Monitoring ship noise to assess the impact of coastal developments on marine mammals

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ABSTRACT

The potential impacts of underwater noise on marine mammals are widely recognised, but uncertainty over variability in baseline noise levels often constrains efforts to manage these impacts. This paper characterises natural and anthropogenic contributors to underwater noise at two sites in the Moray Firth Special Area of Conservation, an important marine mammal habitat that may be exposed to increased shipping activity from proposed offshore energy developments. We aimed to establish a pre-development baseline, and to develop ship noise monitoring methods using Automatic Identification System (AIS) and time-lapse video to record trends in noise levels and shipping activity. Our results detail the noise levels currently experienced by a locally protected bottlenose dolphin population, explore the relationship between broadband sound exposure levels and the indicators proposed in response to the EU Marine Strategy Framework Directive, and provide a ship noise assessment toolkit which can be applied in other coastal marine environments.

1. Introduction

Acoustic measurements in the Northeast Pacific indicate that underwater noise levels in the open ocean have been rising for at least the last five decades due to increases in shipping (Andrew et al., 2002; McDonald et al., 2006; Chapman and Price, 2011) correlated to global economic growth (Frisk, 2012). Closer to shore, escalations in human activity, including shipping, pile-driving and seismic surveys, have transformed coastal marine soundscapes (Richardson et al., 1995; Hildebrand, 2009) with uncertain consequences for the ecosystems that inhabit them.

These large-scale changes in the acoustic environment are of particular concern for marine mammals (Tyack, 2008), which rely on sound as their primary sensory mode. There is growing evidence that marine mammals perceive anthropogenic noise sources as a form of risk, which is then integrated into their ecological landscape, affecting their decision-making processes (Tyack, 2008). Noise also has the potential to mask important acoustic cues in marine mammal habitats, such as echolocation

and communication (Erbe, 2002; Jensen et al., 2009), and may disrupt their prey (Popper et al., 2003) affecting foraging. These anthropogenic pressures may lead to physiological stress (Wright et al., 2007; Rolland et al., 2012), habitat degradation, and changes in behaviour (Nowacek et al., 2007) including evasive tactics (Williams et al., 2002; Christiansen et al., 2010) and heightened vocalisation frequency (Parks et al., 2007), rate (Buckstaff, 2004), or duration (Foote et al., 2004). The cumulative cost of these responses can alter the animals' activity budget (Lusseau, 2003) and energy balance, which may have downstream consequences for individual vital rates (e.g. survival or reproductive success) and, ultimately, population dynamics. Efforts are underway to develop a framework to predict such population consequences of acoustic disturbance (PCAD; National Research Council, 2005).

Detailed investigation of these chronic and cumulative effects will require longitudinal studies of ambient noise trends in marine habitats with concurrent assessment of marine mammal fitness and population levels. However, long-term ambient noise data (on the scale of several or more years) are limited to the Northeast Pacific (e.g. Andrew et al., 2002; McDonald et al., 2006; Chapman and Price, 2011) and data for other ocean basins and coastal regions are rare and comparatively brief (e.g. Moore et al., 2012; Širović et al., 2013). In the European Union (EU), a regulatory framework which seeks to rectify this knowledge deficit is currently developing guidelines for ambient noise monitoring (EU, 2008; Tasker et al., 2010; Van der Graaf et al., 2012; Dekeling et al., 2013). The Marine Strategy Framework Directive (MSFD) will

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ascertain baseline noise levels and track year-on-year trends with a view to defining and attaining 'Good Environmental Status' in EU territorial waters by 2020. There is no specific requirement for long-term monitoring of the acoustic impact of human activities on marine mammal populations, though a proposed register of high-amplitude impulsive noise (e.g. pile driving, seismic surveys) could act as a proxy indicator of high-amplitude acoustic disturbance (Van der Graaf et al., 2012). For ambient noise (including noise from shipping), current recommendations are to monitor two 1/3-octave frequency bands (63 and 125 Hz), targeting areas of intensive shipping activity (Van der Graaf et al., 2012; Dekeling et al., 2013). Consequently, many key marine mammal habitats may not be included in monitoring programs. While such habitats may sustain less pressure from anthropogenic noise, they may, nevertheless, be more vulnerable to increases in underwater noise levels (Heide-Jørgensen et al., 2013).

This study characterises baseline noise levels in the inner Moray Firth, a Special Area of Conservation (SAC) for a resident population of bottlenose dolphins (*Tursiops truncatus*), and an important habitat for several other marine mammal species. The Moray Firth also provides an important base for the development of oil and gas exploration in the North Sea, and there are now plans to develop this infrastructure to support Scotland's expanding offshore renewables industry (Scottish Government, 2011). These developments will increase recent levels of vessel traffic to fabrication yards and ports within the SAC such as those at Nigg and Invergordon (New et al., 2013) and at the Ardersier yard (Fig. 1). Establish-

ing current baseline levels will enable future noise monitoring to quantify the acoustic consequences of this expected increase, supporting analyses of any associated effects on marine mammal populations. In characterising key contributors to underwater noise levels in the SAC, we also advance methods for ship noise monitoring by combining Automatic Identification System (AIS) ship-tracking data and shore-based time-lapse video footage, and explore whether underwater noise modelling based on AIS data could accurately predict noise levels in the SAC. These methods can be applied in other coastal regions to evaluate the contribution of vessel noise to marine soundscapes. Finally, we explore whether noise levels in frequency bands proposed for the MSFD (1/3-octave bands centred on 63 and 125 Hz) are effective indicators of broad-band noise exposure from shipping.

2. Methods

2.1. Study site

The inner Moray Firth was designated a Special Area of Conservation (SAC) for bottlenose dolphins under the European Habitats Directive (92/43/EEC), since at least part of the north-east Scotland population spends a considerable proportion of time in this area (Cheney et al., 2013). Long-term monitoring of the population's size suggests that it is stable or increasing (Cheney et al., 2013). Within the SAC, dolphins have been observed to use discrete
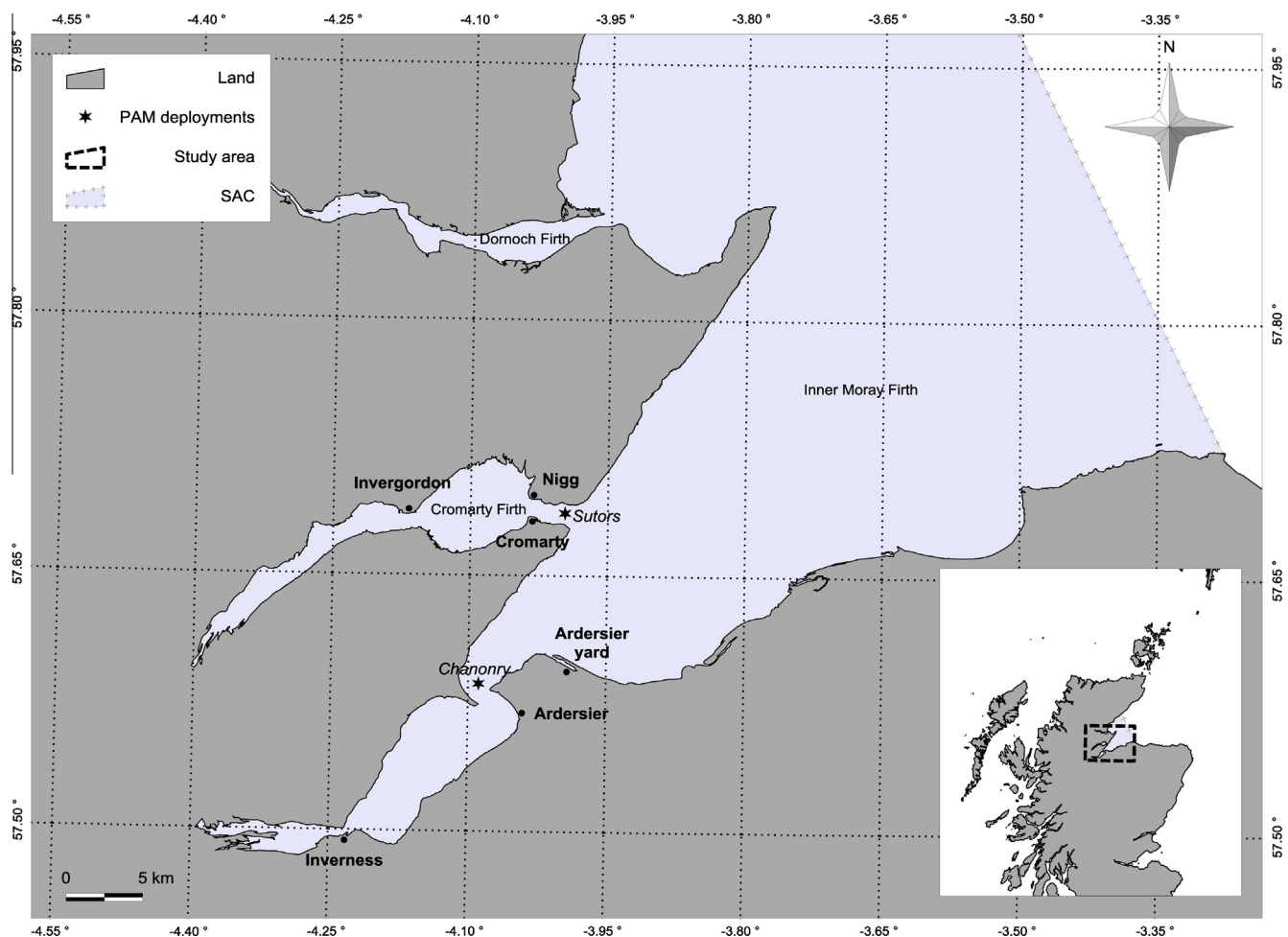

Fig. 1. Map of study area. PAM units were deployed at The Sutors and Chanonry. Meteorological data for Chanonry were acquired from a weather station at Ardersier; time-lapse footage for The Sutors was recorded from Cromarty (see text).

foraging patches around the narrow mouths of coastal estuaries (Hastie et al., 2004; Bailey and Thompson, 2010; Pirotta et al., in press). Other marine mammal species are also regularly sighted in the area: harbour seal (*Phoca vitulina*), harbour porpoise (*Phocoena phocoena*), grey seal (*Halichoerus grypus*), and, further offshore, minke whale (*Balaenoptera acutorostrata*) and other smaller delphinid species (Reid et al., 2003). In addition to the bottlenose dolphin SAC, six rivers around the Firth are SACs for Atlantic salmon (*Salmo salar*), while the Dornoch Firth is an SAC for harbour seals (Butler et al., 2008).

Two locations were selected for underwater noise monitoring: The Sutors (57°41.15′N, 3°59.88′W), at the entrance to the Cromarty Firth, and Chanonry (57°35.12′N, 4°05.41′W), to the southwest (Fig. 1). Both locations are deep narrow channels characterised by steep seabed gradients and strong tidal currents, heavily used by the dolphins for foraging (Hastie et al., 2004; Bailey and Thompson, 2010; Pirotta et al., in press). The Sutors supports commercial ship traffic transiting in and out of the Cromarty Firth, while Chanonry is on the route to and from Inverness and to the west coast of Scotland via the Caledonian Canal (Fig. 2). Water depths at the deployment sites were 45 m (The Sutors) and 19 m (Chanonry). Proposed development of fabrication yards for offshore renewable energy at Nigg, Invergordon and Ardersier yard (Fig. 1) are expected to increase levels of ship traffic in the SAC.

2.2. Acoustic data

Several consecutive deployments of single PAM devices (Wildlife Acoustics SM2M Ultrasonic) were made at the two sites during summer 2012. The units were moored in the water column ~1.5 m above the seafloor. The periods covered by the deployments are shown in Table 1. Gaps in the time series at The Sutors were caused by equipment malfunctions. Noise was monitored on a duty cycle of 1 min every 10 min at a sampling rate of 384 kHz and 16 bits. This regime allowed for detection of ship passages with a similar time resolution to the AIS data (~10 min; see below) while also providing recordings of marine mammal sounds up to 192 kHz. Additionally, noise was recorded at 192 kHz, 16 bits during the remaining 9 min of the duty cycle. These data were only used for detailed analysis of illustrative events.

The PAM units were independently calibrated using a pistonphone in the frequency range 25–315 Hz. This calibration agreed with the manufacturer's declared sensitivity to within ±1 dB, and so the manufacturer's data were used for the entire frequency range (25 Hz–192 kHz). Acoustic data were processed in MATLAB using custom-written scripts. The power spectral density was computed using a 1-s Hann window, and the spectra were then averaged to 60-s resolution using the standard Welch method (Welch, 1967), producing a single spectrum for each 1-min recording. These were then concatenated to form a master file for subsequent analysis. Spectral analysis revealed low-amplitude tonal noise from the recording system at various frequencies above 1 kHz (Merchant et al., 2013). This system noise contaminated a small proportion of the frequency spectrum (<0.1%) and was omitted from the analysis. The analysis also showed that the noise floor of the PAM units was ~47 dB re 1 μPa^2, exceeding background noise levels above ~1.5 kHz. Although anthropogenic, biotic and abiotic sounds could still be detected and measured at these high frequencies, background noise levels above ~1.5 kHz could not be determined.

2.3. Ancillary data

Automatic Identification System (AIS) ship-tracking data were provided by a Web-based ship-tracking network (http://www.shipais.com/) for the duration of the deployments (Fig. 2). Time-lapse footage was recorded at both sites using shore-based digital cameras (Brinno Gardenwatchcam™ GWC100) whose field of view included the PAM locations. One camera was positioned on the Lighthouse Field Station, Cromarty (The Sutors; 57°40.98′N, 4°02.19′W) and the other at Chanonry Point (57°34.49′N, 4°05.70′W; see Fig. 1).

Meteorological data were acquired for the Chanonry site from a weather station at Ardersier (~4 km SE of deployment; Fig. 1) using the Weather Underground open-access database (http://www.wunderground.com/). The dataset included precipitation and wind speed measurements made at 5-min intervals. The POLPRED tidal computation package (provided by the National Oceanography Centre, Natural Environment Research Council, Liverpool, UK) was used to estimate tidal speeds and levels at 10-min intervals (to match the acoustic data) in the nearest available regions to each site.

An autonomous underwater acoustic logger (C-POD, Chelonia Ltd., www.chelonia.co.uk) was independently deployed at each of the two sites as part of the bottlenose dolphin SAC monitoring programme (Cheney et al., 2013). C-PODs use digital waveform characterisation to detect cetacean echolocation clicks. The time of detection is logged together with other click features, which are then used by the click-train classifier (within the dedicated analysis software) to identify bottlenose dolphin clicks. Here, the data from the C-PODs were used only to confirm dolphin occurrence at the two sites throughout the deployment periods. More detailed analysis is ongoing and will be reported elsewhere.

Fig. 2. AIS shipping density in the inner Moray Firth for the duration of the deployments (13 June–27 September 2012). Grid resolution: 0.1 km.

Table 1
Periods covered by successful PAM deployments at each site during summer 2012.

	Deployment	Start date	End date
The Sutors	1	13 June	07 July
	2	14 July	23 July
	3	07 September	27 September
Chanonry	1	20 July	10 August
	2	10 August	01 September

2.4. AIS data analysis

Peaks in the broadband noise level were attributed to AIS vessel movements using the technique developed by Merchant et al., 2012b. The method applies an adaptive threshold to the broadband noise level, which identifies brief, high amplitude events while
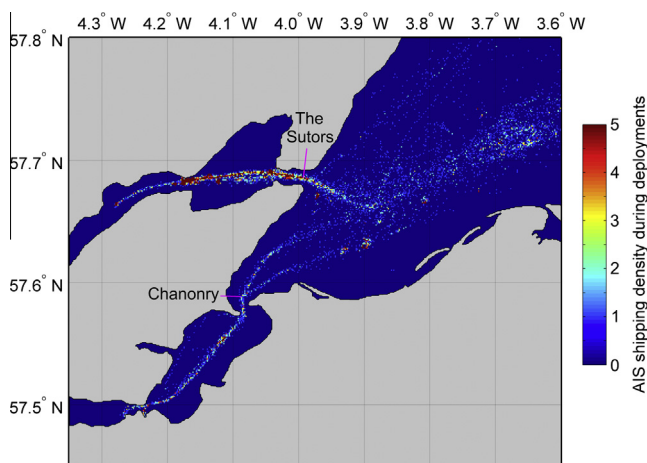
adapting to longer-term variation in background noise levels. The adaptive threshold level (ATL) takes the form

$$ATL(t) = \min \left[SPL(t) \right]_{t-W/2}^{t+W/2} + C \qquad (1)$$

where SPL (t) is the sound pressure level [dB re 1 μPa^2] at time t, W is the window duration [s] over which the minimum SPL is computed, and C is the threshold ceiling [dB], a specified tolerance above the minimum recorded SPL. In this study, a window duration of 3 h and a threshold ceiling of 12 dB was used – a more conservative threshold than in previous work (3 h, 6 dB; Merchant et al., 2012b) – in order to exclude persistent but variable low-level noise from the fabrication yard at Nigg (Fig. 1) which was not associated to vessel movements. A narrower frequency range (0.1–1 kHz, not 0.01–1 kHz) was also used to calculate the broadband noise level, since the spectrum below 100 Hz was contaminated by flow noise (see Section 3).

AIS analysis was only conducted for The Sutors, which had high (>80%) temporal coverage. Coverage at Chanonry was more sporadic, such that only a few illustrative examples could be produced. By comparing AIS vessel movements to the acoustic data, peaks in noise levels were classed as due to: (i) closest points of approach (CPAs) of vessel passages; (ii) due to other AIS vessel movements; and (iii) unidentified. To compute the sound exposure attributable to each event, noise levels exceeding the adaptive threshold on either side of each peak were considered to form part of the same event.

3. Baseline noise levels

3.1. Chanonry

Ambient noise levels differed significantly between the two sites (Fig. 3). Compared to The Sutors (Fig. 3b), noise levels at Chanonry were relatively low, with only occasional vessel passages (Fig. 3a). Variability in ambient noise levels at Chanonry was largely attributable to weather and tidal processes, as example data in Fig. 4 illustrate. Higher wind speeds were associated to broadband noise concentrated in the range 0.1–10 kHz (Fig. 4a and b), while a Spearman ranked correlation analysis (Fig. 4d) shows a broad peak with maximal correlation to wind speed at ~500 Hz, consistent with the spectral profile of wind noise source levels (Wenz, 1962; Kewley, 1990). The influence of rain noise was less apparent, perhaps because of low rainfall levels during the deployment, though the peaks in rainfall rate appear to correspond to weak noise peaks at ~20 kHz, which would agree with previous measurements (e.g. Ma and Nystuen, 2005).

Tide speed was correlated to noise levels at low and high frequencies (Fig. 4d). The high (20–100 kHz) frequency component was attributable to sediment transport, which can generate broadband noise with peak frequencies dependent on grain size (Thorne, 1986; Bassett et al., 2013). Sublittoral surveys of the area show a seabed of medium sand, silt, shell and gravel in the vicinity of the deployment (Bailey and Thompson, 2010), which approximately corresponds to laboratory measurements of ambient noise induced by this grain size (Thorne, 1986). The low frequency component was caused by turbulence around the hydrophone in the tidal flow (Strasberg, 1979) known as flow noise, which is pseudo-noise (i.e. due to the presence of the recording apparatus) and not a component of the acoustic environment. Comparison of the tide speed (Fig. 4c) with the periodic low-frequency noise peaks in Fig. 4a shows that flow noise was markedly higher during the flood tide, possibly owing to fine-scale variations in tidal flow or the orientation of the PAM device in the water column. There was also a correlation to tide level at ~6 kHz (Fig. 4d). This may have been caused by wave action on the shingle beach near the deployment: at higher tides, waves can reach further up the beach face and displace more shingle, and the composition of shingle and incline also vary up the beach face.

3.2. The Sutors

Noise levels at The Sutors (Fig. 3b) were highly variable in the range 25 Hz–1 kHz, and the spectrum featured more frequent vessel passages (these appear as narrow, high-amplitude vertical lines with peaks typically between 0.1 and 1 kHz) than Chanonry (Fig. 3a). There were also two instances of rigs being moored within or towed past The Sutors: firstly from 16–23 June, and the second at the end of the final deployment on 27 September (Fig. 3b). The vessels towing and positioning the rigs [using dynamic positioning (DP)] produced sustained, high-amplitude broadband noise concentrated below ~1 kHz.

The stronger influence of anthropogenic activity at The Sutors is also evident in the diurnal variability of noise levels recorded (Fig. 5a). While the median noise levels at Chanonry were only weakly diurnal, the Sutors data show a marked rise in the range 0.1–1 kHz during the day, corresponding to increased vessel noise. Mean levels (Fig. 5b) are largely determined by high-amplitude events (Merchant et al., 2012a), in this case particularly loud vessel passages, which were both louder (Fig. 5b) and more variable (Fig. 5c) at The Sutors. The week-long presence of rig-towing vessels evident in Fig. 3a was omitted from The Sutors data as this high-amplitude event would otherwise entirely dominate the mean levels for The Sutors in Fig. 5b. Note that the median levels
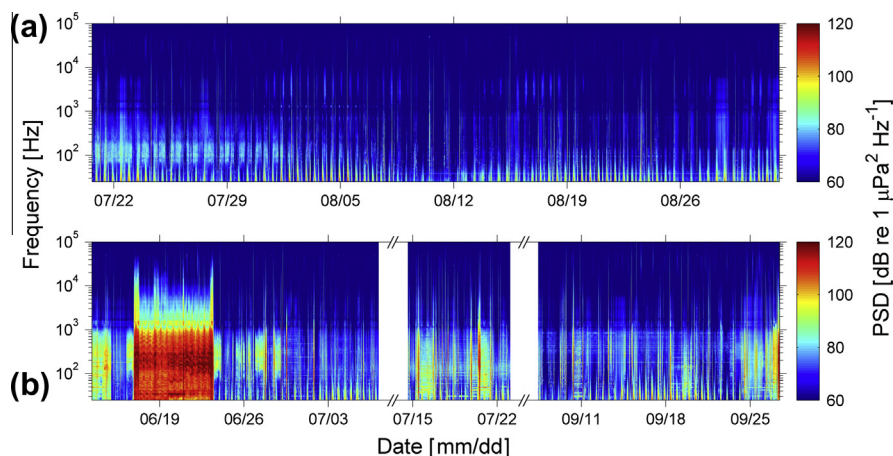
Fig. 3. Ambient noise spectra: (a) Chanonry, and (b) The Sutors. Frequency range: 25 Hz–100 kHz; temporal resolution: 60 s.
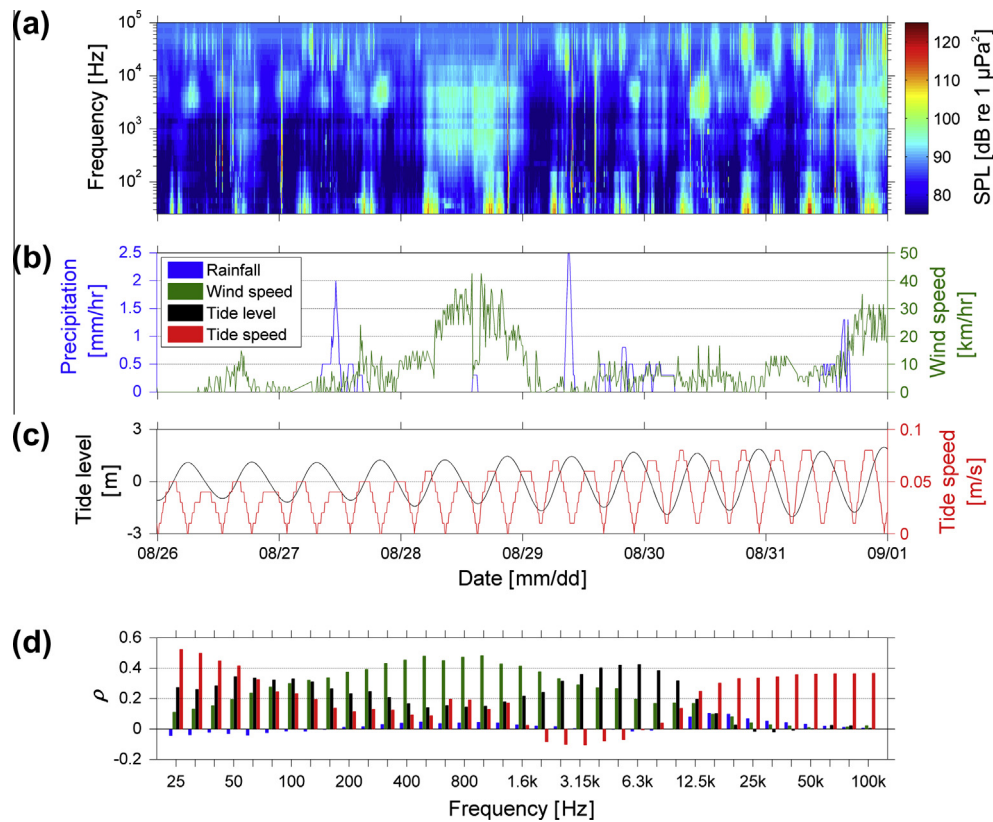
Fig. 4. Effect of weather and tides on ambient noise in Chanonry. (a) 1/3 octave band spectrum from 26 to 31 August, 60-s resolution; (b) rainfall and mean wind speed recorded at Ardersier; (c) tide level and speed predicted by POLPRED model, and (d) spearman ranked correlation coefficient of each process across frequency range for entire dataset.

(Fig. 5a) are likely to be raised by the noise floor of the PAM device above ∼10 kHz (Merchant et al., 2013), and do not represent absolute values.

3.3. Bottlenose dolphin occurrence and vocalisations

The analysis of C-POD data confirmed that the two sites were heavily used by bottlenose dolphins throughout the deployment periods. The animals were present in both locations every day (with the exception of 28 August in Chanonry) with varying intensity. The mean number of hours per day in which dolphins were detected was 8.3 (standard deviation = 4.8; range = 1–18) in The Sutors and 7.3 (standard deviation = 3.0; range = 0–15) in Chanonry.

Bottlenose dolphin vocalisations were also recorded on the PAM units (Fig. 6a). There was considerable overlap between the frequency and amplitude ranges of vocalisations and ship noise observed, indicating the potential for communication masking. Sample spectra from Chanonry of a passing oil tanker (Fig. 6b) and bottlenose dolphin sounds (Fig. 6a) clearly illustrate that observed vocalisations in the range ∼0.4 to 10 kHz coincide in the frequency domain with ship noise levels of higher amplitude during the vessel passage. Although underwater noise radiated by the vessel in Fig. 6b extends as high as the 50 kHz echosounder, masking at high frequencies is likely to be localised due to the increasing absorption of sound by water as frequency increases (Jensen et al., 2011). This is apparent in the form of the acoustic signature: the highest frequencies are only visible at the closest point of approach (CPA), while low-frequency tonals are evident more than 30 min before the vessel transits past the hydrophone, when AIS data indicates it was 9 km away. Note also the upsurge in broadband (rather than tonal) noise following the CPA, as cavitation noise from the

propeller becomes more prominent in the wake of the vessel. These effects can be observed more intuitively in the time-lapse footage (paired with acoustic and AIS data) documenting this passage included in the Supplementary material.

Whether masking occurs and whether this has a significant impact will depend on the specific context (Ellison et al., 2012), including the physiological and behavioural condition of the animals, and will vary with the extent to which the signal-to-noise ratio of biologically significant sounds is diminished by the presence of vessel noise (Clark et al., 2009). Estimates of effective communication range (active space) in the absence of vessels for bottlenose dolphins in the Moray Firth range from 14 to 25 km at frequencies 3.5 to 10 kHz, depending on sea state (Janik, 2000). More detailed analysis would be required to estimate the extent to which vessel passages reduce this active space (e.g. Hatch et al., 2012; Williams et al., in press).

4. Monitoring future ship noise trends

4.1. AIS analysis

Analysis of the AIS vessel movements in relation to peaks recorded in broadband (0.1–1 kHz) noise levels at The Sutors site identified 62% of peaks as due to AIS vessel movements, with 38% unidentified. This was a similar ratio to that reported by Merchant et al. (2012b), who observed a ratio of 64% identified to 36% unidentified in Falmouth Bay, UK. The 62% of peaks identified was composed of 52% attributed to vessel CPAs, with the remaining 10% due to other vessel movements which were clearly distinct from CPAs, such as acceleration from or deceleration to stationary positions (see example in Supplementary material). Fig. 7 shows an
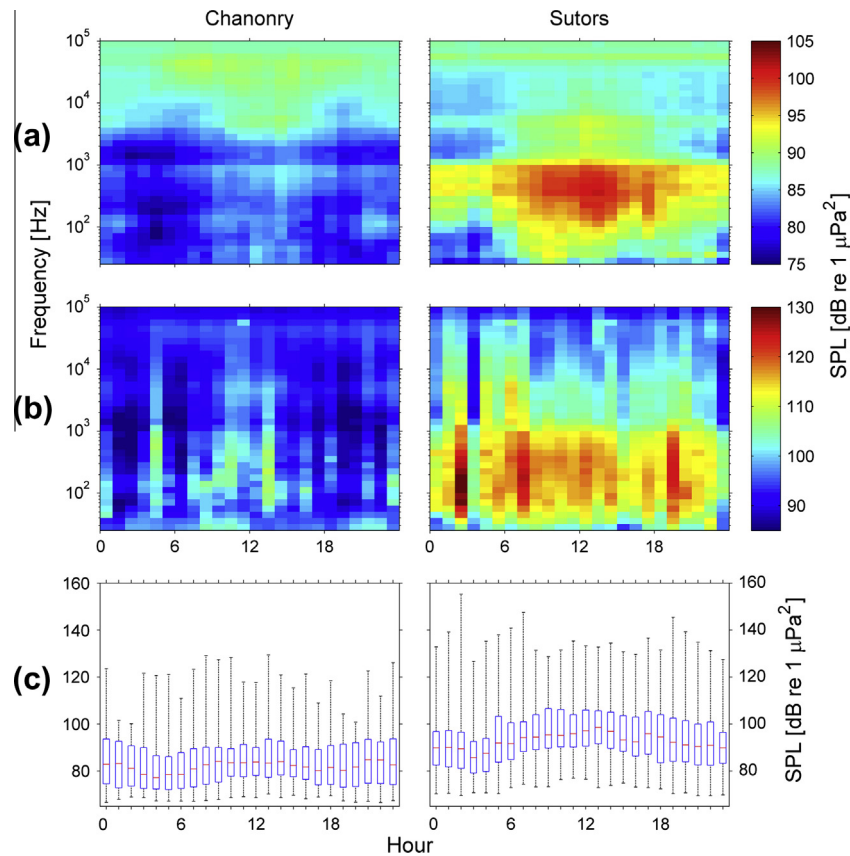
Fig. 5. Hourly variability in noise levels at both sites in 1/3 octave bands. Left column: Chanonry; Right column: The Sutors. (a) Median, (b) RMS mean, and (c) broadband (0.1–1 kHz) level.
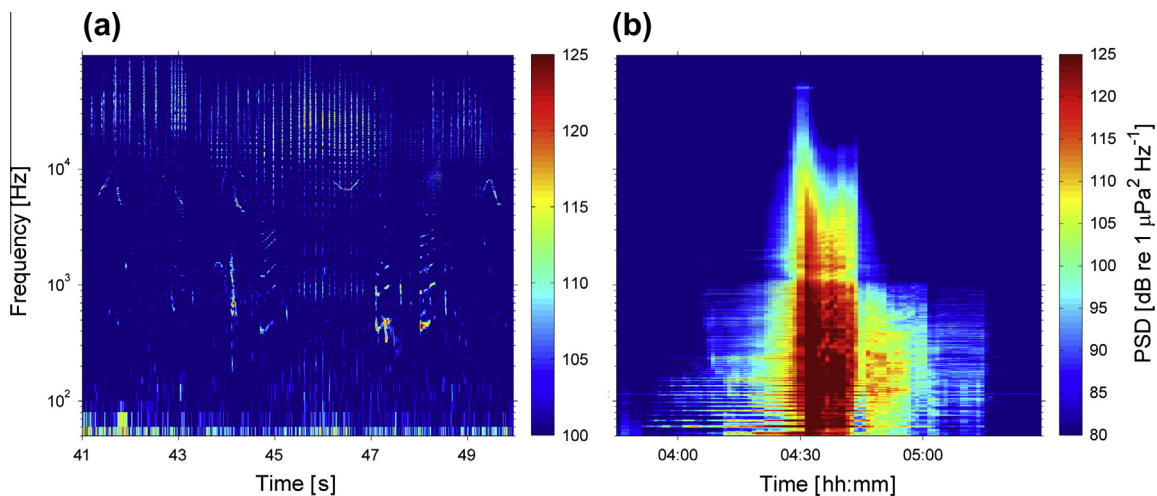

Fig. 6. Sample spectra recorded at Chanonry. (a) Vocalisations and echolocation clicks of bottlenose dolphins on 12 August at 17:50. Spectra have the same frequency range but (a) has a finer amplitude range; and (b) oil tanker with closest point of approach (CPA) at 04:30 on 18 August.

example ship identification of a 125-m vessel at its CPA; examples illustrating identification of a decelerating AIS vessel and an unidentified non-AIS vessel captured on time-lapse footage (see Section 4.2) are provided in the Supplementary material.

Modelling underwater noise levels using AIS data has been proposed as a way to map noise exposure from shipping to enable targeted mitigation measures (Erbe et al., 2012; NOAA, 2012). However, the efficacy of such an approach will depend on the proportion of anthropogenic noise exposure accounted for by vessels with operational AIS transmitters. Vessels below the

current 300 GT gross tonnage threshold (IMO et al., 1974) not carrying AIS transceivers may also contribute significantly to noise exposure in some areas, and other sources of anthropogenic noise such as seismic surveys and pile driving may occasionally be more significant, though their spatiotemporal extent is generally more limited.

To investigate the feasibility of AIS noise modelling in the Moray Firth, the sound exposure attributable to AIS-identified and unidentified noise periods for each day of uninterrupted AIS coverage was calculated for The Sutors. These periods were computed as
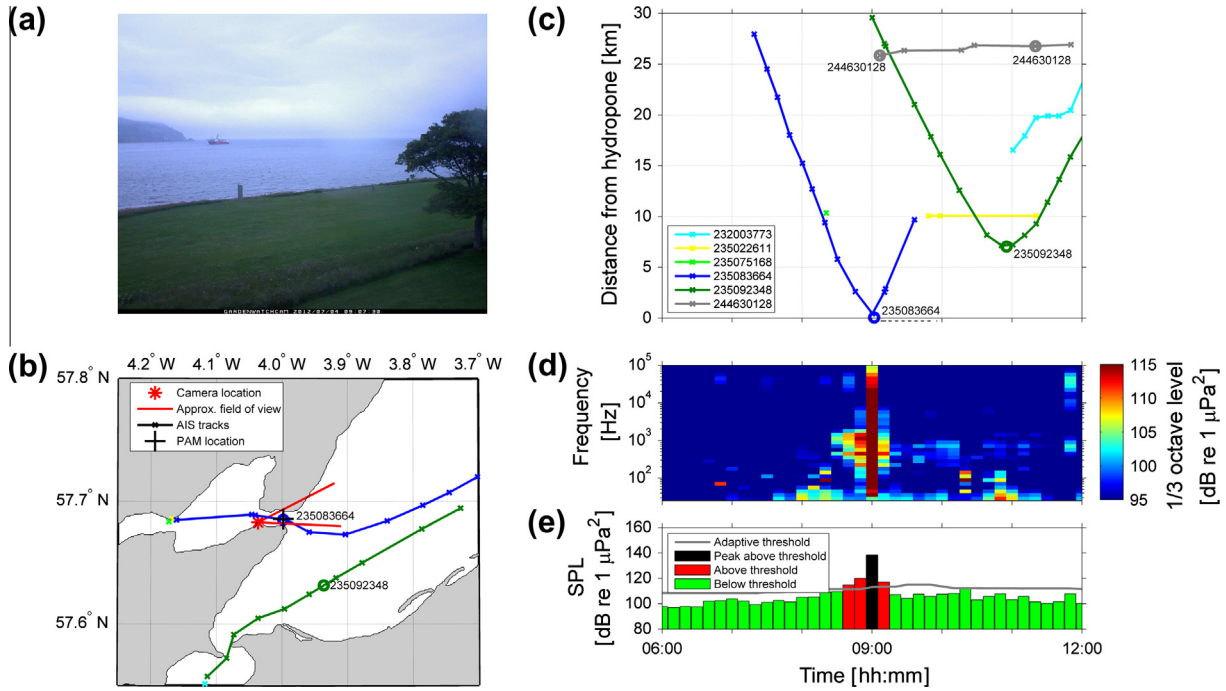
Fig. 7. AIS analysis example with time-lapse footage. (a) Still of time lapse footage showing vessel whose CPA occurred at 09:00 on July 4; (b) map of AIS movements in 6-h period centred on CPA. Black cross denotes location of PAM unit in The Sutors, circles indicate CPAs labelled with Maritime Mobile Service Identity (MMSI) number; (c) range of AIS transmissions from PAM unit versus time; (d) 1/3 octave spectrum of concurrent acoustic data; and (e) broadband level in frequency range 0.1–1 kHz, showing peak identification using adaptive threshold.

the cumulative sound exposure from the period surrounding a noise peak during which the noise level was above the adaptive threshold. So for example, the 'above threshold' and 'peak above threshold' data in Fig. 7e were counted towards the cumulative sound exposure of the AIS-identified component for that day.

The 24-h sound exposure level (SEL) of each component (total SEL, AIS-identified SEL, and SEL from unidentified peaks) is presented in Fig. 8a for the range 0.1–1 kHz. SEL is a cumulative measure of sound exposure appropriate for the assessment of potential acoustic impacts to marine mammals from sources such as shipping (Southall et al., 2007). Note that SEL is a logarithmic measure, so the sum of the component parts of the total SEL does approximate the whole, but in linear space. During the presence of the rig-towing vessels operating with DP from June 16–23 (see Fig. 3b) the noise level was consistently high, such that only two peaks were recorded by the adaptive threshold (both of which
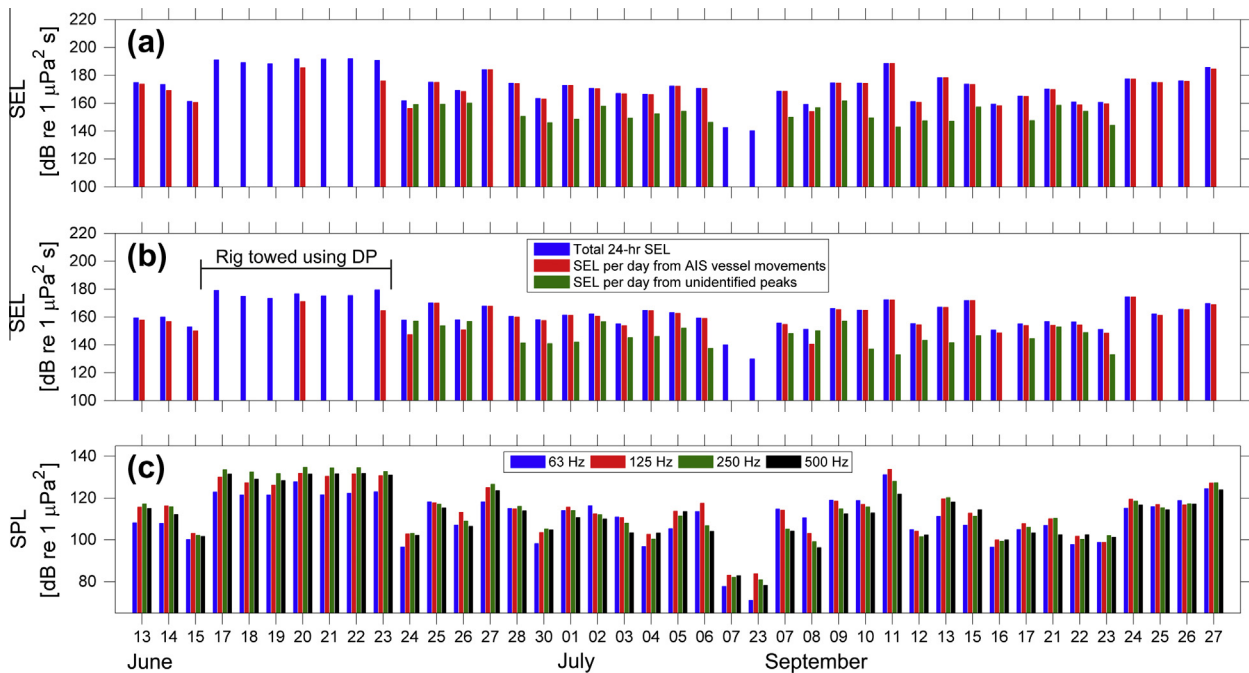

Fig. 8. Broadband SEL per day for days with uninterrupted AIS coverage of The Sutors. (a) 0.1–1 kHz, (b) 1–10 kHz. Noise exceeding the adaptive threshold was attributed to AIS vessel movements or classed as unidentified. 'Rig towed using DP': this data did not exceed the adaptive threshold, but was attributable to AIS vessels (see text). (c) Mean SPL per day for four 1/3 octave frequency bands, including those proposed for use in the MSFD (63 and 125 Hz).

were AIS-identified vessels). As the rig-towing vessels were using AIS, their presence would be included in an AIS-based noise model, though their source levels are likely to be significantly elevated by the use of DP, which may not be accounted for by a generic ship source level database.

For all but four of the remaining days with uninterrupted AIS coverage, the AIS-identified peaks generated the vast majority of sound exposure recorded in this range (Fig. 8a). On two of the four days (24 June and 8 September), unidentified peaks produced marginally greater sound exposure than AIS-identified peaks. This may have been caused by the particularly close presence of a non-AIS vessel or vessels in combination with only small or relatively distant AIS-tracked vessels on these days. On 7 July and 23 July, no peaks were recorded at all, and total sound exposure was ~20 dB lower than the minimal levels recorded with detectable ship passages.

Since small vessels (which are not obliged to carry AIS transceivers) may emit noise with peak levels at up to several kHz (Kipple and Gabriele, 2003; Matzner et al., 2010), the 24-h SEL in the 1–10 kHz bandwidth was also computed (Fig. 8b) to analyse whether higher frequencies were more dependent on unidentified peaks, which are likely to originate from small vessels. This analysis retained the peak classification data used for the 0.1–1 kHz range. As expected, the recorded levels were consistently lower than at 0.1–1 kHz. Only one day (26 June) showed a significant difference, with unidentified sound exposure more dominant than in the lower frequency band. This demonstrates that sound exposure generated by AIS-carrying vessels at the study site was generally greater than that produced by non-AIS vessels for the range of both frequency bands (0.1–10 kHz). Consequently, a modelling approach based on vessel movements derived from AIS data should account for the majority of variability in noise exposure, provided the ship source levels input to the model are sufficiently accurate and acoustic propagation models are sufficiently predictive. Future work could explore whether this is achievable through implementation of such models and comparison with recorded data.

4.2. Time-lapse footage

In addition to analysis of AIS movements, time-lapse footage was also reviewed to explore the potential for corroboration of AIS vessel identifications, detection of non-AIS vessels responsible for unidentified noise peaks, and characterisation of unusual acoustic events. The frame presented in Fig. 7a corresponds to the timing of the noise peak at around 09:00 presented in Fig. 7c–e, and confirms the previous identification of this vessel from the CPA of its AIS track. An example in the Supplementary material of a noise peak unidentified by AIS also shows a small vessel in the field of view of the time-lapse camera (although it is difficult to distinguish). Two examples of time-lapse footage paired with acoustic and AIS data are provided in the Supplementary material as videos, which demonstrate the potential for this method to be used as a quick review tool of ship movements and underwater noise variability in coastal environments. They also provide an intuitive and informative educational tool to highlight the impact of ship noise on marine soundscapes and the potential for masking, behavioural and physiological impacts to marine fauna. As these examples illustrate, improving the visual and temporal resolution and the field of view would significantly enhance the power of this method for vessel monitoring and identification in coastal waters.

4.3. MSFD frequencies

The MSFD proposes to monitor underwater ambient noise in EU waters, using two 1/3-octave frequency bands (63 and 125 Hz) as
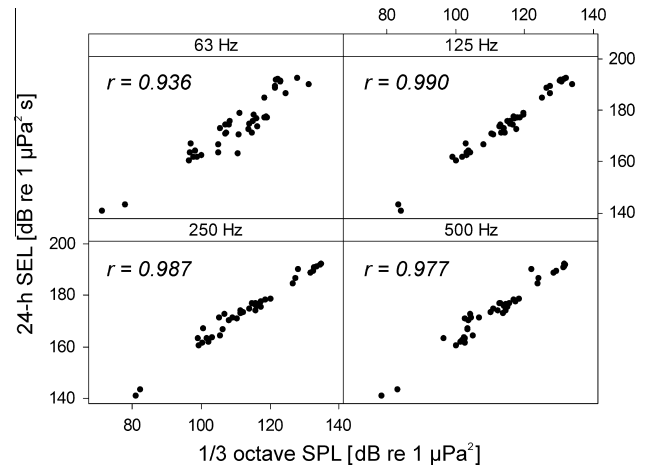

Fig. 9. Relationships between broadband SEL (0.05–1 kHz) per day and mean SPL per day at The Sutors for four 1/3 octave frequency bands, including those proposed for use in the MSFD (63 and 125 Hz).

indicators of shipping noise levels (EU, 2008; Tasker et al., 2010). Ships also generate noise above these frequencies – as was observed in this study [Figs. 5a and 6b] – though at higher frequencies sound is attenuated more rapidly by water and so is generally more localised. To assess whether higher frequency bands may be appropriate indicators for noise exposure from shipping, we compared mean noise levels in 1/3-octave frequency bands centred on 63, 125, 250 and 500 Hz (Fig. 8c) with daily broadband sound exposure levels in the range 0.05–1 kHz. This wider frequency band (0.05–1 kHz) approximately corresponds to the nominal range of shipping noise (0.01–10 kHz; Tasker et al., 2010), but avoids the greatest levels of flow noise, which increases with decreasing frequency (Strasberg, 1979). All four bands were highly correlated with noise exposure levels in the wider frequency band (Fig. 9), but this relationship was strongest at 125 Hz. The reduced correlation in the 63 Hz band may have been caused by the noise related to tidal flows (Fig. 4) or low-frequency propagation effects characteristic of shallow water environments (Jensen et al., 2011). These effects may also limit the efficacy of the 63 Hz band as an indicator of anthropogenic noise exposure in other shallow water, coastal sites.

5. Discussion

The measurements of underwater noise at The Sutors and Chanonry establish baseline noise levels within the Moray Firth SAC during the summer field season, providing an important benchmark against which to quantify the acoustic impact of any future changes in shipping activity or other anthropogenic sources. The recordings revealed conspicuous differences in overall noise level and variability between the two sites (Fig. 3): shipping traffic and industrial activity related to the fabrication yard at Nigg and port activities at Invergordon (Fig. 1) were the dominant sources of noise at The Sutors, generating strongly diurnal variability in median noise levels (Fig. 5a). In contrast, median levels at Chanonry were comparatively low (Fig. 5a), with only occasional vessel passages (Fig. 3a) and variability determined by weather and tidal processes (Fig. 4). Analysis of daily noise exposure at The Sutors highlighted the extent to which ship noise raises the total noise exposure above natural levels: on two days when no ship passages were detected, total daily noise exposure was ~20 dB lower than normal in the 0.1–10 kHz range (Fig. 8).

Both sites used in this study are important foraging areas for the population of bottlenose dolphins in the inner Moray Firth (Hastie et al., 2004; Bailey and Thompson, 2010; Pirotta et al., in press) and

dolphins were confirmed to use them regularly throughout the deployment periods. Since the population appears to be stable or increasing (Cheney et al., 2013), the current noise levels we present are not expected to pose a threat to dolphin population levels. Nevertheless, the difference in baseline soundscape between the two foraging areas could influence how these sites may be affected by any future increases in shipping noise. While The Sutors is currently expected to experience greater increases in traffic associated with offshore energy developments, dolphins may already be accustomed to higher noise levels in this area. On the other hand, Chanonry is currently much quieter, meaning that a smaller increase in shipping noise could result in a greater degradation of habitat quality.

Analysis of noise levels at The Sutors in conjunction with AIS ship-tracking data demonstrated that the majority of total sound exposure at the site was attributable to vessels operating with AIS transceivers (Fig. 8). This indicates that modelling of noise levels based on AIS-vessel movements (e.g. Erbe et al., 2012; Bassett et al., 2012) should account for most of the noise exposure observed experimentally, provided other model parameters (ship source levels, acoustic propagation loss profiles) are sufficiently accurate. This result suggests that models based on planned increases in vessel movements in the Moray Firth (Lusseau et al., 2011; New et al., 2013) may be able to forecast associated increases in noise exposure, and is a promising indication that AIS-based noise mapping could be successfully applied to target ship noise mitigation efforts in other marine habitats. However, caution should be exercised in extrapolating from this result since in areas further from commercial shipping activity, the dominant source of ship noise may be smaller craft not operating with AIS transceivers.

This study also introduces the pairing of shore-based time-lapse footage with acoustic and AIS data as a tool for monitoring the influence of human activities on coastal marine soundscapes. The method enabled identification of abnormally loud events such as rigs being towed past the deployment site, and facilitated detection of non-AIS vessels responsible for noise peaks and corroboration of AIS-based vessel identification (Fig. 7). With improved resolution and field of view, time-lapse monitoring could facilitate more detailed characterisation of non-AIS vessel traffic in coastal areas, enhancing understanding of the relative importance of small vessels to marine noise pollution.

Comparison of spectra documenting bottlenose dolphin vocalisations and a ship passage at Chanonry (Fig. 6) highlights the potential for vocalisation masking by transiting vessels. Odontocetes use echolocation to navigate and to find and capture food (Au, 1993). Disruption to these activities caused by acoustic masking could thus affect energy acquisition and allocation, with long-term implications for vital rates (New et al., 2013). A noisier soundscape could also lead to degradation of the dolphin population's habitat (Tyack, 2008) such as through effects on fish prey (Popper et al., 2003). Moreover, social interactions could be affected by vocalisation masking since sound is critical for communication among conspecifics. Future work could investigate the extent to which the effective communication range – which has been estimated for this population in the absence of vessels (Janik, 2000) – is reduced by the presence of vessel noise (e.g. Erbe, 2002; Hatch et al., 2012; Williams et al., in press). A rise in noise from ship traffic could also induce anti-predatory behavioural responses (Tyack, 2008) and increase individual levels of chronic stress (Wright et al., 2007; Rolland et al., 2012). Research efforts should thus aim to characterise dolphin responses to ship noise in this area, and to understand whether increased ship traffic has the potential to alter the animals' activity budget.

The study also highlighted some important issues for the implementation of the European MSFD. Our measurements show that low-frequency flow noise may dominate in areas of high tidal flow, potentially contaminating noise levels at 63 and 125 Hz – frequencies at which the current legislation proposes to monitor ambient noise (EU, 2008; Dekeling et al., 2013). Flow noise is a form of pseudo-noise caused by turbulence around the hydrophone (Strasberg, 1979), and is not actually present in the environment. While noise from shipping was more dominant than flow noise at both sites (Fig. 5), flow noise exceeded non-anthropogenic noise levels below ∼160 Hz at the Chanonry site (Fig. 4), and so may influence measurements in areas of low shipping density. Since flow noise decreases with increasing frequency (Strasberg, 1979), higher frequency bands would be progressively less susceptible to flow noise contamination than those at 63 and 125 Hz.

Comparison of the proposed 1/3-octave frequency bands with those at 250 and 500 Hz (Fig. 9) indicates that the 250 Hz band may be as responsive to noise exposure from large vessels as the 125 Hz band, and may perform better than the 63 Hz band in shallow water. Although peak frequencies of commercial ship source levels are typically <100 Hz (e.g. Arveson and Vendittis, 2000; McKenna et al., 2012), low-frequency sound may be rapidly attenuated in shallow water depending on the water depth (Jensen et al., 2011), meaning received ship noise levels may have higher peak frequencies than in the open ocean. The 250- and 500-Hz bands are also likely to contain a greater amount of the noise from small vessels (since their spectra can peak at up to several kHz (Kipple and Gabriele, 2003; Matzner et al., 2010)), which may be the dominant source of ship noise in some coastal areas. Inclusion of noise levels at frequencies greater than 125 Hz may therefore be particularly informative for MSFD noise monitoring in shallow waters.

A wider concern for the efficacy of the MSFD with regard to shipping noise is the proposed focus (Van der Graaf et al., 2012; Dekeling et al., 2013) of ambient noise monitoring on high shipping density areas. While it is important that the most acoustically polluted waters are represented in noise monitoring programs, it is arguably the case that habitats most at threat from anthropogenic pressure should be given greater weight. If noise levels in high shipping areas are to determine whether a member state of the European Union attains 'Good Environmental Status', there is a risk that more significant changes to the marine acoustic environment in less polluted areas will be overlooked.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.marpolbul.2013.10.058.

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