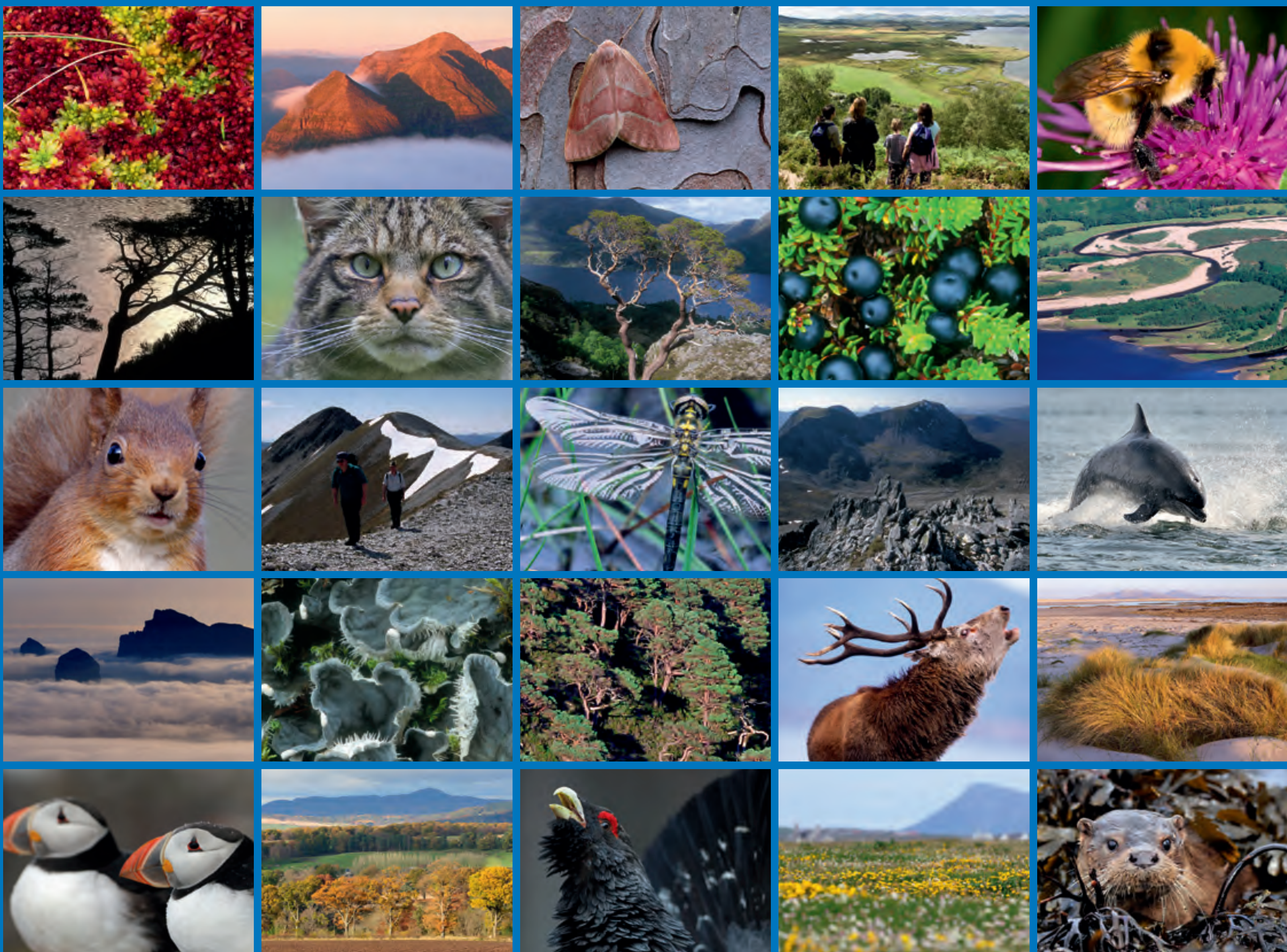
Scottish Natural Heritage
Commissioned Report No. 624

White-beaked dolphin and Risso's dolphin click characteristics and the potential for classification and species identification



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COMMISSIONED REPORT

Commissioned Report No. 624

White-beaked dolphin and Risso's dolphin click characteristics and the potential for classification and species identification

For further information on this report please contact:

Fiona Manson
Scottish Natural Heritage
Battleby, Redgorton
PERTH
PH1 3EW
Telephone: 01738 458641
E-mail: fiona.manson@snh.gov.uk

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COMMISSIONED REPORT
Summary

White-beaked dolphin and Risso's dolphin click characteristics and the potential for classification and species identification

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Background

The Hebridean Whale and Dolphin Trust (HWDT) has conducted visual and acoustic line-transect surveys off the west coast of Scotland since 2003 using its dedicated research vessel, *Silurian*. Passive acoustic monitoring (PAM) plays a key role in these surveys, and HWDT's survey platform has enabled new technologies and methodologies in practical acoustic survey to be developed and used. HWDT has used newly-developed techniques to analyse white-beaked dolphin and Risso's dolphin acoustic data collected from *Silurian* and from other survey platforms around the UK. This report presents the outcomes of this analysis in the following areas:

Main findings

- Clicks from white-beaked dolphins and Risso's dolphins can be readily detected and identified to species level by the frequency banding that can be seen in some of their clicks. Using the average correlation over a whole acoustic event, 90% of white-beaked events were correctly classified and 100% of Risso's events were correctly classified, although the Risso's sample size was only six events.
- This use of clicks in addition to whistles in species detection and identification lends further support to the use of passive acoustics as a means of surveying for these species, most likely in conjunction with visual effort.
- The findings of this report demonstrate that passive acoustic monitoring could make a key contribution to the current requirement to understand the distribution of white-beaked and Risso's dolphins in Scottish waters and identify sites for Marine Protected Areas.
- In addition to providing a valuable proof of concept, this project has also highlighted where further work is required. Recordings of sufficient quality, in particular for Risso's dolphins, are still lacking. There is also a need to increase understanding of the variability between clicks, for which more recordings are required.
- This project did not find sufficiently clear regional differences in click characteristics to determine population units. However, the use of acoustics to make inferences about population structure would merit revisiting, given the potential value for management decisions affecting the conservation of these species of a better understanding of population structure.

For further information on this project contact:
Fiona Manson, Scottish Natural Heritage, Battleby, Redgorton, Perth, PH1 3EW.
Tel: 01738 458641or fiona.manson@snh.gov.uk
For further information on the SNH Research & Technical Support Programme contact:
Knowledge & Information Unit, Scottish Natural Heritage, Great Glen House, Inverness, IV3 8NW.
Tel: 01463 725000 or research@snh.gov.uk

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1. INTRODUCTION

The white-beaked dolphin (*Lagenorhynchus albirostris)* has a restricted range, being endemic to the North Atlantic Ocean, with a mainly northerly distribution over colder continental shelf waters. UK populations comprise a significant proportion of the worldwide population, the only cetacean for which this is the case. An estimated 80% of the European population (UKBAP, 2008) is in UK waters, mostly in the waters around Scotland and off northeast England. On the west coast of Scotland, white-beaked dolphins occur mainly around the northern Minch and Western Isles (Hammond *et al*., 1995; Northridge *et al*., 1995; Reid *et al*., 2003; SCANS II, 2008; Weir *et al*., 2009).

Risso's dolphins (*Grampus griseus*), are more widely distributed worldwide, but are also an important Scottish cetacean species. There are some known high density areas in the Outer Hebrides, but information outside these areas is sparse.

Both species have been proposed as Priority Marine Features (PMF) by SNH (Howson *et al*., 2012). They have also been identified as search features for Scottish Marine Protected Areas (MPAs). However, the ecology, population structure, abundance and distribution of both species are poorly understood, in part as a result of the difficulty and expense of surveying them.

Passive acoustic monitoring is increasingly being used to investigate cetacean distribution and abundance, and may be particularly suitable in the case of white-beaked and Risso's dolphins. Data collected by HWDT on the west coast of Scotland, combined with datasets from other areas in Scotland and the North Sea, have the clear potential to provide new information through analysis of the spectral characteristics of white-beaked and Risso's dolphin clicks. In this project, we have analysed HWDT's white-beaked and Risso's dolphin recordings made during surveys. We have also collated, processed and analysed other recordings from the west coast of Scotland, the east coast of the UK, and the English Channel to assess whether there are sufficient characteristic elements within white-beaked and Risso's dolphin clicks to allow reliable click classification algorithms that distinguish to species level to be developed. Recordings have also been examined for evidence of regional variation in click characteristics which may be indicative of population substructure.

Preliminary analysis which took place prior to this project suggested that there were spectral characteristics in white-beaked and Risso's dolphin clicks which could identify them to species level. These characteristics comprised distinct spectral peaks and troughs at consistent frequencies in the clicks of both species. Previous work by Soldevilla *et al*. (2008) has demonstrated such frequency banding for another *Lagenorhynchus* species, the Pacific white-sided dolphin (*L. obliquidens*), and for Risso's dolphins. This suggested the possibility of banding also being present in white-beaked dolphins, although work on this species in Iceland did not report evidence of such acoustic characteristics (Rasmussen & Miller, 2002). However, Rasmussen & Miller (2002) generally focused on the peak frequency of white-beaked dolphin clicks, which they report as >100 kHz, whereas in this study we focus on the lower frequencies. There was also some indication in the case of white-beaked dolphins that there might be frequency differences in these bands indicative of population structuring. However, these findings were based on a small sample size. By analysing more recordings in a greater level of detail, this project aimed to assess these possibilities in more depth.

The specific aims of the project were to:

1. Describe acoustic characteristics of white-beaked and Risso's dolphin vocalisations from Scottish and adjacent waters. Report on the scope for highly automated detection and classification from vocalisations detected during towed hydrophone surveys.
2. Report on the potential for identifying sub-populations based on acoustic characteristics.
3. Present new information on densities and distributions of white-beaked and Risso's dolphins in the Hebrides based on analysis of acoustic data from *Silurian* towed hydrophone surveys.
4. Report on strategies for cost-effective passive acoustic monitoring schemes for these species in Scottish waters.
5. Recommend useful technical developments and future fieldwork.

2. METHODS

2.1 White-beaked dolphins

For this project we have brought together both our own recordings and acoustic data from several other sources (Table 1). All recordings were WAV files and were collected at a sample rate ≥192,000 samples per second. The majority of recordings incorporated a high pass filter at 20 kHz. The following data were collated for analysis:

- Recordings made from HWDT's research vessel *Silurian* on the west coast of Scotland.
- Recordings made from surveys in areas of planned offshore wind farm developments in the northern and southern North Sea.
- Recordings made by the International Fund for Animal Welfare (IFAW) research vessel *Song of the Whale* in the North Sea and English Channel.

Of these recordings, some were excluded from analysis for the following reasons:

- Detections were of insufficient quality/signal strength (n=14).
- Other species were present at the time of, or close to, the encounter and there was a risk that vocalisations might be confused with them (n=9).
- Encounters were too close together in time. To avoid inadvertently sampling the same group twice, a time period of at least 30 minutes of clear steaming between encounters was enforced (n=1).
- There was no concurrent visual sighting and so there was some level of uncertainty that the detection was of the target species (n=4).

Once these recordings had been excluded, 61 recordings remained which were of sufficient quality for analysis. The raw WAV files were batch-processed using PAMGUARD – free, open-source software developed for the real-time detection and offline analysis of cetacean vocalisations (www.pamguard.org, Gillespie *et al.*, 2008). This batch-processing, using a customised click detector module, converted the WAV files into 'binary' files which included a short sample of WAV data for each click allowing the closer analysis of acoustic characteristics. The click detector settings (specifically the two types of frequency filter used by PAMGUARD to remove noise and maximise the detector's performance, the pre-filter and the trigger filter) were customised based on the broadband click characteristics of white-beaked dolphins. These click detector parameters are shown in Table 2.

The batch-processed data were reviewed in PAMGUARD Viewer, the offline component of PAMGUARD. When an acoustic encounter was identified in the binary file, the clicks comprising this encounter were stored as an 'event' in an MS Access database, which logged the time, position and number of clicks in the stored event. Events varied considerably in duration and in the number of clicks within the encounter. Some events, such as those recordings on wind farm and *Song of the Whale* line transect surveys, were quite brief (approximately 2 to 5 minutes), as the vessel continued on its survey track without slowing down or closing with groups. Other events, chiefly those recorded by HWDT from *Silurian*, were considerably longer, as the vessel would slow down and close with dolphin schools to obtain more information on the animals, take photographs for photo-identification purposes and make more extensive recordings. The latter encounters often resulted in events comprising many thousands of clicks. To overcome this discrepancy in encounter length, once an event had been stored, it was then further divided into 'sub-events' for detailed analysis. These sub-events were batches of ≈20-40 successive clicks within the encounter, and enabled comparable sized samples to be analysed. In some cases, these sub-events comprised all the clicks in an event, but for events with very large numbers of clicks, a selection of random samples was taken and stored as sub-events.

Table 1. Data sources for white-beaked dolphin recordings.

Recording location	Source	Year	Vessel	Recording system	Number of encounters with acoustic recordings	Number of recordings suitable for analysis
Scotland West Coast	HWDT	2008 2011 2012	*Silurian* (18m motor-sailer)	MER/SCANS stereo hydrophone array with near flat frequency response (2-150 kHz). 100m cable length	39	22
Scotland West Coast	HWDT / Ketos Ecology	2007	*Silurian* (18m motor-sailer)	SCANS stereo hydrophone array with near flat frequency response (2-150 kHz). 100m cable length	6	5
Scotland North Sea (Neart na Gaoithe & Inch Cape)	EIA – Mainstream Renewable Power & Repsol	2011 2012	*Fleur de Lys* (22m motor vessel) & *Eileen May* (17m motor vessel)	MER stereo hydrophone array with near flat frequency response (2-150 kHz). 200m cable length	5	2
North Sea (Hornsea)	EIA – SmartWind Ltd	2010 2011 2012	*Southern Star* (35m motor vessel)	MER stereo hydrophone array with near flat frequency response (2-150 kHz). 200m cable length	21	15
North Sea (Dogger Bank)	IFAW	2011	*Song of the Whale* (21m motor-sailer)	Seiche stereo hydrophone array with near flat frequency response (2-200 kHz). 200m cable length	9	8
North Sea (central)	IFAW	2012	*Song of the Whale* (21m motor-sailer)	MCR stereo hydrophone array with near flat frequency response (2-150 kHz). 200m cable length	8	8
English Channel	IFAW	2011	*Song of the Whale* (21m motor-sailer)	Seiche stereo hydrophone array with near flat frequency response (2-200 kHz). 100m cable length	1	1
Total					89	61

Table 2. Filter settings for processing raw data: white-beaked dolphins.

Filter	Cut off frequencies	
Pre-Filter	High Pass	2,000 Hz
	Low Pass	180,000 Hz
Trigger Filter	High Pass	40,000 Hz
	Low Pass	150,000 Hz

It was clear during this stage of analysis that the white-beaked dolphin click repertoire was highly variable, and comprised both broadband and narrowband clicks. As successive clicks within a sequence could have broadband and narrowband characteristics, clicks with different characteristics would sometimes be grouped together within a sub-event.

Sub-events were displayed as concatenated spectrograms. These showed the spectra for each identified click stacked up sequentially and were useful for demonstrating whether there were consistent peaks at certain frequency bands present in broadband clicks, and showing the frequency of a strong narrowband component. An average template of each sub-event was then derived based on the arithmetic mean of amplitudes in each frequency band. The bearing of each sub-event was also noted to enable the investigation of any possible effects of the orientation of animals with respect to the survey vessel on the acoustic characteristics of clicks. Although bearing from the hydrophone does not relate directly to the orientation of the animal, there are circumstances, such as when animals are bow-riding, when a consistent bearing is indicative of certain behaviours and likely relative orientations.

Initial 'model' templates were generated for typical broadband and narrowband clicks based on examination of the frequency spectra of the clicks within a number of events and taking an average from these. The average frequency spectrum from each sub-event was then compared with these model templates. Sub-events with sufficient similarity to the model templates (correlation coefficient >0.6) were used to create overall templates for broadband and narrowband clicks, from the west coast of Scotland (West Coast) and North Sea. Those sub-events where the correlation coefficient was <0.6 (normally due to the sub-event comprising both broadband and narrowband clicks) were not used in these overall templates used for click classification. The overall broadband and narrowband templates were then used to classify the clicks into each category so that the characteristics of each click type could be described and any differences in these click types between areas could be investigated. To investigate differences between areas, each sub-event template was correlated with the overall template for the West Coast and North Sea. The correlation coefficients from this comparison could then be plotted to visually inspect scatter and examine the proportion of sub-events that were classified correctly to area.

To investigate the potential for developing an automated classifier for white-beaked dolphins based on their broadband click characteristics, a sinusoidal template was generated of the form $f(x) = \sin(\omega x + \epsilon)$ with a phase and frequency based on the least squares fit to the average broadband template in the 40 kHz to 80 kHz frequency band.

The relative amplitude of the average template in 22 frequency bands of 1.95 kHz spacing between 39.1 and 80.1 kHz from each sub-event was then correlated with this sinusoidal template.

2.2 Risso's dolphins

Recordings of Risso's dolphins from six encounters were available for analysis (Table 3). A similar protocol was followed for the processing of Risso's dolphin clicks using PAMGUARD as for white-beaked dolphins (see Section 2.1).

Table 3. Data sources for Risso's dolphin recordings.

Recording location	Source	Year	Vessel	Recording system	Number of encounters with acoustic recordings
Scotland West Coast	HWDT	2012	*Silurian* (18m motor-sailer)	MER stereo hydrophone array with near flat frequency response (2-150 kHz). 100m cable length	1
Scotland West Coast (west of Islay)	DP Energy	2010 2011	*Aora* (22m motor-vessel)	MER stereo hydrophone array with near flat frequency response (2-150 kHz). 100m cable length	3
Orkney	SSE Renewables	2013	*Karin* (24m motor vessel)	MER stereo hydrophone array with near flat frequency response (2-150 kHz). 200m cable length	5
English Channel	IFAW	2012	*Song of the Whale* (21m motor-sailer)	Seiche stereo hydrophone array with near flat frequency response (2-200 kHz). 400m cable length	1

Table 4. Filter settings for processing raw data: Risso's dolphins.

Filter	Cut off frequencies	
Pre-Filter	High Pass	2,000 Hz
	Low Pass	180,000 Hz
Trigger Filter	High Pass	5,000 Hz
	Low Pass	150,000 Hz

As with white-beaked dolphins, an acoustic encounter with dolphins was marked as an event and stored to a database, and then divided into sub-events of ≈20-40 clicks. With Risso's dolphins, a differentiation in the click repetition frequency was evident between burst-pulses/buzz click trains (with a very rapid pulse repetition frequency) and 'slow' click trains. These were therefore marked up differently to investigate whether they differed in their acoustic characteristics.

3. RESULTS

3.1 White-beaked dolphins

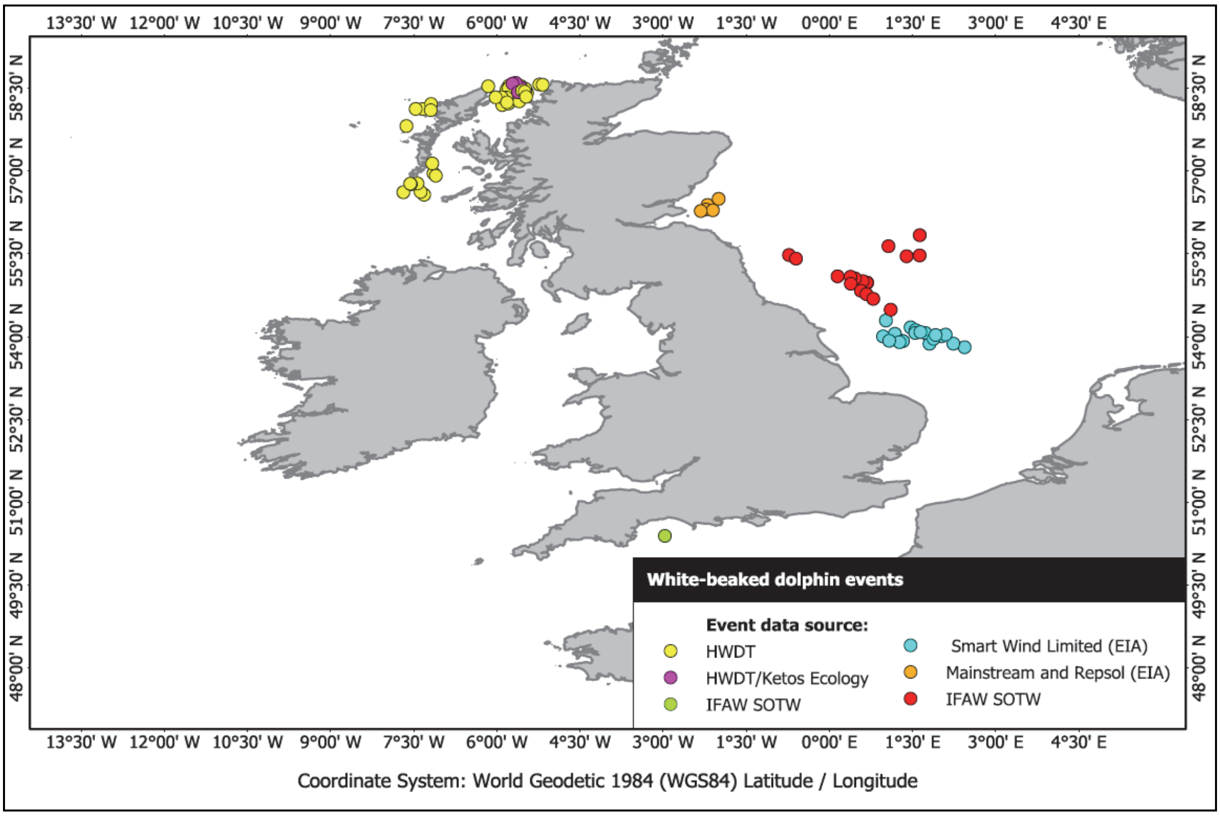

Figure 1. Locations of white-beaked dolphin acoustic encounters.

Figure 1 shows the locations of white-beaked dolphin acoustic encounters. The year-round SmartWind EIA survey data are described in more detail in SmartWind (2012), including density estimates and seasonal patterns for the survey block surveyed. The IFAW data are described in Marine Conservation Research International (2012), including the survey tracks around the Dogger Bank, sightings effort, number of sightings and acoustic detections. Similar data are given in Leaper & Gordon (2012) for the survey area off the east coast of Scotland. All data from the west coast of Scotland come from HWDT during summer. The data collected in collaboration with Ketos Ecology are described in Weir *et al*. (2009). Weir *et al*. (2009) describe a relatively small area of the North Minch where white-beaked dolphins were concentrated, and the more recent data from HWDT also indicate concentrations within this area. The HWDT data also suggest concentrations of white-beaked dolphins in the western Sea of the Hebrides from South Uist to Barra Head. There has been much less survey effort to the west of the Outer Hebrides and so it is difficult to speculate about consistent distribution patterns in this area.

Acoustic characteristics of white-beaked dolphin clicks

White-beaked dolphin events and sub-events are summarised in Table 5. The clicks could be divided into those that had energy across many frequencies (broadband) and those where the energy was confined to a more restricted frequency range (narrowband). Narrowband clicks had peaks between 27 and 37 kHz. Figure 2 shows several bursts of clicks with a frequency centred at approximately 35 kHz. Figure 3 shows the average spectrum across a whole sub-event.

Table 5. Summary of white-beaked dolphin events and sub-events.

Total number of events analysed	**61**
Total number of sub-events	818
Total number of sub-events classified as narrowband	149
Narrowband sub-events North Sea	44
Narrowband sub-events West Coast	105
Total number of sub-events classified as broadband	439
Broadband sub-events North Sea	187
Broadband sub-events West Coast	252

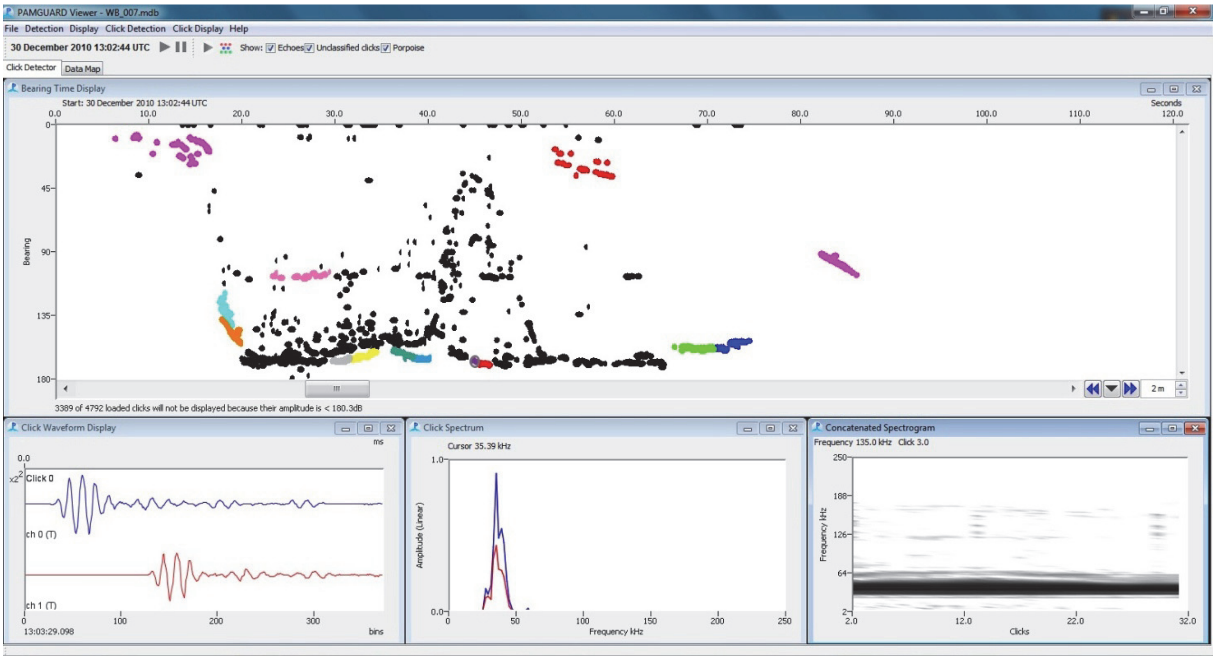

Figure 2. Narrowband clicks at 35 kHz in a single sub-event. The very simple waveform structure of a single click can be seen in the bottom left hand window, the narrowband 35 kHz peak in the middle window, and the concatenated spectrum shows all the energy of the sub-event concentrated at 35 kHz.

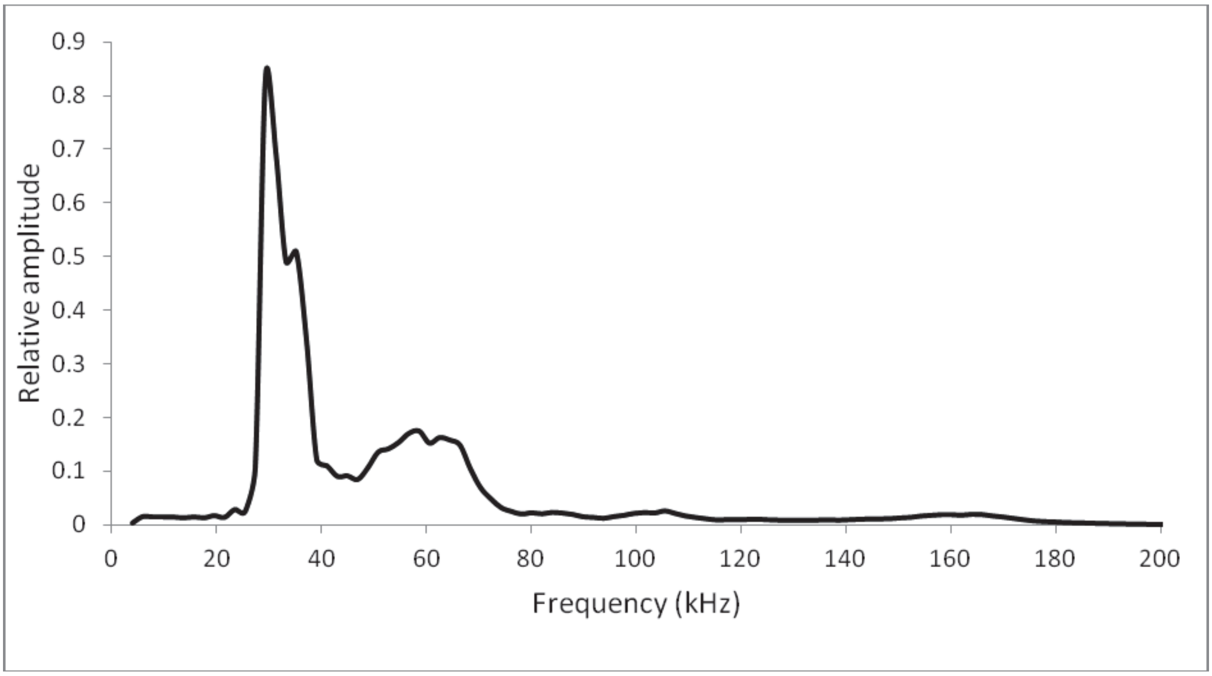

Figure 3. Example of the average of spectra from multiple clicks within a sub-event which was classified as having narrowband properties.

However, as shown in Figure 4, taken from a different part of the same event as Figure 2, broadband clicks from white-beaked dolphins were also recorded.

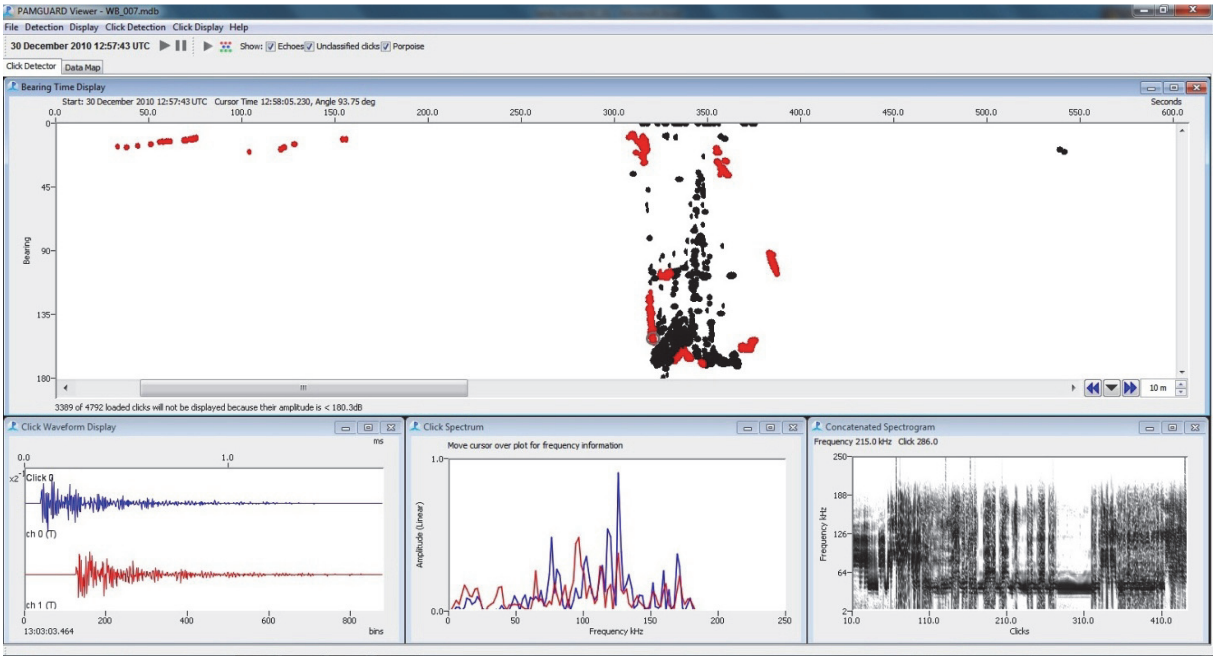

Figure 4. White-beaked dolphin broadband clicks. The complex waveform structure of a single click can be seen in the bottom left hand window, the broadband distribution of frequencies in the middle window, and the concatenated spectrum shows energy across multiple frequencies.

Whilst some broadband clicks showed some energy below 70 kHz (Figure 5), energy in other clicks was predominantly at frequencies above 70 kHz, with very little energy in the lower frequencies (Figure 6).

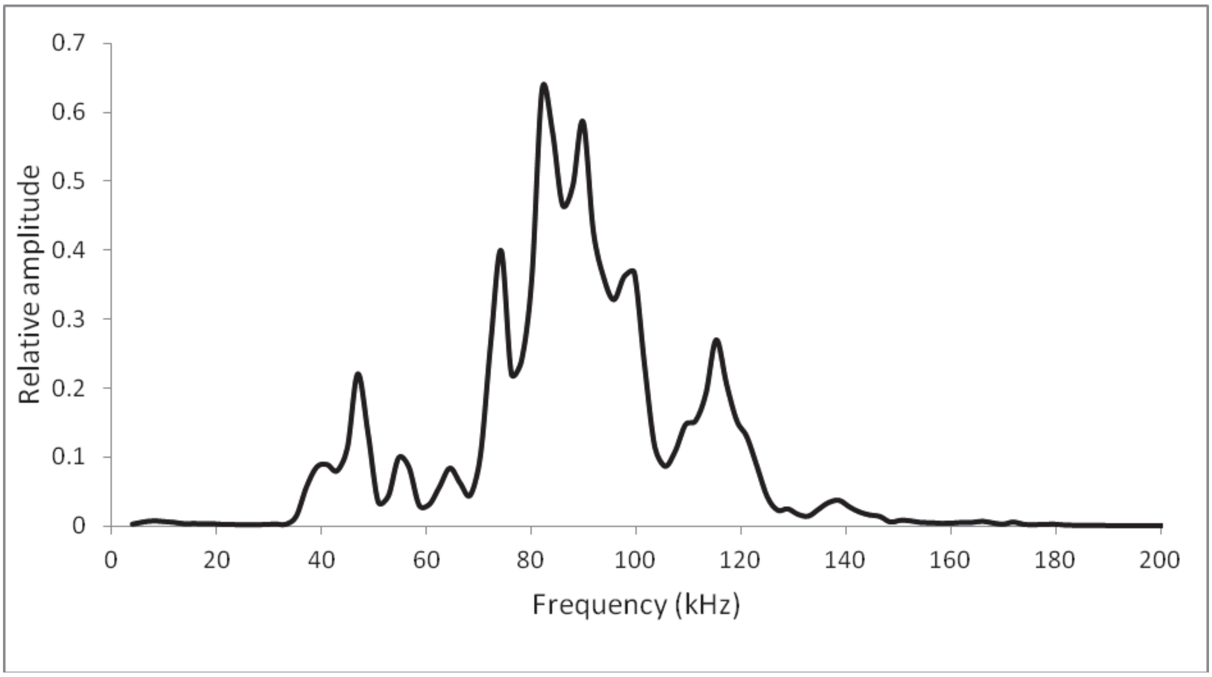

Figure 5. Example of the average spectra from multiple clicks within a sub-event that was classified as broadband, with some energy below 70 kHz.

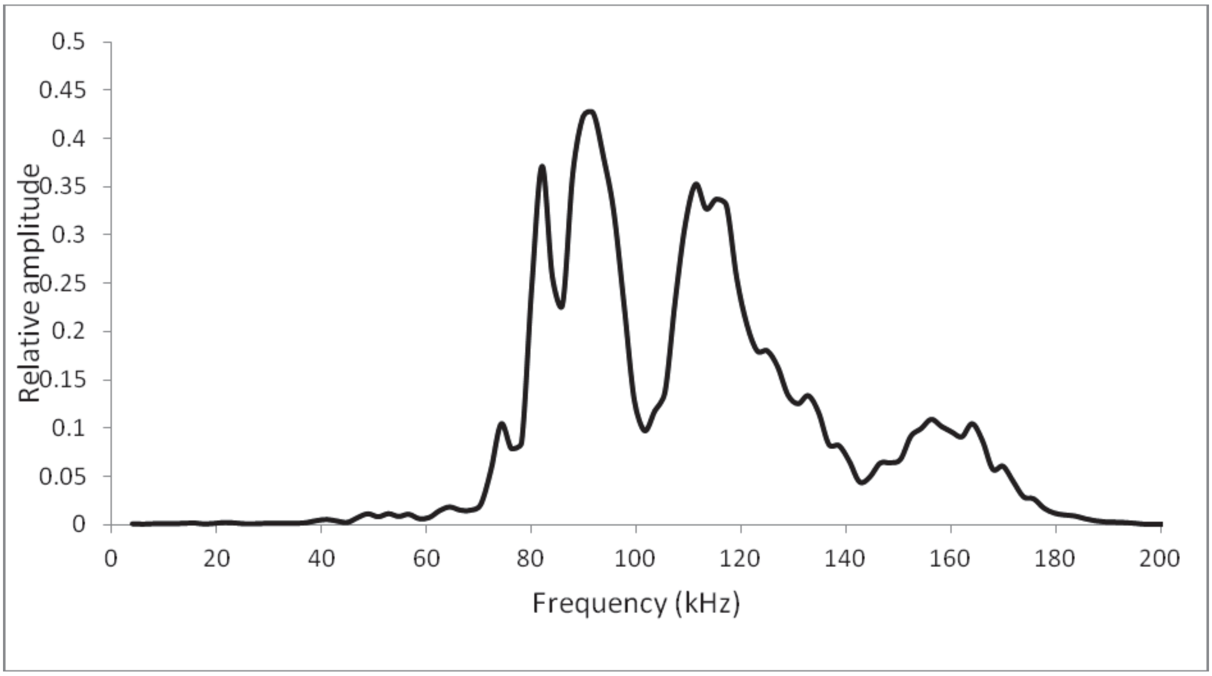

Figure 6. Example of the average spectra from multiple clicks within a sub-event that was classified as broadband, with almost all energy above 70 kHz.

This high level of variability of clicks was evident within single click trains, where successive clicks in a train showed broadband and narrowband properties (Figure 7).

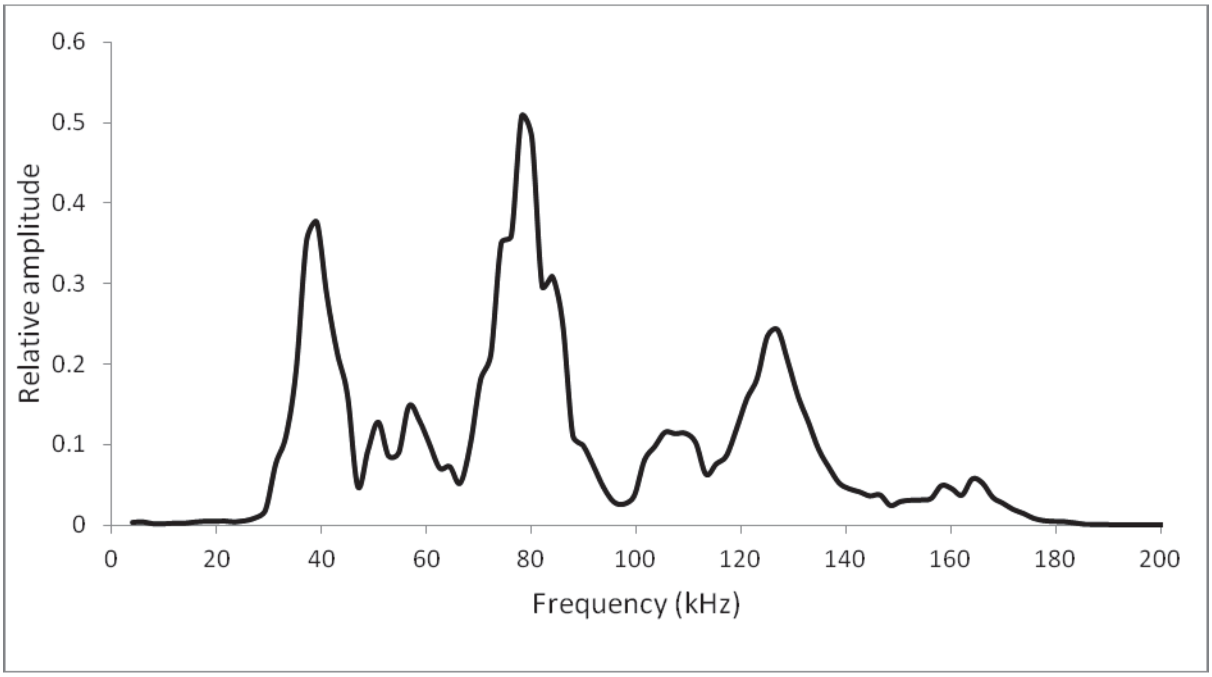

Figure 7. Example of average spectra of a sub-event which contained both broadband and narrowband clicks.

Plots of the bearings of clicks from the hydrophone showed that the majority of sub-events dominated by narrowband clicks were astern of the vessel (Figures 8 and 9). This variation in the relative frequency of broad and narrowband clicks by bearing suggests that they are either produced in different behavioural contexts, or that they reflect the relative orientation of the animals. The data plotted here are, of course, the bearings relative to the vessel but it is likely that there would be a relationship between this and bearing relative to the dolphins' orientation. For example, in a bow-riding scenario, most animals ahead may be bow-riding and thus clicks picked up on the hydrophone will have been transmitted from the back of the animal. Animals behind the hydrophone may be swimming to catch the vessel in which case most clicks would have been transmitted forward from the dolphins. Dolphin clicks are highly directional and the received clicks recorded in the main beam (close to the main directional axis) have been shown to be simpler and to have a narrower bandwidth than those received from dolphins not orientating directly towards the hydrophone (Wahlberg *et al.*, 2011).

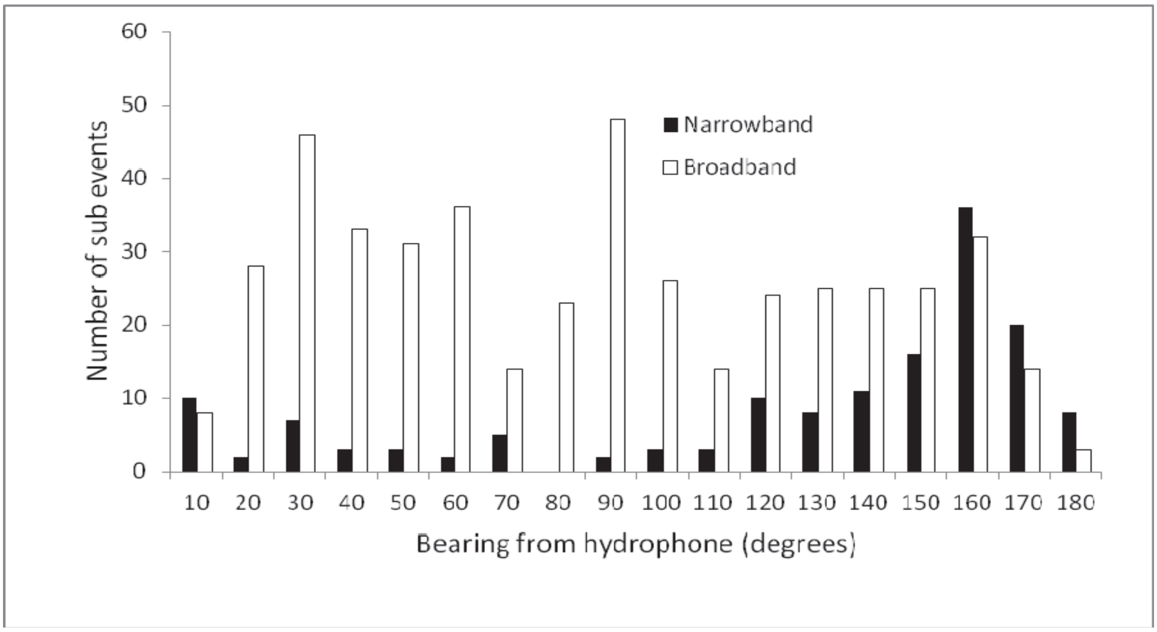

Figure 8. Frequency distribution of broad and narrowband clicks by bearing from hydrophone.

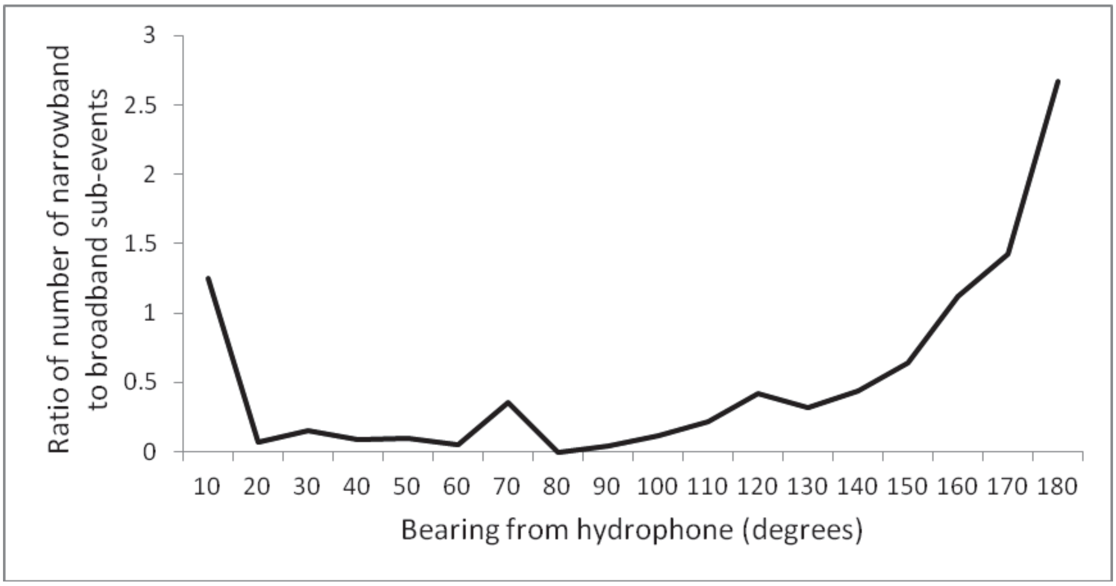

Figure 9. Ratio of narrowband to broadband sub-events by bearing from the hydrophone.

The potential for developing an automated classifier for white-beaked dolphins based on click characteristics

A sinusoidal template of the form $f(x) = \sin(\omega x + \epsilon)$ for frequencies 20 kHz < x < 40 kHz was fitted by least squares to the model template to estimate ω (2π/8.83 kHz) and ε (1.52π). This showed a periodicity equivalent to harmonics at a consistent frequency spacing of integer multiples of 8.83 kHz (peaks at around 47 kHz, 56 kHz, 65 kHz, etc). In total, 72% (44/61) of events had at least one sub-event which showed a significant ($p<0.05$) positive correlation with the sinusoidal template in Figure 10.

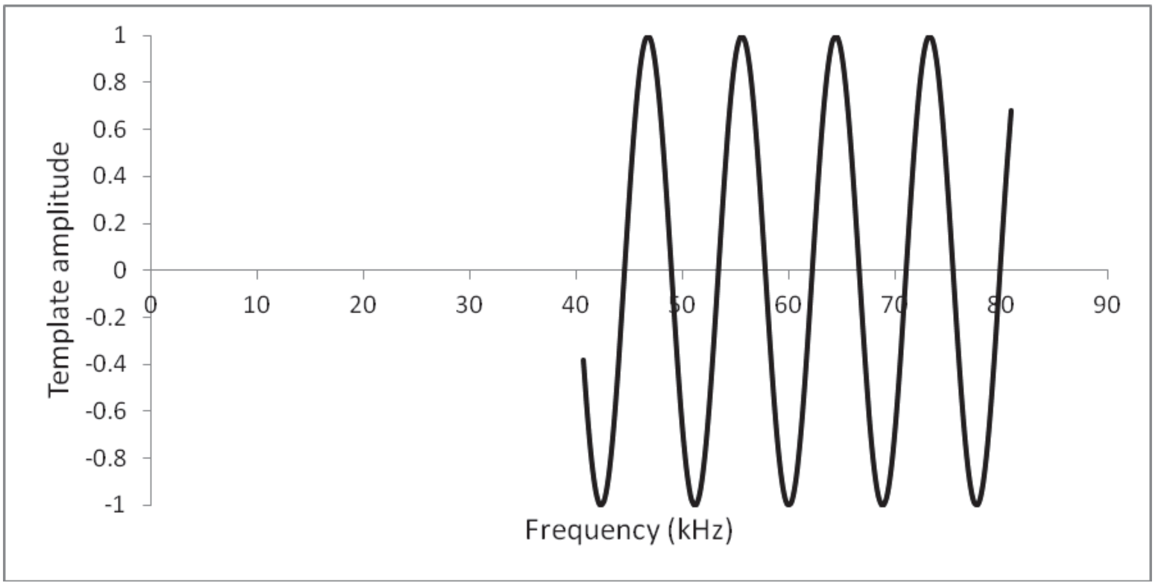

Figure 10. Sinusoidal template for frequencies between 40 and 80 kHz. The phase and frequency of the waveform used in the template was obtained by least squares fit to the average broadband template.

Figure 11, which shows the distribution of correlation coefficients from all sub-events with the sinusoidal template (Figure 10), is skewed towards positive values. The majority, comprising 75% of sub-events (615/818), showed a positive correlation with the template, showing the periodic nature of energy at specific frequencies. Although not all white-beaked dolphin clicks show these banding characteristics, most events contain some clicks which do. Where such banded clicks occur, the location and spacing of peaks in the frequency spectra would appear to be diagnostic (e.g. Figure 12).

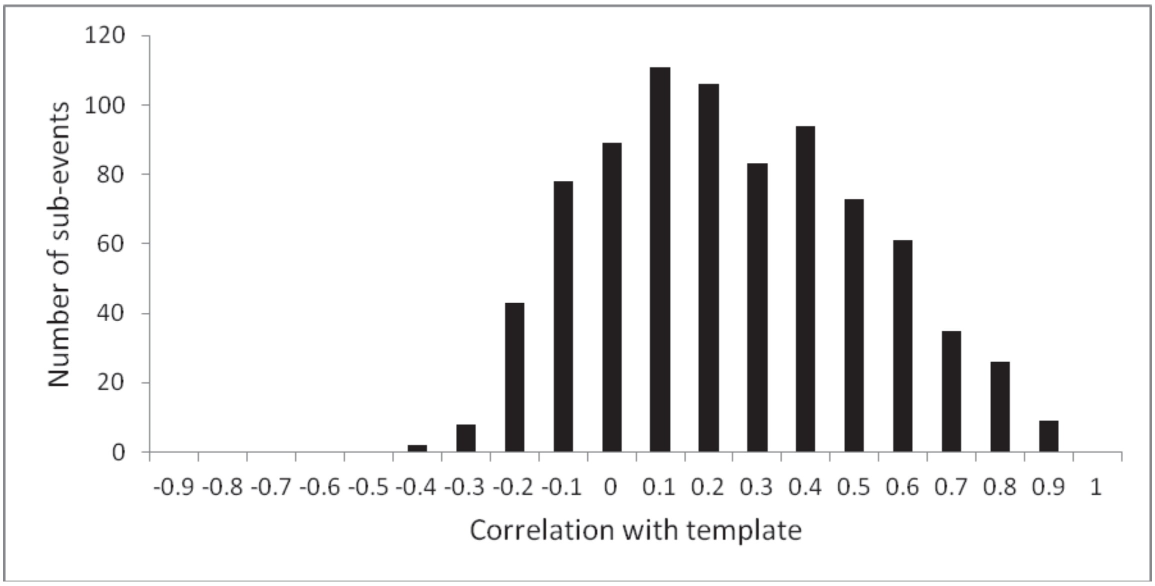

Figure 11. Distribution of correlation coefficients of all sub-event templates with the sinusoidal template. The positive skew indicates consistent peaks in sound energy within the dolphin clicks in addition to consistent 8.8 kHz spacing between peaks.

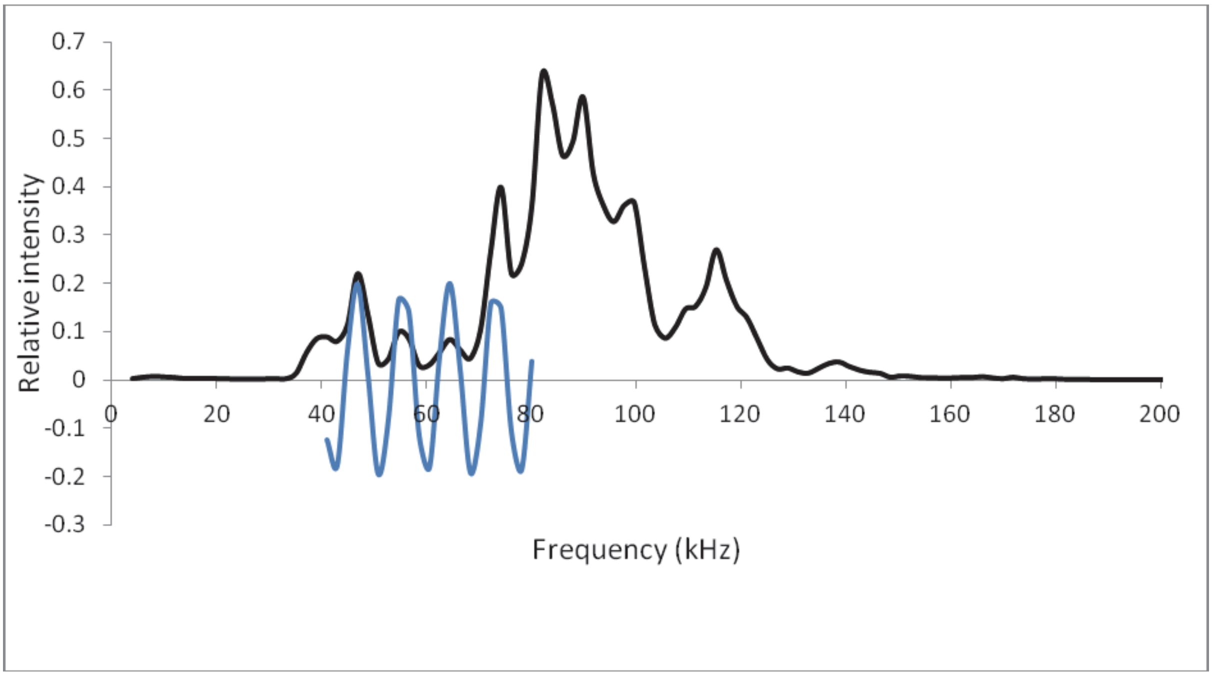

Figure 12. Example of broadband click with sinusoidal template between 40-80 kHz in blue, showing peaks in energy within the click matching the template.

The potential for identifying sub-populations based on acoustic characteristics

A comparison of the overall templates of narrowband clicks between the North Sea and West Coast demonstrated that narrowband clicks were recorded from white-beaked dolphins on both coasts, and the peaks in frequency coincided (Figure 13).

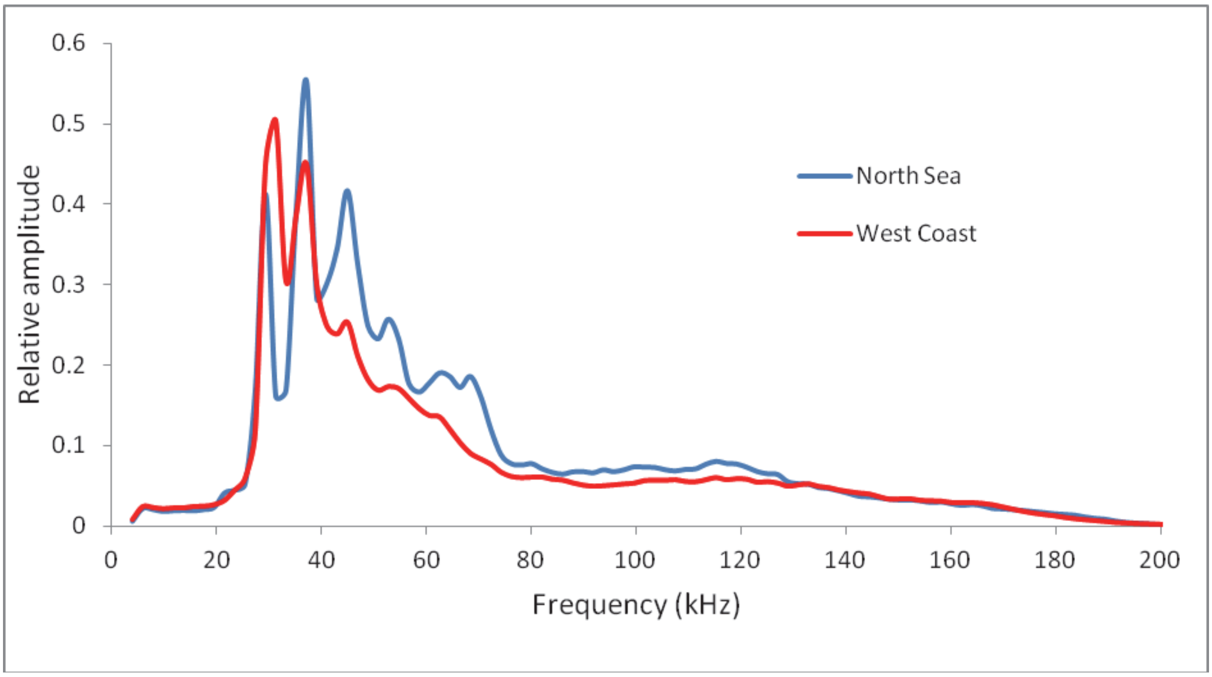

Figure 13. Overall templates for narrowband clicks from North Sea and West Coast, showing coinciding peaks in frequency.

The same was true of broadband clicks, where the overall templates did not show any clear differences between the coasts (Figure 14). This was confirmed by using a single sub-event from each event to give approximately the same weight to each encounter (Figure 15).

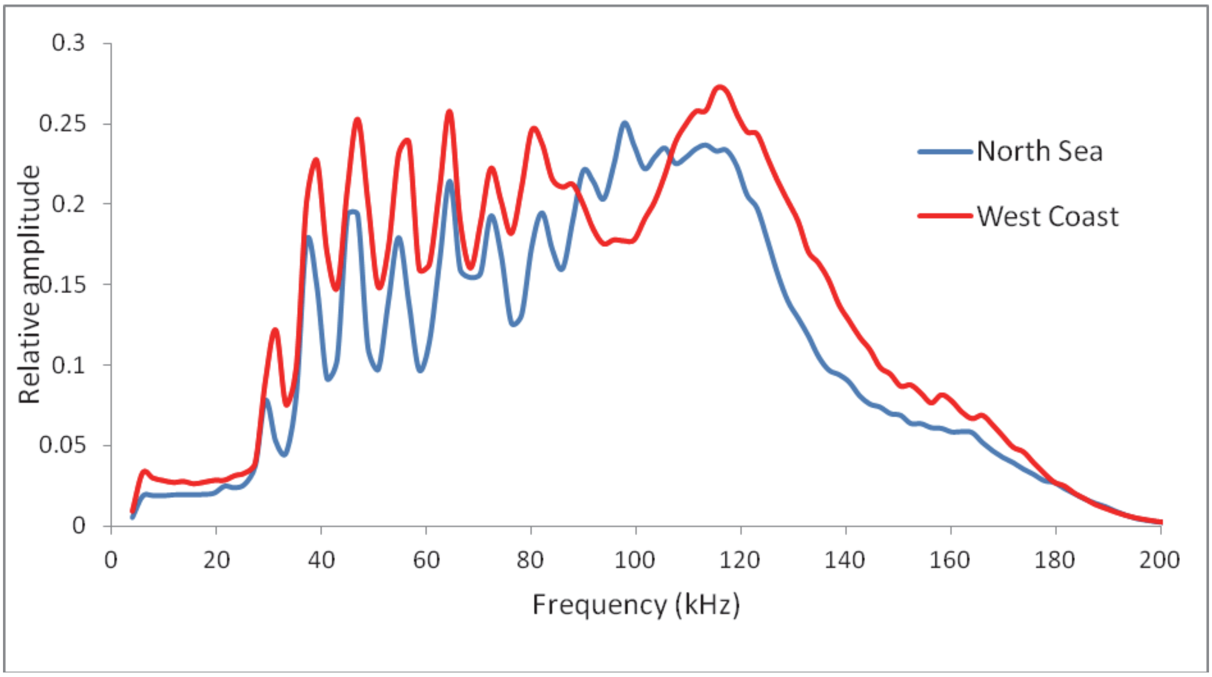

Figure 14. Overall templates for broadband clicks from North Sea and West Coast showing coinciding peaks at lower frequencies (30-80 kHz). The difference at higher frequencies (above 100 kHz) may be due to the differing nature of data collection: on the west coast, encounters usually included longer periods with dolphins closer to the vessel, resulting in the detection of more higher frequency elements of the clicks.

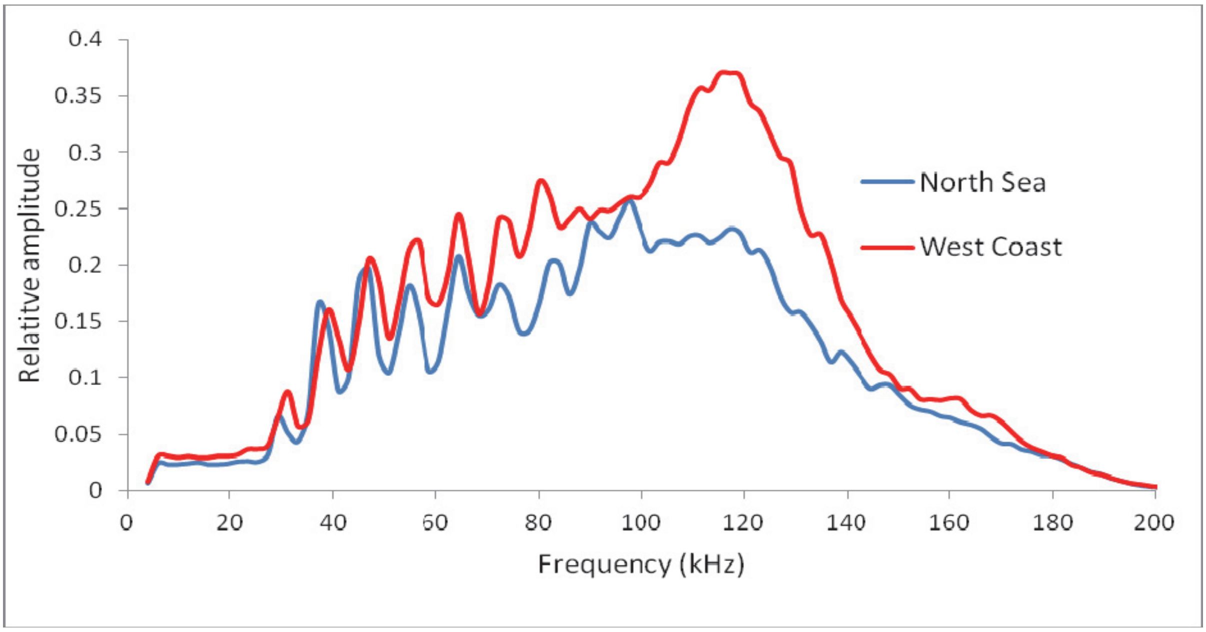

Figure 15. Overall templates for broadband clicks from North Sea and West Coast using a single randomly selected sub-event from those classified as broadband within each event. A single sub-event was chosen randomly in order to have approximately the same number of clicks within each template.

Figure 16 (correlation coefficients of each sub-event template which was classified as narrowband with the North Sea and West Coast narrowband templates) and Figure 17 (correlation coefficients of each sub-event template which was classified as broadband with the North Sea and West Coast broadband templates) show some separation between regions, but not sufficient to allow reliable allocation to region. These results suggest that there may be some differences in vocal behaviour between the North Sea and West Coast but these differences are not sufficiently distinct to propose separate populations.

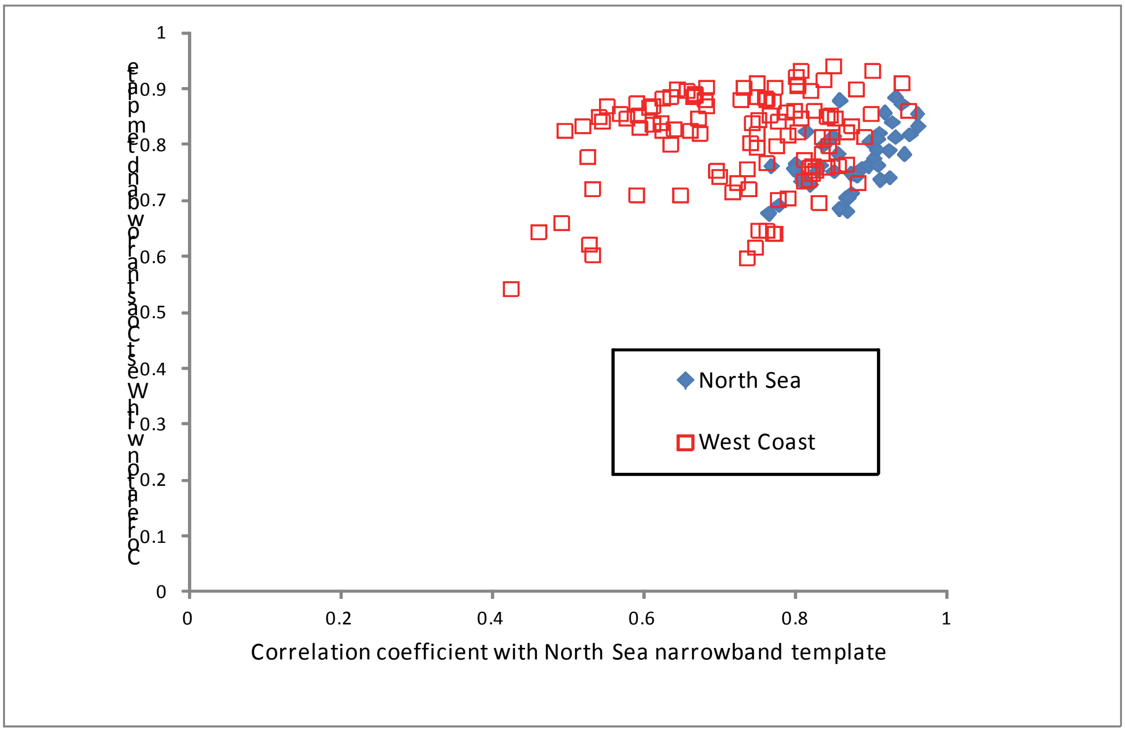

Figure 16. Correlation coefficients of each sub-event template which was classified as narrowband with the North Sea and West Coast narrowband templates.

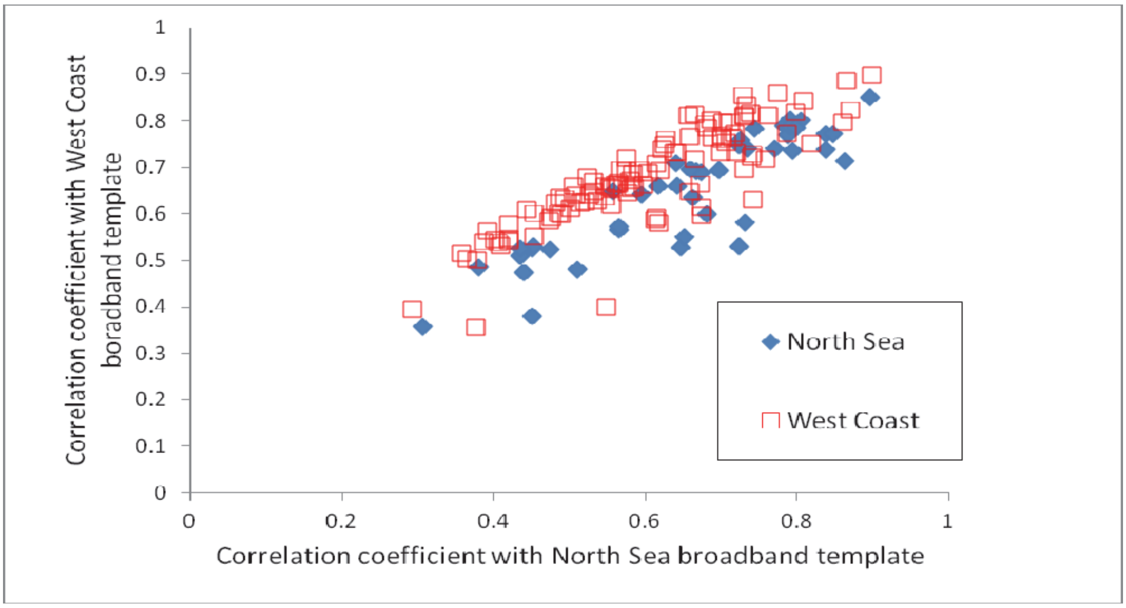

Figure 17. Correlation coefficients of each sub-event template which was classified as broadband with the North Sea and West Coast broadband templates.

White-beaked dolphins in the English Channel appeared to group with the North Sea on both narrow and broadband clicks (Figures 18 and 19). However, dolphins from the Sea of the Hebrides grouped with North Sea on narrowband and West Coast on broadband. The unexpected grouping of West Coast dolphins with the North Sea suggests caution is needed in interpreting any of these results. There are a number of factors including recording from different vessels and using different hydrophones which may contribute to apparent differences in received vocal characteristics between areas.

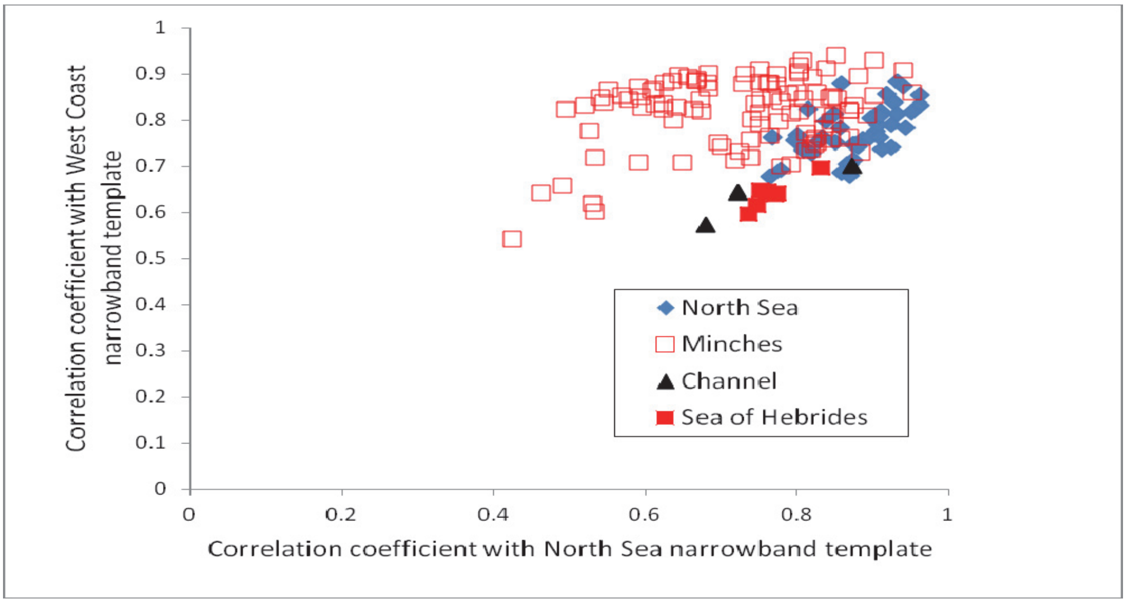

Figure 18. Correlation coefficients of each sub-event template which was classified as narrowband with the North Sea and West Coast narrowband templates showing sub-events from the English Channel and West Coast divided into Minches and Sea of the Hebrides (no sub-events from the northern North Sea were classified as being predominantly narrowband).

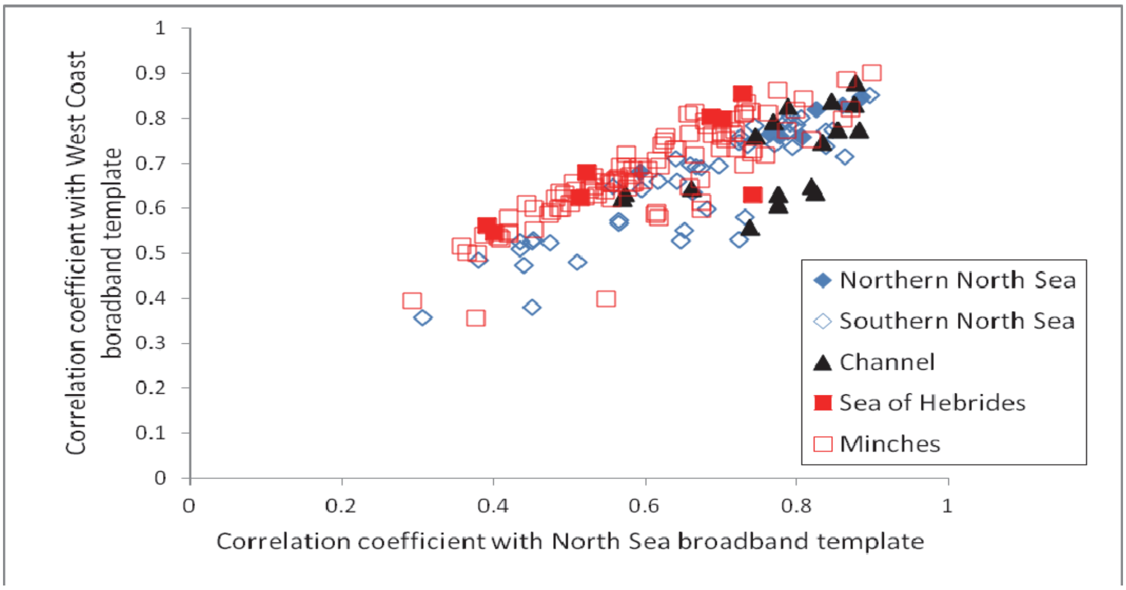

Figure 19. Correlation coefficients of each sub-event template which was classified as broadband with the North Sea and West Coast broadband templates. Sub-event templates are from the English Channel; West Coast divided into Minches and Sea of the Hebrides and North Sea divided into northern and southern regions.

3.2 Risso's dolphins

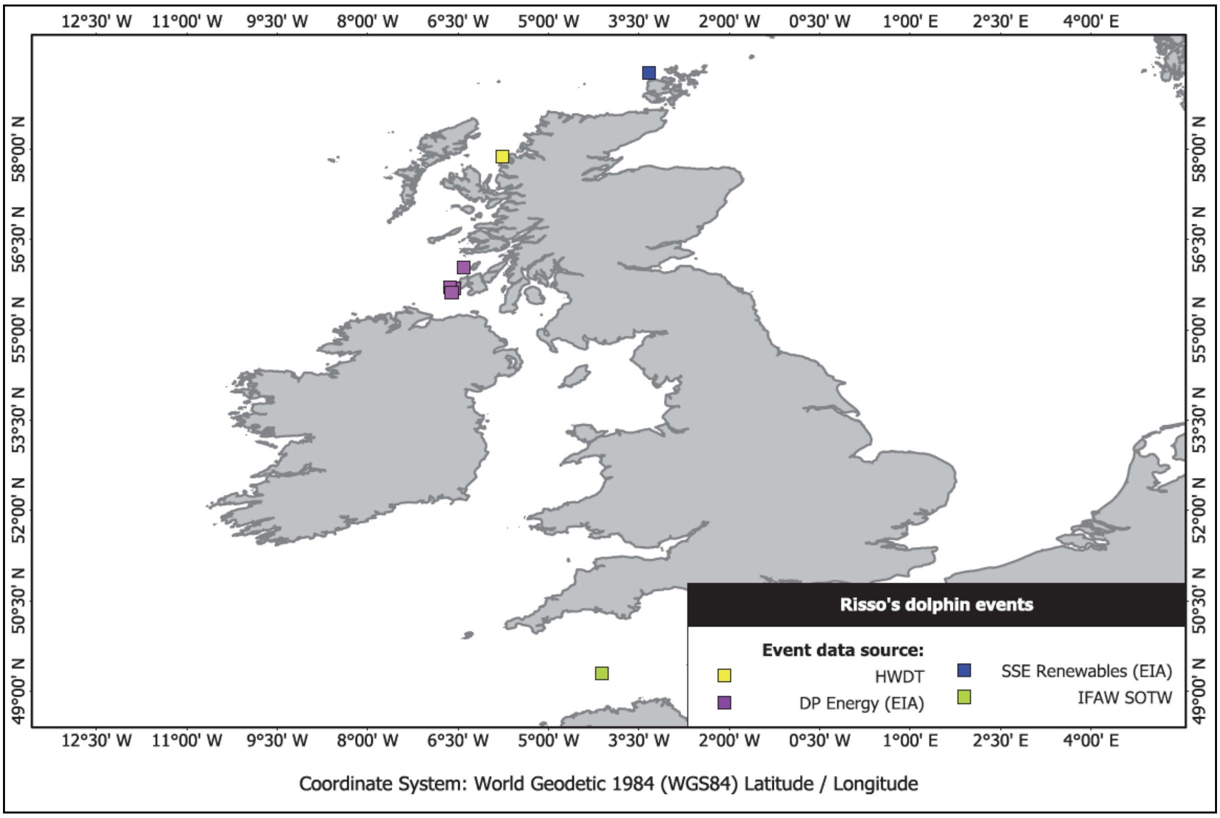

Figure 20. Location of Risso's dolphin acoustic encounters.

Acoustic data from six visually confirmed Risso's dolphin encounters were examined to explore acoustic characteristics of clicks. Encounters occurred from 2010 to 2013 inclusive, and were taken from multiple sources (Table 3). An average spectrum was made from all clicks from each event (Figure 21).

When marking up Risso's dolphin events, there was evidence of clear differentiation in the click repetition frequency between burst-pulses/buzz click trains and 'slow' click trains. Separate spectral templates were therefore also made for 'slow' click train events (Figure 22) and burst-pulse/buzz click events, of which there were four (Figure 23).

Only four of the six events included the characteristic burst-pulse/buzz click trains, and these events were from surveys where time was spent with the dolphins conducting either photo-ID or prolonged acoustic recordings. There were no consistent differences in the acoustic characteristics of clicks that comprised the different click train types.

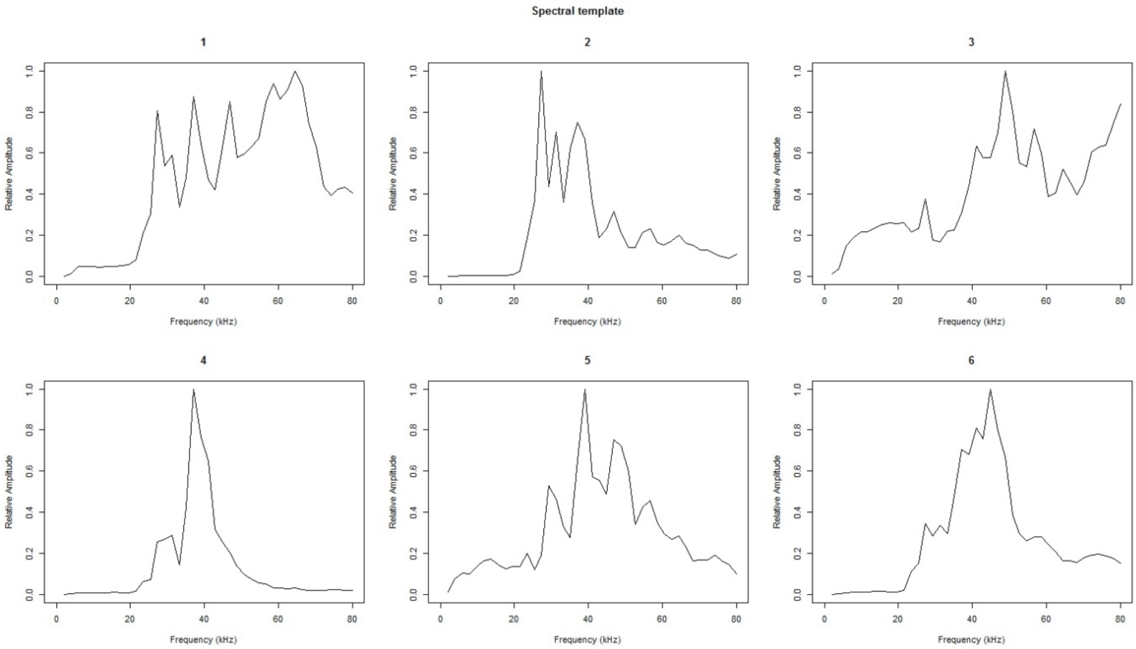

Figure 21. Risso's dolphin spectral templates (<80 kHz relative amplitude – average of all clicks for an event).

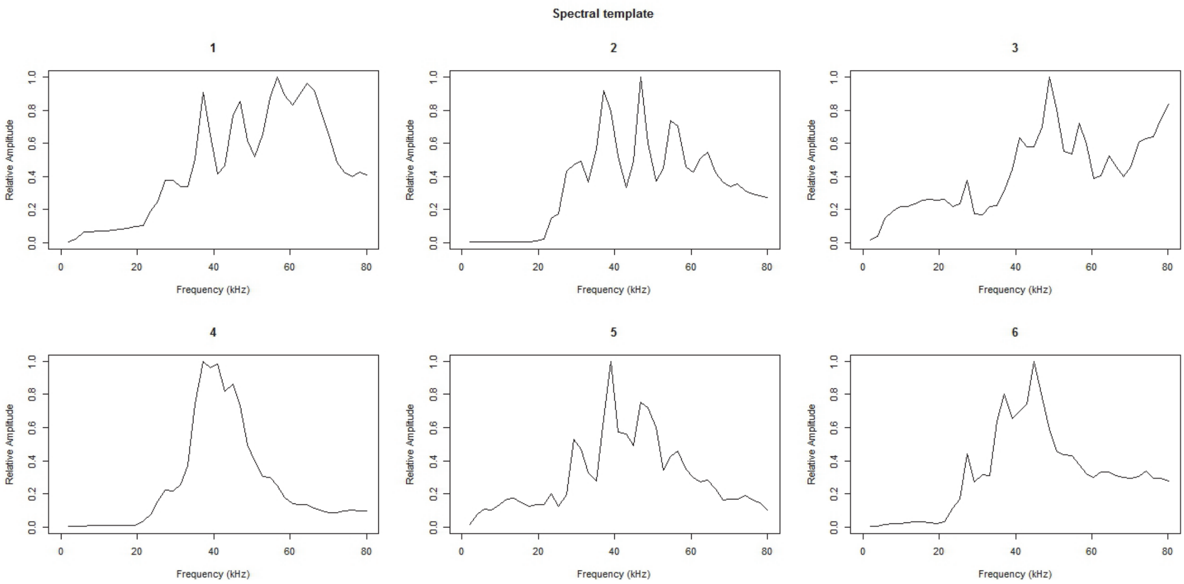

Figure 22. Spectral templates of Risso's dolphin 'slow' click train events (<80 kHz relative amplitude).

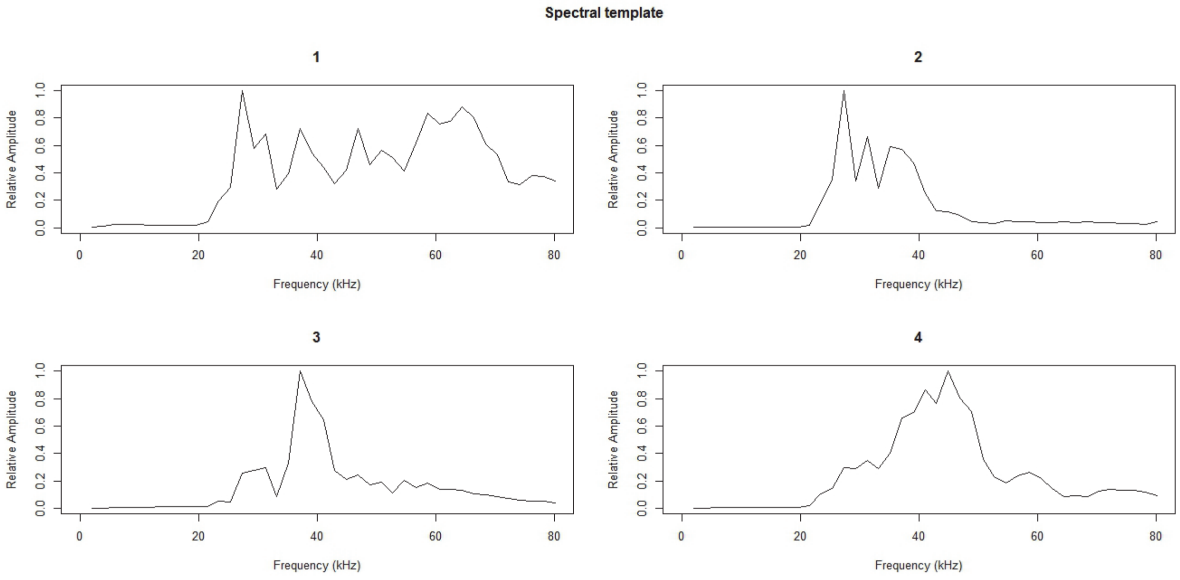

Figure 23. Spectral templates of Risso's dolphin burst-pulses/buzz click train events (<80 kHz relative amplitude). Template 3 corresponds to Template 4 in Figure 21 and Template 4 corresponds to template 6 in Figure 21.

A model template for Risso's clicks (Figure 24) was developed based on an average of spectra from four sub-events which exhibited the range of spectral characteristics shown in Figures 22 and 23. Average templates from 81% of sub-events (211/260) were significantly ($p<0.05$) correlated with this model template. The overall distribution of correlation coefficients between the model template and the average for each sub-event is shown in Figure 25.

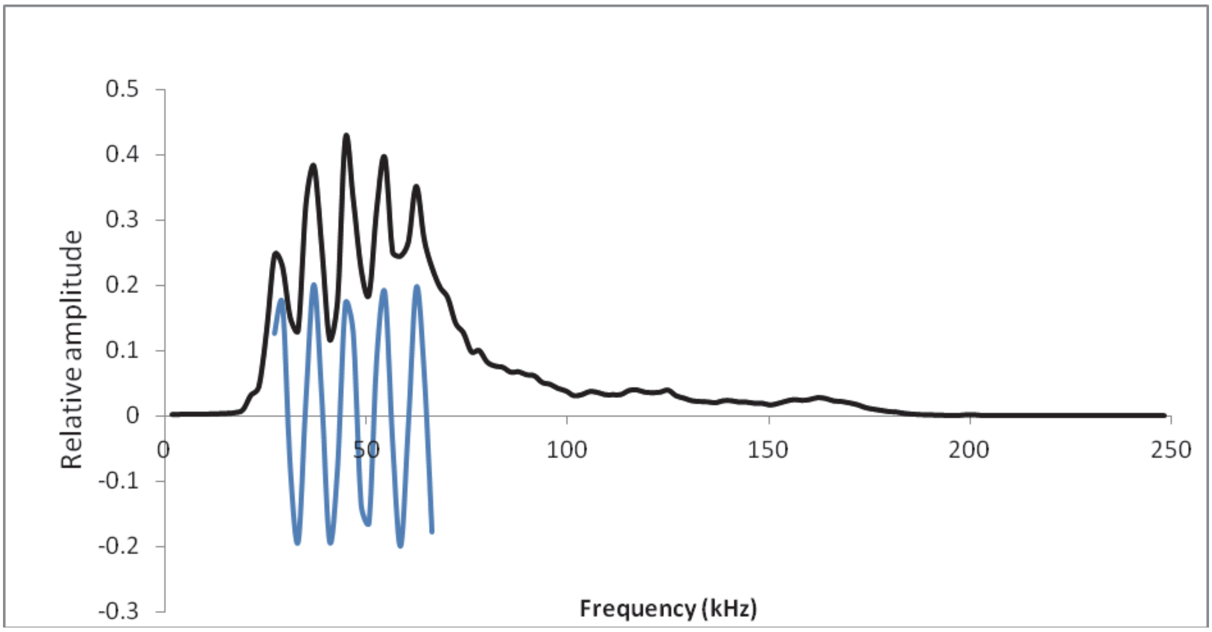

Figure 24. Model template for Risso's dolphin clicks. Blue line shows fitted sinusoidal template.

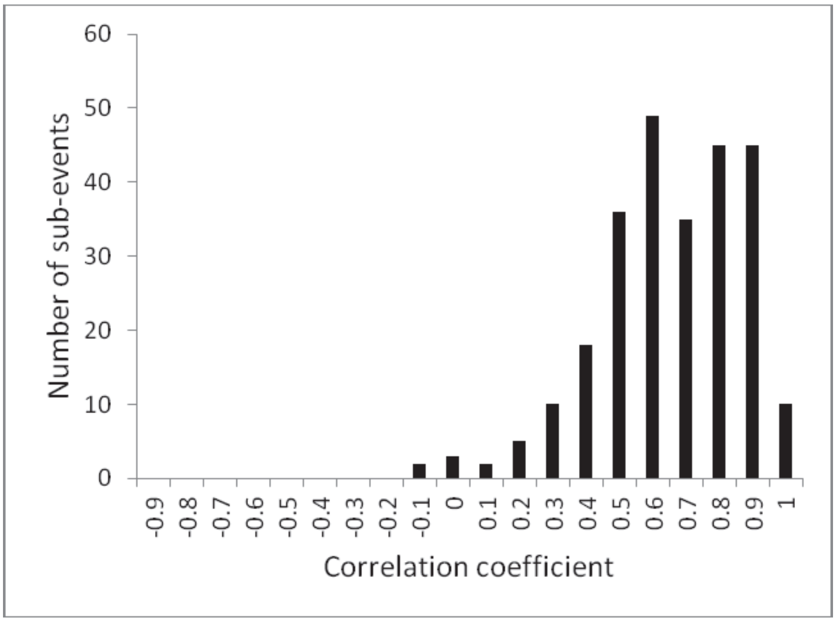

Figure 25. Distribution of correlation coefficients of average templates from all Risso's dolphin sub-events and the model template in Figure 18.

3.3 Distinguishing between Risso's and white-beaked dolphin clicks

Risso's dolphin clicks generally showed less variability than those of white-beaked dolphins. As was the case for white-beaked dolphin broadband clicks, harmonics were evident in many Risso's dolphin clicks, and within the model template. A sinusoidal template of the form $f(x) = \sin(\omega x + \epsilon)$ for frequencies 27 kHz < *x* < 66 kHz was fitted by least squares to the model template to estimate ω (2π/8.55 kHz) and ε (1.22π) (Figure 24). The peaks in frequency of the fitted sinusoidal model at 21, 29 and 38 kHz correspond closely with those reported by Soldevilla *et al*. (2008) at 20, 28 and 36 kHz from Risso's dolphins off California.

Simply correlating the templates of sub-events with the model templates for each species gave a correct classification around 80% for any sub-event. The results of two different types of correlation are shown in Figures 26 to 31. Whilst there was no ability to distinguish between species using narrowband clicks (Figure 26), Figure 27 shows that if broadband clicks were used, in 85% of cases (220/260), Risso's dolphin clicks would be correctly distinguished from white-beaked dolphin clicks. The sinusoidal templates showed a similar ability to distinguish between species using broadband clicks: Figure 28 shows correlations of all white-beaked dolphin sub-events with sinusoidal white-beaked dolphin and Risso's dolphin templates, and Figure 29 shows correlations of average template across each event of all white-beaked dolphin sub-events with sinusoidal white-beaked dolphin and Risso's dolphin templates. Figure 30 and 31 show similar results for Risso's dolphin sub-events correlated with the overall templates.

If the average correlation over a whole event was used (as it would be during any survey), then this resulted in around 90% of white-beaked dolphin events being correctly classified and 100% of Risso's, although the Risso's sample size was only six events.

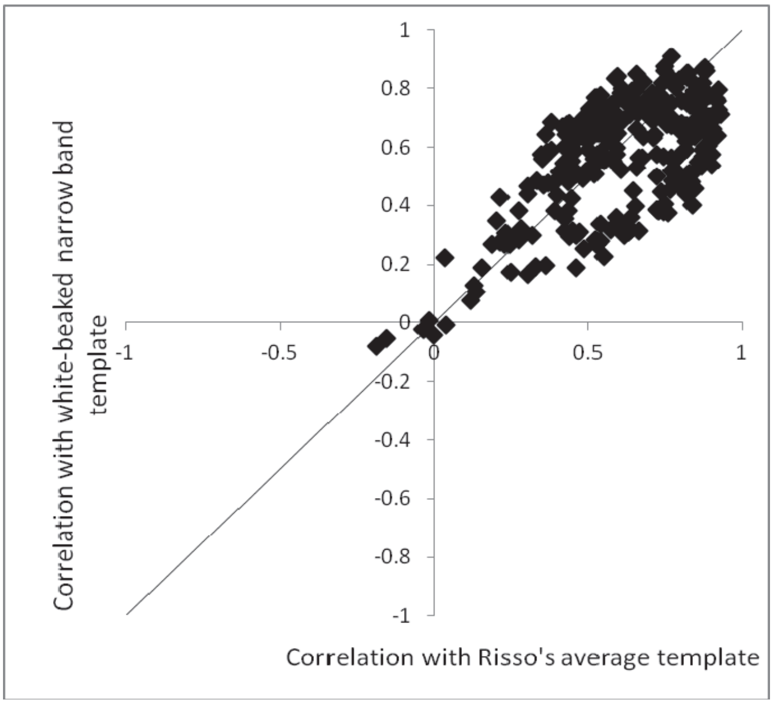

Figure 26. Correlation of average templates from all Risso's dolphin sub-events with the model template for Risso's and the narrowband white-beaked template. There is no ability to distinguish between the species based on these templates showing that Risso's clicks share similar properties with white-beaked dolphin narrowband clicks.

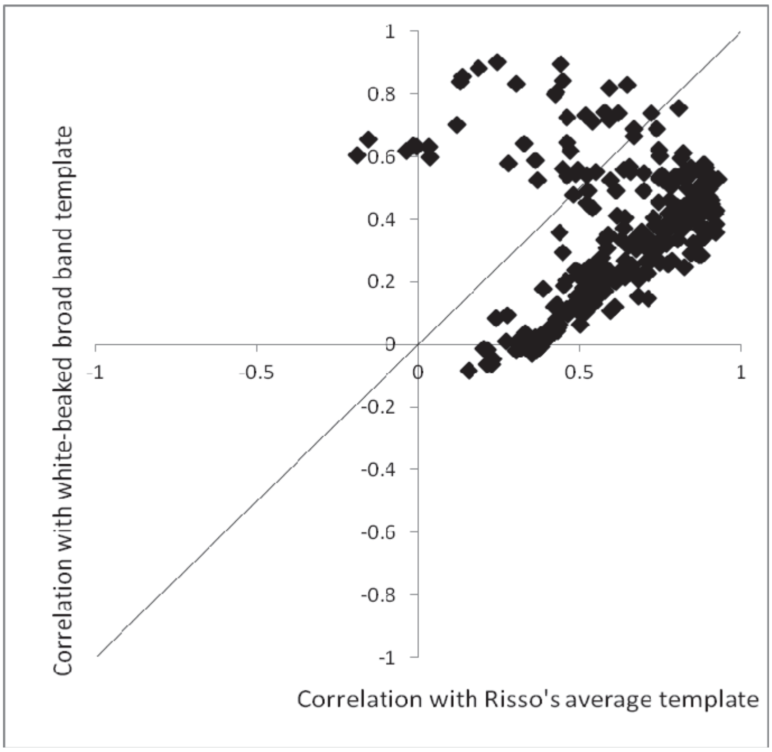

Figure 27. Correlation of average templates from all Risso's dolphin sub-events with the model template for Risso's dolphin and the broadband white-beaked template. There is a good ability to distinguish between the broadband white-beaked dolphin clicks and Risso's clicks. In 85% of cases (220/260), Risso's clicks would be correctly distinguished from white-beaked dolphin broadband clicks.

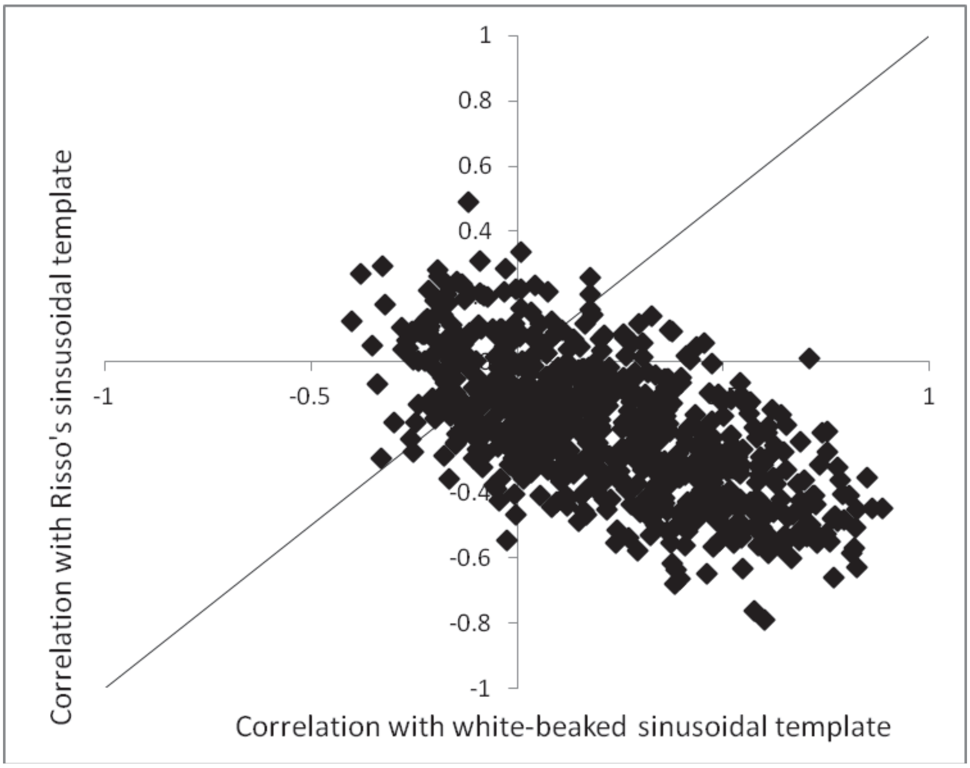

Figure 28. Correlations of all white-beaked dolphin sub-events with sinusoidal white-beaked dolphin and Risso's dolphin templates. All sub-events below the diagonal line would be correctly classified - 81% or 666 out of 818 sub-events.

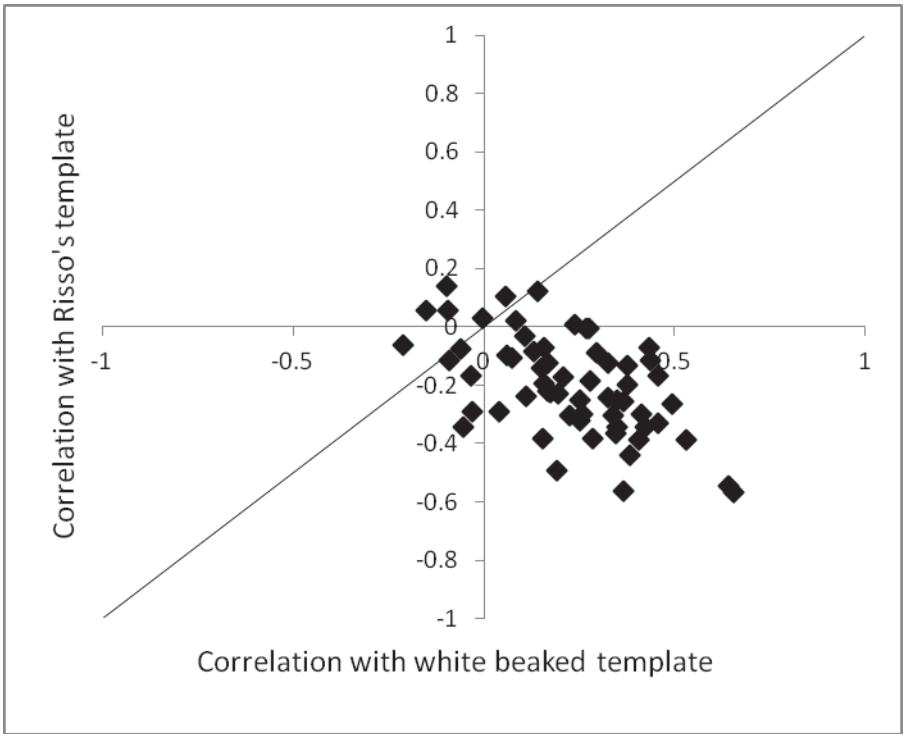

Figure 29. Correlations of average template across each event of all white-beaked dolphin sub-events with sinusoidal white-beaked dolphin and Risso's dolphin templates. All events below the diagonal line would be correctly classified - 90% or 55 out of 61 events.

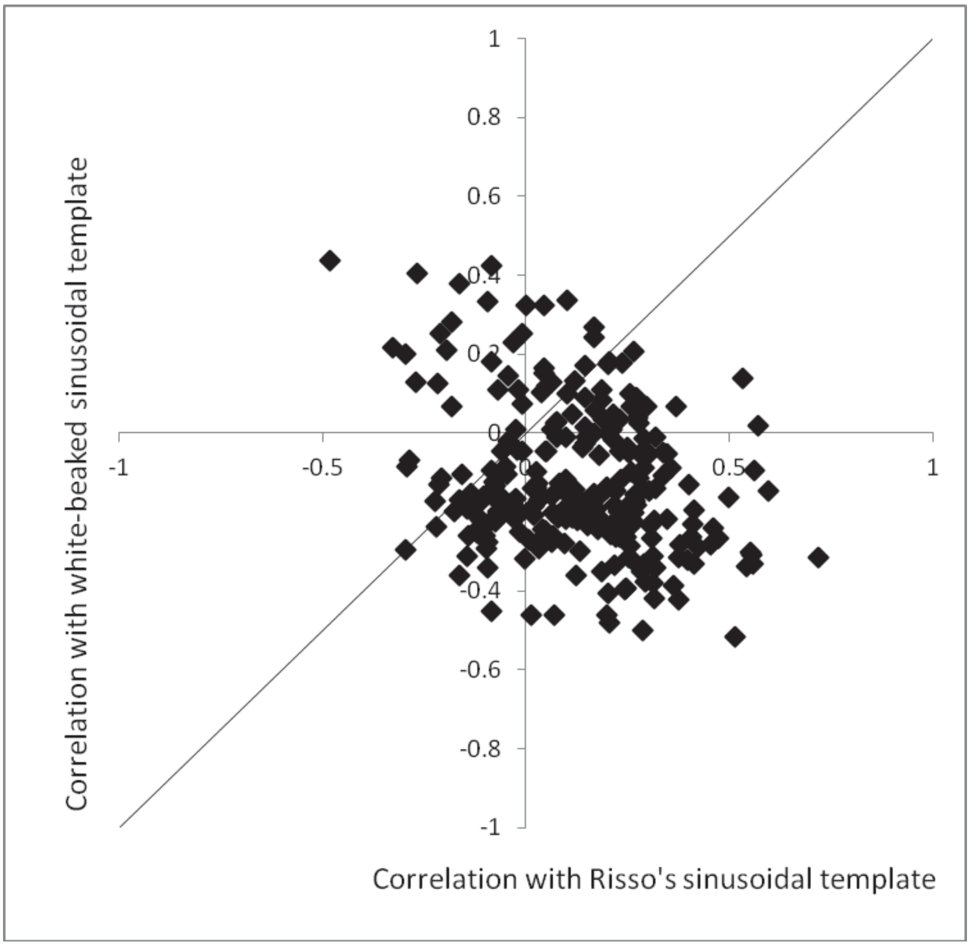

Figure 30. Correlations of all Risso's dolphin sub-events with sinusoidal white-beaked dolphin and Risso's dolphin templates. All sub-events below the diagonal line would be correctly classified - 83% or 218 out of 260 sub-events.

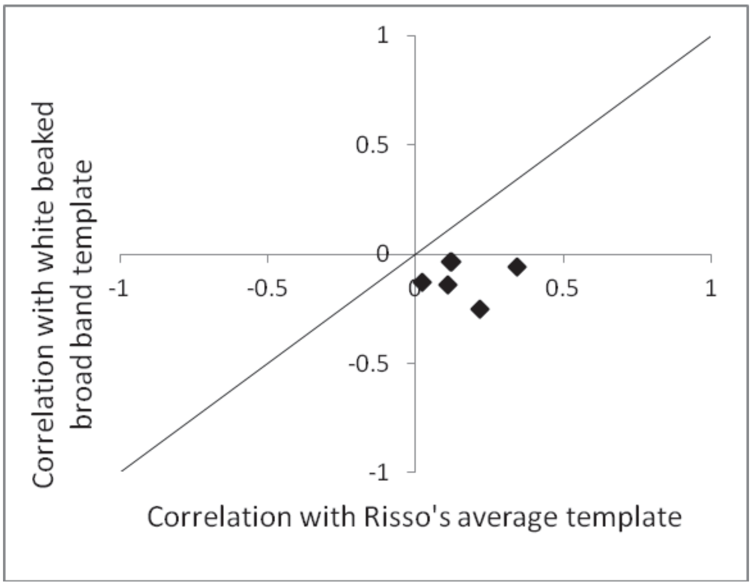

Figure 31. Correlations of average template across each event of all Risso's dolphin sub-events with sinusoidal white-beaked dolphin and Risso's dolphin templates. All events below the diagonal line would be correctly classified - 100% or 6 out of 6 events.

4. DISCUSSION

4.1 Acoustic characteristics of white-beaked and Risso's dolphin clicks

Highly variable clicks are detected from both white-beaked dolphins and Risso's dolphins, with broadband clicks which show banding or harmonics, as well as clicks with no obvious banding being recorded. The intention of this study was not to describe detailed acoustic properties of individual clicks, which will vary depending on factors such as orientation of the animal and its distance away from the hydrophone. The focus was instead on the practical applications for passive acoustic monitoring and whether the acoustic characteristics of clicks received under typical survey conditions could be used for reliable classification of species.

Our experience in the field suggests that white-beaked dolphin vocalisations are usually detected during an encounter. However, Risso's dolphin vocalisations are less likely to be recorded. HWDT logged six visual sightings of Risso's dolphins in 2011 and 2012; however, vocalisations were only recorded during one of these. Other studies have noted a strong diel pattern in acoustic output of Risso's dolphins. For example, Soldevilla *et al*. (2010) found a significant difference between overall click activity (both slow clicks and buzzes) between night and day. Risso's dolphins were more acoustically active during night time (when most foraging activity occurs) than during day time. Similar patterns in vocal activity have been observed in Risso's dolphins around the Azores (K. Hartman pers. comm.).

4.2 Scope for automated detection

The harmonics present in the broadband clicks of white-beaked dolphins and Risso's dolphins allow for the possibility of distinguishing between the two species using these characteristics, and this could lead to the development of an automated classifier. The results presented here are a preliminary investigation of the potential for classification. Whilst this method correctly classifies to species level 90% of the time or better, an improved level of discrimination would be desirable for survey purposes. While these results are promising for a preliminary study, the application of more sophisticated methods should be explored. Such methods take considerable development. However, this project has made an important contribution by highlighting acoustic characteristics that vary between species and by collating a large reference dataset of click samples from white-beaked dolphins around the UK and a smaller amount of data on Risso's dolphins. These datasets will form a valuable resource for the development and testing of any automated classifiers for these species. Within Scottish waters, two other species which occur in the same areas as white-beaked and Risso's dolphins are common dolphins and bottlenose dolphins. Soldevilla *et al*. (2008) examined large numbers of clicks from these species, and did not report any banding in the 1-100 kHz bands, suggesting that the banding properties in Risso's and white-beaked dolphin clicks may be a good way to distinguish them from common and bottlenose dolphins.

4.3 Potential for identifying sub-populations based on acoustic characteristics

Whilst there are some suggestions in our results of population structuring based on vocalisations within white-beaked dolphins, the results in this study do not provide definitive evidence. The small sample size of Risso's dolphin acoustic encounters precluded examination of the potential for identifying sub-populations based on acoustic characteristics. In the case of white-beaked dolphins, the picture is complex. Further investigation would be useful, including ensuring that factors related to recording systems and animal behaviour are accounted for. However, the variability between animals and groups within any one area, based on behavioural or other factors, may be more important in influencing click spectral variability than are population units.

4.4 Information on densities and distributions of white-beaked and Risso's dolphins in the Hebrides based on acoustic data

Passive acoustic monitoring can be used to locate individuals and identify species, examine distribution and density patterns, and more recently it has been used to discover information on species population structure (Roch *et al*., 2011; Soldevilla *et al*., 2011). Whilst this project focused on classifying clicks, the locations of acoustic detections also provided useful information on species distribution.

An estimated 80% of the European population of white-beaked dolphins are located in the waters off Scotland and north-east England (UKBAP, 2008). It is thought that white-beaked dolphins are present in UK waters year-round (Reid *et al*., 2003; Northridge *et al*., 1995). Whilst HWDT data do not cover the winter months, the EIA data used in this study from the east coast of the UK recorded white-beaked dolphins in UK waters every month of the year.

Spatial investigation of the distribution of HWDT/Ketos Ecology white-beaked dolphin acoustic detections on the west coast of Scotland from 2007 indicated a preference for deeper coastal waters, with white-beaked dolphin detections typically occurring between 80 m and 165 m water depth. Three areas of potential importance for white-beaked dolphins were evident: the North Minch, west of the Outer Hebrides and the southern region of the Outer Hebrides. HWDT surveys cover a large area of the west coast of Scotland, and only a few sightings have been recorded outside these three areas of potential importance. Harries *et al*. (2012) also used HWDT data to investigate white-beaked dolphin relative densities and distributions on the west coast of Scotland with respect to oceanographic and physiographic variables. Generalised Additive Models (GAMs) were used to relate visual sightings to a range of variables including depth, seabed slope, sediment type, distance from land, and sea surface temperature. Three potential "hotspots" of occurrence were identified as areas of apparent importance: an area to the south of the Outer Hebrides, the northern Minch and west of the Isle of Lewis.

There were only six Risso's dolphin acoustic encounters. Risso's dolphin encounters on HWDT and DP Energy EIA surveys on the west coast of Scotland were close to the coast, in waters less than 200 m deep. Little is known about the distribution of Risso's dolphin in UK waters or about population structure. It has been proposed that Risso's dolphin are present in UK waters all year round. However, there are a greater number of sightings in shelf waters from May to October, and more sightings in offshore areas during the remainder of the year (Reid *et al*., 2003; Evans *et al*., 2003). A 'resident' population of Risso's dolphins has been described in the waters north-east of the Outer Hebrides (Wharam & Simmonds, 2008; Pollock *et al*., 2000; Atkinson *et al*., 1998). Resights of individually identifiable Risso's dolphins have been made 80 nautical miles apart and encounters have been made over a number of years with the same individuals (HWDT, unpublished data). This suggests that these 'resident' animals may have relatively large home ranges.

4.5 Strategies for cost-effective passive acoustic monitoring schemes for these species in Scottish waters

This project has shown that both white-beaked dolphins and Risso's dolphins can be detected and identified to species level by the analysis of frequency banding which can be seen in some of their clicks. It is likely that white-sided dolphins also have banded clicks; a sister species, Pacific white-sided dolphins, also show distinctive frequency banding (Soldevilla *et al*., 2011). In the past, researchers have usually investigated the characteristics of whistles to distinguish between dolphin species. There are several advantages to being able to use click vocalisations in addition to, or instead of, whistles. Our experience in the field has been that these species do not always produce whistles, and that clicks are more often detected. Clicks are produced with a higher source level and, although absorption, which is greater at higher frequencies, may have a stronger effect on them, they are often detected at greater ranges than whistles in the field. It is also likely to be the case that the acoustic characteristics of clicks are more consistent between different individuals and groups. Some acoustic characteristics of whistles are varied by individuals because whistles are used for communication and individual identification. Fundamentally, however, clicks are an additional cue available for species identification, not an alternative one. Most acoustic systems should be configured to be able to record and analyse both vocalisation types. This work supports the use of passive acoustics as a means of surveying these species, most likely in conjunction with visual effort.

There are two main types of acoustic survey: mobile surveys that typically use towed hydrophone systems, and static surveys that use moored detectors or recorders to collect data at a set of point locations. These methods have contrasting advantages and shortcomings.

Towed surveys, like most boat-based or aerial surveys, can be designed to provide good coverage of an area of interest, but the high cost of platforms usually means that a relatively small amount of survey effort is spread over a large area. Advantages of using towed acoustics alongside or instead of visual monitoring are that survey can continue in worse sea conditions, in poor visibility and at night. Smaller field teams can be employed because data collection is highly automated. PAM systems can be very effective on smaller, less expensive vessels than would be required to support a full visual team and can be very valuable in allowing a more complete use of platforms of opportunity (Embling, 2007). Towed acoustic detections can also provide an alternative detection ‘platform’ for visual surveys allowing the calculation of absolute abundance estimates (Leaper & Gordon, 2012).

By contrast, static monitoring can provide continuous temporal coverage but of a very small area. Because static recorders should not affect the animal’s behaviour they should be a useful way of determining the incidence of important activities, such as foraging. Thus far, static monitoring has only provided population estimates in a few special cases where extensive auxiliary data were also available (Marques *et al*., 2009). Autonomous detectors, PODS (Chelonia Ltd), have been widely used in recent years for detecting porpoises. While these devices can detect dolphin clicks they have not been used successfully to distinguish between species, and they would not extract and store the information used for species ID in this study or data on whistles. Fortunately, static acoustic monitoring devices that can collect full bandwidth recordings rather than simply store detections are now becoming available and more affordable.

It is evident that mobile and static acoustic surveys have complementary strengths and weaknesses and it will often make sense to use them together. For example, mobile surveys are needed to map spatial distributions and provide reliable density estimates; data from these could be used to identify areas of interest where static devices could be deployed to provide long term datasets to establish temporal patterns of usage and trends.

There is currently a requirement to understand the distribution of white-beaked and Risso’s dolphins in Scottish waters and identify sites for Marine Protected Areas. This could be a substantial undertaking, but the findings of this report indicate that passive acoustic monitoring could make a useful contribution to making the task less onerous and more affordable. Towed hydrophone surveys would allow lower cost vessels (similar to *Silurian*) to carry out surveys. Platforms of opportunity providing coverage in areas of interest might also be identified. Once putative MPAs had been identified, static monitoring devices could be deployed to provide a larger dataset from these areas, though the difficulties of providing reliable moorings should not be under-estimated. Ideally, the two monitoring efforts would overlap in time and space allowing a degree of cross calibration.

4.6 Recommendations for useful technical developments and future fieldwork

This project has been a proof of concept study and has highlighted areas where additional work would be useful if PAM is to achieve its full potential with these species. For this work, we have collected together field recordings from as many sources as possible. However, this collection is still quite limited, in part because it is only in recent years that it has been practical to make full bandwidth recordings. Collection of such recordings and the incorporation of new data into the current collection should be encouraged and supported.

We have shown that not all of the clicks recorded during encounters had the banding pattern that is useful for species ID. These differing click types could result because dolphins are making varying click types at source or it could be that clicks are projected directionally and click characteristics, including banding, vary with the animal's relative orientation. It would be interesting to understand which of these explanations is correct. This could be done by making more extensive field recordings in which the location of hydrophones, relative to the orientation of the animals being recorded, was noted. This might be of more than simply scientific interest if it provided insights into how best to collect and analyse data and allowed data on static recorders to be analysed to determine orientation.

White-sided dolphins were not considered in this project but there are good reasons for believing that they should be amenable to a similar approach. Collection of recordings from this species should be encouraged and application of a similar analysis explored.

The method used here for analysing acoustic parameters for species identification is a new one. It will be useful to encourage feedback and scrutiny from other researchers by presenting results at conferences and submitting a paper based on this report for peer reviewed publication.

The analysis method used here is not yet automated or available within standard software such as PAMGUARD. If it is likely to be used widely, work to undertake the necessary coding within PAMGUARD should be funded and this will streamline future analysis.

Our preliminary analysis, conducted prior to this project, suggested acoustic differences in click characteristics between the east and west coasts. This has not been shown conclusively by the work done here which had a larger dataset. However, given the important conservation implications, it would be sensible to revisit this question and investigate alternative classification strategies.

This work provides strong underpinnings for acoustic tools that could be used to identify and support potential sites for Marine Protected Areas, and inform site-characterisation surveys for offshore developments such as marine renewables. We suggest that a useful strategy would be to combine a program of regular boat-based surveys using low cost platforms (supplemented if possible by platform of opportunity surveys) and leading to the deployment of full bandwidth recorders in areas identified as being of particular interest. A similar analysis approach, based on that used here, could be employed to both detect and classify white-beaked and Risso's dolphins as well as harbour porpoises from their clicks. There would also be every possibility of being able to use a combination of click and whistle data to identify other dolphin species.

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Policy and Advice Directorate, Great Glen House,
Leachkin Road, Inverness IV3 8NW
T: 01463 725000

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