ARCTIC
VOL. 64, NO. 3 (SEPTEMBER 2011) P. 307–316

Local Passive Acoustic Monitoring of Narwhal Presence in the Canadian Arctic: A Pilot Project

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(*Received 3 June 2010; accepted in revised form 1 March 2011*)

ABSTRACT. Long-term community-based monitoring of narwhals (*Monodon monoceros*) is needed because narwhals are important to local Inuit and are facing changes in their environment. We examined the suitability of passive acoustic recording for monitoring narwhals, using data gathered in the Canadian Arctic from an autonomous acoustic recorder (Repulse Bay, 2006) and a hand-held digital recorder (Koluktoo Bay, 2006–08). We found a relationship between the number of narwhals observed passing a fixed point and the number of calls heard. In addition, we found that an automated call detector could isolate segments of recording containing narwhal vocalizations over long recording periods containing non-target sound, thus decreasing the time spent on the analysis. Collectively, these results suggest that combining passive acoustic sampling with an automated call detector offers a useful approach for local monitoring of the presence and relative abundance of narwhals.

Key words: animal behaviour, automated detection, Baffin Island, marine mammal, narwhal, participatory monitoring

RÉSUMÉ. La nécessité d'avoir un programme communautaire de surveillance à long terme des narvals (*Monodon monoceros*) s'avère évidente étant donné que les narvals revêtent de l'importance aux yeux des Inuits de la région et que leur environnement est en pleine évolution. Nous explorons la pertinence d'un programme de surveillance par acoustique passive pour les populations de narvals à partir de données récoltées dans l'Arctique canadien à l'aide d'une enregistreuse autonome (Repulse Bay, 2006) et d'une enregistreuse portable (Koluktoo Bay, 2006–2008). Grâce à des enregistrements accompagnés d'observations sur le terrain, nous avons trouvé une corrélation entre le nombre de vocalisations entendues et le nombre de narvals observés. L'utilisation d'un détecteur automatique de vocalisations de narvals a permis d'isoler des segments d'enregistrements contenant des vocalisations de narvals sur de longues périodes d'enregistrement contenant des sons non-ciblés, et ainsi diminuer le temps d'analyse. Ces résultats suggèrent que la combinaison de surveillance acoustique passive avec l'utilisation d'un détecteur automatique offre une approche utile pour la surveillance locale de la présence et de l'abondance relative des narvals.

Mots clés: comportement animal, détection automatique, île de Baffin, mammifère marin, narval, surveillance participative

Révisé pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

Like other Arctic marine mammals, narwhals (*Monodon monoceros*) are experiencing a rapidly changing environment because of climate change (Laidre and Heide-Jorgensen, 2005; Laidre et al., 2008) and an increase in anthropogenic activities (Moore and Huntington, 2008). Narwhals are culturally and economically important to local Inuit residents (Reeves, 1992; Priest and Usher, 2004). The narwhal has been listed as "near threatened" by the International Union for Conservation of Nature (Jefferson et al., 2008) and "of special concern" by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2004). The rationale behind these listings is uncertainty about life-history traits such as generation time, longevity, and population trends and structure; the future state of Arctic marine ecosystems during a period of rapid climate change; and increasing resource exploitation in the Arctic (COSEWIC, 2004; Jefferson et al., 2008). Current management efforts and monitoring of narwhal populations are informed by harvest reporting (Armitage, 2005a), aerial surveys (Richard et al., 2010), and traditional ecological knowledge (Westdal et al., 2010).

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Effective ecological monitoring in the Canadian Arctic requires multiple indicators and scales of observation. On the one hand, explicit objectives, identification of inexpensive, unbiased and generalizable indicators, and rigorous statistical interpretation make monitoring programs more effective (Yoccoz et al., 2001). On the other hand, the degree to which selected indicators resonate with local observations, community priorities, and potential anthropogenic impacts is an important determinant of their relevance to co-management perspectives and decision making (Dowsley and Wenzel, 2008). Marine mammals are especially challenging in this regard because their size and mobility mean that they range over large areas, while their long generation time and low reproductive rates contribute to lagged and latent population responses and recovery times (Lewison et al., 2004). As a result, local observations can differ widely from larger-scale assessments, and responses observed over a short period may not reflect long-term trends (Richard and Pike, 1993). In these circumstances, where impacts and responses occurring locally or more globally over shorter or longer timescales are of interest to different stakeholders, multiple monitoring approaches can help to bridge the gap between the data available from observations of marine mammals and the interests of the various stakeholders (Mallory et al., 2006; Berkes et al., 2007).

Community-based (also called participatory) monitoring has been repeatedly suggested as an effective approach to sampling natural resources (Wismer and Mitchell, 2005). Community-based monitoring involves local people in multiple steps of the process (Holck, 2008) and, in so doing, contributes to local stewardship and capacity building as well as public education and outreach (Conrad and Daoust, 2008). Community-based monitoring is usually less expensive and longer lasting because it uses local expertise and resources (Danielsen et al., 2005), and it is relevant to residents because it is more likely to focus on locally important resources and places (Pearce et al., 2009). However, many community-based monitoring efforts performed by non-scientists have focused on qualitative rather than quantitative measures (Berkes et al., 2007) or used easy, inexpensive indicators rather than those that are of most direct local relevance and importance, such as wildlife. As the research capacity of northern communities expands and community-researcher alliances strengthen (Berkes et al., 2007; Tremblay et al., 2008), a broader set of approaches and technologies will be compatible with community-based monitoring. Wildlife monitoring techniques involving technology and statistics can be compatible with community-based monitoring programs, as long as researchers develop these approaches in partnership with communities and incorporate local methods of observation rather than excluding them.

Passive acoustic monitoring has been suggested as an effective and low-cost technique for monitoring marine mammals, with the capacity to sample 24 hours per day, in poor weather conditions, and over long periods (see review by Mellinger et al., 2007). Most acoustic monitoring programs simply note the presence of calls by species of interest (e.g., Johnston et al., 2008; Todd et al., 2009); however, some have also attempted to estimate marine mammal abundance. These estimates are notably improved by information about the average call rates of individuals and how these call rates vary with group size and behavioural state (Van Parijs et al., 2002; Mellinger et al., 2007; Kimura et al., 2009). Specific acoustic monitoring programs have advanced knowledge of several cetacean species. Topics studied include sperm whale presence in the Gulf of Alaska during the winter, when boat-based surveys cannot be conducted (Mellinger et al., 2004); the extended breeding period of humpback whales on their feeding ground (Clark and Clapham, 2004); and night foraging behaviour of beaked whales (Johnston et al., 2008).

We conducted a pilot study of the feasibility of passive acoustic monitoring for determining narwhal presence and relative abundance in the Canadian Arctic. Specifically, we deployed an autonomous recording system for 25 days in an area known to be frequented by narwhals, then tested the usefulness of an automated detector for extracting narwhal vocalizations from the audio file. We then compared passive digital recording data from a second site to behavioural observations made there to relate the number of vocalizations recorded to the number of narwhals observed and their behavioural state.

METHODS

Characteristics of Narwhal Vocalization

The narwhal is a vocal species that emits echolocation clicks, as well as pulsed calls and whistles (Ford and Fisher, 1978; Shapiro, 2006). The frequency of narwhal clicks might be well above 100 kHz (the highest frequency the system could record), and maximum source levels can reach 218 dB re 1 μPa (Møhl et al., 1990). Pulsed sound frequencies are usually between 0.5 and 24 kHz, while whistles are between 300 Hz and 10 kHz (Watkins et al., 1971; Ford and Fisher, 1978). Source levels of narwhal whistles and pulsed calls are not known (Shapiro, 2006). A detailed description of narwhal vocalizations is provided elsewhere (Marcoux et al., in press).

Recordings and Behavioural Observations

We tested the feasibility of detecting narwhal vocalizations with an automated detector using data from Repulse Bay, Nunavut (66˚20′ N, 86˚0′ W, Fig. 1). Recordings were obtained using an autonomous recorder (AURAL M2, Multi-Électronique Inc, Rimouski Québec) deployed in approximately 30 m of water from 9 August to 2 September 2006. The AURAL M2 contains a HTI-96 MIN series hydrophone (High Tech Inc http://home.att.net/~hightechinc/) with a frequency response from 2 Hz to

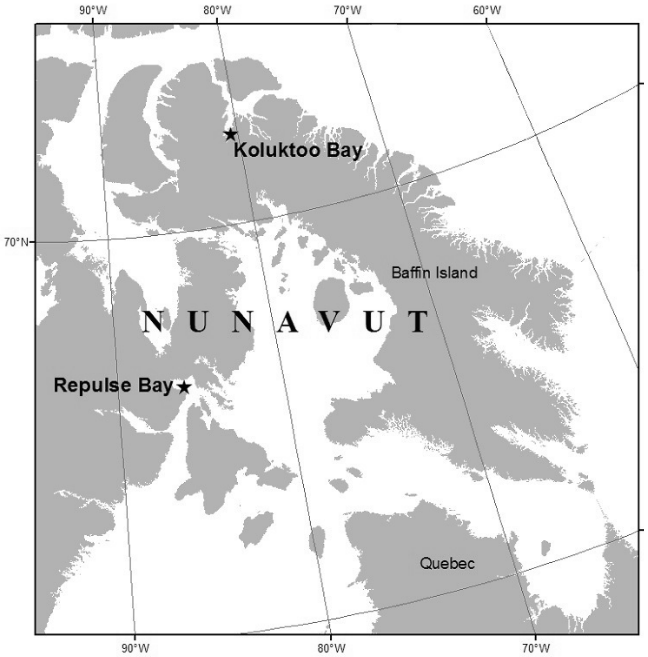

FIG. 1. Map of Nunavut, with stars representing the two study sites.

30 kHz. Using a sampling rate of 32.77 kHz, the AURAL M2 recorded segments of 32 min. 33 sec. at the beginning of each hour, for a total of 302 hours over the 25-day monitoring period. Our recording system did not allow us to determine the detection range of narwhal calls. Behavioural observations could not be obtained at this site, so comparison of acoustic recordings with narwhal observations required research at a second site.

We determined how the number of vocalizations recorded on audio files was related to the number and behavioural state of narwhals present in Koluktoo Bay, Nunavut (72˚04′ N, 80˚32′ W, Fig. 1), near the Hamlet of Pond Inlet. The fieldwork took place in the summers of 2006 to 2008. Technical failure of a continuous autonomous recorder at this site prevented replication of the recording and analytical procedures used for the Repulse Bay recordings. Instead, we used hand-held digital recorders: a Sony MiniDisc Player in 2006, and a Marantz PMD660 from 2006 to 2008. Both recorders used sampling rates of 44.1 kHz, and each had a hydrophone similar to the one described above (HTI-96). Hydrophones were suspended either from a buoy ca. 5 m from shore in water about 3 m deep (in 2006) or from a pole on shore in water 1 m deep (in 2007 and 2008). Since available power and data storage were limited, recordings were initiated after we detected narwhals and stopped before or immediately after narwhals were out of sight. In addition, we noted the wind force measured according to the Beaufort scale as an indication of the background noise that could mask narwhal vocalizations. As in the previous data set, the detection range of narwhal calls could not be determined.

Behavioural observations were performed on the Bruce Head peninsula from a viewing area approximately 30 m above water level (Marcoux et al., 2009). We noted the number of narwhal groups (individuals within 10 body widths of each other) that swam within 400 m of the hydrophone (distance at which narwhals were observable; Marcoux et al., 2009). The average size of the groups was 3.5 individuals (Marcoux et al., 2009) with a median group size of 3.0 and a standard deviation of 2.6 individuals. We used the number of groups instead of the absolute number of narwhals because we were not able to obtain accurate counts for each group. We also noted the prevalent behavioural state of narwhals in each group as either resting (group moving slowly or stationary), traveling (group moving steadily in a constant direction), or socializing (group in physical contact with each other; similar to Mann and Smuts, 1999).

Acoustic Analysis

We used the sound analysis software Raven Pro 1.3 (Cornell Lab of Ornithology, 2003–08) to produce spectrograms from the sound files. Each spectogram represented its sound file on a two-dimension grid, showing time on the abscissa, frequency on the ordinate, and sound intensity as a color gradient. The spectrogram used a Hann Window, with a Fast Fourier Transform size of 256 samples and 50% overlap, providing a 64 Hz frequency resolution and a 7.8 ms time resolution. This setting was selected to optimize the trade-off between time resolution and frequency resolution.

Automated Detection

The Repulse Bay recordings were used to test the feasibility of detecting narwhal calls with an automated detector. We used the sound analysis software XBAT (Figueroa, 2007) based on the signal processing toolbox in Matlab (MathWorks, 2007). Within this software, we used the data template option under the detector menu. This detector uses reference calls (templates) to be detected in an audio file. Then it calculates a time series of cross-correlations between the call template and the sound files. The user sets a threshold value above which peaks in the cross-correlation time series are logged as detections. We targeted the detection of pulsed calls (the most abundant call type in all our recordings) with peak frequency between 1030 and 3110 Hz, since 85% of all manually detected pulsed calls were within this frequency range. To eliminate false detection of noise events, we selected non-targeted sounds identified by the detector and set them as templates for rejections. These non-targeted sounds were mostly mechanical noise caused by friction between parts of the mooring.

We tested 16 detector settings with different combinations of call templates for detection and noise templates for rejection. These settings were applied to a subset of 10 hr. 51 min. of recording (20 segments of 32.5 min.). This subset was first examined visually and aurally to detect and count narwhal vocalizations on the basis of a range of

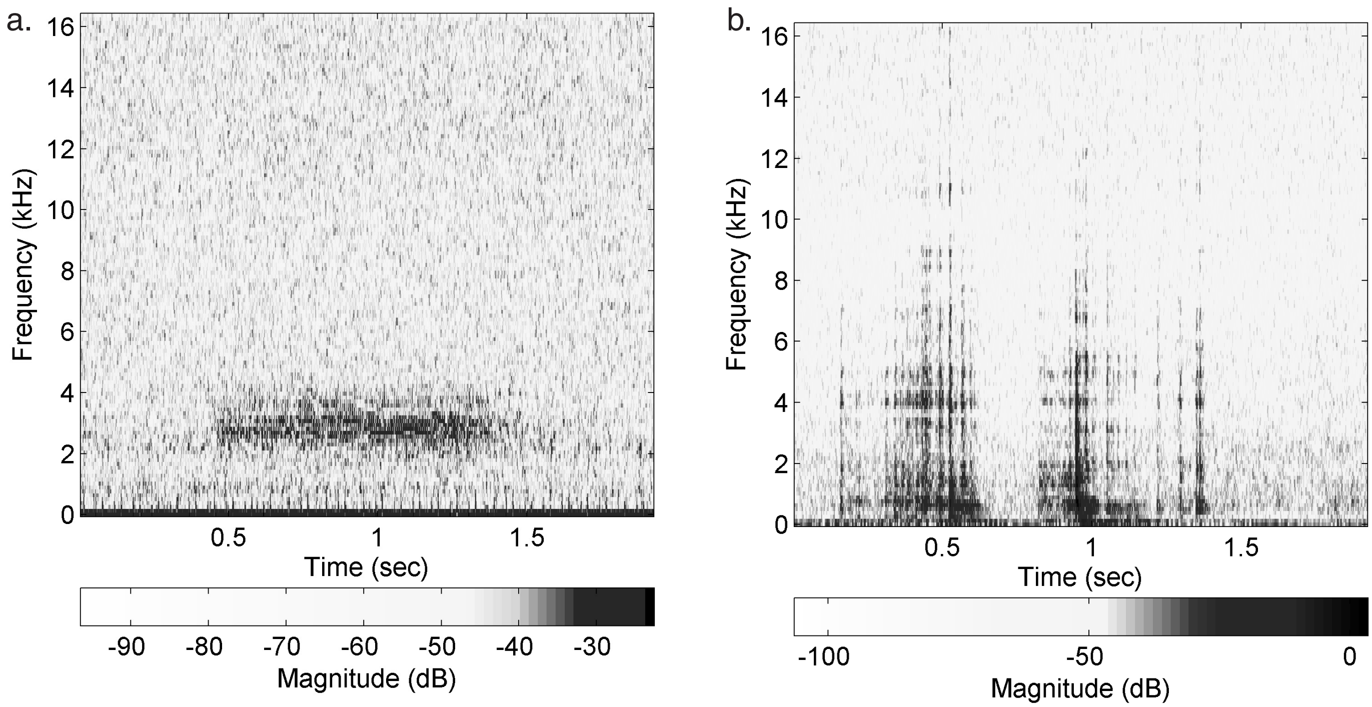

FIG. 2. Templates of (a) narwhal pulsed call and (b) noise example (for rejection) used to set the automated detector.

narwhal pulsed call types described by Marcoux et al. (in press). The number of calls and vocalization events (defined as a recording segment of 32.5 min. containing at least five calls) identified by each detector setting was compared to the number of pulsed calls and vocalization events identified manually in the 10 hr. 51 min. subset.

Adjusting the detector settings to minimize the number of missed calls invariably led to an increase in false detections, so that it was impossible to achieve acceptably low numbers of missed calls and false detections simultaneously. Thus, fully automated call detection, involving the use of a detector to extract the exact number of calls present in a recording sequence, is not currently possible because of the trade-off between minimizing false detections and minimizing the number of missed calls (Mellinger et al., 2007).

As an alternative, we used the call detector as a screening device to identify recording sequences that potentially contained narwhal calls and therefore required manual examination. When the detector is used as a screening device, its priority is to minimize missed vocalization events, even though this will increase the number of false detections. (False detections result in more of the recording being manually examined, but they do not cause noise to enter the dataset as mistaken calls, since all potential calls are verified manually.) We tested various detector settings using the 10 hr. 51 min. sequence known to contain four vocalization events and selected a detector setting that successfully detected all four vocalization events and did not generate false detections. This detector setting was based on templates of a pulsed call with peak frequency of 2688 Hz (Fig. 2a) and three non-target sounds (e.g., Fig. 2b). After applying this detector to the entire 302 hr. recording sequence, we assessed the detected segments manually to confirm whether they did in fact contain narwhal calls.

Relationship between Number of Calls and Number of Narwhals

To test the relationship between the number of calls identified on a recording and the number of narwhals present during the recording, we used the Koluktoo Bay recordings. We counted calls produced during a one-minute period in the middle of a five-minute calling segment (similar to Van Parijs et al., 2002). Only recordings for which narwhal calls were loud enough (10 db above background noise) were retained for analysis (Boisseau, 2005; Díaz López, 2010). We counted the whistles and pulsed sounds in each one-minute bout. We did not investigate echolocation clicks, since they are difficult to isolate and count, and they tend to have frequencies higher than the range of our recordings. Spectrograms were visualized in 10 sec. increments. To facilitate detection, we adjusted the contrast of the spectrogram view or amplified the sound file, or both.

A backward stepwise regression (Crawley, 2005) was used to construct a model, with the total number of detected calls in a one-minute period in the middle of a five-minute calling segment as the dependent variable. The independent variables were 1) the number of groups; 2) their predominant behavioural state, observed within the same five-minute bout; 3) the year, which also accounted for the different recording setups; and 4) the Beaufort wind force scale during the recording. The selection criterion was p-value < 0.1 for the F-test on the type III sum of squares.

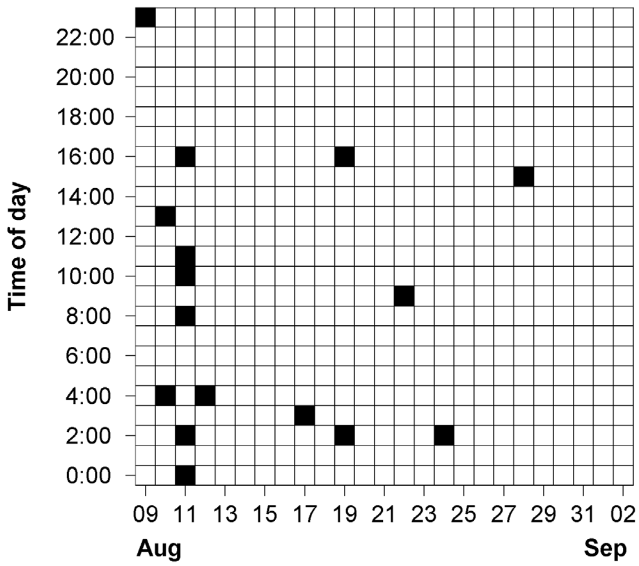

FIG. 3. Acoustic detections of narwhals in the entire Repulse Bay data set. Each grid square represents a recording segment (32.5 min. at the beginning of an hour). Black squares represent a vocalization event (at least five calls) during that segment.

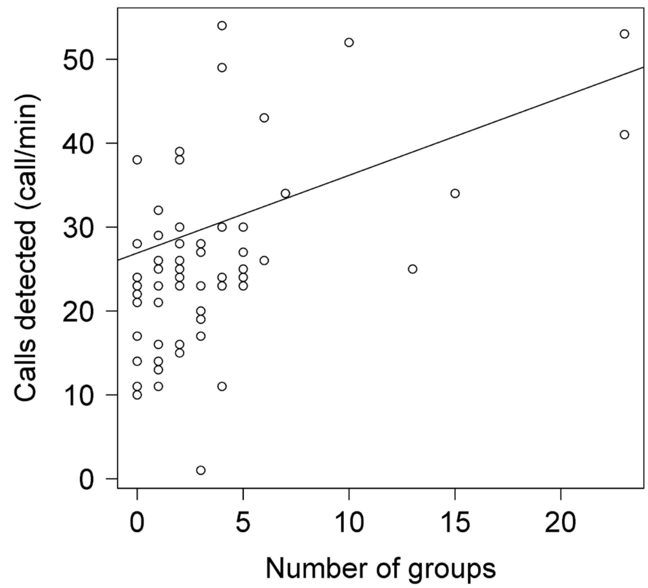

FIG. 4. Regression showing relation between the number of calls detected in five-minute recording bouts and the number of narwhal groups observed during that time.

The analysis was performed with the package "Car" (Fox, 2002) written in R (R Development Core Team, 2008).

RESULTS

Use of the automatic detector as a screening device reduced the recording sequence that had to be inspected manually from 302 hr. to 22 hr. The detector identified 41 segments with possible calls in the entire Repulse dataset. After manual inspection, 17 (41%) of these were determined to contain at least five narwhal calls and thus were classified as vocalization events.

Narwhal vocalization events occurred on 9 of the 24 days that were monitored (Fig. 3), but more than half of the events were concentrated within a single two-day period. Recordings on other days involved discrete detections, concentrated around 0200 and 1600. Collectively, these results indicate precisely when narwhals were present in this locality and distinguish between periods of nearly continuous presence and occasional passages.

For the Koluktoo Bay dataset, we analyzed 63 one-minute recording segments from 12 different days in 2006 to 2008. There was a positive and significant relationship between the number of groups observed visually and the number of calls (pulsed and whistles) identified on recordings (Fig. 4, Table 1). The number of calls identified also declined with increasing wind force (Table 1). The model accounted for 33% of the variation in the total number of calls identified (adjusted $r^2 = 0.33$, $F_{(2,59)} = 15.97$, $p < 0.001$, Fig. 4). The variables "behavioural state" (Fig. 5) and "year" were excluded from the model as non-significant ($p > 0.1$). Thus, we did not find any effect of the behavioural state or year on the rate of narwhal vocalization. Generally,

TABLE 1. Parameters of the model selected by the stepwise regression to predict the number of narwhal calls detected in a one-minute recording bout.

	Estimate	Sum of squares	df	F value	*P* value
Intercept	26.88	9787.1	1	125.83	< 0.0001
Number of groups	0.93	981.5	1	12.31	0.0009
Beaufort	-3.46	650.8	1	8.15	0.006
Residuals	–	4625.6	58	–	–

narwhal calls were present in our recordings whenever we visually observed narwhals in the bay.

In addition to detecting narwhals, we could monitor for the presence of other marine mammal species and shipping traffic. On 2 and 4 August 2008, we detected bowhead whale (*Balaena mysticetus*) vocalizations in our Koluktoo Bay recordings that coincided with visual observations in the bay. Bowhead whale calls are differentiable from narwhal calls because they are emitted at a lower frequency range (Clark and Johnson, 1984). Although we observed killer whales (*Orcinus orca*) in Koluktoo Bay on two different days, we could not identify vocalizations in 50 min. of recordings when they were present. Finally, ships traveling in and out of Koluktoo Bay could also be identified in our recordings, highlighting the potential for monitoring the effect of shipping on marine mammal habitat use, which is of significant interest both in the Arctic (Hovelsrud et al., 2008) and globally (Tyack, 2008).

DISCUSSION

Passive acoustic recording is a promising technique for local monitoring of narwhals in Nunavut. Narwhal calls

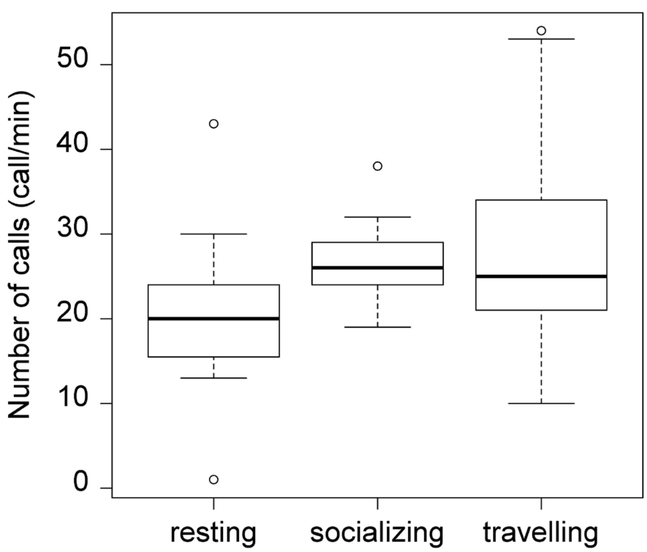

FIG. 5. Number of calls detected in five-minute recording bouts in relation to narwhal behavioural states. The bottom and top of the box represent the first and third quartiles, respectively; the dark line represents the median; the whiskers represent the 95th percentile; and the circles are outliers. The number of calls detected did not differ significantly among behaviours.

can be detected automatically on recordings made by autonomous recorders. Additionally, an index of narwhal numbers can be derived from the number of calls manually detected on recording bouts corrected for the appropriate covariate (Beaufort Wind force). Presence-only data or relative-abundance data (or both) are commonly used in population monitoring (Pollock et al., 2002; Royle and Nichols, 2003; Joseph et al., 2006). For narwhals, acoustic monitoring indicates presence and also provides data about relative abundance. Thus, acoustic monitoring has the potential to provide information about narwhal movement patterns, habitat selection, and daily and seasonal visitation patterns.

Acoustic monitoring programs provide the opportunity to match the design of the monitoring to local ecological knowledge and priorities. Decisions about the location of the recorders and the timing of the monitoring can be guided by local knowledge. For example, our work in Koluktoo Bay was based at Bruce Head, a traditional hunting site that simultaneously represents both known high narwhal abundance and high local value for hunting (Mary-Rousselière, 1984–85). In this way, ecological knowledge of local residents informs the design of monitoring programs (Gagnon and Berteaux, 2006), increasing the relevance of those programs to the local community (Pearce et al., 2009). In addition, existing integrated ocean observing systems (IOOS) use biophysical mooring to monitor marine ecosystems and the impact of climate change on those systems. Including acoustic monitoring in the design of an IOOS offers an opportunity to integrate information about marine mammal movements with biophysical data (Stafford et al., 2010).

Estimating narwhal numbers from recorded vocalizations requires calibration with visual and behavioural observations and environmental measurements (e.g., wind speed). We found a correlation between the number of narwhals observed and the number of calls manually detected on the audio recording. Because each site has unique physical acoustic characteristics and sound transmission rates depending on the water column depth, sea floor composition and geometry, water temperature, and salinity (Richardson et al., 1995; Madsen and Wahlberg, 2007), this relationship between observations and calls is likely to be specific to the site and depth where the hydrophone is located. Thus, we could not apply the correlation found in Koluktoo Bay to the recordings from Repulse Bay. Counts of narwhals in the vicinity of the recorder are required for each specific recorder location to obtain an index of narwhal numbers. Wind speed reduced our ability to detect narwhal vocalizations, probably through increased wave noise. Thus, estimation of narwhal numbers should be corrected with wind speed measurements from an anemometer in situ. Calibrating the relationship between narwhal calls and observations and anemometer deployment introduces opportunities for local involvement.

Once autonomous recorders are retrieved, recordings must be downloaded and calls detected manually or with an automated detector. We have shown that narwhal vocalizations can be detected with a cross-correlation detector (Figueroa, 2007) providing presence/absence data. But our inability to identify detector settings that avoid both missed calls and false detections means that detectors can be used only as screening devices to identify potential calls, which must then be verified and counted manually. Combining automated detection of vocalization bouts with later manual call verification and counting is still preferable to an entirely manual evaluation, since the automated screening step greatly reduces the volume of recordings that must be examined. Most of the detector settings we tested were sensitive to the noise produced by the mooring system of the recording device, resulting in a high rate of false positive detections. Improvements to the mooring to minimize mechanical noise would greatly improve automated detection. In addition, new detectors are currently being developed which could significantly improve the efficacy of detecting narwhal vocalizations (e.g., Adam, 2008; Erbe and King, 2008).

The scale and precision of an acoustic monitoring program depend mainly on the acoustic device used, the number of such devices, and their location (Mellinger et al., 2007; Van Parijs et al., 2009). Our pilot study used only one autonomous recorder in one location for 25 days, so it has very limited spatial and temporal coverage. The use of several recorders would allow for broader spatial coverage, more precise spatial localization, and more information about group size and number. For example, detection distance for beluga (*Delphinapterus leucas*) whistles in the mouth of Saguenay Fjord was estimated to be 3 km under low-noise conditions, equivalent to coverage of 28.3 km^2 per hydrophone (Simard et al., 2010). In that study, an array of four hydrophones covered the study area and permitted estimation of the number of belugas present from the number of whistles. Placement of hydrophones in strategic locations, for example, in known narwhal migration routes, could also increase coverage for narwhal monitoring. The measures developed in this paper provide an index of narwhal abundance, but not absolute numbers. As with other long-term monitoring projects, repetition of the same protocol over several years is crucial to estimate temporal trends in local presence or abundance. Data collected from fixed acoustic devices are easier to standardize over time since they do not involve spatial variation (Evans and Hammond, 2004).

Acoustic monitoring offers a useful addition to existing forms of narwhal monitoring based on aerial surveys and harvest data. Visual and photographic surveys from aircraft or boats are widely used to estimate the size and distribution of narwhal populations (e.g., Innes et al., 2002; Heide-Jørgensen, 2004; Richard et al., 2010). Harvest data are also used to monitor narwhal populations. In six Nunavut communities, all landed, lost or struck narwhals must be reported as part of the co-management agreement (Armitage, 2005b). Occasionally, the sex and size of harvested narwhals are also reported, and tissue samples are collected for further analyses of diet, contaminants, reproductive status, and population condition (Finley and Gibb, 1982; Hay and Mansfield, 1989; Roberge and Dunn, 1990; Muir et al., 1992; Dietz et al., 2004; Wagemann and Kozlowska, 2005). Although these various methods of narwhal research and monitoring have different emphases, strengths, and limitations, all clearly contribute to our knowledge of the species and its management status. Acoustic monitoring certainly cannot substitute for harvest monitoring and aerial surveys, which yield important and spatially extensive information about population size, population distribution, and harvest intensity. Nonetheless, the technique does offer information about local presence and relative abundance of narwhals over time at discrete locations without high cost or observer intensity. Within the diverse but logistically constrained realm of narwhal monitoring approaches, acoustic monitoring offers an additional, independent, low-cost and low-effort method for local monitoring of narwhal populations.

Passive acoustic monitoring provides complementary and novel insight into questions related to the ecology and conservation of narwhals. For example, more exhaustive information on the timing and intensity of specific habitat usage can be examined through passive acoustic methods. Narwhals are known to visit fjords in the summer, but neither the spatial extent nor the duration of their presence in the fjords is well known (Dietz et al., 2001). Moreover, the seasonal extent of narwhals' presence in their known wintering grounds could be explored in more detail (Heide-Jørgensen et al., 2002; Laidre et al., 2003). Passive acoustic monitoring could determine whether harvesting activities or shipping traffic causes narwhals to leave an area, and if so, the duration of the narwhals' avoidance response. In addition, acoustic monitoring could document the rare occurrences of other marine mammal species in particular localities and whether these coincide with the presence or absence of more common species. Finally, this technique may be used to evaluate the impacts of weather and tidal cycles on narwhal movement patterns.

ACKNOWLEDGEMENTS

Thanks to the Arviq and Mittimatalik Hunters and Trappers Organizations for allowing us to do research on their land. We wish to acknowledge K. Beardsley, G.M.J. Chu Yew Yee, J. Côté, A. Kublu, N. Inuarak, J. Orr, L. Putulik, J. Suisangnark, L. Suqslak, J. Tinashlu, and K. Westdal, for assistance, as well as R. Antunes, H. Whitehead, and Polar Sea Adventures for support. P. Richard and two anonymous reviewers provided useful comments on the manuscript. Funding for this study was provided by the Arctic Institute of North America's Lorraine Allison Scholarship, ArcticNet Centres of Excellence, the Canadian Wildlife Federation, the Canadian Marine Environment Protection Society, the Canadian Whale Institute, Fisheries and Oceans Canada, the Natural Sciences and Engineering Research Council of Canada (Northern Research Chair Program to M.M. Humphries, Discovery Grant to S.H. Ferguson, CGS Fellowship to M. Auger-Méthé, and PGS Fellowship to M. Marcoux), McGill University's Eben Hopson Fellowship, the Northern Scientific Training Program, the Nunavut Wildlife Research Trust Fund, World Wildlife Fund Canada, Alberta Innovates–Technology Futures, and the University of Alberta.

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