Fine-scale monitoring of fish movements and multiple environmental parameters around a decommissioned offshore oil platform: A pilot study in the North Sea

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ABSTRACT

A new underwater monitoring system was constructed using time-lapse photography and a suite of oceanographic instruments to characterise the dynamic relationships between changing environmental conditions, biological activities and the physical presence of offshore infrastructure. This article reports the results from a pilot study on fine-scale monitoring of fish movements in relation to changes in multiple environmental parameters observed at an offshore oil platform in the North Sea. Temporal changes in the number of saithe *Pollachius virens* were readily observed with a strong indication of diurnal rhythm of vertical movements. Key environmental parameters such as temperature, salinity, currents, tidal cycle, illumination, chlorophyll and dissolved oxygen also varied spatially (i.e. different depths) and/or temporally. If the monitoring system is to be deployed systematically at multiple offshore locations for longer duration as appropriately controlled experiments, this approach may greatly help understand the influence of redundant offshore man-made structures on the marine ecosystem.

1. Introduction

Any decisions on the issues of decommissioning of offshore infrastructure will need to be made based on an array of selection criteria including, but not limited to, environmental, health and safety, financial, socioeconomic, technological and political considerations (Fowler et al., 2014; Wilkinson et al. 2016). In the North Sea, the question of how aging offshore infrastructure is utilised by different marine fauna has become increasingly important in terms of the environmental considerations. This is because recent studies have suggested that the physical presence of offshore platforms, together with associated subsea infrastructure such as pipelines, wellheads and manifolds, may have beneficial effects on present-day ecosystem functioning as they may serve as artificial reefs that attract marine life (Stachowitsch et al., 2002; Whomersley and Picken, 2003), including species of conservation importance, e.g. a cold-water coral *Lophelia pertusa* (Gass and Roberts, 2006), and thereby increase the number of economically important fishes in the proximity of these foundations (Love and Westphal, 1990; Stanley and Wilson, 1991, 1997; Fabi et al., 2004; Love and York, 2005; Love et al., 2006; Jablonski, 2008).

The North Sea has long been a vital ground for the exploitation of natural resources, supporting one of the world's most active fisheries as well as oil and gas exploration which has led to installation of over 500

offshore platforms across the region primarily since the 1960 s. In this region, commercially important fishes, such as saithe, *Pollachius virens* cod *Gadus morhua*, and haddock *Melanogrammus aeglefinus* have been known to show coherent patterns in their local distributions where significantly higher number of individuals can be found in the immediate vicinity of offshore structures when compared with surrounding open soft-bottom areas (Valdemarsen, 1979; Aabel et al., 1997; Løkkeborg et al., 2002; Soldal et al., 2002; Fujii, 2015). Although there is also a growing body of evidence to confirm that a variety of fish species aggregate around artificial hard structures in marine environments worldwide (e.g. Bohnsack and Sutherland, 1985; Picken and McIntyre, 1989; Aabel et al., 1997; Stanley and Wilson, 1997; Baine, 2001; Løkkeborg et al., 2002; Soldal et al., 2002; Fabi et al., 2004; Love and York, 2005; Wilhelmsson et al., 2006), causality of such attraction effect, however, has not yet been satisfactorily identified. Several mechanisms may be responsible for the increase, for example, enhanced food availability (e.g. Page et al., 2007), shelter from predation (e.g. Hixon and Beets, 1989) or reference point (e.g. Soria et al., 2009), but it still remains unclear whether the fish individuals merely concentrate around offshore artificial structures from surrounding areas or whether such effects can facilitate the reproductive ability of fish populations and thereby produce any net increase in fish stock sizes overall. To ultimately determine the ecological consequences of

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alternative decommissioning options of obsolete offshore infrastructures, it would be necessary to design an appropriate ecological field experiments which allows identification of both causal mechanisms of attraction effect and temporal nature of fish movements in association with the physical presence of the offshore structures. However, there has been a lack of fundamental information on how the life cycle and/or the temporal variations in the movements of fish populations around offshore structures is related to any changes in key environmental factors (environmental cues) such as water temperature, salinity, currents, tidal cycle, light intensity (illumination), surface primary production (chlorophyll *a*), prey availability, dissolved oxygen and so on, which in turn hampers progress in advancing research in this field.

The aim of this article is to describe the design of a newly developed underwater monitoring system which uses time-lapse digital photography and a suite of oceanographic instruments in an attempt to provide sufficient background measurements to characterise the dynamic relationships between changing environmental conditions and biological activities in association with offshore oil/gas platforms at fine temporal resolution. Using the monitoring system, a pilot study was conducted at three different sampling depths in the immediate vicinity of an offshore oil platform in the North Sea, the results of which is therefore presented thereafter. Based on the findings from the pilot study, together with the relevant literature, implications for the ecological influence of obsolete offshore platforms on the marine ecosystem are discussed. If the fine scale monitoring system is to be deployed systematically at multiple offshore locations over longer periods of time as appropriately controlled experiments, this approach may provide a useful tool to help identify the precise role of large offshore man-made structures in the ecology of fish populations in the North Sea.

2. Material and methods

2.1. Study site

The pilot study was conducted at BP's Miller platform situated in the northern central North Sea (Fig. 1). The platform was installed in 1991 in a water depth of approximately 103 m on a dense sandy seafloor. The platform has a large steel jacket supporting structure (eight-legged) weighing approximately 18,600 t with a size of 71×55 m at the base on the seabed, tapering to 71×30 m at the top just under the topsides modules. The Miller platform ceased production in September 2007 and the initial phase of decommissioning has already been completed. A detailed decommissioning programme has also been planned for dealing with the topsides, jacket and drill cuttings pile, and the platform is therefore currently being maintained with minimum on-board personnel, representing some of the redundant offshore oil/gas installations found in the region.

2.2. A new underwater monitoring system

An autonomous underwater monitoring system was newly designed and constructed in an attempt to describe and characterise the dynamic relationship between biological activities and an offshore oil platform in relation to fine-scale changes in various environmental parameters. This system comprised a surface float, three identical observatory frames (Fig. 2) and ballast weights (approximately 1400 kg), all attached to a single mooring rope (Fig. 3). Each observatory unit contained a suite of oceanographic instrumentations (Fig. 2), including: (1) a 10 megapixel digital stills camera and strobe (OE14-408 & OE11-442: Kongsberg Maritime, UK) programmed to take time-lapse photographs of the sea floor or the water column and associated fauna at 60 min intervals; (2) a 3D current metre (Aquadopp Current Metre: Nortek, Norway) programmed to measure current speed (m/s) and direction (degree) at 10 min intervals; (3) a CTD probe (RBRmaestro: RBR Ltd., Canada) programmed to measure salinity, water tempera-
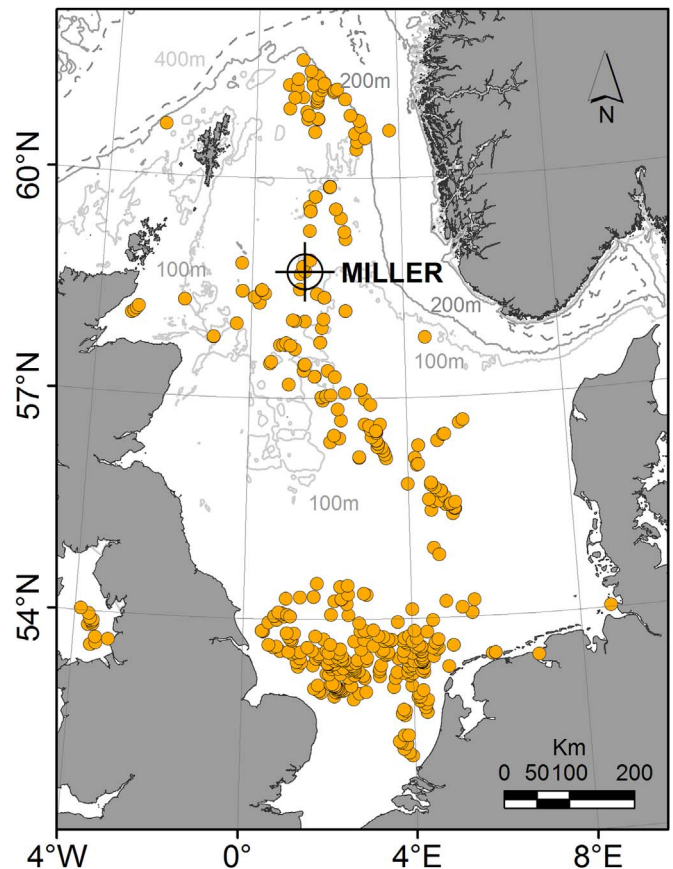

Fig. 1. Map of the North Sea showing the locations of offshore oil/gas platforms (the filled orange circles) (Source: OSPAR, 2012). The black circle and cross symbol indicates the location of the Miller platform. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
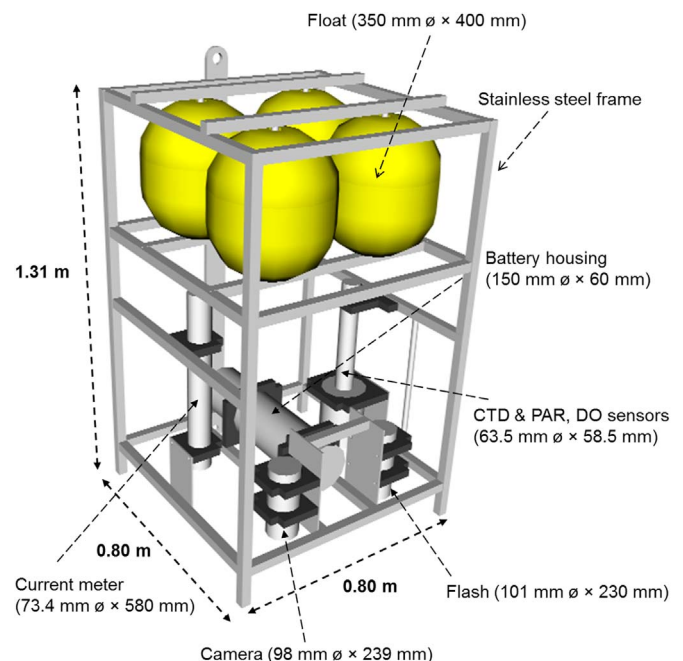

Fig. 2. Schematic diagram of the underwater observatory unit designed and constructed for this study.

ture (°C) and hydrostatic pressure (dbar) at 10 min intervals; (4) a PAR (photosynthetically active radiation) sensor (PAR Quantum 192SA: LI-COR, Inc., US) programmed to measure the photosynthetic photon flux
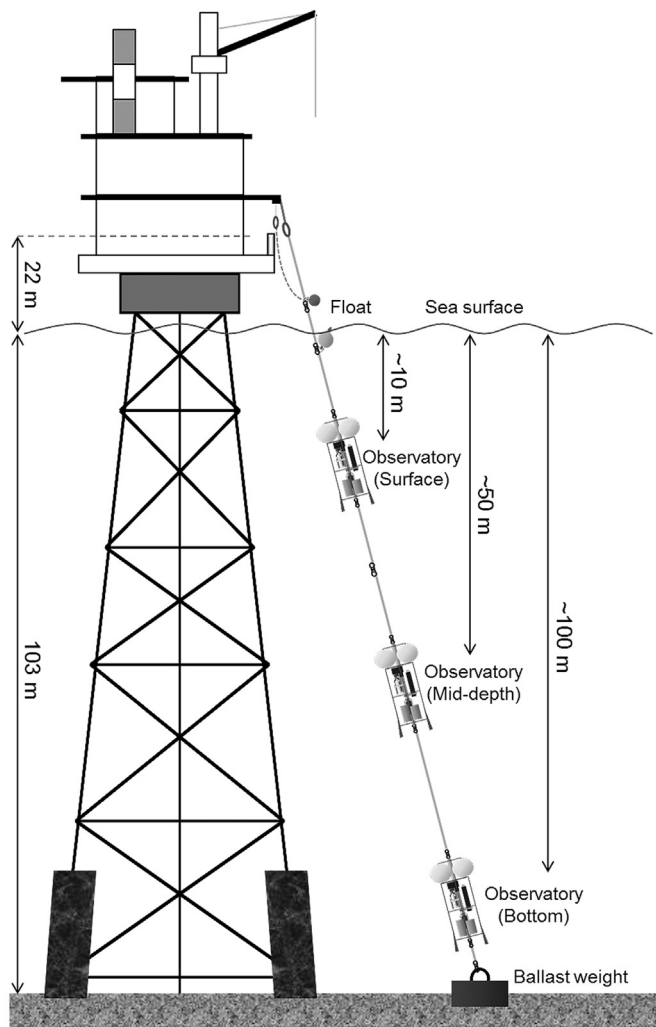
Fig. 3. Schematic diagram of the underwater monitoring system deployed from the Miller platform.

Fig. 4. Changes in the number of fish individuals observed at three different depths at the Miller platform.

density (light intensity) (μMol/m²/s) at 10 min intervals; (5) a fluorometer (Chlorophyll Fluorometer, Seapoint Sensors, Inc., US) programmed to measure phytopigments (μg/l), which can be related to the organic matter content (chlorophyll *a*) of the particle load descended from the surface water, at 10 min intervals; (6) a DO (dissolved oxygen) sensor (Fast Response DO Sensor: Oxyguard, Denmark) programmed to measure dissolved oxygen levels (ml/l) available to the local marine fauna at 10 min intervals.

Within each observatory frame, all of the following three instrument units have sufficient battery and memory capacity independently of each other to operate autonomously: (1) the digital stills camera and strobe for up to a maximum of three months; (2) the 3D current metre for up to six months; (3) the rest of the oceanographic instruments connected to the RBRmaestro data logger (i.e. CTD probe, PAR sensor, fluorometer and DO sensor) for up to nine months. Thus once deployed, the present programme, for example, allows the monitoring system to remain under water for approximately three months and, where a longer duration of deployment is desirable, the observatory system can also be briefly recovered to the surface for service, calibration and data download between deployments.

2.3. A pilot study

Before implementing a full-scale monitoring, a small scale test sampling was conducted at the Miller platform between 21st and 23rd June 2014 using the above monitoring system which was anchored to
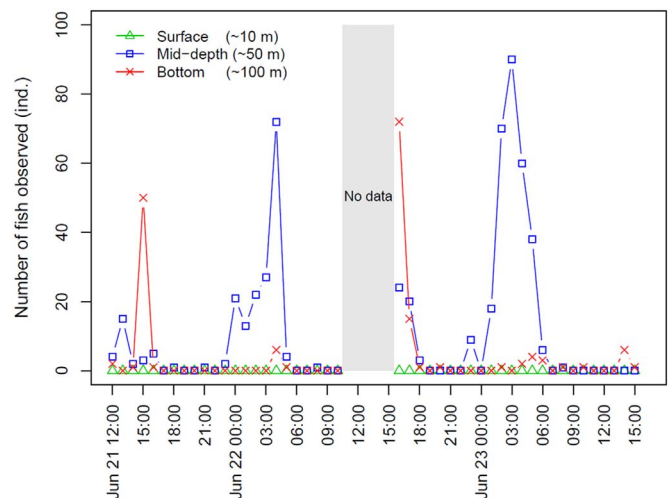
the bottom at one end and tethered to the lower deck of the platform at the other (Fig. 3). The three observatory frames were deployed at depths of approximately 10, 50 and 100 m from the sea surface ("surface", "mid-depth" and "bottom", respectively) and each observatory unit had floatation devices connected to each frame to make the entire monitoring system positively buoyant and thus in suspension throughout the water column (Fig. 3).

This pilot study was conducted in two consecutive deployments as follows: in the first deployment, only digital stills cameras were deployed from 12 PM on 21st June till 10 AM on 22nd June (22 h), whereas in the second deployment, the full set of oceanographic instrumentations was deployed from 4PM on 22nd June till 4PM on 23rd June (24 h). During the first deployment, the digital stills cameras took images at three sampling depths (i.e., 10, 50 and 100 m). During the second deployment, in addition to the hourly time-lapse digital photography, the observatory system also logged the rest of the environmental measurements at the same three sampling depths.

2.4. Data analysis

Upon recovery of the monitoring system, the images and oceanographic data were downloaded. The images from the stills cameras were analysed manually for species identification and fish counting. As the stills images were recorded in the two consecutive deployments, the two fish-count data were combined and a time series was constructed to examine temporal patterns in the number of fish individuals as a proxy for fish movement (rhythm) observed at three different depths over the duration across the two deployments. Subsequently, similar time series plots were constructed for all the oceanographic data over the duration of the second deployment. In addition, trends in current speed and direction were examined for each sampling depth using a stick-plot diagram, where vectors of length (speed) and angle (direction) were placed along a reference line that represent time. These plots were constructed using the 'oce' package (Kelley, 2016) in R v.3.3.1 (R Development Core Team, 2016).

3. Results

The stills cameras completed both the first and second deployments successfully at all three depths and took a total of 141 images over the duration of 23 and 24 h in the first and second deployments, respectively. Not a single fish was observed at 10 m depth during both deployments (Fig. 4). However, the occurrence of fish, mostly saithe *Pollachius virens*, was readily observed in 55.3% and 38.3% of the total images recorded at 50 and 100 m depths, respectively (Figs. 4 and 5).
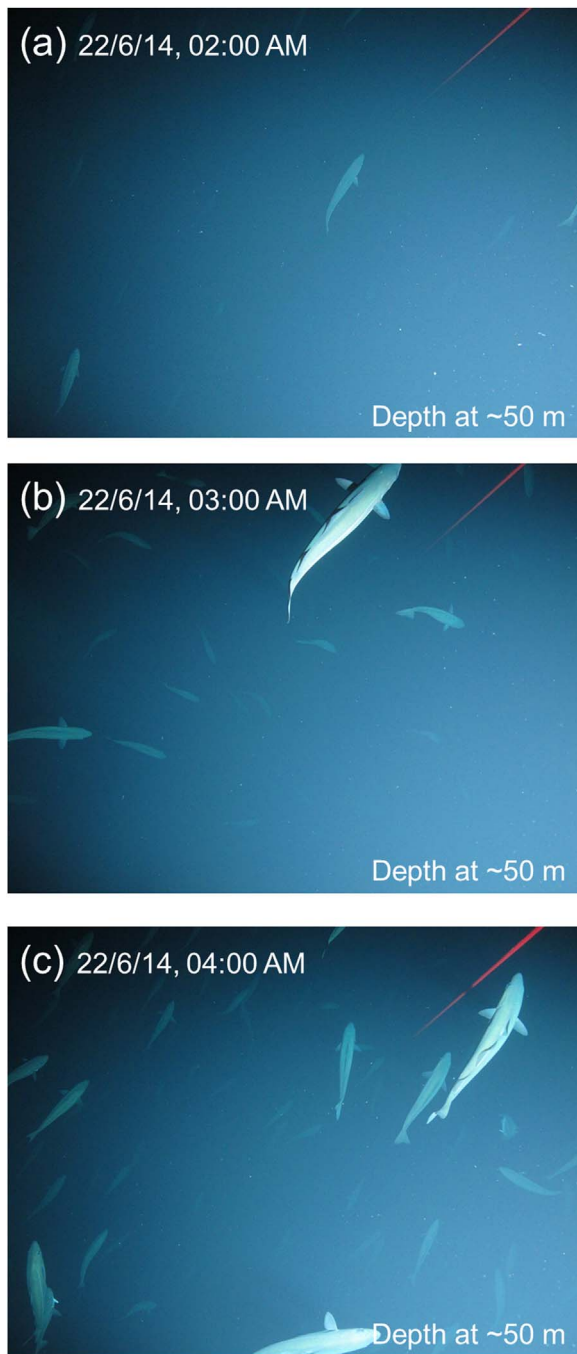
Fig. 5. Example images of fish individuals (saithe *Pollachius virens*) observed around the depth of 50 m at the Miller platform at: (a) 2:00AM; (b) 3:00AM; (c) 4:00AM on 22nd June 2014.

Further, the time series clearly demonstrated the number of fish individuals observed at the Miller platform peaked sharply at around 3–4 AM and 3–4 PM at 50 and 100 m depths, respectively (Fig. 4) showing an indication of diurnal rhythm of fish movements operating across different depths.

During the second deployment, all the physical conditions were recorded successfully except for dissolved oxygen data at 50 m depth due to a sensor failure, and time series plots for these environmental variables were shown in Figs. 6 and 7. With respect to light intensity, essentially no photosynthetically active radiation was measured over the second deployment at depths below 50 m at the Miller platform (Fig. 6b). At 10 m depth, however, there was a well-defined change in the intensity of light observed, which peaked around 5 PM on 22nd

June and decreased to almost none overnight and increased again peaking around 1 PM on the following day (Fig. 6b). In contrast, temperatures stayed relatively constant with average temperatures of 12.93, 7.78 and 7.53 °C at 10, 50 and 100 m depths, respectively, over the duration of the second deployment (Fig. 6c). Although the temperatures were similar between 50 and 100 m depths, it was noticeable that temporal pattern was slightly more variable at 50 m when compared with that at 100 m depth (Fig. 6c). Time series of both chlorophyll and salinity values showed some distinctive variations between depths and, in both cases, temporal patters were markedly variable at 50 m depth in comparison with the other sampling depths (Fig. 6d and e). Dissolved oxygen levels were relatively constant with average values of 6.11 and 5.09 ml/l at 10 and 100 m depths, respectively, at the Miller platform (Fig. 6f).

The temporal patterns of hydrostatic pressures were similar between 10 and 50 m depths, but the amplitude of the range appears to be markedly reduced at 100 m depth (Fig. 7a−c). Further, the patterns of the current speeds and directions also showed some consistency between depths (Fig. 7D-f) with the average current speeds at the Miller field declining from 0.32 through 0.25−0.18 m/s at 10, 50 and 100 m depths, respectively. Thus the observed patterns of hydrostatic pressures corresponded with the observed changes in current speeds and directions at each sampling depth, indicating dynamic coupling between tidal movements and the prevailing oceanographic conditions.

4. Discussion

This study investigated fine-scale temporal variation in the environmental conditions and the occurrence of fish in the immediate vicinity of the Miller oil platform in the North Sea. Temporal changes in the number of commercially important fish, saithe *Pollachius virens*, was readily observed by the newly established underwater monitoring system, showing an indication of diurnal rhythm of vertical movements throughout the water column. With respect to the physical conditions at the Miller platform, temperatures, salinity and dissolved oxygen essentially remained constant throughout the study period. However, the intensity of the light at 10 m, chlorophyll concentration at 10 and 50 m, as well as the patterns of hydrostatic pressures and the prevailing currents at all the three water depths (i.e., 10, 50 and 100 m) showed a distinctive indication of diurnal cycle with the degree of changes differed depending on the parameter and depth in question. Temporal changes in temperature, chlorophyll and salinity values were found to be more variable at 50 m than any other sampling depth at the Miller platform and this could be attributable to the timing of the sampling in this study because, in the northern part of the North Sea, the water column is generally well mixed in winter, but horizontal thermal stratification occurs in summer, typically at a depth of around 50 m (e.g. Umgiesser et al., 2002; Fujii, 2015). Overall, the results of the pilot study indicated there were highly dynamic as well as distinctive temporal patterns observed not only in some key environmental parameters but also in fish movement in the immediate vicinity of the Miller platform even within a very short window of time. However, the question of how and why the observed diurnal rhythm of the fish movement is related to any of the fine-scale predictor variables still remains unresolved and such question could only be answered if the monitoring system is to be deployed systematically at multiple offshore locations, including both experiments and controls, for longer durations of time (Aguzzi et al., 2012; Doya et al., 2014).

For spatial considerations, several research studies have confirmed that commercially important fish species, such as saithe, haddock *Melanogrammus aeglefinus* and cod *Gadus morhua*, show coherent patterns in their local distributions where significantly higher number of individuals can be found in the immediate vicinity of individual offshore platforms (< ~100−300 m) when compared with surrounding open soft bottom areas in the North Sea (Valdemarsen, 1979; Aabel
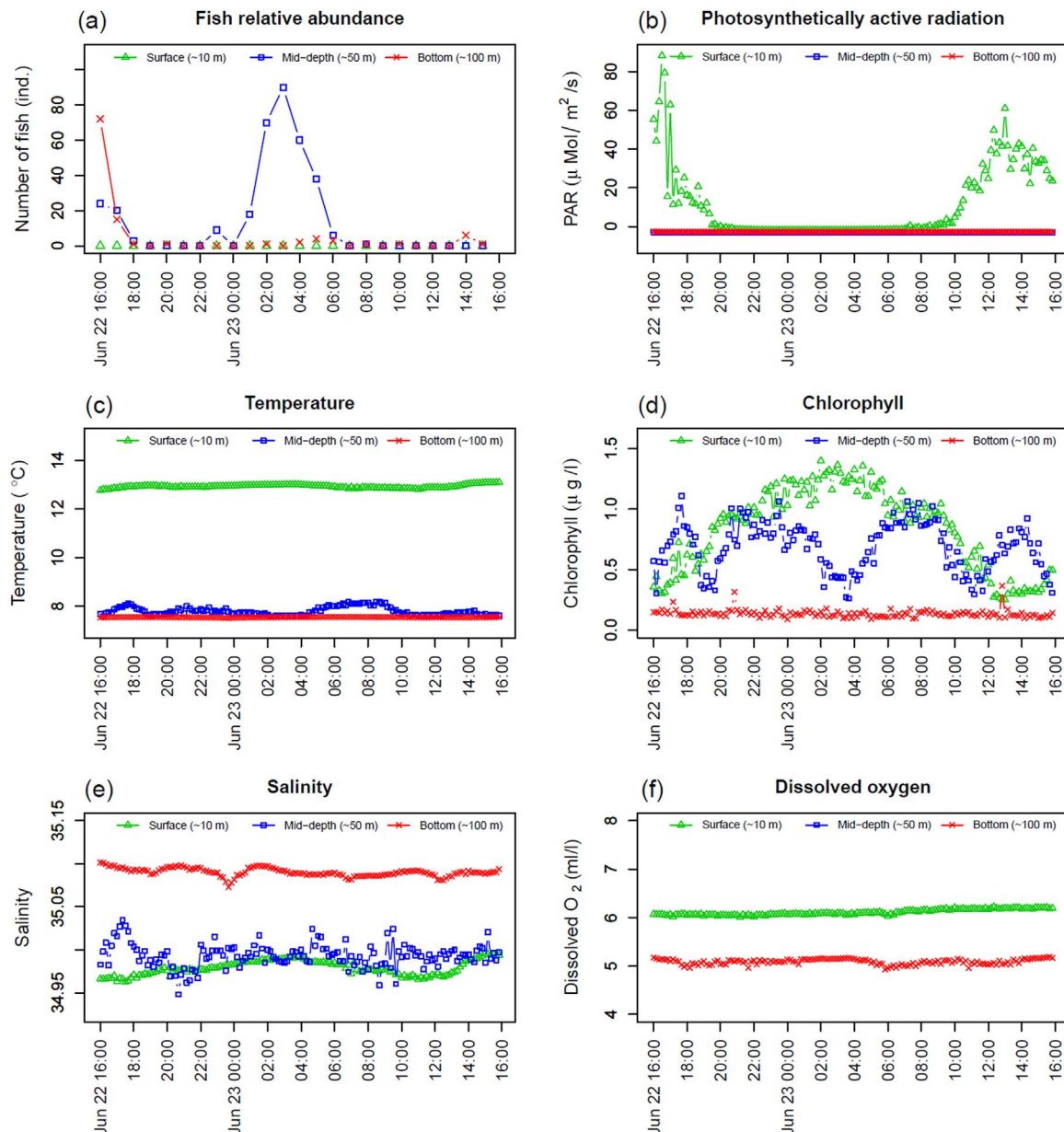
Fig. 6. Time series plots at three different depths for: (a) number of fish individuals; (b) PAR (photosynthetically active radiation); (c) temperature; (d) chlorophyll; (e) salinity; (f); dissolved oxygen, over duration of the second deployment conducted at the Miller platform.

et al., 1997; Løkkeborg et al., 2002; Soldal et al., 2002). However, movements of fish individuals in association with offshore platforms can be complex and variable over different temporal scales. For example, using hydroacoustic quantification, Soldal et al. (2002) investigated temporal changes in the concentrations of fish close to the jacket of a decommissioned platform in the North Sea and found that demersal fish, such as saithe and cod, spread throughout the water column during the night with significantly higher acoustic values being repeatedly recorded late at night in July 1998. This was markedly consistent with the findings obtained in this study, indicating that a large number of saithe individuals may have been undertaking diurnal vertical migration simultaneously across multiple platforms at wider spatial scale. In addition, Fujii (2016) investigated the feeding habits of saithe across the North Sea and found that the observed spatio-temporal variability in the saithe diet was significantly explained by proximity to the nearest offshore platforms and changes in water temperatures, which appear to reflect patterns of euphausiid avail-ability over space and time. Saithe is known to feed preferentially on

euphausiids (e.g. Christensen, 1995; Carruthers et al., 2005), which is also known to undertake diurnal vertical migration (e.g. Lass et al., 2001). The results from the present study may therefore indicate that the physical presence of the offshore structures affects the distribution/ availability of zooplankton (i.e. euphausiids) first and thereby influence the feeding/aggregating behaviour of saithe. In order to substantiate such hypothesis, it would be of great importance for future research to systematically establish appropriately controlled experiments using e.g. the monitoring system described in this study or using alternative techniques such as a stationary acoustic buoy equipped with a scientific split-beam echosounder (e.g. Godø et al., 2014) which could be deployed at the bottom in the close proximity of offshore platforms. The latter option would permit silent environment measurements without disturbance in the surface water and thus allow recording with much higher sensitivity compared to a conventional installation onboard a ship, which would be of a powerful tool to monitor migration patterns of different fish species, their prey (e.g. zooplankton) and their interactions at fine temporal resolution over a long period of time.
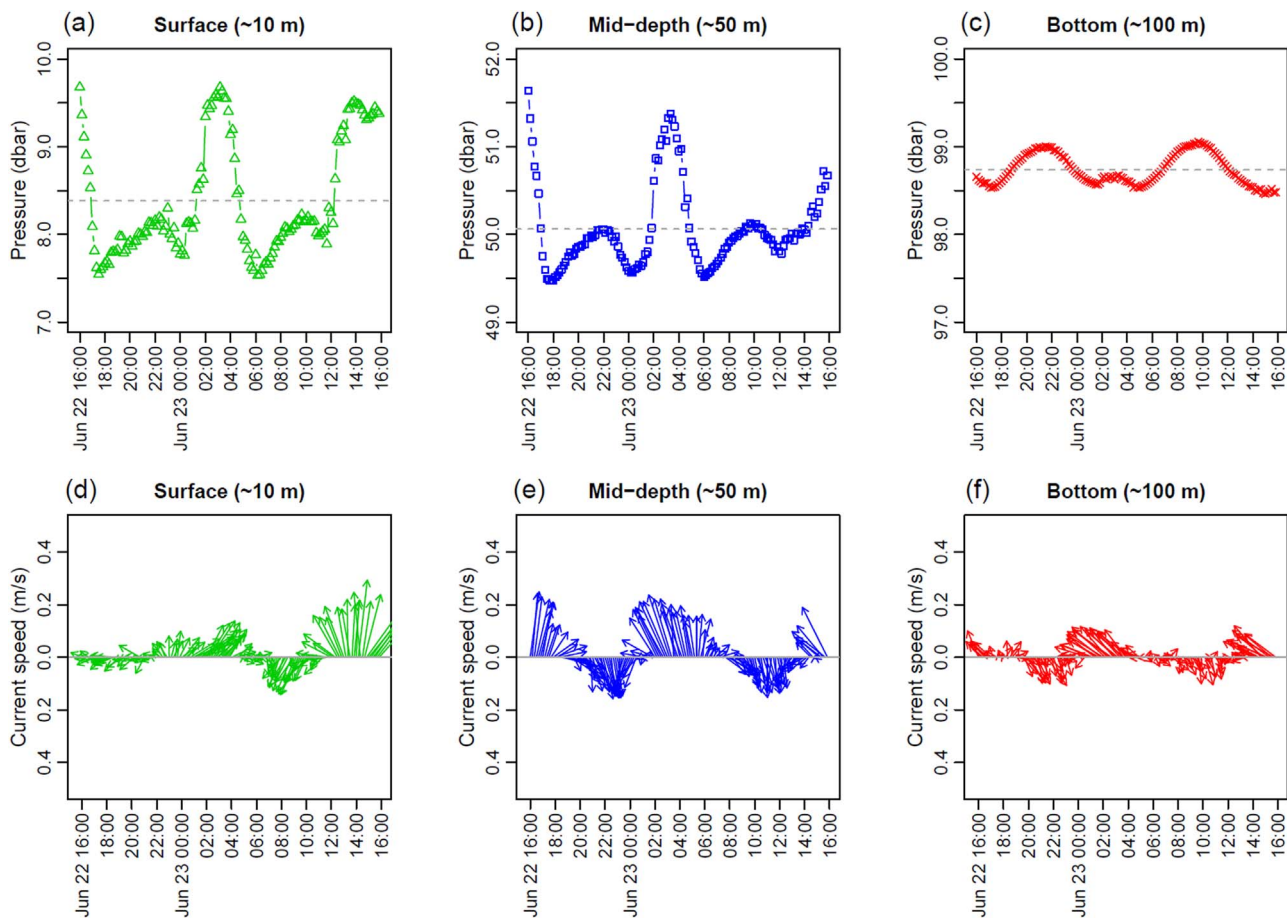
Fig. 7. Changes in hydrostatic pressure recorded at the Miller platform at: (a) surface (~10 m); (b) mid-depth (~50 m); (c) bottom (~100 m). Stick-plots for the patterns in the water currents with the speed and direction indicated by each vector along time reference line recorded at: (d) surface (~10 m); (e) mid-depth (~50 m); (f) bottom (~100 m).

Using mid-water fish traps, Fujii (2015) also investigated temporal variations in the structure of fish assemblages observed in the vicinity of the Miller platform and found that relative abundances of saithe, haddock and cod did not vary significantly within each season. However, the species composition and the relative abundances did vary significantly between seasons as well as years. In particular, saithe showed significant differences in their body size distributions between seasons as well as years, suggesting that there was a series of turnover of individuals in the utilisation of the platform by different age groups across seasons and years and their residence time and between-habitat movement could therefore be regulated at seasonal and/or inter-annual scales (Fujii, 2015). On the other hand, using an acoustic tagging system, Jørgensen et al. (2002) examined the residence time and movement of cod at an offshore platform in the North Sea and found that around 50% of the tagged individuals remained in the direct vicinity throughout the 3-month period, while some individuals were registered at the neighbouring platform and approximately 14% of individuals were still detected at the study site 12-month later. Other fishing study conducted around North Sea platforms has also found evidence of seasonal changes in the abundance in fish assemblages around the structures (Løkkeborg et al., 2002). As has been demonstrated in the other parts of the world, different fish species have different utilisation patterns of an offshore platform which may be influenced by physical factors such as temporal variation in temperature and oceanographic conditions as well as biological factors such as prey availability, species-specific sedentary/migratory behaviour and life cycle stages of individuals (e.g. Bohnsack and Sutherland, 1985; Stanley and Wilson, 1997; Schroeder and Love, 2004; Love et al., 2005; Love et al., 2006; Page et al., 2007, Fujii, 2016). To understand the true role of offshore platforms in the ecology of fish populations, it is vital to identify the biological mechanisms behind such temporal movement patterns in association with large scale environmental drivers.

5. Conclusions

Offshore oil and gas platforms represent some of the largest man-made constructions installed on the seafloor and an increasing number of fishers and scientists have been aware that a variety of fish species aggregate in substantial numbers in the proximity of such large sub-sea structures. The majority of these structures have been in place for decades and they may well have functioned as artificial reefs potentially acting as a network of *de facto* marine protected zones (de Groot, 1982; Osmundsen and Tveterås, 2003; Fujii, 2015). However, an increasing number of existing offshore platforms are approaching the end of their commercial lives and, to date, 7% of existing North Sea installations have already been decommissioned (Royal Academy of Engineering, 2013). Given the number of offshore platforms currently installed in the North Sea as well as the possible association between fish movements and the physical presence of offshore structures as indicated by the available literature to date, there is a need to fully characterise the relationships between changing environmental conditions and biological activities in association with offshore oil/gas platforms at varying temporal resolutions over longer durations of time in the North Sea. The resulting outcome will not only compensate for previous lack of knowledge, but also make a major contribution in providing stakeholders with appropriate information on the issues of decommissioning to allow for informed decisions to be made. It is clear that further study is needed to better understand the influence of the physical presence of the offshore platforms on the life cycle, temporal movements and connectivity of fish populations as well as possible links between large

scale ecological/environmental processes and distributional dynamics of fish populations. The results of this pilot study urge further fine-resolution and long-term monitoring to be conducted as appropriately controlled experiments at multiple locations over wider spatial coverage. Accumulation of such knowledge will increase our ability to identify the true ecological consequences of different decommissioning alternatives as well as to facilitate effective spatial management of marine ecosystems in the North Sea.

Acknowledgements

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