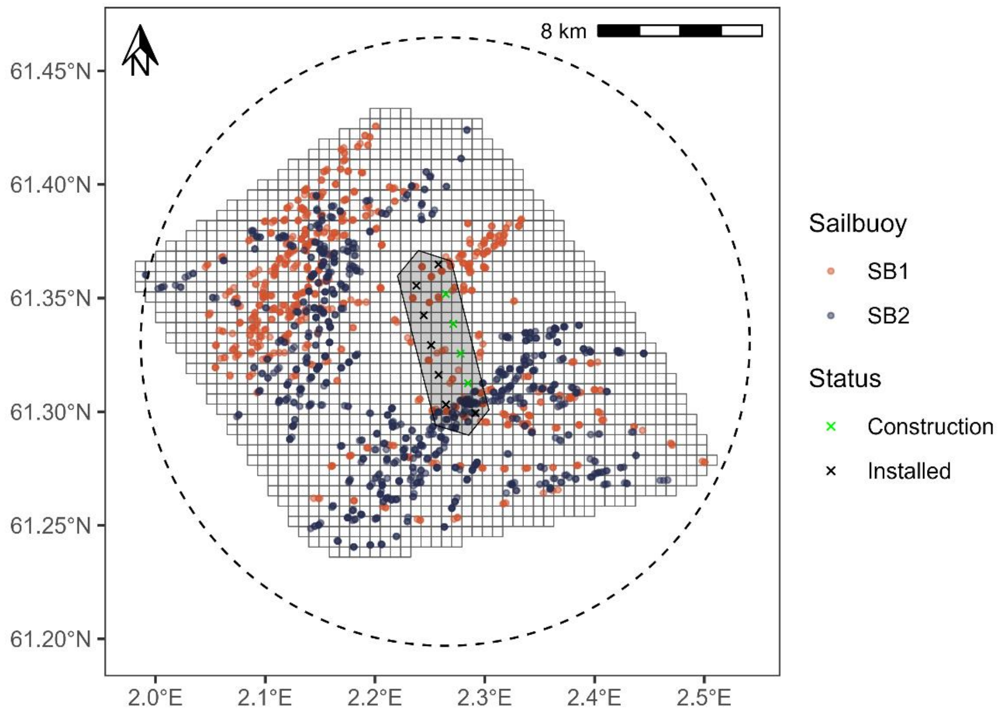

Figure 4 Map showing the grid and the location of acoustic samples from (red dot) Sailbuoy Echo 1 and (blue dot) Echo 2 used for spatial kriging. The dashed circle shows the 15 km radius around the centre of the wind farm. The grid cell resolution is 500 m^2.

Because two Sailbuoys were deployed and were surveying the upstream and downstream transect areas concomitantly, we could evaluate the potential impacts of the wind farm on the vertical distribution and abundance of pelagic fish and zooplankton, reducing temporal variability between transects to a minimum. Potential impacts were evaluated along the transect axis, which was a 47° anticlockwise transformation centred on the wind farm (Figure 5). In this way the transect lines were perpendicular to the isobath lines and main current direction and sampling occurred across different depths for each of the transect. As previously mentioned, a potential influence of the farm, if any, would be expected within or downstream of the farm, therefore in the central part of the downstream transect area. Figure 5 shows the projection of the width of the wind farm on both transect areas (grey shade). This will be used in the figures in the Results section to provide a geographical reference for the width of the farm.

We focused the analyses on days when the Sailbuoys were both surveying the two transects. Since some of the groups found were not present or confounded with others at night due to diel vertical migrations, analysis for daytime and nighttime data were kept separate.

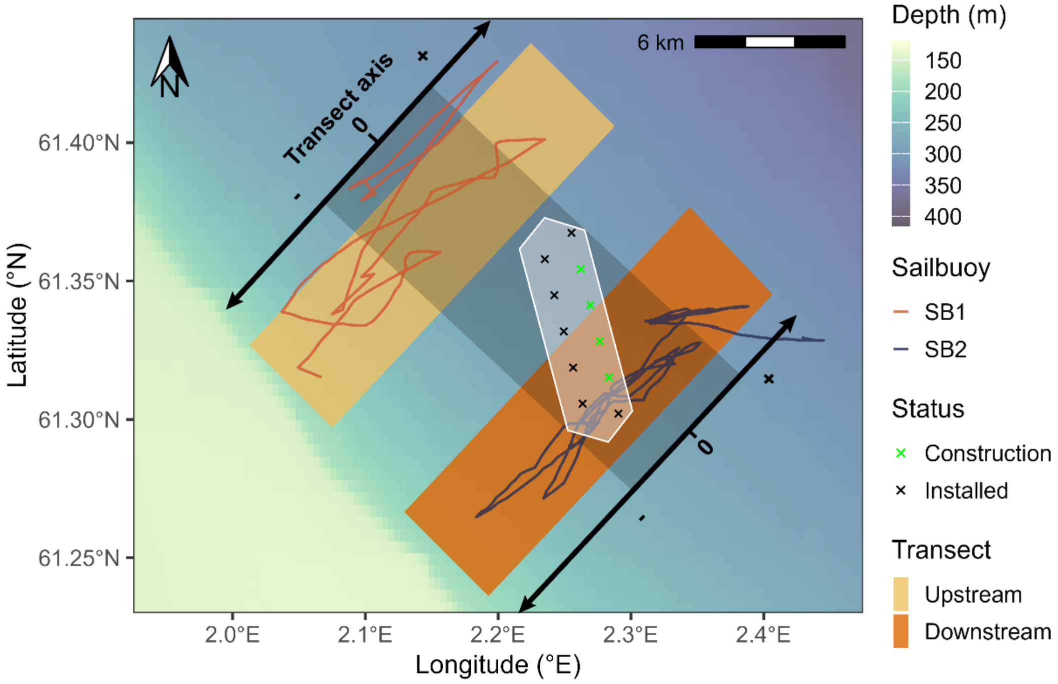

Figure 5 Map of the 6 May 2023 survey showing the location of the sailbuoys (red and blue lines), the Hywind Tampen wind farm (white polygon) and the wind turbines installed (black crosses) and under construction at the time of the survey (green crosses). The black arrow shows the main axes of the repetitive sampling transects perpendicular to the main SE current direction, the orange polygons the areas of interest for sampling along these axes and the grey shadow the width of the farm projected on the axes.

First, we created a synthetic echogram for each group (fish schools, mixed layer, and zooplankton layer) and transect. To do so, we calculated the mean biomass density (S_V) along the transect axis in cells of 500 m horizontal and 2 m depth. Second, for each synthetic echogram and 500 m horizontal depth bin, we calculated mean S_V, centre of mass, inertia, and aggregation index to investigate changes in the density and distribution of each group.

4 Results

There was no instrument failure or malfunction during the survey. On several occasions, the Sailbuoy had to remain outside the wind farm because of stormy conditions (e.g., May 7-9, May 26-28) and logistical constraints due to the wind turbine constructions. In total, the two Sailbuoy sailed ca. 2960 km, collecting 42 upstream transects and 59 downstream transects of varying lengths.

4.1 Environmental conditions

At the beginning of the survey, we observed three water main water masses: surface waters (SW), Atlantic waters (AW), and winter-cooled Atlantic waters (CAW; Figure 6). SW occupied the upper 25 m of the water column and was characterised by low salinity (S < 34.6 psu) and low temperature (T < 7.8 °C). The AW laid below the surface waters and occupied most of the water column (30 – 280 m depth). AW was characterised by higher salinity (S > 35.2 psu) and temperature (T > 8.5 °C) than surface waters. The winter-cooled Atlantic water mass (CAW), characterised by a similar salinity to AW but with lower temperature (T < 8.5 °C), was observed near the seafloor, between 280 and 300 m. The pycnocline was located between the SW and AW at ca. 25 m depth.

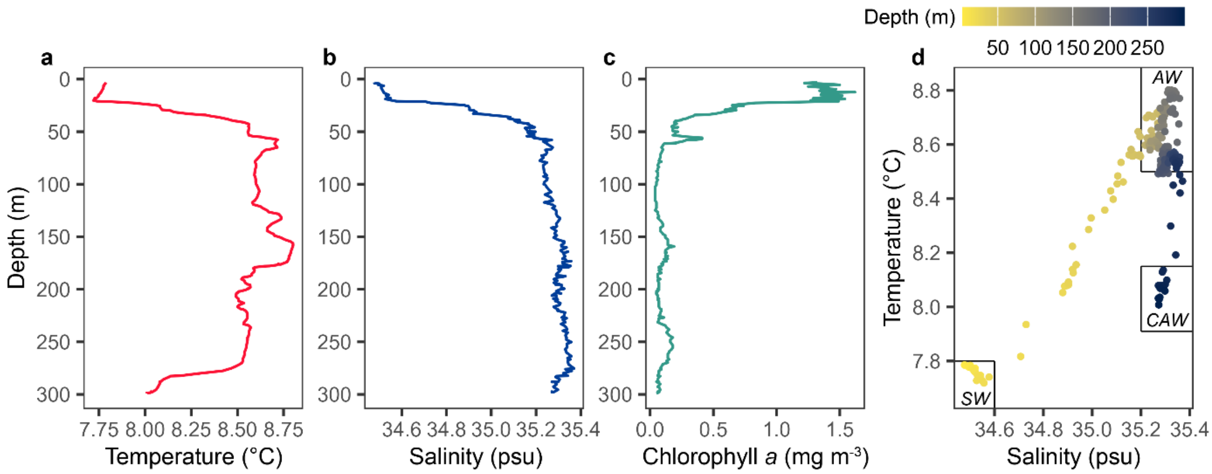

Figure 6 ***a****) Temperature, (****b****) salinity, (****c****) chlorophyll a profile, and (****d****) temperature-salinity diagram collected in the vicinity of Hywind Tampen on 5 May 2023. SW: Surface water mass; AW: Atlantic water mass; CAW: winter-cooled Atlantic water. Water mass definitions from (Svendsen et al., 1991).*

The highest concentrations of chlorophyll *a* – reaching up to 1.5 mg m^{-3} – were found above the pycnocline, in the upper 25 m (Figure 6c). We also observed a sub-surface chlorophyll *a* maximum at 55 m depth with concentrations reaching 0.4 mg m^{-3}.

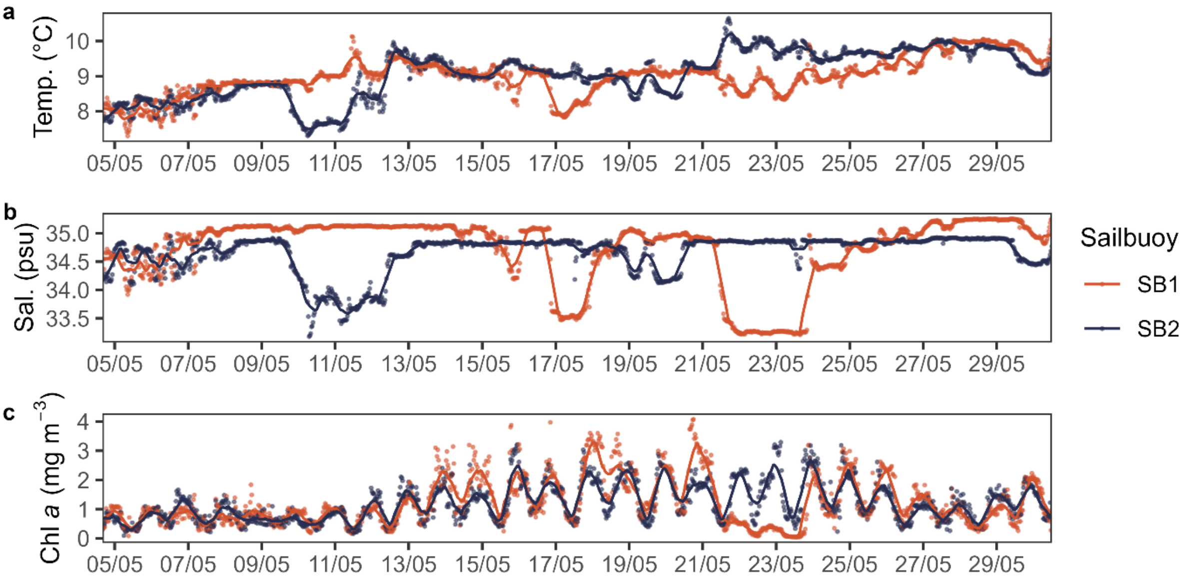

*Figure 7 Surface (**a**) temperature, (**b**) salinity, and (**c**) chlorophyll a from SB Echo 1 (red line) and Echo 2 (blue line) during the Hywind Tampen survey. The dots show the raw data, and the lines represent the rolling mean (rolling window of 20 samples).*

We observed a gradual increase in surface temperature throughout the survey while the surface salinity remained relatively stable (Figure 7a, b). On three occasions (10-11 May, 17 May, 21-24 May), we observed changes in surface salinity and temperature, which may be related to wind mixing, advection of new water masses, and precipitation. The surface chlorophyll *a* peaked between 13-27 May with concentrations up to 3.5 mg m^{-3} stable (Figure 7c).

4.2 Distribution of fish and zooplankton

4.2.1 Scattering features and vertical distribution

Three main scattering features were observed during the survey: a *weak sound scattering layer* characterised by diffuse backscatter (no individual targets observed) and a volume backscattering strength (S_V) generally below -75 dB re 1 m^{-1}, *fish schools* with high S_V (> -65 dB re 1 m^{-1}) and short duration (< 10 min; Figure 8a), and a *strong sound scattering layer* (S_V generally above -75 dB re 1 m^{-1}) of diffuse backscatter, which was only observed during the night (Figure 8b).

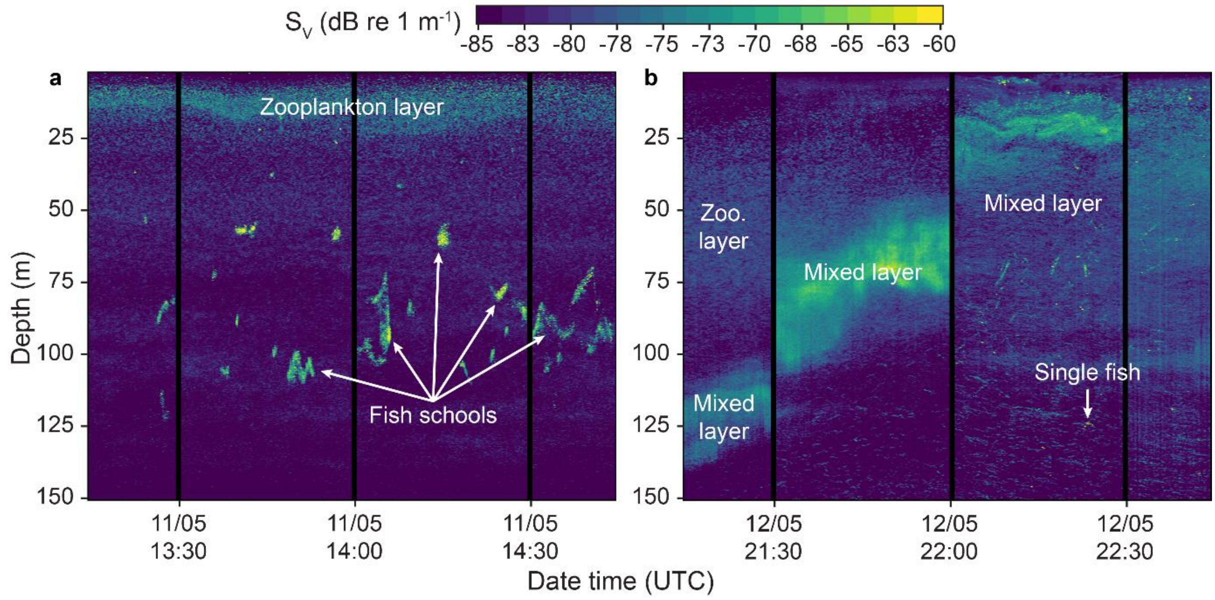

*Figure 8 Zoom on echogram of volume backscattering strength (S_V) showing (**a**) a zooplankton layer and fish schools during daytime and (**b**) the ascent of a mixed scattering layer and single fish at dusk.*

While no ground-truthing of the echosounder data was performed, the characteristics of the different acoustic features may reflect its taxonomic composition. Because of the weak S_V and the diffuse backscatter, we assume that weak sound scattering layers were mainly composed of zooplankton. For the strong sound scattering layer observed during the night, the species composition possibly differed from the zooplankton layer because of its higher backscatter and may be composed of zooplankton and fish. Hence, we refer to the strong sound scattering layer as the *mixed layer* and the weak sound scattering layer as the *zooplankton layer*.

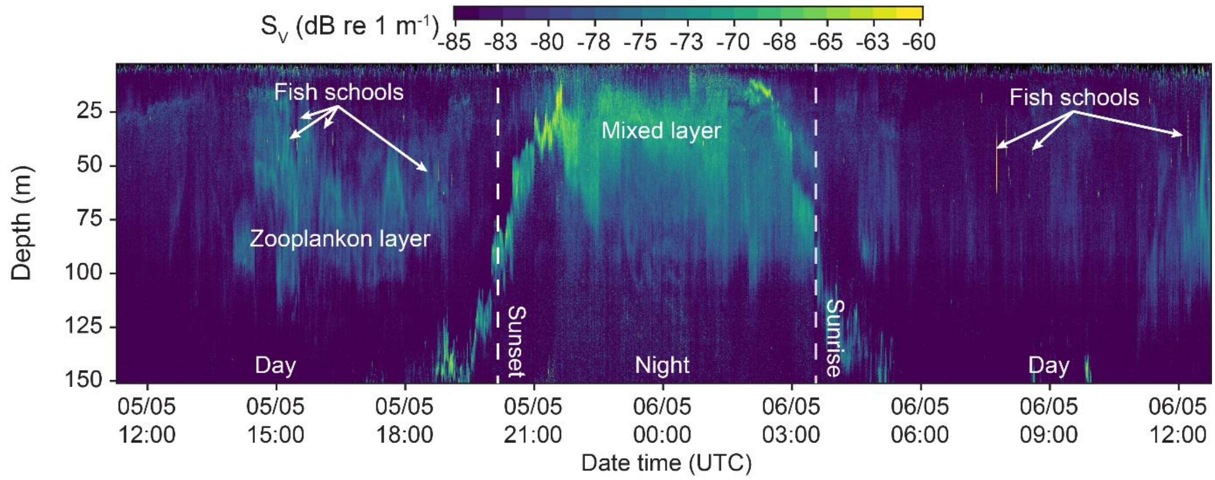

Figure 9 24 h echogram of volume backscattering strength (S_V) collected by Sailbuoy Echo 2 on 5-6 May 2023 showing the DVM of the mixed layer.

We observed DVM of the mixed layer (Figure 9a). During the daytime, the mixed layer was below the maximum observed range of the Sailbuoys – 160 m depth – and, at sunset, it ascended toward the upper layer of the water column (0 – 50 m depth), to remain in surface water throughout the night before descending to deeper layers below 150 m depth at sunrise. We only observed fish schools during the daytime and single fish only during the nighttime.

Throughout the survey, organism density, the vertical distribution of backscatter and patchiness within the water column remain relatively constant (Figure 10a, b, c).

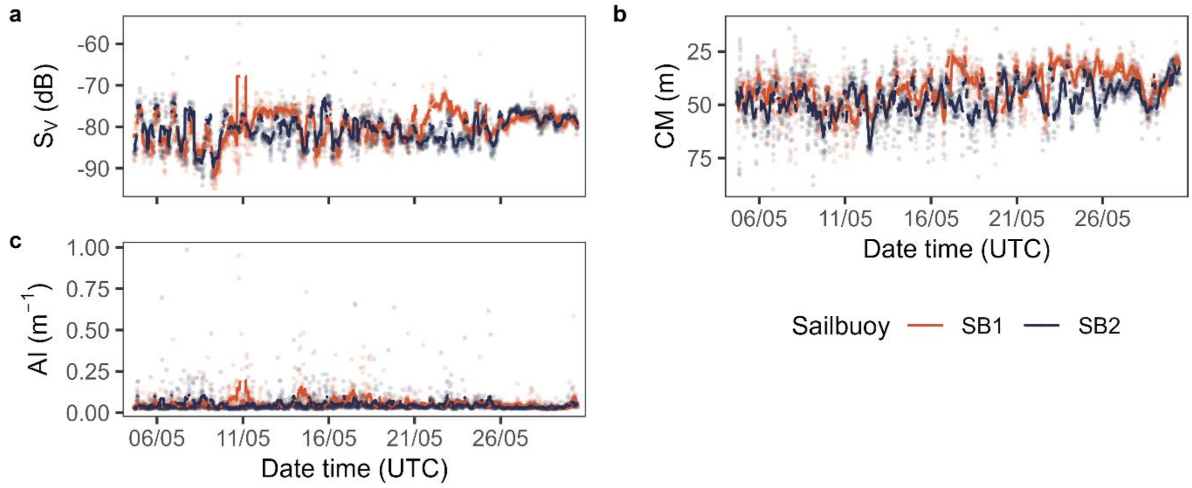

*Figure 10 Echo-metrics throughout the entire survey period for each SB (colours), including (**a**) mean S_V, (**b**) centre of mass, and (**c**) aggregation index. The dots show the 15-minute average value, and the lines represent the rolling mean (rolling window of 20 samples).*

4.3 Potential effects of windfarm on fish and zooplankton

The potential effect analyses were only feasible for the fish schools and the zooplankton layer during the day because they were not observed at night – only individual fish were observed at night – and the zooplankton layer was confounded with the mixed layer in surface waters at night. Similarly, we focused the analyses for the mixed layer during nighttime because it was below the recorded range of the echosounder during daytime.

4.3.1 Maps and distance from the wind farm

During the day, fish schools showed a patchy distribution in the study area without clear spatial patterns in their density or vertical distribution (Figure 11a, b).

In contrast, the zooplankton layer within 5 km of the wind farm showed higher density to the west-northwest than to the south and east of the wind farm (Figure 11c). We observed a deepening of the diurnal vertical distribution of the zooplankton layer to the south of the wind farm during daytime and a shallowing to the southeast (Figure 11d). The differences in the depth distribution of the zooplankton layer were not associated with changes in density, except in the southeast, where the shallower distribution was linked to slightly higher density.

The mixed layer showed a clear gradient in biomass density across the study area, having higher S_V to the east-southeast than in the northwest (Figure 11e), however the absolute value of the difference in S_V was small (less than 2 dB) and the interpolation was based on sparser points, as only night data were used We observed slight changes in the nocturnal depth distribution of the mixed layer to the northeast of the wind farm, where the centre of mass varied between 25 and 55 m depth (Figure 11f).

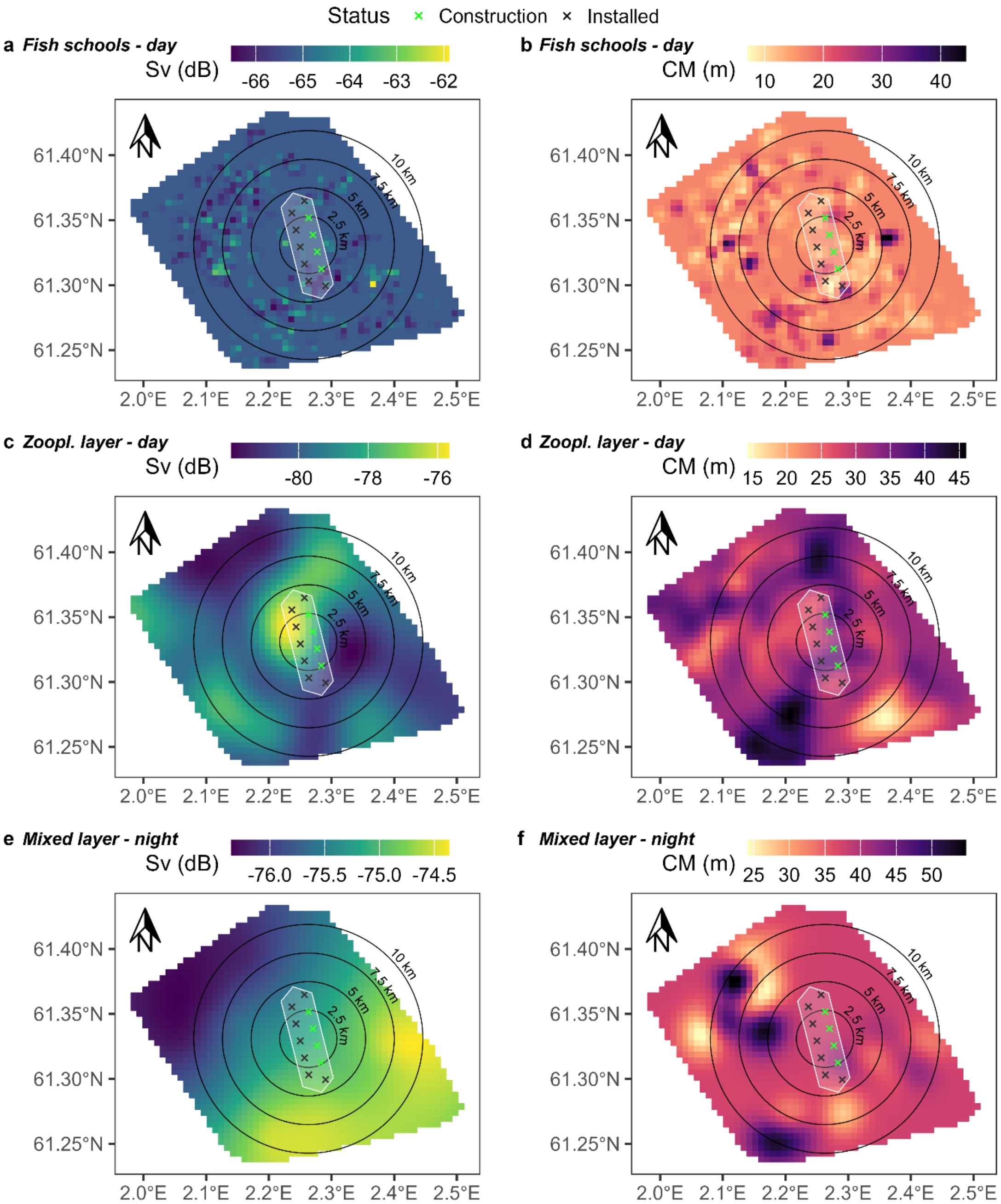

*Figure 11. Map of the (**a**, **c**, **e**) biomass density (S_V) and (**b**, **d**, **f**) vertical distribution of (**a**, **b**) fish schools and (**c**, **d**) the zooplankton layer during daytime and (**e**, **f**) the mixed layer at night. The white polygon indicates the wind farm, the black crosses the installed wind turbines, and the green crosses the turbines under construction at the time of the survey. Each circle is a 2,5 km increment away from the centre of the wind farm.*

4.3.2 Transect analyses

When looking at the vertical distribution of the biota along the length of each transect, we did not observe large changes for fish schools neither in the upstream nor downstream transects in the synthetic echograms (Figure 12a, b). Similarly, there were no clear patterns in the vertical distribution along the upstream and downstream transects for the mixed layer (Figure 12c, d) and for the zooplankton layer (Figure 12e, f).

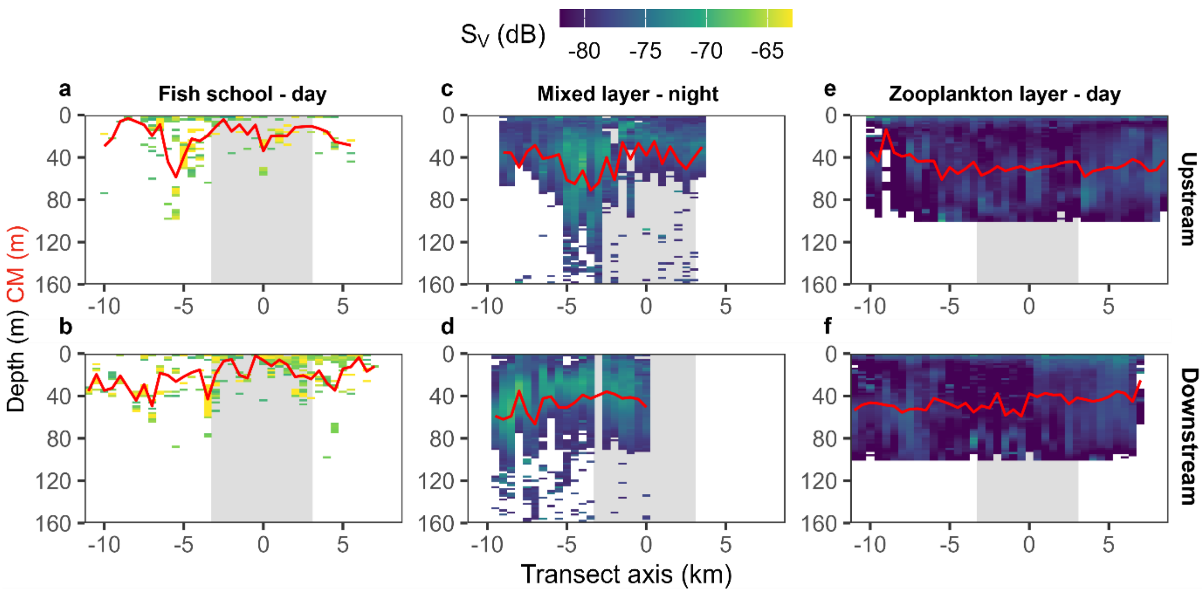

*Figure 12 Synthetic echogram of (**a**, **b**) fish schools during the daytime, (**c**, **d**) mixed layer during nighttime, and (**e**, **f**) zooplankton layer during the daytime of the (**a**, **c**, **e**) upstream and (**b**, **d**, **f**) downstream transects along the sampling axes perpendicular to the main SE current direction. The grey area indicates the centre of the transect corresponding to the width of the farm (see Figure 5). The red line indicates the centre of mass (CM) of each group per transect.*

For the three groups – fish schools, the mixed layer, and the zooplankton layer – we did not observe large differences between the upstream and downstream transects length in terms of mean biomass density (Figure 13a, b, c), vertical distribution (Figure 13d, e, f), dispersion (Figure 13g, h, i), and patchiness (Figure 13j, k, l). For simplicity, confidence bands around the average line are not shown in the figure. However, a statistically significant difference between the upstream and downstream areas at specific points along the transects cannot be necessarily translated as a sign of impact from the farm. The comparison between transect areas needs to be done considering the entire transect to understand if there is any biologically significant difference between the two at the level of the farm. Given the rationale explained in 3.2.3.4, an impact from the farm would be expected if the differences between the upstream and downstream lines at the level of the farm (approximately grey shaded area) would be larger than the naturally occurring differences, expected at the edges of the transects. In Figure 13, despite larger than average differences occur at specific points along the transects, we cannot see a pattern of consistent differences at the centre (around the grey shaded area) which is larger than the overall variability at the edges of the transects.

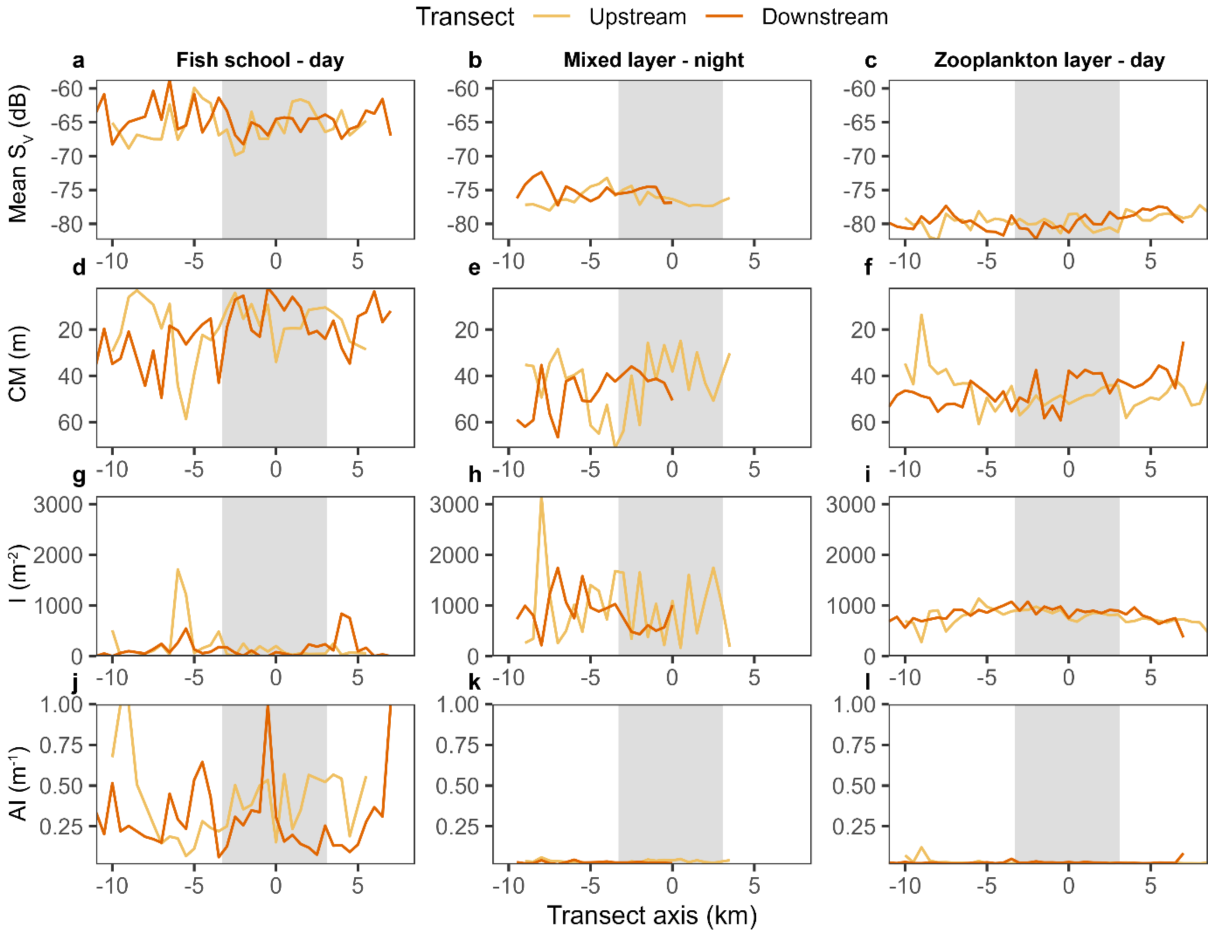

*Figure 13 Averaged echo metric per transect type along the sampling axes (see Figure 5) for (**a**, **d**, **g**, **j**) fish schools, (**b**, **e**, **h**, **k**) the mixed layer and (**c**, **f**, **i**, **l**) the zooplankton layer. The echo metrics include (**a**, **b**, **c**) mean S_V, (**d**, **e**, **f**) centre of mass, (**g**, **h**, **i**) inertia, and (**j**, **k**, **l**) aggregation index. The vertical grey shadowed area shows the width of the farm along the direction of the sampling axis. farm*

5 Discussion

5.1 Baseline data on the biomass density and distribution at Hywind Tampen

Hywind Tampen is located in a deeper area than Hywind Scotland and hosts fish schools, zooplankton layers, and a mixed scattering layer. The mixed scattering layer was not observed at Hywind Scotland and was associated with the deeper areas around Hywind Tampen (cf. Figure 11e). These three groups interacted with each other throughout the day. For example, the mixed layer performed DVM and ascended to the surface waters at night, presumably to feed on the zooplankton layer. Similarly, pelagic fish were schooling during the day only, and single fish were observed during the night – a typical anti-predatory behaviour. However, knowledge gaps remain regarding the species composition and biodiversity of these three groups observed with acoustics. Determining the species composition would help understand prey-predator dynamics and their impacts on the abundance and spatial distribution of zooplankton and fish in the Hywind Tampen area.

5.2 Limited effects of the wind farm on pelagic fauna

We did not observe an increase in biomass density or changes in the depth distribution of pelagic fish schools inside or near the wind farm at the time of the survey, suggesting the farm does not aggregate pelagic fish. Similarly, we did not observe differences in the depth distribution or density of the mixed layer in the vicinity of the wind farm, indicating that the possible changes in hydrography due to the presence of the installations or the biofouling on them does not affect lower trophic levels production and, by consequence, fish aggregation at a noticeable level. However, since the first seven wind turbines at Hywind Tampen were installed in 2022 and the rest were under construction in 2023, there was likely limited biofouling on the turbines. These bio-fouled species are considered to be an important driver of increased production and aggregation around bottom-fixed wind farms (Degraer et al., 2020). Here, potential reef effects may have been restricted because of the limited biofouling on the turbines, which may become apparent in the future as biofouling increases.

In contrast to the mixed layer and fish schools, the distribution of zooplankton is strongly constrained by the hydrography and current regimes. We observed higher zooplankton densities in the northwest area of the wind farm and lower densities in the southeast of the wind farm – where the wind turbines were under construction (cf. Figure 11c). We also documented a deepening of the zooplankton layer to the south of the wind farm and a shallowing to the southeast. Those differences in the depth distribution of the zooplankton layer may be in the wake of the farm under certain wind and current conditions (Equinor, 2019). Here, since the zooplankton layer did not undergo large-scale DVM and remained near the ocean's surface, the potential effect of the wake may be greater than that of the bathymetry. However, further studies of the impact of wind turbines on hydrography using high-resolution modelling approaches, like Computational Fluid Dynamics modelling (CFD), paired with *in situ* hydrographical and biological observations may provide insights into the underlying processes impacting the depth distribution of the zooplankton layer.

5.3 Recommendations for future studies

Documenting the biodiversity of the different groups observed with the echosounder would improve our understanding of the potential effects of the wind farm on the pelagic fauna. These data can help describe predator-prey dynamics, which, in turn, impact the depth distribution of fish and zooplankton. Further, they can also be used to improve the classification of echosounder data using broadband properties.

Pelagic biodiversity can be documented using autonomous instrumentation, such as automatic eDNA sampler or optical sensors, like the UVP6. For example, a glider equipped with a UVP6 could characterise the species composition, biodiversity, and size structure of the zooplankton layer and the mixed layer over the study area. Paired with acoustic data, this information would be valuable for understanding the spatial and depth distribution of biodiversity in the wind farm area.

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