Waves and currents decrease the available space in a salmon cage

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Abstract

Due to increasing demand for salmon and environmental barriers preventing expansion in established sites, salmon farmers seek to move or expand their production to more exposed sites. In this study we investigate the effects of strong currents and waves on the behaviour of salmon and how they choose to use the space available to them. Using video cameras and echo sounders, we show that fish prefer to use the entire water column, narrowing their range only as a response to cage deformation, waves, or daylight. Conversely, fish show strong horizontal preference, mostly occupying the portions of the cage exposed to currents. Additionally, waves cause salmon to move away from the sides of the cage. Even when strong currents and waves decrease the amount of available space, salmon choose to occupy the more exposed part of the cage. This indicates that at least with good water exchange, the high biomass caused by limited vertical space is not so aversive that salmon choose to move to less desirable areas of the cage. However, the dispersal throughout the entire available water column indicates that keeping the cone portion of the cage available in strong currents would be beneficial to salmon welfare.

Introduction

Aquaculture is a major provider of fin fish protein consumed globally, accounting for approximately 52% of all fish produced for human consumption [1]. In aquaculture, Atlantic Salmon accounts for only 4.5% of production in weight, but 19% in value, largely due to the popularity of salmon sushi. While aquaculture production is increasing globally, salmon production in the Atlantic is stagnating. The causes mainly relate to complete exploitation of available farming sites, with pollution and parasite infestations being the major factors limiting expansion in near-shore sites [2].

Salmon lice (*Lepeophtheirus salmonis*) are a major parasite in Atlantic salmon farming. They spend their parasitic life stages on the salmon where they consume mucous, blood, and skin, which leads to sores and in extreme cases, mortality [3, 4]. Even sub-lethally, salmon lice are a cause of poor welfare due to the stress and pain caused both by the parasites themselves and the removal methods [5, 6].

Because of the ever escalating challenges posed by salmon lice and the limitations put on biomass in near shore sites, the salmon aquaculture industry is making investments in adapting current farming methods. One such adaptation is to move farms out to more exposed locations where higher water exchange can mitigate pollution and possibly dilute infectious sea lice [7, 8]. At the current rate of development, salmon will experience substantially larger waves in substantially different farm constructions than those being used in industry for the last 20 years [9].

Due to the forthcoming changes in salmon aquaculture, much work has been carried out in order to determine how well salmon are able to cope with the currently most extreme conditions [8]. From these studies, some information is available on swimming speed capacity [10], sensitivity to variation in temperature and oxygen saturation [11–14], swimming energy expenditure, and how a variety of these factors affect growth and feed conversion [15–17].

Recently, work has also been carried out on how behaviour is affected by waves, mostly investigating vertical preference and swimming effort [18, 19]. Data on how salmon behaviour and welfare is affected by cage deformation, are still limited, however. Furthermore, the combination of waves and currents and their effect on behaviour has not yet been thoroughly investigated.

In addition to increasing demand for salmon driving industry to innovate, there is also an increased awareness of fish welfare considerations [20, 21]. This means that there is growing consumer pressure for not only environmental certifications such as ASC, but also for assurances that the farms can deliver a minimum welfare standard [22]. Being able to farm fish in exposed locations without compromising on welfare requires extensive knowledge of how these new conditions will affect the fish. While most salmon farmers have intimate knowledge of already established sites, it is still necessary to be able to generalise such knowledge to new and more exposed sites. This study is an attempt at detailing how salmon are affected by a combination of many environmental factors and how they interact, particularly the combination of currents and waves.

Here, we monitor fish in a cage exposed to both currents and waves throughout the winter months of 2019/2020.

We predict that currents cause fish to move upwards in the water column, and that this is at least partially caused by the cage bottom being pushed upwards by the current.

We predict that daylight and waves will cause the salmon to move downwards in the water column, and that situations where large waves and strong currents coincide is where salmon have the most limited space available to them.

Materials and methods

Field site

Work was carried out at Hiddenfjord's "Velbastaður" salmon farm on the Faroe Islands, which is a site that is exposed to strong tidal currents as well as large waves in winter. The cages are arranged in a straight line along the coast, which is oriented close to a Northwest-Southeast axis (Fig 1). A small island ("Hestur") west of the farm creates a strait through which tidal currents move, alternating between northbound and southbound currents. Due to the hydrodynamic conditions at the site, the side of the farm nearer the shore is more sheltered than the outer side. Depending on wind direction, waves enter the strait either from the south or north of Hestur, so either the southernmost or the northernmost cage will receive a larger portion of the wave energy.

Fig 1. Study site. The map shows precise close up location of the farm and study cage with 5 m depth contours as well as zoomed out maps of general location in relation to surrounding islands with 10 m depth contours.
Map from the Faroese Environment Agency, Umhvørvisstovan

For the purposes of this study, the southernmost cage was selected for observation. Being located at one end of the row of cages, it was highly exposed to currents, especially from the south. Additionally, the cage was expected to be exposed to waves entering the strait from either side of Hestur.

The cage was stocked with 112 thousand salmon with a mean body length of 54.0 ± 4.1 cm, weighing 2.16 ± 0.6 kg, which amounted to an approximate biomass of 15 kg $m^{3\ -1}$. Additionally, the cage housed approximately 10 thousand lumpfish (*Cyclopterus lumpus*). The fish were fed using air driven surface feed spreaders regulated using a feed camera, which detected uneaten pellets.

Equipment setup

To monitor waves and currents, two Acoustic Doppler Current Profilers (ADCPs) were deployed; one AWAC directly north of the northernmost cage and one Sentinel V directly south of the study cage. Both profilers were set up to collect hourly wave data and current data every ten minutes. To monitor vertical distribution of fish within the cage, two echo sounders were attached to the cage bottom, both positioned half way between the centre and side of the cage at opposite sides parallel to the coast line. The echo sounders were suspended from the bottom of the cage looking up, thereby recording distance to the surface as well as any fish within the echo sounder beam. This allowed us to measure the depth of the cage as well as which parts of the water column were occupied by fish. The echo sounders were equipped with sensors measuring tilt and pressure. These were used to detect any instances where deviations from vertical would invalidate distance data and to validate the distance to the surface measured by the echo sounders. The echo sounders were set up to ping once every four seconds and tilt sensors recorded tilt every five seconds. In addition to the echo sounders, six pressure sensors were attached to the cage in order to properly account for any cage deformation that may occur. These were set up to record pressure every five seconds. To monitor fish behaviour such as swimming effort, shoal cohesion, and swimming direction as well as collisions with the cage netting and jumping, five video cameras were set up within the cage. In the centre of the cage was a camera used by the farmers for feed monitoring ("Feed camera"). Three cameras were at the bottom looking up located approximately equidistantly around the edge of the cage, one towards the south where northbound tidal currents entered the cage ("South"), one towards the north where southbound tidal currents entered the cage ("North") and one towards the east, which was the most sheltered location in the cage ("East"). One camera was placed on the side of the cage at five metres depth looking inward ("Inwards") near the "South" camera (Fig S2). Camera "North" and "South" were positioned such that they would capture current related swimming behaviour, such as maintaining position against the current as well as any potential changes caused by waves. The more sheltered camera was used to record fish avoiding currents or waves and whether consistent swimming behaviour (for example circling the cage) persisted throughout the cage. The camera looking inwards was used to capture close up video of fish either orienting towards the current or swimming alongside the edge of the cage as well as capturing fish near the surface of the water. Finally, the feed camera was used to capture feeding, jumping, and presence within the centre of the cage outside of feeding times. Details about the instruments can be found in Table 1.

Fig 2. Layout of equipment. Aerial and side on view of the study cage with the location of echo sounders, pressure sensors and video cameras. Camera viewing angles are approximate. The camera with diagonal stripes is the feed camera, which was nearer the surface than the bottom mounted cameras.

Table 1. Equipment deployed.

Type	Manufacturer	Specifications
ADCP	Teledyne	RDI Sentinel V 500 kHz with 50m range
ADCP	Nortek	AWAC 600 kHz with 50m range
Echo sounder	Simrad	EK 15 200 kHz 26^o viewing angle
Tilt sensor	Star-Oddi	Starmon Tilt; tilt, pressure, and temperature logger calibrated to 50m
Pressure sensor	RBR	RBRSolo 3 D; Depth logger, range 1700m, calibrated to 50m
Video camera	JT Electric	

Location of equipment in the cage can be seen in Figure S2.

Data collection

Data collection was carried out from the first of November 2019 to the 15th of February 2020 in order to capture as much as possible of both bad weather events as well as different tidal conditions.

Video cameras were remotely controlled using iSpy [23] and scheduled to record for five minutes each once per week. In addition to these baseline recordings, alternative schedules were enacted for bad weather events to record 3-4 times each day to capture behaviours in large wave conditions as well as different current conditions. At the end of the trial, videos to extract behaviours from were chosen based on current and wave data from ADCPs to represent a range in conditions.

Echo data was recorded continuously on a local hard drive and then uploaded remotely to a cloud server. Current and wave data was recorded locally and downloaded when the ADCPs were recovered. Tilt and pressure sensors stored data locally and data were downloaded when the sensors were recovered.

During the sampling period, Operational Welfare Indicators (OWIs) were recorded every two weeks when weather allowed (Table 2). Prior to this, welfare indicators were collected on a more ad-hoc basis, and finally again at harvest. The large gap in data from March until harvest is due to the COVID-19 pandemic preventing fieldwork. The OWIs were collected from 10 fish from each cage in connection with routine louse counting. The fish were caught using a dip net, anaesthetised in Finquel (MS-222) and lice numbers and gill condition were recorded before OWIs were recorded. After regaining consciousness in fresh seawater, they were released back into the cages.

Table 2. Operational welfare scores recorded.

Type	Fins	Pupil	Sclera	Snout	Skin
0	A little wear	Black	White	No injury	No injury
1	Damaged	White spot	10% black	Slightly worn	$<$ 2.5 cm
2	Missing fins	Big white spot	25% black	Wound	$>$ 2.5 cm
3		Bleeding	$>$ 50% black		Bleeding

Each fish was scored on their overall condition, so both eyes and all fins were checked and the greatest score recorded for each.

Data processing

Behaviours extracted from videos depended on the location of the camera. The cameras that were near the edge of the cage looking up were used to record collisions with the net while the cameras that were nearer the surface ("Inwards and "Feed") were used to record jumping behaviour, feeding and presence of fish near the surface. All cameras were used to record swimming effort determined as the time taken to beat with the tail three times (and hence converted into tail beats per second "tbps"). Additionally, a qualitative measure of number of fish present was recorded; "No fish"; fewer than 5 fish visible, "Few fish"; Fewer than 50 fish visible, "Many fish"; More than 50 fish visible. Finally, general swimming direction, in cases where more than 80% of the fish were swimming in the same direction, and whether the fish were shoaling was recorded from all locations. Behaviours were extracted using BORIS [24] and swimming effort was recorded using VLC [25] with the "Time" extension [26].

Echo sounder data was extracted from the raw data files using the "oce" package in R [27] and exported for further processing in Python [28] (github). First, the water surface was found. Second, data above the surface was removed, and depth adjusted to the surface rather than the distance from the echo sounder. Third, the data were binned into 5 minute intervals and 16.5 cm depths and S_v (acoustic back scattering strength) averages were exported. Once data had been exported, the exported files were read into R, where the surface and the lowest 4.5 metres (below the cage bottom) were removed.

Data analysis

Analysis was carried out in R [29] and tidyverse [30] using the packages lubridate [31] and circular [32] for data cleanup, lme4 [33] and lmerTest [34] for statistical inference, and ggplot2 [35] with colorspace [36] was used for plotting .

For video data, the following methods were used; to analyse swimming mode, a general linearised mixed effects model was used with a binomial (log link) family specified where each video was classified as most fish being in either swimming mode, with current strength, current direction, and wave height as predictors, and with camera as the random intercept term. The effects of environmental conditions on swimming effort was analysed using linear models. Nearness to camera was analysed using a general linearised mixed effects model with wave height (Hm0) and period (Tp) as predictors and cameras as random intercept term.

Linear models were used to estimate the effects of environmental variables on the "evenness" of fish dispersal within the cage using raw S_v as a proxy for relative fish density. The residuals from these models indicated how variable S_v was, so large residuals indicated "clumping" and small residuals indicated evenly dispersed fish. We also used linear models to how estimate how environmental variables affected where in the water column the salmon were, weighing the depth variable by S_v. While it is possible to estimate real biomass from the back scatter [37], we did not calibrate gain to do this, as we were more interested in relative changes rather than biomass estimation.

Ethics statement

This study was not a manipulative experiment. However, we did install video cameras within the cage as well as echo sounders underneath it. We do not have reason to believe that these affected the salmon, but they were a deviation from the regular routines on the farm. We also handled the fish in order to perform OWI monitoring, but this was already part of the management routine at Hiddenfjord farms, so didn't deviate from normal practices. Regardless, ethical approval was still applied for and given by Fiskaaling's Ethical Board (Approval number 007).

Results

Environmental conditions

During the monitoring period, currents at the north of the farm ranged from 0.00 to 0.49 m s^{-1} with a mean current of 0.10 m s^{-1}. At the south of the farm, conditions were similar with a range between 0.06 and 0.51 m s^{-1}, and with stronger currents on average (0.16 m s^{-1}) (Fig 3). Flow direction was mostly bimodal switching between a north-westerly current and a south-easterly current, hereafter referred to as Northbound and Southbound current (Fig 3). Due to the difference in particularly current direction between the two ADCPs, the Sentinel V or a tidal analysis built on the data from the Sentinel V were used for further data analysis using current as a predictor.

Fig 3. Current and wave directions from two current profilers. Wind roses of the currents and waves measured by the two profilers. Currents are towards the indicated directions, waves travel from the indicated directions

The maximum significant wave height (Hm0) measured north of the farm was 3.02 m. South of the farm it measured (Hs) 3.24 m (Fig 4). Wave period (Tp) ranged from 2.07 to 22.55 seconds. Low and high wave heights were recorded at the same time in both ADCPs, indicating that they were exposed to similar wave heights, though wave directions differed between the two locations, with waves coming from the south rarely being measured in the Sentinel V (Fig 3). Even though wave directions differed between the two ADCPs, the wave data from the AWAC was used in analyses going forward due to the longer measurement period.

Fig 4. Wave height measured by two current profilers. The wave heights measured throughout the monitoring period. The Sentinel V was located south of the study cage whereas the AWAC was located north of the farm.

Cage deformation

The bottom of the cage moved up from almost -20 m up to -6 m depth. The sides of the cage did not move as much, varying approximately three metres in depth between -9 m and -6 m (Fig 5). The direction of current affected how the pressure sensors moved with oncoming current causing the bottom of the net to move up farther than current from the lee side of the cage. In other words, in a northbound current, the bottom of the south side of the cage moved up more whereas in a southbound current, the bottom of the north side of the cage moved up more. The southern side of the cage was particularly affected in a northbound current, as there were no cages south of the study cage to shelter it.

Fig 5. Depth measured by pressure sensors. Pressure sensors were located in eight locations at the bottom of the cage. Four sensors were located at the bottom of the side net (Side- west, south, east, and north) and four were half way from the side to the centre (Bottom- west, south, east, and north)

Video observations

Swimming mode

There was a connection between current speed and swimming mode. The number of videos where the most prevalent swimming mode observed was keeping place against the current increased with current speed. This effect was decreased in southbound current (Current speed; $z = 3.643$, residual df $= 151$, $P < 0.001$, Flow direction; $z = -3.683$, residual df $= 151$, $P < 0.001$, Fig 6), which is consistent with the indication from the pressure sensors that northbound current affected the cage more than southbound current.

Fig 6. Proportion of time spent by the majority of the fish in frame keeping against the current. Points are proportion of time where the majority of the fish were keeping place against the current in a video and lines are model predictions of the probability of a video having fish keeping place against the current a majority of the time. Lighter colour signifies a northward current direction whereas a darker colour signifies a southward current direction

Swimming effort

Because fish recorded for swimming effort were more likely to be fish that spent a longer time in frame than those who spent a short time in frame, there are likely to be differences between these fish and the general population within the cage.

Swimming mode significantly affected tail beats per second with fish beating faster with their tails when not swimming against the current ($F_{1,445} = 28.34$, $P < 0.001$). Because of this change in swimming effort related to swimming mode, data were analysed with swimming mode as a random predictor in a linear mixed effects model. Swimming effort increased with current speed in northbound current, but this connection was not present in southbound current ($t = -2.358$, df $= 440$, $P = 0.019$, Fig 7). Wave length interacted with current speed in such a way that in weak current, fish had slower tail beats in shorter waves, but in stronger currents, they had faster tail beats in longer waves ($t = 2.309$, DF $= 440$, $P = 0.021$, Fig 7).

Fig 7. Swimming effort measured in tail beats per second (tbps) over current. Swimming effort in fish keeping place against the current in northbound and southbound currents. Shading indicates wave length less than 12 seconds (lighter colour) and more than 12 seconds (darker colour).

Cage perimeter interactions

Fish showed great horizontal preference ($F_{4,160} = 8.641$, $P < 0.001$) with the "South" camera recording "Many" fish 36% of the time compared to the "East" camera, which only recorded "Many" fish 4.5 % of the time. The amount of time where "Many" fish were recorded in cameras generally decreased in large waves (both high Hm0 and Tp) ($F_{3,161} = 3.398$, $P = 0.019$, residual df $= 159$), indicating movement away from the sides of the cage, and in case of the feed camera, the surface. However, in taller waves the amount of fish seen in the "East" camera increased, with the proportion of time when any ("Some","Many", or "Shoal") fish were visible in the "East" camera increasing from 50% in waves smaller than 1 m to almost 100% in waves larger than 1 m ($F_{4,155} = 7.545$, $P < 0.001$).

Collisions with the net decreased in larger waves, but less so if current was strong too ($z = 2.431$, DF $= 41$, $P < 0.015$).

Shoal position

Fish avoided the surface during the day (Fig 8) and this pattern persisted regardless of hydrodynamic conditions.

Fig 8. Depth and dispersal of fish seen in the south echo sounder over hour in the day when current is weak. Back scatter strength (S_v) indicates fish density, with higher values (-70) indicating many fish and lower values (-100) indicating fewer fish. Data presenting current stronger than 0.11 m s^{-1} is not included for simplicity.

As current increased, the fish narrowed their vertical distribution within the water column resulting in stronger localised S_v (South echo sounder; $F_{3,250864} = 2993$, $P < 0.001$, North echo sounder; $F_{3,239438} = 1836$, $P < 0.001$) and greater residuals (South echo sounder; $F_{3,250864} = 759.1$, $P < 0.001$, North echo sounder; $F_{3,239438} = 1265$, $P < 0.001$) as opposed to a lower signal with more even dispersal in weaker currents (Fig 9).

Fish moved upwards in the water column in stronger current. The side of the cage and direction of current affected the degree to which the shoals moved up (South echo sounder; $F_{3,218622} = 8665$, $P < 0.001$, North echo sounder; $F_{3,206399} = 7170$, $P < 0.001$, Fig 9). They still avoided the surface during the day, resulting in a greater concentration of fish below 5m depth (Fig 9).

Fig 9. Depth and dispersal of fish over current. The upper and lower panels indicate the two echo sounders, and the left and right panels the direction of current. Back scatter strength (S_v) indicates fish density, with higher values (-70) indicating many fish and lower values (-100) indicating fewer fish. Data presenting shoal depth during the night is not included for simplicity.

In an effect similar to that of daylight, waves caused fish to move away from the surface (South echo sounder; $F_{4,218621} = 6307$, $P < 0.001$, North echo sounder; $F_{3,206399} = 6026$, $P < 0.001$). However, at the side of the cage where current entered, fish moved upward, countering the effect of waves (Fig 10).

Fig 10. Depth and dispersal of fish over wave height (Hm0) in weak current. The left and right panels are the south and north echo sounder. Data where current exceeded 0.11 m s^{-1} are excluded. Signal strength (S_v) indicates fish density with higher values (-70) indicating many fish and lower values (-100) indicating fewer fish. Data presenting shoal depth during the day not included for simplicity.

Welfare

While injury scores were low throughout the entire production cycle with 90% of fish scoring three or lower in injuries most of the time, there is a period in January and February where more than 25% of the fish have a score of four or higher. In late June, when the fish were harvested, higher scoring fish had decreased again to less than 20% (Fig 11).

Fig 11. Distribution of welfare scores over time Proportion of fish with summed welfare scores between 0 and 9. A score of zero indicates that the fish had no injury at all and higher scores are more injuries.

Discussion

At the study site, currents caused the bottom of the salmon cage to move upwards from almost 20 metres up to almost 5 metres in extremes. The majority of the deformation is in the cone part of the cage, which is not included in biomass calculations for stocking purposes. Therefore, this deformation does not cause a lack of space in the cage in terms of biomass limitations, but rather displaces salmon that might otherwise choose to occupy that space.

Salmon at this study site, did prefer to occupy the cone portion of the cage during the day, while they occupied the entire water column during the night. This caused a concentration of fish above the cone (upwards of 10m) in stronger currents, and an even tighter concentration of fish between 5-10 metres during the day.

In addition to the effect of daylight and current, waves also affected vertical shoal positioning. At night, salmon avoided the surface in tall waves similarly to how they respond to daylight. However, due to the effect of cage deformation, this preference was not so clear on the side of the cage affected by oncoming current, as surface aversion due to waves was weaker than that caused by daylight.

As expected, salmon swimming mode was affected by current speed with a majority of fish changing from swimming freely to maintaining their position against the current once current speed reached 0.2 ms^{-1}. Northbound current more strongly affected swimming effort, most likely due to the lee effect of the adjacent cages in a southbound current. Additionally, longer waves increased salmon swimming effort.

Taken together, the results indicate that salmon prefer to use the entire water column available to them, and only move upwards in the water column due to cage deformation and downwards due to waves and daylight. However, the data suggest that they do not use all of the horizontal space available to them. There are a few potential explanations for this. Two likely candidates are; 1) water quality is undesirable in the more sheltered areas of the cage, 2) salmon prefer to occupy a space with current. We have no reason to suspect poor water quality in the sheltered parts of the cage, particularly as this study was carried out in the winter months with a lot of mixing in the water column and good general water exchange, even in the sheltered areas. Therefore, the more likely explanation is that the salmon actively choose the more exposed side of the cage rather than avoid the sheltered side.

As opposed to our previous paper [18], swimming effort did not decrease in larger waves, but rather increased. However, this effect was most apparent in stronger currents, which were not present at the previous study site. Additionally, in our previous paper, wave data did not coincide with video data, so it is possible that what looks like large waves on camera is not the equivalent of large measured waves. Particularly shorter waves may look more extreme than long waves due to the more rapid vertical movement.

In the current study, salmon increasingly avoid the surface as the wave height increases. While we only had good data up to 2 m wave height (Hm0), the trend indicates that salmon will dive further down in even larger waves. When combining cage deformation due to currents and surface and side avoidance due to waves, the available space decreases dramatically when all these conditions affect the fish at the same time.

In our previous paper, it was not clear whether the change in vertical position caused by current was related to cage deformation or a choice by the salmon. In this paper, we show that the bottom of the shoal moves upwards almost exactly as the bottom of the cage. Therefore, there is no evidence to suggest that the salmon move away from the bottom of the cage at any time, rather that they adjust to the change in space available to them. However, there was horizontal preference in this study related to current with fish preferring areas within the cage exposed to more current to areas with little to no current. Therefore, given zero cage deformation, the factors affecting vertical distribution of salmon within a cage are surface related (such as waves and daylight) and factors affecting horizontal distribution within a cage are current and wave related with fish preferring to swim in more current, but moving inwards away from the net in large waves. This move away from the sides was probably the reason for why observed collisions with the net decreased in larger waves. However, there appears to be an effect of weather on welfare indicators with fish scoring higher in the examinations carried out after large wave events in January and February 2020 compared to late 2019. As fewer collisions were seen, the causes of these injuries must happen off-camera, such as elsewhere in the cage or at night. However, during the large wave events, the cameras lost power, which resulted in limited footage from the most extreme conditioned at the farm. It is possible that the fish were injured during these periods, though it is impossible to say for certain.

Conclusion

The strongest effects that currents and waves have on salmon relate to how they decrease the space available to the fish. Salmon actively choose to occupy areas in the cage exposed to stronger currents, but avoid the surface and sides in large waves. For farming in new sites exposed to strong currents and potentially also in currently used sites, one ought to consider making the cone portion of the cage available to the fish even in stronger currents, as this will provide more space for them. This is particularly relevant during the day, when waves are large, and if the biomass is high, for example close to harvest. It is important to consider that unlike the effect of daylight, which only decreases the vertical availability of space, waves decrease the effective diameter of the cage, greatly reducing the volume of the cage.

Supporting information

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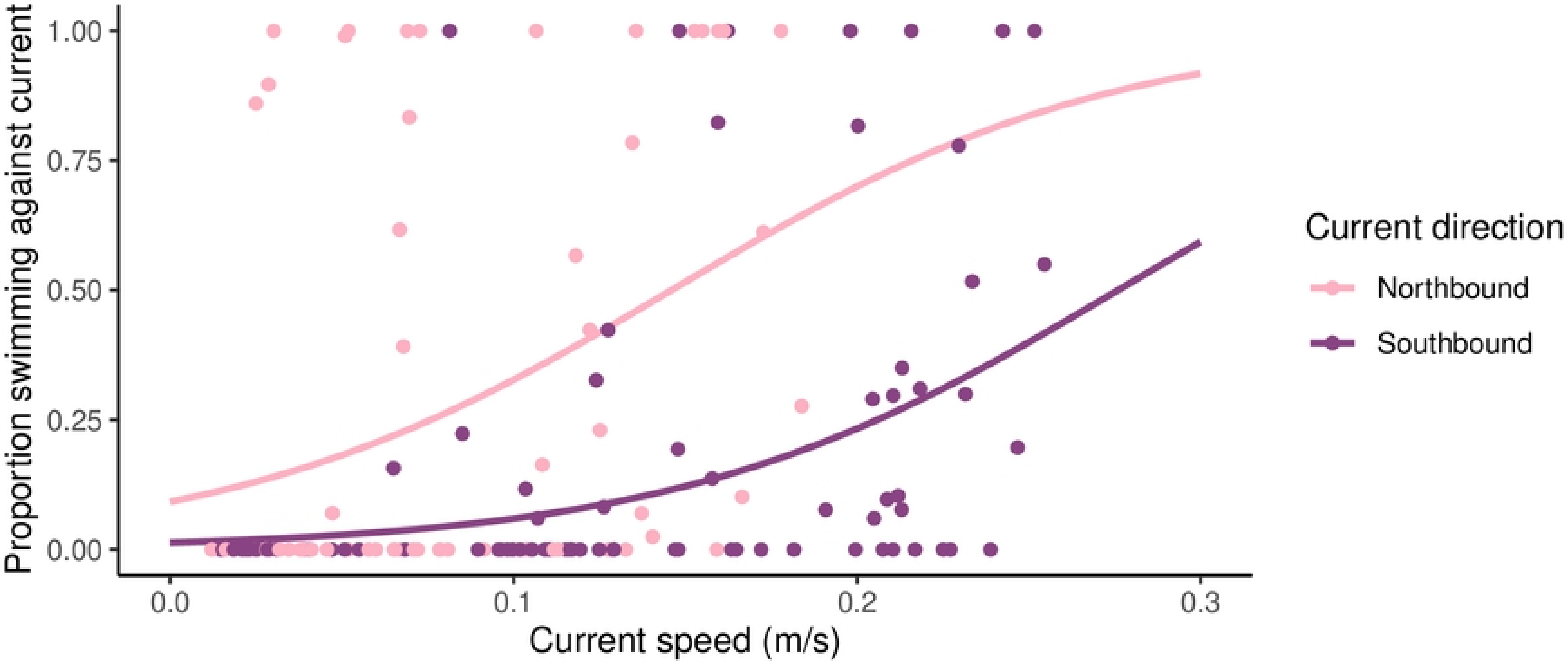

Proportion swimming against current
1.00
0.75
0.50
0.25
0.00
0.0
0.1
0.2
0.3
Current speed (m/s)
Current direction
Northbound
Southbound

Figure 6

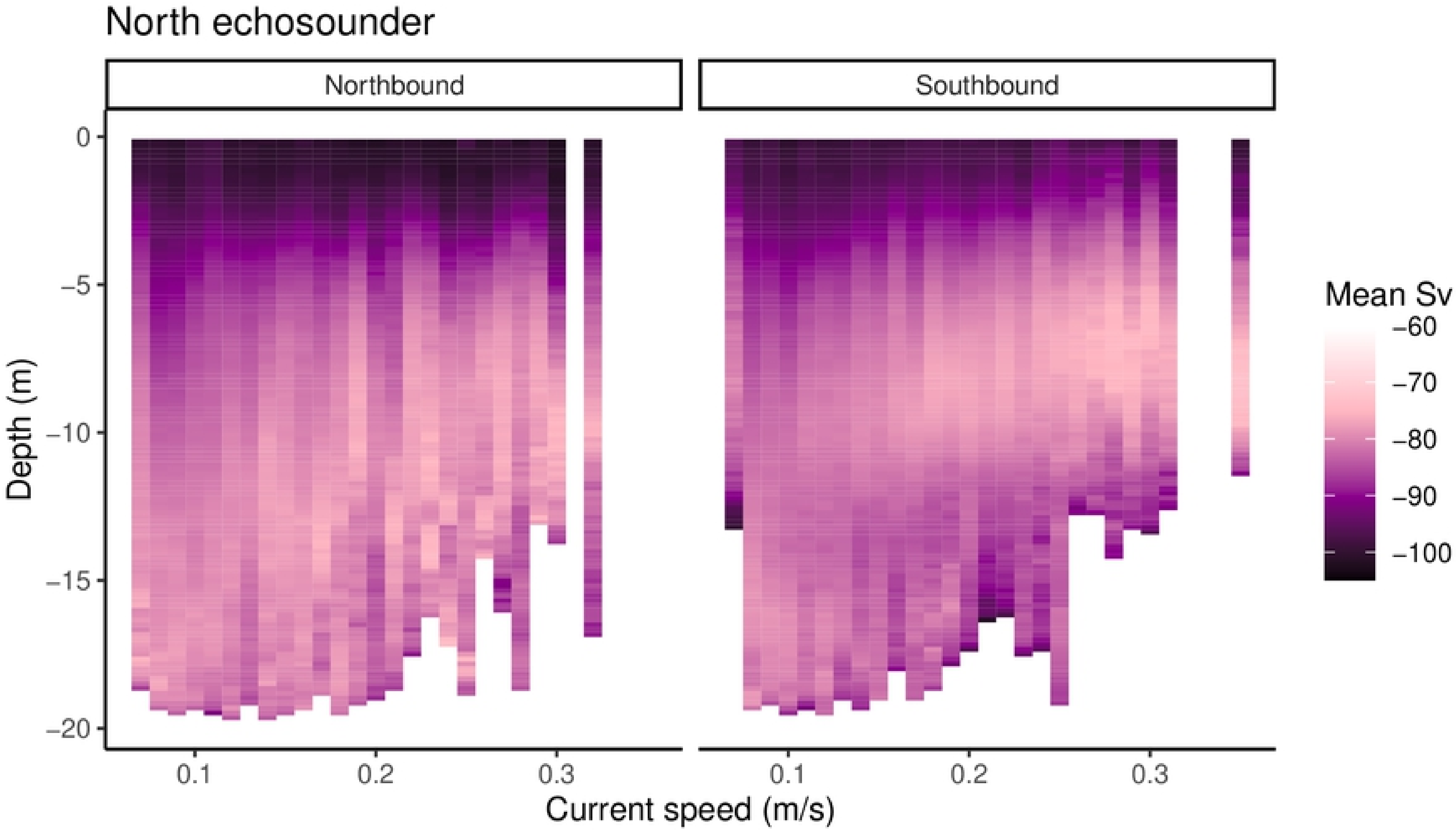

North echosounder
Northbound
Southbound
Depth (m)
0
−5
−10
−15
−20
0.1
0.2
0.3
0.1
0.2
0.3
Current speed (m/s)
Mean Sv
−60
−70
−80
−90
−100

Figure 9

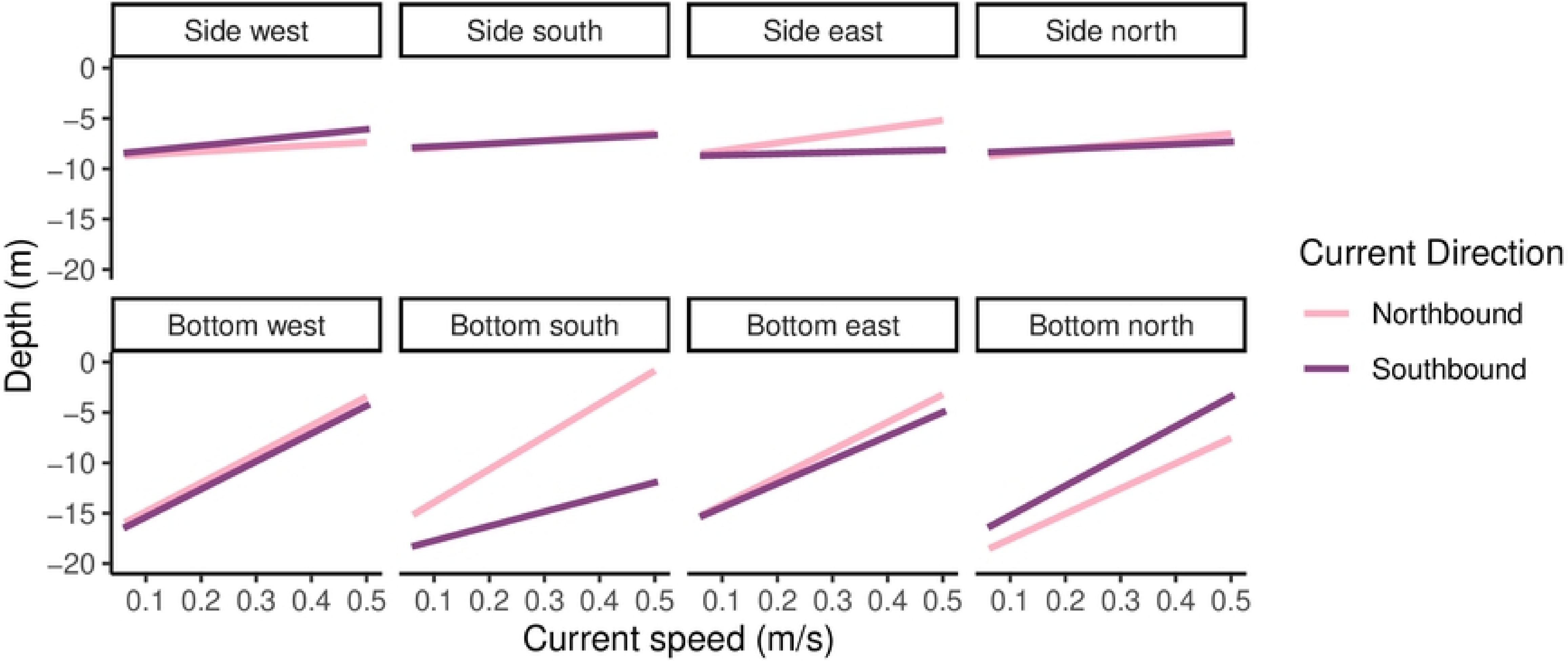

Side west
Side south
Side east
Side north
Bottom west
Bottom south
Bottom east
Bottom north
0
−5
−10
−15
−20
Depth (m)
0.1
0.2
0.3
0.4
0.5
Current speed (m/s)
Current Direction
Northbound
Southbound

Figure 5

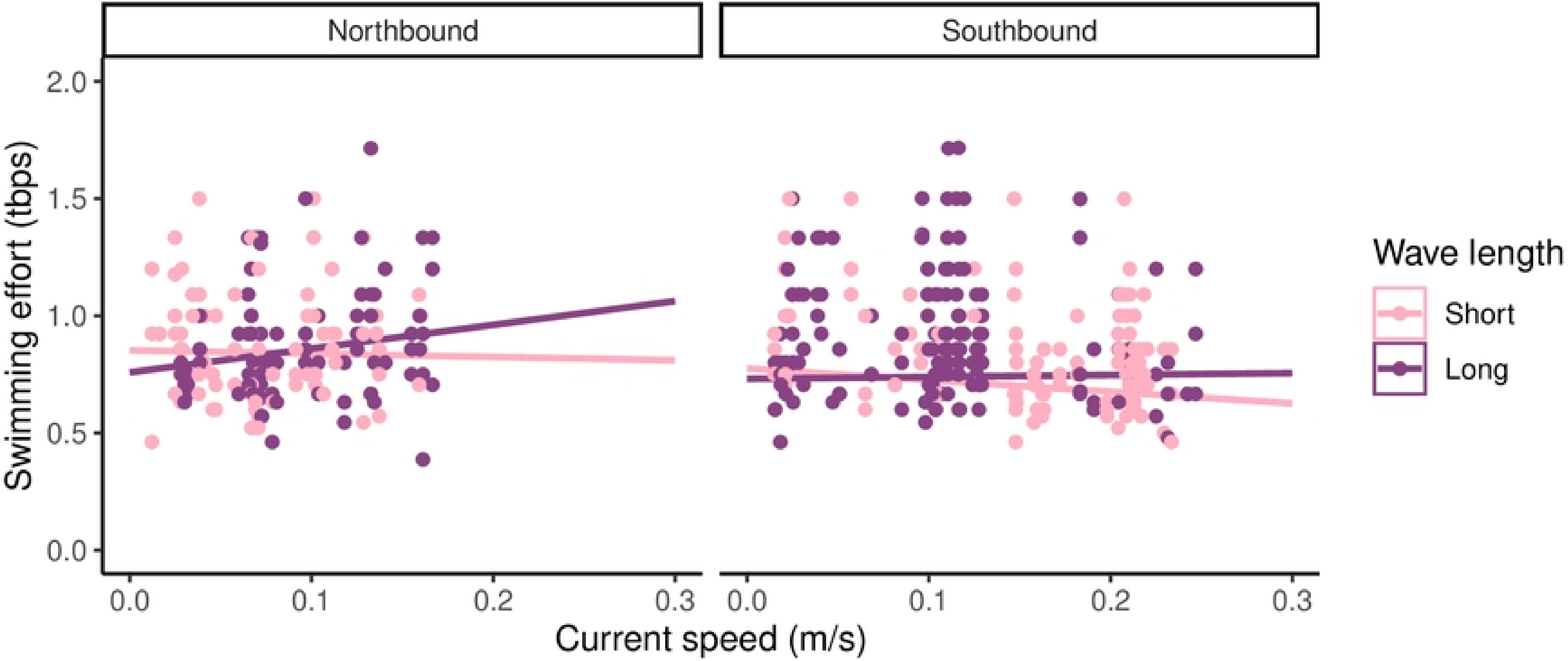

Northbound
Southbound
Swimming effort (tbps)
2.0
1.5
1.0
0.5
0.0
0.0
0.1
0.2
0.3
0.0
0.1
0.2
0.3
Current speed (m/s)
Wave length
Short
Long

Figure 7

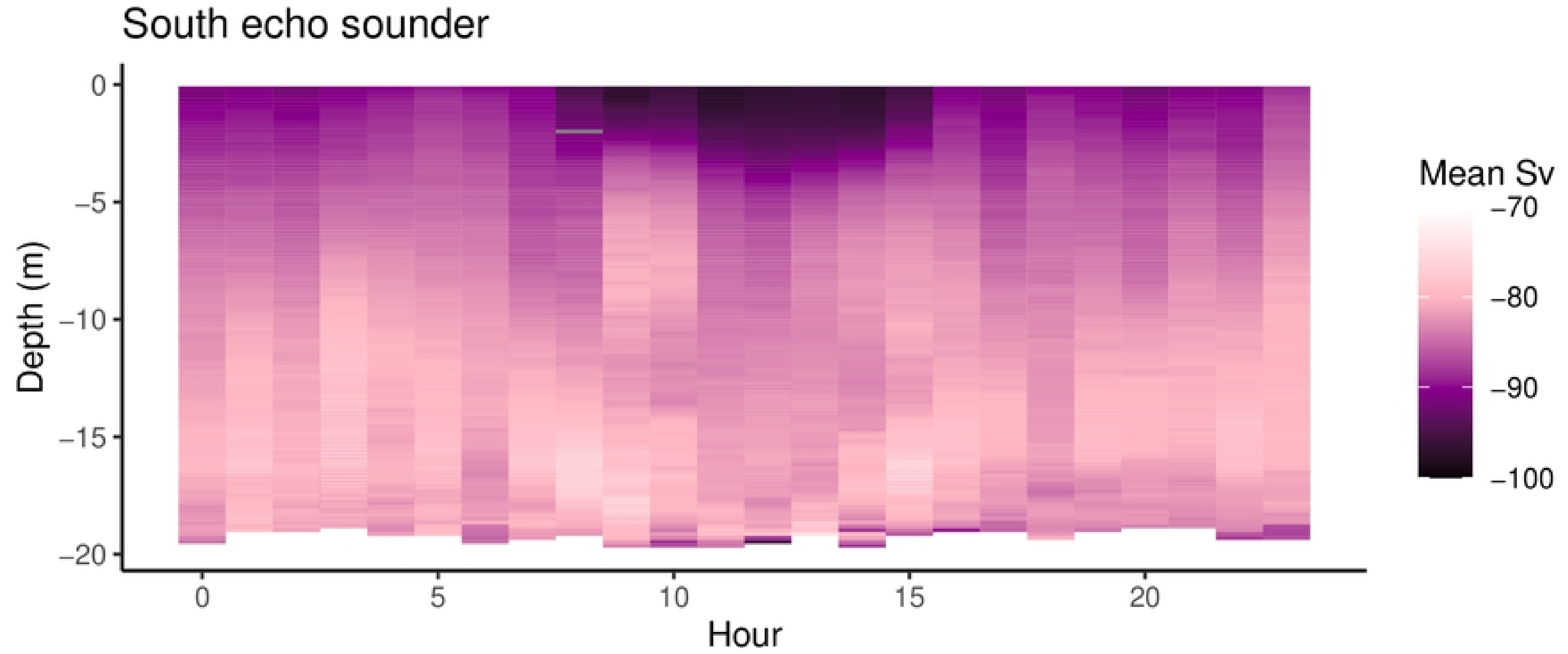

South echo sounder
Depth (m)
0
−5
−10
−15
−20
0
5
10
15
20
Hour
Mean Sv
−70
−80
−90
−100

Figure 8

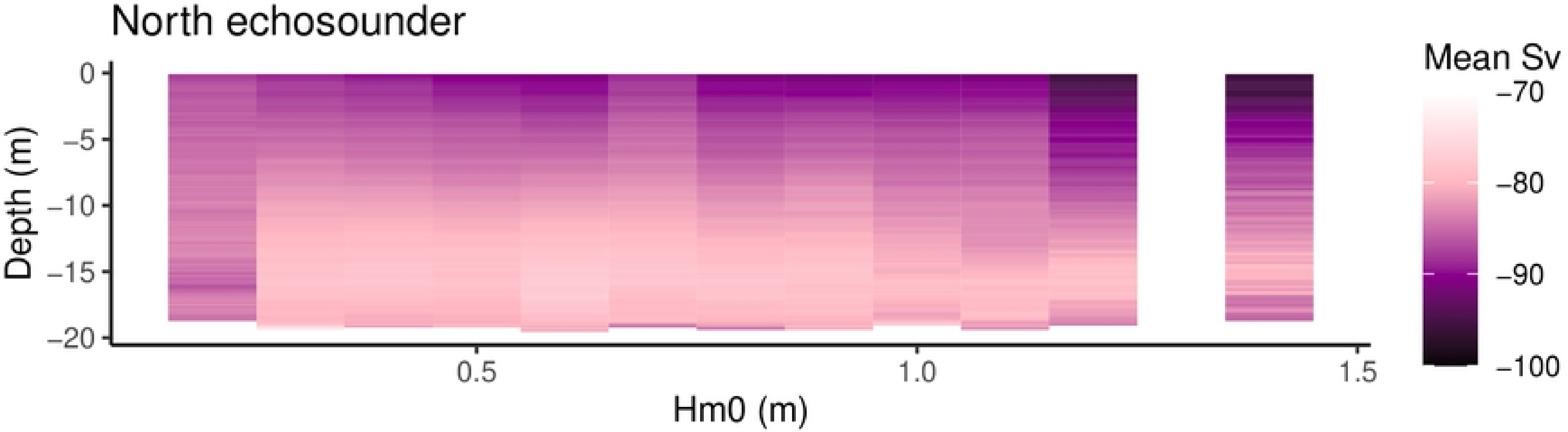

North echosounder
Depth (m)
0
−5
−10
−15
−20
Hm0 (m)
0.5
1.0
1.5
Mean Sv
−70
−80
−90
−100

Figure 10

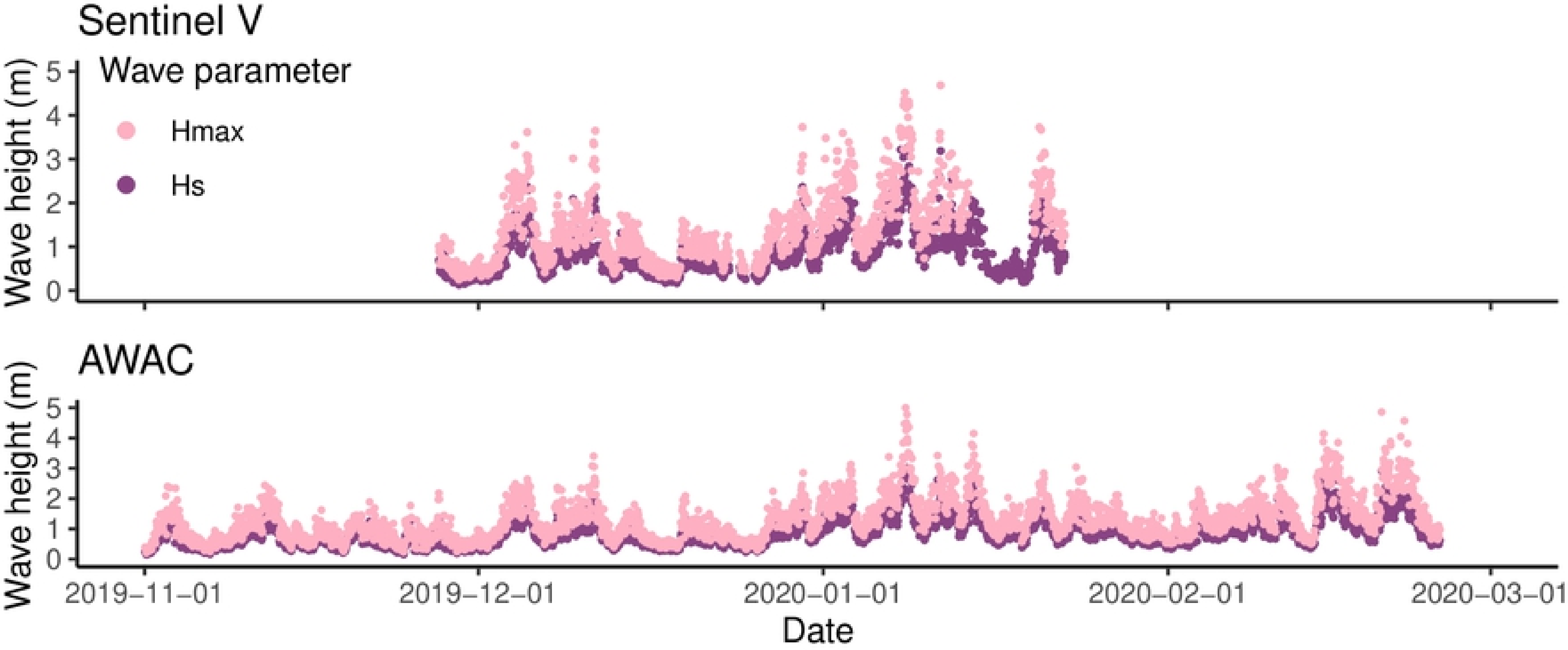

Sentinel V
Wave parameter
Hmax
Hs
Wave height (m)
5
4
3
2
1
0
AWAC
Wave height (m)
5
4
3
2
1
0
2019–11–01
2019–12–01
2020–01–01
2020–02–01
2020–03–01
Date

Figure 4

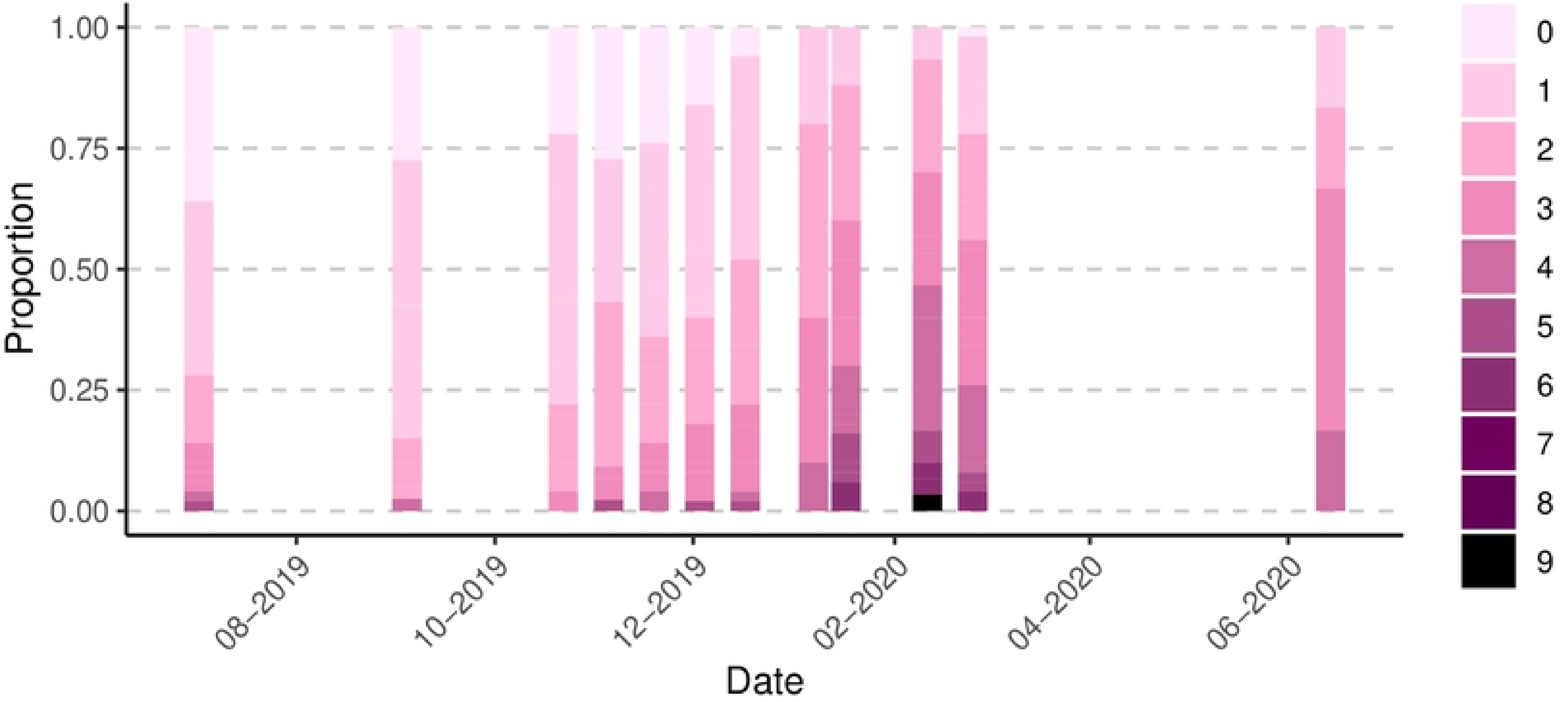
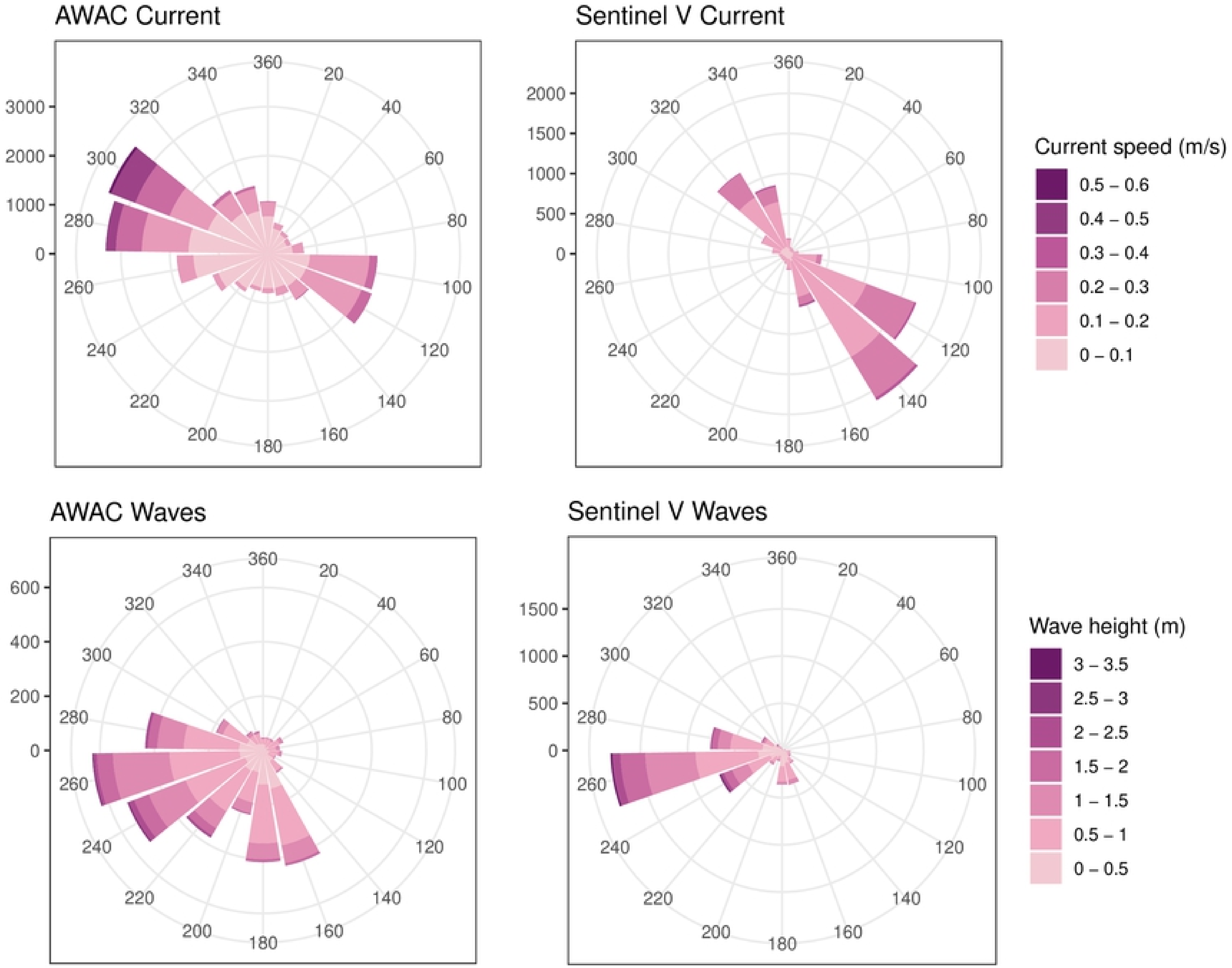

Proportion
1.00
0.75
0.50
0.25
0.00
08–2019
10–2019
12–2019
02–2020
04–2020
06–2020
Date
0
1
2
3
4
5
6
7
8
9

Figure 11


AWAC Current

Sentinel V Current

AWAC Waves

Sentinel V Waves

Figure 3

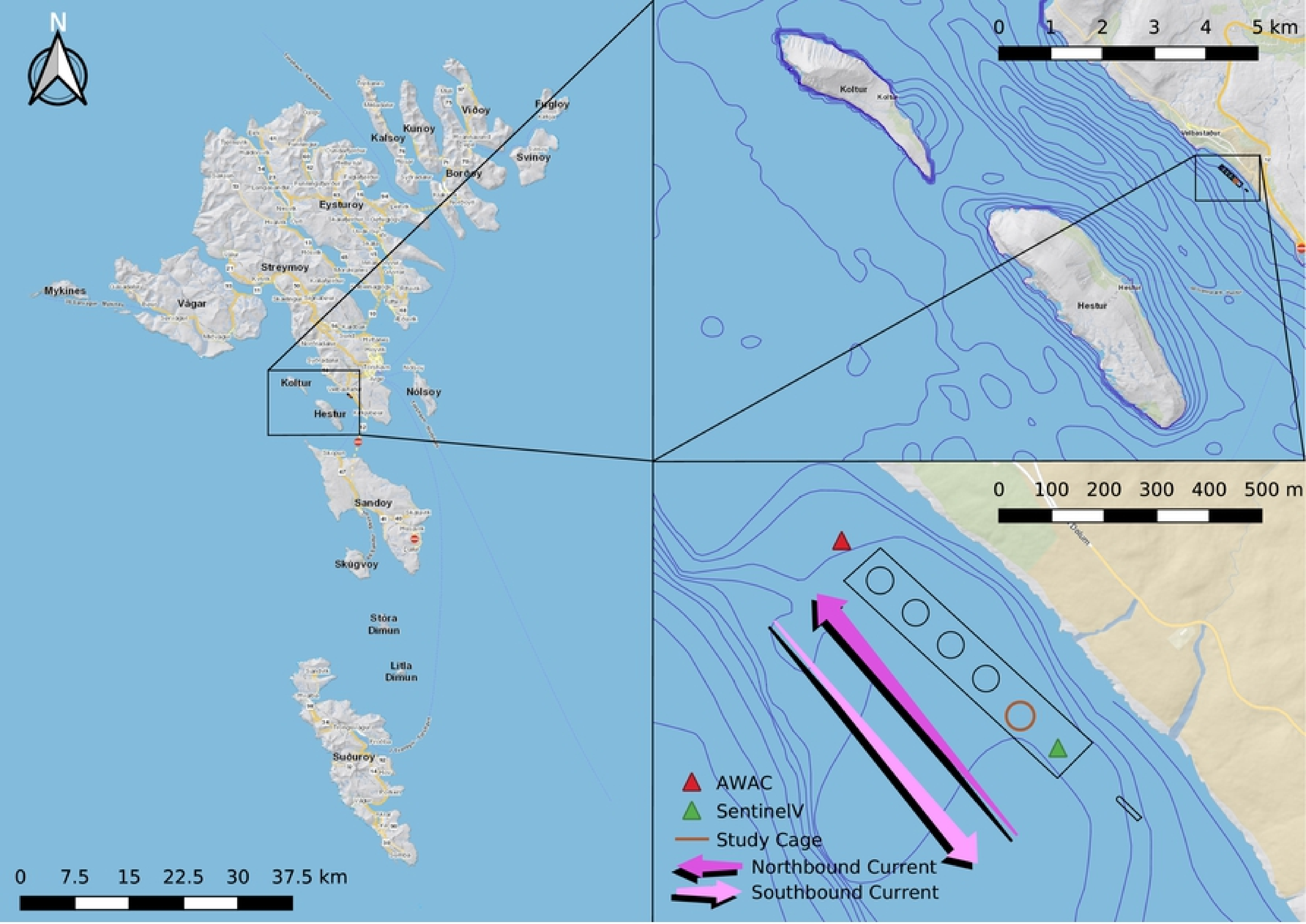

N
Fugloy
Viðoy
Kunoy
Kalsoy
Svinoy
Borðoy
Eysturoy
Streymoy
Mykines
Vágar
Koltur
Hestur
Nólsoy
Sandoy
Skúgvoy
Stóra Dímun
Lítla Dímun
Suðuroy
0 7.5 15 22.5 30 37.5 km
0 1 2 3 4 5 km
Koltur
Hestur
Velbastaður
0 100 200 300 400 500 m
AWAC
SentinelV
Study Cage
Northbound Current
Southbound Current

Figure 1

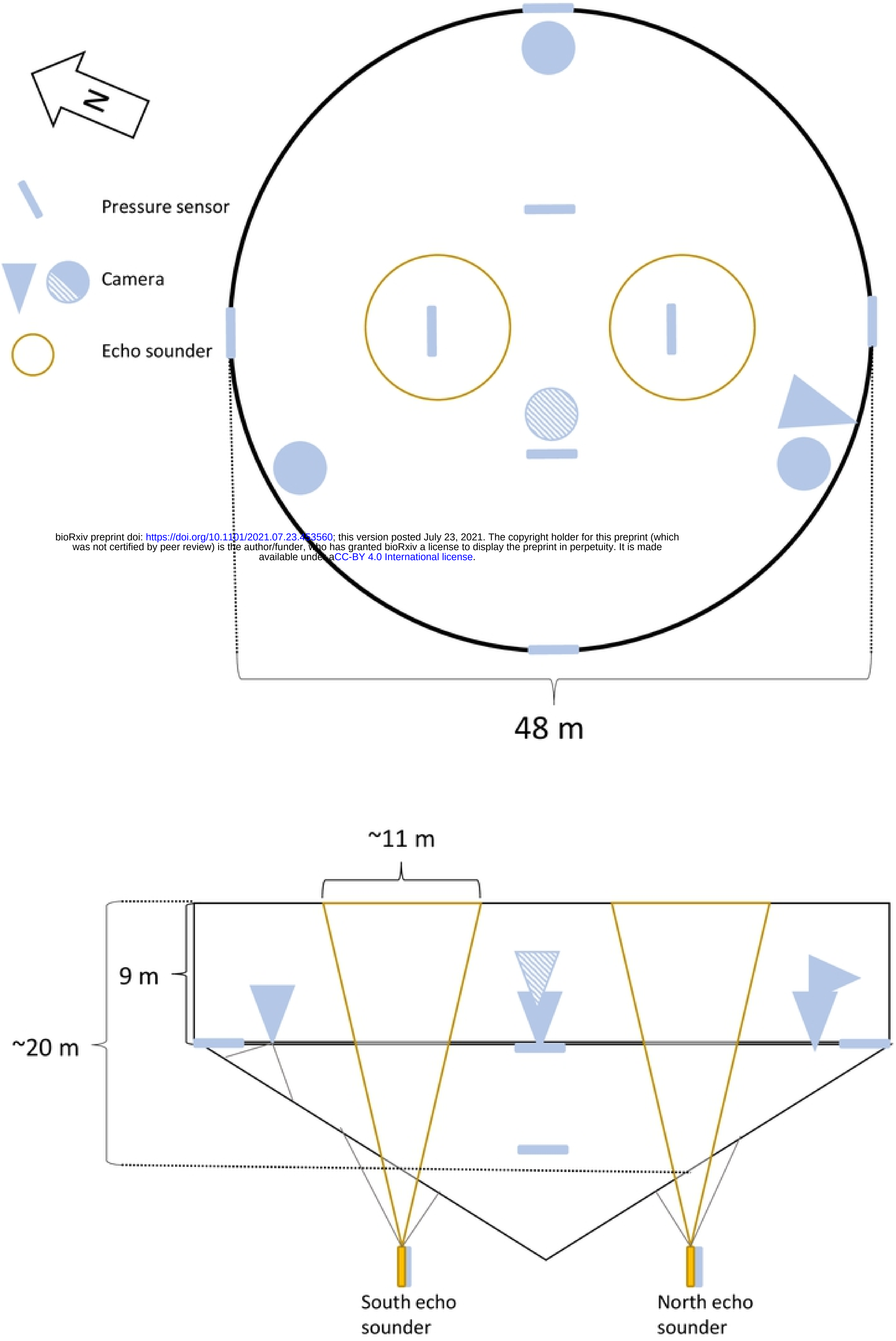

N
Pressure sensor
Camera
Echo sounder
48 m
~11 m
9 m
~20 m
South echo sounder
North echo sounder

Figure 2