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Interactions of aquatic animals with the ORPC OCGen® in Cobscook Bay, Maine: Monitoring behavior change and assessing the probability of encounter with a deployed MHK device

USDOE Award Number: DE-EE0006384

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Executive Summary

Commercial viability of the marine hydrokinetic (MHK) energy industry is contingent on numerous and diverse factors. A major factor is the effects deployed devices have on animals. This factor is multi-faceted since it is dependent on the availability of appropriate scientific approaches to detect these effects. One of the animal groups with overlapping distributions of MHK devices are fishes. As such, individual fish behavior is likely to be influenced by the presence and operation of MHK devices. Depending on the scale of deployment there are implications for changes to essential fish habitat and effects that can be explored during deployment of a single device yet most changes are likely to be realized when multiple devices are deployed over large areas. It is not only important to document these effects and examine the need for mitigation, but also determine whether the methods involved can be used within the economic constraints of this nascent industry. The results presented in this report benefit the MHK industry by providing transferrable environmental monitoring approaches for MHK projects, specifically related to the interactions between static and dynamic tidal turbines and fish. In addition, some of the data can be used to generalize conditions (e.g., the temporal periodicity of fish presence in tidal regions and probability of fish encountering a device) at other MHK sites with similar physical conditions and fish assemblages.

Ocean Renewable Power Company, LLC (ORPC) deployed and tested a prototype OCGen® tidal module in Cobscook Bay, Maine, in the summer of 2014. University of Maine researchers proposed an approach to inform other researchers, regulators, and industry members of the effects of this deployment on fish. While the approach was specifically applied to the OCGen® module, results are applicable to other pilot projects and inform future array deployments. Research funded under this grant allowed us to quantify fish presence as well as individual and group-level behavior changes in the presence of the deployed OCGen® module along with a bottom support frame from a previously deployed device (TidGen®). Specific objectives associated with fish behavior changes were (1) continuation of two long-term datasets: (a) stationary down-looking hydroacoustic dataset near an MHK device (group-level) and (b) stationary side-looking hydroacoustics near the bottom-support frame of a previously deployed MHK device (individual-level); (2) application of new processing methods to down-looking hydroacoustic datasets to improve fish species identification (group-level); and (3) development of an encounter probability model using data on fish abundance, vertical distribution, and behavior.

Objectives

Objective 1a: Continuation of a long-term, down-looking hydroacoustic dataset, was an extension from previous funding used to collect fish vertical distribution and overall abundance around ORPC's TidGen® tidal power system from 2010-13. This multi-year dataset enabled the construction of seasonal trends in fish abundance that was used by regulators to make decisions about the deployment of the OCGen® module. Data collected during this award (2014-15) at the module deployment site revealed similar seasonal trends as those reported from 2010-2013 (Viehman et al. 2015 and unpublished data). Generally, relative densities of fish were lower in winter and higher in early spring and later fall. There were some differences in relative fish density and fish vertical distributions among sites. However, these differences lacked consistency and could not be attributed to only the operations of the turbine because the OCGen® module operation varied throughout the study period. During the first of three surveys when the OCGen® module was present, the module's turbine was rotating, and in the second and third the turbine was present but not rotating. There was a significant interaction was observed in August when the device was static and industry activity was high, leading us to believe that the amount of on- and in-water industry activity may be a driver to decreases in fish density at the impact site.

Objective 1b: The behavior of individual fish in a region of interest for MHK device deployment was explored using a bottom-mounted, side-looking, transducer. This had been stationed near the TidGen® Power System during (2012) and after (2013 – 2015) its deployment. Individual fish movement through the acoustic beam was compared between times when the device was present but static (2012) and when the device was absent (and only the bottom-support frame remained, 2013-2015). Linear models revealed that turbine presence had no significant effect on individual fishes' horizontal deflection from the direction of water flow, indicating minimal behavioral response to the turbine presence, at the ranges sampled (approximately 8-23 m from the turbine face). The same echosounder was used to observe fish abundance at the TidGen® Power System site for a year after its removal. Cyclical patterns related to tidal, diel, and seasonal cycles were found. These temporal patterns were used to develop an optimum sampling design for long-term monitoring of MHK sites with similar physical conditions and fish assemblages. The design reduces variation in results by timing surveys with these natural cycles. For example, 24-hour surveys would encompass short-term variations and when they are carried out at the same stage in the spring-neap tidal cycle throughout the year even more natural variation can be captured. This monitoring approach could be used to maximize the accuracy of survey results while minimizing the necessary number of surveys (and cost) at this and similar tidal energy sites.

Objective 2: "Delta mean volume backscattering strength (ΔMVBS)" or "dB differencing" methods were used to improve fish species identification in previously available hydroacoustic datasets, based on differing backscattering properties. Our goal was to apply this technique to isolate fish with swimbladders, which scatter more sound, from mackerel, which lack swimbladders and scatter less sound. However, closer scrutiny of the dataset revealed that the species with and without swimbladders were present in mixed schools. Unfortunately, in order to separate species using dB differencing the species must also be separated in space. Ultimately, we were able to apply dB differencing to isolate zooplankton from all fish (e.g. those with and without swimbladders), which improved the accuracy of relative fish density estimates obtained from the long-term, down-looking hydroacoustic dataset (Objective 1).

Objective 3: A model was developed to examine the probability of fish encountering an MHK device in Cobscook Bay. Data used in the model included stationary and mobile down-looking hydroacoustic data collected with this and previous DOE funding. The model was composed of three probabilities: (i) the probability of fish being at the device depth when the device was absent; (ii) the probability of fish behavior changing to avoid the device before being detected by stationary sampling near the device (~ 50 m from the device); and (iii) the probability of fish behavior changing to avoid the device between 140 and 10 m from the device. According to the model, in total, the probability of fish encountering the entire TidGen® device was 43.2% (95% CI: 30.5, 55.3), which included the bottom support frame as well as the turbine, and 5.8% (95% CI: 4.3, 7.3) of fish would be at the depth of the dynamic portion of the device (the rotating foils). Understanding where fish are in the water column relative to a deployed tidal energy device provides important baseline metrics for regulators responsible for permitting MHK devices.

Accomplishments

Project Goal: The goal of this project was to quantify aquatic animal behavior changes associated with the presence of a deployed marine hydrokinetic (MHK) device.

Project Objectives: Specific objectives included: (i) continuation of long-term, seasonal hydroacoustic datasets near an MHK device; (ii) application of new processing methods to hydroacoustic datasets to improve species identification; and (iii) development of an encounter probability model using data on fish abundance, vertical distribution, and behavior collected near an MHK device.

DE-EE0006384: Project tasks and milestones.

Task #	Task Description	Associated Milestones	Associated Objectives
1	Development of a detailed work plan, including timing, length, and methodological details for each proposed task	1,2,3,4	i
2	Develop dB differencing methods for down-looking hydroacoustic data	5, 6, 7	ii
3	Develop probability of encounter model	8, 9, 10	iii
4	Collect down-looking hydroacoustic data at control site in March	11	i
5	Collect down-looking hydroacoustic data at a control site (May, Aug, and Nov) and at the OCGen® site and the control site for four weeks while the device was deployed; and 5 benthic and pelagic trawl sampling events in May (1), Aug (3), and Sep (1)	12, 13, 14	i
6	Collect side-looking hydroacoustic data at TidGen®	15, 16, 17	i
7	Side-looking hydroacoustic data analysis	18, 19	i
8	Down-looking hydroacoustic data analysis (of 2014 data)	20	i
9	Finalize dB differencing- incorporating 2014 data with baseline data (2011-2013)	21, 22	ii
10	Finalize probability of encounter model	23, 24	iii
11	Finalize side-looking hydroacoustic data assessment	25	i
12	Final Report	26	i, ii, iii

Summary

Introduction

Recent awareness of the urgent nature of climate change has led to reestablished interest in renewable energy sources. The potential to harness tidal currents is viable in particular geographical locations (http://energy.gov/eere/water/marine-and-hydrokinetic-resource-assessment-and-characterization#Tidal_Streams_Resource_Assessment; accessed Mar 28, 2016), and while it is not as established an industry as wind and solar, tidal resources have the distinct advantage of being predictable. There is a nascent industry developing to harness the energy from tidal currents using novel marine hydrokinetic (MHK) turbine designs, but there have been few opportunities to evaluate the effects of these new energy devices on marine animals. There have been a limited number of deployed devices and the challenges of testing these are exacerbated by the difficulty of collecting data in such high-energy locations (Viehman, et al. 2015; Broadhurst et al. 2014). Although the scientific literature is growing in relation to potential animal interactions with these devices (Staines et al. 2015; Viehman and Zydlewski 2015; Hammar et al. 2014; Broadhurst et al. 2014), there is still much work to be done to properly inform policy makers. Uncertainty in this area is seen as a major regulatory barrier.

The uncertainty of interactions between fish and tidal energy devices was the foundation of this research. Concerns about interactions cover several scenarios, from direct strike and mortality occurring at the turbine foils to far-field effects on behavior due to avoidance reactions which may have implications for foraging and reproductive behavior, influencing long-term survival. Theoretical papers and laboratory experiments have been conducted to provide insight to fish interactions with MHK tidal devices (Amaral et al. 2015; Čada and Bevelhimer 2011; Castro-Santos and Haro 2015; Hammar et al. 2015; Romero-Gomez and Richmond 2014). However, actual deployed devices with associated empirical fish interaction data are limited (Broadhurst et al. 2014, Hammar et al. 2014, Viehman et al. 2015, Staines et al. 2015, Viehman and Zydlewski 2015a, Viehman and Zydlewski 2015b). This report adds to the current understanding of fish behavior near, and interactions with, a single deployed MHK tidal device. Based on successful research in Cobscook Bay (Viehman et al. 2015) with the previously deployed TidGen® Power System, we chose hydroacoustics to collect information on fish at this tidal energy site.

The TidGen® device was removed in July 2013, with the bottom support frame left in place on the seafloor. ORPC followed up with the deployment of a model version of a prototype OCGen® module attached to the seafloor by a gravity anchor mooring system. The impetus for this deployment was to test the gravity anchor mooring system and allow marine animal monitoring during the testing phase, which lasted 2.5 months.

The goal of this project was to quantify aquatic animal (primarily fish) behavior changes associated with the presence of a deployed MHK energy device. Three objectives were used to reach this goal:

- *Objective 1*: continuation of long-term hydroacoustic datasets near an MHK energy device.

  Questions:

  1. Was *fish density* different during times when the OCGen® module was present and absent?
  2. Was *fish vertical distribution* different during times when the OCGen® module was present and absent?
  3. What were *individual fish behaviors* in front of and in the wake of the TidGen® module?
  4. Can a long-term hydroacoustic record of *fish abundance* be used to determine an ideal sampling strategy at this and similar tidal energy sites?

- *Objective 2*: application of new processing methods to hydroacoustic datasets to improve species identification.
  Question: Can acoustically detected mackerel (a seasonally abundant species in Cobscook Bay) be separated from other species using frequency response differences between 38 and 200 kHz?

- *Objective 3*: development of an encounter probability model using data on fish abundance, vertical distribution, and behavior collected near an MHK energy device.
  Question: What were the probabilities of fish encountering an MHK device based on fish vertical distribution, diel and tidal cycles, and behavior near the device?

The study site was the area around the ORPC OCGen® module deployment (44° 54.603 N / 67° 02.754 W) located in the outer bay of Cobscook Bay near the city of Eastport, Maine (Figure 1). Water depth at the device location was approximately 24 m at low tide and 33 m at high tide. Tidal current speeds in the area varied from 0-2 $m \cdot s^{-1}$, depending on time of tide and lunar cycle. Major commercial fisheries in the area were lobster, scallops, and sea urchins. Boat traffic was minimal with only fishing and recreational boats utilizing the nearby waters and no shipping traffic at the deployment location. The site was easily accessible via a pier at the Eastport Boat School, approximately 2.4 km away.

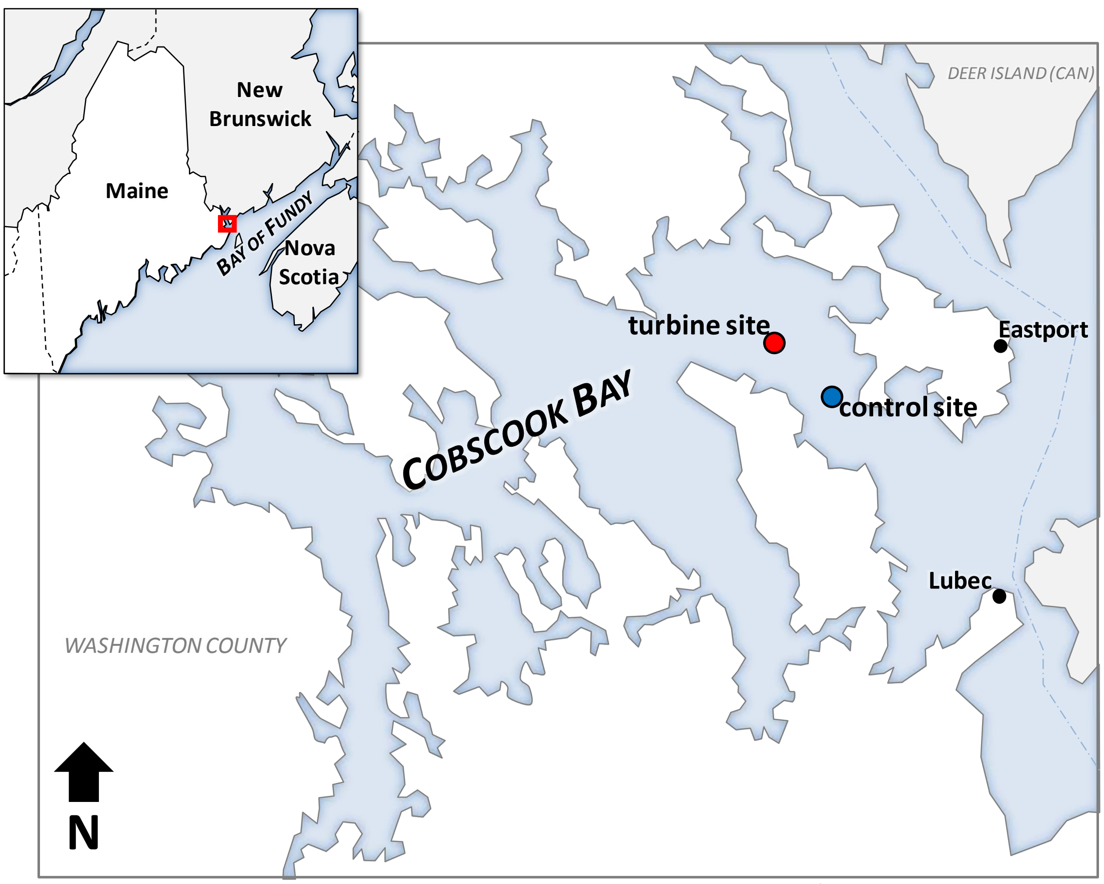

Figure 1. Study area and location of the MHK deployment sites (ORPC's TidGen® device bottom support frame and OCGen® module) and the control site, approximately 1.6 km away.

Results and Discussion

Objective 1

The continuation of two long-term hydroacoustic datasets: (a) discrete 24-h stationary, down-looking hydroacoustic surveys and (b) continuous stationary, side-looking hydroacoustic data collection.

a) Stationary down-looking hydroacoustics

The original down-looking dataset that was collected in Cobscook Bay began in May 2010, as the first step in a before-after-control-impact (BACI) study of relative fish density at this site. Data collected from March through November 2014 were funded by this DOE award. All data (2010 – 2014) were collected using a Simrad ES60 echosounder with a 38/200 Combi W transducer that was mounted on the side of a moored vessel. Similarly to the previous long-term dataset (Viehman et al. 2015), 24-hour surveys were carried out at the turbine site beside (CB1a) and in-line with (CB1b) the OCGen® module, as well as at the control site (CB2) approximately 1.6 km seaward. Data processing included the dB differencing methods (Objective 2) which removed most zooplankton from relative fish density estimates. The 2014 dataset is summarized in Table 1.

Table 1. Months of 24-h down-looking hydroacoustic surveys in 2014. The sampling sites were CB1a (beside), CB1b (in-line), and CB2 (control). Each site was sampled for 24 h. The OCGen® module was present only for Aug surveys. The turbine was rotating for Aug(1) (light gray) and static for Aug(2) and Aug(3) (dark gray) surveys.

Mar	Apr	May	Jun	Jul	Aug(1)	Aug(2)	Aug(3)	Sep	Oct	Nov
CB2		CB2			CB1a CB1b CB2	CB1a CB1b CB2	CB1a CB1b CB2	CB1a CB1b CB2		CB2

To examine the difference in fish density with and without the OCGen® module, fish density was quantified using volume backscattering strength (S_v). S_v is a measure of the sound scattered by a unit volume of water and is assumed proportional to fish density. S_v is expressed in the logarithmic domain as decibels, dB re 1 m^{-3}. Relative fish density was lowest in March and highest in May at the control site (Figure 3). This was typical of other years in the long-term hydroacoustic dataset (Viehman et al. 2015). There were significant differences between the turbine in-line (CB1b) and control (CB2) sites within the Aug(3) survey and between the turbine beside (CB1a) and control sites for the Sep survey (Figure 3). The differences between sites within surveys showed higher fish densities at the sites near the OCGen® module than at the control site, where there was no device. As such, these results do not seem to indicate that the OCGen® module had an effect on the density of fish. There was also a significant difference among surveys at the control site (CB2) between the Aug(1) and Sep surveys (not shown in figure). As this single difference among surveys for a single site was at the control site, it is likely due to a seasonal difference from early August to mid-September.

For detailed processing, analysis, and discussion, see Staines et al. (submitted), Appendix 3b.

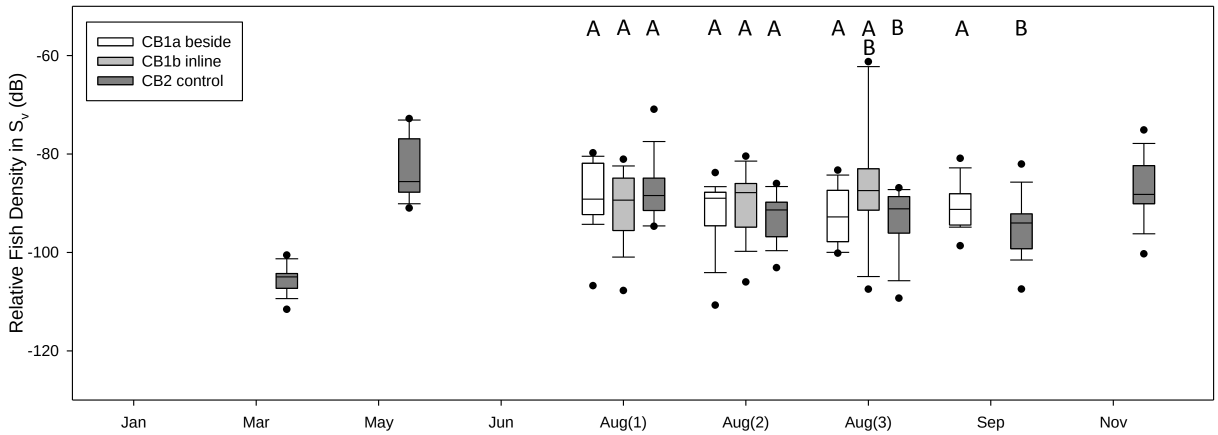

Figure 3. Relative fish density for each stationary down-looking hydroacoustic survey in 2014. The y-axis is relative fish density as mean volume backscatter strength (S_v) from 0-15 m above the sea floor. Boxes represent the median and 25th and 75th percentiles. The whiskers represent the 10th and 90th percentiles, while the dots represent the 5th and 95th percentiles. Statistically significant differences among sites for a single survey (i.e. CB1a, CB1b, and CB2 in Aug(1)) are represented by different letters above each site. The relative fish density estimates were from ebb tides only. Data collected during flood tides were removed due to acoustic interference from the bottom support frame from the previously deployed TidGen® device. The Sep CB1b survey was not included due to contamination of the data by a buoy line.

To examine the difference in fish vertical distribution with and without the OCGen® module the vertical distribution of fish throughout the water column was quantified using area backscatter coefficient, s_a. This is the summation of volume backscatter over a given depth range and is also proportional to fish density. s_a is expressed in the linear domain with units of $m^2 \cdot m^{-2}$ and is additive. Vertical distributions of fish were constructed using the proportion of area backscatter coefficients, s_a, contained within each 1-m depth layer, measured upward from the seafloor. Typically, fish density was highest near the bottom (seafloor) at most sites, with a few exceptions (Figure 4). Within single surveys there were significant differences between the beside and control sites for Aug(2). This result was due to almost half of the area backscatter at the beside site being in the bottom 1 m of the water column. For tests among survey dates for a single site, Aug(1) was significantly different from Aug(3) and Sep at the beside turbine site; Aug(2) was significantly different from Aug(1) and Aug(3) at the in-line with the turbine site; and Aug(1) was significantly different from Aug(2), Aug(3) and Sep for the control site (Figure 4). *Aug(1) was the only survey when the foils were rotating.* Vertical distribution of fishes on that date was significantly different for several comparisons, suggesting a possible effect of the dynamic tidal energy device on fish use of the water column nearby. Differences among comparisons were not consistent, possibly indicating that the differences were caused by the inconsistency of device operation.

For detailed processing, analysis, and discussion, see Staines et al. 2015 in Appendix 1 and Staines et al. submitted Appendix 3b.

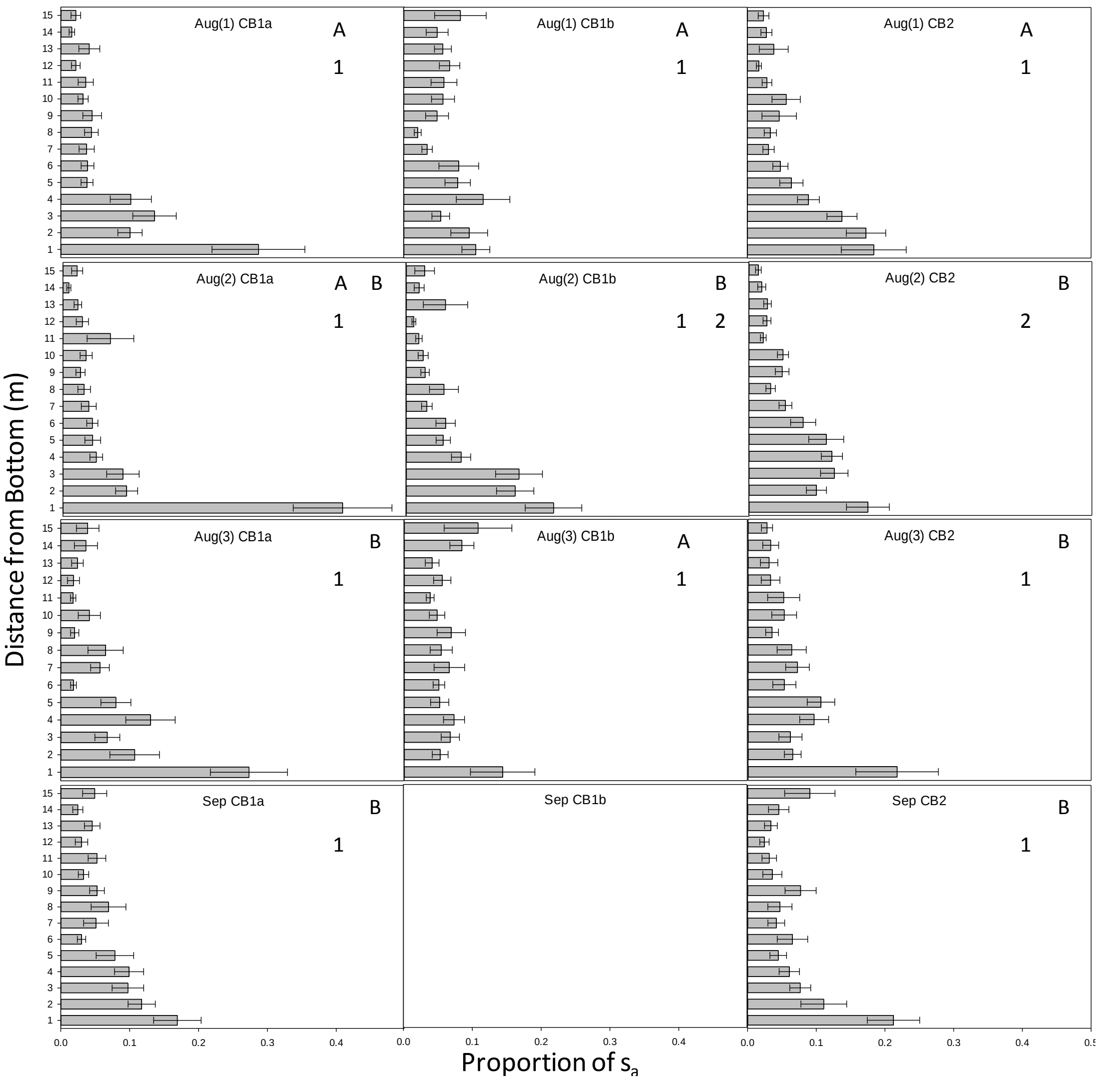

Figure 4. Vertical distribution of fish at each site for Aug(1), Aug(2), Aug(3), and Sep surveys. Horizontal bars represent the proportion of s_a (proportional to fish density) within each 1 m depth bin, from 0-15 m above the seafloor. Whiskers are one standard error. The OCGen® module was deployed for all Aug surveys but not Sep. The Aug(1) survey was the only survey during which the foils were rotating. Data used were from ebb tides only due to acoustic interference from the TidGen® support frame during flood tides. Statistical testing among sites for a single survey are shown left to right, i.e. Aug(1) for CB1a, CB1b, and CB2, with significant differences indicated by different numbers. Statistical testing among surveys for a single site are shown top to bottom, i.e. CB1a for Aug(1), Aug(2), Aug(3), and Sep with significant differences indicated by different letters. The Sep CB1b survey was not included due to contamination of the data by a buoy line.

Trawl samples were taken during each down-looking hydroacoustic survey at the control site in 2014 to examine seasonal patterns in fish presence. Samples were conducted during day and night slack tides. Midwater and benthic trawls were used. All trawls were standardized by boat speed and time. As such, numbers presented can be directly compared. The bathymetry near the control site was not conducive to safe trawling, so each trawling event took place 2.75 km away. Winter flounder (*Pseudopleuronectes americanus*) and longhorn sculpin (*Myoxocephalus octodecimspinosus*) dominated the catches. There was a major influx of Atlantic mackerel (*Scomber scombrus*) to Cobscook Bay starting in July, and though trawl speeds were not sufficient to capture them, mackerel were often caught on hook-and-line during slack tides of the down-looking hydroacoustic surveys. The total trawl catch for 2014 is shown in Table 2.

Table 2. Numbers of each species collected via trawling during down-looking hydroacoustic surveys. Totals are shown for sampling events that occurred before OCGen® module deployment (May 2014), during deployment (Aug 2014), and immediately after deployment (Sep 2014).

Common name	Before Deployment	During Deployment	After Deployment
Winter flounder	1108	559	168
Longhorn sculpin	218	48	42
Red hake	68	30	0
Atlantic herring	24	21	0
Silver hake	14	68	5
Atlantic cod	8	2	0
Shorthorn sculpin	6	19	10
Grubby sculpin	5	24	0
Threespine stickleback	3	0	0
Atlantic halibut	2	3	0
Haddock	2	92	21
Atlantic tomcod	2	0	0
Winter skate	1	0	0
Alewife	1	0	0
Ocean pout	1	0	0
Greenland halibut	1	0	0
Rainbow smelt	1	2	2
White hake	0	66	6
Little skate	0	1	0
Lumpfish	0	1	0
Rock gunnel	0	2	0
Sea raven	0	1	1
Cusk	0	1	0
Pollock	0	2	0
Butterfish	0	1	1
Spotted hake	0	0	1
Lanternfish	0	0	1

b) Side-looking hydroacoustics

The second long-term hydroacoustic dataset was stationary, side-looking hydroacoustic data collection that began in August 2012, when ORPC installed a Simrad EK60 echosounder with an ES200-7C split-beam transducer near the TidGen® Power System. The transducer was mounted on a pile 45 m to the side of the TidGen® Power System. The acoustic beam sampled a conical volume of water spanning 8.1 m - 13.8 m from the turbine face at its near end, and 13.5 m - 23.1 m from the turbine face at its far end (Figure 5). The beam was sampled 5 times per second as continuously as possible from August 2012 to July 2015. Whenever the TidGen® device was generating power, prior to April 2013, data were only collected at slack tides (when the turbine was not rotating) because of electrical interference of power generation on the hydroacoustic electronic equipment during running tides. This report focuses on data collected from April 2013 to July 2013, when the TidGen® turbine was still present but the brake was applied (and it was therefore not rotating); and on data collected from July 2013 to July 2015, when only the TidGen® bottom support frame was present (no turbine).

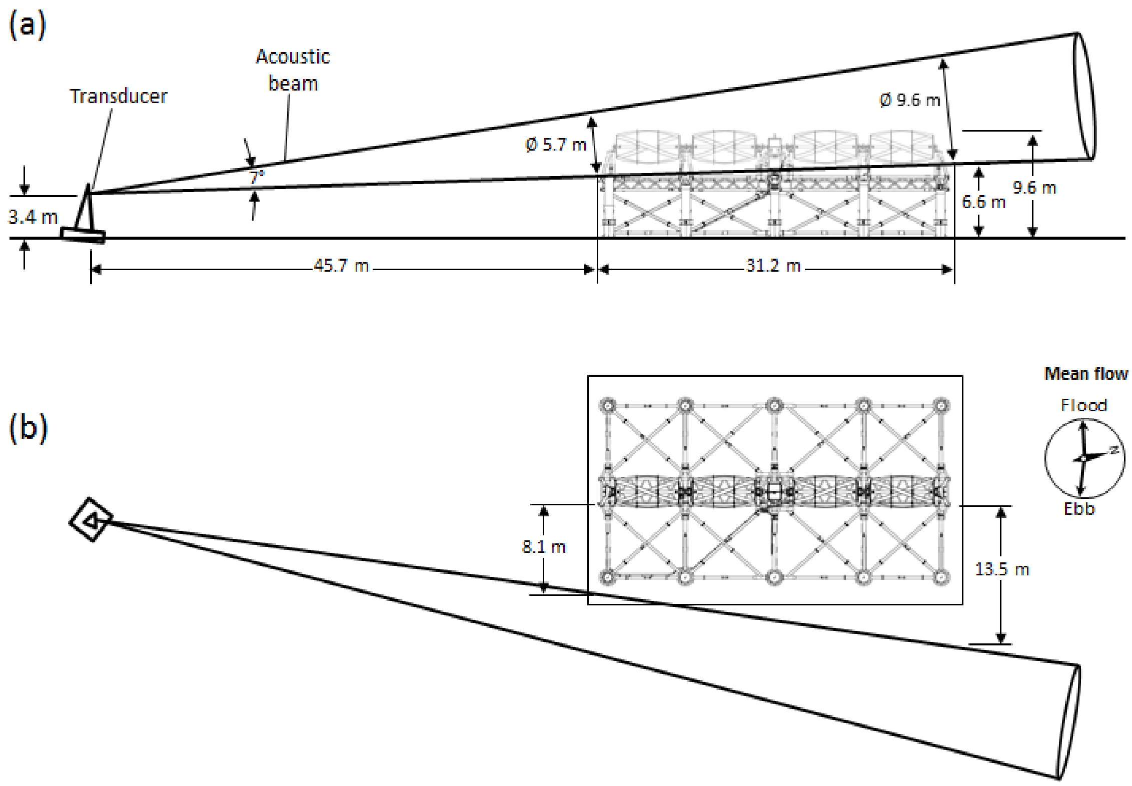

Figure 5. Side-looking hydroacoustic setup for monitoring individual fish behavior near the ORPC TidGen® device and subsequently the bottom support frame after turbine removal in July 2013. The tidal rose represents the mean tidal flow direction relative to north.

To examine individual fish behaviors in front of and in the wake of the TidGen® tidal energy device fish tracks were extracted from the side-looking hydroacoustic dataset during times when the turbine was present (though the brake was applied) and during times when it was absent (and only the TidGen® bottom support frame was present; Table 3). The heading of each fish relative to water flow was used to evaluate device effects on fish behavior.

Table 3. Summary of hydroacoustic data analyzed for this study.

Turbine state	Year	Dates of continuous data collection	Total time in dataset	Total fish detected
TidGen® present, brake applied	2013	4/25 - 5/02 5/07 - 5/14 5/24 - 6/04 6/26 - 7/05	38 days	5,227
TidGen® absent (bottom support frame present)	2014	4/24 - 5/27 6/04 - 6/26 6/30 - 7/05	63 days	5,749

Most tracked fish targets were moving in the same direction as the tidal current, with varying degrees of deflection from the median direction. For each tidal stage (flood, when fish were approaching the turbine; and ebb, when fish were departing from the turbine), a linear model was used to test for effects of turbine state (present or absent), zone (beside the turbine or in-line with the turbine), diel condition (day or night), and fish size (TS) on deflection from the median movement direction. The linear model was statistically significant (likely due to the large sample size) but the fit was poor for both the ebb and flood tide (adjusted R^2 of 0.008 and 0.037, respectively), meaning the factors examined did not have strong enough effects on fish movement to be biologically relevant. The absence of biologically significant factor effects on fish deflection (particularly effects of zone and turbine state) indicated that the turbine did not have a noticeable effect on individual fish movement at the ranges observed in this study (8-23 m), during either fish approach or departure from the device.

For detailed processing, analysis, and discussion, see Viehman and Zydlewski (submitted) in Appendix 3a.

While the above analysis utilized a small portion of the full side-looking hydroacoustic dataset, temporal analyses with Fourier and wavelet transforms were performed on a full year of side-looking fish detections (Table 4) to answer the fourth research question associated with this objective: *can a long-term hydroacoustic record of fish abundance be used to determine an ideal sampling strategy at this and similar tidal energy sites?* During the year of data collection, only the bottom support frame of the TidGen® device was present, and was assumed to have negligible effects on fish abundance in the sampled volume.

Table 4. Summary of side-looking hydroacoustic data collected at TidGen® site in 2014.

Start date	End date	Data collection	Time spanned
12/01/13	01/02/14	No data.	31 d, 18.4 hr
01/02/14	02/23/14	Data collected continuously.	51 d, 9.4 hr
02/23/14	02/24/14	No data.	1 d, 9 hr
02/24/14	04/15/14	Data collected continuously.	49 d, 16.5 hr
04/15/14	04/18/14	No data.	3 d, 6.9 hr
04/18/14	05/27/14	Data collected continuously.	39 d, 5.8 hr
05/27/14	06/04/14	No data.	7 d, 20.5 hr
06/04/14	06/26/14	Data collected continuously.	21 d, 21 hr
06/26/14	06/30/14	No data.	4 d, 9.8 hr
06/30/14	07/05/14	Data collected continuously.	4 d, 9.5 hr
07/05/14	07/14/14	No data.	9 d, 5.1 hr
07/14/14	07/20/14	Data collected continuously.	6 d, 8.8 hr
07/20/14	07/21/14	No data.	0 d, 13.2 hr
07/21/14	08/03/14	Data collected continuously.	13 d, 2.8 hr
08/03/14	08/04/14	No data.	0 d, 20.7 hr
08/04/14	08/27/14	Data collected continuously.	23 d, 4 hr
08/27/14	09/05/14	No data.	8 d, 22 hr
09/05/14	11/01/14	Data collected continuously.	57 d, 6 hr
11/01/14	11/06/14	No data.	4 d, 20.4 hr
11/06/14	11/07/14	Data collected continuously.	1 d, 8.1 hr
11/07/14	11/10/14	No data.	2 d, 19.1 hr
11/10/14	12/27/14	Data collected continuously.	46 d, 22.6 hr
12/27/14	01/05/15	No data.	9 d, 0 hr

The Fourier transform revealed cyclical patterns in fish abundance related to tidal and diel cycles, with periodicities of 6.2, 12.4, and 24 hours, as well as a cycle lasting approximately 60 days (Figure 6).

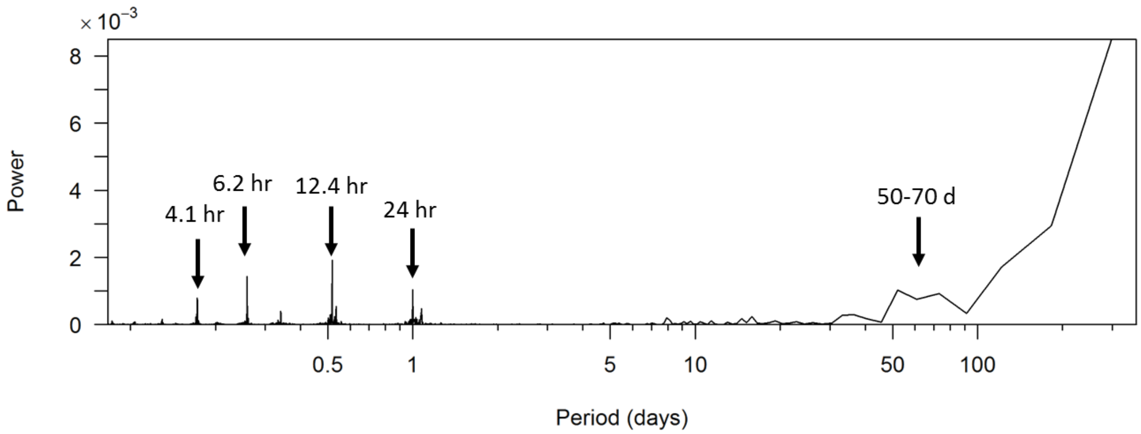

Figure 6. Power spectrum from Fourier transform of time series of fish abundance in the sampled volume of side-looking hydroacoustics data collected at the TidGen® site in 2014. Principal periodicities in the time series are indicated by arrows.

The wavelet transform revealed that the patterns identified by the Fourier transform were present throughout the year, but varied over time (Figure 7). The 12.4-hr tidal periodicity was present throughout most of the year, indicating one tidal stage may have more fish than the others. The diel pattern became important in the summer, perhaps due to seasonal changes in the local fish community. While the diel pattern was present, more fish were detected at night than during the day. A 15-day periodicity starting in July was also apparent in the wavelet transform, indicating a potential influence of the spring-neap tidal cycle (i.e., lunar phase) on fish abundance.

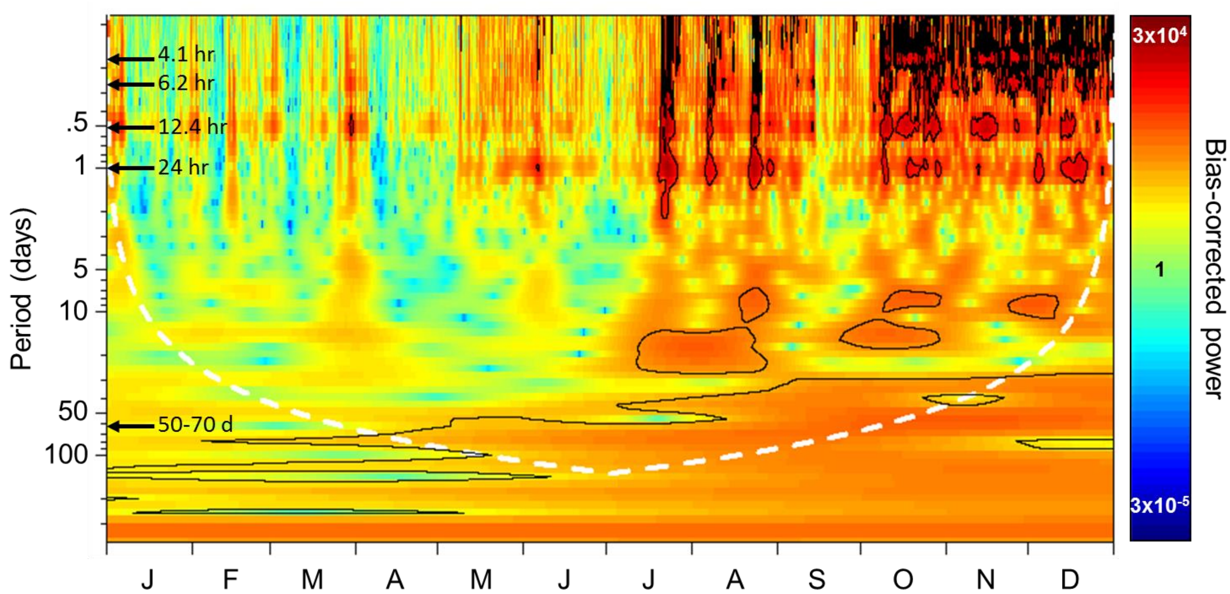

Figure 7. Wavelet spectrum of fish abundance time series collected with side-looking hydroacoustics at the TidGen® site. Color indicates the magnitude of the bias-corrected wavelet power, with red indicating higher power and blue indicating lower power. Black contours enclose areas of significance at the 0.95 level. Arrows correspond to the periodicities indicated in Figure 4. The dashed white line indicates the cone of influence, below which power values may be reduced by edge effects.

This variation over the course of a year has implications for long-term monitoring of fish abundance at this and other tidal power sites. To explore the effects of survey timing on the observed long-term trends in fish abundance, four different survey designs were simulated by subsampling the 1-year dataset: 1) six

1-hour surveys per year on random days; 2) six 24-hour surveys per year on random days; 3) one 24-hour survey per month in Mar, May, Jun, Aug, Sep, and Nov, timed to hold lunar phase constant (i.e. spring or neap tides); and 4) one 24-hour survey every 60 days (first day chosen randomly) (Figure 8). 24-hour surveys were best at reducing the effects of short-term variation (e.g. tidal and diel cycles) on observed trends, and the most consistent and accurate observations were achieved using designs which timed surveys based on existing patterns in fish abundance (designs c and d; Figure 8).

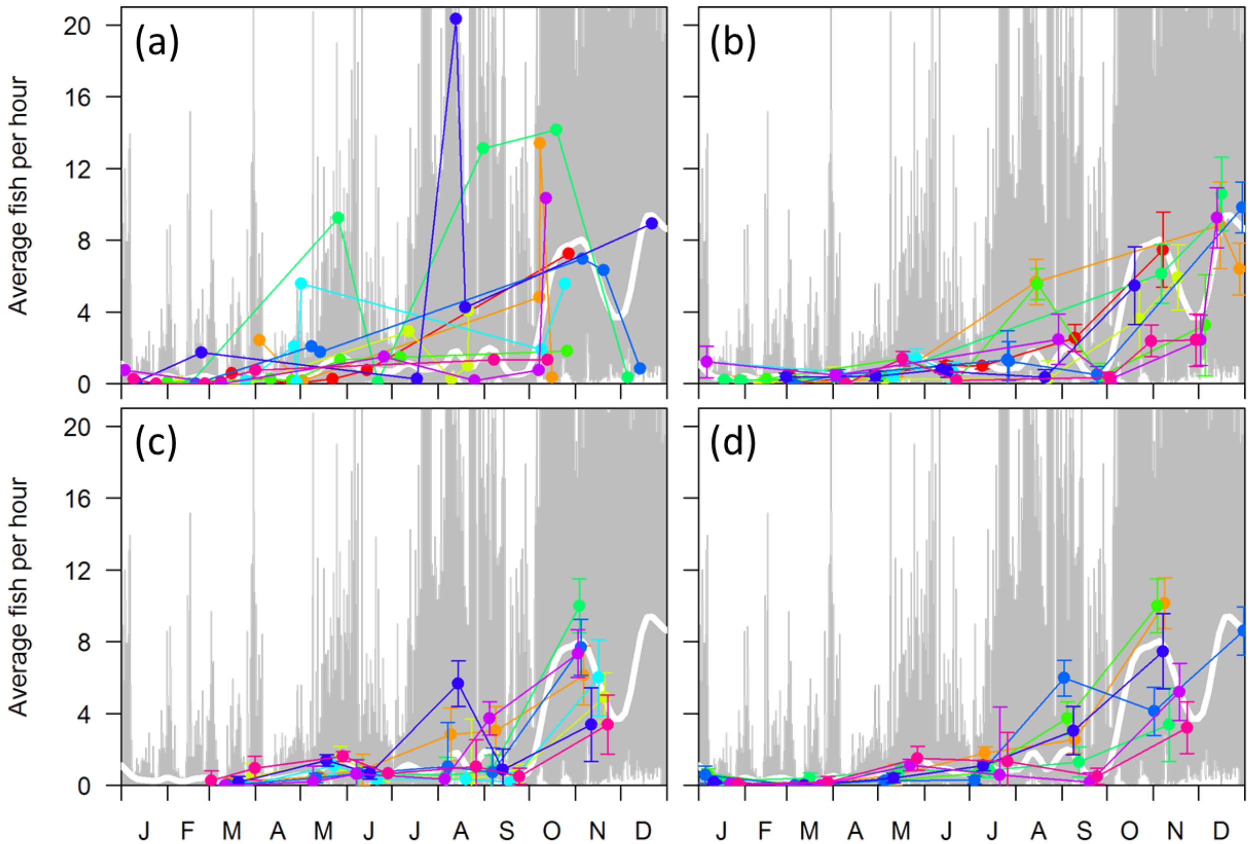

Figure 8. Influence of survey timing and duration on apparent trends in fish abundance (average number of fish per hour). Grey line is the fish abundance time series. Thick white line is the Lowess-smoothed abundance time series. Sampling schemes shown are: (a) 6 randomly spaced 1-hour surveys; (b) 6 randomly spaced 24-hour surveys; (c) 24-hour surveys carried out in March, May, June, August, September, and November, with lunar stage held constant; (d) 24-hour surveys spaced 60 days apart. Each colored line is the result of one iteration of the sampling scheme (n = 10). For 24-hour surveys, points are medians of data included in a given survey, and error bars represent one standard error.

For detailed processing, analysis, and discussion of a 3-month data subset see Viehman and Zydlewski 2015 in Appendix 1. For details on entire year of data, see Viehman et al. submitted Appendix 3d.

Conclusions

- ***Stationary down-looking hydroacoustics***
  - Fish density was highest in May.
  - Fish density tended to be higher near the sea bottom.
  - There were some significant differences in fish density and vertical distribution when testing between sites within surveys and between surveys within sites but they were inconsistently related to turbine presence and operation.
- ***Side-looking hydroacoustics***

- The presence of the static turbine did not significantly affect fish movement relative to the bulk water currents at the site.
- There were distinct cyclical patterns of fish abundance at the site of the TidGen® that coincided with tidal and diel cycles.
- Survey timing can affect how long-term trends in fish abundance are observed and documented at a tidal energy site. Survey timing can be adjusted to account for these natural cycles, reduce variation in observed fish abundance, and minimize cost of surveys.

Objective 2

A major limitation of hydroacoustic data used in fisheries applications is the inability to separate fish density by species. New processing approaches to improve species identification were attempted on the long-term, down-looking hydroacoustic dataset. We used a method known as dB differencing (Kang et al. 2002, Madureira et al. 1993). This method compares backscatter data collected at two or more frequencies to identify differences specific to particular species. We used our existing down-looking hydroacoustic data collected with 38 and 200 kHz in Cobscook Bay from 2011-2013 to test if dB differencing could be used to separate fish species with swimbladders (e.g. Atlantic herring) from those without (e.g. Atlantic mackerel).

The backscatter from 200 kHz was subtracted from 38 kHz backscatter to provide a metric called the frequency response, r(f). The r(f) was used to categorize groups of backscatter. The following r(f) ranges were used for our backscatter type classifications based on peer reviewed literature (Korneliussen and Ona 2002):

- r(f) < 2 dB = fish with swimbladder
- 2 dB < r(f) < 6 dB = mackerel
- r(f) > 6 dB = zooplankton

This information along with knowledge that mackerel were absent in Cobscook Bay until July each year led us to propose that the r(f) of swimbladdered fish and zooplankton would be observed in all sampled months while the r(f) of mackerel would only be present from July onward. However, we observed the mackerel r(f) in all sampled months and amounts of related backscatter varied little. In other words, based on the hydroacoustics, mackerel were present during all sampled months (Figure 9), although they could not have been based on knowledge of their physical absence in certain months (e.g., May and June).

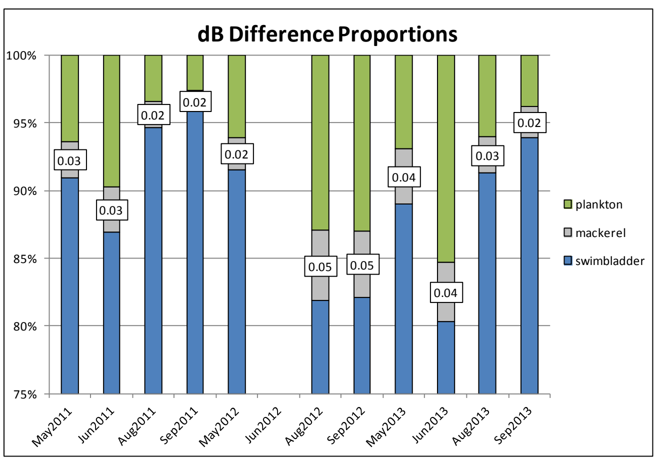

Figure 9. Proportions of the three categories of backscatter from dB differencing methods using control site (CB2) data. Note that the proportion of mackerel was similar for all months when it should be low or absent in May and June and higher in August and September.

For dB differencing methods to separate species by r(f) they must be separated by range if they are ensonified in the same sampling volume (ping), or separated by time if they are ensonified in different sampling volumes. In Cobscook Bay, fish of differing species shoal together (e.g. herring and mackerel). A major food source for herring and mackerel in the bay is zooplankton. So groups of backscatter could possibly be composed of two or more of our backscatter type classifications. This leads to a mixed r(f) that could be misleading. For instance, a mixed shoal of herring and krill (zooplankton) could lead to an r(f) that was representative of neither but resemble that of mackerel. This is a possible scenario for sampled months of May and June when we know mackerel to be absent but still observe their r(f) signature.

While this mixed signal made it challenging to separate mackerel from other scatterers, we have confidence in our estimation of fish with swimbladders, i.e., separating them from zooplankton. The r(f) signal that was representative of mackerel acts as a buffer between the r(f) signal of fish with swimbladders and the r(f) signal of zooplankton. Within the full spectrum of r(f) signals that we encounter, there were two major thresholds; one that separated fish with swimbladders and mackerel (-2 dB), and one that separated mackerel and zooplankton (6 dB) (Figure 6). We can therefore provide an overall estimate of fish (swimbladder and mackerel), excluding zooplankton. Using the 2 dB threshold does not affect our overall fish estimate but the 6 dB threshold does not provide a distinctive cutoff between mackerel and zooplankton. At the 6 dB threshold, depending on the mixture of r(f) signals, we were confidently estimating fish with swimbladders and mackerel, with the possibility of including a small amount of zooplankton in the estimate or excluding a small amount of mackerel. Our confidence in the estimation of fish with swimbladders was further strengthened by the fact that they will always contribute more to overall backscatter and thus be better represented in the S_v metric. These methods were incorporated for all stationary, down-looking hydroacoustic data from Objective 1.

For detailed processing steps see Staines et al. (in progress) in Appendix 2.

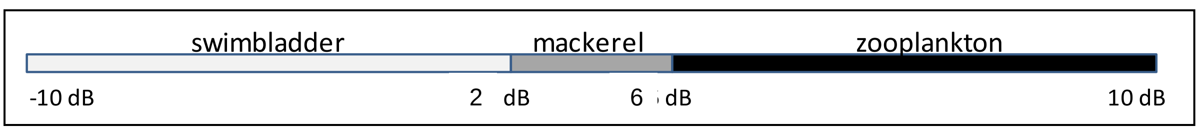

Figure 10. The frequency response, r(f), value line for dB differencing methods. Note that the mackerel r(f) is between the swimbladder and zooplankton r(f)s.

Conclusions

- Using dB differencing methods, the frequency response, r(f), of mackerel was observed in the data during months when they were known to be physically absent, leading to the conclusion that other factors were contributing to the r(f) observed.
- Mackerel, herring, and zooplankton (e.g. krill) reside in Cobscook Bay in mixed shoals, which confounded the frequency response metric, r(f), used to separate mackerel from other species.
- While we were unable to separate mackerel from other fish species, there was improved confidence in using dB differencing methods to remove zooplankton from relative fish density estimates.

Objective 3

To develop an encounter probability model, we used empirical data on fish abundance, vertical distribution, and behavior collected near two MHK energy devices. Two separate datasets were used for this objective. The first was the dataset presented in Objective 2, collected from 2011 – 2013 using this and other DOE awards. The second dataset was collected under a different funding source and used mobile, down-looking hydroacoustic data. These data were collected with a Simrad EK60 echosounder with an ES200-7C split-beam transducer. The transducer was attached to a vessel and repeated transects were conducted over and beside (control) the deployed OCGen® module by drifting with the tidal current. We used three proportional fish density values for a probability of encounter model, P = p_1 * (1 - p_2) * (1 - p_3). The first was p_1, the proportion of fish at the depth of the device when the device was absent; the second was p_2, the proportion of fish avoiding the device prior to detection in our down-looking hydroacoustic data collected near the device. The first two proportions used the first dataset of stationary, down-looking hydroacoustics. The third proportion was p_3, the proportion of fish avoiding the device between being detected in our down-looking hydroacoustic surveys near the device and actually encountering the device; this proportion was derived from mobile, down-looking hydroacoustic surveys.

The first proportion, p_1, was estimated using a Bayesian Generalized Linear Model (BGLM) with stationary down-looking data from 2011-2013 and took into account potential effects related to month, diel, and tidal variation. This proportion was also separated by those depths that include the entire TidGen® Power System (0.5 - 9.5 m) and just the dynamic parts (foils) of the device (6.5 - 9.5 m) above the sea floor. The overall mean probability for the depths of the entire device ranged from 0.658 - 0.689, and the overall mean probability for the depth of the foils ranged from 0.079 - 0.093.

The second proportion, p_2, was determined by testing for differences in the vertical fish distributions between the project and control sites before and after the installation of the TidGen® device (Figure 11). There were no significant differences for any comparisons. This resulted in the value for p_2 = 0.

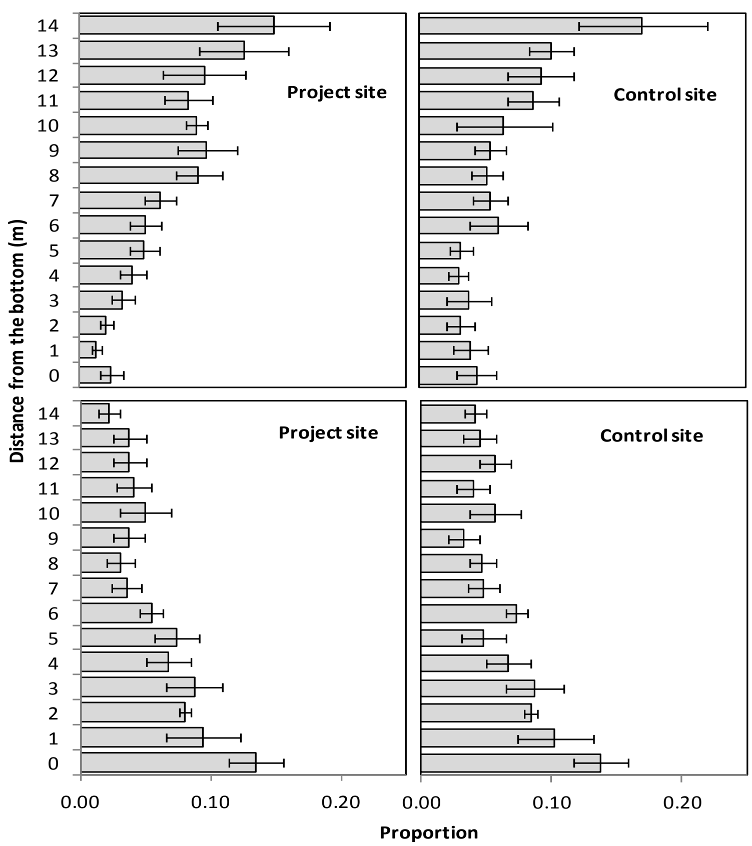

Figure 11. Vertical distribution of fish during ebb tide in May (upper panels) and September (lower panels) 2012 surveys at project and control sites. Vertical axis is distance above bottom (m). Each horizontal bar represents the proportion of area backscatter (s_a) within each 1 m water column layer. Whiskers denote one standard error.

Proportion three, p_3, was determined using mobile, down-looking hydroacoustic transects. Transects started 200 m upstream of the OCGen® module. The number of fish detected decreased as the vessel approached the OCGen® module. A linear regression was fitted to the data ($R^2 = 0.86$), and it was determined that a 37.2% mean decrease in the number of fish occurred from 140 m to 10 m upstream of the device (Figure 12), so $p_3 = 0.372$. Control transects (those not traveling over the device) showed no such decrease in fish numbers.

For detailed processing, analysis, and discussion, see Shen et al. 2015 in Appendix 1 and Shen et al. (2016) in Appendix 3a.

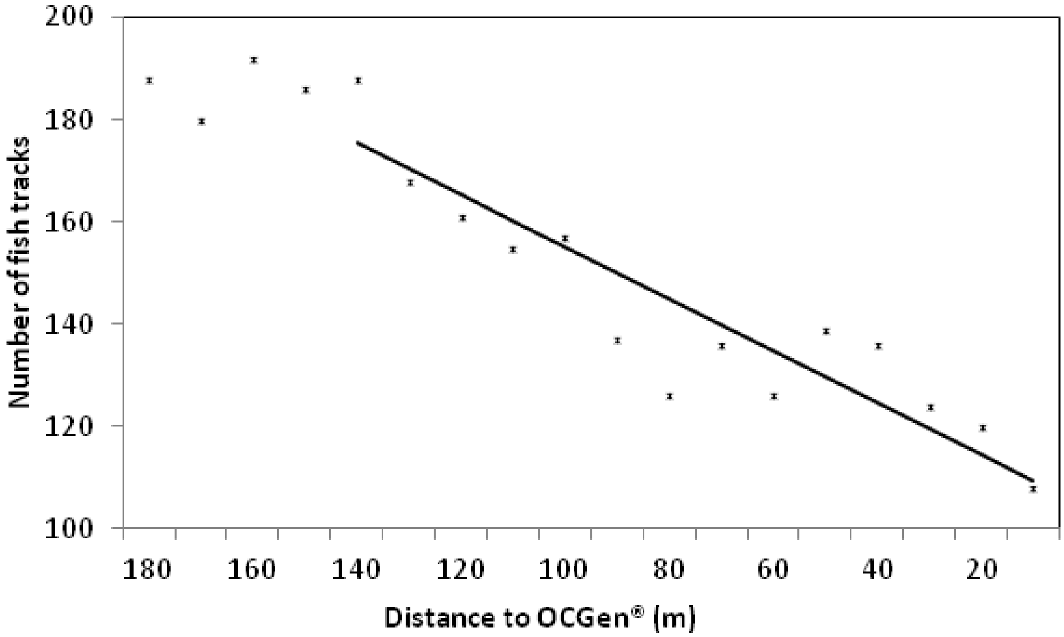

Figure 12. Number of fish tracks upstream of the OCGen® module from transects over the device. Note that the number of tracks begin decreasing at approximately 140 m from the device.

Conclusions

- Modeled maximum probability of fish encountering the whole TidGen® Power System (including bottom support frame) was 0.432 (95% CI: 30.5, 55.3), and the probability of fish encountering only the device foils was 0.058 (95% CI: 4.3, 7.3).
- The third proportion, p_3, had the highest value of the three model components and represented the closest proximity to a deployed device.
    - This was evidence that individual fish avoidance can occur as far away as 140 m.
    - In combination with evidence from Objective 1, behavioral changes can occur between 140 and 10 m from a device.

Problems Encountered

The originally proposed project was to examine the installation and redeployment of ORPC's TidGen® device. Technical issues arose and its installation was postponed. The OCGen® module mooring test installation was planned for a similar time and this device replaced the originally planned TidGen® for proposed research. The goal and objectives of the research did not change but addressed animal interactions with the OCGen® module instead. Additionally, the OCGen® module was deployed in a location close to the proposed TidGen® location and was also located at a similar depth in the water column, making processing, analysis, and interpretation of data comparable between the two devices.

There were three down-looking hydroacoustic surveys in August during the OCGen® deployment. During the first survey all components of the device were intact and operating according to plan. The second and third surveys occurred during times when the turbine foils were static for unknown reasons (see ORPC final technical report to USDOE: *OCGen®Module Mooring Project DE-EE0002650* for further details).

The OCGen® module was deployed close to the TidGen® bottom support frame (BSF). An attempt was made to place survey moorings in positions that would prevent the survey vessel from being located over the TidGen® BSF during flood tides, but the scope of the mooring lines still placed the transducer over the BSF. The combined size of the acoustic beam and space between the BSF and OCGen® module did not enable positioning to avoid the BSF contaminating the acoustic data from 0-5 m above the seafloor during flood tides. As such, those data were unusable for the proposed analyses. So, we processed data with and without the 0-5 m in both tidal stages and relative fish density estimates from both processing methods, including seasonal trends, were not different. From previous research, we knew that fish densities were higher near the seafloor, so we decided the best solution was to exclude flood tide data (contaminated by the BSF), in order to include the bottom 5 m of the water column.

During the September CB1a (beside) survey, there was an object in the water column that contaminated the data to the point of being unusable for the proposed analyses. The object was most likely a buoy and associated line from a lobster pot. We removed this survey from processing (Figures 3 and 4).

Recommendations

The continuation and development of the MHK industry will depend on determining effects of operational devices on fishes. Methods for monitoring will require further research, and refinement will help reduce the regulatory barrier for industry to progress toward commercial viability. The research summarized in this report represents viable approaches that could be used at other MHK tidal power sites with similar physical dynamics and fish assemblages, e.g., Canada and Europe.

Stationary, down-looking hydroacoustic approaches provided data that revealed seasonal differences at our Northwest Atlantic study site. The same data were processed to quantify fish vertical distribution and relative density at both the turbine site and a nearby control site. Collecting data at both a turbine and control site allowed meaningful comparisons for examining effects on fishes in the area. While we do recommend stationary, down-looking hydroacoustics as a valid means of environmental assessment for fishes near MHK tidal device deployments, certain details must be considered: (1) transducer type (balance between cost and detailed behavior); and (2) stationary approach (feasibility in extreme flows).

(1) To minimize monitoring costs, we used a single-beam transducer (~$10,000 US). A split-beam transducer (~$50,000) would have enabled collection of target strength data, which can be used to approximate fish size. It would also provide fish position within the beam, which can provide individual behavior (see Objective 1: Side-looking hydroacoustics).

(2) Sites that are deeper and have stronger tidal currents may not be suitable for stationary hydroacoustics methods. The tidal current speeds in our study area rarely exceeded 2 $m \cdot s^{-1}$, and the maximum depth was less than 50 m. Other locations, such as Minas Passage in Nova Scotia, could be too deep with currents too swift to allow stationary surveys from a moored vessel. Such locations would warrant the use of mobile, down-looking hydroacoustic surveys similar to those in Objective 3, though processing and analyses of these data would be similar to stationary surveys. The same limitations posed by current speed and depth on stationary, down-looking hydroacoustic surveys would apply to stationary, bottom-mounted applications similar to the side-looking echosounder in Cobscook Bay at the TidGen®. Installation and maintenance of a side-looking echosounder would be challenging and expensive, but not impossible.

Results from side-looking hydroacoustics data collection near a static turbine (Objective 1, Research Question 3) suggest the need for data collection closer to a device if the goal is to observe distinct behavior changes related to turbine evasion. In previous research (Viehman and Zydlewski 2015a), data collected within 0-3 m of a turbine allowed the assessment of individual-level responses of fish interacting with a device. Data collected under Objective 3, however, also suggest a need to examine responses as far away as 140 m, though individual-level responses at these ranges may not be as abrupt or obvious as those observed in the immediate vicinity of the device. *The spatial distance of observation must therefore be chosen based on the question asked*; e.g., what does a fish do when it physically encounters a device, vs. at what distance do fish respond to devices? Both questions are important for various species, and results will be dependent on fish species and size (Viehman and Zydlewski 2015; Hammar et al. 2014). So, while probability of encounter estimates incorporating far-field fish behavior are informative, particularly during initial monitoring, documenting near-field events such as fish strike occurrence and the fate of those fish remains important, as well. Collecting meaningful data on the direct interactions of fish with turbine foils in these high-energy and often turbid environments will continue to be a challenge. Multi-beam echosounders, acoustic cameras, and optical cameras are all viable methods but create large amounts of data and require time-consuming processing. Such methods will aid in determining fish interactions with individual turbines, but medium- and large-scale approaches will be required if we wish to document effects of arrays of tidal energy devices.

Sampling to control for the influence of seasonal, daily, and tidal cycles at different tidal power sites will improve study consistency across sites, streamlining the monitoring process and allowing comparisons between sites. Results from Objective 1, Research Question 4, indicate that cyclical temporal patterns in fish abundance can be used to design long-term monitoring schedules to yield accurate longer-term trends of fish abundance at tidal power development sites. Results indicated that surveys should be 24 hours long to capture tidal and diel variation in fish abundance, and should take place at the same point in the neap/spring tidal cycle. Monthly or semi-monthly surveys would likely capture seasonal changes such as emigration and immigration of different species, but analysis of a longer dataset (Viehman and Zydlewski submitted, Appendix 3) will allow us to determine the minimum number of surveys needed per year.

Multi-frequency methods should be used to improve quantitative hydroacoustic fish metrics. Dual frequency single beam hydroacoustics can be used to remove the majority of zooplankton from relative fish density estimates using dB differencing methods. This enables more appropriate measures of relative fish density than considering the return signal from just a single frequency. Determining the species of fish sampled with hydroacoustic gear remains an area of intense research in fisheries science. The traditional means of estimating species sampled is through physical capture (MacLennan and Simmonds 2008; Simmonds and MacLennan 2005). Numerous studies have shown that certain targets (e.g. fish and zooplankton) scatter sound differently depending on acoustic frequency (Kang et al. 2002; Madureira et al. 1993). We used dB differencing methods to attempt to separate Atlantic mackerel from swimbladdered fish in Cobscook Bay but were challenged by the mixed shoals of species (i.e. mackerel and herring). While differentiating fish species using only hydroacoustic data eluded us, we were able to confidently remove the majority of zooplankton from our relative fish density estimates using dB differencing methods. We stress that these methods will require the use of at least two frequencies, which could increase survey equipment costs.

As potential tidal power sites are proposed, it will be important to provide baseline data for regulators to consider potential effects of tidal power devices on fishes. The probability of encounter model produced from this research was a prime example of the utility of such baseline information. Collecting data on fish location in the water column, combined with the knowledge of depths spanned by a proposed device, and concurrently-collected data at a control site allowed us to determine the first probability component of the encounter model. Collecting data after device installation allowed us to resolve the second and third model components. The probability of encounter model was an important first step toward determining the overall effects of a tidal turbine on nearby fishes.

The early stages of this industry have provided pilot project deployments where empirical data on fish have been collected. While this begins to answer questions about small-scale turbine effects, the future of the industry involves multiple-device arrays, which has implications at a larger scale. Determining effects on fish in these scenarios could prove more challenging with confounding spatial variation of the larger geographical coverage.

Capturing fish behavior and movement around arrays will be necessary to determine array-level effects. Mobile, down-looking hydroacoustics from a vessel would likely be the most ideal method. Collecting data in the area planned for array deployment both before and after device installations along with surveys at one or more control sites would allow for a Before-After-Control-Impact (BACI) study design. A BACI design has the advantage of compensating for variation that may be spatially or temporally specific (i.e. annual variation and site specific variation). A BACI design that uses metrics similar to those used to address research questions 1 and 2 of Objective 1 of this study and the survey timing suggested in Objective 1, question 3, would provide useful results by showing changes in water column use and overall fish density in the area of the array while minimizing effects of natural cycles in abundance. We also will likely need to develop new approaches to produce meaningful results at multiple spatial scales.

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Viehman, H., G. B. Zydlewski. 2015b. Using temporal analysis techniques to optimize hydroacoustic surveys of fish at MHK devices. *Proceedings of the 11th European Wave and Tidal Energy Conference.* 6-11 September. Nantes, France.

Appendix 1

Publications

Viehman, H.A., G.B. Zydlewski TO BE SUBMITTED. High-resolution, long-term observation of fish passage at a tidal energy site: Predictable patterns on multiple temporal scales. *PLOS One.*

Viehman, H.A., G.B. Zydlewski, W. Halteman, D. Degan. *Submitted*. Fish behavior near a static tidal energy device. *PLOS One*.

Staines, G., G.B. Zydlewski, H. A. Viehman. *submitted*. Changes in relative fish density around a deployed marine hydrokinetic (MHK) device in Cobscook Bay, Maine. International Journal of Marine Energy.

Shen, H., G.B. Zydlewski, H. A. Viehman, G. Staines. 2016. Estimating the probability of fish encountering a marine hydrokinetic device. Renewable Energy 97: 746-756.

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Appendix 2

Conference/Presentation List

Zydlewski, G.B., G. Staines, H. Viehman, H. Shen. 2016. Fish Behavior, Presence, and Distribution in a Tidally Dynamic Region, with and without a Tidal Energy Device. Poster presentation to Ocean Sciences annual meeting. New Orleans, LA. 26 February.

Viehman, H., G. B. Zydlewski, G. Staines, H. Shen. 2015. What about the fish? Studying effects of tidal power turbines in the USA. Oral presentation to zoology faculty and graduate students at the University of Aberdeen. Aberdeen, Scotland. 17 September.

Viehman, H., G. B. Zydlewski. 2015. Using temporal analysis techniques to optimize hydroacoustic surveys of fish at MHK devices. Oral presentation at the European Wave and Tidal Energy Conference. Nantes, France. 6-11 September.

Staines, G., G. B. Zydlewski, H. Viehman, H. Shen, J. McCleave. 2015. Changes in vertical fish distributions near a hydrokinetic device in Cobscook Bay, Maine, USA. Oral presentation at the European Wave and Tidal Energy Conference. Nantes, France. 6-11 September.

Viehman, H., G. B. Zydlewski. 2015. Altered fish behavior near a static hydrokinetic turbine. Oral presentation at the 145th meeting of the American Fisheries Society. Portland, OR. 16-20 August.

Zydlewski, G.B. 2015. State of the Science on MHK monitoring technology. At the 2015 NOAA National Hydropower Meeting. Greater Atlantic Regional Fisheries Office, Gloucester, MA. 9 July.

Shen, H., Zydlewski, G.B., Viehman, H., Staines, G. 2015. Estimating the probability of fish encountering a marine hydrokinetic device. Oral Presentation at the 3rd Marine Energy Technology Symposium, Washington, DC. 28 April.

Shen, H., G. B. Zydlewski, H. Viehman, G. Staines. 2015. Estimating the probability of fish encountering a marine hydrokinetic device. Oral presentation at the Marine Energy Technology Symposium. Washington, D.C. 27-29 April.

Viehman, H., G. B. Zydlewski. 2015. A unique approach to developing alternative energy from the ocean. Oral presentation to University administrators, engineering and biology faculty at Hirosaki University. Hirosaki, Japan. 7 January.

Viehman, H. 2014. Do tidal turbines affect fish? Poster presentation at the International Network on Offshore Renewable Energy North American Symposium. Halifax, Canada. 2 November.

Zydlewski, G.B. 2014. Effects monitoring of fish at/near an ORPC turbine. Given by Webinar at the Environmental Monitoring, Regulatory Needs & Scientific Capabilities workshop in Wolfville, Nova Scotia, Canada, sponsored by Annex IV, Acadia University and NS Energy. 1 November.

Shen, H., Zydlewski, G.B., Staines, G.S, Viehman, H. 2014. Modeling the Probability of Fish Encounter with a Tidal Energy Turbine. 144th meeting of the American Fisheries Society in Quebec, Canada. Given in the Symposium: Understanding Fish and their Ecosystems in Challenging Environments. 20 August.

Viehman, H., Zydlewski, G.B. 2014. Optimizing Sampling Based on Temporal Variation in Fish Abundance at a Tidal Energy Site in Cobscook Bay, Maine. 144th meeting of the American Fisheries

Society in Quebec, Canada. Given in the Symposium: Understanding Fish and their Ecosystems in Challenging Environments. 20 August.

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Appendix 3:

Submitted Manuscripts

a. Shen et al. 2015. *Renewable Energy*
b. Staines, G.J., Zydlewski, G.B., Viehman, H.A. submitted to the *International Journal of Marine Energy*
c. Viehman , H.A., Zydlewski, G.B., Halteman, W., Degan, D. submitted to *PLoSOne*
d. Viehman, H.A., Zydlewski, G.B. submitted to *PLoSOne*

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Estimating the probability of fish encountering a marine hydrokinetic device

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ABSTRACT

Strong tidal currents in eastern Maine, USA, make that region attractive for tidal power development. Little is known about the effects of marine hydrokinetic (MHK) devices on fish, yet many fish species use tidal currents for movements. We used empirical data from stationary and mobile hydroacoustic surveys to examine the probability that fish would be at the depth of an MHK device and may therefore encounter it. The probability was estimated using three components: 1) probability of fish being at device-depth when the device was absent; 2) probability of fish behavior changing to avoid the device in the far-field; and 3) probability of fish being at device-depth in the near-field when the device was present. There were differences in probabilities of fish encountering the MHK device based on month, diel condition and tidal stage. The maximum probability of fish encountering the whole device was 0.432 (95% CI: [0.305, 0.553]), and the probability of fish encountering only device foils was 0.058 (95% CI: [0.043, 0.073]). Mobile hydroacoustics indicated that fish likely avoided the device with horizontal movement beginning 140 m away. We estimated the encounter probability for one device, but results can be applied to arrays, which may have bay-wide implications.

1. Introduction

Tidal power projects are being developed around the world in recent years to harness this predictable, regular and renewable energy from ocean currents [1–4]. Large, in-stream marine hydrokinetic (MHK) devices can be used to generate electricity from the kinetic energy of fast-flowing water using moving device foils [5–7]. Unlike barrage tidal power generation and tidal fences, which block off a channel, MHK devices are free-standing, open structures that are expected to be an environmentally sound tidal power option. The open configuration and relatively slow movement of MHK devices allow fish, water, and sediment to pass through the channel and provide opportunities for fish to avoid the areas of the device(s) [8–10].

Tidal currents play an important role in the life cycles of many fish species in estuaries and coastal ocean waters. By changing vertical position in the water column, migratory species can use tidal flow to access suitable foraging, spawning, and sheltering grounds [11–13]. The tidal currents provide an energetic advantage for directed movements between habitats [14–16]. Devices may sufficiently alter water flow patterns or other features to influence the behavior of fish using the tidal currents if there is spatial overlap between fish and MHK devices [6,8,17]. Effects on behavior may include interference with migration, habitat selection, and avoidance or evasion [4,17,18]. Concerns have been raised regarding the risk of foil strike to fish because some devices have tip velocities exceeding 10 m s^{-1} [19]. Although some studies have examined the survival of fish passing through tidal devices in laboratory flumes [9,10,18], little empirical data have been collected that directly document interactions between fish and MHK devices [4,19,20]. Thus, different quantitative models have been explored to model fish interactions with MHK devices [6,10,19,21,22]. Wilson et al. [21] used predator-prey interaction to predict the encounter rate of herring with MHK devices. A mark-recapture model was used to assess the survival rate for three riverine species [10]. More complicated models have been developed to cover different aspects of fish interactions with MHK devices [19,22], including interactions of certain species (e.g., sturgeon [22]) and interactions of different assemblages with a device [19]. Romero-Gomez and Richmond [6] first modeled the flow and turbulence characteristics around an MHK device and then simulated flow conditions in a Lagrangian particle model and estimated fish survival at

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96.7–99.1%. They determined that fish collision with a foil was dependent on fish size and turbulence resolution in the model.

It is difficult to accurately predict the effects and impacts of MHK devices on fish because relatively few commercial-scale devices have been deployed. In the USA, few MHK projects have been developed, tested, and deployed. To date, two devices have been tested in Cobscook Bay, Maine, the eastern-most bay of the USA, which opens into the Bay of Fundy. The mean tidal range is 5.7 m in Cobscook Bay [23] and current speed can exceed 2 m s^{-1} in the channel of the outer bay. Ocean Renewable Power Company, LLC (ORPC) has taken a sequential approach to developing tidal power in this region and conducted initial test deployment of two MHK devices: TidGen® and OCGen® prototype. Deployment of these test devices provided the opportunity to investigate fish responses to MHK devices and to estimate the probability of fish encountering a single MHK device.

The dynamic environment at tidal power sites presents challenges for monitoring the physical and biological characteristics around MHK devices. The extreme turbulence and sediment-laden water impair optical visibility, which reduces the effective use of camera or video monitoring techniques [20,24,25]. The strong tidal flows make the use of standard biological sampling tools such as nets and trawls difficult and dangerous. Passive acoustic telemetry has been used in such environments to monitor behavior of individuals of certain species such as striped bass (*Morone saxatilis*) [26] and Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) [22]. However, most tidal power sites have high levels of background noise from high flows, which limit detection due to the reduced efficiency of acoustic telemetry systems [26]. Hydroacoustic techniques have been successfully used to sample these high-velocity areas [7,27–29]. Nearly the entire water column can be sampled continuously using hydroacoustics, and the technique is less invasive to animals than other methods, such as trawling and tagging [30].

The probability that fish will encounter an MHK device located at a fixed depth depends on the natural distribution of fish in the water column. Fish vertical distribution has rarely been examined in strong tidal regions [7], and more typically investigated in regions with little or moderate currents [31–33], lakes [34], and rivers [35]. These studies demonstrated that the vertical distribution of fish depends on natural variations, e.g., year, month, tidal stage, diel condition, and location. Significant diel or tidal differences in fish vertical distribution have been documented by several studies [7,32,35], with additional variation related to time of year, location, and species [7,32]. Fish may detect changing hydrodynamics based on device presence and operation, sense device noise from the moving foils, or visually identify the structure, and thereby initiate an avoidance or attraction response to the MHK device [17]. Due to the complex nature of fish behavior, previous studies have not modeled avoidance in detail or included avoidance in modeled estimates of fish collision with MHK devices [6,21]. Although Hammar et al. [19] included fish behavior in their probabilistic model, there are no available empirical data for model validation. The lack of empirical data makes it difficult to quantify fish avoidance of devices in an open marine environment.

In this study, we aimed to estimate the probability of fish being at the same depth as (i.e., potentially encountering) an MHK device. Empirical data were collected using hydroacoustic techniques before, during, and after ORPC deployed two devices at the Cobscook Bay Tidal Energy Project (CBTEP) area during 2011–2014. Mobile hydroacoustic surveys were conducted to explicitly estimate the avoidance by fish as they approach a device. Stationary hydroacoustic surveys were carried out to estimate the vertical distributions of fish at the project area. Empirical data collected from these two hydroacoustic survey types were combined to estimate the probability of fish encountering an MHK device.

2. Methods

2.1. MHK devices

Two MHK devices were deployed by ORPC during different periods: TidGen® power system from March 2012 to July 2013, and prototype OCGen® module from July 2014 to August 2014 (Fig. 1). Hereafter each device is referred to generally as the TidGen® and OCGen® unless referencing specific components. The entire TidGen® (bottom support structure and device foils) was 31.2 m long, 15.2 m wide, and 9.5 m high, and was bottom-mounted using a solid steel frame. The foils of the TidGen® were 6.7–9.5 m above the seafloor (Fig. 1). Unlike the TidGen®, the OCGen® was moored to the seafloor with gravity anchors and cable (Fig. 1). The entire OCGen® (the float and foils) was 19.7 m long and 5.1 m high. The foils were located 8.0–10.5 m above the seafloor at slack tide. The depth of the OCGen® changed slightly with the current flow due to horizontal displacement, and foils were 5.9–7.4 m above the seafloor during maximum flow. The OCGen® can be displaced horizontally approximately 6.8 m from its neutral position during maximum flow. The two MHK devices had similar device foil designs (Gorlov helical design). The TidGen® had four sets of foils, while the OCGen® had two (Fig. 1).

2.2. Study region

From 2011 to 2013, stationary down-looking hydroacoustic surveys were conducted to monitor relative fish density and vertical distribution over time at the site of the TidGen® in outer Cobscook Bay (44°54.60′ N, 67°2.74′ W), and at a control site (44°54.04′ N, 67°1.71′ W) about 1.6 km seaward from the project site (Fig. 2; also, [7]). The control site allowed the differentiation of effects of the MHK devices from natural variation [7]. The water depth at the project site averaged 24.5 m at low tide and 32.3 m at high tide. At the control site, the water depth averaged 33.8 m at low tide and 41.3 m at high tide. The current speeds were generally less than 2 m s^{-1}, with a maximum speed of 2.5 m s^{-1}. The TidGen® stopped functioning in April 2013 and ORPC removed the foils and generator, leaving the bottom support frame. As such, mobile hydroacoustic surveys were carried out over and around the OCGen® in August 2014. The center location of the OCGen® (44°54.58′ N, 67°2.68′ W) was about 100 m seaward from the center location of the TidGen® bottom support frame.

2.3. Stationary down-looking hydroacoustics

From 2011 to 2013, stationary down-looking hydroacoustic surveys were conducted at the project and control sites on or near neap tides during multiple months (March, May, June, August, September, and November). After March 2013, ORPC operations around the TidGen® prevented hydroacoustic surveys at the project site, so following surveys were only conducted at the control site. In each month, 24-h surveys were conducted to cover diel and tidal variation in fish abundance and vertical distribution. Before and during the time that the first device (TidGen®) was deployed at the project site, stationary down-looking surveys were carried out from a boat moored approximately 100 m from the device location. The boat moved approximately 50–100 m around the mooring point. Hydroacoustic data were collected with a single-beam Simrad ES60 echosounder mounted 1 m below the surface, facing downward. The echosounder had a circular transducer (Simrad 38/200 CombiW) with a half-power beam angle of 31°, operating at 200 kHz and 38 kHz simultaneously at a rate of 2 pings s^{-1} and pulse

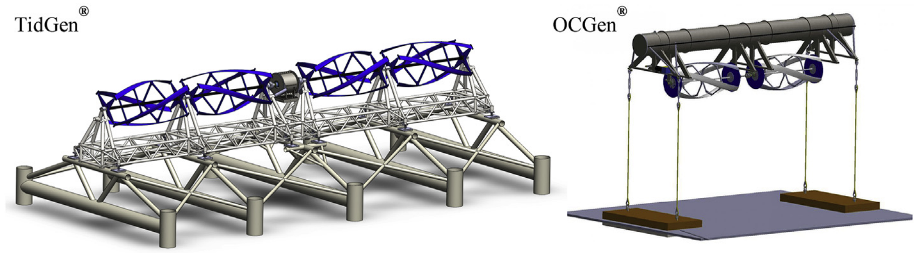

Fig. 1. Schematic representation of the TidGen® device with bottom support frame (length: 31.2 m; width: 15.2 m; height: 9.5 m) and prototype OCGen® module (length: 19.7 m; width: 5.3 m; height: 5.1 m) installed in outer Cobscook Bay, Maine by Ocean Renewable Power Company. Schematics are not to scale.

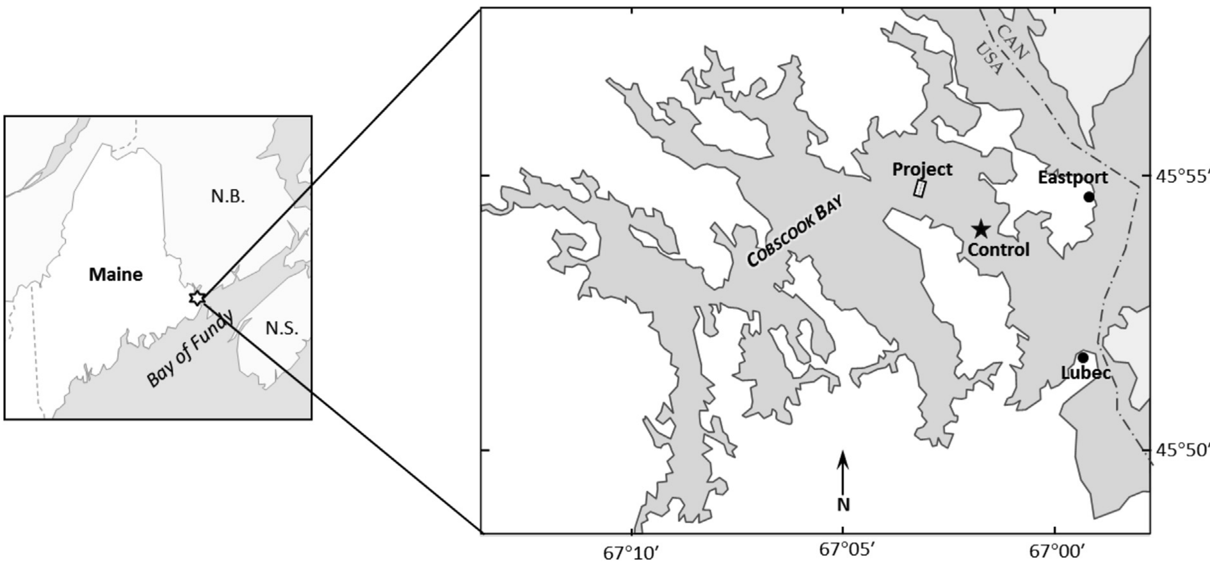

Fig. 2. Map of Cobscook Bay, Maine with locations of the project and control sites for fish-MHK interaction research.

duration of 0.512 ms. In each year, on-axis calibrations were carried out in winter on a frozen lake using copper calibration spheres (13.7-mm diameter with −45 dB nominal target strength, TS, for 200 kHz; 60-mm diameter with −33.6 dB nominal TS for 38 kHz) [36]. During surveys, current speed was recorded every 30 min using an Acoustic Doppler Current Profiler (ADCP), which was also mounted 1 m below the surface.

Echoview® (6.1, Myriax, Hobart, Australia) software was used to process the down-looking hydroacoustic data collected with the 200-kHz frequency. General processing included the following steps. Calibration values were applied to the raw data and the upper 10 m of the water column were excluded because entrained air caused acoustic interference. The Echoview bottom-line-pick algorithm was used to automatically detect a bottom line, which was manually corrected for errors and offset upward by 0.5 m. Any spike noise (e.g. noise from the ADCP) was removed and replaced by the signal from neighboring pings. Background noise was removed, and echograms were visually scrutinized to remove any interference from surface or other sources (e.g. nearby vessel echosounders, cables and boat noise). To exclude hydroacoustic signals from unwanted targets (such as plankton, krill and fish larvae), a TS threshold was set to −60 dB. Finally, the echogram was divided into cells spanning 30 min in time and 1 m in depth. For each cell, the area backscattering coefficient (s_a), which is proportional to fish density [30,36], was exported for analysis.

Data from slack tides were removed because the focus of this study was flowing tides when device foils would be rotating. The TidGen® foils started rotating when the current speed increases above 1 m s^{-1} and stop rotating when the current speed falls below 0.5 m s^{-1}. The current speed data, collected with ADCP each half hour, were used to determine when the slack tides occurred. To standardize the comparisons between the project and control sites, only data from the lower 15 m of the water column were used to investigate fish vertical distribution because fish distributions were bottom-oriented in most months [7] and the TidGen® was located at a fixed distance above the bottom. Since fish distributions were bottom-oriented, comparisons were less likely to be affected by excluding different amounts of surface water at project and control sites [7]. Viehman et al. [7] successfully used data collected in 2010 and 2011 to compare fish distribution in the lower 15 m of the water column and demonstrated that the control site provides a reference for monitoring fish presence in the region of, and at the depth spanned by, the MHK device.

2.4. Mobile down-looking hydroacoustics

Mobile hydroacoustic surveys near the OCGen® were used to observe fish behavior as they approached the device (Fig. 3). In summer 2014, a Simrad EK60 split-beam echosounder was used to conduct mobile hydroacoustic surveys around the OCGen®. The echosounder used a circular transducer with a half-power beam angle of 7°, operating at 200 kHz and 5 pings·s^{-1}, mounted 0.62 m below the surface, facing downward. This frequency is beyond the hearing range of Atlantic herring (~10 kHz) [51], which are likely

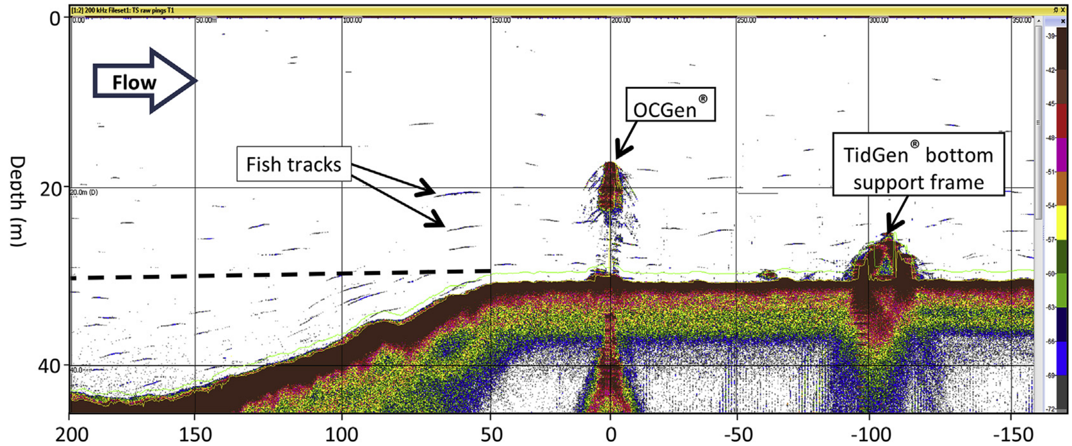

Fig. 3. One mobile transect over the OCGen® and the TidGen® bottom support frame during a flood tide. Fish tracks below the dashed line were excluded from analysis to ensure equal amounts of water sampled during the length of one transect.

the most sound-sensitive species present in our study region [44]. Thus fish behavior should not be affected by the echosounder. Before each survey, the echosounder was calibrated using a copper calibration sphere of 13.7-mm diameter with −45 dB nominal TS [36]. The mobile down-looking hydroacoustic surveys involved transects in which the boat drifted with the current (with the engine not in gear) from 200 m upstream to 200 m downstream of the OCGen®. Boat direction was maintained with minor steering and throttle adjustments as needed. Mobile surveys were conducted on neap tide, carried out during 10 sequential flood tides and 4 ebb tides over 5 continuous days, with more than 20 transects conducted during each tide. One-third of transects were not over the OCGen® in order to be used as control transects. Only data collected during flood tides were used in the following analysis because the TidGen® bottom support frame affected fish behavior when they approached the OCGen® during ebb tides (Fig. 3). Water velocity data were collected continuously by ORPC using a bottom mounted ADCP adjacent to the OCGen®.

As with stationary surveys, because the highest risk to fish would occur when the device is rotating, we focused analyses on data collected when the current velocity at the device was greater than 1 m s^{-1}, which is the velocity at which the device begins to rotate. Mobile hydroacoustic data were processed using Echoview® software, and fish were tracked using parameter settings shown in Table 1. The TS threshold used was lower than that for the stationary data collection in an effort to include more single targets, which improved our ability to track fish. To ensure the quality of detection, detected fish tracks were manually inspected for accuracy. Data exported for single target variables in fish tracks included location (GPS coordinates), TS, range from transducer, and angles of deviation from the beam axes. Because boat motion could affect the results of single target detection and fish tracking, a YEI Technology 3-Space Sensor was used to collect the IMU (inertial measurement unit) data (pitch, roll, and yaw), which were used to calibrate the location and depth of each single target with 3D rotation matrices in R (version 3.1.1, R Core Team, Vienna, Austria). The calibrated single targets in fish tracks were used to recalculate the fish track variables, including location and depth.

2.5. Encounter probability model

The probability that fish would encounter an MHK device was estimated from three components: 1) the probability of fish being at device-depth when a device was absent (p_1); 2) the probability of fish behavior changing to avoid the device between the control and the project site (separated by 1.6 km) when an MHK device was present (p_2); and 3) the probability of fish behavior changing to avoid the device between the location of the stationary survey and the device (p_3). Data from the stationary hydroacoustic surveys (from 2011 to 2013) carried out near the TidGen® were used to estimate the first two probability components (p_1 and p_2). Data collected from mobile hydroacoustic surveys near the OCGen® in 2014 were used to estimate the third probability component (p_3). Because the device foils of the TidGen® and the OCGen® have a similar design and were located at similar depths, the probability of fish encountering an MHK device can be calculated as

$$p = p_1 * (1 - p_2) * (1 - p_3) \quad (1)$$

A Bayesian Generalized Linear Model (BGLM) [37] was used to estimate the probability of fish being at certain depths of interest in absence of the MHK device (p_1): 1) at the depth spanned by the entire TidGen® (0.5–9.5 m above the seafloor) and 2) at the depth spanned by the moving components (device foils) of the TidGen® (6.5–9.5 m above the seafloor). Three factors that influence fish vertical distribution were considered: month, diel condition, and tidal stage. These factors have been shown to have significant influences on fish vertical distribution [7]. The model is given as

$$y = \beta_0 + \sum_{j=1}^{J_1} \beta_{1,j} x_{1,j} + \sum_{k=1}^{J_2} \beta_{2,k} x_{2,k} + \sum_{l=1}^{J_3} \beta_{3,l} x_{3,l} + \sum_{j=1}^{J_1} \times \sum_{k=1}^{J_2} \beta_{1\times 2,j,k} x_{1\times 2,j,k}. \quad (2)$$

where y denotes the probability of fish being at the depth of interest, β_0 denotes the baseline which is the overall mean probability of fish at a certain depth of interest, β_1 denotes the deflection of the baseline due to diel condition (x_1) (i.e. how much y changes when x_1 changes from neutral to category j), β_2 denotes the deflection based on the month (x_2), β_3 denotes the deflection based on the tidal stage (x_3), and $\beta_{1\times 2}$ denotes the interaction of diel condition and month. The baseline is constrained so that the deflection sums to zero across the level of x [37]. The probability of different months, diel conditions, and tidal stages was estimated as the sum of the baseline and the deflection. The "rjags" package in R was used to fit BGLM [38]. The posterior distribution was computed based on 100,000 Markov Chain Monte Carlo simulations and a

Table 1
Parameters settings for single target and fish track detection in Echoview.

Process	Parameter	Value
Single target detection	TS threshold	-70.00
	Pulse length determination level (dB)	6.00
	Minimum normalized pulse length	0.70
	Maximum normalized pulse length	0.50
	Beam compensation model	Simrad LOBE
	Maximum beam compensation (dB)	12.00
	Maximum standard deviation of minor-axis angles	10.00
	Maximum standard deviation of major axis angles	10.00
Fish track detection	Algorithm	
	Data	4D
	Alpha (Major axis/Minor axis/Range)	0.50/0.50/0.70
	Beta (Major axis/Minor axis/Range)	0.40/0.40/0.20
	Exclusion distance(m) (Major axis/Minor axis/Range)	1.50/1.50/0.10
	Missing ping expansion (%) (Major axis/Minor axis/Range)	0.00/0.00/0.00
	Weight	
	Major axis	30.00
	Minor axis	30.00
	Range	40.00
	TS	0.00
	Ping gap	0.00
	Track acceptance	
	Minimum number of single targets	3
	Minimum number of pings in track	5
	Maximum gap between single targets	3

burn-in of 2000 draws was removed from the beginning of the chain. From the posterior distribution, we calculated the mean and 95% Highest Density Interval (HDI) [37].

Fish vertical distributions were compared between the project site and the control site, before and during the installation of the TidGen®, to estimate p_2. Five hydroacoustic surveys were carried out in the presence of the bottom support frame of the TidGen® (2012: March and May) or the entire TidGen® (2012: August, September and 2013: March). The Hotelling's T^2 permutation test [39,40] was used to examine if fish vertical distribution differed at the two sites before and during the deployment (package "Hotelling" in R; [41]). Because the device was fixed on the seafloor and the stationary hydroacoustic surveys took place from a moored boat, the distance between the device and the boat was different for ebb and flood tides. Since there was no information about the distance at which the device may affect fish behavior, the datasets were separated by tidal stage for each month and then compared between sites.

Mobile hydroacoustic data collected during flood tides were processed to estimate p_3. Because the seafloor sloped upward when the boat approached the device during the flood tide, fish tracks deeper than the dashed line (Fig. 3) were excluded to ensure equal amounts of water were sampled during the length of a transect. Since our focus was on the probability of fish encountering the MHK device, data collected upstream of the OCGen® were used to obtain the number of fish present. To investigate how fish avoided the OCGen®, transects over the OCGen® were grouped together and fish tracks were binned into distance segments of 10 m, with distance measured between the middle of fish tracks and the OCGen®. The same method was used for control transects for comparison. If fish avoided the device, the number of fish tracks would decrease closer to the device. Fish could not be detected within 10 m of device due to its strong acoustic backscatter. Thus, a simple linear regression was fitted to fish counts between 10 m from the device and where the number of fish tracks began to decline. The predicted values from the model were used to estimate probability of fish avoidance. The confidence interval (CI) of p_3 was estimated using a bootstrap method. The total probability of fish encountering an MHK device was estimated by combining the three probability components using Equation (1). The delta method was used to estimate the confidence interval [42].

3. Results

The data collected at the project site in 2011 were used to illustrate the procedure, and results of the BGLM were used to estimate the probability (p_1) of fish being at the depths of the entire device in the absence of a device. From the BGLM, the posterior distribution of p_1 was given for the baseline, different months, diel conditions, and tidal stages (Fig. 4). The baseline is the annual probability of fish at the depth of the entire TidGen® device (0.5–9.5 m above the seafloor) in 2011 (Fig. 4), which has a mean of 0.675 with 95% HDI: 0.618–0.732 (Table 2). The probability was higher during the nighttime than during the daytime; nighttime: 0.750 (HDI: 0.682–0.817), daytime: 0.588 (HDI: 0.501–0.676) (Table 2; Fig. 4a). The effect of the tidal stage was not significant for this dataset (Table 2; Fig. 4b). The effect of month was significant, especially in May when the probability was significantly lower than other months (0.240, HDI: 0.137–0.350) (Table 2; Fig. 4c). Baseline and associated environmental deflection posterior distributions of p_1 suggest a significant diel and month effect, but not a tidal effect (Fig. 4). The interactions of diel condition and month were significant in May, June, and November.

The probability of fish being at the depth of the whole TidGen® (p_1) was estimated for the whole year, different months, diel conditions, and tidal stages during 2011–2013 (Table 2). The estimated probabilities for year were not significantly different between sites and among years. The probabilities for year ranged from 0.658 to 0.689 during 2011–2013. The tidal stage was not a significant factor for data collected in 2011 and 2012; however it significantly affected probabilities in 2013. The diel condition was a significant factor for data collected at the project site in 2011. Generally speaking, the probability in May was significantly lower than other months by about 50%. The estimated probabilities of fish being at the depth of the foils of the TidGen® (p1) in any year ranged from 0.079 to 0.093 and were not significantly different between sites

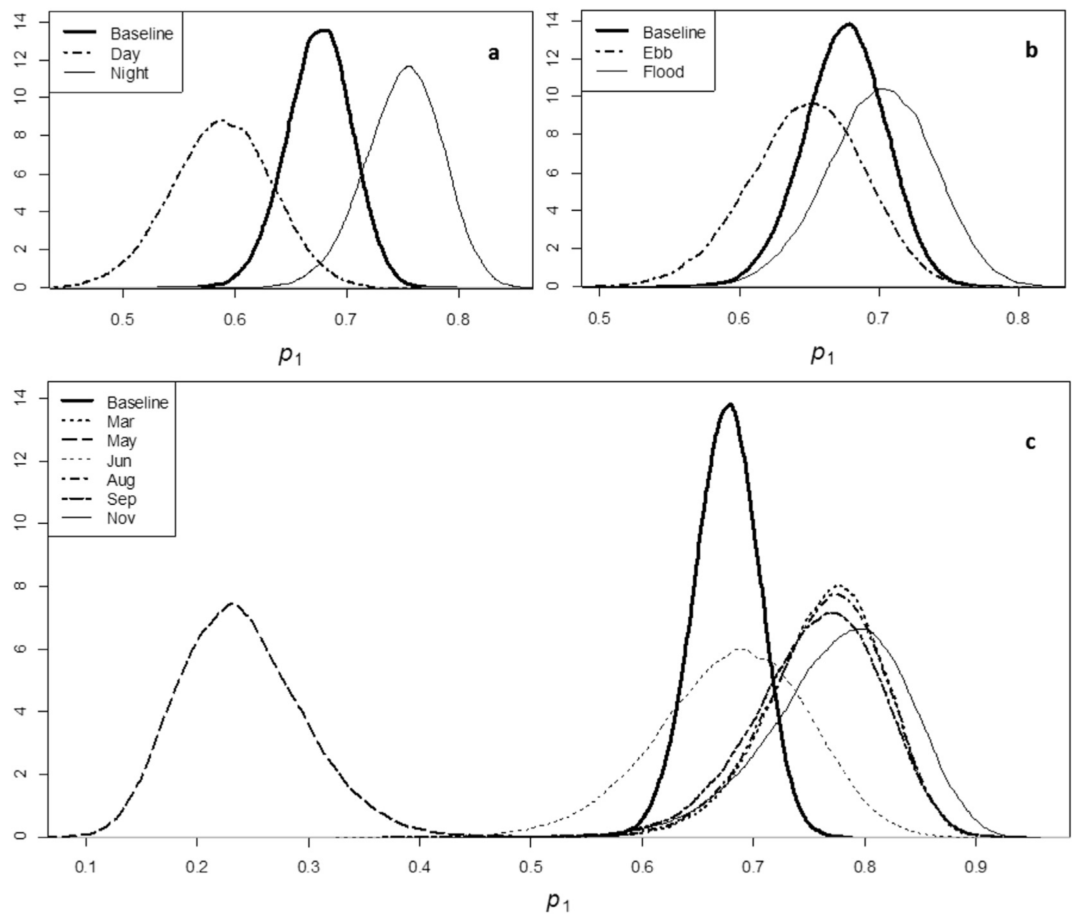

Fig. 4. The posterior distribution of the baseline with its HDI at the projected MHK deployment location in 2011 (prior to deployment). Horizontal axis is the probability of fish at the depth of the whole device. Top left panel denotes the deflection of diel condition. Top right panel denotes the deflection of tidal stage. Bottom panel denotes the deflection of month.

Table 2
Probability (p_1) of fish at depth of the whole device (0.5–9.5 m off the bottom) in absence of the MHK device with the 95% HDI (High Density Interval) in 2011–2013. Overall mean is the baseline, which is the mean probability in each year. The probabilities in different months, diel and tidal conditions are also listed.

	Site	Project site	Control site		
	Year	2011	2011	2012	2013
	Overall mean	0.675 (0.618 – 0.732)	0.689 (0.656 – 0.725)	0.674 (0.615 – 0.731)	0.658 (0.614 – 0.701)
Diel condition	Day	0.588 (0.501 – 0.676)	0.659 (0.607 – 0.709)	0.674 (0.593 – 0.754)	0.624 (0.561 – 0.688)
	Night	0.750 (0.682 – 0.817)	0.721 (0.674 – 0.765)	0.673 (0.589 – 0.751)	0.691 (0.632 – 0.744)
Tidal stage	Ebb	0.763 (0.658 – 0.864)	0.651 (0.582 – 0.817)	0.623 (0.573 – 0.821)	0.745 (0.664 – 0.821)
	Flood	0.679 (0.546 – 0.805)	0.792 (0.723 – 0.859)	0.877 (0.805 – 0.941)	0.510 (0.411 – 0.612)
Month	Jan			0.877 (0.805 – 0.941)	
	Mar	0.764 (0.662 – 0.859)	0.618 (0.537 – 0.697)	0.693 (0.559 – 0.821)	0.651 (0.557 – 0.741)
	May	0.24 (0.137 – 0.35)	0.390 (0.291 – 0.492)	0.225 (0.119 – 0.347)	0.475 (0.371 – 0.581)
	Jun	0.679 (0.546 – 0.805)	0.792 (0.721 – 0.859)	0.778 (0.664 – 0.882)	0.512 (0.405 – 0.618)
	Aug	0.763 (0.658 – 0.861)	0.751 (0.681 – 0.816)	0.703 (0.573 – 0.821)	0.743 (0.687 – 0.815)
	Sep	0.756 (0.643 – 0.861)	0.781 (0.715 – 0.845)	0.651 (0.511 – 0.785)	0.883 (0.772 – 0.889)
	Nov	0.775 (0.652 – 0.886)	0.736 (0.663 – 0.805)		

and among years during 2011–2013 (Table 3). The diel condition was a significant factor for data collected at the project site in 2011 and the control site in 2012. The tidal stage and month were not significant factors in estimating the probability at the depth of the foils of the TidGen®.

Fish behavior did not change between the control site and the project site when the device was deployed ($p_2 = 0$). The proportion of fish generally increased toward the seafloor at both the project and control sites except in May (Fig. 5). By comparing fish vertical distributions between the project site and the control site, we found that vertical distributions were not significantly different in all months at the two sites before the device was deployed (Hotelling's T^2 test: $p > 0.05$). When the bottom support frame of the TidGen® or the whole device was in the water, from March 2012 to June 2013, fish vertical distributions were not significantly different between the two sites (Hotelling's T^2 test: p values ranged from 0.145 to 0.594).

The BGLM was also used to estimate p_1 in 2012 at the project site

Table 3
Probability (p_1) of fish at depth of just the device foil (6.5–9.5 m off the bottom) in absence of the MHK device with the 95% HDI in 2011–2013. Overall mean is the baseline, which is the mean probability in each year. The probabilities in different months, diel and tidal conditions are also listed.

	Site	Project site	Control site		
	Year	2011	2011	2012	2013
	Overall mean	0.079 (0.062 – 0.098)	0.084 (0.072 – 0.097)	0.086 (0.067 – 0.106)	0.093 (0.081 – 0.105)
Diel condition	Day	0.056 (0.039 – 0.076)	0.091 (0.073 – 0.110)	0.064 (0.043 – 0.082)	0.093 (0.076 – 0.110)
	Night	0.112 (0.078 – 0.149)	0.079 (0.063 – 0.095)	0.117 (0.083 – 0.156)	0.094 (0.077 – 0.112)
Tidal stage	Ebb	0.089 (0.052 – 0.133)	0.0858 (0.061 – 0.112)	0.097 (0.055 – 0.145)	0.086 (0.063 – 0.106)
	Flood	0.064 (0.047 – 0.105)	0.058 (0.037 – 0.078)	0.079 (0.042 – 0.121)	0.103 (0.079 – 0.129)
Month	Jan			0.079 (0.043–0.122)	
	Mar	0.097 (0.057 – 0.143)	0.118 (0.084 – 0.154)	0.145 (0.080 – 0.217)	0.082 (0.061 – 0.108)
	May	0.069 (0.038 – 0.101)	0.073 (0.052 – 0.113)	0.064 (0.034 – 0.098)	0.081 (0.059 – 0.103)
	Jun	0.083 (0.046 – 0.125)	0.057 (0.040 – 0.079)	0.069 (0.037 – 0.105)	0.102 (0.078 – 0.0125)
	Aug	0.091 (0.052 – 0.133)	0.086 (0.061 – 0.118)	0.096 (0.055 – 0.139)	0.096 (0.073 – 0.119)
	Sep	0.053 (0.026 – 0.083)	0.091 (0.065 – 0.121)	0.094 (0.052 – 0.139)	0.108 (0.082 – 0.138)
	Nov	0.105 (0.055 – 0.166)	0.084 (0.060 – 0.109)		

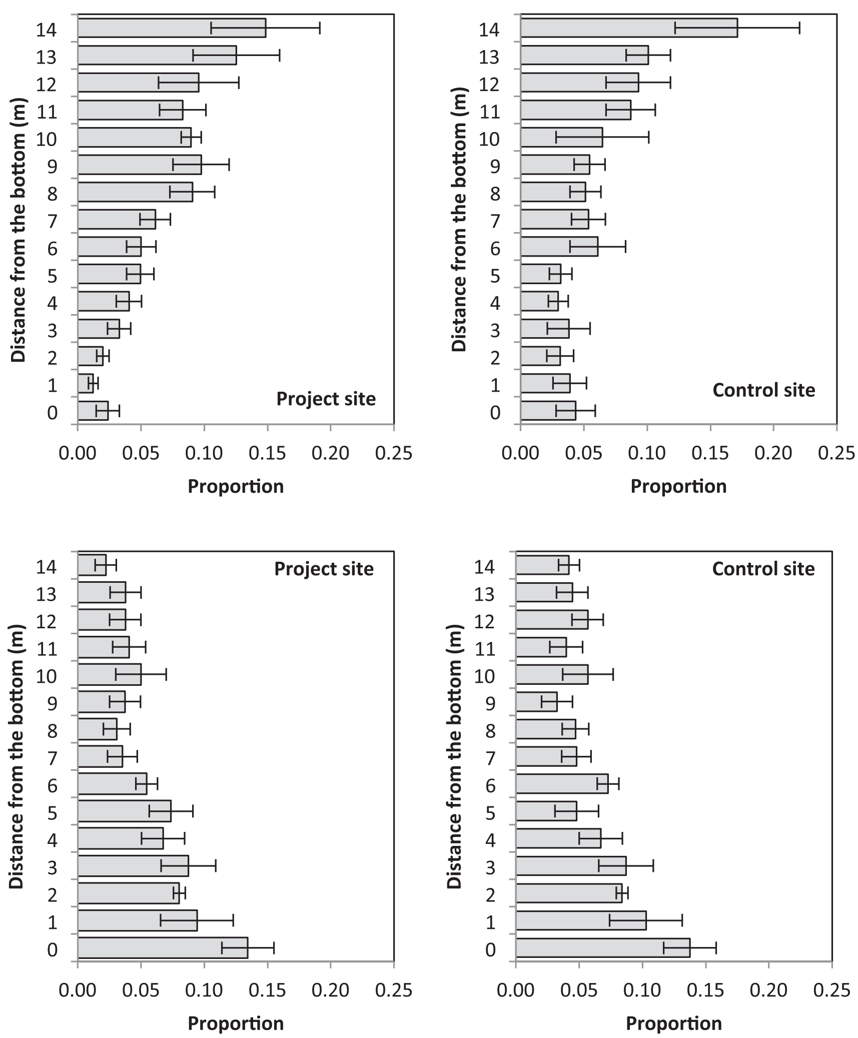

Fig. 5. Vertical distribution of fish during ebb tide in May (upper panels) and September (lower panels) 2012 surveys at project and control sites. Vertical axis is distance above bottom (m). Each horizontal bar represents the mean proportion of area backscatter (s_a) within each 1 m water column layer. Whiskers denote one standard error. Error bars are shown to indicate variance in depth bins over time, but were not used in statistical comparisons among sites.

(when the device was present). In 2012, the probability of fish being at the depth of the entire device was 0.652 (HDI: 0.543 to 0.762) at the project site, and the probability of fish being at the depth of the device foils was 0.090 (HDI: 0.069 to 0.113) at the project site. The estimated probabilities were similar between the project and control site in 2012 (Tables 2 and 3).

The number of fish in 10 m distance segments decreased nearer to the device (Fig. 6a), however, this decreasing trend was not observed for control transects (Fig. 6b). Fish numbers began decreasing 140 m upstream of the OCGen® when transects were

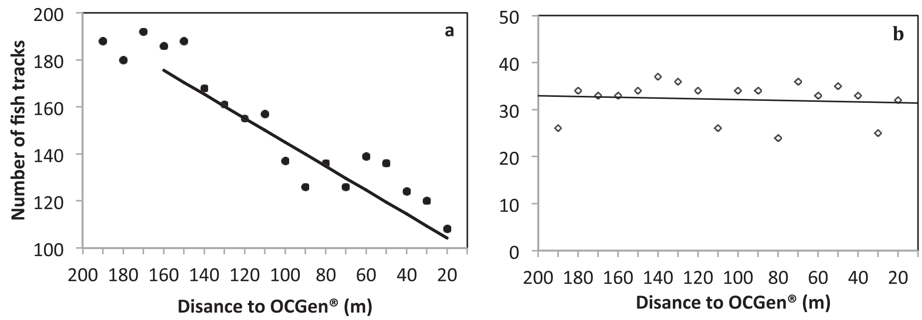

Fig. 6. Number of fish tracks upstream of the OCGen® from transects over the device (left panel: linear regression line is $y = 103.781 + 0.509x$, $R^2 = 0.862$) and control transects (right panel: linear regression line is $y = 33.023 - 0.082x$, $R^2 = 0.012$).

over the device (Fig. 6a). A simple linear regression was fitted to the data from 10 m to 140 m upstream of the OCGen® (Fig. 6a). The fitted linear regression had an intercept of 103.781, slope of 0.509, and R^2 of 0.86. Over all transects, there was a 37.2% (95% CIs: [21.8%, 49.4%]) decrease in the number of fish from 140 m to 10 m upstream of the device (i.e. $p_3 = 0.372$).

The probability of fish encountering the device was estimated by combining the three probability components using Equation (1). Because the mobile hydroacoustic surveys were only carried out in August 2014 and we wanted to estimate the highest risk, we chose to use the highest estimates of p_1 to estimate the probability of encountering the MHK device. The maximum values for p_1 were 0.689 for the probability that fish would be at the depth of the entire TidGen®, and 0.093 for the probability that fish would be at the depth of the device foils. The probability of avoiding between the control and project site (p_2) was 0 and the probability of avoiding between the down-looking hydroacoustic survey site and 10 m from the device (p_3) was 0.372. In total, the probability of fish encountering the whole TidGen® was 0.432 (95% CI: [0.305, 0.553]) and the probability of fish encountering the device foils was 0.058 (95% CI: [0.043, 0.073]).

4. Discussion

Our work has been the first opportunity to collect and apply empirical data to estimate the probability of fish encountering an MHK device under natural conditions. This, along with laboratory experiments [10,18] and *in-situ* observations [4,20,43], is informing our understanding of fish interactions with MHK devices. *In situ* observations revealed fish evasion responses to MHK devices that suggest near field evasion [4,20,43]. Laboratory experiments inform near-field behaviors as well as survival rates during encounter [10,18]. In this paper, our objective was to examine fish avoidance of MHK devices by estimating the encounter probability. To estimate encounter probability, first we needed to know how many fish would spatially overlap with the MHK device. Our stationary hydroacoustic data allowed us to investigate the vertical distribution of fish with and without an MHK device, and how fish vertical distribution fluctuated on seasonal, diel, and tidal time scales. Mobile hydroacoustic data provided information on how and when fish responded to the device. Combining stationary and mobile hydroacoustic data, the encounter probability was estimated under natural conditions. Until now, this probability has been estimated only from laboratory experiments or modeling without empirical data.

Since the TidGen® was not available for all hydroacoustic surveys, the estimated probability of encounter consisted of a combination of empirical data at two similarly designed devices. The foil design and depth of the TidGen® and the OCGen® were similar, so the data collected around the OCGen® were used with data collected around the TidGen®. The TidGen® was bottom mounted and had a large support frame [7]. On the other hand, the OCGen® was buoyed in mid-water, and moored to the seafloor with cables. The support frame of the TidGen® can affect the current, and this may result in underestimating the encounter probability due to fish detecting the larger device at a greater distance.

Our surveys were conducted with hydroacoustics, limiting our ability to isolate fish species within the mixed fish community of Cobscook Bay [44]. Vieser reported that Cobscook Bay has many pelagic and benthic fish species, and the five most abundant species captured by trawls were Atlantic herring (*Clupea harengus*), winter flounder (*Pseudopleuronectes americanus*), longhorn sculpin (*Myoxocephalus octodecemspinosus*), silver hake (*Merluccius bilinearis*), and grubby (*Myoxocephalus aenaeus*) [44]. Additionally, Atlantic mackerel (*Scomber scombrus*) are known to occur in this region during summer months [45] and their presence was verified using hook-and-line sampling during summer hydroacoustic surveys. Because the device foils were approximately 6–10 m above the seafloor, pelagic species might have a higher probability of encountering the foils than benthic species. Atlantic herring and Atlantic mackerel were therefore the most likely to be interacting with the tidal energy devices in Cobscook Bay.

Fish interactions with MHK devices have been characterized using other technologies which provided more species-specific or size-specific information [4,43], but they also had some limitations. Stereo-video underwater cameras, for example, were used to study MHK effects on swimming behavior of different fish species [43]. However, video cameras cannot detect fish at night without artificial lighting, which could alter the natural behavior of fish [46]. Multibeam DIDSON hydroacoustic cameras have the advantage of being able to observe fish during both day and night and provide estimates of fish size and shape [4], but fish species is difficult to discriminate. The detection range of high-resolution multibeam sonars (such as the DIDSON) is limited, and ranges that may be viewed with video cameras depend on water turbidity. Although our methods cannot separate species, we were able to apply hydroacoustics to describe general fish distribution under the limiting conditions of the environment with readily-available technology. Further assessment of device-animal interactions in these environments will be best accomplished using multiple approaches, e.g., split and single beam hydroacoustics, video, and multibeam hydroacoustics, until better technology is developed.

The probabilities of fish being at the depth of the whole device and device foils (p_1) were similar at both the project and control sites during 2011–2012 (Tables 1 and 2). The variation in p_1 was not significant from 2011 to 2013 even though 2012 was an extraordinarily warm year in the Gulf of Maine [47], which suggested that fish vertical distribution was not affected by changes in temperature and associated fish abundance. Three factors (month, diel condition, and tidal stage) were included in the BGLM to estimate p_1. Although the three factors were not significant in all datasets, all were included so that we could compare the probabilities between sites and among years. Month was a significant factor for all datasets, due to less fish in the depth of the whole device in May (Table 2) when dense schools were present in the middle and upper water column. In other months, fish density increased toward the bottom (Fig. 5). The diel difference was only significant at the project site in 2011 (Table 2). Generally, there was a higher probability of fish at the depth of the device at night, consistent with observations of Viehman et al. [7]. The tidal stage was only significant for data collected in 2013. The interaction of diel condition and month was significant for most of the dataset, which means the diel difference in fish vertical distribution was different among months. One possible explanation for this is the presence of different fish species in different months in Cobscook Bay. For example, Atlantic mackerel are only present in summer months [44,45]. Different species have different diel vertical migration behavior, which could result in the significant interaction of the diel condition and month observed here.

Mobile hydroacoustic surveys spanning 200 m upstream to 200 m downstream of the MHK device made it possible to monitor fish behavior from 200 m to 10 m upstream of the device. Fish numbers began to decrease when they were about 140 m upstream of the device. This decreasing trend was not observed for control transects. Although fish have different remote sensory systems including vision, hearing, the lateral line system, and olfaction, the MHK devices, which produce low-frequency sounds [48,49], might be first detected by hearing for some species [50]. Atlantic herring is a hearing-sensitive species which may be able to detect an operating device hundreds of meters away [19]. Device noise has been hypothesized to induce distinct avoidance by herring at 10–100 m distance [19]. Thus, the avoidance by Atlantic herring and potentially other species may result in the decrease of fish tracks approximately 140 m upstream of the device. Atlantic mackerel, since they lack a swimbladder, are less sensitive to sound than herring [52]. As such, Atlantic mackerel may not avoid the device until they are closer than Atlantic herring. Since we analyzed hydroacoustic data collected with only one frequency (200 kHz), it is difficult to separate Atlantic herring from Atlantic mackerel and other species, so we cannot differentiate response distances of different species. Multi-frequency hydroacoustic systems or stereo-video underwater cameras may help better understand the avoidance of different species in future studies.

Hammar et al. [19] categorized avoidance behavior as turning in a reverse direction (avoiding the device by swimming against the current, away from it) or a divergent direction (avoiding the device by slightly changing direction and swimming past it). In Cobscook Bay, captured Atlantic herring were a mix of larval and early juvenile life stages (2.9 cm to 23.3 cm) [44]. The TS of fish tracks ranged from −70 dB to −40 dB in the mobile hydroacoustic survey, corresponding to herring sizes less than ~23 cm [53]. Larval and juvenile herring of this size range are not strong enough to swim against a strong current [54], but may be capable of avoiding obstacles by diverging slightly from the main current direction [53]. Atlantic mackerel caught at the project site averaged 20 cm and mackerel are stronger swimmers [55], which could allow them to avoid the device by swimming against the current (reverse direction) and turning in a divergent direction. Fish are known to avoid boats [55–57] and trawls by changing their direction horizontally and/or vertically [58,59]. To examine whether fish avoid an MHK device by sounding (vertically) or moving to the side (horizontally), we calculated the proportion of fish at the depth of the entire device relative to all fish in the whole water column and plotted it versus the distance to the OCGen® (Fig. 7). The proportion did not change significantly throughout the 180–10 m distance upstream of the device. As such, the decrease in numbers between 140 and 10 m can only be explained by a change in horizontal position as they approach the device, rather than vertical change in position in the water column.

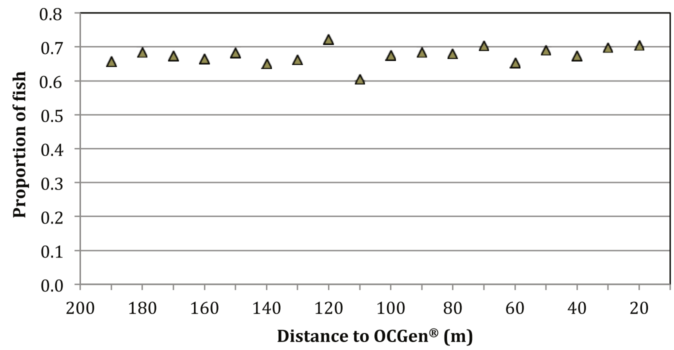

Fig. 7. Proportion of fish at the depth of the entire device (0–10 m above the seafloor) relative to fish in the whole water column in 10 m sections based on the distance to the OCGen®.

By combining all three probability components, our results indicated that the probability of fish encountering the whole TidGen® was about 0.432 and the probability of fish encountering the device foils was 0.058. Previously, fish have been observed evading a similar rotating device within very short distances (0–3 m; [4,43]), as have fish in laboratory settings [10,18]. Therefore, the probability of fish entering the device upon encountering it will likely be lower. In this study, the horizontal extent of the MHK device is relatively small compared to the width of the entire Cobscook Bay, about 2.5% of the width of the Bay. If the whole of Cobscook Bay is considered (rather than the slice of water column associated with the beam we used for analysis), the probability of encountering one MHK device would be considerably smaller (i.e. 0.0015 by multiplying the probability of 0.058 by 2.5%). However, commercial-scale development of arrays would occupy larger portions the Bay to generate more power and would need further consideration. Our results can be used to inform the effects of commercial arrays on fish in the future.

With the increasing development of tidal power, there are great concerns about collision risk of marine animals with devices. In the absence of conclusive observational data, collision risk has been explored through different models [6,19,21]. Although Hammar et al. [19] constructed a generic collision risk model to include base events, the collision risk is still poorly understood without empirical data. In this paper, we estimated the encounter probability of fish as close as 10 m upstream of an MHK device. Since the hydroacoustic data collected could not monitor fish behavior when they are closer than 10 m to the device, we could not estimate the events in the near-field, such as evasion and foil strike. However, some studies have demonstrated that fish can escape (evade) even when they are very close to a device foil by burst swimming [4,10,19]. Small fish like larval and juvenile herring may have higher survival because the pressure field around the foil may help them to pass around the foils, similarly to passive particles [6,60]. Even if struck, their small size relative to foil dimensions may also increase survival [61]. Studies in laboratories indicate that the probability of foil strike is low and survival rate was high even for fish entering a device [10,18]. However, data certainty and power of analysis are still questionable [18]. Although this study only estimated the probability of fish encountering one MHK device, the results allow a path to characterize fish responses to arrays of MHK devices and identify technological limitations that should be considered in future studies. Our results characterized some effects of MHK devices on fish, which can aid commercial developers in identifying mitigation options, for example, those required by the National Environmental Policy Act (NEPA) in the US.

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Abstract: Global interest in mitigating climate change effects is a driver for development of renewable energy resources. In-stream tidal power, which uses marine hydrokinetic (MHK) devices to generate electricity with high-velocity tidal currents, is one example of a developing renewable energy industry. Effects and impacts on fishes in areas of tidal power development are a concern, and presently there are many unanswered questions in this field of research. Knowledge of how fish use these areas before and after device installation is essential for establishing baseline information and informing regulators for decision-making. We used a Before-After-Control-Impact (BACI) study design to compare indices of fish density near and away from an MHK tidal device, Ocean Renewable Power Company's TidGen® Power System. The index of fish density was mean volume backscattering strength (Sv) obtained from 24-h surveys using stationary, down-looking hydroacoustics. Data were collected within 50-75 m of the device and at a control site > 1 km away, both before and after device installation. Fish density was lowest in March and highest in May at both sites. Three out of five BACI comparisons (March 2011 v. 2013, March 2012 v. 2013, August 2011 v. 2012) indicated statistically significant effects after device installation. Operational status of the deployed device and other site disturbances (e.g. industry activities) varied at the impact site, likely influencing the results. This research has been used for permit licensing by federal and state regulatory bodies at this site and others.

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Dr. AbuBakr S. Bahaj
Editor in Chief
International Journal of Marine Energy

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Dear Dr. Bahaj,

My colleagues and I are pleased to submit the manuscript, "Changes in relative fish density around a deployed marine hydrokinetic device in Cobscook Bay, Maine" for publication in the International Journal of Marine Energy (IJOME). A previous publication "Changes in vertical fish distributions near a hydrokinetic device in Cobscook Bay, Maine, USA" from the proceedings of the 2015 European Wave and Tidal Energy Conference in Nantes, France, is built upon.

This submitted manuscript uses a Before-After-Control-Impact study design to show differences in fish densities around a deployed marine hydrokinetic turbine. During this study, in addition to the deployed device in several operational modes, there are other effects from industry activities in the area that may determine fish density differences.

This manuscript fits the aim and scope of IJOME as it relates to environmental assessment and marine life monitoring. There have been few instances of fish surveys around a deployed tidal power device. This work provides empirical data related to potential fish interactions and provides work to be built upon in the future. In addition to showing an effect of a deployed MHK device on fish density in the area we also show that industry activities such as boat traffic and dive operations could be a driver. The hydroacoustic methods presented are effective and repeatable for other sites targeted for tidal power.

This manuscript has not been published or submitted for publication in any other journal. We know of no conflicts of interest and funding resources are disclosed in the Acknowledgements.

Thank you.

Garrett Staines

Garrett Staines

*Highlights (for review)

1. Established methods for characterizing relative fish densities near a marine hydrokinetic tidal device deployment
2. Before-After-Control-Impact study design used to account for temporal and spatial variability
3. Detected effects on fish density from the installed turbine and coincidental industry activities nearby

*Manuscript

Changes in relative fish density around a deployed marine hydrokinetic device in Cobscook Bay, Maine

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Abstract

Global interest in mitigating climate change effects is a driver for development of renewable energy resources. In-stream tidal power, which uses marine hydrokinetic (MHK) devices to generate electricity with high-velocity tidal currents, is one example of a developing renewable energy industry. Effects and impacts on fishes in areas of tidal power development are a concern, and presently there are many unanswered questions in this field of research. Knowledge of how fish use these areas before and after device installation is essential for establishing baseline information and informing regulators for decision-making. We used a Before-After-Control-Impact (BACI) study design to compare indices of fish density near and away from an MHK tidal device, Ocean Renewable Power Company's TidGen® Power System. The index of fish density was mean volume backscattering strength (S_v) obtained from 24-h surveys using stationary, down-looking hydroacoustics. Data were collected within 50-75 m of the device and at a control site > 1 km away, both before and after device installation. Fish density was lowest in March and highest in May at both sites. Three out of five BACI comparisons (March 2011 v. 2013, March 2012 v. 2013, August 2011 v. 2012) indicated statistically significant effects after device installation. Operational status of the deployed device and other site disturbances (e.g. industry activities) varied at the impact site, likely influencing the results. This research has been used for permit licensing by federal and state regulatory bodies at this site and others.

Keywords: fish, tidal power, hydroacoustics, BACI, TidGen®, Cobscook Bay

1.0 Introduction

Development and deployment of marine hydrokinetic (MHK) tidal devices represent a concerted effort to mitigate environmental concerns surrounding climate change via the development of a new sector of renewable energy. Tidal energy's inclusion in a renewable energy portfolio, while currently limited to certain geographical locations, is expected to have positive impacts on reducing carbon emissions [1]. Realization of expected positive effects will require technological research and development to advance from pilot experiments to installation and in-water testing [2]. Such testing requires permission from governing institutions. As such, the process of regulation and decision-making must occur simultaneously for advancement to occur. The permitting process often requires monitoring effects of devices on the environment and adaptive management of that monitoring [3], particularly in the early stages of such new technology.

Tidal power devices are planned for [4] and have been deployed in [5] areas of fast tidal currents where interactions with fishes are likely. While the human goal is to harness the energy from this moving water, fish and other animals are known to use tidal currents as a means of transport [6]. However, specific details associated with how fish utilize these areas are unknown or limited for many sites targeted for tidal power development, often due to the difficulty of and safety concerns with collecting data in such areas [7]. The consequences of direct interactions with devices and potential behavior changes associated with their presence are a concern [8]. Due to the early stages of this industry and the difficulty of surveying fishes in these environments, there is a lack of empirical data to inform such questions. While there have been several peer-reviewed field studies [9] [10] [11] [12] and reports [13] [14] that have decreased uncertainty in this area, sample sizes are limited and many questions still remain. For example, at what distance might fish change behavior to avoid a device, and to what features are they responding?

Spatial scale of observation must be considered when quantifying interactions of fish with devices or explaining their behavioral responses to a device's presence. The near-field evasion zone (0-5 m or < 2 turbine diameters from a device, mesoscale) and mid-field avoidance zone (5-100 m or > 2 turbine diameters from a device, macroscale) have been proposed as the most important for assessing fish interactions with a single-device deployment [15] [2]. Near-field observations have been few to date [11] [16] [9] and reflect the difficulty of observation in close proximity to an operating device. Mid-field effects of a deployed device on fish, if any, will probably involve behavior changes related to general avoidance associated with optimizing swimming speed while minimizing energetic costs [17] [18]. While far-field (> 100 m) effects may be detected with deployment of a single device, larger scale ecological effects will likely only be realized when multiple devices are deployed over large areas.

Observing fish responses in highly energetic tidal regions is not only difficult but unusual, and it requires specialized approaches. Fish research in such regions usually focuses on areas sheltered from tidal currents or on slack tide periods [19] because physically sampling fish in high tidal currents can be both difficult and dangerous. Remote sensing of active acoustic tags with stationary receivers has been used successfully in Minas Basin for several species [20], but poor receiver efficiency resulted when current speeds exceeded 2 $m \cdot s^{-1}$, when risk from turbines would be greatest. Additionally, such studies require a large number of captured fish of the species of interest, adding significantly to the cost and logistics of conducting the research. Down-looking hydroacoustics is ideal for sampling these areas because it can be used from a small- or medium-sized boat in high current speeds under most weather conditions [21]. The technique provides a relative metric of density from the acoustic backscatter of fish present in the water column [22]. Data can be processed with good temporal (< 1 sec) and vertical (< 1 m) resolution. Vertical resolution is critical for the assessment of fish interactions with devices because the turbines will be present in a well-defined portion of the water column [12]. Of similar importance, seasonal changes in abundance are related to the changing presence of different fish species and their life stages [19] [24] [25], so relative density can also be used to assess the abundance of fish with regard to tidal, diel, and seasonal cycles [21] [23].

This paper presents research designed to assess mid-field effects on fish from the installation, industry activities, and deployment of a device in Cobscook Bay, Maine, USA. In this paper, installation refers to the act of fixing a device in place; deployment refers to the time period that the device is in place, from installation to decommissioning. The Cobscook Bay Tidal Energy Project (CBTEP) was implemented by Ocean Renewable Power Company (ORPC) LLC and revolved around their in-stream, MHK tidal device, the TidGen® Power System, which consisted of a turbine unit supported by a steel bottom support frame

(BSF) fixed to the seafloor by 10 piles (Fig. 1). Because variation in fish presence and abundance in space and time can be difficult to separate from effects related to the TidGen®, we collected data at the TidGen® site and a control site, both before and after device installation. This was a Before-After-Control-Impact study design that accounted for site-specific differences and natural temporal variation. The BSF was installed on the seafloor in March 2012 and the TidGen® was installed in August 2012. The dynamic part (turbine) of the device was 6.7 to 9.5 m from the seafloor. Our research question was: would relative fish density in the area change because of device presence? We hypothesized that there would be a detectable change in relative fish density after device installation compared to before, and this difference would be represented by a significant interaction in a 2-way ANOVA.

2.0 Materials and methods

2.1 Data collection and study area

We used a Simrad ES60 echosounder with a single beam Simrad 38/200 Combi W transducer which operated simultaneously at 38 and 200 kHz and had a 31° half-power beam angle. Both frequencies had a ping rate of 2 $\text{pings} \cdot \text{s}^{-1}$ and pulse duration of 0.512 ms. Transmit power was 320 W for 38 kHz and 225 W for 200 kHz. The only exception to these collection settings was in March 2011, when the pulse duration was 0.256 ms for both frequencies and transmit power was 200 W for 38 kHz and 225 W for 200 kHz. We calibrated the echosounder annually on a frozen lake prior to that year's surveys. A frozen lake provided a stable platform that allowed precise placement of the copper calibration spheres (60.0 mm for 38 kHz and 13.7 mm for 200 kHz) on the maximum response axis of the acoustic beam. These calibrations were performed for both sets of echosounder settings used during surveys. *In-situ* on-axis calibrations were performed once every survey during a slack tide to ensure consistent system performance.

All data were collected in outer Cobscook Bay (Fig. 2) at an impact site where the ORPC device was installed (44° 54.60’ N, 67° 02.74’ W) and at a control site 1.6 km seaward (44° 54.04’ N, 67° 01.71’ W).

The transducer was mounted 1.8 m below the water surface on the port side of a 12.2 m boat that was moored at these sites for consecutive 24-hr periods. During each 24 h survey, the boat changed positions (<100 m) as it swung around its mooring with the change of each tide. The depth at the impact site was approximately 24 m at low tide and 33 m at high tide, and at the control site, depth was approximately 33 m at low tide and 42 m at high tide. Surface current speeds in the area were measured with a flowmeter (Marsh McBirney) or Acoustic Doppler Current Profiler (ADCP) (RD Instruments) and were typically less than 2.0 $m \cdot s^{-1}$ but as fast as 2.5 $m \cdot s^{-1}$ at maximum flow during a spring tide.

Impact and control sites were surveyed for 24 hours each at least once a season in 2011 and 2012 (Table 1). Collecting data for 24 hours captured both diel and tidal periodicities. All surveys were scheduled on neap tides to avoid potential confounding effects from lunar tidal variation. Data from the bottom 3 m of the water column were removed in May 2011 at both sites due to the presence of a lobster trap and line that remained in the beam for the majority of the survey. The control site survey for March 2012 was split into two days (Feb 29 and March 2) because of poor weather. There were no June 2012 data because the impact site was not accessible due to industry activities. Only 20 hours of data were collected for the August 2012 survey due to electronic complications. The TidGen® was not rotating or generating electricity during the August 2012 survey due to communication troubleshooting activities. The TidGen® was rotating and generating electricity during the September 2012 survey, except for part of the time during the control site survey. In March 2013, the turbine was rotating but not generating electricity.

In 2011, surface temperature was collected using the transducer's temperature sensor, and salinity was measured with a hand-held refractometer (Sper Scientific 300011). In 2012-2013, we deployed a conductivity, temperature, and depth (CTD) sensor (SeaBird Scientific SBE19) during at least one slack tide per survey for salinity and temperature profiles.

2.2 Data processing and analysis

All hydroacoustic data processing was conducted using Echoview® [26]. Calibration parameters from the winter calibrations were applied to the raw acoustic backscatter data, and sound speed and absorption coefficients were calculated based on water temperature and salinity collected during surveys. A known systematic triangle wave error in data collected with a Simrad ES60 echosounder was investigated and found to be negligible [21]. Using 38 kHz backscatter echograms, a bottom line 0.5 m above bottom was created and smoothed using an algorithm in Echoview®. Data below this line were excluded from processing. The upper 10 m of data were excluded from analyses, as they often contained entrained air bubbles that masked fish signals.

The simultaneous use of ADCPs (one on the boat and one deployed on the sea floor at the impact site) resulted in noise spikes consisting of a single contaminated ping in both the 38 and 200 kHz hydroacoustic data. The contaminated ping was compared to those on either side, and if the difference between them was below a threshold (~10 dB), the contaminated ping was replaced by interpolating its adjacent pings [27] [28].

The 38 and 200 kHz backscatter data were dB differenced using ΔMVBS analysis [29] [30] [31] [32]. The majority of our data processing methods followed [33]. The following processing steps were taken for all backscattering coefficient data (s_v): (1) data were smoothed and background noise was removed; (2) noise outliers were removed using a series of median filters followed by erosion and dilation filters; (3) a virtual echogram was created using $s_v = (s_{v,\,38\,kHz} + s_{v,\,200\,kHz})/2$ to find common backscatter between the two frequencies; (4) the 38 kHz mean volume backscattering strength (S_v) was subtracted from the 200 kHz S_v to provide the frequency response, r(f), of the sound scatterers; (5) backscatter was classified based on frequency response categories, where r(f) < 6 dB were fish and r(f) > 6 dB were zooplankton; (6) a mask was created that removed all backscatter from the echogram except for that from fish, as classified in step 5; (7) a -60 dB target strength threshold was applied to fish backscatter.

Data from running ebb and flood tides, but not slack tides, were analyzed because we were most concerned with fish interactions with a rotating turbine, and the turbine would be static during slack tides. Removing slack tide data also eliminated the possible effects of lengthy detections of the same fish while ensonified in the sound beam for long periods of time, as well as effects of unpredictable boat movements (e.g., swinging about the mooring, along with pitch, roll, and heave which increased when currents were slow). We defined slack tides as the times when the boat was not stable against a taut mooring line, which usually amounted to a time span of 1 hr. Additionally, only data from 0-15 m above the sea floor were analyzed in order to standardize comparisons between the control and impact sites and to focus analyses on the depths encompassing the turbine. Ebb and flood tide data were divided into bins that were 30 min wide by 15 m high, measured upward from the sea floor. Our index of fish density, S_v was then calculated and exported from each bin. S_v is a measure of sound scattered by fish in a unit volume of water, with units of decibels (dB re 1 m^{-1}), and it is assumed to be proportional to fish density [22].

Two-way (year and site) ANOVA permutation tests [34] were performed using a significant alpha value of 0.05 with S_v data as the dependent variable. The interaction term was used to indicate significant BACI results, separating the one-way differences related to annual and site variation alone. As such, interaction effects indicated differences due to the combination of time (before-after) and device presence (control-impact). These comparisons included times before and after the TidGen® installation (same months in different years; Table 1). Permutation tests were used because some of the months had non-normal distributions. Power analysis was performed on parametric 2-way ANOVAs of the same comparisons. While this is not an exact value, it does provide an approximation. The significance results of the parametric 2-way ANOVA analyses were the same as the permutation ones. Effect sizes for each comparison were the difference in mean change in S_v between the two sites (Eq. 1).

$$\text{BACI effect size} = (\text{mean}_{\text{after,control}} - \text{mean}_{\text{before,control}}) - (\text{mean}_{\text{after,impact}} - \text{mean}_{\text{before,impact}}) \quad (1)$$

3.0 Results

Fish density was lowest in March and highest in May for all years at both sites (Fig. 3). In March surveys, prior to installation, fish density was higher at the impact site than at the control site (2011 and 2012). However, after installation, when the device was present and rotating but not generating electricity (2013), fish density was higher at the control site than at the impact site. This reversed relationship of fish density with site after device installation was statistically significant for both March BACI comparisons ($p = 0.033$ for March 2011/2013 and $p = 0.047$ for March 2012/2013) (Table 1; Figure. 4).

Fish density was higher at the impact site when only the bottom support frame (BSF) was present without the device (May 2012). This same difference was observed prior to the installation of the BSF (May 2011). Overall fish density was higher in May 2012 than May 2011, but there was no significant interaction term in the BACI comparison ($p = 0.592$) (Table 1; Figure 4).

Fish density was higher at the control site than the impact site when the turbine was present but braked (static) in August 2012. However, fish density was lower at the control site compared to the impact prior to deployment but when the BSF was present (August 2011). There was a significant interaction term in the BACI comparison of August 2011 and 2012 ($p = 0.019$) (Table 1; Figure 4).

Fish density was higher at the control site when the turbine was present, rotating, and producing power in September 2012. This was also the case prior to deployment in September 2011. There was no significant interaction term for the BACI comparison ($p = 0.740$) (Table 1; Figure 4).

4.0 Discussion

Fish densities in the water column before and after deployment around the deployed TidGen® at the CBTEP varied throughout the year and with device presence, providing an indication of effects of the device on fish presence. The use of a control site enabled a complete BACI analysis. The use of BACI sampling and analyses have been effectively used in previous research for fish and environmental stressors [35] [36]. In this study, down-looking, stationary hydroacoustic methods and data initiated with previous research in this region [21] were used for the “Before” component of this study. For perspective, data were collected at the proposed impact site along with separate, yet temporally consistent surveys at a nearby control site. In this study, the interaction term of the 2-way ANOVA provided a statistically robust examination of differences due to turbine presence, independent of natural drivers of fish presence in the region.

The index of fish density used in this work was mean volume backscattering strength (S_v) of the bottom 15 m of the water column obtained with a single beam echosounder. Other research applications using down-looking hydroacoustics scale backscatter with target strength information provided by split-beam transducers or apply statistical deconvolution techniques to scale backscatter with fish size for exact density or abundance estimates [22] [37] [38]. Their goals were different from those of this study. Our goal was not to separate species by target strength or create absolute fish density estimates. Instead, we wanted to generate an index of fish presence at the project and control sites as a baseline assessment. Single-beam echosounders are less expensive than split-beam models and were financially ideal for early stage monitoring efforts. The use of dual frequency (38 and 200 kHz) hydroacoustics enabled the application of dB differencing processing methods that removed the majority of unwanted zooplankton backscatter from that of fish, resulting in a good density index of fishes that may be exposed to the MHK device at the times surveyed.

Each of the separate statistical comparisons had conditions that made them different and difficult to equate to one another. Separating effects from a known stressor in combination with other, unquantified stressors can prove difficult [39]. There were five occasions where BACI comparisons could be made in association with the TidGen® deployment. In this study, the known stressors were the installed BSF by itself and the deployed turbine in several operational conditions. However, additional stressors known to affect fish, including boat traffic [40] [41] [42] and industrial diving operations [43], were also present at times. While the effects of these additional stressors were not separately quantified, they could have contributed to some of the observed differences in fish presence during device deployment.

No significant effect on fish abundance was observed for May (2011/before to May 2012/after) or September (2011/before to 2012/after); both may be related to the lack of stressors additional to turbine presence and operation. The “after/impact” component in May included only the BSF with no moving components of the actual turbine, and the hydroacoustic survey took place several months after the installation of the BSF, so there was little industry activity in the area at the time. Interestingly, we also did not observe an effect when the TidGen® device was fully operational, in September 2012. During this time, the turbine was rotating and generating electricity. Intuitively, we would expect to detect a change in fish presence at this time. However, during this time there was little in the way of industry activity: boat traffic was reduced and there was no diving taking place. Further perspective is provided by the August survey, which occurred near a static device with high industry activity when the device had been installed just two weeks prior to the survey. A significant interaction was observed under those conditions, leading us to believe that the amount of on- and in-water industry activity may be a driver to of decreases in fish density at the impact site. This is further supported by the fact that the turbine was static in the August survey, and therefore effectively an extension of the BSF. As the BSF did not affect fish density in the May comparison, the influence of other activities on fish density is likely.

Effects of industry-related activities on animal presence at marine renewable energy sites have been observed at other locations. Similar results have been reported for the responses of little tern (*Sternula albifrons*) to offshore wind installations [44]. This study correlated negative impacts of mono-pile installation on herring spawning success, which created a trophic effect of less forage for little tern chicks. The authors urged precaution of installation timing and associated pile-driving activity. Research on juvenile pink salmon (*Oncorhynchus gorbuscha*) and chum salmon (*O. keta*) distribution in Puget Sound showed lower fish abundance at a construction site during days of pile driving compared to days without [45]. Existing research, along with results presented here, suggests that the effect of construction activities should be separated from the effect of a deployed, operational MHK device, and even managed separately.

Differences in fish density near the TidGen® were also observed in a separate study which used a different metric, fish vertical distribution [12]. As with water column fish density in this research, the vertical distribution of fish was significantly different after device installation in August and March comparisons, but not in the September comparison. Using the same dataset as this research, the approach used by [12] separated the water column into depth bins, which was helpful in examining fish location in relation to depth of a deployed device. However, the vertical distributions were not used to determine if fish movement changed in response to the entire deployed device, or if fish were reacting to the dynamic portion (turbine) only. Fish reactions may vary based on their encounter with a static or dynamic device component and this should be further investigated.

Depth distributions [12] using stationary, downlooking hydroacoustics not only provided insight to water column fish density, but further informed the probability of those fish being at the depth of a device, and therefore their likelihood to directly interact with it. Shen et al. [46] used these vertical distributions and other hydroacoustic data to model the probability of fish encountering the deployed TidGen®. They determined the probability of fish encountering the entire device (BSF and turbine, 0-9.5 m above the bottom) was approximately 50%, and the probability encountering just the turbine (6.5-9.5 m above the bottom) was approximately 6%, depending on diel conditions. If only those fish at the depth of the turbine (~6% of the water column total S_v) modify their behavior (e.g., in response to dynamic device components) by vertical [12] or horizontal movement, it is likely that the change in water column density or vertical distribution would be difficult to observe and statistically insignificant. However, if fish encountering the entire device (~50% of the water column total S_v) change their behavior (in response to both dynamic and static device components), the change would be more evident. As such, the significant differences observed in the August and March BACI comparisons from this study and [12] may reflect fish changing their distribution elsewhere in the water column, not just at the depth of the TidGen® turbine. It may be necessary to determine if the driver for behavior change at a device is related to its dynamic parts only or includes the static components as well, because its effects on a large-scale could impact fish immigration and emigration through high energy areas targeted for tidal power devices.

The changes in fish density around a single deployed device are unlikely to be representative of a larger disturbance in the form of operational, commercial-scale arrays. A single device presents little in the way of an obstacle when compared to the entire cross-sectional area of a tidal channel like outer Cobscook Bay. However, the probability that multiple devices will disrupt movement, whether small-scale daily excursions or large-scale migrations, is yet to be tested and will present a new set of challenges for separating the effects of environmental variables from those of an MHK device array. Similar challenges have been associated with birds and bats around wind turbines. Doty and Martin [47] studied a single pilot turbine for one year in South Africa and noted 18 bat casualties and 1 bird casualty. Similar to our study, they referenced a single pilot device and showed an effect on bats and birds. However, a single operational device is difficult to scale-up to several devices or an array. Associated scaling of monitoring to capture differences between single devices and arrays is developing, as there are also studies referencing large-scale arrays that also find bat and bird mortality [48]. The array studies did not develop from single device studies and without the early, single-device monitoring it is difficult to say how effects change with the increasing number of devices. Monitoring should begin as early as possible in the research and development stage for any new technology, and this should include single pilot device research. The referenced bird and bat studies along with this research show that as renewable energy industries move forward, it will be important to continue research on fish behavior around deployed devices during installation and deployment as the effects and potential impacts could change. Early-stage, single-device monitoring can provide preliminary data on potential effects of devices on fish and provide the basis for array-stage research questions and sampling methods to answer them.

Effects of a deployed MHK device on fish density in its surrounding tidally dynamic area were demonstrated here. The impact of these effects on the fish assemblage in the region is yet unknown. Other construction-related disturbances in the area in combination with the TidGen® deployment may explain some of the observed fish density differences. Device installation, maintenance, and decommissioning will likely prove to be times of highest disturbance in the area of MHK devices [49]. It will be important to time such activities to avoid major fish migrations or presence of endangered and threatened species. Insight from this research has aided local and regional regulatory bodies, industry, and local stakeholders to make decisions regarding the social and legal acceptance of tidal power development and future device deployments [50]. Continued research is needed in the area of fish monitoring, along with other environmental assessments (e.g. mammals, birds, acoustics), to allow this renewable energy source to develop into a sustainable, commercially viable market to further enable carbon emission mitigation of climate change effects.

Acknowledgements

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Table 1. BACI comparisons of water column S_v data collected at impact and control sites before and after the TidGen® was installed, with device status. Interaction results of 2-way permutation ANOVAs and associated p-values are shown. The BACI effect size and statistical power of the test are presented for significant results.

Fig. 1. Illustration of Ocean Renewable Power Company's TidGen® Power System with turbine and bottom support frame (length 31.2 m; width: 15.2 m; height 9.5 m).

Fig. 2. Map of Cobscook Bay, Maine. The star indicates the location of the impact site and the square indicates the location of the control site.

Fig. 3. Fish density index, S_v, from 0-15 m above the sea floor for each 24-hour survey of control and impact sites from 2011-2013 in Cobscook Bay, ME. Boxes indicate the 25th, 50th, and 75th percentiles. The whiskers represent the 10th and 90th percentiles, while the dots represent the 5th and 95th percentiles. The impact site is the white box of each pair and the control site is gray.

Fig. 4. Two-way ANOVA interaction plot showing all five BACI comparisons. The x-axis indicates the month and year of compared surveys. The y-axis is S_v, in decibels, which is proportional to fish density. The squares with solid line represent S_v at teach site "before" TidGen® installation and triangles with dotted lines represent "after" installation. Asterisks indicate which comparisons were significant (significance level = 0.05). The impact site is the first symbol in each pair and the control site is the second.

Table 1

Month	Before device installation	After device installation	Device status in “after” survey	2-way ANOVA interaction p-value	BACI effect (dB)	Power
March	2011	2013	turbine present rotating not generating	**0.033**	6.4	0.62
March	2012	2013	turbine present rotating not generating	**0.047**	4.9	0.45
May	2011	2012	BSF present turbine absent not generating	0.592	-	-
August	2011	2012	turbine present not rotating not generating	**0.019**	5.3	0.53
September	2011	2012	turbine present rotating generating	0.740	-	-

Figure

Figure 2

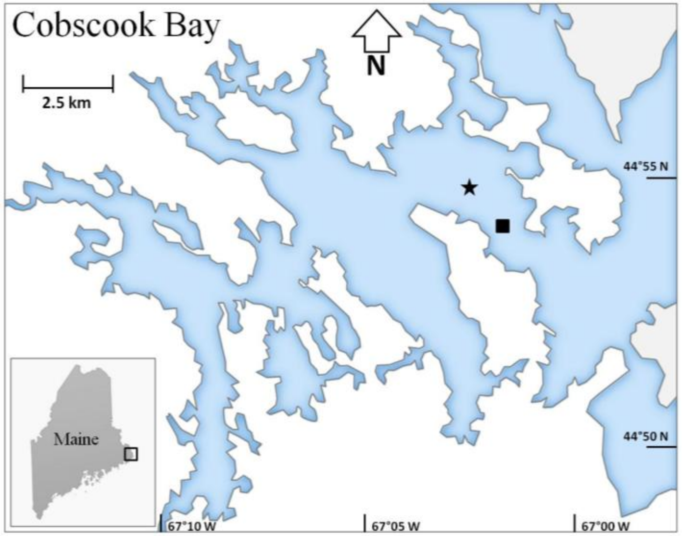
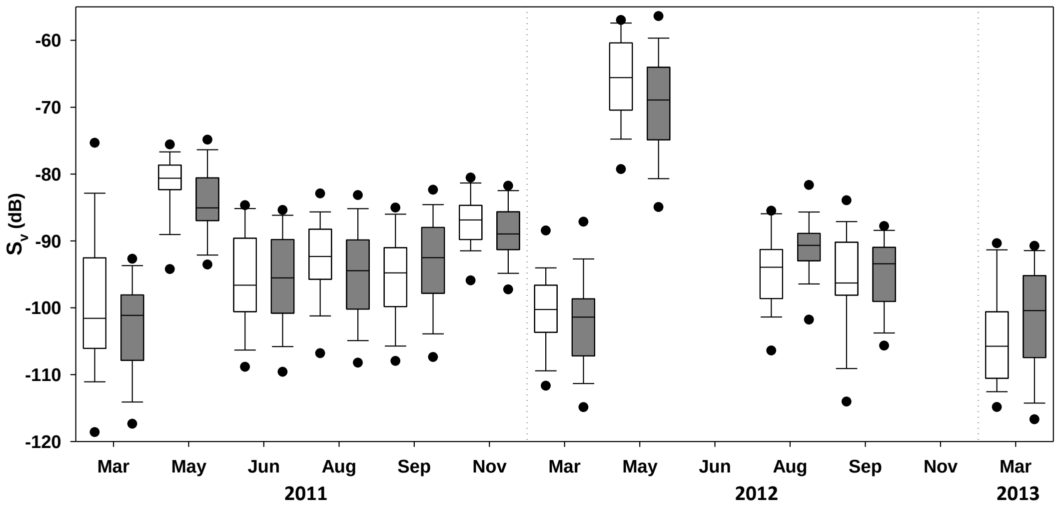
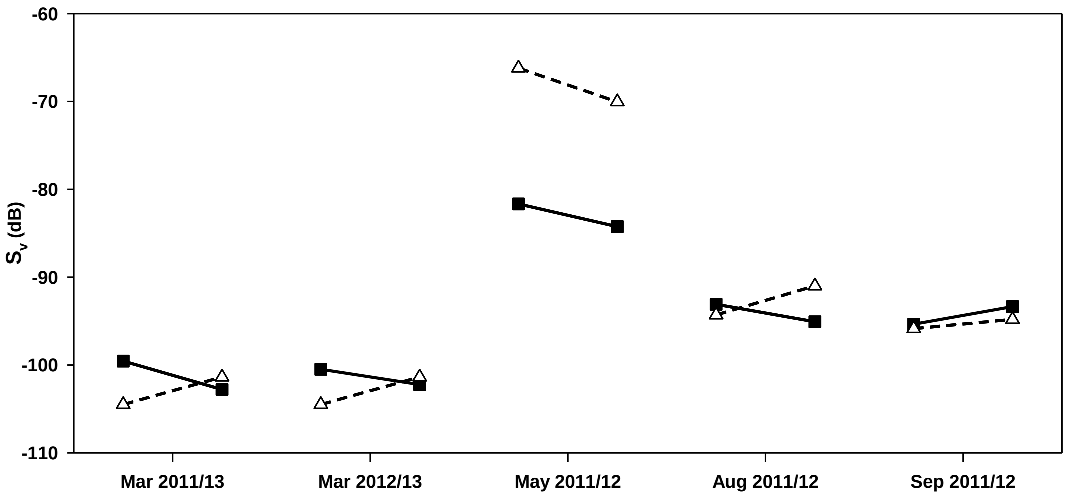


Figure 3



Sv (dB)
-60
-70
-80
-90
-100
-110
-120
Mar
May
Jun
Aug
Sep
Nov
Mar
May
Jun
Aug
Sep
Nov
Mar
2011
2012
2013

Figure 4



-60
-70
-80
-90
-100
-110
S_v (dB)
Mar 2011/13
Mar 2012/13
May 2011/12
Aug 2011/12
Sep 2011/12

PLOS ONE

Fish behavior near a static tidal energy device

--Manuscript Draft--

Manuscript Number:	PONE-D-16-33981
Article Type:	Research Article
Full Title:	Fish behavior near a static tidal energy device
Short Title:	Fish behavior near a static tidal energy device
Corresponding Author:	Gayle Barbin Zydlewski University of Maine Orono, ME UNITED STATES
Keywords:	Tidal energy; fish behavior; static turbine; marine hydrokinetic; hydroacoustics
Abstract:	Tidal energy is a developing form of renewable energy that uses free-standing turbines to generate electricity from tidal currents. The effects of these marine hydrokinetic (MHK) devices on fish are uncertain but of concern. Interactions of fish with MHK devices, such as avoidance, evasion, blade strike or aggregation, depend on where and how individuals detect and respond to the device. We investigated the responses of fish to a non-operational (static) MHK device in Cobscook Bay, ME, USA. Using a bottom-mounted, side-looking, split beam hydroacoustic echosounder, we observed the horizontal movements of fish in an area spanning 7-18 m from the face of the turbine. The fish detected were generally small (on the order of a few cm in length), and moved almost exclusively with the tidal current. However, when fish were approaching the device, the presence of the static turbine resulted in a greater difference between their movement and that of the current, suggesting avoidance. This divergence of fish movement from the current was present both day and night, suggesting that fish used visual as well as non-visual (e.g., hearing or lateral line) cues to avoid the obstacle. When fish were departing from the device, we detected no significant changes in their horizontal movement relative to the current. Together, these data suggest that fish avoidance behavior occurred as far as 18 m upstream of the static device and wake effects on behavior did not extend beyond 7 m downstream. Operating turbines would emit different physical cues than a static one, and responses would likely differ under those conditions as well as with fish species and life stage. More information on the visual, acoustic, and hydrodynamic signatures of MHK devices (static and operational), and sensory response thresholds of the fish likely to encounter them, could inform future efforts to better understand behavioral responses. Further mechanistic understanding of cues and their relation to behavior change would aid in predicting effects of single devices and commercial arrays on individual fish and populations.
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Opposed Reviewers:	
Additional Information:	
Question	**Response**
Financial Disclosure Please describe all sources of funding that have supported your work. **This information is required for submission and will be published with your article, should it be accepted.** A complete funding	This work was supported by awards from the United States Department of Energy (energy.gov), project #DE-EE0000298, #DE-EE0003647, and #DE-EE0006384 and Maine Sea Grant (seagrant.umaine.edu), project #NA10OAR4170081. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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Ethics Statement You must provide an ethics statement if your study involved human participants, specimens or tissue samples, or vertebrate animals, embryos or tissues. All information entered here should **also be included in the Methods section** of your manuscript. Please write "N/A" if your study does not require an ethics statement. **Human Subject Research (involved human participants and/or tissue)** All research involving human participants must have been approved by the authors' Institutional Review Board (IRB) or an equivalent committee, and all clinical investigation must have been conducted according to the principles expressed in the Declaration of Helsinki. Informed consent, written or oral, should also have been obtained from the participants. If no consent was given, the reason must be explained (e.g. the data were analyzed anonymously) and reported. The form of consent (written/oral), or reason for lack of consent, should be indicated in the Methods section of your manuscript. Please enter the name of the IRB or Ethics Committee that approved this study in the space below. Include the approval number and/or a statement indicating approval of this research. **Animal Research (involved vertebrate animals, embryos or tissues)** All animal work must have been conducted according to relevant national and international guidelines. If your study involved non-human primates, you must provide details regarding animal welfare and steps taken to ameliorate suffering; this is in accordance with the recommendations of the Weatherall report, "The use of non-human primates in research." The relevant guidelines followed and the committee that approved the study should be identified in the ethics statement.	N/A

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Please describe where your data may be found, writing in full sentences. **Your answers should be entered into the box below and will be published in the form you provide them, if your manuscript is accepted.** If you are copying our sample text below, please ensure you replace any instances of XXX with the appropriate details.	Data are from the DOE study DE-EE0006384. Contact Gayle Zydlewski at gayle.zydlewski@maine.edu.

If your data are all contained within the paper and/or Supporting Information files, please state this in your answer below. For example, “All relevant data are within the paper and its Supporting Information files.” If your data are held or will be held in a public repository, include URLs, accession numbers or DOIs. For example, “All XXX files are available from the XXX database (accession number(s) XXX, XXX)." If this information will only be available after acceptance, please indicate this by ticking the box below. If neither of these applies but you are able to provide details of access elsewhere, with or without limitations, please do so in the box below. For example: “Data are available from the XXX Institutional Data Access / Ethics Committee for researchers who meet the criteria for access to confidential data.” “Data are from the XXX study whose authors may be contacted at XXX.” * typeset	
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24 August 2016

PLOS One

Dear Editor:

I am writing on behalf of myself and coauthors, Haley A. Viehman, William Halteman, and Donald Degan, concerning the manuscript entitled "***Fish behavior near a static tidal energy device***", which is being submitted as a research article. This manuscript details fish responses to the presence of a tidal turbine in a dynamic bay. The responses of animals to alternative developing energy sources remain an active area of research. Field-collected data like this are difficult to come by and these represent a unique dataset that has given us insight to fish behavior in an under-studied environment. Our previous work focused on relative densities of fish near this device and these data build on that work, providing a more individual fish assessment of behavior. The content of this manuscript is relevant to the focus of this journal.

All coauthors fully participated in and accept responsibility for the work submitted. The manuscript is one chapter of the PhD dissertation of first author, Haley Viehman. It has **not** been submitted to another journal and has **not** been considered for another journal. Some potential referees included: Dr. Anna Redden (Anna.Redden@acadiau.ca, Acadia Centre for Estuarine Research, Acadia University, Canada), Mark S. Bevelhimer (bevelhimerms@ornl.gov, Environmental Sciences Division, Oak Ridge National Laboratory, USA), and Linus Hammar (linus.hammar@chalmers.se, Department of Energy and Environment, Chalmers University of Technology, Sweden).

Sincerely,

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Fish behavior near a static tidal energy device

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Author Contributions

Conceived and designed experiment: HV, GBZ, DD. Performed experiments: HV, GBZ. Processed the data: HV, DD. Analyzed the data: HV, WH. Wrote the paper: HV, GBZ. One chapter of the dissertation of HV with GBZ as advisor and WH and DD on committee.

Abstract

Tidal energy is a developing form of renewable energy that uses free-standing turbines to generate electricity from tidal currents. The effects of these marine hydrokinetic (MHK) devices on fish are uncertain but of concern. Interactions of fish with MHK devices, such as avoidance, evasion, blade strike or aggregation, depend on where and how individuals detect and respond to the device. We investigated the responses of fish to a non-operational (static) MHK device in Cobscook Bay, ME, USA. Using a bottom-mounted, side-looking, split beam hydroacoustic echosounder, we observed the horizontal movements of fish in an area spanning 7-18 m from the face of the turbine. The fish detected were generally small (on the order of a few cm in length), and moved almost exclusively with the tidal current. However, when fish were approaching the device, the presence of the static turbine resulted in a greater difference between their movement and that of the current, suggesting avoidance. This divergence of fish movement from the current was present both day and night, suggesting that fish used visual as well as non-visual (e.g., hearing or lateral line) cues to avoid the obstacle. When fish were departing from the device, we detected no significant changes in their horizontal movement relative to the current. Together, these data suggest that fish avoidance behavior occurred as far as 18 m upstream of the static device and wake effects on behavior did not extend beyond 7 m downstream. Operating turbines would emit different physical cues than a static one, and responses would likely differ under those conditions as well as with fish species and life stage. More information on the visual, acoustic, and hydrodynamic signatures of MHK devices (static and operational), and sensory response thresholds of the fish likely to encounter them, could inform future efforts to better understand behavioral responses. Further mechanistic understanding of cues and their relation to behavior change would aid in predicting effects of single devices and commercial arrays on individual fish and populations.

Introduction

Tidal energy is a form of renewable energy converts the kinetic energy of water currents generated by tidal forces to electricity, using free-standing underwater turbines. Any fast-flowing water can be used in this way, including ocean currents, tidal streams, and rivers (Charlier and Finkl 2010). Many different marine hydrokinetic (MHK) devices have been designed for this purpose, and generally consist of one or more large turbines and a static support frame or mooring system holding the turbine(s) in place. Though difficult to estimate, globally, MHK devices may be able to generate up to 180 TWh of energy per year if all sites were fully developed (Jacobson 2009; estimate excludes riverine applications).

As tidal currents are considered for renewable energy development, concerns arise regarding the effects of MHK devices on the environment. Deploying MHK structures in fast-moving ocean (or river) currents is likely to affect the surrounding ecosystem, but because very few MHK devices have been deployed worldwide, their actual effects are not yet well understood (Boehlert and Gill 2010, Polagye et al. 2011). Harvesting energy from tidal currents may cause changes to the physical environment, including flow patterns (Rao et al. 2016, Shapiro 2011), water quality (Wang et al. 2015), sediment transport (Martin-Short et al. 2015), and underwater noise and electromagnetic fields (Boehlert and Gill 2010). Such environmental alterations may in turn have implications for the biotic components of the ecosystem, including seabirds (Waggitt and Scott 2014), benthic organisms (Broadhurst and Orme 2014), and pelagic animals (e.g. marine mammals and fish; Gill 2005).

Fish are a key biological component of marine ecosystems and coastal economies, both of which could be affected by MHK devices. Many fish species target the same strong tidal currents ideal for tidal energy extraction to carry out large-scale movements to complete their life cycles (Gibson 2003). Potential effects of MHK devices are diverse and numerous, from direct effects, such as strike by rotor blades, to less direct effects, such as population-level responses to altered physical environments or disruption of migratory pathways (Polagye et al. 2011, Boehlert and Gill 2010, Gill 2005). Simply adding structure to a dynamic environment could also provide new shelter and prove to be an attractant (Čada and Bevelhimer 2011, Broadhurst et al. 2014, Kramer et al. 2015, Inger et al. 2009).

Effects of MHK devices on fish can occur on multiple spatial and temporal scales, and these effects are being explored with a combination of laboratory and field studies. In the laboratory, fish responses to MHK turbines can be examined at very close-range (within 1-2 m), blade strike can be observed, and rates of survival and injury of entrained fish can be calculated, which is currently virtually impossible in a field setting. These flume laboratory studies indicate high survival rates (>90%) for the species entrained in MHK turbines, with behavior, injury, and survival being species- and size-dependent (Amaral et al. 2015, Castro-Santos and Haro 2015). Efforts in the field have so far focused on two spatial scales: the near-field (within the first few meters of MHK devices), and the far-field (the general area of MHK devices, e.g. >10 m away). Near-field studies of fish interactions with MHK turbines in the field echo results of laboratory studies, finding that behavior approaching a turbine depends on fish size, species, and turbine visibility (Hammar et al. 2013, Bevelhimer et al. 2015, Viehman and Zydlewski 2015a). Farther-field studies (hundreds of meters from MHK turbines) have focused on predicting the probability for spatial and temporal overlap of MHK turbines and fish based on natural fish distributions. These studies indicate that the probability of interactions varies on a wide range of temporal scales (Seitz et al. 2011, Bradley et al. 2015, Staines et al. 2015, Shen et al. 2016, Viehman et al. 2015, Viehman and Zydlewski 2015b).

A gap in knowledge exists between the near-field (within meters) and the far-field (hundreds of meters) of MHK devices. Shen et al. (2016) made progress toward linking these two spatial scales in the field by conducting hydroacoustic transects over an MHK device, analyzing fish presence in the space from 10 m to 200 m upstream of the turbine. The numbers of fish detected over this distance showed some evidence of avoidance beginning as far as 140 m upstream. Shen et al. (2016) combined data on the vertical distributions of fish in the region (Staines et al. 2015, Viehman et al. 2015) with near-field behavioral observations (Viehman and Zydlewski 2015a) to model the probability that fish would encounter the device. They concluded that the probability of fish upstream of the device encountering the turbine was 0.058 (0.043, 0.073 = 95% CI), and the probability of entrainment in the turbine was on the order of 0.028 (0.022, 0.037). This model relied on what was known of fish behavior as they approach the device at distances less than 10 m (Viehman and Zydlewski 2015a), but there remains a need to determine at what ranges, beyond 10 m, fish begin to respond. This distance depends on many environmental and biological factors, including (but not limited to) how the device alters the physical environment, the ability of the life stages of fish species present to sense those alterations, how individual fish perceive the device (e.g., as a threat to be avoided), and the ability of individuals to control their movement within the tidal current (Lima et al. 2015, Weihs and Webb 1984, Kim and Wardle 2003).

The presence of a static MHK device, be it the unmoving structural components or the turbine itself during slack tides, may affect fish and the surrounding ecosystem (Boehlert and Gill 2010, Polagye et al. 2011, Frid et al. 2012). Very little has been published on the effects of the MHK device infrastructure. However, other static offshore platforms have been reviewed in this context (Kramer et al. 2015). The static portion of MHK devices could act as an artificial reef, providing hard surfaces for the attachment of sea life and shelter for various species, including fish (Broadhurst and Orme 2014, Wilhelmsson and Langhamer 2014). Hydraulic shelter is structure that creates areas of low-velocity water in an otherwise high-velocity flow field, and has mainly been examined in the context of river channel usage by resident and migratory fishes (Čada and Bevelhimer 2011). Some evidence of the use of MHK device structures as hydraulic shelter in tidal flows has been reported. Viehman and Zydlewski (2015a) observed fish pausing within the wake (within 7 m) of a test MHK device in the field, but because the fish were quite small it was unclear whether this was voluntary use of shelter or if the fish were caught within the turbulent flow. Broadhurst et al. (2014) found that Pollack (*Pollachius pollachius*) aggregated around an MHK device, particularly at lower current speeds (< 2 $m \cdot s^{-1}$). They speculated that predatory fish like these may be inclined to use the sheltered area downstream of such obstacles to lie in wait for passing prey, a common predation method in many fish species. Aggregation of fish downstream of MHK device structures may have effects at higher trophic levels, where marine mammals and diving birds could also target areas adjacent to MHK turbines to forage (Waggitt and Scott 2014, Williamson et al. 2015).

This study examines the behavior of fish in the vicinity of a static MHK device at distances between those examined by near-field and far-field studies that have occurred to date, 7-18 m from the turbine face. Fish behavior was observed with a bottom-mounted split-beam echosounder, both in 2013 when a complete MHK device was present (i.e. bottom support frame and turbine, with the brake applied and therefore static) and in 2014 when the turbine was absent from the device (only the bottom support frame remained). Fish behavior was examined upstream and downstream of the MHK turbine, the former for signs of avoidance and the latter for signs of wake effects such as those seen by Viehman and Zydlewski (2015a). Upstream observations made at this static MHK device may be applied to understand fish behavior at an operational device. For example, the range at which fish detect and react to a static MHK device may represent a minimum distance of detection and avoidance for a rotating, power-generating MHK turbine.

Methods

The MHK device studied was the Ocean Renewable Power Company, LLC (ORPC) TidGen® Power System (Fig 1). The system consists of four helical cross-flow rotors aligned along a central axis, with a permanent magnet generator at the center. Each rotor has a diameter of 2.8 m and length of 5.6 m. A bottom support frame holds the turbine 6.7 m above the sea floor, for a total device height of 9.5 m. When operational, this turbine begins to rotate at current speeds of approximately 1 $m \cdot s^{-1}$ (from either direction), with a maximum rotational velocity of approximately 40 rpm (ORPC 2013). A device of this design was deployed in Cobscook Bay, Maine, in August 2012. It operated until the brake was applied to the turbine in April 2013, after which time the turbine did not rotate (was static). The turbine was removed in July 2013, though the bottom support frame remained on the sea floor. This study used data collected while the turbine was present but static (April to July 2013), and data collected at the same time the following year (April to July 2014), when only the bottom support frame was present.

Fig 1. Ocean Renewable Power Company's TidGen® Power System, deployed in outer Cobscook Bay, Maine from August 2012 to July 2013. *Turbine image source*: Ocean Renewable Power Company.

The TidGen® was deployed in outer Cobscook Bay, Maine (Fig 2). At this location, the tidal range is approximately 6 m, and current speed ranges from 0 to approximately 2 $m \cdot s^{-1}$ over the course of a tidal cycle (Viehman et al. 2015, Brooks 2006). In Cobscook Bay, the fish community changes dramatically over the course of a year, with strong seasonal cycles in both the species and life stages of fish present (Vieser 2014). The extensive intertidal areas of the inner bays are highly productive and serve as nursery habitats for the juveniles of many fish species. Based on physical sampling in May and June 2013 (Vieser 2014), fish present while the turbine was present and static were likely to be mainly larval Atlantic herring (*Clupea harengus*) and juvenile winter flounder (*Pseudopleuronectes americanus*), as well as a lesser number of juveniles of several other species. Physical sampling at the site in May 2014 (while the turbine was absent) mainly captured juvenile red hake (*Urophycis chuss*) and adult Atlantic herring (Zydlewski et al. 2016).

Fig 2. Map of study area with location of Ocean Renewable Power Company's TidGen® Power System.

Acoustic data were collected using a calibrated 200 kHz, 7° split beam Simrad EK60 echosounder installed by ORPC in August 2012 on the sea floor near the TidGen® bottom support frame (Fig 3). The echosounder was mounted 3.3 m above the sea floor, 45.7 m from the TidGen® support frame, and angled 6.2° above horizontal. The transducer was angled away from the turbine using a pan and tilt unit until most backscatter from the turbine support structure was no longer visible in the echogram (approximately

10.2° between the acoustic beam's central axis and the face of the turbine). The echosounder sampled an approximately conical volume of water 5 times per second, using a pulse duration of 0.256 ms and transmit power of 120 W. The current flowed approximately perpendicular to the sampled volume, though this varied slightly between ebb and flood tides (Fig 3b). Most fish moved with the current and were therefore detected by several sequential pings as they passed through the acoustic beam, even at peak tidal flows.

Fig 3. Echosounder and TidGen® setup from (a) the side and (b) above. The "turbine" zone of the sampled volume is indicated by the darker hatched region, and the "beside" zone by the lighter hatched region. The median current direction for each tidal stage, estimated from fish heading data (see text), is shown at right in (b). *Turbine schematic source*: Ocean Renewable Power Company.

Only the sampled volume at the depth of the turbine was used in this study, spanning 6.7 to 9.5 m above the sea floor (Fig 3a). This analysis volume was then partitioned into two zones: the "turbine" zone, which was directly aligned with the turbine face, and the "beside" zone, which included the area sampled to the side of the turbine. The inner 5° of the sampled volume were used in analyses (see below).

Data were collected while the turbine was present and its brake was applied (static, not rotating), which occurred from April 25 to July 5 2013. Data could not be collected while the turbine was fully operating (rotating at current speeds > 1 $m \cdot s^{-1}$ and generating power) because the cable carrying the generated power to the shore interfered with the echosounder data transfer cable at these times. The echosounder continued to collect data after the turbine was removed in July 2013, so a comparison dataset was selected when the turbine was absent (though the bottom support frame was still present), spanning April 24 to July 5 2014. Matching the dates of the 'absent' dataset to that of the 'static' one helped best match the species and life stages of fish during the two collection periods, despite seasonal changes, though interannual variability could not be controlled.

The echosounder operated nearly continuously, but there were several gaps in data collection due to technical issues or necessary shut-down of the echosounder during turbine-related activities, such as diver inspection (Table 1). The final dataset included 38 complete days of data collected while the turbine was present and static and 63 days collected while the turbine was absent. More gaps occurred while the turbine was present.

Table 1. Summary of hydroacoustic data collection at the TidGen® site in Cobscook Bay, ME.

Turbine state	**Year**	**Dates of continuous data collection**	**Total time in dataset**
Turbine present, static	2013	4/25 - 5/02 5/07 - 5/14 5/24 - 6/04 6/26 - 7/05	38 days
Turbine absent (bottom support frame present)	2014	4/24 - 5/27 6/04 - 6/26 6/30 - 7/05	63 days

Data processing

Acoustic data were processed using Echoview® software (6.1, Myriax, Hobart, Australia). There were several types of 'noise' in the data (signals not from individual fish) that had to be removed before fish could be tracked. These included small, non-fish targets (e.g., large zooplankton), interference from the surface and entrained air near the surface, schools of fish (in which individual fish could not be tracked accurately), and a mobile object that frequently appeared in the beam during ebb tide in the 2013 dataset (perhaps a rope attached to the seafloor; Fig 4). Target strength (TS) measures the proportion of sound energy that is reflected back to the transducer by an object. A TS threshold of -50 dB was used to eliminate most signal from small, non-fish targets and fish less than roughly 4 cm in length (Love 1971). Surface interference was removed by limiting the maximum analysis range to 64 m from the transducer face, which is the range at which entrained air from the surface began interfering with the acoustic signal. Background noise tended to increase with range but also varied over time with water height (which changed with the tide) and weather conditions. This type of noise, which gradually changed over time, was removed using the method developed by De Robertis and Higginbottom (2007), slightly modified to apply to TS data. Intermittent noise such as schools, entrained air, and the moving 'rope' object was removed using multiple resampling and masking steps with Echoview virtual operators. All of these methods were worked into an Echoview template, which was then applied to all data using Echoview's scripting module (Fig 4).

Fig 4. Processing steps for hydroacoustic data collected with a side-looking split beam echosounder near a static MHK device in Cobscook Bay, Maine. This example is from 22:25 to 22:26 on 30 June 2013. The x-axis is time (minutes and seconds after 22:00) and the y-axis is range from transducer. (a) Raw target strength data (scale in dB, to right of each panel) showing multiple fish tracks, background noise gradient, and 'rope' object near 46 m range. (b) Target strength data with noise and 'rope' removed and -50 dB TS threshold applied. (c) Single targets detected from cleaned target strength data. (d) Fish tracks (colored lines) overlaid on raw target strength data (in grayscale).

Once noise was removed from the acoustic data, single targets were detected and fish were tracked using Echoview's 4D fish tracking algorithm (Fig 4, Table 2). Information about the tracks and the single targets within them were exported from Echoview to be further processed in R (3.1.1, R Core Team, Vienna, Austria).

Table 2. Single target and fish tracking parameters used in Echoview.

Process	Parameter	Value
Single target detection	TS threshold	-50 dB
	Pulse length determination level	6.00 dB
	Minimum normalized pulse length	0.20
	Maximum normalized pulse length	2.00
	Beam compensation model	Simrad LOBE
	Maximum beam compensation	12.00 dB
	Maximum standard deviation of:	
	Minor-axis angles	0.500°
	Major-axis angles	0.500°
Single target filters	Angle filters:	
	Minor-axis range	-2.5° – 2.5°
	Major-axis range	-2.5° – 2.5°
	Pulse length filters:	
	Pulse length at 18 dB range (normalized)	0.40 – 1.50
Fish tracking	Data	4D
	Alpha (major, minor, range)	0.7, 0.7, 0.8
	Beta (major, minor, range)	0.5, 0.5, 0.5
	Exclusion distance (major, minor, range)	1.5, 1.5, 0.5 m
	Missed ping expansion (major, minor, range)	0, 0, 0 %
	Weights:	
	Major axis	0
	Minor axis	0
	Range	0
	TS	0
	Ping gap	0
	Minimum number of single targets in a track	5 targets
	Minimum number of pings in a track	5 pings
	Maximum gap between single targets	3 pings

Single target detection and fish tracking parameters were chosen to exclude the worst-quality data from fish tracks, but visual inspection of fish tracks after they were exported from Echoview indicated that some error remained. This was particularly true within the ranges spanned by the turbine, where echoes from the support frame, turbine (when present), and sea surface and bottom interfered with the location data of detected fish (i.e., the angular measurements along the major and minor axes of the beam). Many tracks that were detected in the area of the turbine had accurate range measurements and minor-axis angle estimates (position in the beam's horizontal cross-section), but highly variable major-axis angle measurements (position in the beam's vertical cross-section; Fig 5a). For this reason, the following analyses were carried out in two dimensions, focusing only on fish heading (movement trajectory in the horizontal plane, relative to north) and ignoring fish inclination (movement trajectory in the vertical plane, relative to horizontal).

Even after limiting analyses to the horizontal plane, some poor-quality tracks needed to be identified and removed from the 2D dataset. Poor-quality tracks were therefore those that were physically improbable. These were tracks with highly tortuous paths (Fig 5c,d), which were unlikely to be accurate given the speed of the current and the short time each fish spent within the beam (95% of fish detected remained in the beam for 3 seconds or less). In reality, fish were most likely traveling in a roughly straight line across the sampled volume (Fig 5a,b), consistent with previous observations at this site (Viehman and Zydlewski 2015a). To help separate good and bad tracks, a line was fit to each track using the time and position of the track's single targets. Six parameters were then calculated (in the horizontal plane) for each track to classify it as either good or bad: the R^2 of the line fit, the ratio of the straight-line distance between the start and end points and the distance covered by the path, the polarity of the track segments, the average distance of the track's single targets from the fitted line, and the average and standard deviation of the angles between consecutive track segments. Four-hundred tracks were manually scrutinized and categorized as either 'good' or 'bad.' Half of these tracks were used to build a general additive model (GAM) to predict track quality based on the six factors, and half were used to test the model's accuracy. This method was found to reduce the prevalence of poor-quality tracks to less than 10% of the final dataset. More poor-quality tracks were present in the turbine zone due to the acoustic interference from the support frame and the turbine. The numbers of fish reported in each zone are therefore unlikely to represent the true proportion of fish that passed through each, but their direction of movement direction can still be used to assess their responses to the turbine. After poor-quality tracks were removed from the dataset, the fitted line of each remaining track was used to define fish heading, i.e., the direction of the track with respect to north.

Fig 5. Example fish tracks from the flooding tide, collected using a side-looking split beam echosounder in Cobscook Bay, Maine. (a) Single targets (spheres) and fitted line (black line) of a fish track classified as "good" in the horizontal plane, showing the typical high variation in the vertical dimension. (b) Same track as in A, shown in the horizontal plane with fitted line (black), true North (N), fish heading (black arrow), median direction of the tidal current (red arrow), and divergence of fish heading. (c) Poor-quality ("bad") track with fitted line (black). (d) Same track as in c, shown in horizontal plane. Single target color indicates order of detection (red = first point, blue = last point). Axes are in meters, with the origin at the center of the turbine face: the x axis is parallel to the turbine face, with the positive direction away from the transducer; the y axis is perpendicular to the turbine face, with the positive direction away from the turbine; and the z axis is vertical, with the positive direction upward.

Data Analysis

The metric used to assess device effects on fish behavior was fish heading divergence: the difference between each fish heading and the direction of the water current. Generally speaking, at this site, fish move almost exclusively with the current during the flowing tides and exhibit random 'milling' behavior at slack tides when current speed is low (Viehman and Zydlewski 2015a). If fish normally travel with the current, departure from the direction of the current may indicate a change in their regular behavior, such as avoidance of the turbine or response to its wake.

We approximated water current direction as the median fish heading for each individual tide. This approach was validated by comparing current speed data from an ADCP deployed on the sea floor (by ORPC) at this site in March 2013 to concurrent fish heading data collected using the same hydroacoustic setup from this study (Fig 6). Fish heading in the March 2013 data followed a square-wave pattern (Fig 6a), with shifts between high and low values corresponding to periods of slack tide as indicated by the ADCP velocity data (Fig 6b). This pattern was very similar to current direction measured and modeled at a nearby location by Xu et al. (2006). Additionally, fish heading during the ebb and flood tides aligned very well with the average current directions at this site (approximately 120° and 285°, respectively;

ORPC personal communication). Based on the March 2013 data, slack tides were defined as the 2-hour periods which encompassed each shift in fish heading between ebb and flood directions. For the current study, the times of these shifts were determined for the duration of the dataset by fitting a sinusoidal model with tidal periodicities to the fish heading data, as shown in Fig 6a and Viehman and Zydlewski (unpublished data).

Fig 6. Fish heading and current velocity collected at the TidGen® site in March 2013. (a) Individual fish heading (gray points) shown with fitted tidal model (dashed line) used to calculate times of slack tide (gray areas). (b) Current velocity collected concurrently by a bottom-mounted ADCP at the same site.

Once slack tide periods were removed from the data, the median fish heading for each individual ebb and flood tide was used as current direction during that time. If fewer than 10 fish were present in a given tide, the median was not considered reliable, and tracks from that tide were omitted from further analysis. Divergence was then calculated for each fish track as the magnitude of the difference between its heading and the corresponding estimated tidal current direction. This method helped avoid false inflation of variation in fish heading due to shifts in flow over time.

Ebb and flood tides were analyzed separately because during flood tide, fish were approaching the device, and during ebb tide, fish were departing from it. For each tidal stage, a linear model (function *lm* in package *stats* in R) was used to test for effects of four factors and their interactions on fish divergence from the current: static turbine state (absent or present), sampling zone (beside or turbine), diel condition (day or night), and fish size (TS). The continuous factor, TS, was centered at its mean, and to meet assumptions of residual normality, the normal scores of divergence were used as the response variable. The initial models included main factor effects as well as interaction terms, and final models included only those terms that were found significant at the 5% level (single terms that were part of significant interaction terms were also included).

Results

While the static turbine was present (2013), 4,104 good-quality fish tracks were identified, and 4,696 while the turbine was absent (2014). More fish were tracked beside the turbine than in the turbine zone during both the flood (Fig 7) and ebb (Fig 8) tides, likely due to acoustic inference at turbine-zone ranges. More fish were detected during the ebb tide than the flood tide. During the flood tide, we detected many more fish at night than during the day (Fig 7), but there was not a large diel difference for the ebb tide (Fig 8).

Over 90% of fish had TS ranging from -48 to -38 dB (Figs 7 and 8). This TS range equates to fish lengths of approximately 4 to 11 cm using Love's general lateral-aspect equation, though this relationship varies greatly with fish species and orientation (Love 1971). TS tended to be higher in the turbine zone than beside the turbine, indicating larger fish, and this difference was more substantial when the turbine was present. This apparent difference in size between zones was likely due to acoustic interference from the MHK device (particularly the turbine), which made weaker acoustic targets more difficult to track at the further range, where the turbine was located. TS also appeared higher during the ebb tide than the flood tide, but this may have been due to slightly different orientation of the fish with respect to the acoustic beam during different tide phases than to actual size differences. The ebb tide current, and presumably the fish moving with it, was more perpendicular to the acoustic beam's central axis than the flood tide current (Fig 3b), increasing the TS of fish detected at ebb tide relative to those detected during flood-tide, which would travel at a more oblique angle (Boswell et al. 2009).

Fig 7. Target strength (TS, in dB) of fish detected during the flood tide, when fish would be approaching the MHK device, beside the turbine (white boxes) and in the turbine zone (grey boxes) during the day and night, (a) when the turbine was absent, 2014; (b) when the turbine was present and static, 2013. Horizontal line is the median, boxes span interquartile range, whiskers span 5^{th} to 95^{th} percentile, and points indicate minima and maxima. Numbers are sample size of each group.

Fig 8. Target strength (TS, in dB) of fish detected during the ebb tide, when fish would be departing from the MHK device, beside the turbine (white boxes) and in the turbine zone (grey boxes) during the day and night, (a) when the turbine was absent, 2014; (b) when the turbine was present and static, 2013. Horizontal line is the median, boxes span interquartile range, whiskers span 5^{th} to 95^{th} percentile, and points indicate minima and maxima. Numbers are sample size of each group.

Fish divergence from the current direction suggested that fish swam in the direction of the current when the tide was flowing (Figs 9 and 10). Ninety-five percent of all fish trajectories diverged from the current direction by 15° or less. Median fish heading (e.g., estimated tidal current direction) ranged from 115° to 128° during ebb tide and from 279° to 290° during the flood tide. Against-current movement was only visually obvious in the turbine zone at night, when the static turbine was present (Fig 9b, lower right panel): approximately 4% of fish diverted more than 100° from the median direction, whereas no more than ~0.3% did so in any of the other sets of conditions. During this time, the polarity of the fish headings was 0.91, as opposed to 0.99 for all others (polarity of 0 would indicate completely random headings, and 1 would indicate completely uniform).

Fig 9. Day and night fish divergence from tidal current direction (histograms) and fish heading relative to North (inset rose diagrams) during the flood tide, when fish would be approaching the MHK device. (a) When the turbine was absent, 2014; (b) when the turbine was present and static, 2013. White and black bars correspond to the beside-turbine zone and turbine zone, respectively. Gray background indicates night. The number of fish (n) and the polarity of their headings (P) are shown for each group.

Fig 10. Day and night fish divergence from tidal current direction (histograms) and fish heading relative to North (inset rose diagrams) during the ebb tide, when fish would be departing from the MHK device. (a) When the turbine was absent, 2014; (b) when the turbine was present and static, 2013. White and gray bars correspond to the beside-turbine zone and turbine zone, respectively. Gray background indicates night. The number of fish (n) and the polarity of their headings (P) are shown for each group.

Linear models fit to flood and ebb tide data were both statistically significant (model p-values < 0.05), suggesting a relationship between the dependent variable (fish divergence) and independent variables (turbine state, zone, diel stage, and TS). The model fits were low, accounting for only 2.0% and 0.6% of the variation in fish divergence for flood and ebb tides, respectively. The model therefore had little predictive power. However, it did indicate that several factors affected fish behavior.

During the flood tide, when fish would have been approaching the MHK device, turbine state and sampling zone had statistically significant main effects on fish divergence at the 5% level (Table 3). There were also interaction effects involving turbine state, sampling zone, and diel stage. Given these interaction effects, the fitted values of the model for each combination of factors can best illustrate the relative differences in divergence (Fig 11). These modeled values indicated that when the turbine was absent, divergence was greater beside the turbine than in the turbine zone during the day, but at night, there was no zone effect (Fig 11a). When the static turbine was present, divergence was greater in the turbine zone than beside the turbine during both day and night (Fig 11b). Divergence was higher at night for both sampling zones, but the difference between zones was greater during the day.

Table 3. Final linear model fit to divergence of fish movement from median direction during the flood tide (when fish would have been approaching the MHK device).

Model term	Coefficient estimate	Standard error	P-value
Intercept	0.208	0.058	<0.001
Turbine state (static)	-0.554	0.090	<0.001
Zone (turbine)	-0.348	0.104	0.001
Diel stage (night)	-0.110	0.066	0.095
Turbine state (static):zone (turbine)	0.855	0.194	<0.001
Turbine state (static):diel stage (night)	0.363	0.098	<0.001
Zone (turbine):diel stage (night)	0.349	0.119	0.003
Turbine state (static):zone (turbine):diel stage (night)	-0.475	0.223	0.033
Adjusted R^2	0.019		
Model p-value	<0.001		

Fig 11. Normal scores of divergence estimated by the linear model summarized in Table 3, to show main and interaction effects of significant factors: turbine state (static turbine absent or present), diel stage (day or night), and sampling zone (beside or turbine). (a) Static turbine absent. (b) Static turbine present. White and gray points correspond to the beside-turbine zone and turbine zone, respectively. Gray areas indicate night.

During the ebb tide, when fish would have been departing from the MHK device, the only significant factor affecting divergence was TS (coefficient estimate: 0.038; standard error: 0.012; p-value: 0.001). This indicated that larger fish showed greater variation in movement with respect to the current than smaller fish, but divergence was not influenced by turbine state, diel stage, or sampling zone.

Discussion

Fish approaching the MHK device responded to the static turbine at the distances observed. The fish observed were mainly small, likely on the order of a few cm in length, and they generally traveled in the same direction as the tidal current. However, those directly upstream of the static turbine showed more variable movement with respect to the current than those that were to the side. This difference occurred when the static turbine was present but was not apparent when the turbine was absent, and suggests turbine avoidance. Previous studies of fish evasion of operating MHK devices have sampled the first few meters from the turbine and observed evasion (Hammar et al. 2013, Viehman and Zydlewski 2015a). As we observed a volume spanning 7-18 m from the face of the static TidGen® turbine, our results suggest the range of MHK device effects on fish behavior extends 18 m upstream and perhaps farther. Shen et al. (2016) carried out transects over an MHK device similar to the TidGen® with a rotating, but not generating, turbine, and they found evidence that fish were moving out of the path of the device as far as 140 m upstream.

Reactions to the static turbine that we observed were generally confined to small-scale adjustments in trajectory, as most fish (95% of tracks) diverged 15° or less from the current direction. Evasion maneuvers have been observed to range from small-scale adjustment to complete reversal of movement (Hammar et al. 2013, Viehman and Zydlewski 2015a), but these studies occurred within a few meters of the devices and involved rotating turbines. At the distances from the turbine which we sampled here, slight deflection from the strong current is likely an effective and energy-efficient method of downstream obstacle avoidance. For the small fish that we sampled, it may also be the only possible maneuver, as fish swimming power is directly related to length (Beamish 1978). Fish of Cobscook Bay are generally small, and consist mainly of juveniles of multiple species (Vieser 2014, Zydlewski et al. 2016). During this study, a large portion of fish sampled were likely larval or recently-metamorphosed juvenile Atlantic herring (Vieser 2014, Zydlewski et al. 2016), which would be weak swimmers relative to the tidal current. In their transects over a similar ORPC device, in August 2014, Shen et al. (2016) observed slightly larger fish, which were likely a mix of juvenile Atlantic herring (~20 cm) and adult Atlantic mackerel (~30 cm; Vieser 2014, Zydlewski et al. 2016). Those fish would be stronger swimmers than the ones observed here in Apr-Jun 2012 and 2013, and they, too, moved almost exclusively with the current. As their numbers decreased beginning 140 m upstream, and vertical distribution did not change, they too were likely using small movements to avoid the downstream obstacle.

At multiple meters upstream of an MHK device, small movements in relation to the current may be the chosen method of avoidance for both the small ($\leq$ 10 cm) and large (10-30 cm) fish. Within a few meters of the turbine, fish size may be of greater importance to evasive behavior. In the first 3 m upstream of a rotating MHK turbine, Viehman and Zydlewski (2015a) found that small fish (10 cm and under) tended to enter the turbine if it was in their path, with at most 2% actively evading by swimming up, down, or against the current. Larger fish (most of which were still less than 20 cm) had a greater likelihood of evading the turbine (up to 11%), likely due to greater maneuverability in the fast currents. Studies of fish responses to trawls have also found close-range evasion to be more evident for larger fish (e.g., Rakowitz et al. 2012, Sajdlová et al. 2015). Fish size, and therefore species and life stage, is therefore an important factor when considering if and how fish avoid MHK devices.

Avoidance of an MHK device depends on whether fish can detect the device, and at what range this occurs. Fish have a variety of sensory systems to alert them to approaching objects, including visual and auditory senses and the lateral line system, which is sensitive to the local flow field and may play a role in detecting distant, low-frequency sounds (Popper and Schilt 2008, Bleckmann and Zelick 2009, Evans 1993). As we saw evidence of avoidance during both day and night, fish were likely detecting and responding to visual cues and non-visual cues (e.g. acoustic and hydrodynamic) from the device. The turbine had a larger effect on fish divergence from the current during the day than at night, indicating that sight played an important role in eliciting avoidance behavior. This agrees with the close-range studies by Viehman and Zydlewski (2015) and Rakowitz et al. (2012), which found the probability of turbine and trawl evasion, respectively, to be higher during the day than at night. However, at night we also observed a small portion of fish (~4%) in the turbine zone that moved against the current, which was not seen during the day or beside the turbine. It is possible that in the absence of vision, the acoustic and hydrodynamic cues of the static device evoked stronger and less uniform reactions to its presence. This would be in agreement with the less-directed responses of herring to obstacles in the dark (Blaxter and Batty 1985) and of various fish species to approaching trawls at night (Rakowitz et al. 2012).

We cannot rule out that the behavioral difference which we observed at night could be related to different species or life stages of fish being sampled at that time. During the flood tide, many more fish were detected at night than during the day, which could have been the result of the activity of nocturnal species within the water column (Reebs 2002, Vieser 2014), or of schools spreading out at night and the individuals from the schools becoming trackable (Pitcher 2001). The result of either would be sampling a different community of fish at night than during the day, and therefore comparing the responses of fish with different sensory and locomotory abilities. TS during day and night indicated that fish size did not change dramatically, but different species may respond to the same cues in different ways. Species-dependent responses have been observed for other MHK devices. Amaral et al. (2015) and Castro-Santos and Haro (2015) found fish responses to turbines in laboratory flumes to be species-dependent, with turbine responses related to each species' swimming behavior (e.g., active rheotaxis or passive drifting) and direction of travel (upstream- or down-stream migrating). Hammar et al. (2013) found the same in the field, where they observed certain species (mainly predatory fish) to approach MHK turbines more than others, hypothesizing that they were 'bolder' individuals. The species of fish present at a tidal power site and how species composition changes over time must therefore be considered when predicting or interpreting their responses to MHK devices, as the type of response will largely determine the risk of entrainment, injury, and mortality.

In this study, we examined fish movement in the horizontal plane, but it is also possible that fish responses to the MHK device were taking place in the vertical plane (i.e., swimming upward or downward to avoid the upcoming turbine). Diving is commonly observed as the primary reaction of fish to disturbances such as passing vessels and approaching trawls (Ona et al. 2007, Sajdlová et al. 2015), often seen before lateral movements and at great ranges (450 m, Handegard and Tjøstheim 2005; 75-275 m, Handegard et al. 2003). Additionally, Bevelhimer et al. (2015) found evidence of downward fish movement 0-15 m from an HK device deployed in the East River, NY. As such, we cannot rule out vertical avoidance of the TidGen® device at the ranges we observed. Two other studies carried out at the same site as the present work provided conflicting evidence of vertical movements in response to MHK devices. In their transects over the MHK device, Shen et al. (2016) did not observe vertical fish movements related to the device. On the other hand, Staines et al. (2015) found some differences in the vertical distributions of fish near the TidGen® (~50 m away) before and after its installation that may have been related to device presence. The different vertical distributions may have resulted from vertical and/or horizontal movements by fish, but individual movements could not be inferred from the distribution data.

The acoustic data contamination which prevented us from assessing vertical movement is a common issue in hydroacoustics, particularly when collecting data near solid boundaries such as an MHK device, the seafloor, and the sea surface. Possible methods of addressing this issue include using a narrower beam, (which could reduce surface and bottom interference), moving the beam farther from the device (though this could reduce the likelihood of observing fish responses), or using multibeam sonars (Williamson et al. 2015, Melvin and Cochrane 2014). Additional improvements could be made to the data processing techniques used here. Automated processing is necessary for such large datasets, which are too time-consuming to process manually. The processing method used here was effective at removing many types of noise from the data, but it was also conservative and likely omitted many useable fish tracks from analyses. Improvements to acoustic data processing techniques, such as incorporating visual signal processing, could help reduce unnecessary data omission. Changing levels of noise in different parts of the sampled volume resulted in unequal detection probabilities over time and in different parts of the acoustic beam, making it impossible to use fish numbers as indicators of turbine effects (e.g., beside vs. turbine zones, or present vs. absent). However, overall, the diel and tidal differences in fish numbers that we observed were consistent with a more detailed assessment of temporal patterns of fish passage rate at this site (Viehman and Zydlewski, unpublished data) and likely reflected natural patterns as opposed to device effects.

Unlike the flooding tide, we saw no effects of MHK turbine presence on fish movement during the ebbing tide, when they would be departing from the device. The wake of the device can extend over 100 m before flow velocity reaches 90% of its undisturbed magnitude (Rao et al. 2016), but fish apparently were not responding to it in a way which we could detect. The only statistically observed effect on fish movement downstream of the device was of fish TS, which suggested that larger fish were diverging farther from the current direction than smaller ones, regardless of turbine presence. Viehman and Zydlewski (2015a) reported that fish were almost always milling in the wake of the test turbine they examined, though that viewing window extended only 3 m downstream of the device. Those fish may have been sheltering from the fast currents in the low-velocity area just behind the turbine structure (Čada and Bevelhimer 2011), or were potentially disoriented by turbine passage or the sudden change in flow conditions. Regardless of the cause of the turbine-wake milling behavior, if it was occurring near the static TidGen® in the present study, it did not extend beyond 7 m downstream of the turbine.

To predict and interpret fish responses to MHK devices, we need a better understanding of the physical signature of the static and dynamic devices. To date, detailed measurements of the visibility, noise generation, and hydrodynamic signatures of MHK devices are sparse and spread over a wide range of designs and deployment configurations (Copping et al. 2014). Measuring these physical conditions around MHK devices in strong tidal currents poses its own set of challenges (e.g., Martin and Vallarta 2012) but in many cases is more easily accomplished than observing fish behavior at all the possible spatial and temporal scales of interaction. The distance at which fish detect and respond to MHK devices will depend on the fish present and site characteristics, as detection thresholds of fish sensory systems (e.g. vision, hearing, and the lateral line) vary with species and life stage and their sensitivity is modified by environmental conditions (Kim and Wardle 2003, Bleckmann and Zelick 2009, Blaxter 1986). Knowledge of the physical ‘footprint’ of MHK devices, combined with knowledge of the sensory capabilities of the fish that may encounter them, would aid in planning studies of fish behavior by identifying where fish are most likely to detect and respond to the device, and would afterward inform interpretation of study results. Our understanding of fish sensory abilities is limited, and more information on a wider range of marine species would be necessary for this approach.

To develop a better understanding of how fish interact with MHK devices, we should aim to collect concurrent information on the physical signatures of devices and the behaviors of fish encountering them. Williamson et al. (2015) have taken a step in this direction by developing a bottom-mounted monitoring platform that includes multibeam and split beam echosounders, a flow meter, and a fluorometer, with the possibility for adding other equipment. Collecting data with these instruments simultaneously may allow animal behavior to be linked to local physical conditions affected by MHK devices; for example, fish movement with respect to the turbulence generated downstream. Studies using integrated approaches such as this will help build a more complete understanding of how and why MHK devices affect fishes and other marine organisms.

The results of this study and others indicate the effects of an MHK device on fish will vary with the species and life stages that are present at the same location. At a tidal energy site, the composition of the fish community is likely to change on a variety of spatial and temporal scales (Viehman and Zydlewski, unpublished data, Vieser 2014), and the effects of proposed MHK devices must be assessed with these changes in mind. As more individual devices are deployed and monitored, preferably with integrated biological and physical monitoring systems, we can begin to expand predictions of effects from individual animals and devices to population-level effects and device arrays. This information can inform the design and location of MHK device arrays as we seek to responsibly develop this renewable energy source.

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Data available upon request.

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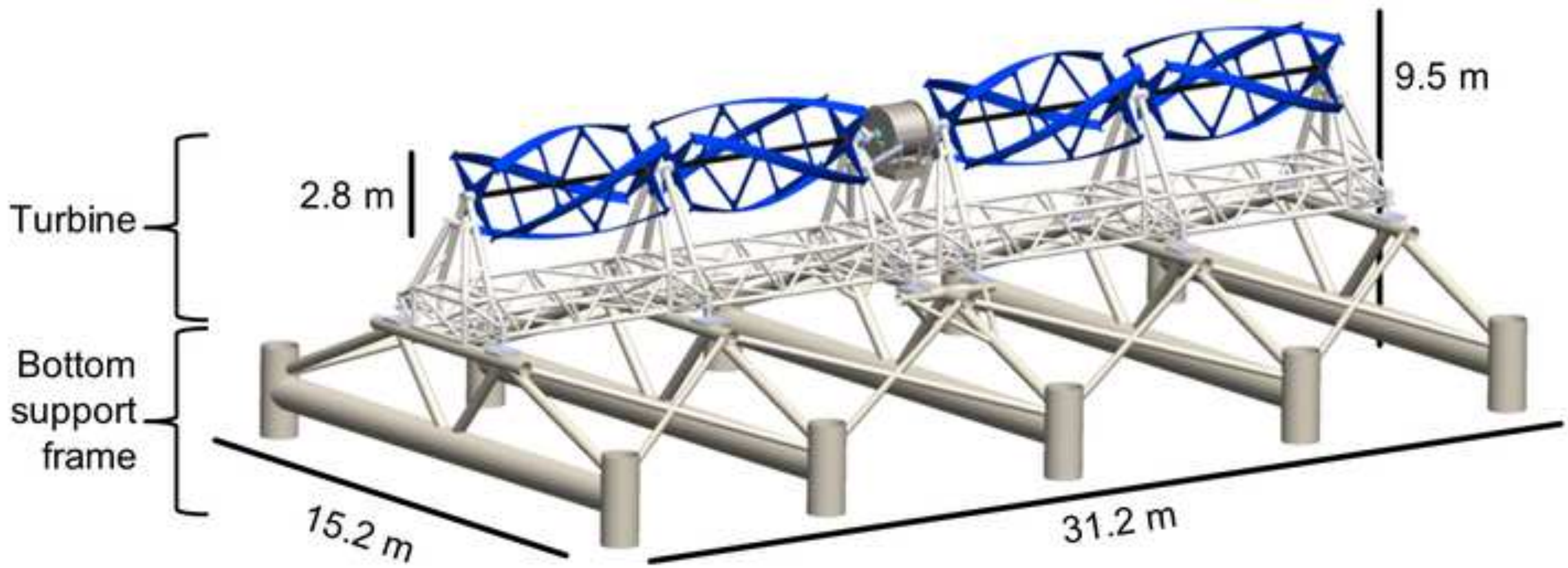
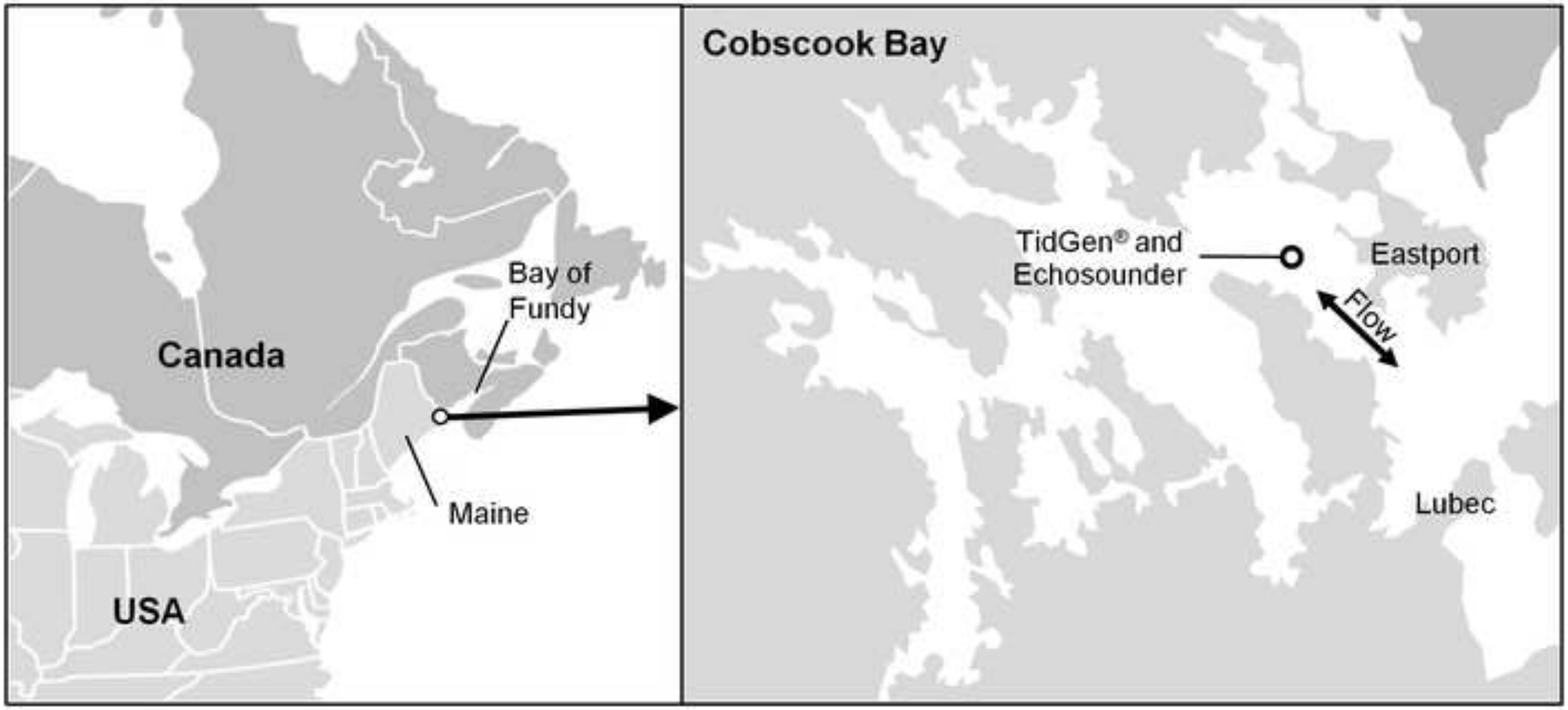

9.5 m
2.8 m
Turbine
Bottom
support
frame
15.2 m
31.2 m

Fig 2

Click here to download Figure Fig2.tif



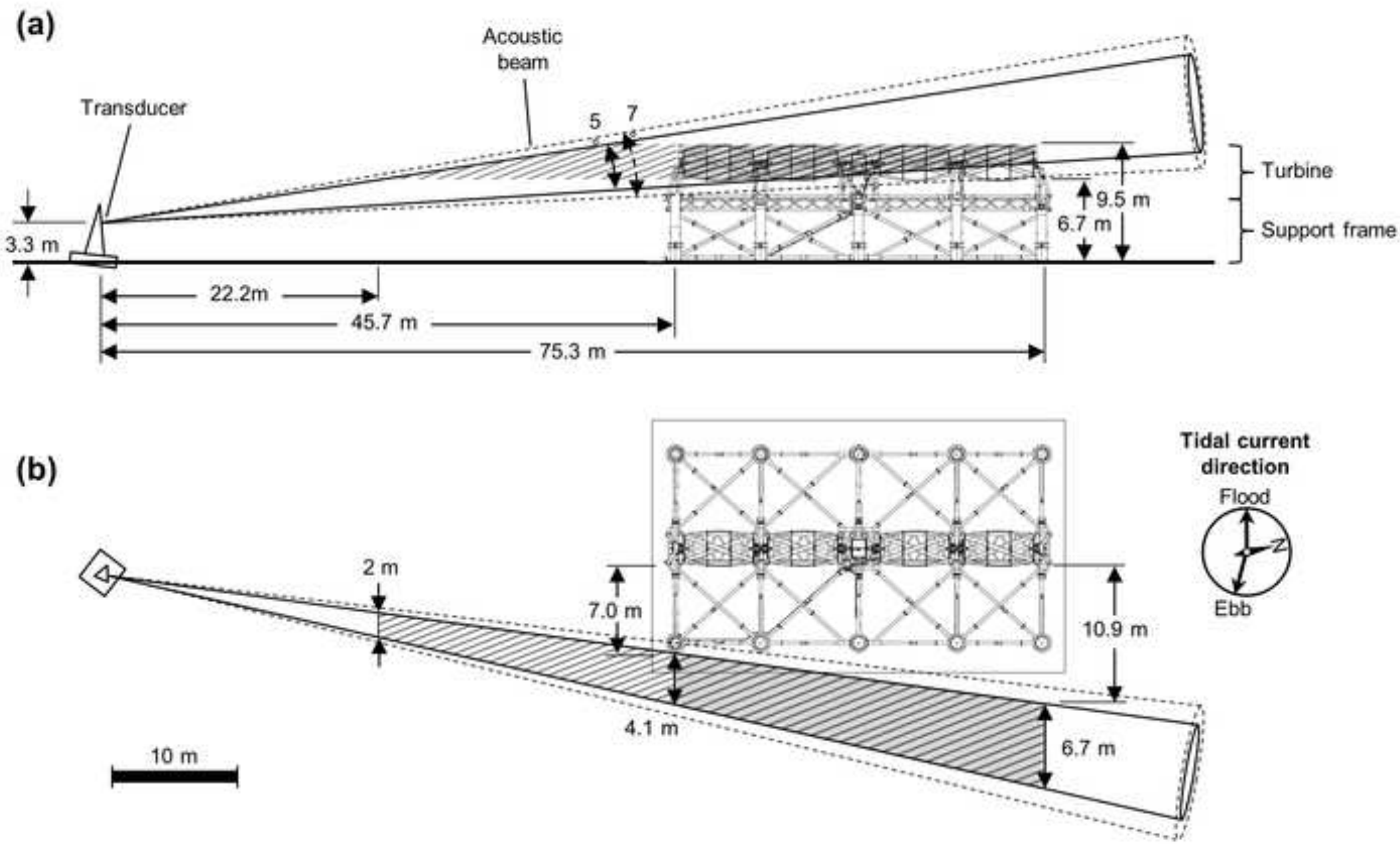
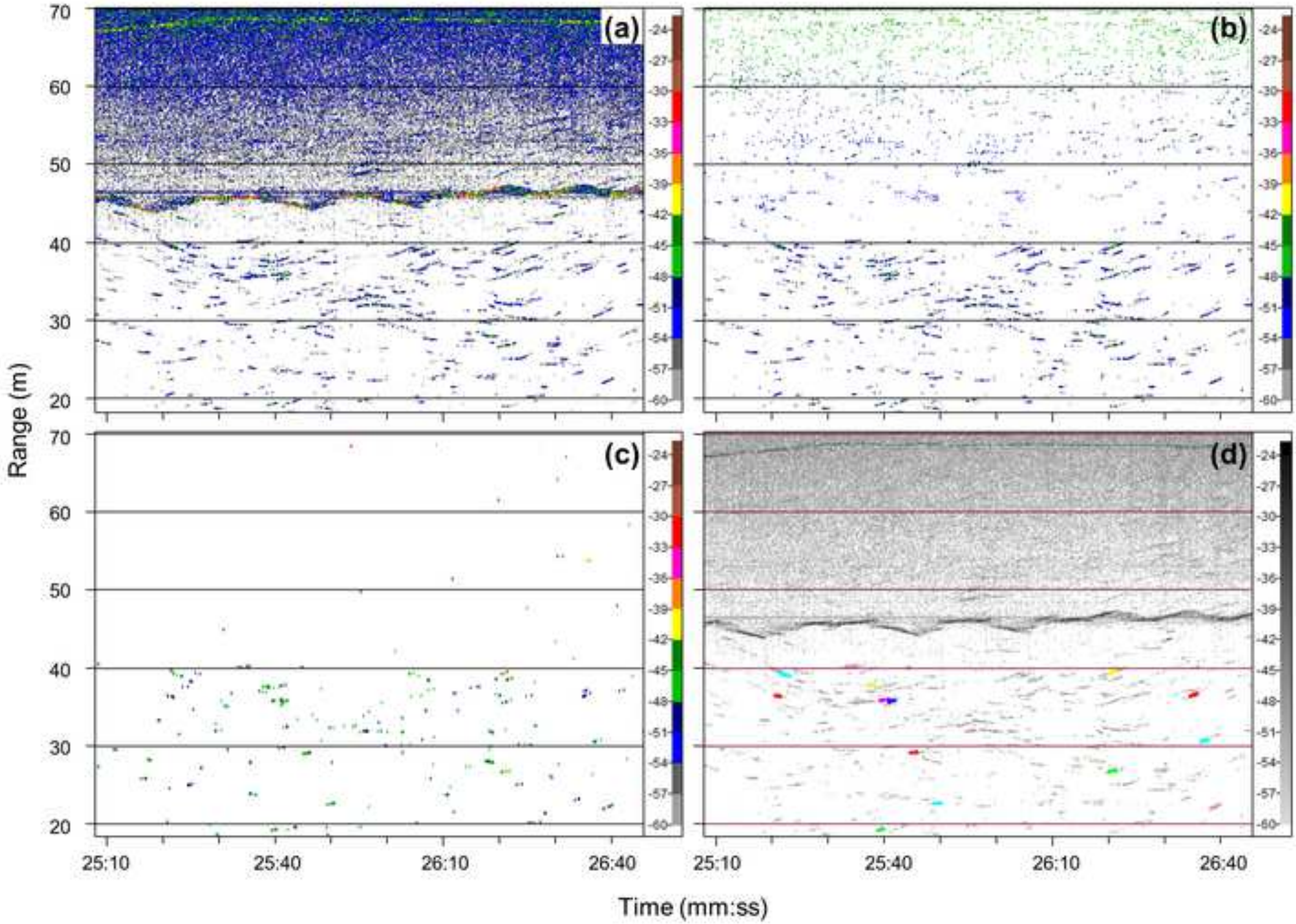

(a)
Acoustic beam
Transducer
5
7
Turbine
Support frame
9.5 m
6.7 m
3.3 m
22.2m
45.7 m
75.3 m
(b)
Tidal current direction
Flood
Ebb
N
2 m
7.0 m
10.9 m
4.1 m
6.7 m
10 m

Fig 4


(a)
(b)
(c)
(d)
Range (m)
70
60
50
40
30
20
-24
-27
-30
-33
-36
-39
-42
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25:10
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26:10
26:40
Time (mm:ss)

Fig 5

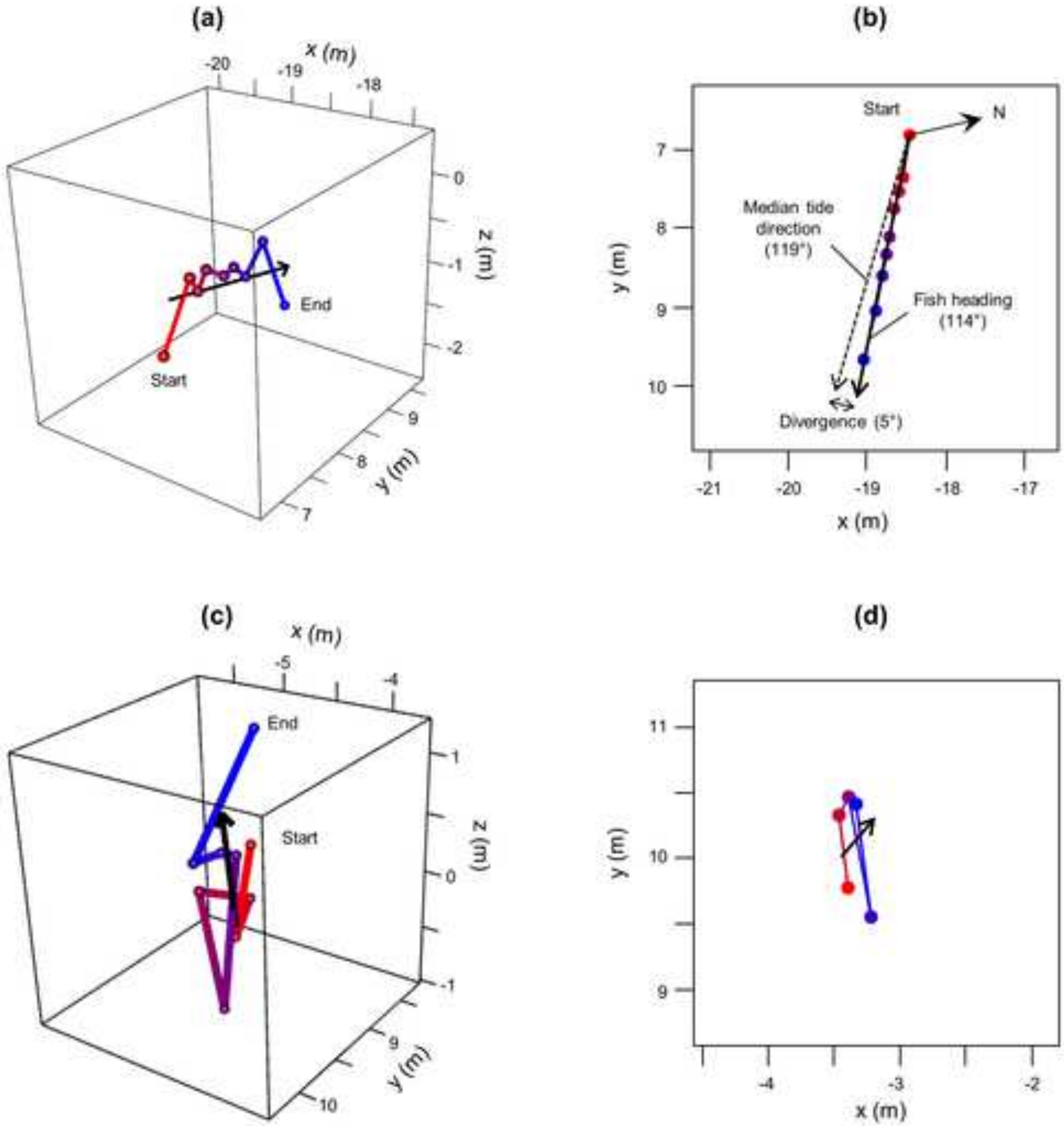
(a)
x (m)
-20
-19
-18
0
-1
-2
z (m)
End
Start
9
8
7
y (m)
(b)
Start
N
Median tide
direction
(119°)
Fish heading
(114°)
Divergence (5°)
7
8
9
10
y (m)
-21
-20
-19
-18
-17
x (m)
(c)
x (m)
-5
-4
End
Start
1
0
-1
z (m)
9
10
y (m)
(d)
11
10
9
y (m)
-4
-3
-2
x (m)

Fig 6

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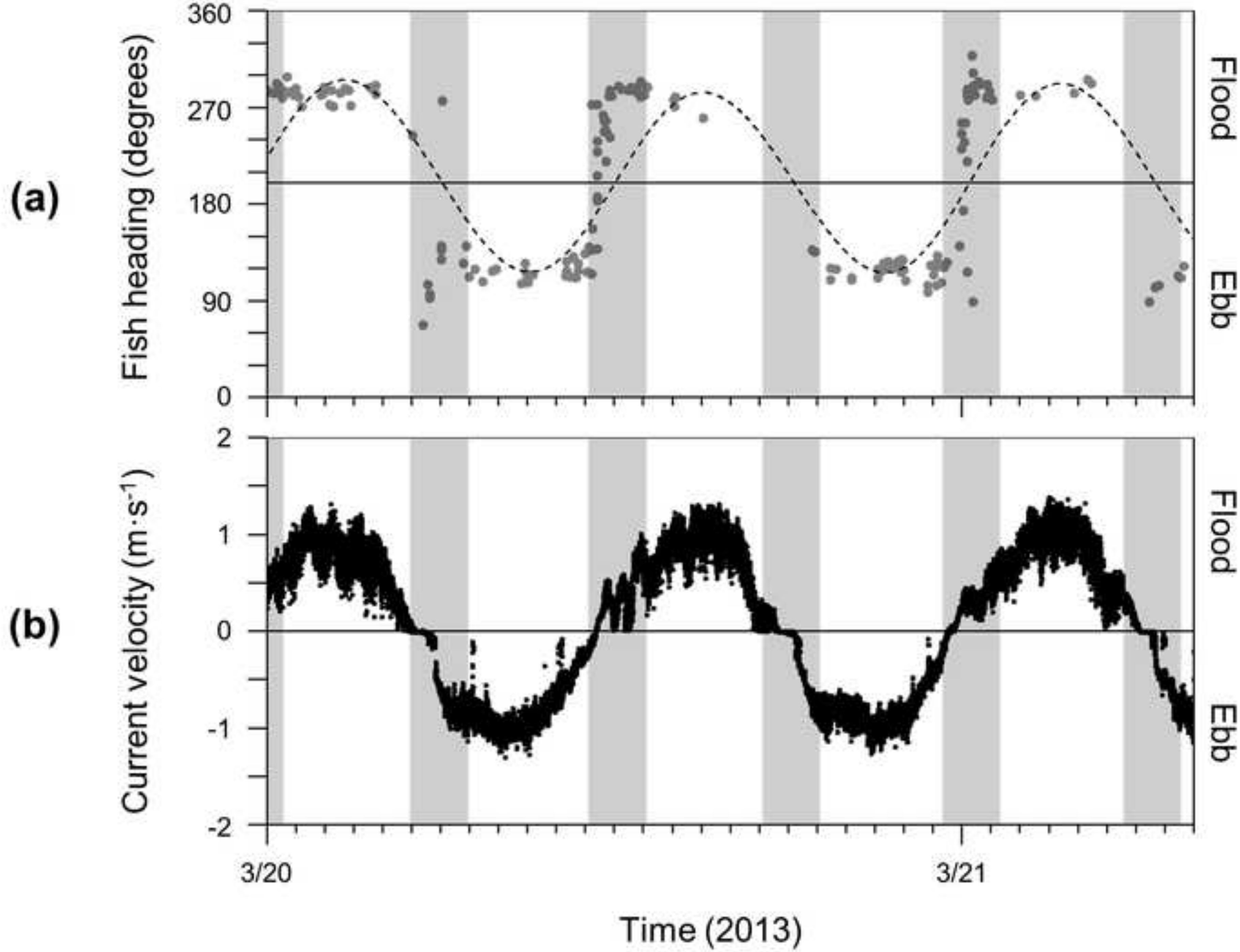

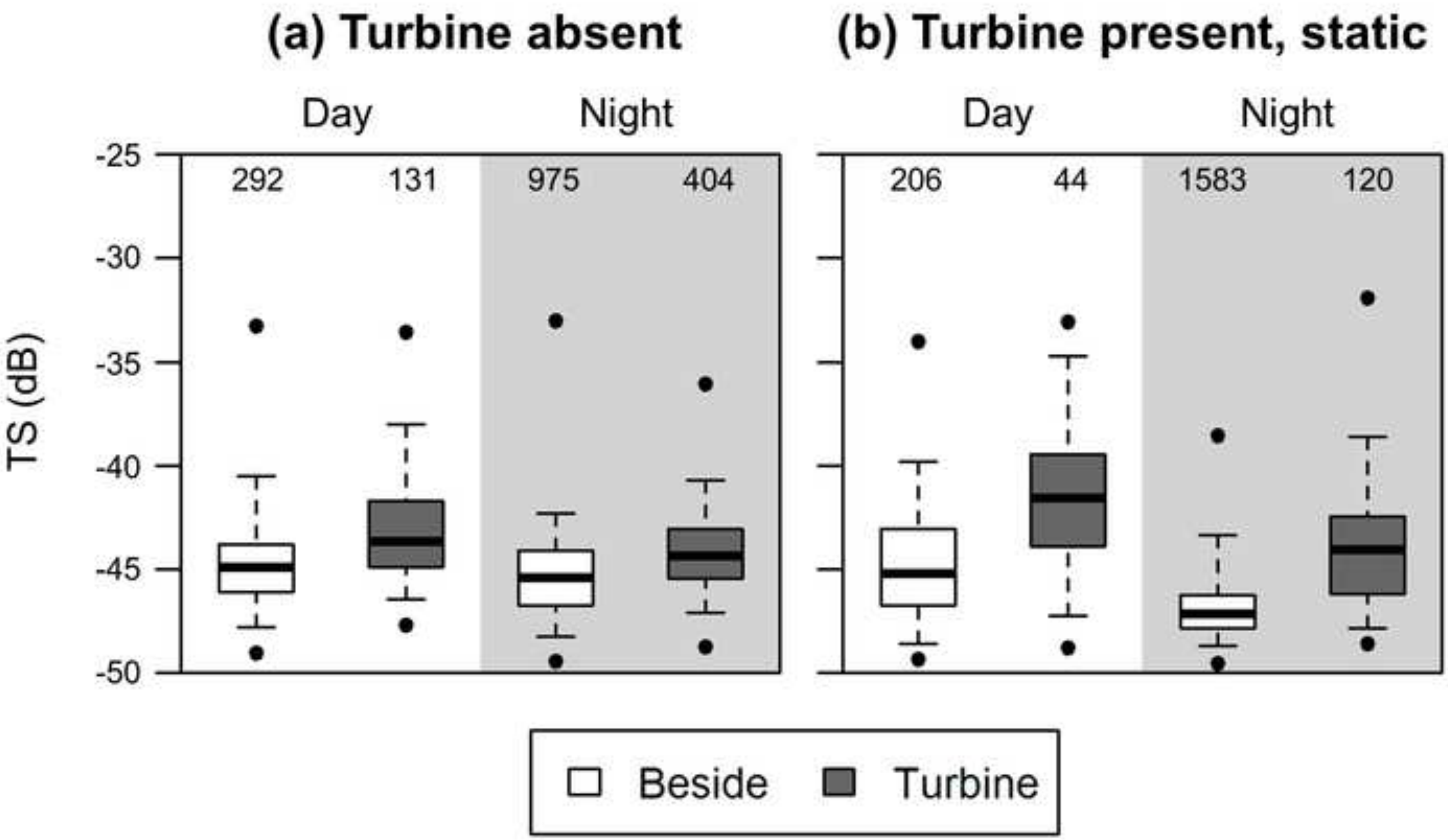
(a) Turbine absent
(b) Turbine present, static
Day
Night
Day
Night
-25
-30
-35
-40
-45
-50
TS (dB)
292
131
975
404
206
44
1583
120
Beside
Turbine

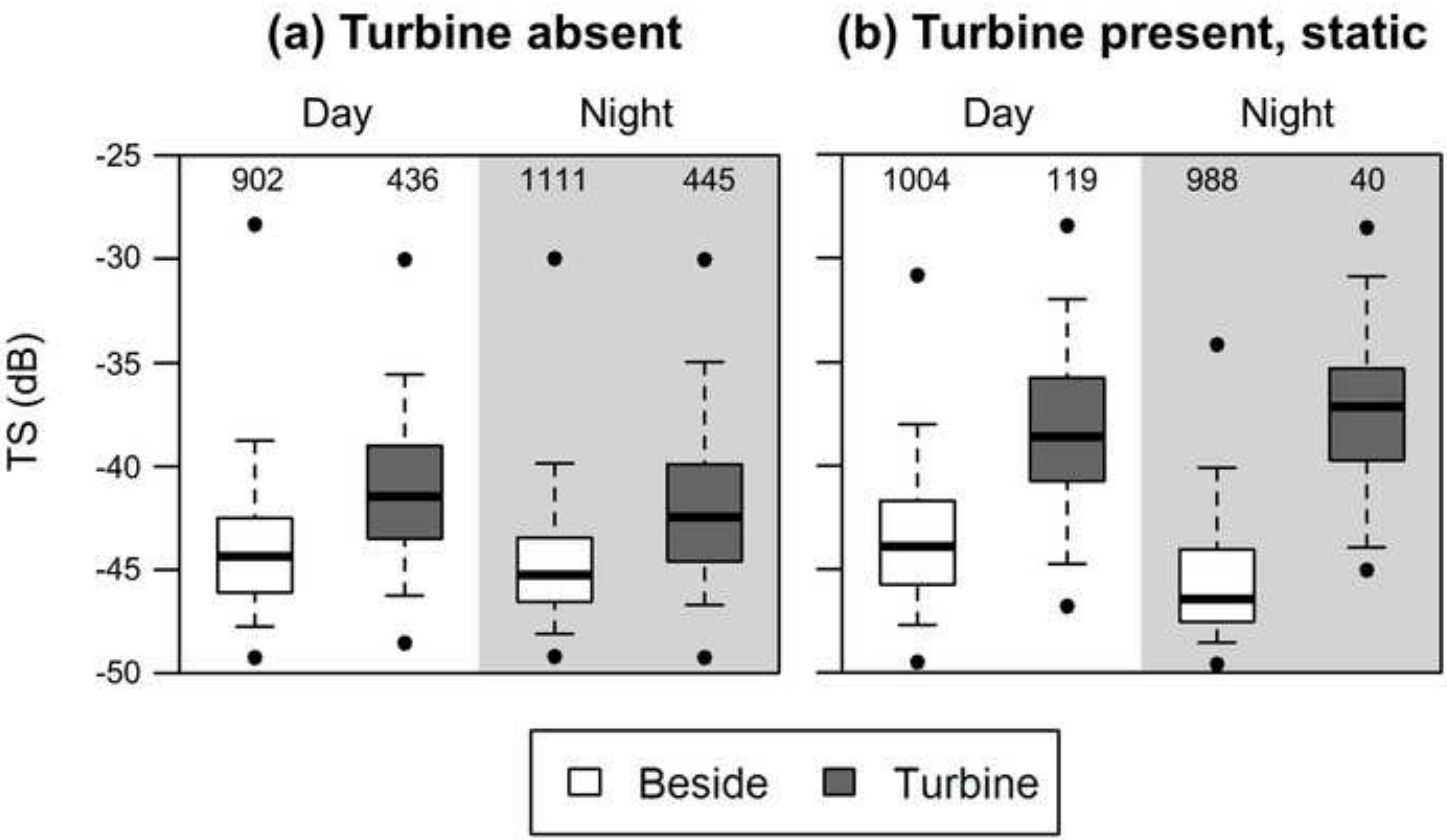
(a) Turbine absent
(b) Turbine present, static
Day
Night
Day
Night
-25
-30
-35
-40
-45
-50
TS (dB)
902
436
1111
445
1004
119
988
40
Beside
Turbine

Fig 9

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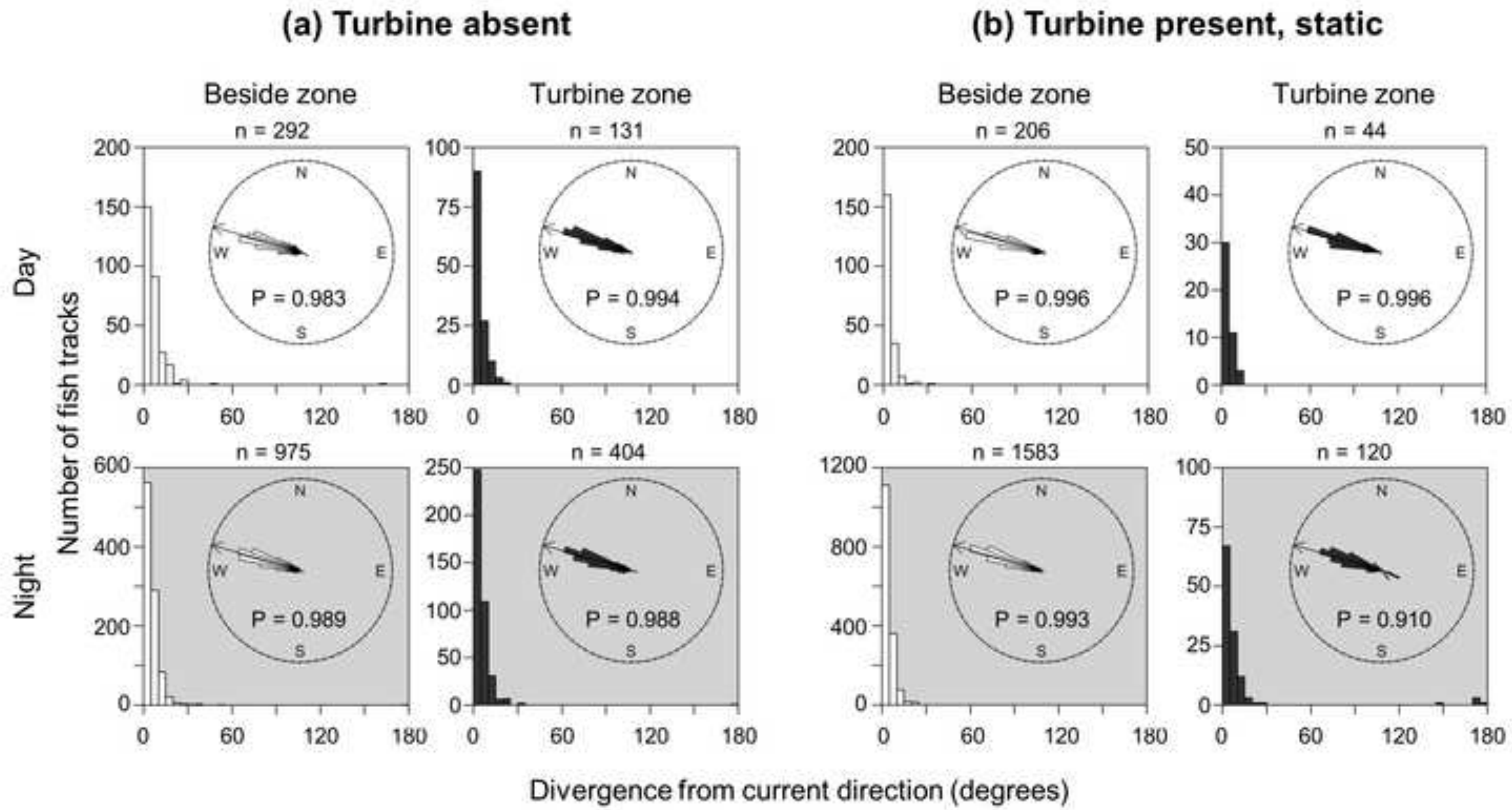

Fig 10

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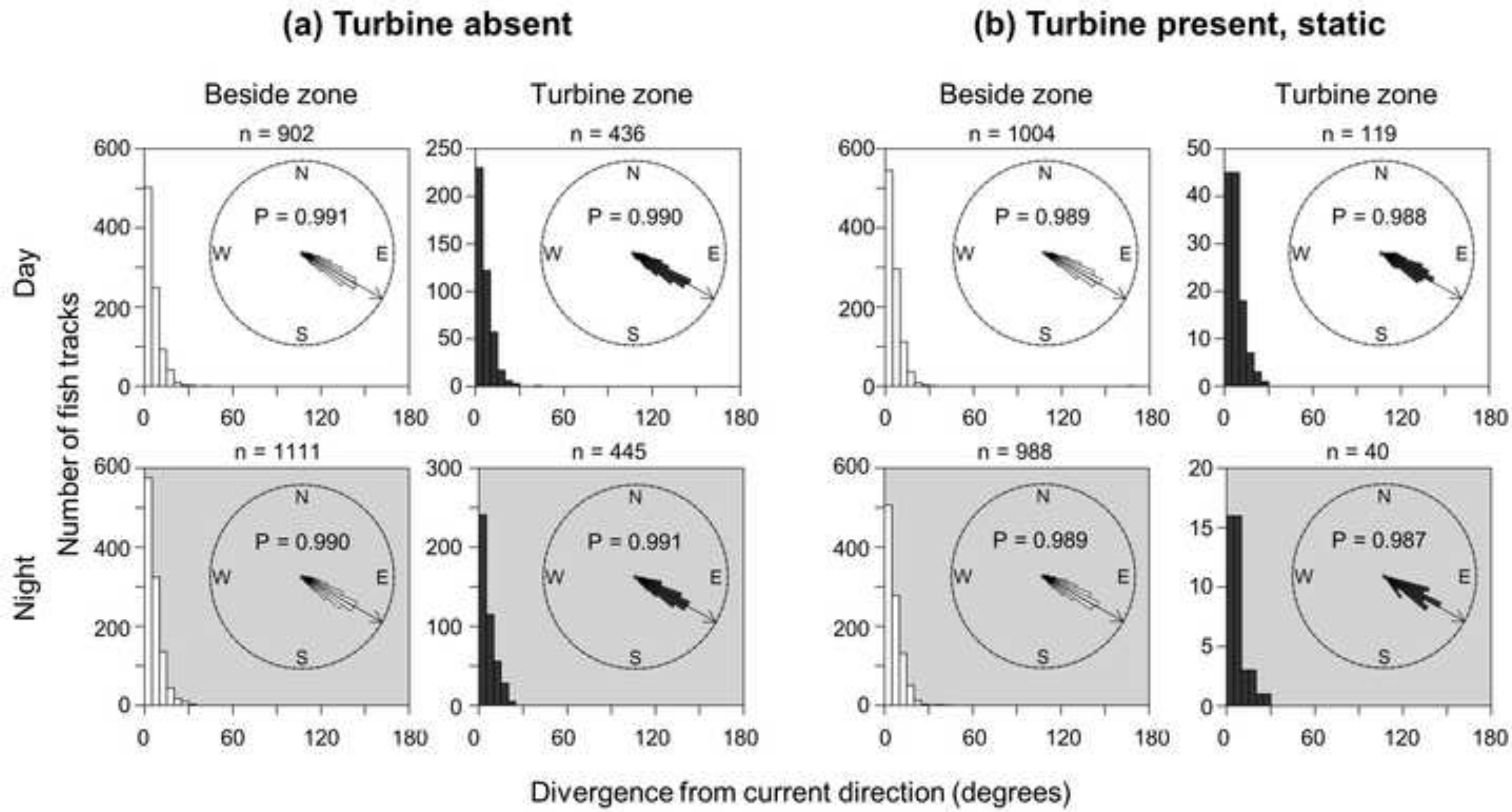

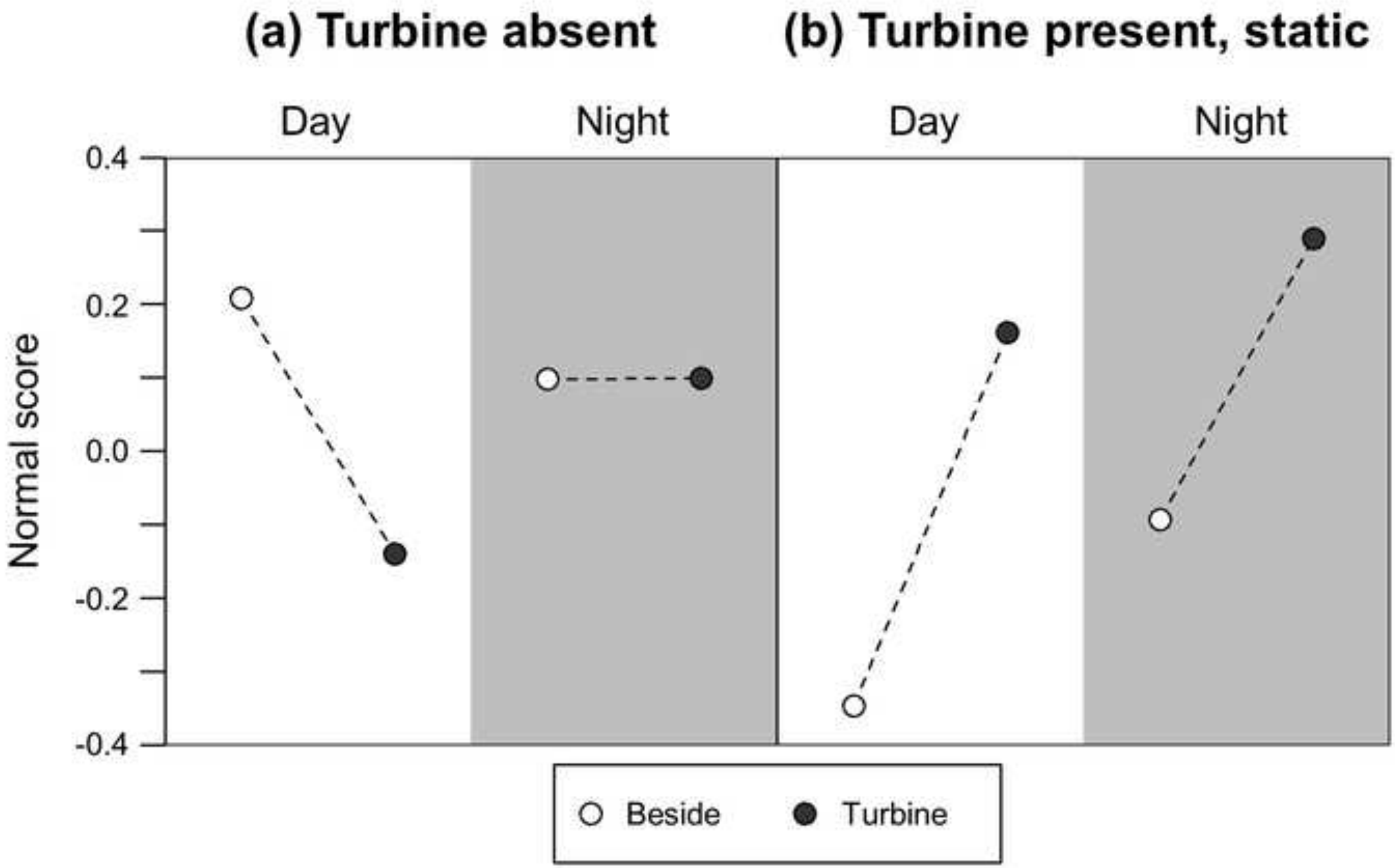
(a) Turbine absent
(b) Turbine present, static
Day
Night
Day
Night
Normal score
0.4
0.2
0.0
-0.2
-0.4
Beside
Turbine

PLOS ONE

Multi-scale temporal patterns in fish passage in a high-velocity tidal channel

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Abstract:	The natural variation of fish presence in high-velocity tidal channels is not well understood. A better understanding of fish use of these areas would aid in predicting fish interactions with marine hydrokinetic (MHK) devices, the effects of which are uncertain but of high concern. To characterize the patterns in fish presence at a tidal energy site in Cobscook Bay, Maine, we examined two years of hydroacoustic data continuously collected at the proposed depth of an MHK turbine with a bottom-mounted, side-looking echosounder. Fish passage rate maxima ranged from hundreds of fish per hour in the early spring to over 1,000 fish per hour in the fall. Rates varied greatly with tidal and diel cycles in a seasonally changing relationship, likely linked to the seasonally changing fish community of the bay. In the winter and spring, higher passage rates were generally confined to ebb tides and low slack tides near sunrise and sunset. In summer and fall of each year, the highest fish passage rates transitioned to night and occurred during ebb, low slack, and flood tides. Fish passage rate was not linked to current speed, and did not decrease as current speed increased, contrary to observations at other tidal power sites. As fish passage rate may be proportional to the encounter rate of fish with an MHK turbine at the same depth, highly variable passage rates indicate that the risk to fish is similarly variable. The links between fish presence and environmental cycles at this site will likely be present at other locations with similar environmental forcing, making these observations useful in predicting potential fish interactions at tidal energy sites worldwide.
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Competing Interests You are responsible for recognizing and disclosing on behalf of all authors any competing interest that could be perceived to bias their work, acknowledging all financial support and any other relevant financial or non-financial competing interests. Do any authors of this manuscript have competing interests (as described in the PLOS Policy on Declaration and Evaluation of Competing Interests)? **If yes**, please provide details about any and all competing interests in the box below. Your response should begin with this statement: *I have read the journal's policy and the authors of this manuscript have the following competing interests:* **If no** authors have any competing interests to declare, please enter this statement in the box: "*The authors have declared that no competing interests exist.*" * typeset	The authors have declared that no competing interests exist.
Ethics Statement You must provide an ethics statement if your study involved human participants, specimens or tissue samples, or	The study was conducted in accordance with the Fisheries and Marine Life Monitoring Plan required in Ocean Renewable Power Company's (ORPC's) Federal Energy Regulatory Commission (FERC) Pilot License, Cobscook Bay Tidal Energy Project, P-12711. Other permits obtained by ORPC for use of the Cobscook Bay site included the Maine

vertebrate animals, embryos or tissues. All information entered here should **also be included in the Methods section** of your manuscript. Please write "N/A" if your study does not require an ethics statement. **Human Subject Research (involved human participants and/or tissue)** All research involving human participants must have been approved by the authors' Institutional Review Board (IRB) or an equivalent committee, and all clinical investigation must have been conducted according to the principles expressed in the Declaration of Helsinki. Informed consent, written or oral, should also have been obtained from the participants. If no consent was given, the reason must be explained (e.g. the data were analyzed anonymously) and reported. The form of consent (written/oral), or reason for lack of consent, should be indicated in the Methods section of your manuscript. Please enter the name of the IRB or Ethics Committee that approved this study in the space below. Include the approval number and/or a statement indicating approval of this research. **Animal Research (involved vertebrate animals, embryos or tissues)** All animal work must have been conducted according to relevant national and international guidelines. If your study involved non-human primates, you must provide details regarding animal welfare and steps taken to ameliorate suffering; this is in accordance with the recommendations of the Weatherall report, "The use of non-human primates in research." The relevant guidelines followed and the committee that approved the study should be identified in the ethics statement. If anesthesia, euthanasia or any kind of animal sacrifice is part of the study, please include briefly in your statement which substances and/or methods were applied.	Department of Environmental Protection's Maine Waterway Development and Conservation Act General Permit and Water Quality Certification, Eastport, #L-25468-35-A-N, and the Maine Department of Conservation's Submerged Land Lease #1684. Hydroacoustic data were collected at a tidal energy site in Cobscook Bay, ME, from July 15, 2013, to July 28, 2015 (Fig 1). The echosounder was installed by Ocean Renewable Power Company (ORPC) to observe fish behavior near ORPC's TidGen® tidal energy device, which was deployed at the site from August 2012 to July 2013. The use of this location by ORPC was authorized by the Federal Energy Regulatory Commission (FERC), the Maine Department of Environmental Protection, and the Maine Department of Conservation.

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Please describe where your data may be found, writing in full sentences. **Your answers should be entered into the box below and will be published in the form you provide them, if your manuscript is accepted.** If you are copying our sample text below, please ensure you replace any instances of XXX with the appropriate details. If your data are all contained within the paper and/or Supporting Information files, please state this in your answer below.	Data are from the DOE study DE-EE0006384. Contact Gayle Zydlewski at gayle.zydlewski@maine.edu.

For example, “All relevant data are within the paper and its Supporting Information files.” If your data are held or will be held in a public repository, include URLs, accession numbers or DOIs. For example, “All XXX files are available from the XXX database (accession number(s) XXX, XXX)." If this information will only be available after acceptance, please indicate this by ticking the box below. If neither of these applies but you are able to provide details of access elsewhere, with or without limitations, please do so in the box below. For example: “Data are available from the XXX Institutional Data Access / Ethics Committee for researchers who meet the criteria for access to confidential data.” “Data are from the XXX study whose authors may be contacted at XXX.” * typeset	
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6 October 2016

PLOS One

Dear Editor:

I am writing on behalf of myself and coauthor, Gayle B. Zydlewski, concerning the manuscript entitled "*Multi-scale temporal patterns in fish passage in a high-velocity tidal channel.*" In this manuscript, we present a high-resolution, long-term time series of fish presence in a tidal channel targeted for tidal energy development. Time series like these are rare in the realm of fish biology, and this work was a unique opportunity to examine fluctuations in fish presence on a wide range of time scales, from hours to years. This improves our understanding of fish use of such high-velocity areas, which are generally understudied. This information is also valuable for understanding how the emerging tidal power industry may affect fish, which is an issue of high concern and uncertainty around the world. This manuscript adds to our previous studies revolving around the tidal energy device that was installed in Cobscook Bay, Maine, but our results have applications at tidal power sites around the world. The content of this manuscript is relevant to the focus of this journal.

Both coauthors fully participated in and accept responsibility for the work submitted. The manuscript is one chapter of my PhD dissertation. It has **not** been submitted to another journal and has **not** been considered for another journal.

Some potential reviewers include: Beth Scott (b.e.scott@abdn.ac.uk, University of Aberdeen, Aberdeen, Scotland), Dale Jacques (djacques@uw.edu, University of Washington, Seattle, WA), and Samuel Urmy (samuel.urmy@stonybrook.edu, Stony Brook University, Stony Brook, NY).

Sincerely,

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Multi-scale temporal patterns in fish passage in a high-velocity tidal channel

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Author Contributions

Conceived and designed experiment: HV, GBZ. Performed experiments: HV, GBZ. Processed the data: HV. Analyzed the data: HV. Wrote the paper: HV, GBZ. One chapter of the dissertation of HV with GBZ as advisor.

Abstract

The natural variation of fish presence in high-velocity tidal channels is not well understood. A better understanding of fish use of these areas would aid in predicting fish interactions with marine hydrokinetic (MHK) devices, the effects of which are uncertain but of high concern. To characterize the patterns in fish presence at a tidal energy site in Cobscook Bay, Maine, we examined two years of hydroacoustic data continuously collected at the proposed depth of an MHK turbine with a bottom-mounted, side-looking echosounder. Fish passage rate maxima ranged from hundreds of fish·hr^{-1} in the early spring to over 1,000 fish·hr^{-1} in the fall. Rates varied greatly with tidal and diel cycles in a seasonally changing relationship, likely linked to the seasonally changing fish community of the bay. In the winter and spring, higher passage rates were generally confined to ebb tides and low slack tides near sunrise and sunset. In summer and fall of each year, the highest fish passage rates transitioned to night and occurred during ebb, low slack, and flood tides. Fish passage rate was not linked to current speed, and did not decrease as current speed increased, contrary to observations at other tidal power sites. As fish passage rate may be proportional to the encounter rate of fish with an MHK turbine at the same depth, highly variable passage rates indicate that the risk to fish is similarly variable. The links between fish presence and environmental cycles at this site will likely be present at other locations with similar environmental forcing, making these observations useful in predicting potential fish interactions at tidal energy sites worldwide.

Keywords

Fish, hydroacoustics, time series, wavelet analysis, marine hydrokinetic, tidal energy, tidal currents

Introduction

Relatively little is known about how fish use areas with fast tidal currents. Fish activity levels and movement patterns vary on a wide range of spatial and temporal scales over the course of their lives, often in ways that are species- and life-stage specific (Pittman and McAlpine 2001, Reebs 2002, Gibson 2003). Many fish movements are related to environmental changes; for example, vertical migrations linked to the diel cycle, tidal movements into the intertidal zone, or seasonal movements on- or off-shore (Pittman and McAlpine 2001). In the high-velocity channels targeted for tidal energy extraction, underwater conditions change rapidly and fish presence and distribution likely fluctuates with similar magnitude and frequency. For example, there is already well-established evidence of some fish species changing their location in the water column to take advantage of favorable tidal currents in on- or off-shore migrations, a behavior known as selective tidal stream transport (Forward and Tankersley 2001). However, we lack data with sufficient temporal resolution and duration to fully describe the wide-ranging scales of temporal variation in fish presence in these environments.

The resolution and duration of a study aiming to describe the temporal distribution of marine organisms would ideally be defined relative to the highest- and lowest-frequency cycles present: for sampling to be considered high-resolution, sampling would ideally occur at several times the frequency of the highest-frequency cycle present, and a long-term study would sample for several times the duration of the lowest-frequency cycle (Heath et al. 1991). However, studies must typically be designed to focus either on resolution or duration, rather than both (Urmy et al. 2012), because of cost or gear limitations (such as soak time for nets). Many high-resolution studies occur over the short-term (e.g., Embling et al. 2012, Axenrot et al. 2004, Simard et al.

2002, Zamon 2003, Gibson et al. 1996, Heath et al. 1991). Some have sought to characterize both short- and long-term variability by carrying out multiple short-term, high-resolution surveys over a long period of time (Viehman et al. 2015, Vieser 2014). Prior assumptions about patterns present in the variable of interest influence study design and can greatly restrict the scope of results (Heath et al. 1991).

Long-term, high-resolution sampling has been less common, but is ideal for understanding biological processes at sites where large changes may occur over multiple, wide-ranging time scales. One method of sampling large volumes of water rapidly for long periods of time is stationary hydroacoustics. Long-term stationary echosounder deployments have been used to examine the temporal variability of different biological sound scatterers in the ocean, including phytoplankton and zooplankton (Flagg et al. 1994), zooplankton (Cochrane et al. 1994, Picco et al. 2016), and zooplankton and fish (Urmy et al. 2012). These studies all found their pelagic subjects to be linked to changes in their physical environment on a variety of time scales, including tidal, diel, and/or seasonal cycles, and these patterns were generally not constant over the duration of sampling time.

Transient patterns are a common characteristic of biological processes, and wavelet analysis is an effective tool for detecting and describing such patterns (Cazelles et al. 2008). Wavelet analysis works by simultaneously decomposing time series data across both the frequency and time domains. Blauw et al. (2012) used wavelets to explore the patterns present in their time series related to phytoplankton, as well as to relate phytoplankton growth with the tidal cycle and suspended particulate matter. Urmy et al. (2012) applied wavelets in part of their assessment of changing patterns in nekton density and vertical distribution. Apart from Urmy et al., the use of wavelets in studies of marine fish has been primarily to assess patterns in fishery catch rates and relate them to climatic oscillations, which occur on long time scales relative to what is pertinent in a tidal channel (Rouyer et al. 2008, Ménard et al. 2007).

In this study, we used wavelet analysis to describe the temporal variation in fish passage rate in Cobscook Bay, Maine. Data collection occurred at a site evaluated for tidal energy development, where an echosounder had been installed on the seafloor to monitor fish encounter with a marine hydrokinetic (MHK) turbine. After the turbine's removal, the echosounder continued to operate, and we detected fish in 2 years of high-resolution hydroacoustic data collected at turbine depth. Our goals were to obtain a better understanding of fish presence in this portion of the water column of this high-speed tidal channel, and to consider the implications of our findings for potential turbine effects.

Methods

Data Collection

Hydroacoustic data were collected at a tidal energy site in Cobscook Bay, ME, from July 15, 2013, to July 28, 2015 (Fig 1). The echosounder was installed by Ocean Renewable Power Company (ORPC) to observe fish behavior near ORPC's TidGen® tidal energy device, which was deployed at the site from August 2012 to July 2013. The use of this location by ORPC was authorized by the Federal Energy Regulatory Commission (FERC), the Maine Department of Environmental Protection, and the Maine Department of Conservation. The transducer was oriented to sample the area along the face of the TidGen® turbine (Fig 2), and though the turbine was removed in July 2013, the echosounder continued to collect data while the turbine was not present. The Simrad EK60 echosounder used a 200 kHz, 7° split beam transducer, which was mounted 3.4 m above the sea floor and 44.5 m from the turbine's support frame, and angled 6.2° above horizontal. The echosounder sampled an approximately conical volume of water 5 times (pings) per second, using a pulse duration of 0.256 ms and transmit power of 120 W. The current flowed approximately perpendicular to the sampled volume, and speed in the channel can range from 0 to approximately 2 $m \cdot s^{-1}$, depending on the tide and lunar phase (Viehman et al. 2015, Xu et al. 2006, Brooks 2006). Most fish moved with the current and were therefore detected by several sequential pings as they passed through the acoustic beam.

Fig 1. Map of study area with location of echosounder.

The echosounder operated nearly continuously for the two years it was deployed, but there were several gaps in data collection due to technical issues or necessary shut-down of the echosounder during turbine-related activities, such as diver inspection (Fig 3). The final dataset included 582 days of data. However, not all of these data were complete: at times, the angular information associated with detected fish was not returned, which meant 3D positioning of fish within the beam during these times was not possible (Fig 3).

Fig 2. Echosounder setup in Cobscook Bay, Maine. The bottom support frame of Ocean Renewable Power Company's TidGen® device was present during data collection. The gray area indicates the sampled volume used in this study. TidGen® schematic provided by Ocean Renewable Power Company.

Fig 3. Periods of continuous data collection. 2D denotes data which did not always include angular information, which were used for obtaining fish counts; 3D denotes data which did include angular information, which were used for determining times of slack tide (description in text).

Data Processing

Acoustic data were processed using Echoview® software (6.1, Myriax, Hobart, Australia). Processing consisted of noise removal, fish tracking, and fish track export. Fish tracking was carried out both in 2D (which uses only time and range of single targets to detect fish) and 4D (which uses time, range, and position in the beam's cross-section). 4D tracking could only be carried out when 3D information was available, which left large gaps in the dataset (Fig 3). 2D tracking was therefore used to generate the time series of fish passage rates, as range and time information were returned whenever the echosounder was running. When angular data were available, fish were tracked in 4D in order to obtain accurate measures of fish target strength (TS), to verify fish counts supplied by 2D tracking, and to accurately model the tidal cycle using the direction traveled by fish (for identifying start and end times of tidal stages).

Noise removal

The acoustic data included several types of 'noise,' signal that was not from individual fish, which had to be removed before fish could be tracked. This noise included small, non-fish targets (e.g., large zooplankton), interference from the surface and entrained air near the surface, and schools of fish (in which individual fish cannot be accurately tracked). TS is a measure of the proportion of sound energy that is reflected back to the transducer by an object, and it is roughly proportional to the object's size. Applying a TS threshold of -50 dB eliminated most signal from small, non-fish targets, and roughly equates to a fish length of 4 cm (though fish TS varies greatly with anatomy and orientation relative to the beam; Love 1971). Surface interference was removed by limiting the maximum analysis range to 64 m, which is the range at which entrained air from the surface began heavily interfering with the acoustic signal.

Background noise tended to increase with range but varied over time with water height and weather conditions. This type of gradually changing noise was removed using the method developed by De Robertis and Higginbottom (2007), modified to apply to TS data. Intermittent noise such as schools and clouds of entrained air was removed using multiple resampling and masking steps with Echoview® virtual operators. All of these methods were worked into a template that was then applied to all data using Echoview®'s scripting module (Fig 4).

Fig 4. Acoustic data processing example. (a) Raw target strength data (scale in dB to right) showing multiple fish tracks and background noise. (b) Target strength data with noise removed and -50 dB TS threshold applied. (c) Single targets detected from cleaned target strength data with fish tracks (colored lines) overlaid.

Fish tracking

Once noise was removed from the acoustic data, single targets were detected and fish were tracked using both split beam (4D) and single beam (2D) methods (single target detection and fish tracking parameters shown in Table 1). As mentioned above, both tracking methods were used because of the intermittent angular data. Split beam single target detection and 4D-fish tracking rely on these angular data to determine if each echo was caused by a single object or multiple, and to correct TS values for beam pattern effects. Single beam single target detection and 2D fish tracking methods do not incorporate angular data. While this can result in less accurate fish tracking and TS estimates, in this case it provided a more complete time series of fish passage rates. Fish tracked via single beam, 2D methods were therefore used to construct the time series of passage rate, and split-beam, 4D methods were used to supplement our interpretation of this time series, providing estimates of fish TS and fish swimming direction (as an indicator of tidal stage), and verifying temporal patterns in the time series made from fish tracked in 2D.

All tracks were exported for further analysis in R (3.1.1, R Core Team, Vienna, Austria).

Table 1. Echoview® acoustic data processing parameters

Process	Parameter	Value
Single target detection: single beam method 2	TS threshold	-50 dB
	Pulse length determination level	6.00 dB
	Min. normalized pulse length	0.50
	Max. normalized pulse length	2.00
Single target detection: split beam method 2	TS threshold	-50 dB
	Pulse length determination level	6.00 dB
	Min. normalized pulse length	0.20
	Max. normalized pulse length	2.00
	Beam compensation model	Simrad LOBE
	Max. beam compensation	12.00 dB
	Max. standard deviation of:	
	Minor-axis angles	0.5°
	Major-axis angles	0.5°
	Minor-axis angle range	-2.5° - 2.5°
	Major-axis angle range	-2.5° - 2.5°
Fish tracking: 2D	Data	2D
	Alpha (range)	0.8
	Beta (range)	0.5
	Exclusion distance (range)	0.5 m
	Missed ping expansion (range)	0 %
	Weights:	
	Range	0
	TS	0
	Ping gap	0
	Min. number of single targets in a track	5
	Min. number of pings in a track	5 pings
	Max. gap between single targets	3 pings
Fish tracking: 4D	Data	4D
	Alpha (major, minor, range)	0.7, 0.7, 0.8
	Beta (major, minor, range)	0.5, 0.5, 0.5
	Exclusion distance (major, minor, range)	1.5, 1.5, 0.5 m
	Missed ping expansion (major, minor, range)	0, 0, 0 %
	Weights:	
	Major axis	0
	Minor axis	0
	Range	0
	TS	0
	Ping gap	0
	Min. number of single targets in a track	5
	Min. number of pings in a track	5 pings
	Max. gap between single targets	3 pings

Data analysis

Data analysis included time series construction, time series gap-filling, the wavelet transform, and tidal stage modeling. The TS of fish tracked with 4D methods was summarized with median and interquartile range, but closer examination was avoided due to the mixed nature of the fish assemblage in Cobscook Bay and our inability to identify the species of each detected fish.

Time series construction

The time associated with each tracked fish was used to acquire counts of fish in 1-hr time increments, equating to a rate of fish passage through the sampled volume with units of fish·hr^{-1}.

Gap-filling

Before the time series could be used in wavelet analysis, the gaps in the data needed to be filled by new values which would minimally impact subsequent temporal pattern analysis. This was done by mimicking the temporal patterns of the time series to the sides of each gap. For each gap, a Fourier transform was used to identify the most prevalent frequencies in the data within one gap-width before and after the gap (or 48 hours, if the gap was shorter). The upper 50% of the most important frequencies were chosen, which allowed the number of frequencies used to vary with gap size and mimicked the nearby data well. For each set of data from before and after a gap, the selected frequencies were used to construct a model of fish passage rate in the form:

$$y = \sum_{i=1}^{N} A_i \sin(2\pi f_i t) + B_i \cos(2\pi f_i t) + \varepsilon$$

where y is modeled fish passage rate, f_i is the i^{th} frequency of the N frequencies selected via the Fourier transform method, A_i and B_i are amplitudes, and ε is random error. Coefficients A and B and residual error values were obtained by fitting a linear model of the above form to data before and after the gap. Passage rate was predicted for each time point within the gap using both models, the results of which were weighted and summed: values from the before-gap model were weighted by 1-1/j, where j was the index of the predicted data point; data from the after-gap model were weighted in an opposite fashion. Though residual error was useful in evaluating each model's fit, error was not added to the predicted gap values. Introducing random error based on residuals simply exaggerated high-frequency noise within gaps that was uncharacteristic of the rest of the dataset, and this omission did not significantly alter results.

Wavelet transform

Once gaps in the time series were filled, a wavelet transform was used to inspect patterns in passage rate and how they changed over time. Wavelet transforms simultaneously decompose time series data across both the frequency and time domains by convolving the time series with a wave form (the 'wavelet'), which is scaled up or down within a chosen range as it is moved along the time axis. The result is a wavelet spectrum: a 2D representation of the prevalence of periodicities ($frequency^{-1}$) that compose the original time series, across the time spanned by the dataset (2 years, in this case). We applied a continuous wavelet transform using the Morlet wavelet to our time series of fish passage rate (package *WaveletComp* in R; Roesch and Schmidbauer 2014). The maximum frequency included was 2 times the sampling frequency (a periodicity of 2 hours), as this would be the highest possible frequency that could theoretically be characterized (i.e., the Nyquist frequency). The maximum periodicity was limited to one-half of the total sampling period (1 year) because larger periodicities are overwhelmed by edge effects. The wavelet spectrum was tested at a 95% confidence level against a theoretical spectrum of white noise fit to the series using 100 iterations.

Tidal stage modeling

Fish tracked using split-beam, 4D methods were used to indicate the tidal stage via their direction of movement. At this site, fish move almost exclusively in the direction of the current except at slack tides, when movement was more uniformly distributed for a brief period of time (Viehman and Zydlewski 2015, Viehman et al. submitted). Fish direction could therefore be used as a proxy for tidal current direction, which could indicate tidal stage. This correlation was verified by comparing predicted tidal stages to several instances of ADCP current speed data that were collected from a moored vessel at the same site during the study period (Fig 5). Shifts in fish swimming direction (Fig 5a) corresponded to slack tides as indicated by the ADCP data (Fig 5b). The square-wave pattern of fish movement direction was very similar to the measured and modeled current direction at a nearby location presented by Xu et al. (2006), and flood and ebb tide movement directions (approximately 285° and 120°, respectively) aligned well with the known current direction at our study site (ORPC personal communication).

Fig 5. Fish heading and current velocity collected at the TidGen® site in August 2014. (a) Individual fish heading (gray points) shown with fitted tidal model (solid line) and its midline (horizontal line), which were used to estimate times of slack tide (vertical dashed lines).   (b) Current speed collected concurrently by an ADCP at the same site, with same times of slack tide as shown in a.

As large gaps existed in the 3D acoustic data, and therefore in the swimming directions available for tidal stage assignment, a tidal model was fit to existing fish direction data which could then be used to accurately predict tidal stage, even when 3D data were missing (thick solid line in Fig 5a). This tidal model was a summation of multiple sinusoids with varying periodicities, including the ten tidal components that have been used in shorter-term modeling studies of Cobscook Bay tidal currents (M2, K1, K2, N2, S2, O1, L2, M4, NU2, 2N2; Rao et al. 2015) and five other tidal periodicities that would be relevant to this 2-year span (P1, Q1, MF, MM, SSA). The model was constructed as for the gap-filling step, except in this case f_i was the i^{th} tidal frequency of the 15 tidal components listed above (frequency = period^{-1}). Amplitudes A and B were obtained by fitting a linear model of the above form to the available fish direction data from the 3D dataset. The sinusoid peaks were defined as peak flood tides, the troughs were peak ebb tides, and slack tides (high or low) occurred wherever the sinusoid crossed its midline (Fig 5a).

Results

Target strength

The median target strength estimated from fish tracked using the 4D method was -45.1 dB, with an interquartile range of -46.5 to -43.4 dB. Using Love's (1971) general TS-length equation, this corresponds to a median fish length of approximately 6 cm, with an interquartile range of 5 to 7 cm.

Time series

Passage rates determined through 2D and 4D tracking methods agreed well with each other (Fig 6). Counts obtained via 2D methods were slightly higher than those obtained using 4D methods due to the less stringent target quality requirements of 2D tracking (Fig 6a), but when data were available in both datasets, the patterns were the same (Fig 6b).

Fig 6. Comparison of fish passage rates (fish per hour) obtained via 2D and 4D tracking. (a) 4D rates vs. 2D rates, shown with 1:1 line. (b) Subset of 2D (solid line) and 4D (dashed line) passage rates from October 2014.

Fish passage rate varied greatly over the two years spanned by the dataset, on both short and long time scales (Fig 7a). Overall, passage rate was highest in late summer and fall of both years, reaching over 1000 fish·hr^{-1}. During winter and spring, rate maxima were in the hundreds of fish·hr^{-1}. Passage rate could increase from 0 to hundreds of fish·hr^{-1} in a matter of hours, and it was evident that this variation was cyclic in nature (Fig 6b, Fig 7a). Values generated to fill the 20 gaps that existed in the 2D dataset appeared consistent with patterns in the surrounding data (Fig 7a) and were unlikely to interfere with interpretation of the wavelet spectrum.

Wavelet transform

The wavelet transform (Fig 7b) revealed the presence of a 365-day periodicity, which is indicative of the seasonal cycle that was evident in the raw time series (Fig 7a). This seasonal change in passage rate slightly lagged the seasonal change in temperature, with lowest rates in between winter and spring (e.g., March) and highest rates in the fall (August through November). A continuous band in the wavelet transform at the 183-day periodicity and fainter, less continuous bands at around 14 and 28 days were also present, and coincided with tidal periodic components (Rao et al. 2016).

The strongest features of the wavelet transform were bands near 12- and 24-hr periods, which indicated variation in fish passage rate related to the tidal (and/or semi-diel) and diel cycles. These two periodicities were not constant throughout the dataset, but followed similar patterns in every year sampled, though with some variation in timing. The 24-hour periodicity was present only in the summer and fall, emerging in June in 2014 and 2015. The 12-hour periodicity was present throughout the year, but was most evident in the winter and spring (from January through May). For the rest of the year, the 12-hr periodicity was present but intermittent.

Fig 7. (a) Time series of fish passage rate (fish·hour^{-1}). Gaps in data that were filled using the method described in the text are shown in gray. Inset expands time series from July 2014. (b) Wavelet transform of log-transformed time series. Color indicates the magnitude of the wavelet power, with darker, redder colors indicating higher power. Black contours enclose areas of significance at the 5% significance level. The transparent white fill indicates the cone of influence, within which power values may be reduced by edge effects. Darkened rectangles indicate where gaps in the time series were filled. (c) Fish passage rates during each hour of each day of the time series, condensed here for easy comparison to a and b. An expanded version of c is shown in Fig 8. Darker, redder colors indicate higher passage rates. Horizontal curved lines indicate times of sunrise and sunset, and shaded rectangles indicate filled gaps in the time series.

Visual inspection of passage rate at each hour of the day (Fig 7c) revealed obvious changes in passage rate that corresponded with the presence and absence of 12- and 24-hr periodicities in the wavelet transform. When viewed in relation to tidal and diel stage (Fig 8), it was clear that fish passage rate varied with tidal and diel cycles in a seasonally shifting relationship. In the winter and spring of each year (from January through May), when the 12-hr periodicity was present but not the 24-hr, the highest rates occurred on the second half of the ebb tide and at low tide, mainly near sunrise and sunset but with no strong difference between day and night. In the summer (June through August), when both the 12-and 24-hr periodicities were evident, the highest passage rates began shifting to night and were still mostly associated with low tide, though sometimes in the second half of ebb or first half of flood. In the fall and early winter (September through December), the 24-hr periodicity became more prominent while the 12-hr periodicity became less consistent. At this time, passage rate was clearly higher at night than during the day, and the association with tidal stage was less clear, though the rate was generally lower at high tide than at ebb, low, and flood tides. Between December and January, this pattern in passage rate quickly returned to peaks at low or ebb tides at sunrise and sunset.

Fig 8. Fish passage rate at each hour of the day (rows) for every day of the time series (columns), which spans July 2013 to July 2015. Darker, redder colors indicate higher passage rates. Gaps in the time series (filled using method described in text) are indicated by darkened rectangles. Horizontal curved lines indicate time of sunrise and sunset. Points indicate times of low (open circles) and high (solid circles) slack tides. A condensed version of this figure is shown in Fig 7c.

Discussion

This high-resolution, long-term time series indicated that fish passage rate was highly variable and strongly linked to multiple cyclic changes in the physical environment, including tidal, diel, and seasonal cycles. This is not surprising, given the high-magnitude seasonal shifts and tidal forcing at this site, and that fish movements have been linked to such environmental changes in previous studies (Pittman and McAlpine 2001). The passage rate of fish varied most with tidal and diel cycle, but its relationship with these cycles did not remain constant over a year. Rate was linked strongly to the interaction of these two cycles in a relationship that varied with season. This adds to previous findings linking similarly interacting environmental cycles with fish presence and feeding in intertidal habitats (Krumme et al. 2008, Gibson et al 1996) and spatial distribution of fish and their predators and prey in tidal current systems (Simard et al. 2002, Embling et al. 2012, Zamon 2003).

All interactions of fish passage rate with the tidal cycle were modified by the diel cycle. In the winter through spring, the highest passage rates were confined to low slack and ebb tides, but within crepuscular periods. Higher rates shifted into night during the summer, expanding to flood and ebb tide in addition to low slack tide and remaining this way through the fall. These results are consistent with a previous study we carried out at this site, in which we conducted 24-hr surveys of fish density and vertical distribution using a downward-looking, vessel-mounted echosounder in March, May, June, September, and November 2011 (Viehman et al. 2015). In that study, we did not examine slack tides. However, we found that fish density was generally higher during the ebb tide than the flood tide in the first part of the year, and that this difference was less evident toward the end of the year. The vertical distribution of fish did not differ consistently between ebb and flood tide, so higher ebb- or flood-tide passage rates may be related to horizontal, rather than vertical, tidal fish movement. For example, fish may move between channel edge habitats and the middle of the channel based on flow direction, or be carried through different parts of the channel during ebb and flood tides on asymmetric flow paths.

The diel differences in passage rate which we observed, on the other hand, could have been related to changes in vertical fish distribution. Unlike tidal stage, our previous study of this site found consistent changes in fish vertical distribution related to diel stage: during the day, fish were more concentrated near the sea floor or surface, depending on time of year, but at night, fish spread out in the water column (Viehman et al. 2015). In that study, this difference was visually apparent in May, June, August, and September surveys, but not in March. In the present study, we sampled only the mid- or lower-water column (depending on water height). So, if the same diel shifts in vertical distribution were occurring during the present study period, from spring through fall most fish would have been outside of our sampled volume during the day but would have moved within view at night, and there would be little day-night difference in passage rate in the winter and early spring. This is consistent with our results, with higher passage rates occurring at night from June through December. However, the influence of diel cycle was not completely lacking in the winter and early spring, as passage rate consistently peaked near dawn and dusk when those times coincided with low or ebbing tides. Our previous work only compared day- and night-averaged vertical distributions, so we had not captured any changes in fish activity related to dawn and dusk. By expecting and searching for 24-hr diel differences in fish distribution at this site, we did not detect this crepuscular activity pattern that dominated for a large portion of the year. Prior assumptions such as this have likely constrained results in other studies of fish biology, as well (Heath et al. 1991), highlighting the utility of long-term, high-resolution data collection.

It is important to remember that only individual fish were included in this study, as individuals within schools could not be separated from their neighbors, and fish schools often could not be distinguished from patches of entrained air. Fish in schools were therefore omitted, which potentially affected the patterns in passage rate we were able to measure. For example, we previously observed that many dense schools are present in Cobscook Bay in the spring (Viehman et al. 2015, unpublished data), likely larval Atlantic herring (*Clupea harengus,* Vieser 2014). These schools contributed to high density indices in spring that were comparable to indices from the fall (Viehman et al. 2015, unpublished data). However, in the present study, passage rates in the spring were much lower than in the fall, which could have been due to the exclusion of these schools. Individually, larval herring may not be strong enough acoustic targets to be tracked with a -50 dB TS threshold, so even if schools were to spread out (e.g., at night; Heath et al. 1991, Ferreira et al. 2012), they would be unlikely to contribute to fish passage rate. However, many schooling fish species have been observed to spread out in lower light levels, including adult Atlantic herring (Blaxter 1985) and Atlantic mackerel (*Scomber scombrus*, Glass et al. 1986), both of which would be detectable above our TS threshold. These fish are present in the area in high numbers in the summer and fall (Vieser 2014, MacDonald et al. 1984), when the diel pattern in passage rate was strongest. It is possible that the diffusion and formation of schools of fish, such as herring and mackerel, could have influenced the observed passage rates. Ideally, schools would be included in this study, but to do so, new processing techniques to separate schools of fish from entrained air need to be developed.

Hydroacoustics could not reveal the species of fish at this site, but physical sampling that occurred from 2011 to 2014 (Vieser 2014, Zydlewski et al. 2016) indicated which species were likely present. These studies sampled the tidal channels of the bay with pelagic and benthic trawls and the intertidal areas with seine and fyke nets from spring to fall of each year. They found that Cobscook Bay has a diverse fish assemblage, with 46 species sampled, many of which have seasonal in- and off-shore movements in the Gulf of Maine (Bigelow and Schroeder 2002, Tyler 1971). Atlantic herring and winter flounder (*Pseudopleuronectes americanus*) were by far the most abundant species caught in the tidal channels, making up 59.6% and 27.1% of the catch (Vieser 2014). Most fish sampled were juveniles, with lengths agreeing well with the TS of fish detected in this study. Some larger fish were also likely present and able to avoid the trawls, such as adult Atlantic mackerel in the summer and fall. Four diadromous species, which have well-defined annual on- and off-shore movements related to spawning, were also captured: alewife (*Alosa pseudoharengus*), rainbow smelt (*Osmerus mordax*), blueback herring (*Alosa aestivalis*), and American eel (*Anguilla rostrata*). The life stages of some of the fish species sampled were also found to change seasonally: herring sampled in May and June were typically larval, while those sampled in August and September were juvenile or adult. Some of the patterns we observed could have been related to fish growing into the size ranges we sampled by setting a -50 dB TS threshold. For example, while individual larval herring (not schooling) may be too weak to detect, juvenile herring several cm long would likely be strong enough targets. If larval fish remain in Cobscook Bay and mature over the course of the spring and summer, their growth could contribute to the comparably higher passage rates observed in summer and fall.

The changing patterns in fish passage rate that we observed each year are also likely related to the seasonally changing fish assemblage of Cobscook Bay. Vertical and horizontal movement patterns of fish in response to environmental cues are often specific to species and life stage (Pittman and McAlpine 2001, Neilson and Perry 2001), and can change seasonally even for one species as fish respond to changing day length and temperature (Gibson et al. 1996). Though the vertical diel and tidal movements of most of the species present in Cobscook Bay (Vieser 2014) are not well known, particularly in such fast flows, a seasonally shifting fish assemblage is likely to result in seasonally shifting patterns in passage rates, such as those we observed. The presence of herring and mackerel in the summer and fall, for example, could have substantially contributed to the increase in night-time passage rates, e.g. due to school diffusion (Blaxter 1985, Glass et al. 1986) or diel vertical migrations (Huse and Korneliussen 2000, Nilsson et al. 2003) bringing more individuals into the sampled volume. Without the ability to separate acoustically detected fish by species, the unique movement pattern of any one species at this site is virtually impossible to separate from the combined movement patterns of all the others. In future studies of regions with diverse fish assemblages, it may be helpful to collect data with multiple acoustic frequencies to aid in distinguishing anatomically distinct groups of fish (Korneliussen and Ona 2004).

In the present study, we saw no consistent correlation between fish passage rate and current speed, and this has implications for potential MHK device effects. Previous work by Broadhurst et al. (2014) and Hammar et al. (2015) used video to observe fish interacting with MHK turbines at two other locations, and both studies concluded that fish were less abundant at high current speeds and therefore less likely to come in contact with moving turbine blades. This or any other consistent response to the tidal currents at our study site would have appeared in the wavelet transform as a strong band near the 6-hr periodicity, which was not the case. Instead, we observed that passage rate was frequently high during the flowing tides (not only at slack tides), particularly at night from summer through fall. If passage rate is assumed proportional to rate of encounter with an MHK turbine at the same depth, fish may be more likely to contact moving turbine blades than might be expected based on results of previous studies, particularly if combined with the finding by Viehman and Zydlewski (2015) that fish were less likely to evade an MHK turbine at night than during the day. However, this speculation should be balanced with the results of laboratory studies of fish entrained in MHK turbines, which found survival rates generally exceeded 90% (Amaral et al. 2015, Castro-Santos and Haro 2015). So, even if the rate of fish encountering and entraining in the MHK turbine is high, the magnitude of direct turbine effects such as blade strike may still be minimal. This is particularly true for small fish, such as those detected here: as fish size relative to blade diameter decreases, injury and mortality have also been found to decrease (Amaral et al. 2015).

The high temporal variability in fish passage rate also has implications for monitoring the effects of tidal energy turbines on fish. For example, to monitor near-field interactions of fish with an MHK device (e.g., direct strike by turbine blades), it would be best to focus sampling efforts on times with high passage rates and a rotating turbine. At this site, the best time to observe turbine interactions in the winter and spring would be near sunrise or sunset during the second half of ebb tide, and in the summer and fall, at night during either flood or ebb tide. Consideration should be given to the fish species and life stages that would be present at different times of the year, as they may all respond differently to an MHK device.

One approach to quantifying less direct MHK device effects is to monitor fish abundance in the area of a device before and during its deployment (Viehman and Zydlewski 2015, Staines et al. 2015). Unless monitoring can be continuous, as in this study, the high temporal variability in fish presence in such dynamic environments could influence results of long-term studies if they are not designed to consider these cycles. This must be kept in mind when interpreting results from tidal energy sites. For example, if our echosounder were duty-cycled to collect data for just a few hours of the month (and therefore reduce processing and analysis time substantially), samples occurring at low tide would be capturing higher passage rates relative to samples occurring at high tide. The timing of observations in relation to underlying cycles in fish presence, which are based on the environment and the behavioral responses of fish, could alias results and produce trends that are not actually there. It is important that results of such monitoring reflect actual trends in fish abundance. Overestimating effects on fish could harm this developing industry but underestimating effects could harm the marine ecosystem. Carrying out 24-hr surveys, which capture the high variation occurring over 12- and 24-hr cycles, spaced over time to characterize the seasonal cycle each year, would be a first step toward achieving accurate long-term monitoring results at tidal energy sites like this one. As more data are collected in the coming years, longer environmental cycles (e.g., climatic oscillations) will need to be taken into account, as they may also influence observed trends. This long-term variation would be difficult to characterize without studies spanning decades, but sampling a control or reference site alongside a tidal energy site would aid in separating this and other sources of natural variation from effects of MHK devices.

Results presented here are specific to one depth at one site, but they may be applicable to other tidal energy sites characterized by similarly high-magnitude environmental cycles. In strongly tidal channels frequented by valuable or endangered fish species (e.g., salmon in the northwest USA or Atlantic sturgeon in the northeast), observing passage rates with high temporal resolution could be very useful in predicting and mitigating MHK device effects. Fish passage rates at turbine depth could be combined with observations of close-range evasion behavior in the field, as well as fish injury and mortality rates obtained in laboratory settings, to estimate the effects of a single turbine on the fishes sharing its depth. When continuous or high-frequency sampling is not an option, known environmental cycles should be used to inform plans for monitoring turbine effects on fish, as well as the interpretation of study results. Better understanding of the effects of a single MHK device on individual fish may help us predict the effects of devices on fish populations as this new renewable energy industry moves toward the deployment of commercial-scale MHK device arrays.

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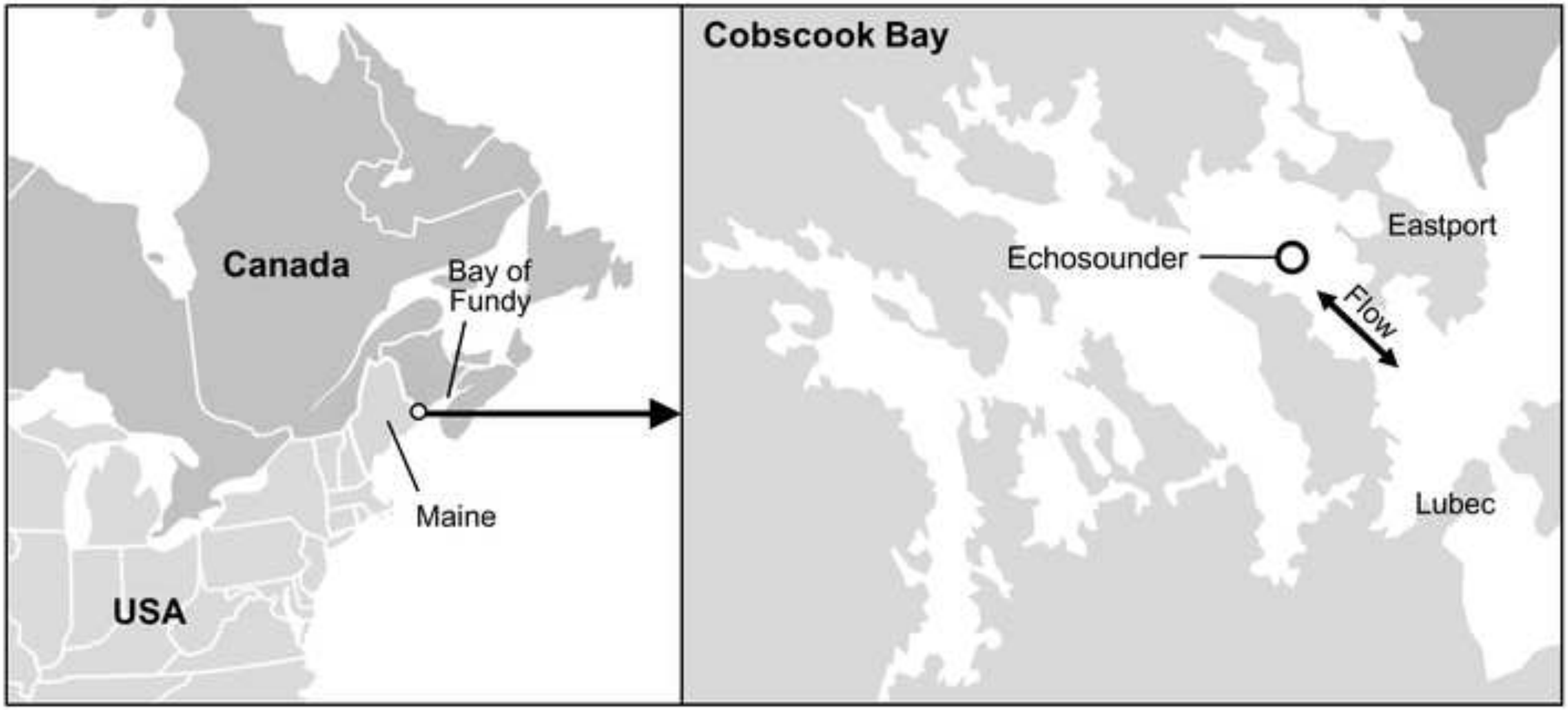

Figure 2

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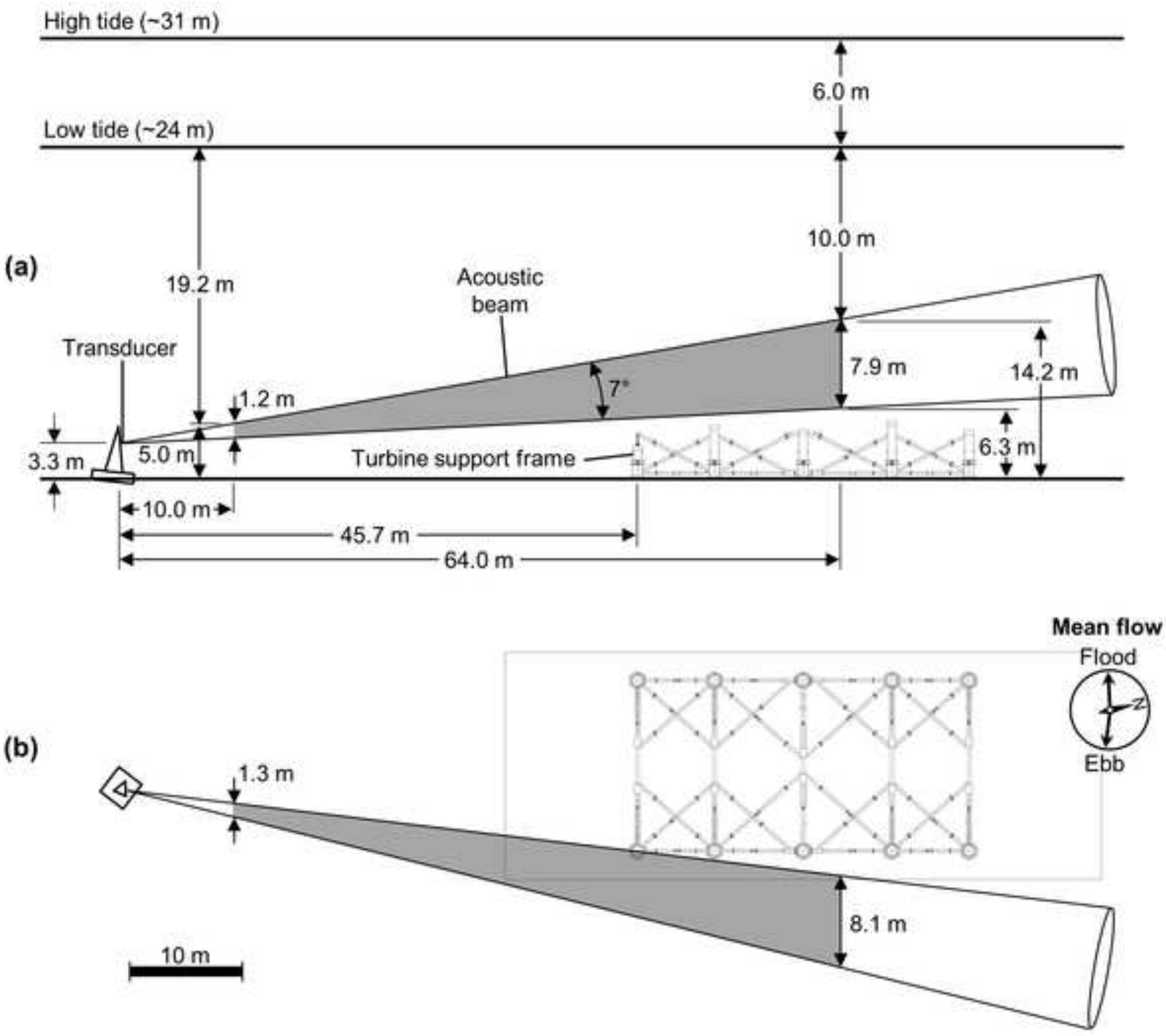

Figure 3

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Figure 4 Click here to download Figure Fig4.tif

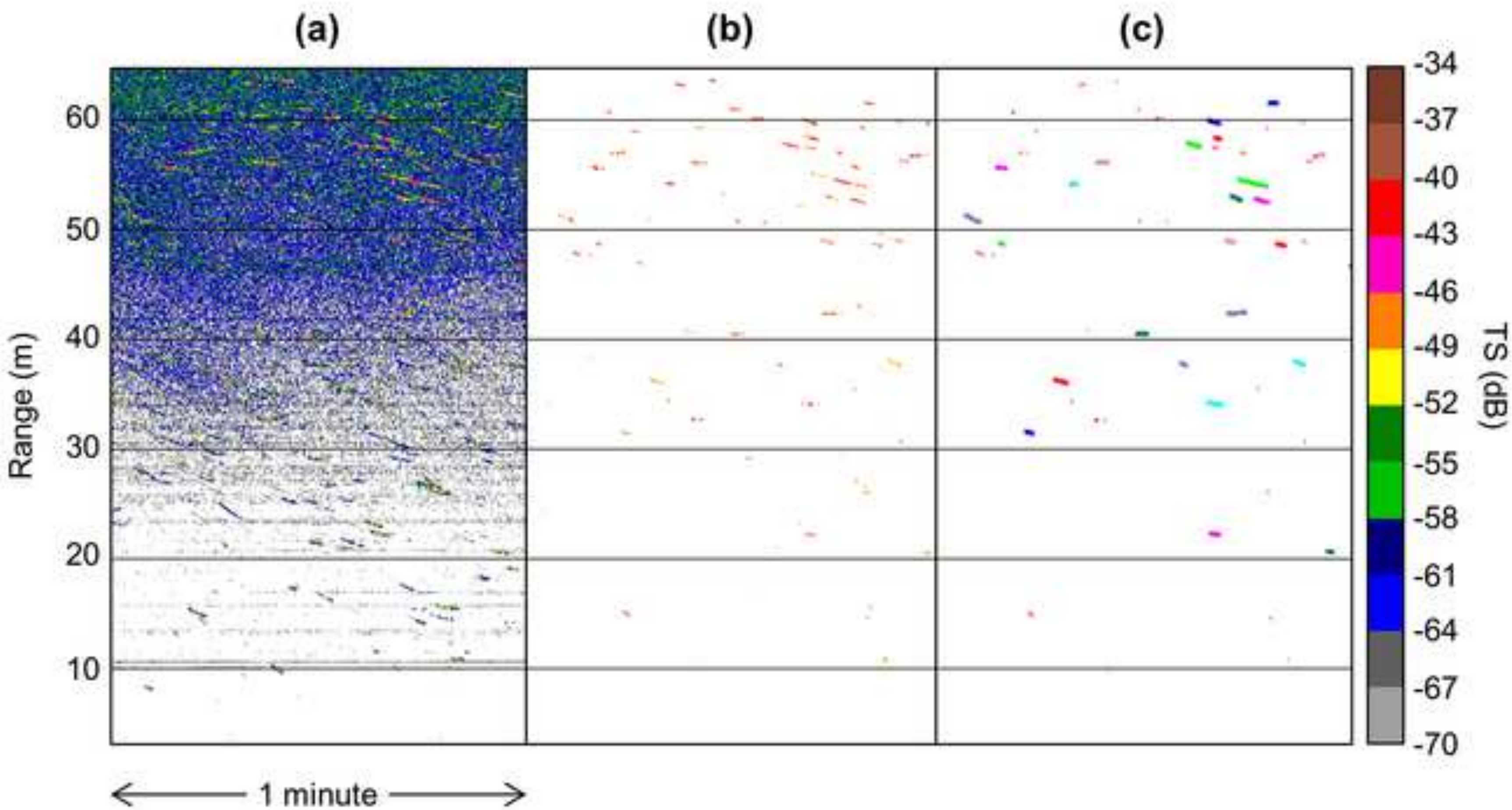


Figure 5

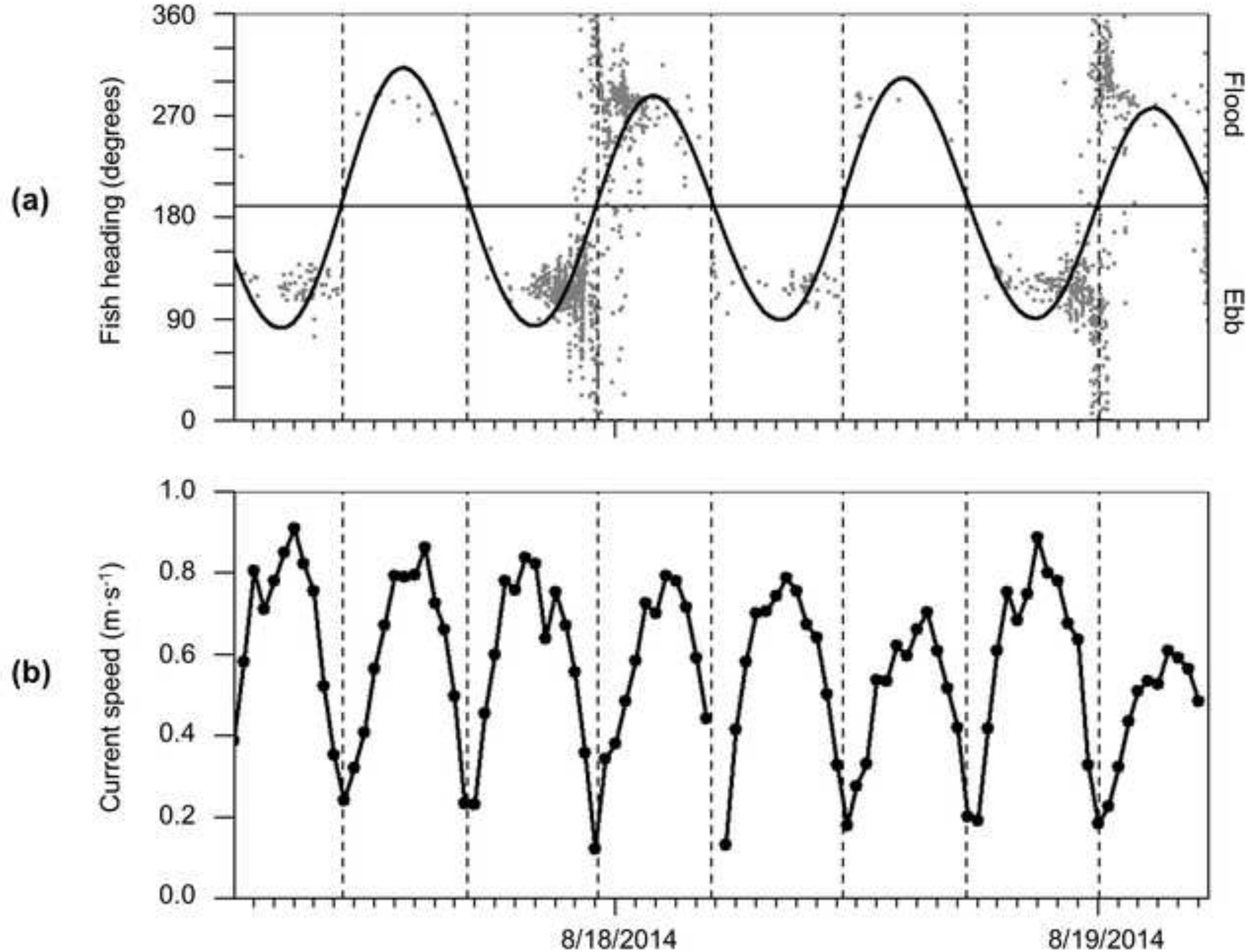

(a)
Fish heading (degrees)
360
270
180
90
0
Flood
Ebb
(b)
Current speed (m·s⁻¹)
1.0
0.8
0.6
0.4
0.2
0.0
8/18/2014
8/19/2014

Figure 6

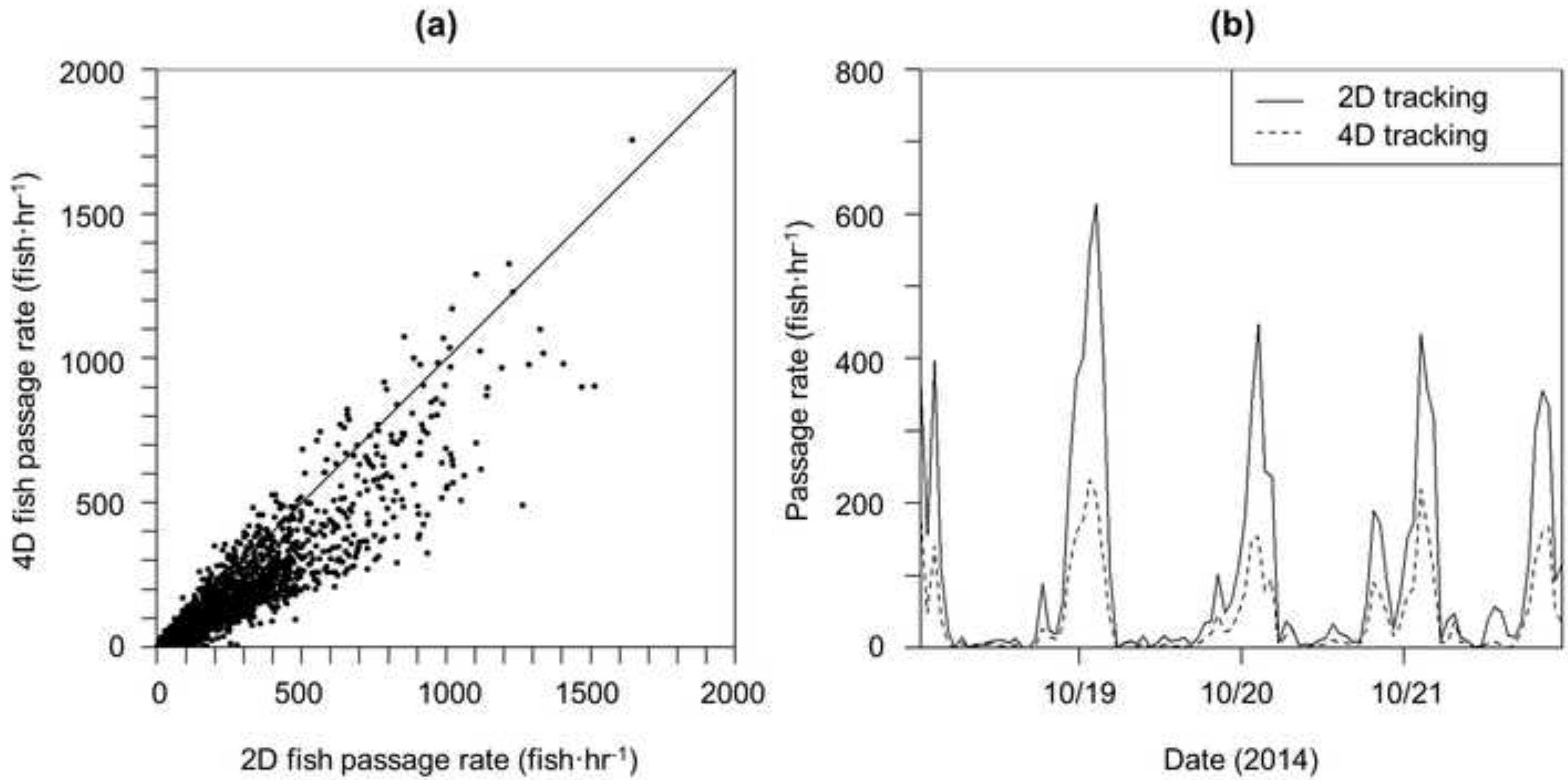
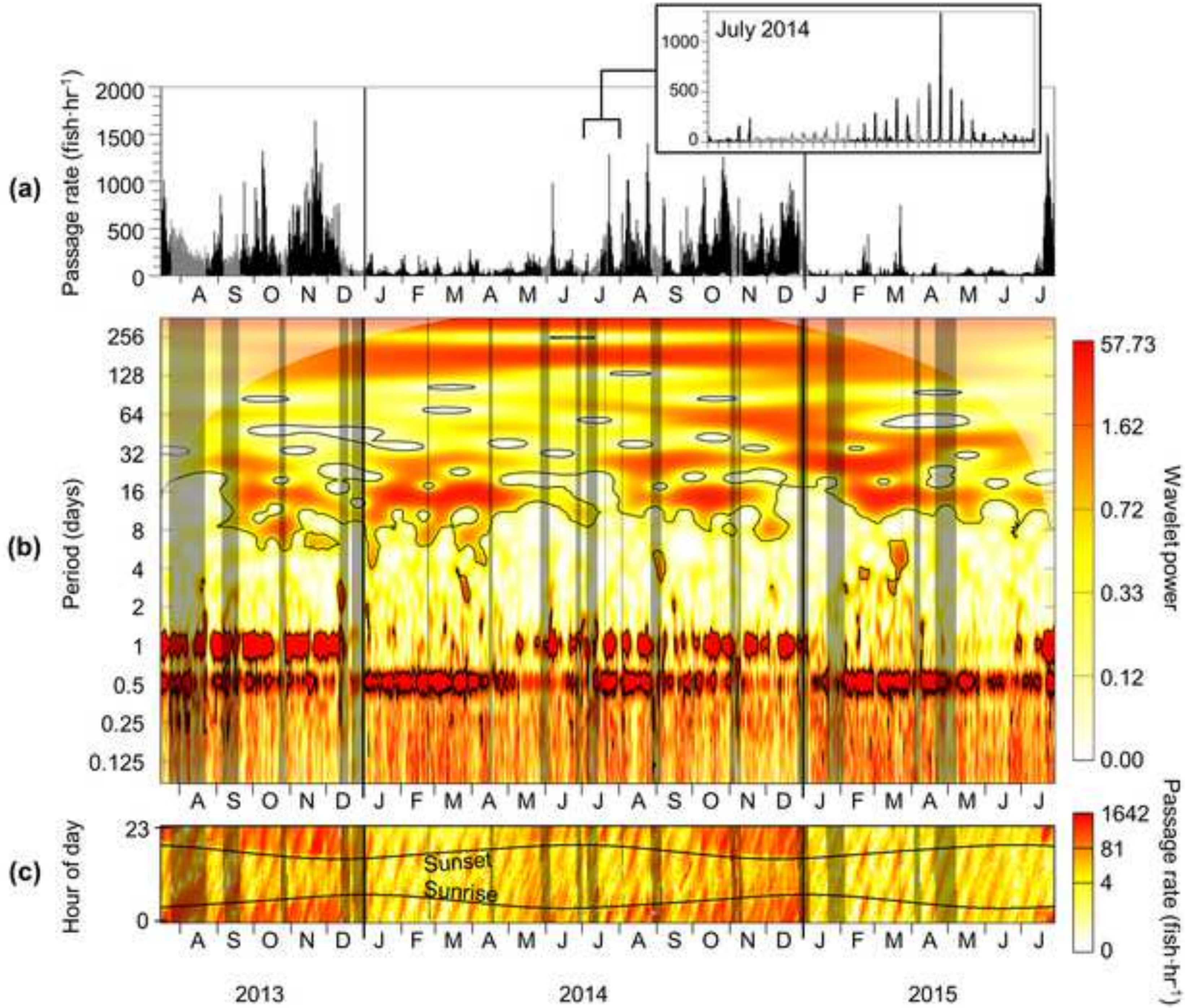
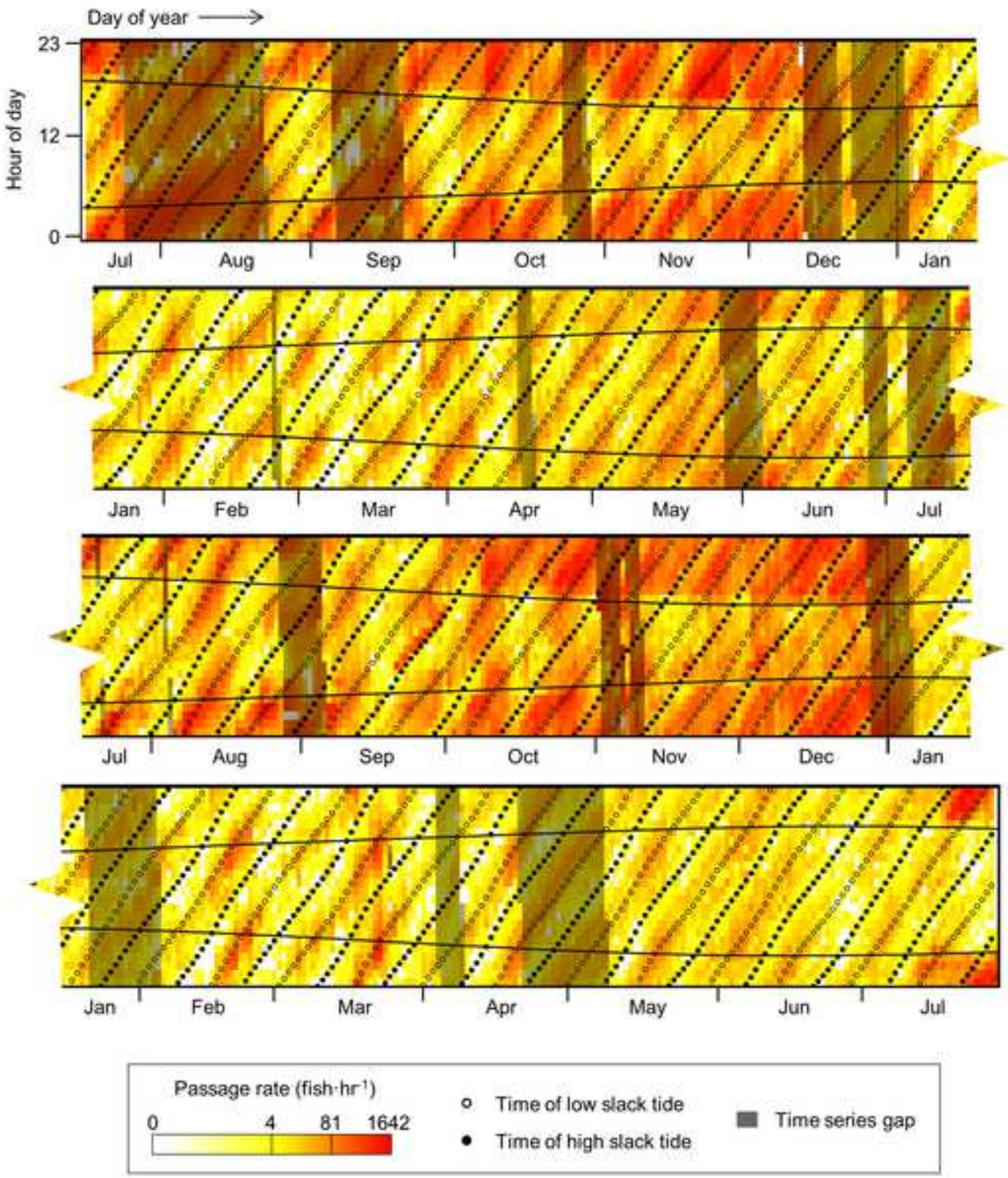

(a)
2000
1500
1000
500
0
0
500
1000
1500
2000
4D fish passage rate (fish·hr⁻¹)
2D fish passage rate (fish·hr⁻¹)
(b)
800
600
400
200
0
2D tracking
4D tracking
10/19
10/20
10/21
Passage rate (fish·hr⁻¹)
Date (2014)

Figure 7



July 2014
1000
500
0
(a)
Passage rate (fish·hr⁻¹)
2000
1500
1000
500
0
A S O N D J F M A M J J A S O N D J F M A M J J
(b)
Period (days)
256
128
64
32
16
8
4
2
1
0.5
0.25
0.125
57.73
1.62
0.72
0.33
0.12
0.00
Wavelet power
(c)
Hour of day
23
0
Sunset
Sunrise
1642
81
4
0
Passage rate (fish·hr⁻¹)
2013
2014
2015

Figure 8


Day of year
Hour of day
23
12
0
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Jan
Feb
Mar
Apr
May
Jun
Jul
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Jan
Feb
Mar
Apr
May
Jun
Jul
Passage rate (fish·hr⁻¹)
0
4
81
1642
Time of low slack tide
Time of high slack tide
Time series gap