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ACOUSTIC ASSESSMENT OF POPULATIONS OF COMMON DOLPHIN *DELPHINUS DELPHIS* IN CONJUNCTION WITH SEISMIC SURVEYING

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Common dolphin, *Delphinus delphis (bairdi)*, were monitored acoustically across a survey area of 2747 km^2 during a three month period before, during and after an oil industry two dimensional (2D) seismic reflection survey. Over 900 h of audio survey data were collected and analysed, along with GPS positional data, to reveal trends in presence and distribution of animals. The presence of dolphins was determined from vocalization events on the survey recordings. Dolphin presence was assessed by a system of percentage acoustic contact. This was highest before and after the seismic survey, with common dolphins showing a clear south-westerly skew within the survey area and a probable south-westerly migration of animals between September and December. Acoustic contact with dolphins during the seismic survey also showed a south-westerly skew within the survey area, although percentages were lower. Monitoring during the period of seismic activity was restricted to the immediate vicinity (1–2 km) of the seismic vessel, so percentage contact most likely reflects the response of dolphins to such immediate activity. The overall result suggests an avoidance reaction by common dolphins to air gun emissions, although certain observations suggest tolerance to these sounds outside a 1 km radius of the guns.

INTRODUCTION

Conducting meaningful assessment of cetacean populations in the wild has always been extremely difficult. In recent years a concerted attempt has been made to collate sightings of cetaceans around the UK coast (Evans, 1992). These data have much value but inevitably fall short of the ideal. For many years such collation relied on a network of volunteers whose observations were usually opportunistic and mainly confined to land based sites, although the scheme has recently used more systematic observations. However, the generally poor weather and sea conditions around the UK coast means that visual methods of assessing cetacean populations may be compromised. Such factors also make short term impact assessments that rely on visual techniques extremely difficult.

Toothed cetaceans (odontocetes), including all dolphins, emit loud echolocation clicks with which they search their surroundings and find food. Some species, such as the common dolphin *Delphinus delphis* also communicate with high pitched frequency modulated whistles (Caldwell & Caldwell, 1968). Such sounds provide ideal cues for the detection of these animals using passive acoustics. In the simplest scenario a hydrophone can be lowered into the water from the side of a boat and any vocalizing cetaceans in the area detected with ease. For practical assessment of populations over a wide area it is necessary to have either a number of widely spaced stationary hydrophones in a large array or towed hydrophone(s) from moving vessel(s). The advantages of a passive acoustic detection system are several fold: (i) the system is independent of daylight, so surveys can run 24 h; (ii) weather conditions and sea state have a much lesser effect on acoustic detection than they do on visual detection; (iii) detection ranges are usually greater than for visual methods in anything other than flat calm conditions; (iv) it is possible to monitor for other underwater acoustic activity which may have bearing in a particular case. There are also disadvantages in that (i) animals may be silent, although this is seldom the case with common dolphins but much more so with bottlenose dolphins; and that (ii) it is difficult to estimate numbers of animals within a large vocalizing group purely by acoustic means.

Over the last decade there has been much concern and speculation about the possible effects of maritime seismic surveying upon cetacean species. Such activities occur year round in UK coastal waters as industry searches for new supplies of oil and gas beneath the sea bed, effectively using their own version of echolocation. Seismic operations usually entail a large survey ship towing arrays of air guns and hydrophone streamers through the water column, the latter being several kilometres in length. The air guns are brought up to working pressure and designated guns fired to produce the desired sound characteristic. The term gun is applied as the sound characteristic produced is loud and impulsive. The low frequency source level of these guns is high, typically 200–250 dB re 1μPa (Barger & Hamblen, 1980), as the resulting low frequency sounds are required to penetrate the seabed, reflect from underlying discontinuities in the rock strata and subsequently be received by the trailing hydrophone array.

It is the high source level, and impulsive nature, of air gun emissions that has caused concern amongst the environmental community. Cetaceans are acoustically sensitive species, as their sonar systems must be capable of detecting faint echo-returns when they scan small and distant targets. Dolphin hearing can, in many ways, be considered analogous to our own except that peak sensitivity thresholds are typically at an order of magnitude higher frequency (Au, 1993). Nevertheless, dolphins are sensitive to a wide range of frequencies and many of their vocalizations overlap the human hearing range.

Au (1993) shows graphs of hearing sensitivity thresholds for various dolphin species. The bottlenose dolphin, *Tursiops truncatus*, has undergone the most intensive study and its' hearing sensitivity threshold to a 200 Hz continuous tone lies at ~110 dB re 1μPa. It is clear from both published (Barger & Hamblen, 1980) and unpublished data that air gun source levels (in terms of sound pressure level) in the 200 Hz range are many orders of magnitude above this hearing threshold. It seems reasonable to speculate therefore, that even the low frequency components in air gun emissions are audible to small cetaceans such as dolphins, and that there is the potential for an animal response.

The present work attempts the use of continuous passive acoustic monitoring, in conjunction with seismic survey operations, to assess the possible effects of seismic emissions on the presence and distribution of small cetaceans, particularly common dolphin, in a region of the southern Irish Sea.

MATERIALS AND METHODS

Field work

During October and November 1994, Chevron UK ran a 2D seismic reflection survey of hydrocarbon prospect blocks 106/28, 106/29 and 103/3 in the southern Irish Sea off the coast of Pembrokeshire. As part of their survey operations Chevron commissioned a continuous acoustic cetacean survey. To this end a 'Cetacean Survey Area' of 2747 km^2 (i.e. 40x20 nautical miles) was drawn up to encompass the blocks and a considerable expanse of sea adjacent to them (Figure 1). The cetacean survey operation was designed to assess the presence and distribution of small cetaceans, mainly dolphin, in the area before, during and after seismic operations. This region of the Irish Sea is known to be rich in common dolphin, *Delphinus delphis*, and so presented a good study site for such an impact assessment. Seismic surveys usually employ two or more ships for safety reasons, namely the main survey ship and a smaller guard ship to keep maritime traffic clear of the towed arrays. It was the guard ship that was used to conduct the cetacean survey work.

Before seismic began, five days were designated between 21 and 26 September during which the guard ship surveyed the cetacean survey area using a systematic sweep pattern of north-east – south-west sail lines. The vessel towed a hydrophone/ preamplifier assembly 180 m aft using multicore screened cable from a 4-m outrigger, thus displacing the towline from the centre of the ships' wake. Audio signals were recorded onboard the vessel continuously using digital audio tape (DAT). Excessive mechanical and turbulence noise was removed on-line by high pass filtering the signal. In addition to audio data, which was continually time coded, the vessels' position was logged every hour by differential GPS with timed positional printouts. As only dolphin whistles, and the low frequency components of dolphin echolocation clicks, were recorded, the orientation of animals with respect to the hydrophone was not a serious constraint upon acoustic detection. Dolphin clicks contain peak energy at frequencies as high as 120 kHz (Au, 1980), and at such frequencies a narrow beam forms ahead of the animal. At audio frequencies <22 kHz (i.e. those recorded by the DAT system) click components are more omni-directional and detectable at much wider off axis angles (Au, 1993), although source level is reduced relative to the ultrasonic frequencies; whistles are also poorly directional.

During seismic operations from 2 October to 18 November, the guard ship continued 24 h recording but was restricted in its' mobility, the prime duty being to protect the seismic arrays from shipping traffic. Typically the guard ship would remain ~800 m ahead of the seismic ship on each sail line, occasionally moving off to warn shipping. Therefore, the guard ship was restricted to the survey pattern, and the immediate vicinity, of the seismic ship, which tended to restrict the distribution of survey effort in a given time. However, over the whole period of the seismic survey virtually the entire cetacean survey area was covered. The seismic vessel restricted the timing of its' survey line shots to slack water periods. Shooting along a survey line would typically last from 1 to 3 h, with individual air gun shots at ~10 s intervals. Seismic surveying ceased on 30 November and two weeks later, from 13 to 16 December, the pre-seismic survey pattern was repeated as closely as possible.

Laboratory work

The survey recordings, >900 h, were replayed in the laboratory and dolphin vocalizations identified by ear. Only one operator (the author) analysed all recorded data in this way. Dolphin vocalizations were readily distinguishable from the prevailing noise sources when animals approached to within ~500 m of the hydrophone, but the animals themselves were only evident visually at closer ranges due to the poor weather and sea state conditions that prevailed. Photographs were taken at every available opportunity to aid species identification, although common dolphin were virtually the only species encountered during the surveys, encounters with bottlenose dolphins were comparatively rare and infrequent. Acoustic encounters with common dolphins were typically hailed by faint, frequency modulated (FM) whistles at intervals of several minutes (sometimes tens of minutes). As animals approached the hydrophone the whistles became louder and echolocation clicks were clearly audible. At close ranges common dolphins tended to rapidly scan the hydrophone, presumably out of curiosity towards a foreign object, their signals exceeding the dynamic range of the recording system but leaving no doubt as to the presence of animals. Common dolphins were quite recognizable from their vocal patterns, and particularly their distinctive FM whistles. Every available photographic record confirmed correct acoustic species identification, enabling acoustic only contacts to be identified with considerable confidence. Bottlenose dolphins tended to approach the hydrophone, perform a quick sonar scan, and then leave with no other audible sound. Common dolphins were far more vocal.

It was not feasible to count individual dolphins in a large school by the use of passive acoustics, and no attempt was made to count individual animals. Rather the detected vocalizations served as an indication of the animals' presence in a given area. With this constraint in mind it was chosen to express dolphin presence in terms of a percentage acoustic contact.

The entire seismic survey operation was divided into 'weeks' (approximate 7-d periods between port calls by the guard ship), with pre- and post-surveys considered as separate weeks at either end, although each individually constituted less than seven days. For each week the total number of hours of survey effort was calculated from the GPS and tape logs. Acoustic dolphin contacts were designated as periods of time during these weeks that identifiable cetacean vocalizations could be heard on the survey recordings. The start and end points of dolphin contacts were carefully measured from the recordings using the time code data. The acoustic contact for a given week was then expressed as a percentage of the total survey effort for that period.

The actual duration of individual clicks and whistles were not measured, instead vocalization events were scored alongside the time code. For cetaceans close to the hydrophone, vocalization events occurred at intervals of less than a minute to several minutes. For animals at the periphery of audition (i.e. at ranges where they could only just be heard) there could be tens of minutes between vocalization events. As all these scenarios indicated the presence of cetaceans within the vicinity of the vessel it was judged that a time lag of >30 min should elapse between individual vocalization events before one contact was considered separate from the next. This procedure resulted in individual timed dolphin contacts from several minutes to several hours. The precise time lag value was not of major significance, but maintaining it at a constant value throughout the entire study was very important and rigidly adhered to. In the event even reducing to a time lag of 15 min would have made little difference to the final numerical results. Contacts with bottlenose dolphin were included in the overall results as they were insufficient in number to be treated separately and produce meaningful results.

The distribution of dolphins within the cetacean survey area was assessed by further subdividing the area into a 4 x 8 grid pattern, thereby producing 32 separate blocks, each with dimensions of 9·3x9·3 km (i.e. 5x5 nautical miles) and labelled alpha numerically (Figure 2). For each week of the survey operation the GPS log was used to plot the ship's ground track as vectors on charts with the grid pattern overlaid. For each block the total survey effort in hours was measured as the total of the vector lengths in a given block. Timed acoustic contacts were also plotted as vectors on top of the ship's track, enabling hours of acoustic contact in each block to be measured. The data were used to calculate percentage acoustic contact for each block on a weekly basis.

RESULTS

Table 1 summarizes the general survey data for the entire survey operation, subdivided into weeks. It will be seen that there was relatively high presence of common dolphins during the pre-seismic survey, with contact running at 37·7%. Week 1 shows a 12·7% contact, although most of this occurred within the first 3 d whilst air gun arrays of differing capacity were being tested. In the event it proved necessary to use a 0·03474 m^3 (2120 $inch^3$) array with a peak source level of ~205 dB re 1μPa at 200 Hz (Horizon Exploration technical specifications). During week 2 dolphin contact dropped to 2·4% and during week 3 was virtually zero. Contacts improved during weeks 4–6 of the seismic survey but were still greatly reduced from the pre-seismic level, peaking at only 3%. The post seismic survey dolphin contact was 6·4%, an improvement on the seismic period but still somewhat down on the pre-seismic level.

Table 1. *General survey data.*

Survey		Survey duration (h)	Seismic duration (h)	Dolphin contact (h)	Dolphin contact (%)
Pre-seismic	21/09–26/09	76.08	–	28.70	37.7
Week 1	02/10–09/10	140.54	40.11	17.78	12.7
Week 2	09/10–18/10	183.25	53.92	4.37	2.4
Week 3	19/10–25/10	142.83	26.30	0.06	<0.0
Week 4	27/10–02/11	110.33	30.14	3.12	2.8
Week 5	03/11–10/11	156.83	26.91	4.68	3.0
Week 6	16/11–18/11	48.85	4.55	0.57	1.2
Post-seismic	13/12–16/12	74.20	–	4.72	6.4

Table 2 compares the acoustic dolphin contact during periods when air gun shots were in progress with periods when the air guns were silent. In all weeks, except week 4, the majority of dolphin contact occurred when the air guns were silent. Totalling the results from the individual weeks revealed that during the entire seismic operation 86% of contact with dolphins occurred when air guns were silent. The result for week 4 is interesting, as it suggests that common dolphins were able to tolerate the sound pressure levels at some distance from the air guns. The majority of this tolerance of air gun shots occurred during one lengthy contact (>3 h) through blocks 3B, 3C and 3D of the grid. Using GPS data the mean distance between the two vessels during this contact was calculated at 1·34 km. As the dolphins were close to the guard ship most of the time the data would suggest that they tolerated the sound pressure levels outside a 1 km radius of the air guns. Week 2 also shows an appreciable dolphin contact during air gun shots, but positional data for the seismic vessel was not available to calculate inter-ship ranges.

Table 2. *Comparison of dolphin contact between periods of shooting seismic and periods of 'silence' between shotlines.*

Survey	Total dolphin contact (h)	Dolphin contact during seismic (h)	Dolphin contact between seismic (h)
Week 1	17.78	0.76	17.02
Week 2	4.37	1.68	2.69
Week 3	0.06	0.00	0.06
Week 4	3.12	1.98	1.14
Week 5	4.68	0.00	4.68
Week 6	0.57	0.00	0.57
Total	30.58	4.42	26.16

During the pre- and post-surveys the distribution of survey effort was approximately even, with ~2–3 h of survey effort in most blocks. From week 2 of the seismic operation survey effort concentrated at the north-eastern end of the survey area but progressed to the south-western end as the weeks passed. Therefore the seismic survey pattern had a modal distribution on a weekly, and indeed total, basis. However, as acoustic contacts have been expressed as a percentage of the survey time, they take account of survey effort distribution by definition, although increased survey effort in a given area will produce more statistically significant estimates.

Figures 3–10 show charts of percentage acoustic contact distribution for each week of surveying. The pre-seismic acoustic contact distribution (Figure 3) shows a considerable concentration of common dolphins in columns 1–6 of the grid, with ~100% contact

Figures 1–10. (1) Chart showing the three hydrocarbon prospect blocks off the Pembrokeshire coast, and the encompassing cetacean survey area. (2) Chart showing the cetacean survey area subdivisions, used to monitor the distribution of dolphins. (3) Chart showing percentage acoustic dolphin contact distribution within the cetacean survey area during pre-seismic survey. Percentage contact is illustrated with ● of varying size, key to circle sizes is illustrated. Absence of circles in any grid square indicates no survey effort during that period. (4) Percentage acoustic contact distribution during week 1 of seismic surveying. (5) Percentage acoustic contact distribution during week 2 of seismic surveying. (6) Percentage acoustic contact distribution during week 3 of seismic surveying. (7) Percentage acoustic contact distribution during week 4 of seismic surveying. (8) Percentage acoustic contact distribution during week 5 of seismic surveying. (9) Percentage acoustic contact distribution during week 6 of seismic surveying. (10) Percentage acoustic contact distribution during post-seismic survey.

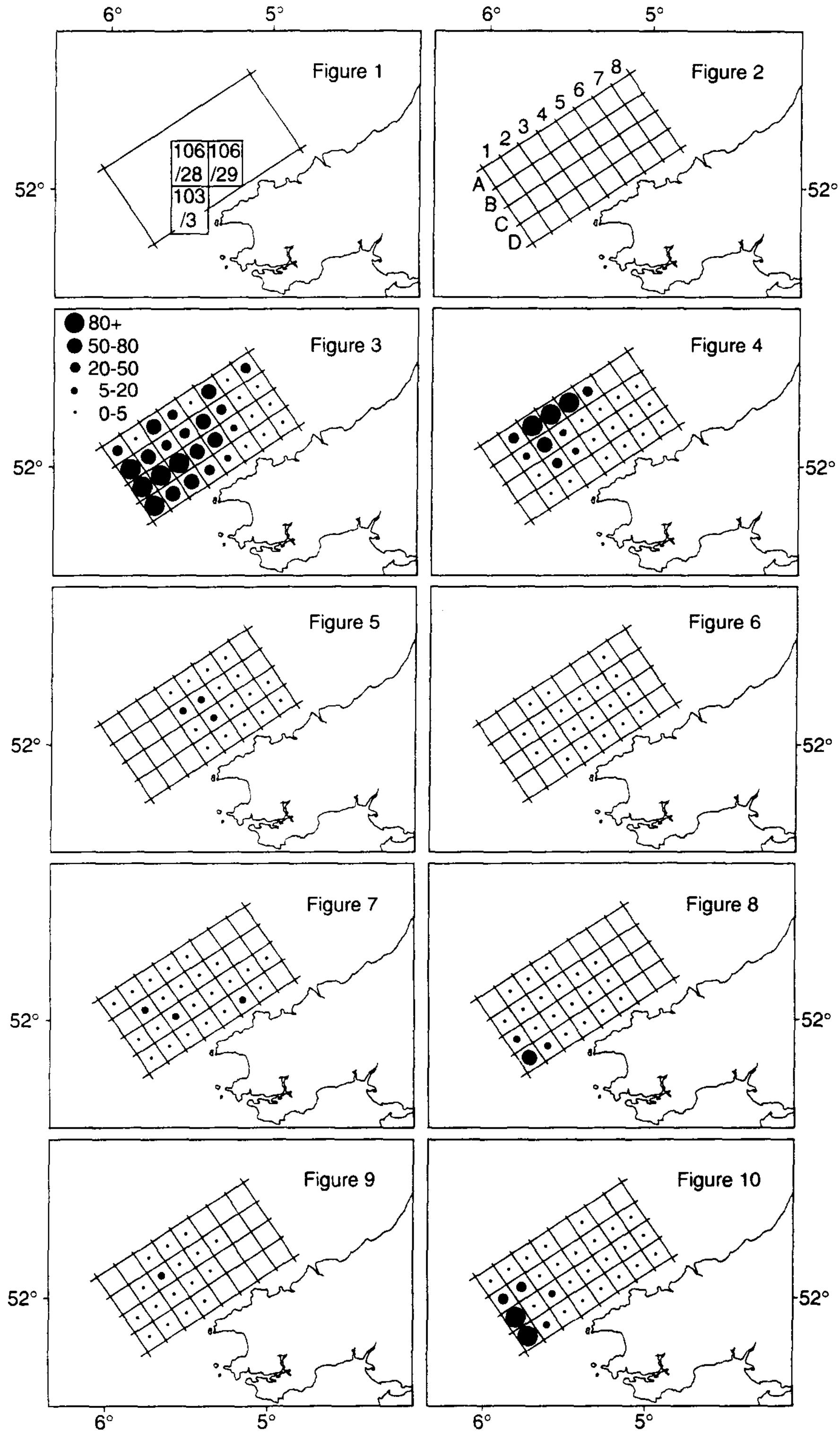

Figure 1
106/28
106/29
103/3
Figure 2
1 2 3 4 5 6 7 8
A B C D
Figure 3
80+
50-80
20-50
5-20
0-5
Figure 4
Figure 5
Figure 6
Figure 7
Figure 8
Figure 9
Figure 10
6°
5°
52°

along the south-west margin. It is evident from this figure that one might expect relatively low levels of dolphin contact further to the north-east during the following weeks. During the first week of seismic (Figure 4) the contact distribution had changed considerably and showed a high percentage in blocks 3A–5A. During weeks 2 and 3 the bulk of survey effort was concentrated away from the south-west which may offer a partial explanation as to the low levels of contact that resulted (Figures 5 & 6). Survey effort during weeks 4 through 6 was more intensified to the south-west, which resulted in low but appreciable levels of dolphin contact (Figures 7–9). During week 5 (Figure 8) there was a high percentage of dolphin contact in the southern most block 1D, although this did not recur in week 6 (Figure 9). The post-seismic survey (Figure 10) showed that acoustic dolphin contact was again high at the south-west margin, two weeks after cessation of seismic, and was noticeably greater than during the seismic period. However, the concentration of animals was very much more restricted to this margin than had been the case during the pre-seismic survey (Figure 3).

DISCUSSION

The data from this study suggest a general avoidance reaction by common dolphins to seismic emissions. The pre- and post-seismic surveys were designed in such a way as to show the distribution of cetaceans within a large area under normal conditions. This has been successful in showing the clear distribution of dolphins to the south-west. Surveying during the seismic operation was concentrated in the immediate vicinity of the seismic vessel and has effectively measured the response of dolphins to this immediate activity (i.e. presence or absence). Common dolphins are not usually 'shy' of ships and frequently approach vessels to ride the bow wave. Bow-riding occurred on several occasions during the pre-seismic survey, but animals approached relatively infrequently during the seismic survey.

The fact that dolphins approached the guard boat relatively infrequently during the seismic survey, especially when air gun shots were in progress, suggests that air gun shots were a source of disturbance within a limited radius. A useful by-product of the acoustic survey technique was the wideband recording of the air gun shots themselves at varying ranges from source. These were subsequently analysed to yield broadband spectra and sound pressure levels, the results of which will be the subject of a separate paper. It is sufficient to note in this paper that the emissions were broadband and sound pressure levels 5 km from source, in 80–100 m water depth, were ~170 dB re 1μPa at 250 Hz, although sound pressure level decreased with increasing frequency. Sound pressure levels at 2 kHz, 10 kHz and 20 kHz for the same distance were ~140 dB, 115 dB and 90 dB re 1μPa respectively.

Given that most dolphins have similar hearing characteristics to each other, and that data from Au (1993) suggest hearing sensitivity thresholds for bottlenose dolphin of 80 dB re 1μPa at 2 kHz and 50 dB re 1μPa at 20 kHz, it would seem likely that seismic sounds are audible to small cetaceans over a broad bandwidth and at considerable ranges from source. However, one must be cautious in that the figures quoted above are for hearing sensitivity to continuous tones as opposed to pulsed tones. The dolphin ear "behaves like an integrator with an integration time constant, energy is summed over the duration of a tone pulse until the pulse is longer than the integration time constant" (Au, 1993). In other words, dolphins will be less sensitive to pulsed sounds than they will to continuous sounds, provided that the pulsed sound is shorter in duration than the integration time constant of the hearing system. Au (1993) has summarized much of the known data in this area and it seems that integration times generally reduce with frequency. Interestingly, across the audio bandwidth, integration times for the dolphin ear are very similar to the human ear.

For bottlenose dolphin the integration time peaks at ~0·2 s between 1 and 4 kHz, i.e. dolphins will be least sensitive to a pulsed tone of a given duration between these frequencies. At 20 kHz the integration time is ~0·1 s. At close ranges of ~800 m the high frequency waveform of the air gun emissions had a considerable pulse length, with major energy over at least 0·1 s. Therefore the continuous tone threshold of dolphin hearing is likely to apply at close ranges. At 5 km range the major spike of high frequency seismic energy was confined to some 0·02 s, a pulse length now considerably shorter than the integration time constant and as such the dolphin hearing sensitivity threshold to this sound might be raised by ~10 dB. In fact, even allowing for pulse durations, the sound pressure levels 5 km from source are still at least three orders of magnitude above the hearing sensitivity threshold quoted for bottlenose dolphin (in terms of sound pressure level). It is reasonable to infer that these figures will be broadly similar for common dolphin.

This is not to say that several orders of magnitude over threshold will be harmful to the animals *per se*; after all, the logarithmic nature of hearing is designed to encompass a large range of sound pressure levels. At close ranges of less than 1 km, however, the sudden onset and duration of such sounds may be sufficiently 'discomforting' that small cetaceans choose to move to a distance at which sound pressure levels are more acceptable. As the guard boat was restricted to the seismic vessel survey pattern there was no adequate way to determine what such a range might be, although the data from week 4 suggested a tolerance to seismic emissions outside a 1 km radius from the air guns. A similar operation in future, using an additional ship to survey the area independent of the main seismic operation, might well produce better data to this effect. Such an operation would ideally have been attempted here but the cost of an additional vessel was prohibitive.

An interesting comparison is that between pre- and post-seismic survey acoustic contact distribution for common dolphins (Figures 3 & 10). The paucity of contact during the post-seismic survey, other than near the south-western margin, suggests a seasonal migration of animals offshore, which might be expected at the time of year from published data (Evans, 1992). In fact the virtual absence of dolphins during week 3, whilst survey effort was concentrated almost centrally in the survey area, may partly indicate a time at which such a movement of animals was taking place, although contacts did improve from week 4 onwards. It is unfortunate in one sense that the seismic survey has spanned this migration period, as such a natural movement may conspire to mask the pure effects of seismic sounds.

The fact that animals still tended to occur to the south-west during the seismic period, but with a reduced presence, suggests that dolphins will persist in certain areas despite increased noise levels. Sightings by fishermen indicate that dolphins are present in this area year round and hence suggests an important area for feeding. If the rewards are great enough it may be that the animals are prepared to tolerate higher levels of noise than would otherwise be the case. In addition one must consider that the bulk of the seismic survey effort was concentrated near the centre of the survey area, which means that seismic activity would have been less intense towards the margins than it would nearer the central region. Therefore dolphins to the south-west would have been subject to less intensive periods of noise.

CONCLUSIONS

This study has been successful in the application of passive acoustics to monitor overall presence and distribution of common dolphin in the cetacean survey area. The trends in dolphin presence, with regard to seismic survey activity, are not as alarming as had been feared from many environmental groups, although the data suggest a localized disturbance to the normal population of dolphins. The results presented here highlight the utility of passive acoustics as a monitoring tool and the role it could play in further research.

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