Temporal variability in pelagic biomass distributions at wave and tidal sites and implications for standardization of biological monitoring

S. Gonzalez, J. K. Horne, and E.J. Ward

Abstract—**Commercial viability of Marine Renewable Energy (MRE) is progressing but no national or international monitoring standards have been established for wave or tidal energy sites. Standardized biological monitoring within and across MRE sectors is necessary to expedite project permitting/consenting, detect environmental impacts, and to enable comparison among sites and technologies. Acoustic backscatter from a bottom-deployed platform at a pilot wave energy site off Newport, Oregon was compared to acoustic data collected at a tidal turbine site in Admiralty Inlet, Washington to assess the potential of using standard monitoring methods across sectors of the MRE industry. Metrics that quantify fish and macrozooplankton densities and vertical distributions were compared using wavelets and Autoregressive Moving Average models (ARMA). Mean density and vertical distribution values significantly differed between sites. Metrics of density and location in the water column displayed diel (24 h) and tidal (12 h) cycles. Dispersion of animals in the water column varied at 64- and 128-h periods at both sites. Applicability of methods in these MRE sectors suggests that a standard approach to biological monitoring is possible. Stationary acoustics and analytic methods can characterize pre-installation conditions and detect impacts on fish and zooplankton biomass associated with MRE development and operation.**

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I. INTRODUCTION

EFFECTS of Marine Renewable Energy (MRE) wave and tidal development and operation on biological communities remain uncertain [1]–[3], and the ecology of many MRE sites has been traditionally understudied due to dynamic environmental conditions. As a result, regulators have taken a precautionary approach and evidence of no (or minor) measurable effects associated with MRE development is required before approval of a MRE license [4]. As part of the permitting/consenting process, biological characterization of pre-installation conditions (e.g. abundance, diversity, and fluctuations of biological communities), and post-installation monitoring that ensures detection of change in biological attributes are mandatory conditions for every MRE project.

Environmental monitoring plans are industry sector, site, and project specific. No standard monitoring requirements exist for wave or tidal energy projects in the world. This makes it difficult to assess environmental impacts (i.e. detection of change above a threshold), impedes permitting/consenting, and hampers industry development [5], [6]. Standardized monitoring goals and methods would expedite project development, enable assessment of MRE device effects on the environment, and facilitate comparisons of impacts among sites and sectors to evaluate if changes are site/device specific.

Within MRE sectors, sites are primarily chosen by similarities in their physical characteristics such as current velocities for tidal sites, and favourable wind conditions for wave sites, but this does not mandate that biological characteristics (e.g. fish and zooplankton biomass and biomass distributions) among sites are also similar. A comparison of fish and zooplankton densities and vertical distributions at two tidal sites showed that similarities exist and that a common method to determine thresholds for environmental monitoring is possible [7]. To establish if standard methods could be applied across MRE industry sectors, comparisons of sites with different physical environments are needed. The next logical step is to compare biological characteristics at wave (open coastal area) and tidal (tidally dynamic) MRE sites. Observations from this comparison will highlight general similarities and site/sector-specific differences that can be considered when developing monitoring strategies for the MRE industry.

Stationary active acoustic methods can be used to monitor the water column in a wide range of environmental conditions. Wave and tidal energy sites are typically located in relatively shallow water (<60 m), that maximize amplitudes of ocean surface waves and tidal currents. Traditional biological sampling (i.e. vessel-based net deployments) can be operationally challenging in these environments due to high flows, turbulence, and the presence of energy conversion devices. Deployment of active acoustic packages overcomes these sampling challenges and is not subject to net availability/selectivity, increased sampling mortality, or large investments in time and resources.

The objectives of this study were to: (1) characterize and compare temporal variability in densities and distributions of fish and macrozooplankton at a wave and a tidal energy test site; (2) identify environmental variables influencing observed patterns; and (3) discuss the potential for standardizing analytic methods to acoustically monitor biomass across MRE industrial sectors.

II. Methods

A. *Study sites*

We investigated the dynamics of marine animals living in the water column (i.e. pelagic organisms) at two sites that have been selected for testing and developing MRE from tidal currents and waves in the United States (Fig. 1). The tidal site was selected by the Snohomish Public Utility District 1 (SnoPUD) for the deployment of two OpenHydro (http://openhydro.com/home.html) turbines in northern Admiralty Inlet, the main entrance to Puget Sound, Washington, characterized by currents reaching circa 3 ms^{-1} [8], [9]. This project obtained a Federal Energy Regulatory Agency (FERC) license in 2014 but due to funding constraints it was discontinued that same year.

The second site is at the PacWave test site (formerly known as the Pacific Marine Energy Center South Energy Test Site) (Fig. 1). PacWave is a planned grid-connected test facility for wave energy converters (WECs), located circa 11 km off the coast of Newport, Oregon. This wave energy pilot site (hereafter wave site) is currently in the permitting process and is expected to be available for device testing in 2019.

B. *Data acquisition*

Active acoustic data collected at fixed locations were used to quantify temporal variability of pelagic fish and macrozooplankton at both study sites. Our approach focused on communities in the area of a site rather than on individual animals in the area of a device, as impacts to populations will affect long term viability of MRE sites. Acoustic backscatter (i.e. ensemble reflected energy) data were collected using bottom-mounted Sea Spider platforms (http://www.teledynemarine.com/sea-spider) with upward looking echosounders. Tidal site data were collected using a BioSonics DTX echosounder operating at 120 kHz with a 7° (between half power points) beam. The echosounder was placed at 55m depth about 750 m to the west of Admiralty Head at the SnoPUD tidal turbine site from May 9th to June 8, 2011. The echosounder sampled at 5 Hz for 12 minutes every 2 hours. The bottom package located at the wave site consisted of a Simrad WBAT (www.simrad.com) operating at 70 kHz, with an 18° beam at a depth of 61 m. The WBAT echosounder sampled 175 pings at 1 Hz (~ 3 min) every hour from April 19th to September 30, 2016. Acoustic sampling parameters are listed in Table I. Both echosounders were calibrated prior to deployment following standard procedures outlined by Demer et al. [10].

At both sites, no energy conversion devices were deployed during field measurements. Therefore, collected data characterize pre-installation conditions and may be used in the future to assess biological changes associated with the installation and operation of energy devices.

C. *Data processing*

Processing of tidal site backscatter data were completed prior to this study and is described in [9]. A threshold of -75 dB re 1 m^{-1} (hereafter dB) [11] was applied to remove background noise and data were limited to 25 m from the bottom to minimize backscatter from surface turbulence. The original 12 minute samples collected at the tidal site were subsampled to match the ~ 3 min samples acquired at the wave site. From each 12 min sample, 4 different data sections can be analysed. Using continuous acoustic data from a tidal site in the Fall of Warness, Scotland, Wiesebron et al. [7] demonstrated that there were no significant differences between equal length subsets from the original series. Thus, the first 875 pings (175 pings x 5 Hz) were selected and analysed from each data series.

Acoustic data from the wave site was processed in Echoview (version 7.1). The data range was also constrained to 25 m from the bottom and a threshold of -75 dB was applied to match the Admiralty Inlet data. Echoes within 3 m from the face of the transducer were excluded from the analysis to avoid the integration of echoes in the acoustic nearfield. Background noise was estimated from passive acoustic measurements collected during a mobile surface survey conducted in the area. Noise level was obtained by finding the value that minimized the sum of the squared differences between observed and expected mean volume backscattering

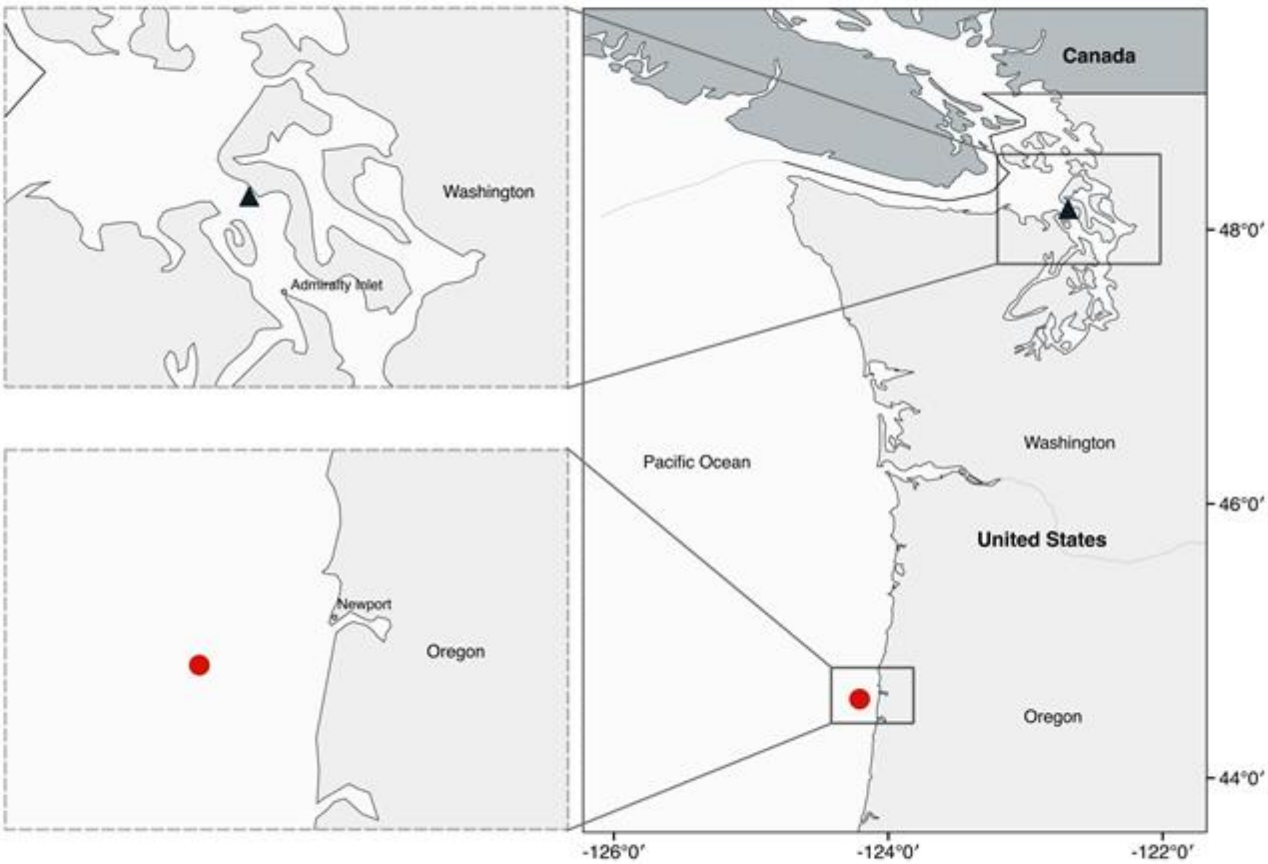

Fig. 1. Study sites showing locations of the acoustic deployments at SnoPUD's tidal energy pilot site in Admiralty Inlet, WA (triangle) and PacWave test site (circle), a wave energy test site off the coast of Newport, OR.

strength (mean Sv). Noise was estimated using (1) where NL is the noise level at 1 m (dB), r the range in m, and α the absorption coefficient (dB/m). The estimated noise level at 1 m (-136.24 dB) was then used to subtract noise from the water column.

$$NL(r) = NL + 20log_{10}(r) + 2\alpha(r - 1) \quad (1)$$

To align sampling density at both sites, one of the two samples collected in a 2-hour period at the wave site (i.e. hourly samples) was selected to match the sampling frequency of the tidal site (a sample every 2 hours). A *t*-test was performed between mean acoustic backscatter when selecting the 1st versus the 2nd hour of each 2 hour period. No significant difference was found so the 1st hour was arbitrarily selected for analysis. A one month period (May 8th to June 9th) from the wave site dataset was used to match calendar dates of the tidal site.

D. Data analysis

1) Biological descriptors: echometrics

A suite of metrics derived from acoustic data, collectively referred to as echometrics [12], [13], was used to describe temporal variations in density and vertical distributions of fish and macrozooplankton in the water column. The echometrics suite includes: (1) mean Sv, proportional to mean density of organisms [11]; (2) center of mass (units: m), the mean weighted location of backscatter in the water column relative to the bottom; (3) inertia (units: m^2), a measure of organism dispersion (i.e. variance) from the center of mass; and (4) an aggregation index (units: m^{-1}), which measures vertical patchiness of backscatter through the water column. The aggregation index is calculated over a scale from 0 to 1, with 0 being evenly distributed throughout the water column and 1 being aggregated.

Echometrics can be used to summarize temporal (and spatial) variability in abundance and behaviour in large datasets and to detect and quantify variability in animal densities across temporal scales (e.g. transient events, diel vertical migrations, interannual changes).

Time series of metrics were tabulated to summarize biological characteristics at each site. Mean density (i.e. mean Sv) was obtained by integrating backscatter through the entire water column within 3 min bins. Computed metrics for each 3 min sample resulted in a time series with 1 datapoint every 2 hours (n=362 datapoints). Mean and variance of normally-distributed metrics (mean Sv, center of mass, and inertia) were compared using t-tests and F-tests (α = 0.05). For the non-normally distributed aggregation index, non-parametric Kolmogorov-Smirnov [14] and Bartlett's [15] tests were used to compare means and variances.

TABLE I
ECHOSOUNDER SAMPLING PARAMETERS USED IN ADMIRALTY INLET (TIDAL SITE) AND AT PACWAVE (WAVE SITE) DEPLOYMENTS.

	Tidal site	Wave site
Manufacturer	BioSonics	Kongsberg/Simrad
Model	DTX	WBAT
Frequency	120 kHz	70 kHz
Pulse form	CW	CW
Pulse length	500 μs	512 μs
Pulse rate	5 Hz	1 Hz

2) Scales of variation in biological characteristics

Wavelet analysis [16] was used to describe and compare dominant periodicities in biological characteristics (i.e. density and vertical distribution of pelagic organisms) at both study sites. A wavelet transform decomposes a time series across time and frequency domains. The result is a 2-dimensional heat-map, called a scalogram, that represents the wavelet power (i.e. variance) contributed by each temporal period (i.e. scale) at each time step. Therefore, a wavelet transform allows, not only the detection of constituent periods or frequencies (analogous to a Fourier Transform), but also the location of frequency components in the time series [16], [17].

A continuous Morlet mother wavelet function [16] was applied to each time series from both sites. Continuous wavelets enable the localization of transient patterns in variance and have been previously used for the analysis of temporally-indexed acoustic data (e.g. [9], [18], [19]). Temporal scales analysed ranged from 4 hours (2 times the data resolution) to 256 hours. Wavelet power was calculated using the R package *biwavelet* (version 0.20.11, [20]). Statistical significance in localized wavelet power was tested against a white noise (constant value, equal to the time series variance) null hypothesis at a 95% confidence level [16].

Horizontal integration of wavelet power at each scale over the entire deployment—the global wavelet spectrum—allows the measurement of variance contributed by each scale across the entire series. Significance of this time-averaged variance was tested against both white and red (modelled as a first order autoregressive process with the variance and autocorrelation empirically derived from the time series) noise at a 95% confidence level [16].

Wavelet coherence was calculated to compare dominant periodicities in biological descriptors of density and vertical distributions between the two study sites. Coherence is a measure of the local correlation between two time series in the time-frequency domain, taking values between 0 and 1 [21]. Statistical significance in wavelet coherence was tested against a white noise null hypothesis at a 95% confidence level.

3) Selection of environmental predictors and time series models

To select environmental predictors for temporal patterns in density and vertical distribution of pelagic organisms at both study sites, linear regression models were fit using different sets of covariates. Mean Sv, center of mass, inertia, and a $\log_{10}$-transformed aggregation index were used as response variables. Only covariates available for both sites were included in the regression models: Julian day, daily tidal range (daily difference between high and low tide), 24-hour periodicity introduced as a Fourier series, and day-tidal range interactions representing the phase of the moon. Tidal data were obtained from the NOAA tide and current database (https://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels). The best fit model was identified using the corrected Akaike Information Criterion (AICc) [22]. Residual plots and the variance inflation factor (VIF) [23] were examined to evaluate model fit and multicollinearity.

Autoregressive Moving Average (ARMA) models [24], [25] were used to model density and vertical distribution of pelagic organisms over time at both study sites. These models include an autoregressive, AR(p), component which regresses a process on p past values, and a moving average, MA(q), component which models the error based on q previous values [24] . Modelling the errors with MA(q) components is often used to model unexplained variability in the environment.

ARMA models can be formatted as a Regression-ARMA model (Reg-ARMA)—a linear regression with autocorrelated errors—to model dependent data using environmental predictors in addition to lagged dependent values [26]. Linder et al. [27] used Reg-ARMA models as candidate models for the characterization of acoustic data from the Admiralty Inlet tidal energy site. These models are structured as shown in (2) and (3), where n_t is the error remaining from the linear regression model, b_1-b_p represents the parameters multiplied by the autoregressive error terms, and θ_1–θ_q represents the parameters multiplied by the moving-average error term.

$$y_t = a + b_1 x_{1t} + \cdots b_p x_{pt} + n_t \quad (2)$$

$$n_t = b_1 n_{t-1} + \cdots b_p n_{t-p} + e_t + \theta_1 e_{t-1} + \cdots \theta_q e_{t-q};\ e_t \sim Normal(0, \sigma) \quad (3)$$

The auto.arima function of the R package *forecast*, version 8.2 [26], was used to fit and select Reg-ARMA models for each metric and site. Environmental predictors from the selected linear regression model (see section D3) were included in the Reg-ARMA model selection. Response variables and covariates were standardized using a z-score transformation to enable comparison of relative effects of the variables at both sites. The non-normally distributed aggregation index was $\log_{10}$ transformed prior to being transformed to a z-score.

Autocorrelation plots of model residuals were visually inspected for statistically significant values (i.e. autocorrelation values outside the 95% critical value bounds). A seasonal component was included in the Reg-ARMA model when significance was observed at a lag of 12 hours that corresponds to daily cycles in the data.

III. RESULTS

E. *Echometrics time series*

There were both similarities and clear differences in densiy and vertical distributions of pelagic organisms between wave and tidal sites (Fig. 2 and Table II). Mean density values (mean Sv) were lower at the tidal site than at the wave site, where an increasing trend was present. Location of organisms in the water column (i.e. center of mass) was, on average, higher off bottom at the wave site than at the tidal site but there were no significant differences in the dispersion (i.e. inertia) from the mean location between sites. Standard deviations for all metrics except the aggregation index were significantly ($p < 0.05$) greater at the wave site than at the tidal site (Table II). The aggregation index remained close to zero throughout most of the time series for both sites, punctuated by episodic occurrences of high aggregation values at the tidal site.

F. *Scales of variation in biological characteristics*

Dominant periodicities in density and vertical distributions of pelagic organisms were observed at both sites (Fig. 3). All metrics varied at the 24-hour diel period at both sites but the significance of this periodicity was more consistent through time in mean Sv and center of mass at the tidal site (Fig. 3, left panel). Significance at a 12-hour periodicity was also detected at the tidal and wave sites suggesting the importance of tidal processes in both environments. Site-specific periodicities were also observed. Longer-period variability—between 64 and 256-hour (~2 weeks) periods—was observed at the wave site in mean Sv, center of mass and aggregation index (Fig. 3, right panel). At the tidal site, there was variability at the 128 and 256-h periods in mean Sv, corresponding to lunar phase and neap-spring tidal cycles (Fig. 3, left panel). Inertia had significant variability at the 64 and 128-hour (~1 week) periods at both sites.

Significant peaks in the global wavelet spectrum were observed at the 24-hour period for density and center of mass at the tidal site only (Fig. 4, left panel) suggesting a major influence of diel cycles at the tidal site. Significant peaks at longer periods (128-256 hours) were observed when contrasted with white noise for mean Sv, aggregation index, and center of mass at the wave site (Fig. 4, right panel), and only mean Sv at the tidal site (Fig. 4, left panel).

Both sites were in phase (i.e. high coherence) at 12-h and 24-h periods in all metrics and at the 64-h period for inertia (Fig. 5). These periods are consistent with observations from the wavelet analyses for each site (Fig. 3).

G. *Selection of environmental predictors and time series models*

Common environmental predictors explained patterns in metrics at tidal and wave sites (Table III). The regression model selected for mean Sv as the response variable included all covariates at both sites (Table III). Tidal range and moon phase (tidal range-Julian day interaction; TR:D) were included in regression models for center of mass and inertia of both sites. Aggregation index models for both sites included the 24-hour period. Selected models for all metrics at the wave site included day of year as a predictor, whereas tidal range was included in all selected models for the tidal site (Table III).

Reg-ARMA orders and standardized coefficients that best explained the structure of the time series are presented in Table IV and fits of the selected models are shown in Fig. 6. Overall, selected models accurately described periodicity and amplitude of mean Sv and center of mass values at both sites. The amplitude of inertia values for both sites and aggregation index for the tidal site were not well described by the models. AR and MA orders differed for each metric and site. In general, higher AR orders at the wave site suggest smoother changes and longer 'memory' (i.e. dependence on 1-5 previous time steps) in biological characteristics than at the tidal site (i.e. generally dependent only on the previous time step). Higher MA orders were observed at the tidal site compared to the wave site (MA components generally explain autocorrelation in the unexplained residual variation of the model). Seasonal components (1-day lag) were only included in mean Sv models, indicating the presence of daily cycles in organism density at both sites.

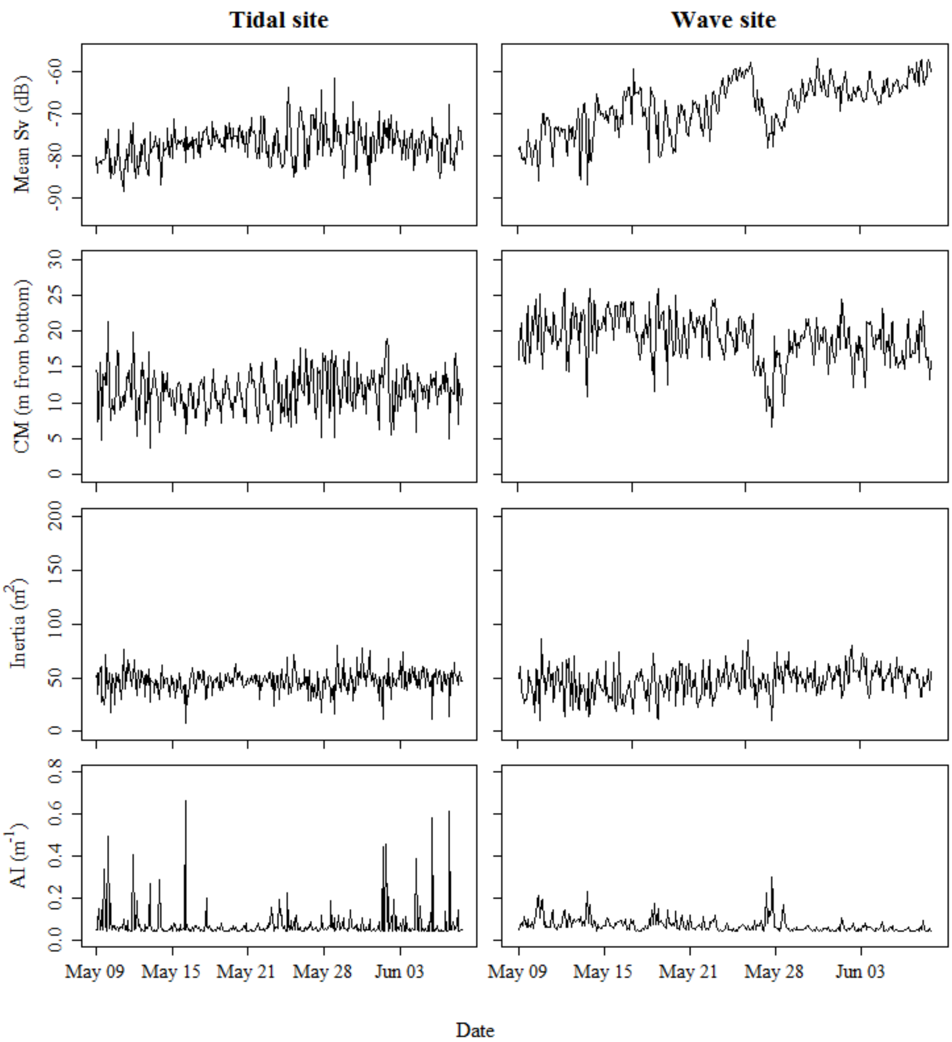

Fig. 2. Time series (N=362) of mean volume backscattered energy (mean Sv), center of mass (CM), inertia, and aggregation index (AI) from a tidal energy pilot site located in Admiralty Inlet (WA) (left panel) and a wave energy pilot site located off the coast of Newport (OR) (right panel).

IV. Discussion

Understanding temporal patterns in changes to biological characteristics at wave and tidal energy sites is essential to inform MRE development and operation. Monitoring strategies that ensure detection of biological changes associated with the installation, operation, and decommissioning of MRE devices are required to ensure sustainable development of the industry and to meet regulatory requirements [4]. But, detecting biological changes in highly variable aquatic environments is challenging. Densities and distributions of aquatic populations vary across a wide range of spatial and temporal scales as a result of multiple physical and biological processes acting and/or interacting across an equally wide range of scales (e.g. [28], [29]). Therefore, characterization of "natural" or pre-installation variability in the biological characteristics of a site (e.g. abundance, diversity, vertical distributions) maximizes the probability of detecting changes associated with MRE deployment and operations from natural variability [27]. After installation of MRE devices, departures from expected variations in biological characteristics based on pre-installation data can be detected, and quantified; after which action plans to modify, mitigate, or cease operations can be developed and implemented. Quantification of temporal patterns in biological characteristics and the identification of environmental drivers can be used to design environmental monitoring plans. To ensure detection of biological changes, monitoring plans should include all relevant variables and corresponding sample designs. Understanding temporal biological patterns is therefore essential to establishing appropriate sampling resolutions, regulations, and reporting requirements for MRE environmental monitoring.

Despite differences in physical characteristics of tidal and wave site environments, similarities in biological characteristics were observed. A primary criterion for wave and tidal energy development site selection is their physical attributes: high tidal flows at tidal sites and open coastal areas with favourable wind conditions at wave energy sites. Since biological communities are shaped by the physical characteristics of their environment [28], it is

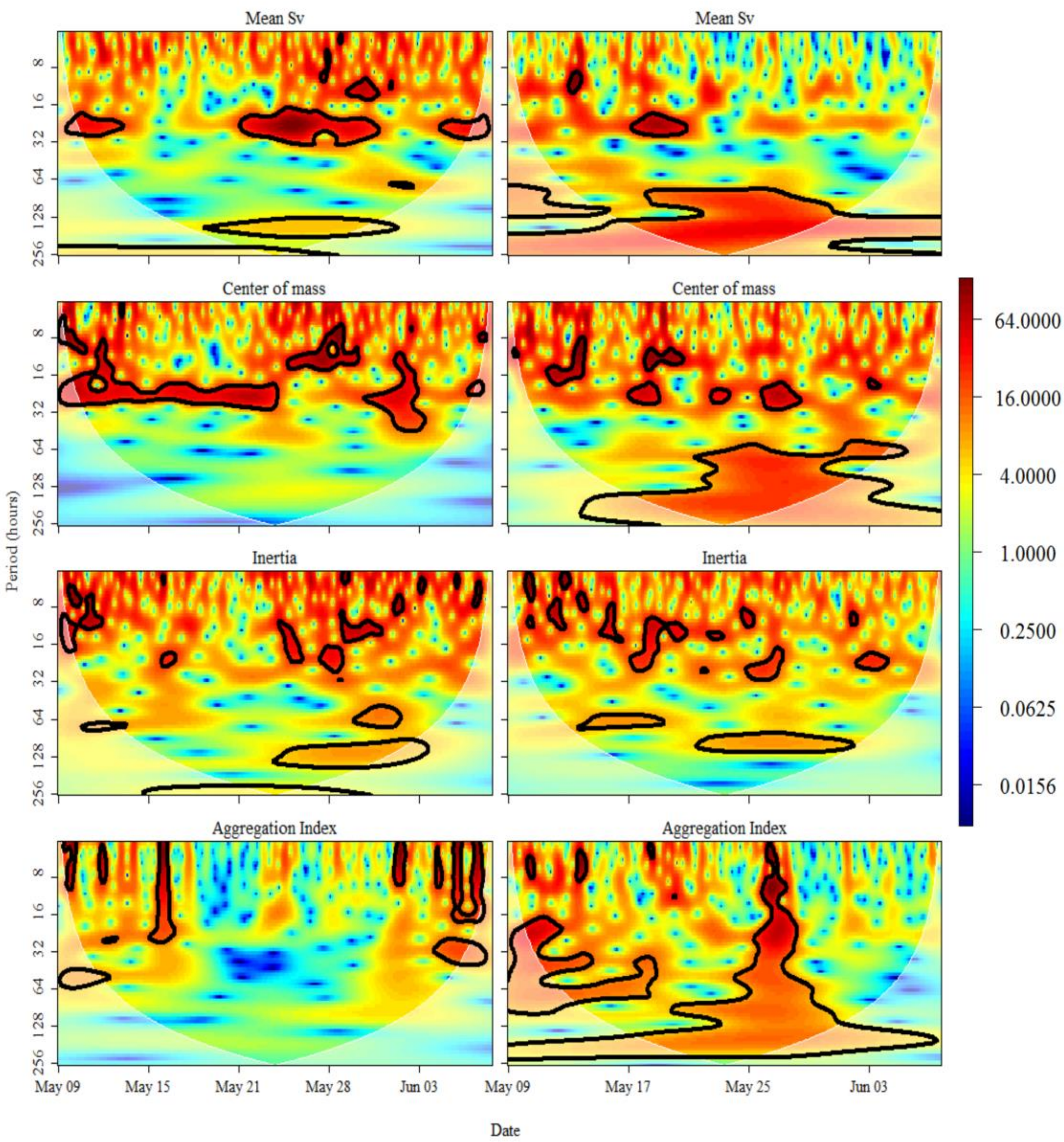

Fig. 3. Wavelet decomposition of the temporal variability in pelagic fish and macrozooplankton characteristics (Mean Sv, center of mass, inertia, and aggregation index) at Admiralty Inlet (WA) tidal site (left panel) and the PacWave energy site (right panel). Areas of significance are traced with a black line. Color bar represents wavelet power (σ^2).

TABLE II
MEANS AND STANDARD DEVIATIONS OF FOUR METRICS REPRESENTING BIOLOGICAL CHARACTERISTICS AND TIDAL RANGE AT THE ADMIRALTY INLET (WA) TIDAL SITE AND THE PACWAVE (OR) WAVE ENERGY SITE.

	Mean			Standard Deviation		
	Tidal Site	Wave Site	p-Value	Tidal Site	Wave Site	p-Value
Mean Sv (dB)	-77.26	-68.36	< 2.20e–16	4.06	6.18	4.00e–15
Center of mass (m)	11.62	19.05	< 2.20e–16	2.76	3.24	2.26e–03
Inertia (m2)	46.94	46.16	0.38	10.48	13.56	1.13e–06
Aggregation Index (m-1)	0.074	0.070	1.00e–07	0.08	0.03	< 2.20e–16
Tidal range (m)	8.88	8.43	5.09e–03	2.37	1.91	5.24e–05

expected that biological characteristics of two MRE sites with distinctive physical attributes would differ. We found numerous common biological characteristics at the studied wave and tidal sites. Dispersion (i.e. inertia) magnitudes and dominant periodicities were similar at both sites, and at least one regression covariate was shared between the sites for all metrics. For example, density and location of fish and macrozooplankton metrics indicated common diel and/or tidal cycles at both sites. Diel and tidal patterns have also been reported as dominant variables in studies of fish density in the Fall of

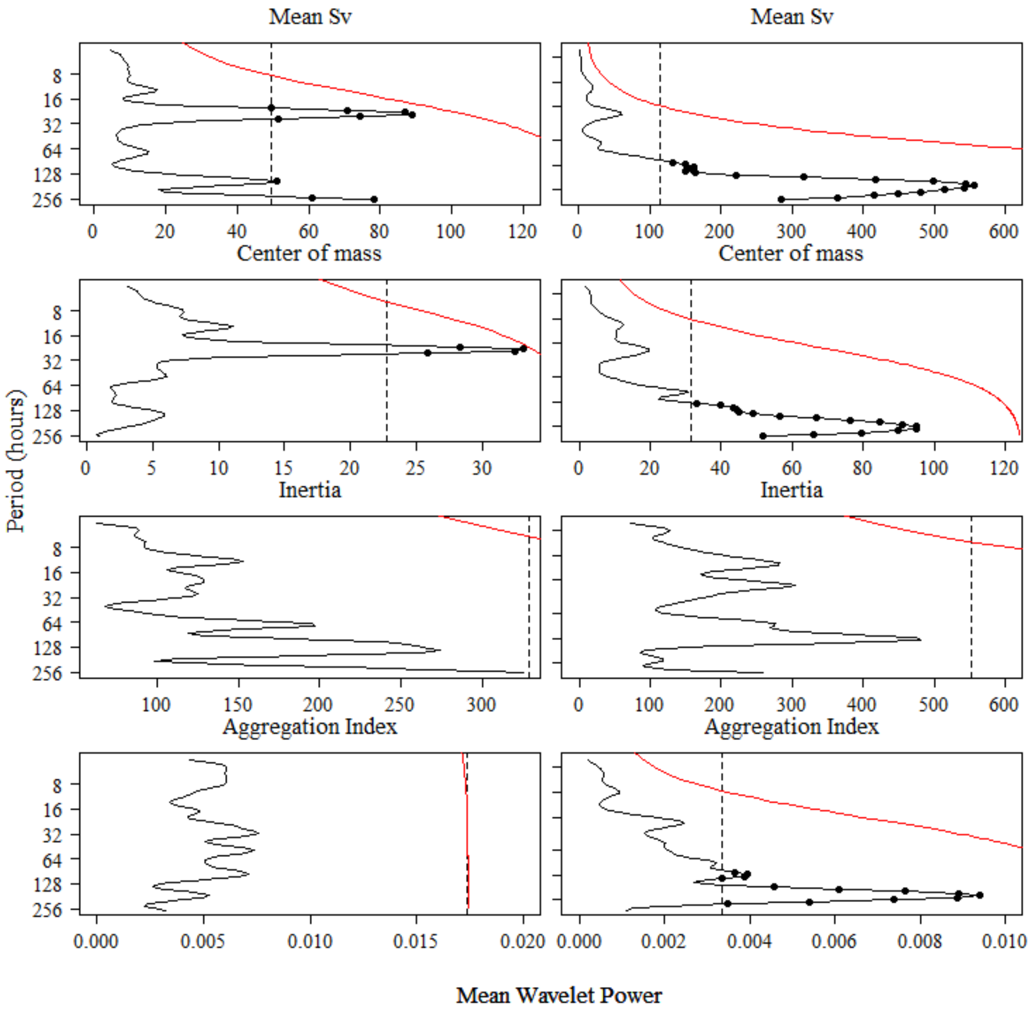

Fig. 4. Time averaged variance (global wavelet spectrum) of biological descriptors at the Admiralty Inlet (WA) tidal site (left panel) and the PacWave Energy Test Site (OR) wave energy site (right panel). Dashed black line represents white noise and the red solid line represents red noise.

Warness (Scotland) [7] and fish counts at Cobscook Bay (Maine, US) [19] tidal sites.

Differences in biological characteristics between tidal and wave energy sites (i.e. sector-specific characteristics) were also observed. One major difference between sites was the dominant periods of variation in biological characteristics. At the tidal site, dominant periodicities were shorter and more consistent through time compared to the wave site. In contrast, longer period processes dominated at the wave site as shown by significant peaks at longer periodicities and higher order autoregressive component in ARMA models. This difference in temporal variability is attributed to differences in the hydrodynamics of the sites. Admiralty Inlet is located at the confluence of waters with different oceanographic properties coming from Deception Pass, the Hood Canal basin, and the Puget Sound main basin [30]. Each of these water masses potentially carries distinctive species assemblages, so differences in biological characteristics could be expected between ebb and flood tides when different water masses are transported through the study site. The PacWave site is located in an open coastal area where water masses are more uniform during tidal cycles and changes in water masses occur over longer periods in response to changes in wind-driven circulation patterns [31], [32]. Diel patterns in density and location of organisms were relatively more important than tidal cycles at both sites as illustrated by greater wavelet power at the 24- compared to the 12-hour period. Fish and zooplankton species undergo vertical and horizontal diel (24-hour) migrations for feeding and predator avoidance in response to environmental cues such as changes in light intensity (e.g. [33]–[35]).

Although diel patterns were dominant at both sites, the influence of diel cycles on biological characteristics was not consistent within or between sites through the deployment. Density changes were more intermittent and lower in magnitude at the wave site compared to the tidal site. Changes in the relative importance of diel fluctuations could be due to multiple factors such as episodic decreases in light intensity (e.g. cloud cover), or occurrence of storms that can mix the water column and attenuate diel migration patterns. Diel patterns are species and life-stage specific [36], [37], so changes in species and size composition of the community could also explain changes in dominant periodicities of biological fluctuations observed in this study. At the wave site an increasing trend in biomass density suggests that

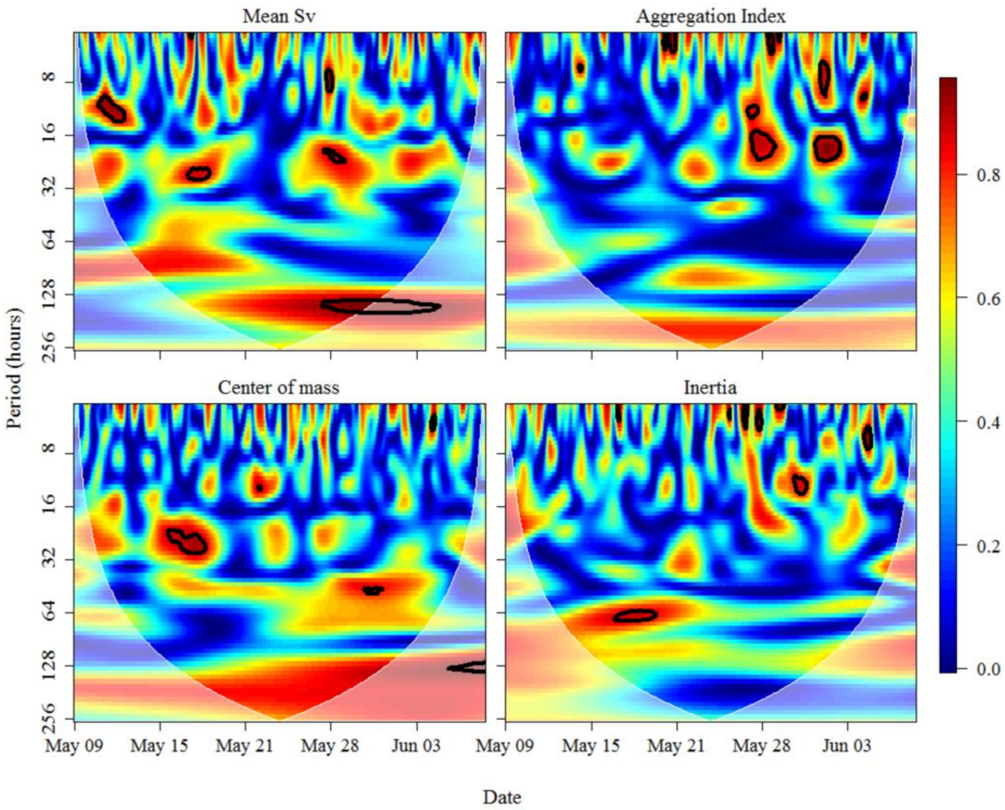

Fig. 5. Wavelet coherence in biological characteristics (Mean Sv, center of mass, inertia, and aggregation index) between the Admiralty Inlet (WA) tidal site and the PacWave energy site. Areas of significance are traced with a black line. Color bar represents coherence.

sampling may have occurred during a transition with new species or size groups entering the study area. Sampling at the wave site (May-June) corresponds to the formation (April-May) and establishment (May-July) of seasonal upwelling off the Oregon coast [38]. Occurrence of seasonal coastal upwelling enhances nutrient availability and primary productivity, which ultimately translates into increased zooplankton and fish abundances [39], [40]. Acoustic observations of species ensembles may obscure the detection of diel patterns of individual species [19].

The study of temporal variability using stationary platforms including acoustic and other environmental sensors has great potential for biological monitoring at MRE sites (e.g. [9]). Stationary active acoustics can detect biological changes and trends in short (e.g. diel migrations) to long (e.g. tidal dynamics, seasonal) period fluctuations at highly variable and energetic environments where traditional sampling is constrained. Autonomous acoustic sensors also provide advantages over shipboard spatial surveys by reducing or eliminating: (1) long term cost and effort required to acquire data; (2) bias in measurements due to ship avoidance behaviours by marine animals; and (3) convolution of temporal and spatial variability that occurs during mobile, spatial surveys [41]. A previous comparison of active acoustic technologies showed that scientific echosounders can identify patterns not present in data from ADCPs or acoustic cameras, and were therefore recommended to monitor fish density at tidal energy sites [9]. Internationally accepted calibration protocols for scientific echosounders [10], [42] ensure equivalency among datasets, which is crucial to make progress in understanding effects of the MRE industry on marine environments. For instance, if effects are not site-specific but device-specific, then alternate device designs can be selected or mitigation measures can be regulated to minimize impacts.

Acoustic sampling technologies are constrained like any other sampling device. Acoustic data alone rarely provides sufficient information for species identification [43]. For the MRE industry, species discrimination and identification is particularly relevant when addressing regulations for species of special status. Supplementary information from literature, increased acoustic frequency spectrum, direct net sampling, and optical sampling can be used to verify acoustic targets. The quality of acoustic data can also be affected by entrained air [44] in surface layers typically found in the high velocity environments of tidal energy sites. Although automated methods to remove turbulence are being developed (e.g. [45]), methods to filter or predict backscatter in turbulent areas are still needed to allow a full characterization of the water column using acoustics. Despite covering a wide spectrum of temporal scales (e.g. seconds to months or years), point source measurements using stationary acoustics do not include a large range of spatial scales when characterizing variability in animal densities or

TABLE III
COVARIATES AND P-VALUES FROM LINEAR REGRESSIONS FOR ADMIRALTY INLET TIDAL SITE AND THE PACWAVE SITE TIME SERIES. * INDICATES SIGNIFICANT P-VALUES (< 0.05). TR:D IS THE INTERACTION BETWEEN TIDAL RANGE AND JULIAN DAY, AND REPRESENTS THE MOON PHASE. 24H SIN AND COS ARE THE SINE AND COSINE COMPONENTS OF A 24-HOUR PERIODICITY.

	Tidal site		Wave site	
	Estimate	p-value	Estimate	p-value
Mean Sv				
Tidal range	4.22e–02	4.16e–09*	-1.53e–02	0.034*
Julian day	3.33e–01	6.07e–12*	4.42e–01	4.53e–16*
TR:D	-2.91e–04	8.61e–09*	9.38e–05	0.05*
24H sin	-1.30	3.48e–07*	-1.044	0.000732*
24H cos	2.13	6.05e–16*	1.47	2.42e–06*
Center of mass				
Tidal range	-8.14e–03	0.000483*	-1.84e–02	0.000517*
Julian day	–	–	-2.39e–01	9.25e–10*
TR:D	5.34e–05	0.000908*	1.25e–04	0.000501*
24H sin	-1.40	2.87e–13*	–	–
24H cos	7.57e–01	4.94 e–05*	–	–
Inertia				
Tidal range	-2.44e–02	0.01*	4.95e–02	0.0273*
Julian day	–	–	7.03e–01	1.76e–05*
TR:D	1.74e–04	0.0099*	-3.25e–04	0.0320*
24H sin	–	–	-1.48	0.1215
24H cos	–	–	2.4	0.0124*
Aggregation index				
Tidal range	-9.72e–05	0.05*	–	–
Julian day	–	–	-0.02	<2e-16*
TR:D	–	–	–	–
24H sin	7.58e–02	3.44e–02*	0.04	0.07447
24H cos	-9.82e–02	6.20e–03*	-0.13	2.27e–08*

behaviours. By quantifying the spatial area that is represented by a point source measurement (i.e. representative range, [46]), we can ensure an appropriate characterization and monitoring of biological communities, and at the same time, optimize the cost-effectiveness of remote monitoring. Pre-installation spatial characterization through concurrent acoustic mobile surveys and point source measures can be used to calculate the spatial representative range and define the number of monitoring packages needed to optimize sampling for environmental monitoring goals.

Data processing that reduces acoustic data volumes and automates analysis is required to ensure timely responses to changes in biomass distributions during MRE monitored operations. Storage, processing, and analysis of large volumes of acoustic data over long-term deployments can be challenging [41]. Advantages of using distributional metric suites include the reduction of large acoustic data volumes into a manageable and informative form. Metric suites can be used as ecological indicators. Ecological indicators are intended to examine composition (e.g. number and variety of species), structure (e.g. vertical distribution pattern) and function (e.g. ecological processes) of ecosystems to assess the magnitude of stress, degree of exposure, and ecological responses to stress [47], [48]. Mean Sv and center of mass monitor ecosystem structure whereas inertia and the aggregation index tracks changes in ecosystem function [7]. These metrics can also be used to detect and describe potential responses of fish and macrozooplankton to MRE devices. Moving devices generate noise and electromagnetic fields that can be evaded or avoided by fish [1], [49]. Aggregation behaviours can also be expected as new structure in a homogeneous seascape can potentially act as fish aggregation devices (FADs) and can provide refuge from high speed currents in the wake of the device [1], [50], [51]. Removal of hydrokinetic energy may change local hydrodynamics affecting turbulence and stratification patterns that in turn, can affect vertical movements of organisms [1]. Avoidance and aggregation effects can be measured as a decrease or increase in mean Sv values, and changes in vertical distribution patterns can be measured as changes in center of mass, inertia, and aggregation index.

TABLE IV
ESTIMATED SIGNIFICANT COEFFICIENTS FOR REGRESSION AUTOREGRESSIVE MOVING AVERAGE MODELS THAT DESCRIBE BIOLOGICAL CHARACTERISTICS OF TIDAL AND WAVE ENERGY PILOT SITES.

	Mean Sv		Center of Mass		Inertia		Aggregation Index	
	Tidal Site	Wave Site	Tidal Site	Wave Site	Tidal Site	Wave Site	Tidal Site	Wave Site
ARMA coefficients								
AR1	0.15	1.33	–	1.28	0.10	0.20	–	0.70
AR2	–	-0.62	–	-0.42	–	0.00	–	–
AR3	–	0.23	–	-0.03	–	-0.07	–	–
AR4	–	–	–	0.10	–	-0.06	–	–
AR5	–	–	–	–	–	0.14	–	–
MA1	–	-0.66	-0.87	-0.77	–	–	-0.05	-0.31
MA2	–	–	-0.21	–	–	–	0.08	–
MA3	–	–	-0.07	–	–	–	0.09	–
MA4	–	–	0.17	–	–	–	0.11	–
SAR1	0.25	0.18	–	–	–	–	–	–
Covariate coefficients								
Tidal range	0.05	-0.12	-0.06	-0.05	0.07	0.08	0.00	–
Julian day	0.18	0.71	–	-0.37	–	0.30	–	-0.45
TR:D	-0.29	0.03	0.08	0.11	0.17	-0.09	–	–
24H sin	-0.32	-0.17	-0.50	–	–	-0.11	0.15	0.12
24H cos	0.53	0.24	0.28	–	–	0.18	-0.20	-0.36
24H total	0.62	0.29	0.58	–	–	0.21	0.25	0.38

Wavelets and Reg-ARMA enabled the detection of generic and specific biological features of the MRE sites and are therefore recommended as standard tools for the analysis of biological monitoring data. Wavelet analysis detected differences in biological patterns across sites, which illustrates its potential for detecting changes before and after the installation of MRE devices—a required attribute to be an effective tool for environmental monitoring. Reg-ARMA models were used to identify relevant environmental factors that shape biological patterns and are important in the forecast of biological responses (e.g. [52]). These models quantified amplitudes and periodicities of all metrics except inertia (at both sites) and amplitudes of the aggregation index (at the tidal site). Other environmental covariates (e.g. current speed, temperature, stratification) or alternate models may be needed to capture amplitudes of all biological fluctuations. A set of models have been recommended to quantify pre-installation conditions [27] and measure environmental change [52], based on the statistical properties of ecological indicators (normal and non-normal distributions), quantity of interest (mean or variance), and application (detection, quantification, or forecast of change).

A standard approach for pre-installation characterization and post-installation monitoring enables comparisons among sites, and will streamline the current, long and expensive MRE permitting process [6], [53]–[55]. To date, monitoring plans have been designed for individual sites and species of special status (e.g. harbour seal populations at the SeaGen tidal site and southern resident killer whales at Snohomish Public Utility District 1 tidal site). Moreover, choices of monitoring technologies and sampling resolutions have differed among tidal energy sites within the U.S. (e.g. Coobscook Bay (MA) [44] vs Admiralty Inlet (WA) [45]). Near identical acoustic sampling used at the Admiralty Inlet (US) and the Fall of Warness (UK) tidal energy sites enabled the characterization and comparison of fish and macrozooplankton densities, with results suggesting that standardization of biological monitoring within the tidal MRE sector is feasible [7]. In this study a comparison of wave and tidal energy sites representing two sectors of the MRE industry suggests that standard remote sensing technologies (stationary active acoustics), biological indicators (echometrics), and analytic methods (wavelets and Reg-ARMA models) could be used for biological monitoring across all sectors in the MRE industry.

While standard monitoring practices are desirable to facilitate sustainable development of the MRE industry, site-specific characteristics should be used to tailor monitoring plans. Pre-installation characterization data are needed to identify dominant temporal scales in biological characteristics and then used to set sampling resolutions to minimize monitoring costs while maximizing the quality of monitoring data (i.e. optimization). Timing of post-installation sampling can also be determined using pre-installation characterization data. For instance, if natural variations in a monitoring metric are associated with tidal states, then sampling

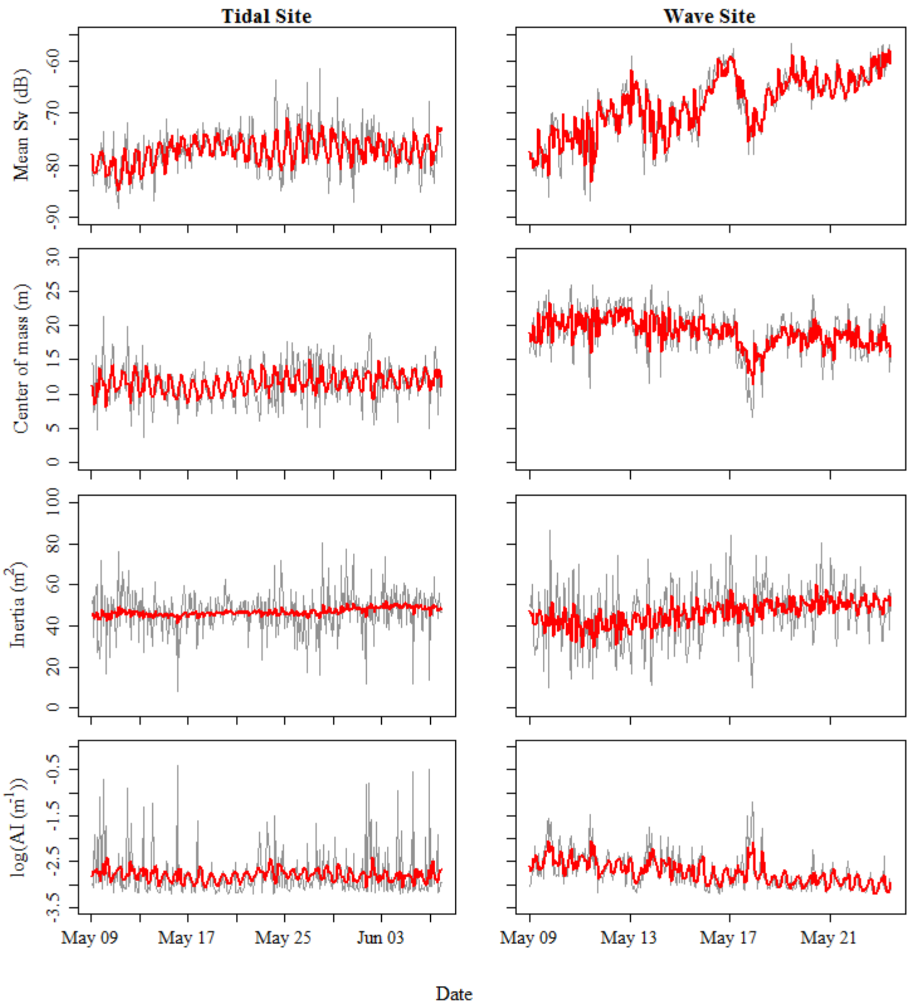

Fig. 6. Regression Autoregressive Moving Average models for mean Sv, center of mass, inertia and aggregation index for a tidal and a wave energy site. Raw data are in grey and in red are shown the mean model predictions.

should occur at the same tidal state or averaged across tidal states to detect change rather than patterns being convolved over time due to sampling. This approach using continuous acoustic data can also be used to design discrete sampling (e.g. net tows) [58]. Identification of environmental covariates is important when forecasting and discriminating sources of biological change. During pre-installation monitoring, environmental variables believed to influence biological temporal patterns should be measured and included in data analyses to identify environmental forcing of natural variability at each site. Identified variables should then be monitored along with response variables during post-installation monitoring to help distinguish biological changes associated with MRE from natural variability. Assuming that representative data are obtained, pre-installation acoustic data can be used to define thresholds of change in monitored variables at a site [59].

V. Conclusion

Stationary active acoustics is a cost-effective tool to sample biological communities through the entire water column over long periods of time in variable or high-energy aquatic environments. Acoustic-derived density measurements are a strong candidate as a common/standard data stream to be used for biological monitoring across sectors of the MRE industry. Standard practices (e.g. sampling methods and analytic approaches) are possible for biological monitoring at MRE sites but should be adapted to site/sector-specific characteristics (e.g. major influencing covariates and periodicity). Pre-installation characterization is important to quantify natural variability and to tune monitoring strategies to include site-specific characteristics for post-installation monitoring. This approach will maximize cost-effective detection, understanding, and prediction of MRE development impacts on the environment. Current climate change and declines in non-renewable energy sources accentuate the need for alternatives to fossil fuels to meet energy demands. Monitoring strategies that facilitate the development of MRE industry while preserving aquatic ecosystems are required to sustain environmental viability.

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