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Biodiversity characterisation and hydrodynamic consequences of marine fouling communities on marine renewable energy infrastructure in the Orkney Islands Archipelago, Scotland, UK

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ABSTRACT
As part of ongoing commitments to produce electricity from renewable energy sources in Scotland, Orkney waters have been targeted for potential large-scale deployment of wave and tidal energy converting devices. Orkney has a well-developed infrastructure supporting the marine energy industry; recently enhanced by the construction of additional piers. A major concern to marine industries is biofouling on submerged structures, including energy converters and measurement instrumentation. In this study, the marine energy infrastructure and instrumentation were surveyed to characterise the biofouling. Fouling communities varied between deployment habitats; key species were identified allowing recommendations for scheduling device maintenance and preventing spread of invasive organisms. A method to measure the impact of biofouling on hydrodynamic response is described and applied to data from a wave-monitoring buoy deployed at a test site in Orkney. The results are discussed in relation to the accuracy of the measurement resources for power generation. Further applications are suggested for future testing in other scenarios, including tidal energy.

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Biofouling; floating pontoon; harbour; wave; buoy; invasive non-native species

Introduction

The Scottish Government has set the objective of delivering the equivalent of 100% of electricity from renewable sources by 2020 (Scottish Government 2013). The assessment of the potential for electricity generation from these sources has created significant interest in Orkney as being highly suitable for large-scale deployment of wave and tidal energy converting devices. The European Marine Energy Centre (EMEC) was established in Stromness in 2003, to test marine renewable energy devices (MREDs) in the resource-rich waters around Orkney (EMEC 2016). Subsequently, in March 2010, The Crown Estate (TCE) announced leasing agreements with several developers and energy providers for deployment of devices, predominantly within Orkney waters and the Pentland Firth (CE 2010). Since its inception, EMEC has hosted over 17 wave and tidal developers testing 27 subsea and surface energy converters (EMEC 2016).

Owing to a rich local tradition of working in the sea, Orkney has a well-developed infrastructure supporting the marine energy industry, recently enhanced with the construction of additional piers and harbour structures designed to facilitate the growth of the marine energy sector. Through the establishment of grid-connected and scale test sites for both wave and tidal energy, EMEC has helped develop marine infrastructure to support device testing including subsea electrical cables, surface buoys, moorings, and an environmental monitoring pod used for integrating environmental sensor data gathering.

A major concern to industries working in the marine environment is biofouling: the settlement and growth of organisms on submerged structures. Biofouling has been a recognised concern for mariners since ancient times (Almeida et al. 2007). Impacts of marine growth on shipping are well known and have been researched from hydrodynamic (Houghton & Gage 1979; Coutts et al. 2010) and economic perspectives (Schultz et al. 2011), and have led to development of coatings to protect ships' hulls and promote fuel efficiency. In shipping, biofouling is often viewed as simply a nuisance, albeit with serious economic consequences owing to increased fuel

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expenditure, costs of removing fouling, and replacement of corroded components. In the oil and gas industry, concerns have focused on loading issues caused by biofouling of offshore structures (Baltrop & Adams 1977). Ecological concerns exist over the role that artificial structures in the marine environment may have in creating 'stepping-stone' habitats for the spread of fouling communities, including non-native species (NNS) (Apte et al. 2000; Floerl et al. 2009; Nall et al. 2015).

In the marine renewable energy sector, increased weight and drag from biofouling of wave and tidal devices may compromise device performance in two general ways: changes in the hydrodynamic performance of power delivery, and alterations to structural loading on the device itself or on its moorings. Many wave devices rely on their dynamic response to operate, while tidal stream devices rely on rotor dynamics. Biofouling may affect the response and efficiency of both wave and tidal devices. As the marine renewable energy (MRE) sector develops, biofouling issues are being recognised that are specific to this industry. Aspects of devices that may be particularly affected by biofouling include: utilising moving parts unique to MREDs (Tiron et al. 2015); introduction of novel materials used in ways that have not been trialled before in marine environments (Polagye & Thomson 2010); and deployments taking place in habitats where structures have not been previously installed and studied (eg in strong tidal flow areas) (Shields et al. 2011).

There exists a paucity of published research in this field owing partly to the early developmental stages of wave and tidal energy technologies, and to confidentiality concerns with what may be considered commercially sensitive studies (Shields et al. 2011). Marine energy technologies are considerably varied at present, typical of an emerging industry (Twidell & Weir 2015). Indeed, both wave and tide resources present unique engineering and maintenance challenges for their respective hydrodynamic loading environments, for which widely differing solutions have been proposed by technology developers. To investigate the effects that biofouling has on MREDs requires an understanding of the type of structure, eg floating, fixed, turbines, and the mechanics of operation.

In addition to affecting device hydrodynamics and survivability of materials, the consequences of biofouling to the MRE sector include compromised functioning of sensors used to accurately characterise energy resource and monitor device performance. Industry standard sensors include buoys, for collecting wave and environmental data, and acoustic Doppler current profilers (ADCPs), for collecting tidal current data. At EMEC, the current maintenance regime is to undertake regular (~12 months) servicing of buoys and their moorings in order to change batteries, clean or replace moorings, and remove biofouling, as necessary. The choice of maintenance interval is primarily dictated by battery life, as opposed to build up of biofouling. Similarly, deployment and retrieval of ADCPs is scheduled by battery life and data retrieval, depending on specific application. Additional variability in the period of instrument deployment results from highly changeable sea conditions typical of high marine energy resource locations which limit operations owing to shortened weather 'windows'. While the primary function of wave buoys and ADCPs in this sector is to collect hydrodynamic and other environmental data, these structures provide valuable information of fouling communities in poorly studied habitats. Wave records over this period may allow comparative studies to be made of buoy data in both 'clean' (early in deployment) and 'fouled' (late in deployment) states.

Given these issues, the aims of this work were to provide baseline information regarding the composition and degree of biofouling on marine devices and infrastructure of relevance to the marine energy sector, and to illustrate, in a case study, how biofouling may influence the performance of data buoy recording accuracy in deployed settings. Surveys focused on the main harbours and marinas around the Orkney Islands archipelago and, as the opportunity arose, on MREDs and monitoring instrumentation; these studies investigated whether biofouling communities varied between these different locations. A case study was developed which focused on the effects of biofouling on device performance and whether or not these effects can be identified from received buoy data. This might allow for remote assessment of the degree of biofouling extant on the buoy and thus the necessity for remedial maintenance. Based on these studies, recommendations for maintenance and deployment scheduling of MREDs and data buoys may be made to best mitigate the consequences of biofouling to this sector.

Methods

Biofouling community surveys

Between May and June 2015 marine surveys were undertaken at 10 locations around the Orkney Archipelago to assess the biodiversity of submerged marine fouling communities, and for comparative purposes at Scrabster Marina, Caithness (Figure 1). Surveys were conducted at harbours and marinas throughout the archipelago where MRED deployment and service vessels operate. In addition, three structures associated with the marine renewable energy industry were evaluated at EMEC test areas during this same period: Waverider buoys at Billia Croo and the Bay of Sandoyne; and a frame-mounted fixed ADCP at the Fall of Warness. The fixed ADCP was resurveyed in January 2016.

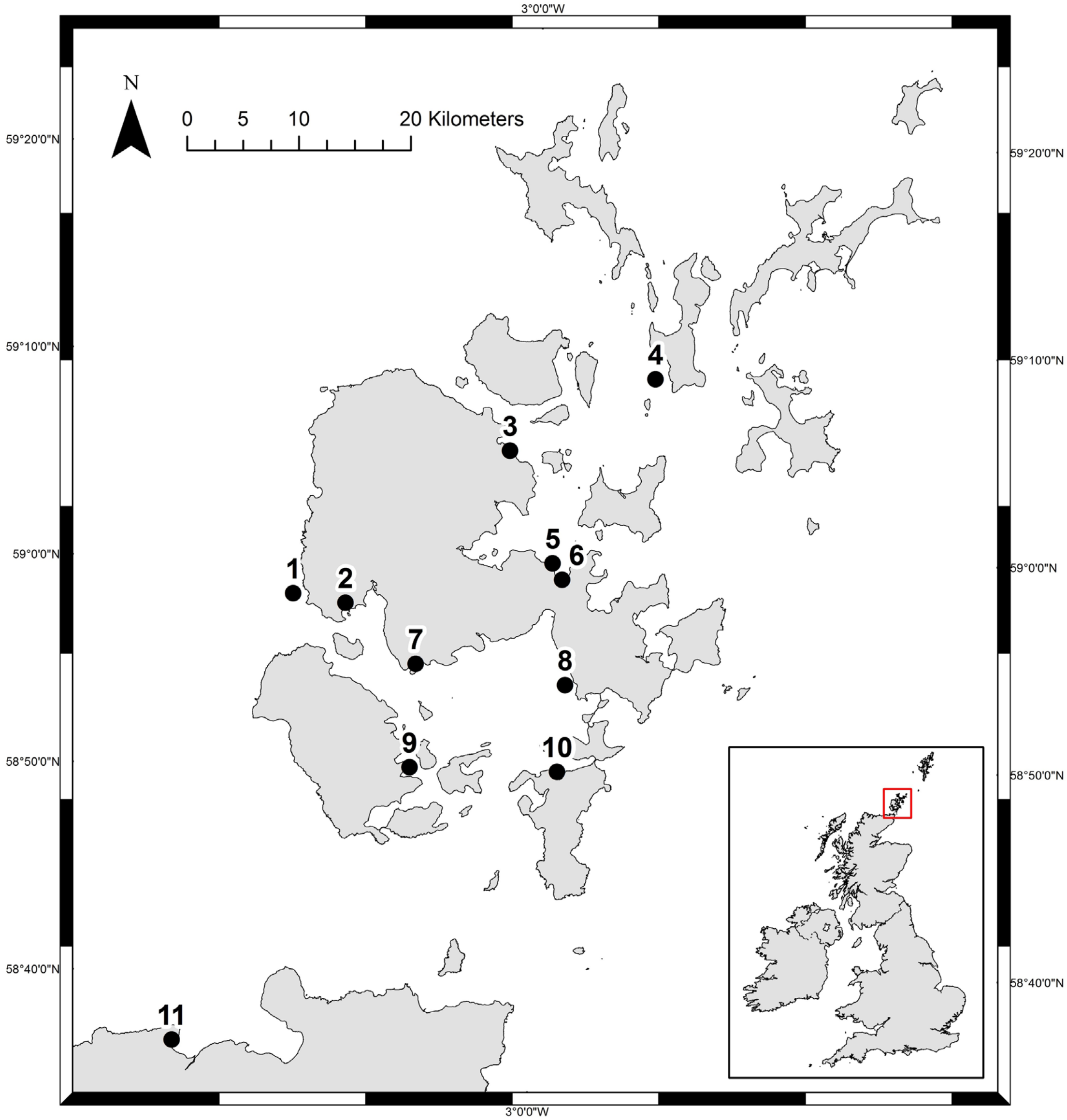


Figure 1. Map of the sampling sites in Orkney waters and the Pentland Firth. (1) Billia Croo; (2) Stromness (including Polestar and Copland's piers, and the marina); (3) Tingwall; (4) Fall of Warness; (5) Hatston; (6) Kirkwall Marina; (7) Houton; (8) Bay of Sandoyne; (9) Lyness, Hoy; (10) St Margaret's Hope, South Ronaldsay; and (11) Scrabster Marina, Caithness.

The current studies aimed to record as comprehensive a list as possible of fouling species present at each site and to identify the most dominant species based on qualitative assessment of contribution to total fouling. The team employed a rapid assessment survey approach based on Arenas et al. (2006) and was led by a member of this previous study; to ensure consistent application of effort at each location, surveys were conducted to equal a 1-h search by a team of four. The team was comprised of trained experts in major fouling groups and NNS including ascidians, barnacles, bryozoans, colonial fauna, hydroids, and macroalgae. Team members recorded species and abundances independently but confirmed identification with other members with specialist expertise, when necessary. Lists of species were recorded as they were sighted and qualitative characterisation of each site based on identifying the most dominant members of the fouling assemblage (typically two or three species) was determined. Photographic records were made using a digital SLR camera (Nikon D7100, Tokyo, Japan); Figure 2 illustrates some examples of the field locations and the types of habitat surveyed.

Laboratory analysis

When necessary, species not easily identifiable in the field were collected for identification in the laboratory, eg using microscopy. Samples of particular significance, eg rare or non-native species, were preserved in 70% ethanol

Figure 2. Field survey images (clockwise from upper left): sample identification at Tingwall harbour; Waverider buoy from Billia Croo; and camera lens on acoustic Doppler current profiler (ADCP), Fall of Warness.

for voucher material to be deposited in an appropriate repository for long-term curation.

Statistical analysis of biofouling communities

Species occurrence data from the survey locations were entered into an Excel spreadsheet and imported into Primer v6 software for analysis of biological community composition (Clarke & Gorley 2006). Bray–Curtis similarities (Digby & Kempton 1987) were used to quantify resemblance of species presence–absence composition between samples. Groupings of samples with similar species were identified using non-metric multi-dimensional scaling (MDS) ($\alpha = 0.1$). Data plots were used to represent the similarities in two dimensions. Analysis of similarity (ANOSIM) function was used to explore how biofouling communities differed between harbours, marinas, wave test site infrastructure and tidal test site infrastructure. Similarity percentage analysis (SIMPER) was used to identify which species were most responsible for differences between these groupings (Clarke 1993).

Case study – data buoy fouling response

Figure 3 shows EMEC's (Directional) Waverider (DWR) MkIII buoy (Datawell 2016) studied after retrieval for maintenance. This and similar buoys have been deployed continuously at the Billia Croo wave test site in Orkney (Figure 1) for the past 12 years for measuring wave height, period, and direction.

The use of a wave data buoy as a test platform was considered appropriate for this study based on several important features. A wave data buoy is: (1) a MRE industry-accepted measurement unit in which dynamic

Figure 3. Datawell DWR MkIII data buoy with approximately 12 months accumulation of biofouling from the EMEC wave test site at Billia Croo, Orkney.

response is accurately measured and the effects (eg heave) may be used as an indicator of biofouling; (2) a physically small unit with expected large biofouling/body mass ratio allowing increased sensitivity to biofouling in comparison to large offshore structures; (3) a relatively simple shape with an uncomplicated mooring system allowing easier analysis of hydromechanics and system simulation through numerical modelling; (4) installed long term, allowing study over a sufficient timescale to detect seasonal biofouling and community changes; (5) accessed relatively easily, allowing regular monitoring.

This case study involved numerical modelling of a data buoy to provide a parametric analysis of heave response (vertical displacement) and how this may be impacted by biofouling, along with interpretation of received data from a field data buoy deployed at EMEC's wave test site (for wave energy converters) at Billia Croo. Significant wave height and period data obtained from EMEC's wave buoy allowed identification of similar sea states at differing temporal stages in the biofouling succession, thus providing a basis for isolating the effects of biofouling on measurement of wave statistics.

Numerical modelling of data buoy

A 3-D model was constructed using OrcaFlex software (OrcaFlex 2016) to simulate buoy response under varying sea states. In this part of the study only biofouling on the buoy was considered; mooring line influences were deemed secondary (in this preliminary investigation). The level of biofouling was incorporated by varying specific buoy input parameters[1]: mass, moments of inertia, centre of mass, drag and added mass coefficients, and unit damping force, as well as buoy radius. Known major biofouling species in this site (acorn barnacles, kelp, and mussels) and their effects were assessed for each of the above variables, eg for mass, various species of kelp observed on buoys have neutral buoyancy; these organisms should not affect the mass of the buoy at the surface or submerged. It should be noted however that certain species of fouling macroalgae, eg fucoids, possess gas-filled bladders. While these give the plant positive buoyancy, the effect on buoy mass when at the surface is assumed to be negligible. In contrast, in the event of buoy and bladders being submerged, these fouling seaweeds will tend to increase buoyancy. Sessile organisms (barnacles, mussels, limpets, etc.), however, have negative buoyancy and will add mass even when the buoy is submerged. Hallam et al. (1978) estimated that the mass of the object could be increased by up to 250 kg m^{-2} of surface area, depending on deployment depth and type of fouling.

For the Orcaflex numerical simulation, an International Ship and Offshore Structures Congress (ISSC) wave spectrum (also known as Bretschneider or modified Pierson–Moskowitz) (Tucker & Pitt 2001) was chosen to best model particular sea states at the Billia Croo test site. This model was applied to specific significant wave height (H_s) and peak period (T_p) values, under both moderate (H_s=4 m; T_p = 8 s) and extreme sea conditions (H_s=15 m; T_p = 12 s).

Field wave data analysis incorporating biofouling

As well as the numerical modelling study described above, field data from Datawell MkIII Waverider buoy deployed at EMEC's Billia Croo wave energy site were analysed. To investigate the effect of biofouling, two datasets were chosen, where wave buoys recorded similar sea conditions. The first dataset was taken from a newly deployed 'clean' buoy and the second dataset was taken from a 'fouled' buoy that had been deployed for approximately 10 months. Fast Fourier transforms were used on the raw heave data to create the spectra to be compared with numerical simulations (Newland 1984).

Results

Biofouling community survey

In total, 14 surveys of individual harbours, piers, marinas, and MRE infrastructure identified 141 fouling species (see Supplemental material), six of which were non-native to Orkney waters: *Caprella mutica*, *Colpomenia peregrina*, *Codium fragile fragile*, *Corella eumyota*, *Dasysiphonia japonica*, and *Schizoporella japonica*. Organisms contributing greatest to the overall cover of fouling at each survey location were qualitatively identified as 'dominant species' (Table 1). *Schizoporella japonica* at Hatston was the only instance where a NNS was considered dominant.

Based on abundance observations, these studies identified a subset of fouling organisms which play a major role in fouling in MREDs in these waters. These species were of particular concern owing to the extent of fouling on the structures. Information from published studies has

Table 1. Biofouling assessment sites (with decimal latitude and longitude) and species information.

Site	Date (2015)	TS	NNS	Dominant species
Tingwall 59.090° −3.042°	5 May	33	0	• *Semibalanus balanoides* • *Fucus spiralis*
Stromness marina 58.965° −3.295°	7 May	45	3	• *Mytilus edulis* • *Saccharina latissima* • *Semibalanus balanoides*
Kirkwall marina 58.987° −2.959°	11 May	48	5	• *Ciona intestinalis* • *Metridium senile* • *Laminaria digitata*
Bay of Sandoyne* 58.902° −2.936°	15 May	35	0	• *Amphisbetia operculata* • *Mytilus edulis* • *Semibalanus balanoides*
Houton 58.917° −3.184°	17 May	54	0	• *Semibalanus balanoides* • *Ulva intestinalis*
Stromness Polestar 58.959° −3.299°	19 May	32	1	• *Mytilus edulis* • *Semibalanus balanoides* • *Palmaria palmata*
St Margaret's Hope 58.832° −2.962°	3 June	39	1	• *Semibalanus balanoides* • *Fucus spiralis*
Billia Croo* 58.972° −3.373°	4 June	19	0	• *Alaria esculenta* • *Ectopleura larynx* • *Lepas anatifera*
Lyness, Hoy 58.834° −3.190°	5 June	30	0	• *Semibalanus balanoides* • *Patella vulgata* • *Fucus spiralis*
Copland's Dock, Stromness 58.960° −3.293°	16 June	23	1	• *Semibalanus balanoides* • *Porphyra umbilicalis* • *Fucus spiralis*
Scrabster, Caithness 58.611° −3.550°	16 June	28	2	• *Saccharina latissima* • *Ciona intestinalis*
Hatston 59.000° −2.974°	22 June	42	4	• *Ciona intestinalis* • *Schizoporella japonica* • *Obelia geniculata*
Fall of Warness** 59.149° −2.817°	23 June	18	0	• *Chirona hameri* • *Ectopleura larynx* • *Botryllus schlosseri*

*Waverider buoy (including moorings); **ADCP with frame – re-evaluated on 17 March, 2016.
TS = total species; NNS = non-native species.

allowed periods of reproductive activity and larval settlement to be identified (Table 2).

Using a 'traffic-light' system, periods of greatest settlement (red), intermediate settlement (orange), and least or no settlement (green) have been identified (Table 3). For many species, the prime settlement timing is in late spring–early summer. However, there are some exceptions such as *Saccharina latissima* and *Schizoporella japonica*, which are most reproductively active during the winter.

Statistical analysis of biofouling community

The multi-dimensional scaling (MDS) plot of fouling communities shows three clear groups of surveyed marine sites (Figure 4). Group 1 comprises all harbour locations, all marinas, and one of the Waverider buoys; group 2 comprises the Fixed ADCP frame surveyed twice from the Fall of Warness tidal test-site; and, group 3 is a single record from a Waverider buoy located at the Billia Croo wave test-site off the West Mainland of Orkney. The 2-D stress of the MDS plot is 0.08, indicating good level of support for the observed groups (Clarke 1993).

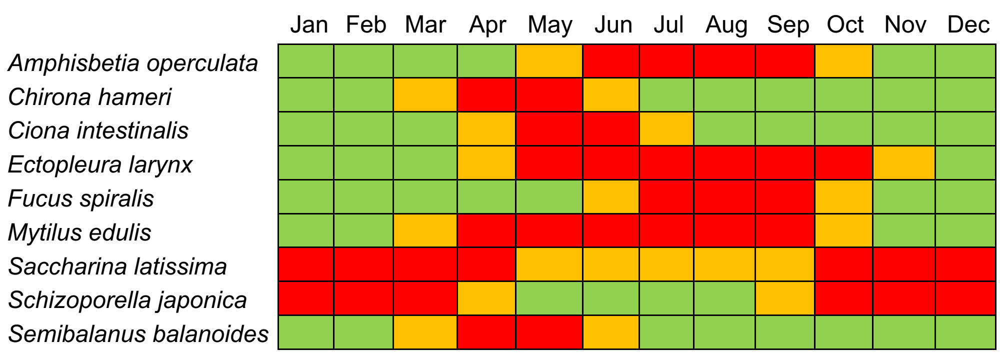
ANOSIM confirmed that there was a statistically significant difference in community composition between substratum types (global $r = 0.724$; $p = 0.001$). MDS analysis identified three discrete groups, as described above. SIMPER analysis was performed which identified species contributing most to dissimilarities between groups

Table 2. Dominant fouling organisms associated with MREDs in Orkney, including the known seasonality of fouling periods in the North Atlantic.

Biofouling organism	Common name	Reproductive(R)/settlement (S) period (reference)
Amphisbetia operculata	A hydroid	June–September (R) (Cornelius 1995)
Chirona hameri	A subtidal barnacle	April–May (S) (Crisp 1962)
Ciona intestinalis	A sea squirt	May–June (S)[1] (MBA 1957)
Ectopleura larynx	A hydroid	May–October (S) (Schuchert 2012)
Fucus spiralis	Spiral wrack	Late summer (S) (MarLIN 2016)
Mytilus edulis	Common mussel	Spring & late summer (S)[2] (Seed 1969)
Saccharina latissima	Sugar kelp	October–April (R) (Parke 1948)
Schizoporella japonica	A bryozoan	Winter (R) (Ryland et al. 2014)
Semibalanus balanoides	An intertidal barnacle	April–May (S) (Southward 1991)

[1]Year-round reproductive activity
[2]Protracted settlement with regional variability.

Table 3. Periods of settlement associated with the major fouling organisms.



Months in red indicate the highest recognised settlement season; orange months are of intermediate concern, and green months are of least concern.

(Figure 4). In the larger group, these species included *Fucus spiralis*, *Ulva lactuca*, Laminarians, and the barnacle *Semibalanus balanoides*; in the tidal test-site group, these species included *Botryllus schlosseri*, *Ophiothrix fragilis*, and *Chirona hameri*, the latter found only in the Fall of Warness, in this study. Dissimilarity between these groups is expected: the larger group contains shallow water fouling species where photosynthetic algae are often key members of the assemblage; in contrast, sublittoral habitats, such as the tidal test-site, become increasingly animal-dominated with greater depths. The importance of water depth and hydrodynamic forces as selection factors in major biofoulants is evident in the species of barnacles found in these study habitats: in heavy wave conditions, one of the key foulers on surface buoys was the littoral *Semibalanus balanoides*; on the hard moorings of these buoys (at depths below the photic zone), the fouling assemblage included the larger *Balanus crenatus*; and, in the high current habitat at the Fall of Warness (depth ~35 m), the dominant fouler was the massive *Chirona hameri*. Images of key species from SIMPER analysis, along with two examples of non-native fouling species, are shown in Figure 5.

Dynamic assessment of data buoy

Spectral analysis of numerical model

The effects of biofouling on wave buoy measurements were simulated for different wave conditions by varying H_s, the wave period, and the degree of biofouling. Simulations were run for various spectral parameters (ISSC spectrum; H_s and T_p) to assess the effects of biofouling on the heave response of the buoy system. Little variation was observed in the low frequency response of the spectrum and therefore attention was placed on the higher frequency range of the response (>0.3 Hz). For illustration purposes, frequency responses of the buoy, representative of moderate sea conditions at Billia Croo, are shown in Figure 6 with attention drawn to spectral moments applied to the higher frequency range. Table 4 shows an example of the first five spectral moments obtained from a typical test series for the high frequency end of the wave spectra.

Although a limited series of tests was undertaken, biofouling was observed to have little to no effect on the low frequency response, whereas high frequency response is reduced with increased amounts of biofouling (Figure 6). These effects are not unexpected; a buoy with increased

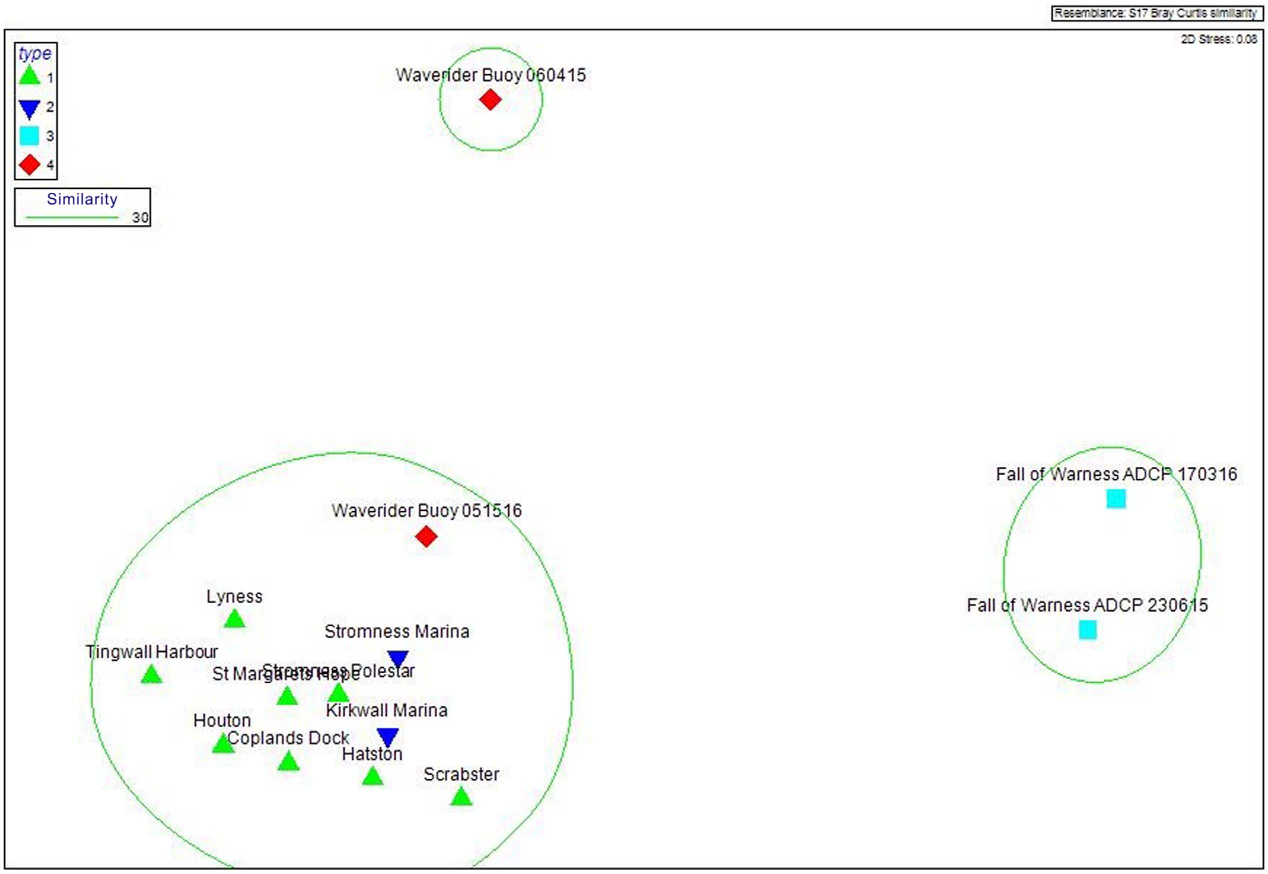


Figure 4. MDS plot using biofouling community data associated with various types of substratum: (1) harbour walls; (2) marina pontoons; (3) fixed ADCP outer surface and frame; and (4) Waverider buoys and moorings. Ellipses represent groups identified by average-linkage cluster analysis based on Bray–Curtis similarities.

mass and radius should not be able to track high frequency changes in sea elevation as accurately as a non-fouled buoy. From the series of test runs, an overall reduction in M_0 (zeroth moment, representing the area under the spectrum) was seen, from 'no' to 'heavy' fouling of up to 2%. When considering simulated storm conditions based on field data from the EMEC site, a change was observed (from 'no' to 'heavy' fouling) in M_0 of 10% associated with the high frequency response, compared with a 1% change in the overall spectral moment M_0.

Analysis of EMEC Waverider buoy field data

During the study, initial investigation was made into the field data to assess whether any clear biofouling 'signature' could be identified. This entailed the analysis of buoy heave spectra for clean and fouled conditions; a suitable pairing of sea conditions was identified (Table 5). While data collection from simultaneously operating 'clean' and 'fouled' buoys is preferred, deployment scheduling of data buoys by EMEC at their wave test site meant that this was not possible at the time of the present study. Based on numerical response data and known wave buoy behaviour, it was assumed that a high-frequency source (ie small wavelets) was present in both conditions, and that biofouling might affect responses at these frequencies. When compared with numerical simulation model results, similar trends in the spectral moments were observed in buoy field data, ie M_0 reduction of 13% for high frequency response, compared with a 1% change in the overall spectrum moment M_0. While this was a limited data sample, it corroborates the outcomes of the numerical simulations using the OrcaFlex model. More studies are necessary to clearly identify if this can be used as an indicator for heavy fouling and to inform cleaning scheduling. The regularity of buoy maintenance at EMEC does not allow the option of monitoring a 'very heavily' fouled buoy as their interval of maintenance is normally less than one year.

Discussion

The aim of the study was to provide baseline information regarding community composition and the degree of biofouling on MREDs and supporting infrastructure, and to illustrate, using a case study, how an understanding

Figure 5. SIMPER analysis highlighted several species as contributing most to the distinction between sample groups. Clockwise from upper-left: *Schizoporella japonica* (NNS) on tidal energy device; *Semibalanus balanoides* on harbour wall; *Ulva lactuca* on Waverider buoy; *Chirona hameri* on tidal mooring; *Corella eumyota* (NNS) on marina pontoon, and *Botryllus schlosseri* on fixed-ADCP.

of these data can be applied to assess the performance of data buoys in deployed settings. The first aim was achieved by conducting surveys of the main harbours and marinas around the Orkney Islands archipelago, as well as on MREDs and monitoring instrumentation, as the opportunity arose. Key species have been identified that are chiefly responsible for biofouling in the different survey habitats. For example: in more sheltered shores, where marinas and harbours are sited, major fouling species include *Semibalanus balanoides*, *Fucus spiralis*, and *Mytilus edulis*; in extreme wave exposure conditions off West Mainland, Orkney, shallow depth fouling is dominated by *Alaria*

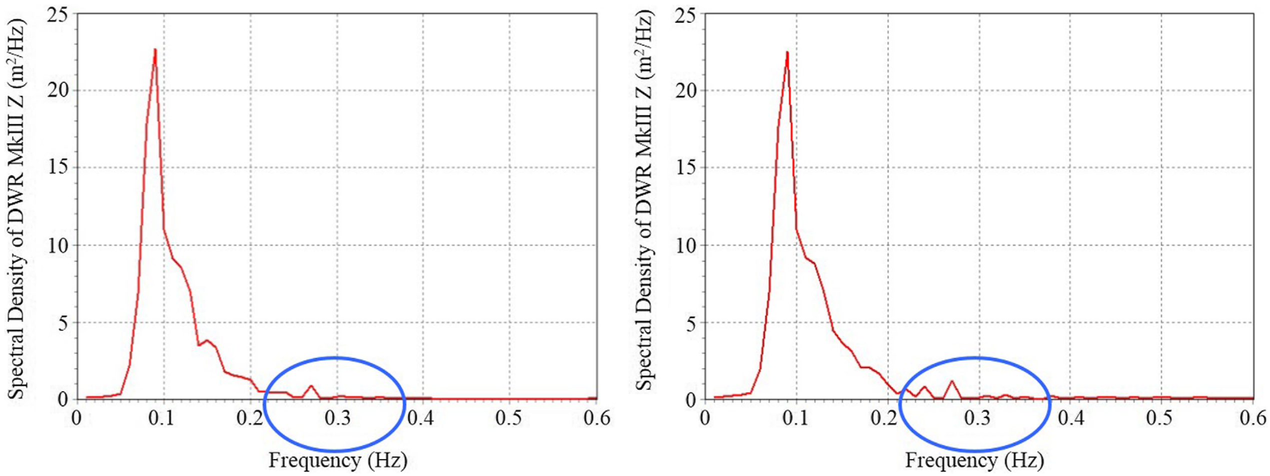


Figure 6. ISSC spectral density of buoy heave response (H_s 4 m, T_p 8 s). (Left) no fouling; (right) heavy fouling. Higher frequency spectral components are identified in the circles.

Table 4. Values of heave spectral moments using simulated biofouling (>0.3 Hz, H_s 4 m, T_p 8 s).

Simulation	M_0 (m^2)	M_1 ($m^2\ s^{-1}$)	M_2 ($m^2\ s^{-2}$)	M_3 ($m^2\ s^{-3}$)	M_4 ($m^2\ s^{-4}$)
No fouling	1.0886	0.1317	0.0276	0.0261	0.1121
Light	1.0857	0.1321	0.0294	0.0305	0.1145
Medium	1.0793	0.1345	0.0317	0.0364	0.1124
Heavy	1.0653	0.1359	0.0323	0.0383	0.1202

M_0, zeroth moment is the area under the spectrum; M_1, 1st moment is the mean; M_2, 2nd moment is the SD; M_3, 3rd moment is the skewness; M_4, 4th moment is the kurtosis (Sokal & Rohlf 1995).

Table 5. Summary of two similar datasets characterised as 'moderate' seas (data courtesy of EMEC).

Date	20 January 2008 02:30	18 November 2008 19:30
Wind speed (m s^{-1})	11.43	11.43
Wind direction (°)	270	280
T_p (s)	10.53	11.36
Peak spread (°)	27	26.5
Peak direction (°)	295.2	309.4
T_z (s)	6.54	6.88
Significant wave height (m)	3.6	3.8

T_z (s), zero-crossing wave period.

esculenta, *Ectopleura larynx* and *Lepas anatifera*; in high-tidal flow conditions, sublittoral fouling is dominated by *Chirona hameri*.

Analysis of the biofouling community data identified significant differences in fouling communities between harbours/marinas and MRED infrastructure. Species contributing most to these differences included *Ulva lactuca*, *Semibalanus balanoides*, and *Chirona hameri*. During this study, six NNS were identified at marinas and harbours; none were recorded at wave and tidal testing sites. However, NNS have been recorded on MREDs moored in harbour settings (Ryland et al. 2014; Loxton et al. 2017; Want, personal observations [Figure 5]). This suggests that fouling of MREDs by NNS may occur during maintenance. Evidence suggests that increased vessel traffic associated with developing marine renewable energy industry might promote movement of NNS already established in harbours (Nall et al. 2015). It is recommended that MREDs returned to harbour environments for maintenance are inspected and all biofouling removed prior to re-deployment. This preventative measure will ensure that device performance is not affected by biofouling load on site and would mitigate against spread of NNS. Recommendations, based on data identified in Table 2, are to consider timing of deployment and maintenance schedules of MREDs to minimise major biofouling settlements and to ease removal before the organism can consolidate. Timing maintenance for early summer to remove the majority of young barnacles and, if possible, at the end of the summer to remove most of the seasonal growth of macroalgae is recommended. Biofouling, in itself, creates habitat for more fouling organisms; compounding effects of biofouling succession might be mitigated against by deploying only cleaned devices. The sheltered nature of harbours might be expected to provide more favourable conditions for the early stages of the successional development of biofouling communities.

The second part of the study was to assess measurement of wave statistics using an instrumented buoy and to explore methods of quantifying the impact of marine fouling on the accuracy of received data. A better understanding of the consequences of measurement inaccuracy is of vital importance in survival design of devices; in extreme wave conditions, reduction in heave response owing to biofouling would lead to underestimated measurement of extremes. In addition, underestimating wave energy resource may have implications to assessing device performance and economic deliverables. The OrcaFlex model allowed assessment of the effect of biofouling on the hydrodynamic response of the buoy system. While analysis of heave data identified only small changes to the overall spectral response, most of the changes were observed in the high frequency response. A possible physical explanation is that fouling dampens out high frequency responses in buoys; if confirmed with additional data, this dampened response could be used as a measure of biofouling in operational conditions. Using overall measured response to identify suitable 'similar sea states', high frequency response can be compared to study biofouling influence. This early stage work uses limited field data but suggests a means of identifying when a buoy is fouled. Additional studies will help to establish the relationship between numerically modelled data and field data, necessary to confirm assumptions on operational buoy responses. In the future, directed experiments using parallel deployment of buoys in varying states of fouling are recommended.

Fouling impacts on wave buoys at Islandsberg Test Park at Lysekil, west coast of Sweden were studied by Langhamer et al. (2009). The impact of biofouling on a fixed point wave absorption buoy was studied using a linear wave theoretical model. Input parameters to the model were extrapolated from data collected from biomass of fouling organisms on marking buoys. This resulted in an increase in biomass of 140 kg, and represented an increase in the draft of their buoy by about by 5%. The study reported no significant effect on the dynamic behaviour of the buoy in these environmental conditions. While both the Langhamer study and the case study described here analysed heave responses in buoys, the fundamental difference is the greater wave resource prevalent in Orkney waters. In contrast with the Langhamer study, where no dynamic response was observed, in the Orkney study, differences due to biofouling were detected in more extreme conditions, typical of environments suitable for large-scale WEC deployment.

In comparison, a study by Thomson et al. (2015) was carried out in a deep water environment at Ocean Station P, 50° N, 145° W in the North Pacific Ocean. The data buoy was moored to a false bottom deployed 150 m below the sea surface. Similar to the Orkney case study, a Waverider buoy MkIII was used to study the effects of biofouling on buoy response. The Thomson study included comparisons between one heavily fouled buoy and one newly deployed clean buoy. Despite severe biofouling on the first buoy, the difference between responses was limited to high frequency spectra. When compared with the Orkney data, similar influences in the response characteristics of such buoys to biofouling is observed in differing environments, except that the EMEC Waverider buoy was deployed in shallow water (50 m depth maximum).

A study by Macleod et al. (2016) focused on the weight and density of the biofouling communities on navigation buoys across the Scottish region, including communities dominated by hard and soft fouling. The authors identified that the situation becomes more complex when considering dynamic load on marine structures. In the present study, the choice of a data buoy as a platform for monitoring and modelling was ideal because it allowed *in situ* measurement of dynamic motions. Furthermore, for the first time, the heave of the Waverider buoy at the Billia Croo wave test site is matched with the knowledge of the specific type of biofouling community (including *Ectopleura larynx*, *Alaria esculenta* and *Lepas anatifera*).

Introductory premises, based on fouling from acorn barnacles, mussels and kelp, can be enhanced in future studies using knowledge of specific roles of locally important fouling organisms in input parameters. Research in high-energy 'surf-zones' have examined strategies employed by organisms to mitigate against extreme hydrodynamic forces. These strategies include flexible stipes in macroalgae and rigid shapes in encrusting animals such as limpets and barnacles (Denny 1987; Gaylord 2000). In the future, modelling dynamic buoy responses following fouling may be improved by applying species-specific hydrodynamic signatures to input data. In this study, a first step has been achieved towards this by incorporating real biofouling community data into the consideration of the model parameters.

From a developer's standpoint, accurate assessment of biofouling on deployed structures is essential for maximising energy capture. Determining biofouling contribution to wave data buoy sensor accuracy is critical as wave resource assessment and device capture may be underestimated as organisms affect movement of buoys and devices. In order to achieve this, a full understanding of the mechanism of biofouling and the rates of growth are essential. In the future, it may be possible to identify a biofouling signature on the spectral response which could inform maintenance schedules. Future studies will be informed with additional examples of comparable sea conditions obtained through continuing analysis of recent and historical wave buoy data. In addition, it will be necessary to collect new data to include the degree/type of biofouling on a temporal basis during deployment, therefore allowing direct correlation with the wave data.

Another line of future study could be to artificially introduce biofouling to the wave data buoy and make *in situ* comparisons with the numerical buoy dynamic model. This would allow a fuller understanding of the effects of various biofouling organisms on the hydrodynamic coefficients and refinement of the numerical model. Having shown in this case study how the wave data buoy can be used in biofouling studies, it would be useful to develop a similar case study sentinel for tidal stream application. Knowledge gaps of specialist foulers of high energy environments, including the barnacle *Chirona hameri*, have been highlighted in this study; little is known about the impact of this species on tidal devices for energy generation. The present studies provide an assessment of biofouling communities and consequences of fouling unique to the MRE sector, and have identified several strands of research for further development. With increasing interest in generating electricity from renewable marine energy sources, understanding the effects of biofouling to this industry will become increasingly important.

Note

1. For definitions of parameters used in describing hydrodynamic processes, the reader is directed to an appropriate textbook such as Bhattacharyya (1978).

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