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Article

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Research paper

Fish distributions in a tidal channel indicate the behavioural impact of a marine renewable energy installation

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ABSTRACT

In the dynamic environments targeted for marine renewable energy extraction, such as tidal channels, the natural distribution of fish and behavioural impacts of marine renewable energy installations (MREIs) are poorly understood. This study builds on recent methodological developments to reveal the behaviour of fish schools using data collected by a seabed-mounted echosounder deployed in extreme tidal flows and in the wake of a MREI (composed of the foundation of a full-scale tidal stream energy turbine). The results show a significant change ($p < 0.001$) in the vertical distribution of fish schools in the vicinity of a MREI compared to a nearby control location representative of the natural conditions. The MREI is associated with an overall increased rate of fish school observations (+74%), particularly at night (+163%) and in the MREI wake flow (+378%), related to the disruption of natural diurnal behavioural patterns in school characteristics (size, relative density, and distance from seabed). These results indicate an attraction effect of the MREI, and show that the aggregation and vertical distribution of fish in the modified flow conditions is dependent on tidal phase with evidence of avoidance of the MREI depth range during peak flow velocities. The behavioural responses observed in this study provide new information relevant to the environmental impact assessment of marine renewable energy developments and highlight priorities for further research.

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1. Introduction

In recent years there have been rapid developments in the extraction of tidal stream energy with numerous marine renewable energy installations (MREIs), including full-scale tidal stream turbines, deployed around the world (Zhou et al., 2017). Energetic tidal channel environments are of high ecological importance (Benjamins et al., 2015), and the unknown effects of MREIs on marine animals are a major challenge for the development of the marine renewable energy industry (Copping et al., 2015; Fox et al., 2017). The potential behavioural impacts of MREIs could result from direct interaction of mobile animals with devices, or over larger scales due to the hydrodynamic consequences of changes to the natural flow structure with unknown ecological implications (Shields et al., 2011).

The potential for impacts on fish behaviour from MREIs may influence risks to larger predators and has been identified as a research gap (Roche et al., 2016). However, in the turbulent environments targeted for marine renewable energy extraction there is still a lack of baseline ecological data (Inger et al., 2009; Haslett et al., 2016). Recent field observations around marine renewable energy devices have focussed on fish interactions with turbine components at very fine scales using optical (Hammar et al., 2013; Broadhurst et al., 2014) and acoustic (Viehman and Zydlewski, 2015) cameras. However, only echosounder instruments with a sufficient range provide the practical means to investigate the behaviour of fish throughout the entire water column of a typical tidal channel. The functionality of echosounders in energetic environments has so far been limited due to the operational difficulties of data collection in such conditions and the intense interference caused by backscatter related to turbulence (Melvin and Cochrane, 2015). Consequently, previous field observations have been limited in the depth range or temporal coverage available, for example by excluding data from the upper part of the water column (Viehman et al., 2015) or during slack conditions (Shen et al., 2016).

Developments in data collection approaches (Williamson et al., 2015), data processing algorithms (Fraser et al., 2017a), and instrument integration techniques (Williamson et al., 2017) enable the first continuous observations of fish aggregations from nearly the entire water column around a MREI in a tidal channel. This study

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investigates the nature and significance of potential behavioural impacts of a MREI by comparing the vertical distribution of fish schools in a control location representative of the natural conditions with results from a location where a full-scale tidal stream energy turbine foundation is present.

2. Material and methods

2.1. Study site

This study considers the data collected during two instrument platform deployments at the Fall of Warness tidal test site (59°7′ to 59°11′N, 2°47′ to 2°50′W) in Orkney, Scotland. The conditions at the site are characterised by exceptionally strong semidiurnal tidal currents exceeding 3.5 m s^{-1}. The natural tidal flow in the site is approximately directionally-symmetric, with flow from the north-west to the south-east during the flood tidal phase, and from the south-east to the north-west during the ebb tidal phase. Previous surveys of the site indicate that the seabed is primarily composed of exposed swept bedrock with occasional boulders, cobbles, and patches of gravel and shelly sand (Aurora, 2005). Baseline environmental studies of the area (Aurora, 2005) indicated that the aggregating fish species likely to be present during data collection include: mackerel (*Scomber scombrus*), pollack (*Pollachius pollachius*), saithe (*Pollachius virens*), sprat (*Sprattus sprattus*), herring (*Clupea harengus*), and sandeels (*Ammodytes spp.*).

2.2. Data collection

Data were collected by the seabed-mounted FLOWBEC platform during a field campaign at the European Marine Energy Centre (EMEC) in summer 2013 (Williamson et al., 2015). These platform deployments gathered multifrequency echosounder data using a Simrad EK60 scientific echosounder operating at 38, 120, and 200 kHz. The EK60 transducers were mounted on top of the platform, 0.9 m from the seabed, and were orientated directly upwards with overlapping 7° conical beams. All EK60 transducers were calibrated and pinged simultaneously at 1 Hz using a 1024 μs pulse length. Supporting data on the flow were provided by an acoustic Doppler velocimeter mounted on the platform and hydrodynamic model data for the site (Waggitt et al., 2016).

The first platform deployment was from June 3rd–15th and was positioned 15 m downstream (during flood) from the Atlantis AK-1000 seabed-mounted turbine foundation to provide the "MREI present" dataset. The turbine foundation lacked the nacelle and blades during data collection and was composed of a steel tripod base with a 10 m high central piling surrounded by three 4 m high concrete ballast blocks.

The second platform deployment was positioned in the same site 424 m away from the first deployment and recorded data out of the wake of any installations from June 18th–July 5th to provide the "control" dataset. Both deployments were during similar meteorological conditions and at locations approximately 35 m deep. Video footage from a remotely operated underwater vehicle during platform recoveries showed that comparable seabed characteristics were encountered in both deployment locations and confirmed the presence of aggregations of gadoid fish in the site. Maximum temporal comparability between the two deployments was achieved within logistical constraints by the shortest possible time gap between deployments (three days) and by coverage of the spring-neap cycle in each case. Similarly, spatial comparability was established by considering the bathymetry, natural hydrodynamics, and surrounding substrate at both deployment locations so that behavioural changes of marine animals could reasonably be attributed to the MREI.

2.3. Data processing and analysis

Information on the vertical distribution of fish aggregations was derived from the EK60 backscatter measurements following an adaptive processing method (Fraser et al., 2017a) developed to detect fish schools with high sensitivity throughout the dynamic conditions and intense acoustic interference encountered in tidal channel environments. Schools were validated by multi-frequency characteristics and by direct inspection of the data, and further supported by co-registration with observations from a synchronised multibeam echosounder also mounted on the platform (Williamson et al., 2017).

The vertical distribution of fish is characterised by calculating the distance to the centre of each school from the seabed. The local time (BST) at which each fish school is observed is used to find the proportion of observations during the daylight (approximately 04:00 to 22:00) and night. The diurnal phase for the time of each fish school observation is also computed, which varies between 0 and 1 through the 24 hour cycle so that 0 and 1 represent midnight and 0.5 represents noon. Similarly, flow velocity information from the hydrodynamic model is used to find the proportion of fish school observations during flow in the flood and ebb directions, and to compute the tidal phase for each observation. Tidal phase is defined between 0 and 1 through the approximately 12.5 hour flood-ebb cycle by flow velocity so that 0 to 0.5 represents flow in the flood direction and 0.5 to 1 represents flow in the ebb direction (i.e., peak flow velocities at approximately 0.25 and 0.75, and reduced flow velocities centred around slack conditions at 0, 0.5, and 1). The vertical distributions of fish schools for different deployments and flow directions are statistically compared using the non-parametric two-sample Kolmogorov–Smirnov test and considered significantly different if $p < 0.05$. The size of each school is characterised by the observed cross-sectional area, A. The relative density of each school is characterised by the mean volume backscattering strength measured at 200 kHz, $MVBS_{200}$, which is proportional to the number of fish in a given volume neglecting differences in target strength associated with species, orientation, and other effects.

3. Results

A total of 523 fish schools were observed in the presence of the MREI, and 396 fish schools observed in the control location representative of the natural conditions. The presence of fish schools is considered in terms of an occurrence rate by dividing the number of observed schools by the sampled time for a variety of cases (Table 1). The occurrence rate of fish schools increased overall from 1.10 schools $hour^{-1}$ in the control to 1.91 schools $hour^{-1}$ in the presence of the MREI. An increased occurrence rate is associated with the MREI presence in all cases considered, in particular at night and during the flood phase. The largest increase in fish school observations is associated with the lower part of the water column during flood flow (+378%), corresponding to observations in the wake of the MREI.

The overall vertical distribution of fish schools (Fig. 1) was significantly different ($p < 0.001$) between the two datasets, with a decreased mean distance from the seabed observed in the presence of the MREI (18.56 m) compared with the control (20.64 m). Control results show that most schools are recorded in the upper half of the water column, with increased mean distance from the seabed at night. In the presence of the MREI the day/night trend is reversed and a higher proportion of fish schools are recorded in the lower part of the water column. Flood and ebb results are similar in the control and not significantly different ($p = 0.89$); while a clear and significant ($p = 0.02$) difference between flood and ebb results is apparent in the presence of the MREI and dominated by the increase in fish school observations in the wake flow.

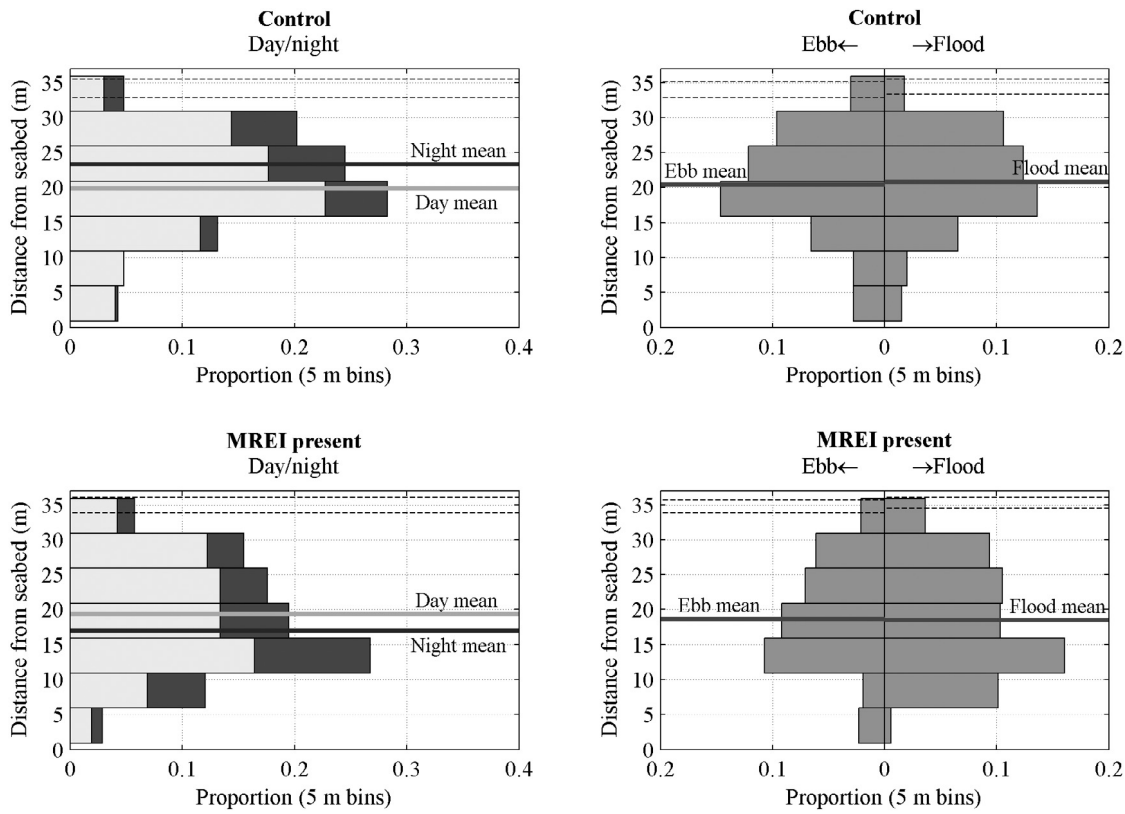

Fig. 1. Comparison of the vertical distributions of fish schools in the presence of a MREI and at a control location. In the left panels, the overall vertical distribution of fish schools is shown for each dataset with light and dark colours representing results during daylight and night, respectively. In the right panels, flood results increase to the right and ebb results increase to the left. The dashed lines indicate the maximum and minimum sea surface height above the seabed measured during spring tides.

Table 1
Occurrence rates of fish schools calculated for a variety of cases.

Case considered	Control	MREI present	Difference
Overall rate (schools hour^{-1})	1.10	1.91	+74%
Day rate (schools hour^{-1})	1.14	1.72	+51%
Night rate (schools hour^{-1})	0.97	2.54	+163%
Flood rate (schools hour^{-1})	1.11	2.41	+117%
Ebb rate (schools hour^{-1})	1.09	1.45	+34%
Flood rate <15 m from seabed (schools hour^{-1})	0.21	0.99	+378%
Ebb rate <15 m from seabed (schools hour^{-1})	0.23	0.46	+100%

Analysis of the size and relative density of fish schools indicates that school characteristics are related to diurnal and tidal phases (Fig. 2) with consistent associations often at particular depths. In the control results, the largest and densest fish schools are consistently observed during the fading light before sunset. However, in the presence of the MREI the large and dense schools are randomly distributed through diurnal phase at mid-depths and appear to be associated with peak flow velocities. Tidal phase results also show a reduction in observations of fish schools in the lower part of the water column during peak flow velocities in the vicinity of the MREI. However, high numbers of small schools are consistently recorded in the lower part of the water column during reduced flood flow velocities (shortly after and before slack) in the wake of the MREI.

4. Discussion

Previous studies have suggested how a MREI may act as an artificial reef (Inger et al., 2009) or so-called "fish aggregation device" (Boehlert and Gill, 2010) which can attract a variety of fish species. The results of this study show increased rates of fish schools observed in the presence of a MREI compared to control data, which indicate an attraction effect that varies depending on daylight, depth, and flow conditions.

The control results suggest that the natural vertical distribution of fish in the study site is not statistically different between flow directions, but that school characteristics show behavioural responses to diurnal phase. Daily cycles have been shown to effect the presence of individual fish in tidal flows (Viehman and Zydlewski, 2017), and the aggregation and vertical migration of schools are well known responses to daylight for a range of fish species. The control results show that such behaviour is also present for schools of fish even in dynamic tidal channel environments. However, diurnal patterns were disrupted in the vicinity of the MREI, with significantly different flood and ebb vertical distributions indicating some behavioural impact in the wake of the MREI.

Analysis of behavioural characteristics with tidal phase showed that the apparent MREI attraction effect was concentrated in the lower part of the water column during the flood phase, corresponding to the MREI wake flow. In particular, reduced flood flow velocities were consistently associated with increased observations of small fish schools. This result supports previous observations at very fine scales which have shown the presence of fish in device

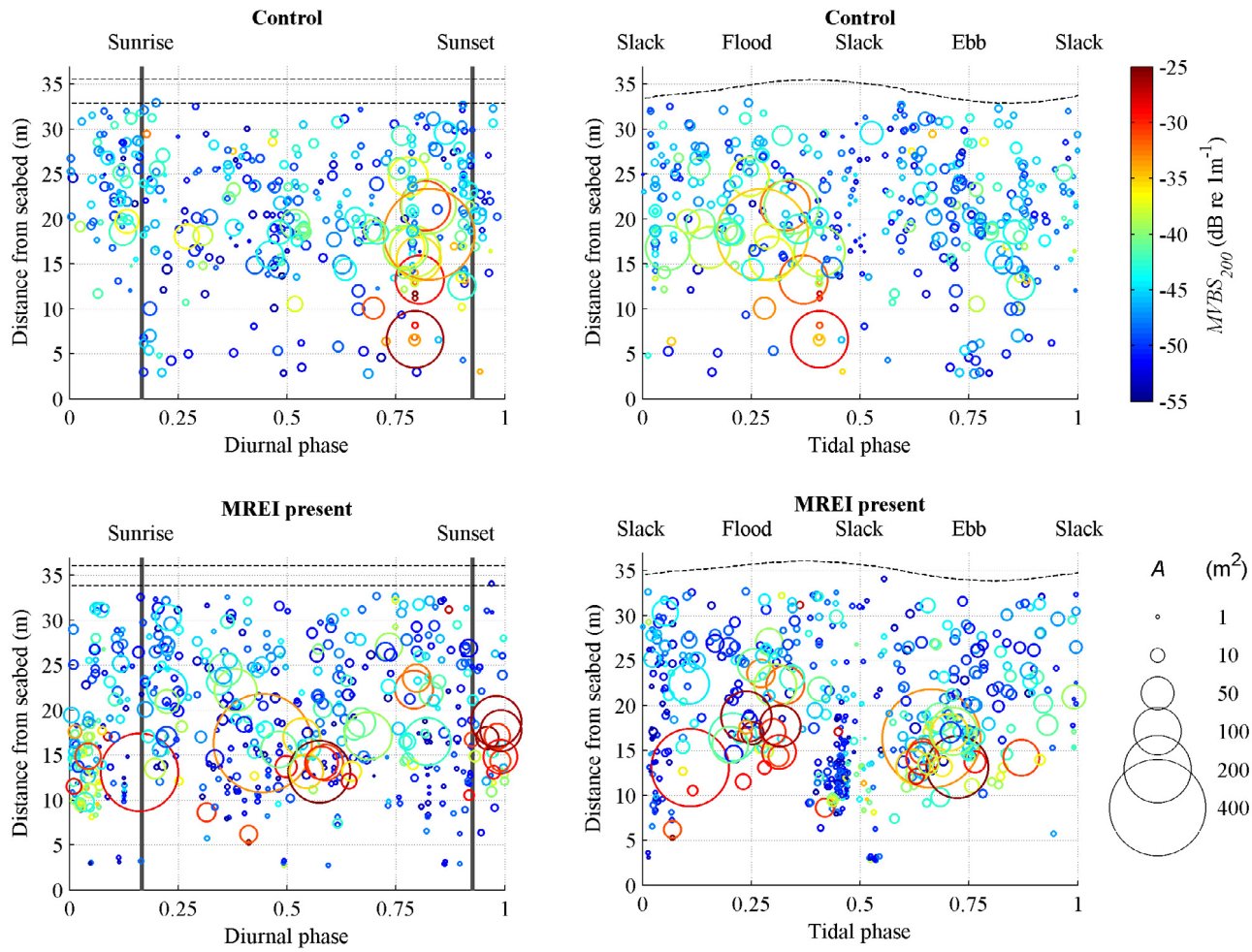

Fig. 2. Vertical distributions of fish schools plotted for diurnal and tidal phases. Marker size is proportional to the observed cross-section area, A, while colour represents the relative density as characterised by the mean volume backscattering strength, $MVBS_{200}$. The diurnal phase for each observation is defined for the 24 hour daily cycle. The tidal phase for each observation is defined for the approximately 12.5 hour flood-ebb cycle. The dashed lines indicate the maximum and minimum sea surface height above the seabed measured during spring tides. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

wakes (Viehman and Zydlewski, 2015) and increased abundances related to reduced flow velocity (Broadhurst et al., 2014), and provides new evidence on the depth dependence and horizontal scale of such effects. Further behavioural impacts are suggested by the reduction in fish school observations in the lower part of the water column at peak flow velocities in the vicinity of the MREI, which may indicate some avoidance behaviour as observed by Shen et al. (2016) and Bevelhimer et al. (2017).

The tidal phase dependence of fish behaviour in the presence of the MREI suggests that some behavioural patterns during the flood phase are linked to the modified flow conditions in the MREI wake. Related hydrodynamic analysis of the study site (Fraser et al., 2017b) has shown that the MREI wake is characterised by the breakdown of the natural structure of the flow, a reduced mean flow velocity, and elevated levels of turbulence intensity. For fish, such conditions may provide foraging opportunities and flow refuges (Cotel and Webb, 2012), or may be related to dispersal and disorientation (Waggitt et al., 2016) with implications for energetic costs and exposure to predators.

As the direct sampling of fish (typically undertaken by nets and trawls) is impractical in the energetic conditions considered here, the ecological interpretation of behavioural responses is limited by the lack of direct and specific biological information on the observed schools. However, by maximising the comparability between datasets (by considering the natural physical characteristics of the study site and minimising the time gap between deployments) the overall species composition and age structure of fish schools present in the site are assumed to be similar in the control data and in the vicinity of the MREI. This comparability between datasets also means that behavioural results are unlikely to be related to seasonal variations or minor natural differences between the deployment locations. The effectiveness of reference to a nearby control location has previously been demonstrated by Viehman et al. (2015) in the analysis of fish distributions in tidal flows, and the behavioural differences between datasets in this study are considered a useful indication of the ecological impacts of MREIs.

The hydrodynamic and behavioural impact of an active marine renewable energy device is likely to be greater than in the case of the turbine foundation considered here. Nonetheless, these results do indicate that fish demonstrate a significant behavioural response to a MREI in a tidal channel, and consequently further research in the presence of active devices of different designs is required.

5. Conclusion

This study addresses the need for information on the behaviour of mobile animals in energetic marine environments and provides insights into the potential ecological impacts of MREIs. Field observations in such environments are rare due to the operational

difficulties of data collection and interference to acoustic instruments caused by high levels of turbulence. The vertical distributions of fish schools were investigated using an adaptive processing method applied to echosounder data collected in a tidal channel at a control location and in the vicinity of a tidal turbine foundation.

In the control data, an overall rate of 1.10 schools hour^{-1} was observed and the distribution of schools was not significantly different ($p = 0.89$) when comparing flow directions. School characteristics showed a natural response to daylight, with schools occupying an increased distance from the seabed at night and observations of large dense schools aggregating before sunset.

Data collected in the vicinity of a MREI (15 m away) showed a significant change ($p < 0.001$) in the vertical distribution of fish schools, and indicated an overall attraction effect with an increased rate of 1.91 schools hour^{-1} observed. Natural diurnal patterns were disrupted in the vicinity of the MREI with the vertical distribution and aggregation of fish linked to tidal phase and significantly different ($p = 0.02$) distributions observed for flood and ebb flow directions. The consistent aggregation of small schools was observed during reduced flood flow velocities in the wake of the MREI (corresponding to a 378% increase in fish school observations at <15 m distance from the seabed during the flood phase), while at peak flow velocities there was evidence of avoidance behaviour at the MREI depth range.

These results demonstrate systematic behavioural responses to environmental cycles and disturbance by a MREI. The vertical distribution of schools can be related to the encounter probability with MREIs and so the behavioural responses indicated in this study should be considered during the modelling of device interactions with fish. Further, the distribution of fish is likely to drive the foraging behaviour of larger predators, such as marine mammals and seabirds, and will likely influence the associated risks (e.g., collision) to protected species. Consequently, these results are relevant to the environmental impact assessment of marine renewable energy projects and provide evidence of behavioural effects with potential ecological consequences requiring more studies of this kind.

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Conflicts of interest

None.

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