Zooplankton community structure in response to turbulent flow over a sill in Nootka Sound

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Abstract

Zooplankton behaviors have been well studied, and their movement in the water column can be activated by a number of reasons. They may migrate or maintain position in preferred light levels, avoid predation or relocate in search of food sources. In this study, I focused specifically on *Euphausia pacificas'* response to small-scale turbulent flow over a sill in Muchalat inlet of Vancouver Island, Canada. I examined acoustic data (200 kHz) collected during daylight hours, focusing on the dominant zooplankton in the area. During this time period, *Euphausia pacifica* descend to preferred low light depths of 100-120 m. The study consisted of continuous transects over the same location to compare responses to different tidal currents. As expected, the zooplankton aggregations were forced against the sill on the upstream side. Movement of these aggregations tracked the targets moving below their preferred depth or above. I suggest that their movements are a response to turbulence caused by tidal flow against the sill. My results show that euphausiids must actively swim downward to avoid being pulled over the sill by currents.

Introduction

Although light intensity and primary production are important factors in the development of zooplankton communities, currents and mixing also play key roles in the structure of biodiversity and energy flow of the ecosystem (Blachowiak-Samolyk et al. 2008, Falk-Petersen et al. 1999). Zooplankton communities are often patchy and occur for various reasons, including; predation avoidance, social behavior, food sources and to maintain position in convergent currents. Areas of high turbulence could create aggregations attracting predators (Ianson, 2011). Zooplankton have an ability to actively move vertically in a water column. It is common for them to move down below light penetrating depths during the daytime to avoid predators, and return to the euphotic zone at night to feed. Typically, horizontal movements are the passive consequence to tides and currents. Previous observations of aggregations in response to upwelling over abrupt topographies showed a behavioral response to vertical currents in order to maintain the depth of the plankton patch (Genin, 2004). In instances of small-scale turbulence, species of zooplankton have been observed migrating in the opposite direction of their natural behavior to areas absent of predators (Ohman, 1990).

Wind generated and tidal currents cause upwelling and downwelling around a sill. These events will transport the upper water layer out or into inlets over the sill. The transfer of this water layer can exchange up to 50% of the upper layer within 1-2 days (Asplin, 1999). Within these transfers, planktonic organisms can be carried into or out of the fjords. During daylight hours, upwelling pulls from intermediate depth water where zooplankton resides to avoid predation. Large removal or placement of zooplankton can reduce or increase a carrying capacity for planktivorous organisms and reduce retention of the early life stages of marine fish. Additionally, frequent exchanges between neighboring fjords' coastal waters can increase a community's genetic diversity.

In this study, I tracked the response of the euphausiid *Euphausia pacifica* to turbulent flows caused by tidal currents over a sill in Nootka Sound, British Columbia, Canada. *Euphausia pacifica* is one of the five dominant species of zooplankton in B.C. accounting for 70 to 100% of the euphausiid biomass (Canadian Science Advisory Secretariat Site). They are an integral part of the food chain and an important food source for a variety of marine animals. The average specimen size was around 13mm, from a maximum depth of around 200 meters. They have large eyes which are sensitive to light gradients allowing them to determine their depth and swimming direction (Mauchline, 1980).

Nootka Sound was formed 20,000 years ago when glaciers covered the entire region. The advance and retreat of the glaciers over time carved U-shaped valleys in the surrounding bedrock. As the glaciers grew, they removed sediment pushing it forward to its maximum advance. At this point, all sediment removed along its advance accumulated at the front of the glacier forming a sill. A sill is the accumulation of sediment forming a ridge marking the terminal extent of the ice sheet. Once the glacier completely receded, the water from the melting ice caused sea levels to rise, filling in the carved valleys. These glacial carved valleys called fjords contain a series of sills throughout their length. A typical sill is characterized as an abrupt shallow topography located at the mouth of an inlet but may also be found within the inlet as well.

To determine if turbulence is causing zooplankton populations to aggregate below or near the sill, water samples and bioacoustic measurements were collected around Muchalat inlet of Vancouver Island, Canada, focusing around the main sill off Gore Island in Williamson passage. The survey collected data at different depths and times of the day. Zooplankton net tows were used to verify bioacoustic readings and to characterize taxonomic composition of the community. The bioacoustic data collected were used to compare aggregation displacement during different tidal cycles. Based on earlier studies, the expected behavior of *Euphausia pacifica* is to actively swim downward once they encounter the bottom boundary layer of the current.

METHODS

Study site

Nootka Sound is located on the west coast of Vancouver Island, British Columbia, Canada and is comprised of three major Inlets. Muchalat Inlets was the focus of my study. The Inlet was a long (>32 km), steep-sided fjord formed by glaciers (Pickard, 1963). Inside Muchalat Inlet there are four major fresh water inputs from rivers, the largest being Gold River. A prominent sill in Muchalat Inlet is located near Gore Island in the Williamson Passage (Fig. 1). Wind conditions were weak to moderate during our cruise (noaa.gov). Due to increased stratification, wind forces would have little to no effect on the water movement at depth (Baker and Pond, 1995). We can assume that physical circulation would then be dominated by tides and river run off.

Field collection

The research was conducted aboard the R/V Thomas G. Thompson at Muchalet Inlet on 15th December from 1000 to 2400 local time. Two-layered estuarine circulation was high due to peak river runoff in the winter (Pickard, 1963). Bioacoustic measurements were collected using a Simrad scientific echosounder, model EK-60. The transducer head was pole-mounted midship 4.9 m below the surface. The acoustic parameters were set at a ping rate of 0.8 ping$\bullet$s^{-1} and Gain of 26.57 dB. CTD data was used to get the average temperature of 8.7° C and salinity 32.3 between the transducer and the target. The average temperature was then used to calculate a sound speed of 1468 m$\bullet$s^{-1}. Sound absorption (α) was determined to be 48 dB$\bullet$km^{-1} using the acoustic frequency, average temperature, and salinity. A single frequency of 200 kHz was used to map the spatial distributions of the most abundant large euphausiid species *Euphausia pacifica* (Fig. 2). Surveys were conducted across the center of each sill extending approximately 1 km in each direction past the highest point of the sill. Multiple transects were repeated across the sill during day and night operations to cover at least one high and one low tide. A HydroBios MultiNet (type Midi) was used to sample obliquely at different depths. A total of five 335-µm mesh nets were used on each tow, each net had a mouth area of 0.25 m^2. Large zooplankton aggregations were targeted using the information received from the echosounder. The five nets could be opened and closed at any point during the cast by controllers at the workstation. For this study net 1 collected from the surface to maximum depth of approximately 100 m, net 2 collected from 100 m to 85 m, net 3 from 85 m to 60 m, net 4 from 60 m to 15 m, and net 5 from 15 m to recovery of the net. Horizontal collections were made moving at an average of 2 knots. Each net sample was preserved in 5% buffered formalin. The samples were then used to characterize taxonomic composition and target abundance in scattering layers.

Data analysis

Zooplankton data are reported as the number of organisms per cubic meter, which were calculated as follows: Volume of water filtered: $V= \alpha N_g A$, where: V = Volume of water filtered (m^3), α = Flow meter calibration factor, N_g = Number of revolutions (read from the flow meter dial), and A = Area of the mouth of the net (m^2) = 0.1963 m^2 for a 0.5 m diameter net. The EK60 raw acoustic data was pre-processed for further data analysis using Echoview (Ver. 6.1). Zooplankton contributed substantially to the volume back scattering strength (S_v in dB or s_v in $m^2 \cdot m^{-3}$). Target species were separated from nontarget backscatter. Regions near the sill where zooplankton aggregations formed were selected and compared between different tidal phases. Data from these regions were exported into separate files for comparing mean S_v values. The mean S_v values can be used to calculate density from acoustics using the formula (Parker-Stetter *et al*, 2009): $\rho = S_v / \sigma_{bs,}$ where: S_v = volume backscattering coefficient, σ_{bs}= average backscattering cross section. Densities calculated using S_v values and zooplankton samples collected provide "sea truth" for the images processed on Echoview.

Four time periods were compared from acoustic observations taken at Muchalat sill before zooplankton vertical migration into the epipelagic zone. The four periods cover one flood, slack and ebb tidal flow. Only volume back scattering strength (S_v) values for zooplankton measurements were chosen ranging between -70 to -80 dB. The sill was divided in half to compare the northwest to the southeast side. The sill was a 102 m in height reaching a maximum depth of 175 m. The two sides were broken into 20 m depth intervals beginning above the sill at 60 m to 140 m at the base. The four 20 m layers extended from the center of the sill out 500 m in each direction. The southeast side's deepest 40 m, from 140 to 180 m were not taken into account due to an abundance of fish signatures and no corresponding depth range on the northwest side. Background noise was removed along with any artificial ping values such as material being towed by the research vessel. The seafloor bottom was corrected to account for sediment suspended in the water and only back scattering strengths for zooplankton were processed. Zooplankton preferred depth of 100-120 m was inferred from adjacent readings beyond the area of research.

RESULTS

Analysis of acoustic observations

Initial survey of Muchalet sill began in the final hour of a flood tide at 1040 local time (Fig. 3). The research vessel was moving along a southeast to northwest transect with an average speed of 4.0 knot through the water (STW), and a 3.5 knot speed over ground (SOG) indicating a surface velocity of 0.5 knots. Flood currents were moving in a northwest (upstream/down-fjord) to southeast (downstream/up-fjord) direction. Initial echo returns recorded a total of 32,109 targets. The results during flood tide show an even distribution of around 16,000 targets on either side of the sill. The top of the sill contained the least echo returns, mostly on the upstream side with 396 targets. It is possible that these targets may be a result of sediment that has been lifted off the sill rather than zooplankton targets. In the water column, the downstream side was more evenly distributed with the largest amount in the preferred depth 100-120 m, accounting for almost 20% of the entire transect abundance. The remaining amounts of targets directly above and below the preferred light depth were similar, with about 14% above and 16% below. On the upstream side, the preferred depth again accounted for the majority of targets making up almost 26% of the total with about 11% above and 12% below this depth.

The second survey was conducted near slack tide, crossing the sill at 1130 local time (Fig. 4). The research vessel was moving along a southeast to northwest transect with an average speed of 4.3 knot STW, and a 4.2 knot SOG. There were very little tidal currents during this period. Acoustic readings directly below the vessel calculated a total abundance of 28,364 targets, a decrease of almost 12% from flood tide. The results showed a distribution of 54% on the southeast side (left side in Fig./up-fjord) and 46% on the northwest (right side in Fig./down-fjord). The left side of the sill had the most targets in the 100-120 m range, accounting for 25% of the total transect. The layer above this consisted of 13% and the bottom layer remained around 15% of the total abundance. On the right side of the sill, the preferred depth recorded a total of 21% of the targets. The layers above and below the preferred light depth were 10%, and 11% respectively. There were a small number of targets at the top left side of the sill, possible the same sediment disturbance seen in the flood tide.

The third survey was conducted during ebb tide, crossing the sill at 1434 local time (Fig. 5). The research vessel was moving along a southeast to northwest transect with an average speed of 4.0 knot STW, and a 4.0 knot SOG indicating a strong ebb tide. Ebbing currents were moving in a southeast to northwest direction. Acoustic readings directly below the vessel calculated a total abundance of 30,281 targets, an increase of almost 7% from slack tide. The results show a distribution of 56% on the southeast (upstream/up-fjord) side and 44% on the northwest (downstream/down-fjord) side. There was a large aggregation at the top the sill similar to the previous surveys covering both the up and downstream sides, again most likely due to the same sediment disturbance seen before. The upstream side of the sill had the highest abundance at the 100-120 m depth accounting for 23% of the total targets. The layer above and below the preferred depth were 14% and 17% respectively. On the downstream side of the sill, the preferred depth was 20% of the total targets. The layer above had 16% of the total, and below the preferred depth were 7% of the total targets.

The final survey was conducted an hour after the third survey still during ebb tide, crossing the sill at 1521 local time (Fig. 6). The research vessel was moving along a southeast to northwest transect with an average speed of 2.1 knot STW, and a 1.5 knot SOG. Ebbing currents were moving in a southeast to northwest direction. Acoustic readings directly below the vessel calculated a total abundance of 28,945 targets, a decrease of 4% from the previous hour. The results show a distribution of 51% on the southeast (upstream) side and 49% on the northwest (downstream) side. The large aggregation seen previously at the top the sill had moved to the downstream side extending into the layer below. In the upstream side (up-fjord) of the sill, the preferred depth was again the most abundant with 23% of the total targets. The layer above stayed around 13% and the bottom layer recorded about 12% of the total targets in transect. On the downstream side of the sill, the preferred depth accounted for 18% of the total individuals. The 80-100 m layer had the highest amount of targets making up 22% of the entire transect, and the bottom layer had the second least with 6% total targets.

DISCUSSION

Currently bioacoustics is the best source to track zooplankton movements in the water. The still images that are produced from these returns don't accurately describe zooplankton behavior. Zooplankton community structure is clearly more complex than what my data represents. My echo returns show zooplankton patches forming against the sill on the upstream side. These areas seem to have targets moving up and down along the sill face. The data shows a change in abundance from the preferred depth to layers above this on the upstream side and increases in the total abundance on the opposite sides (downstream).

Initially during the flood tide, there is an even distribution of targets on either side of the sill, with the majority of targets (26%, total transect) on the upstream (down-fjord) preferred depth layer. As the currents change to slack tide during the second survey, the top right side had a large aggregation moving up from the 80-100 m section consisting of almost 4% of the total. The left side of the sill had an increase of 5% in the preferred depth from the previous hour, accounting for 25% of the total. There was a slight decrease in the layer above down to 13% and the bottom layer remained mostly the same with 15% of the total abundance. On the right side of the sill, the preferred depth decreased by 5%, down to a total of 21% of the targets. The layers above and below the preferred depth also decreased slightly, down to 10%, and 11% respectively (Fig. 7). During the third survey as the tide changed from slack to ebb, the upstream side of the sill had a decrease of 2% in the preferred depth from the previous tide, accounting for 23% of the total. There was a slight increase of targets in the layer above and below the preferred depth up to 14% and 17% respectively. On the downstream side of the sill, the preferred depth decreased only 1%, down to a total of 20% of the total targets. The layer above had the largest change, increasing 6% making it 16% of the total. Below the preferred light depth decreased the most between slack and ebb tide, down from 11% to 7% of the total targets (Fig. 8). In the final survey still in ebb tide, the preferred depth remained the most abundant with 23% of the total targets. The layer above this remained relatively the same but the bottom layer decreased by 5%. On the downstream side of the sill, the preferred depth continued to decrease, down to a little more than 18% of the total targets. The layer below saw very little change but the layer above jumped 6% up to 22% of the total (Fig. 9).

My results show that when *Euphausia pacifica* encounters small-scale velocity near a sill they actively swim downward to avoid being forced out of their preferred depths. The velocity shear may at times however be too powerful for them to swim against, forcing them into a shallower depth with some individuals getting pulled over the sill to the opposite side. During slack tide when the higher turbulence levels decrease, zooplankton then return to their preferred depth of 100-120 m. It also appears that zooplankton do not fight the currents away from the sill. This is why my data shows increases and decreases in the study area of total abundance. There is also a possibility that *Euphausia pacifica* are responding to the presence of predators. In several of the still images, it would appear that when a large predator moves into zooplankton aggregations the area immediately surrounding the predator becomes clearly less dense of individuals. There is also a small number of predator sized targets in the 120-140 m depth, this could account for the zooplankton to prefer the layer above this. In the final survey, we see the beginning of zooplanktons' upward vertical migration to their feeding depths. This is most likely the cause of the large increases in targets seen at the 80-100 m depth.

Acoustic recordings continued for another hour showing the complete migration to shallower depths (Fig. 10 and 11). These observations were not the focus of this study and their data was not included in my results. It is interesting to note that as *Euphausia pacifica* move up in the water column, a high number of large targets move into the downstream (down-fjord) side. These targets are most likely fish preying on zooplankton. The images clearly show the fish targets scattering the zooplankton aggregations, and focusing their attention on the top of the sill.

CONCLUSION

My results showed similar patterns to previous studies on this topic (Ianson et al. 2011). Light-sensitive animals choose to maintain at depth during the day to avoid predation. My study examined the behavior of zooplankton caused by turbulence altering their depth in the water column. I believe my results show that *Euphausia pacifica* actively swim in a downward movement to avoid strong currents which along a sill would raise them out of their preferred level depth. By swimming down against the sill, they can move into slower moving water, increasing their ability to maintain their preferred depth. It has been suggested that this is an evolved response to small-scale velocity shear, caused by wind, tides or predators, throughout the water column (Ianson et al. 2011). Further studies done during spring or summer when production is higher would increase the ability to determine zooplankton behavior. Also acoustic recordings collected away from a sill would be useful to compare zooplankton behavior and preferred depths during daylight hours.

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Figures

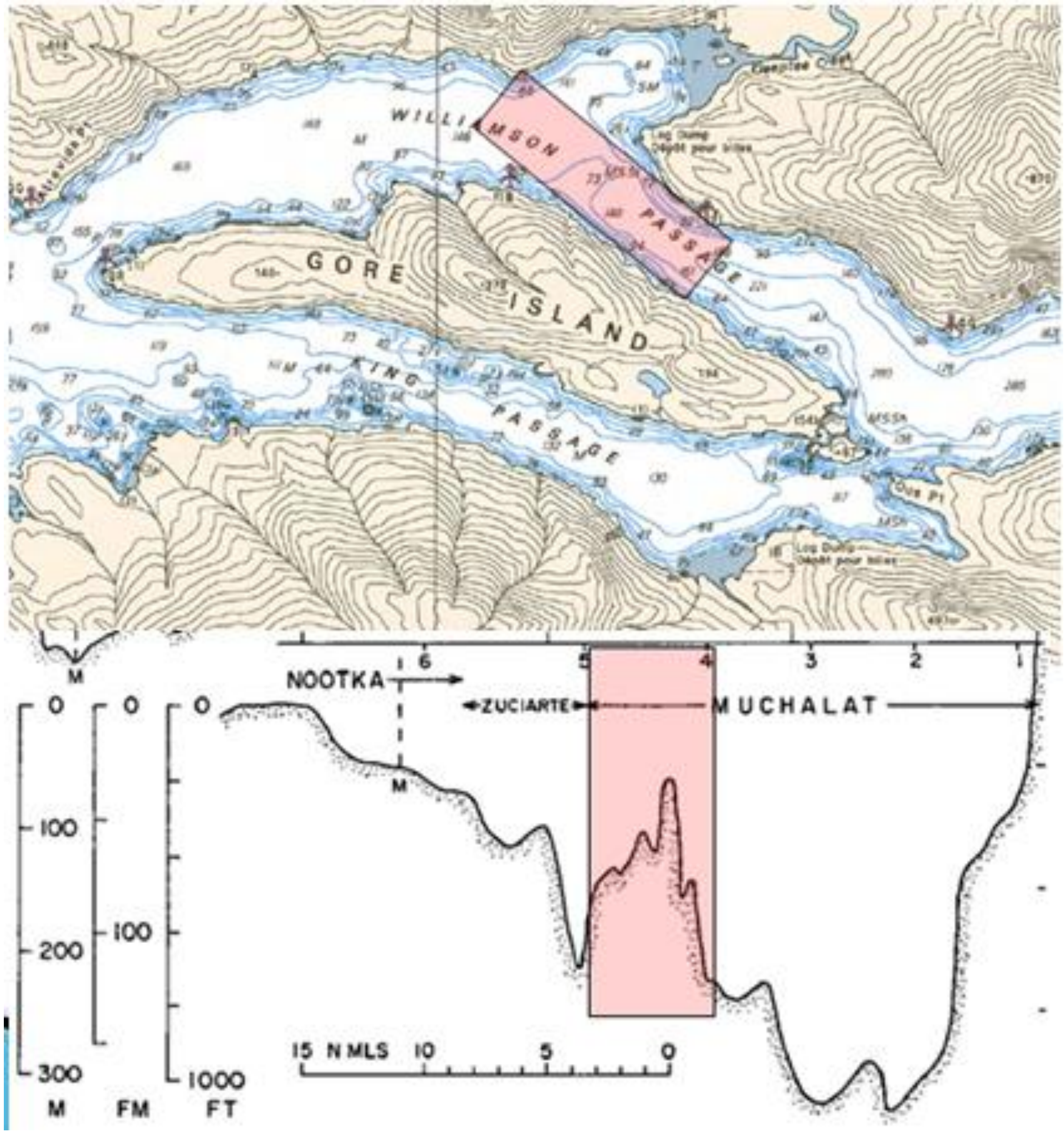


Figure 1. Muchalat Inlet, Vancouver Island. Location of survey site. Sill near Gore Island. Lat. 49° 39' 19.9974", Long. -126° 23' 17.3688". Path of data collection. Total length 4 km, 2.16 nautical miles.

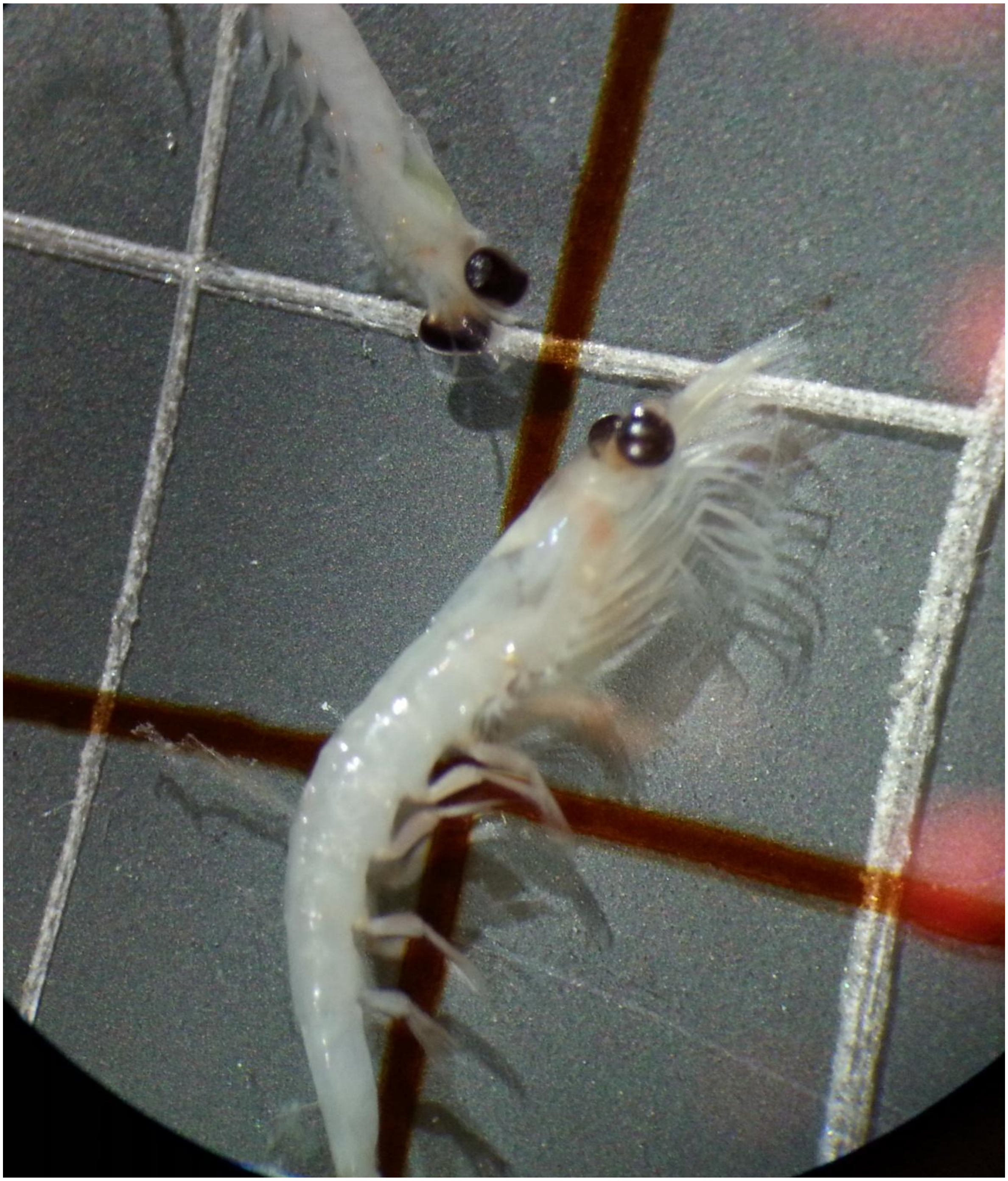


Figure 2. ***Euphausia pacifica*****, collected zooplankton during research. Average size 12.7 mm.**

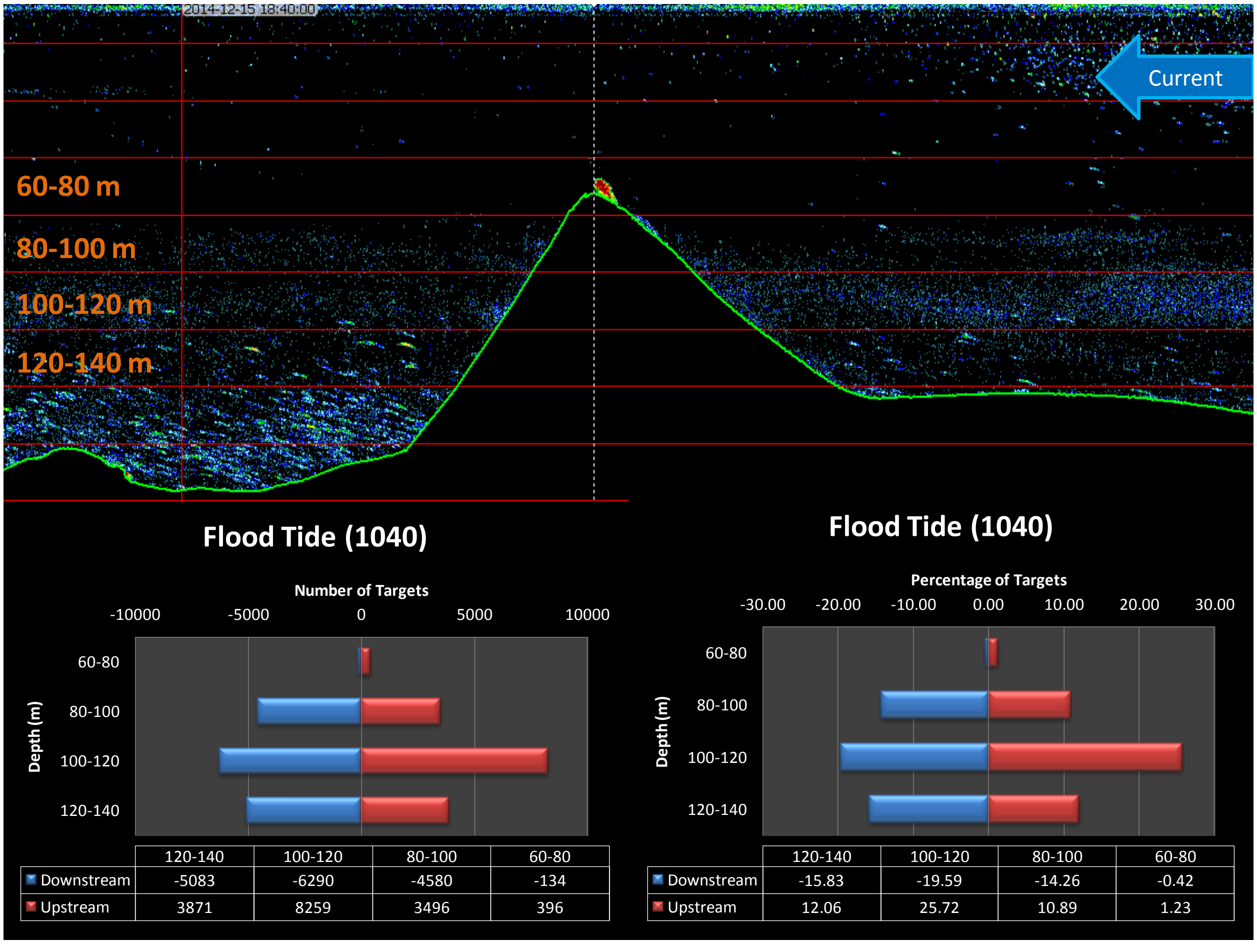


Figure 3. Flood tide, 1040 local time. Current moving from NW to SE. Number of targets represented on left graph, blue indicates SE (left) side of sill, red indicates NW (right) side. Left side values were changed from their actual positive values to negative for comparison only. Four target regions are indicated on left side of figure. Horizontal red lines indicate depth increments of 20 m.

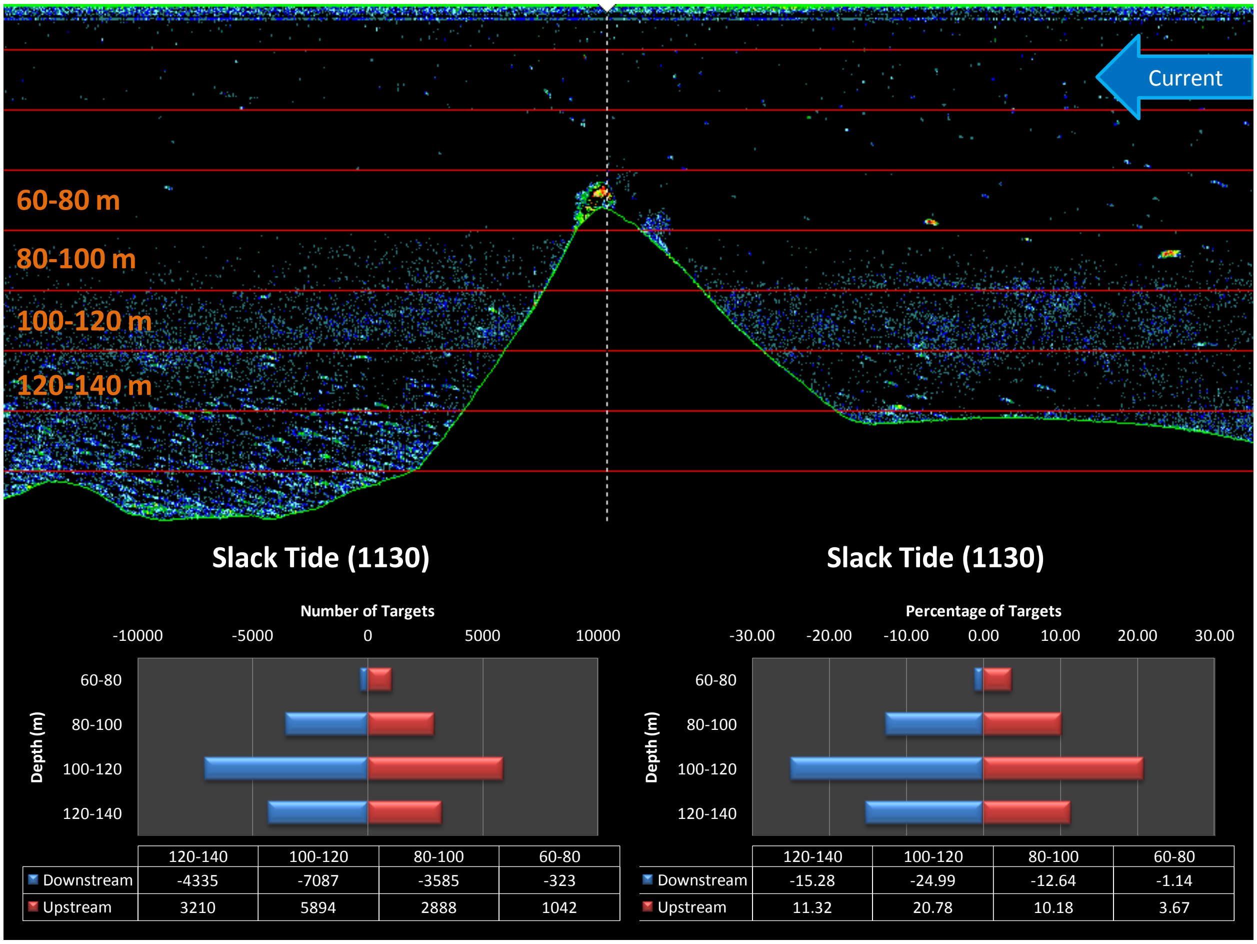


Figure 4. Slack tide, 1130 local time. Current moving from NW to SE. Number of targets represented on left graph, blue indicates SE (left) side of sill, red indicates NW (right) side. Left side values were changed from their actual positive values to negative for comparison only. Four target regions are indicated on left side of figure. Horizontal red lines indicate depth increments of 20 m.

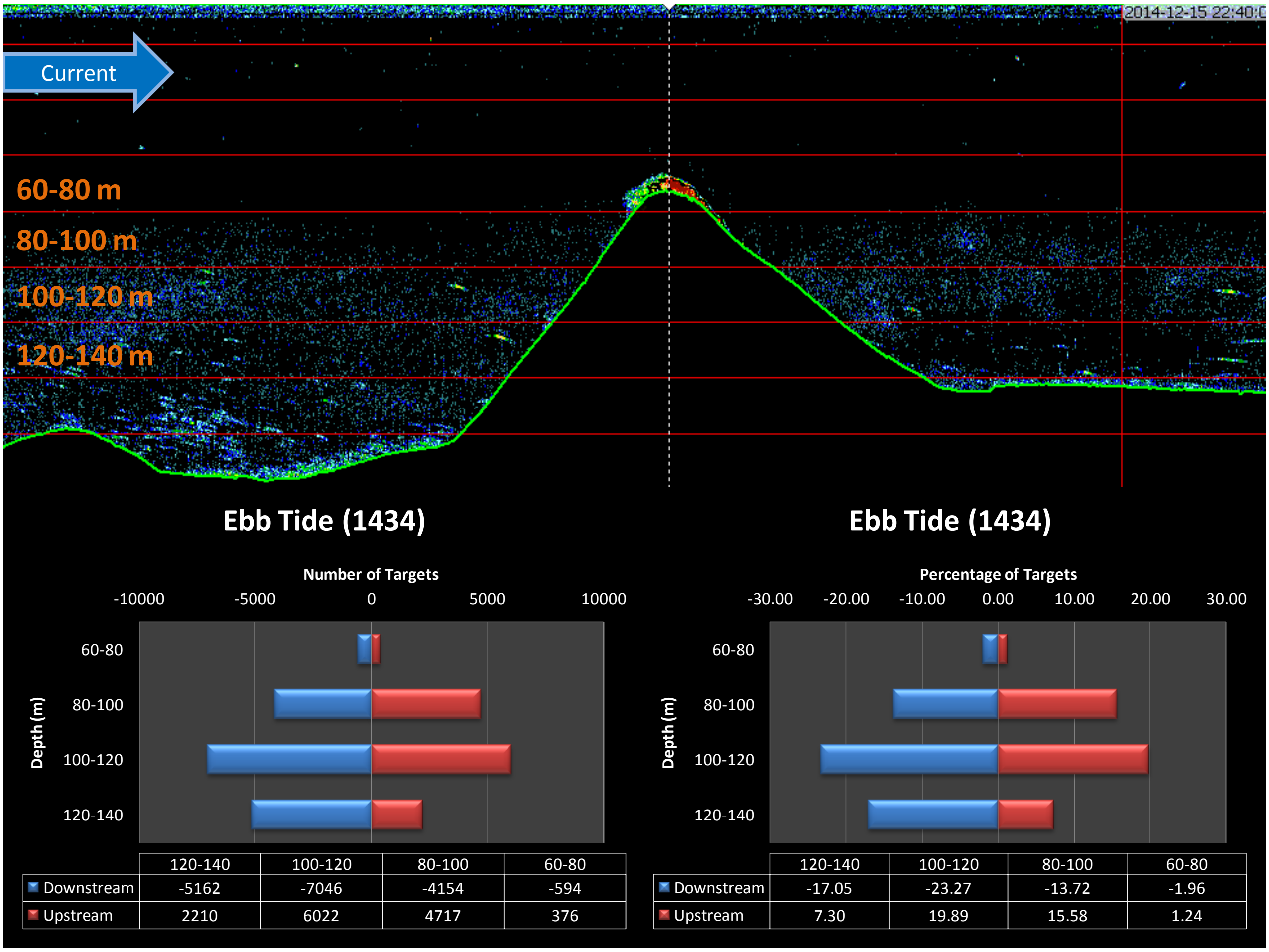
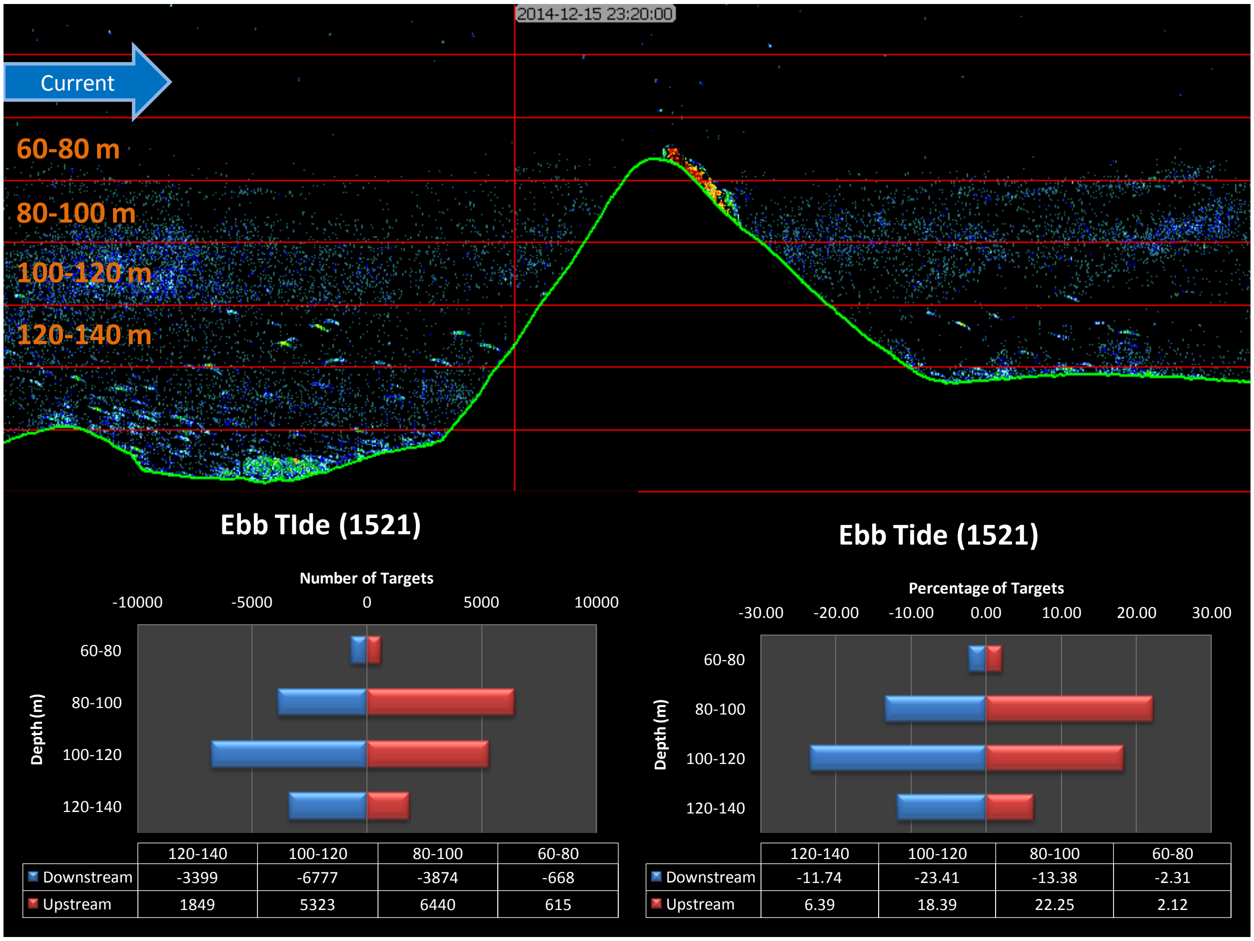


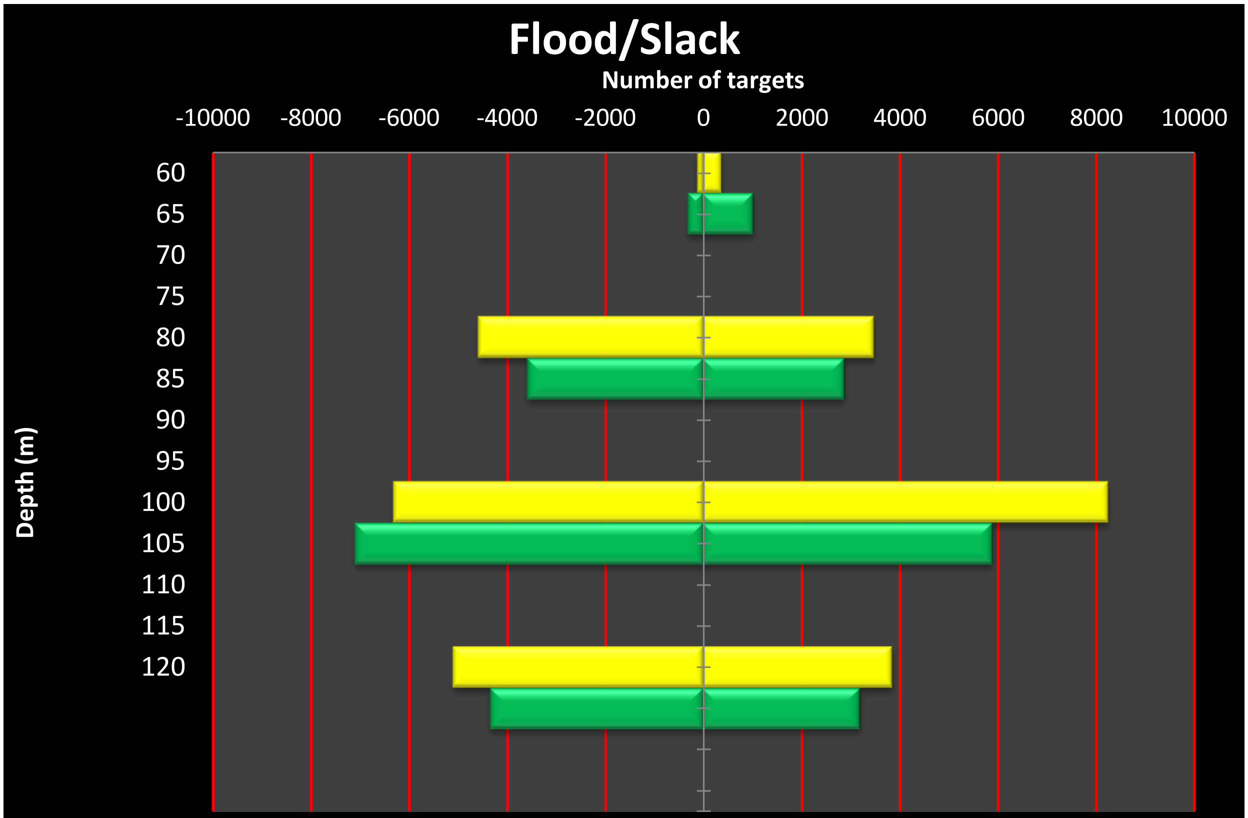
Figure 5. Ebb tide, 1434 local time. Current moving from SE to NW. Number of targets represented on left graph, blue indicates SE (left) side of sill, red indicates NW (right) side. Left side values were changed from their actual positive values to negative for comparison only. Four target regions are indicated on left side of figure. Horizontal red lines indicate depth increments of 20 m.



	120-140	100-120	80-100	60-80
Downstream	-3399	-6777	-3874	-668
Upstream	1849	5323	6440	615

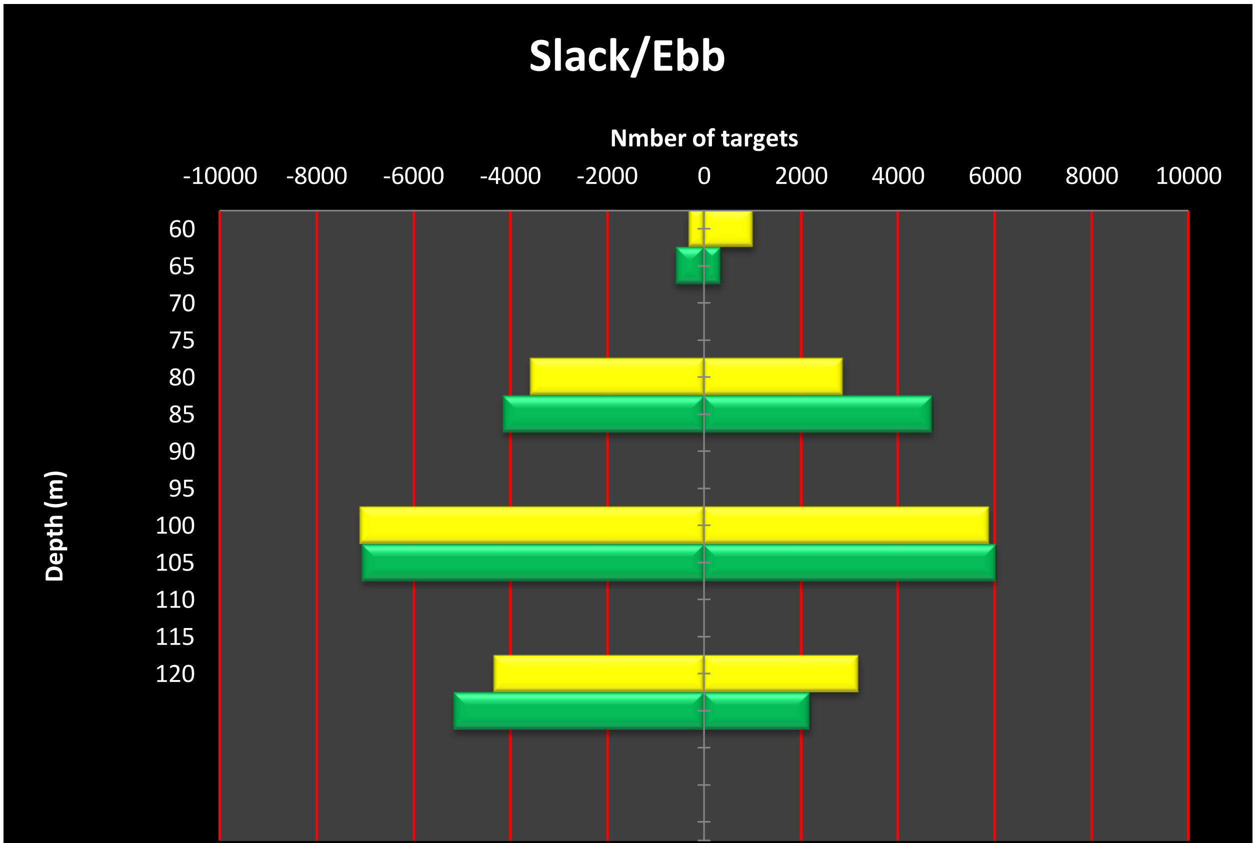
	120-140	100-120	80-100	60-80
Downstream	-11.74	-23.41	-13.38	-2.31
Upstream	6.39	18.39	22.25	2.12

Figure 6. Ebb tide, 1521 local time. Current moving from SE to NW. Number of targets represented on left graph, blue indicates SE (left) side of sill, red indicates NW (right) side. Left side values were changed from their actual positive values to negative for comparison only. Four target regions are indicated on left side of figure. Horizontal red lines indicate depth increments of 20 m.



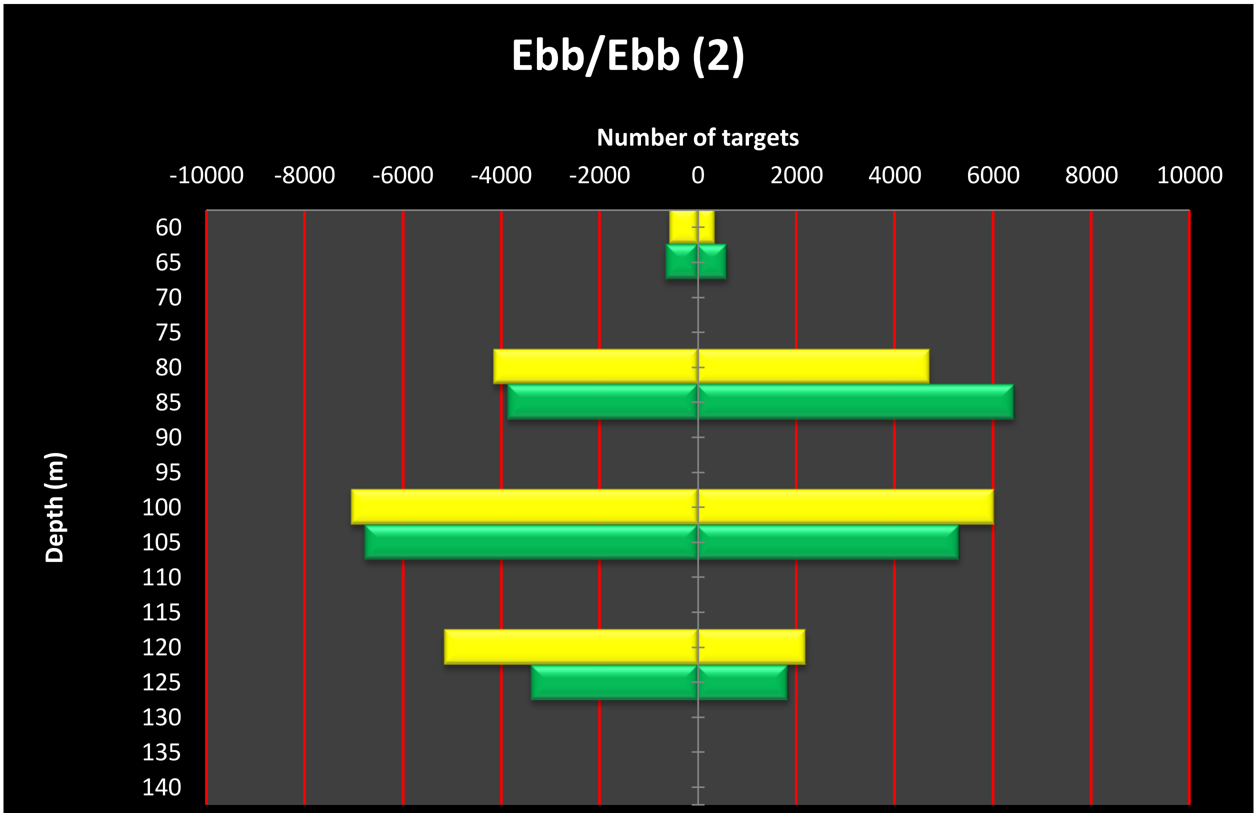
				120	115	110	105	100	95	90	85	80	75	70	65	60
SE Flood tide				-5083				-6290				-4580				-134
NW Flood tide				3871				8259				3496				396
SE Slack tide			-4335				-7087				-3585				-323	
NW Slack tide			3210				5894				2888				1042	

Figure 7. Graph represents a comparison of the number of targets recorded at flood and slack tide. Flood tide represented in yellow bars. Slack tide represented in green bars. Table shows number of targets at the different depth ranges. Values offset in table for alignment purposes on graph. Top of sill located at 73 m. SE values were changed from their original positive to negative values for comparison purposes only.



					120	115	110	105	100	95	90	85	80	75	70	65	60
SE Slack tide					-4335				-7087				-3585				-323
NW Slack tide					3210				5894				2888				1042
SE Ebb tide				-5162				-7046				-4154				-594	
NW Ebb tide				2210				6022				4717				376	

Figure 8. . Graph represents a comparison of the number of targets recorded at slack and ebb tide. Slack tide represented in yellow bars. Ebb tide represented in green bars. Table shows number of targets at the different depth ranges. Values offset in table for alignment purposes on graph. Top of sill located at 73 m. SE values were changed from their original positive to negative values for comparison purposes only.



	140	135	130	125	120	115	110	105	100	95	90	85	80	75	70	65	60
SE Ebb tide					-5162				-7046				-4154				-594
NW Ebb tide					2210				6022				4717				376
SE Ebb (2)				-3399				-6777				-3874	0	0	0	-668	0
NW Ebb (2)				1849				5323				6440				615	

Figure 9. Graph represents a comparison of the number of targets recorded at the beginning of an ebb tide and an hour later ebb tide. Initial ebb tide represented in yellow bars. Late ebb tide represented in green bars. Table shows number of targets at the different depth ranges. Values offset in table for alignment purposes on graph. Top of sill located at 73 m. SE values were changed from their original positive to negative values for comparison purposes only.

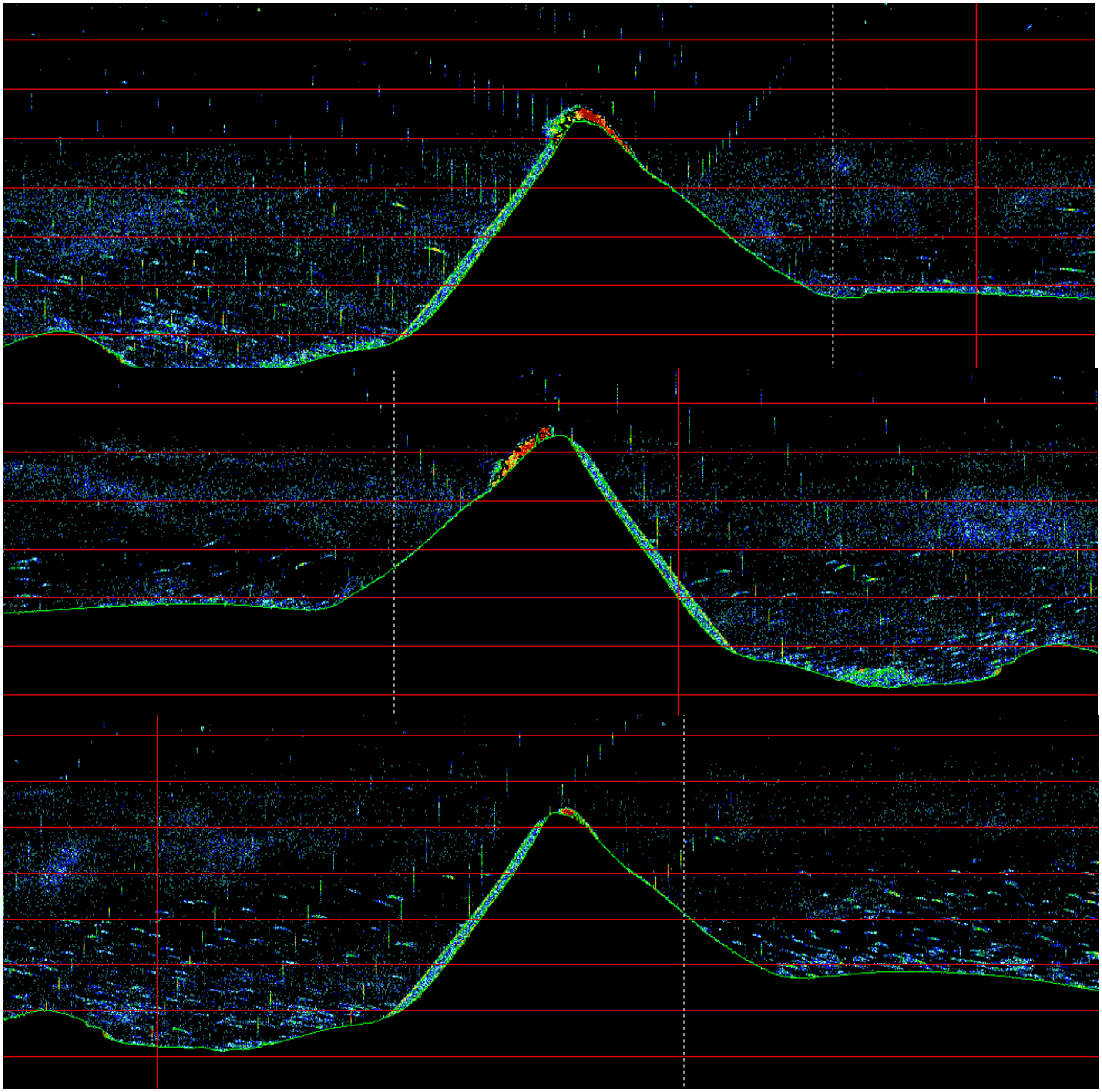


Figure 10. Williamson sill continuing Ebb tide. Zooplankton vertical migration to surface after sunset. Large amount of fish targets moving in from the NW (right), and dispersal of zooplankton aggregations.

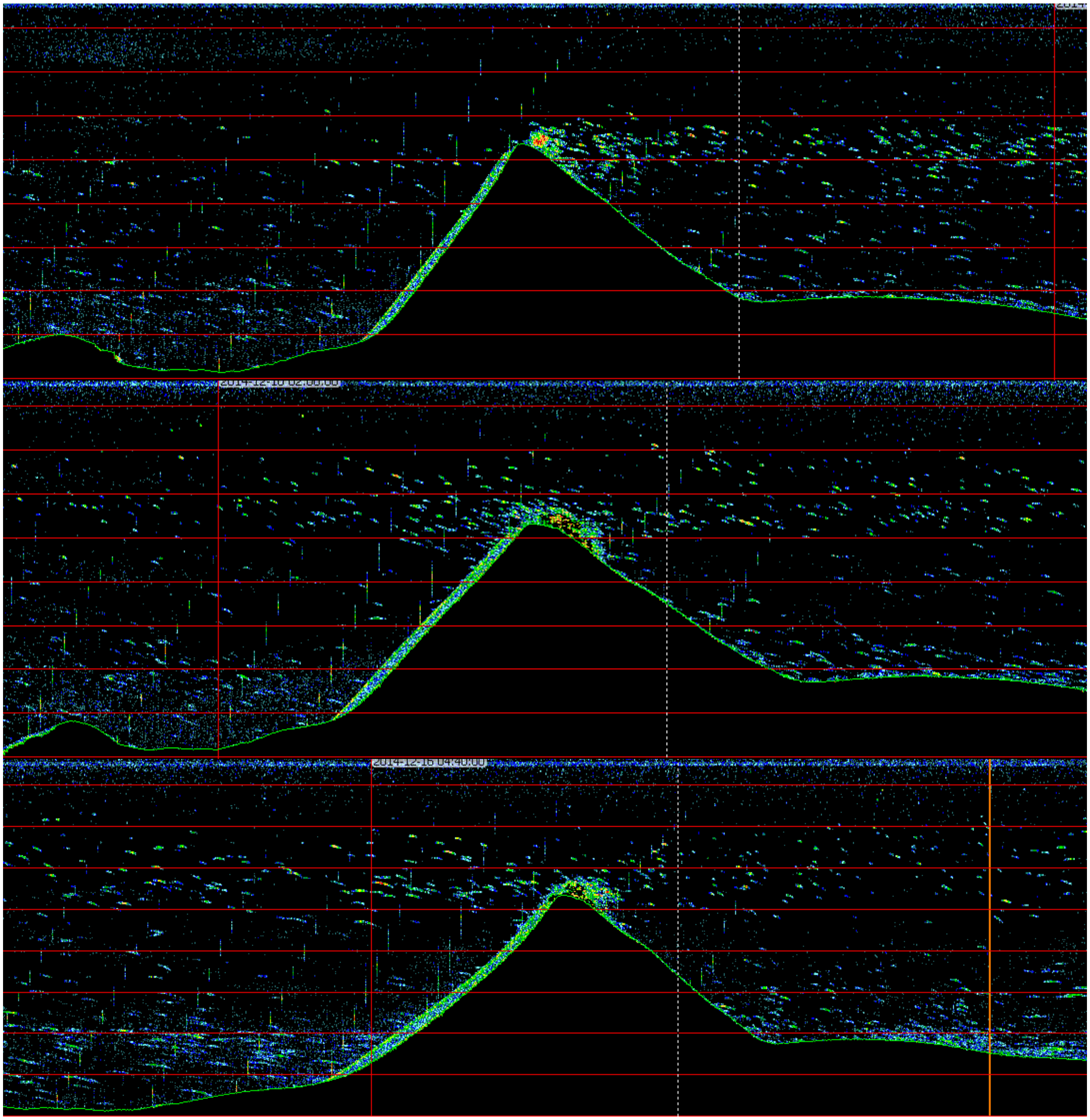


Figure 11. Williamson sill, continuing observation of zooplankton vertical migration after sunset. Fish targets from the NW (right) following zooplankton movement. High amount of activity at top of sill.