PAPER

Glider-Based Passive Acoustic Monitoring in the Arctic

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ABSTRACT

Persistently poor weather in the Arctic makes traditional marine mammal research from aircraft and ships difficult, yet collecting information on marine mammal distribution and habitat utilization is vital for understanding the impact of climate change on Arctic ecosystems. Moreover, as industrial use of the Arctic increases with the expansion of the open-water summer season, there is an urgent need to monitor the effects of noise from oil and gas exploration and commercial shipping on marine mammals. During September 2013, we deployed a single Slocum glider equipped with a digital acoustic monitoring (DMON) instrument to record and process *in situ* low-frequency (<5 kHz) audio to characterize marine mammal occurrence and habitat as well as ambient noise in the Chukchi Sea off the northwest coast of Alaska, USA. The DMON was programmed with the low-frequency detection and classification system (LFDCS) to autonomously detect and classify sounds of a variety of Arctic and sub-Arctic marine mammal species. The DMON/LFDCS reported regularly in near real time via Iridium satellite detailed detection data, summary classification information, and spectra of background noise. The spatial distributions of bowhead whale, bearded seal, and walrus call rates were correlated with surface salinity measured by the glider. Bowhead whale and walrus call rates were strongly associated with a warm and salty water mass of Bering Sea origin. With a passive acoustic capability that allows both archival recording and near real-time reporting, we envision ocean gliders will become a standard tool for marine mammal and ocean noise research and monitoring in the Arctic.

Keywords: autonomous vehicle, marine mammals, ocean noise, habitat, Chukchi Sea

Introduction

The Arctic environment is changing rapidly because of modification of the physical environment by climate warming and increased anthropogenic activities made possible by an extended open-water season. At present, we have very little understanding of the implications of these changes for Arctic marine mammals. There is a pressing need to increase monitoring efforts to document and understand these changes and to mitigate the risks posed by human activities to marine mammals, including oil and gas exploration and commercial shipping. However, the Arctic poses particular challenges to at-sea scientific research that hinder our efforts to study these important changes. Shipboard access to the sea by all but the largest and most expensive ice-breaking ships is limited to the summer and early fall months (July to November) because of winter sea ice. Moreover, port facilities in the U.S. Arctic are severely underdeveloped, and much seagoing research is done from very small ships working out of coastal Alaskan villages. Arctic weather is notoriously poor, which further limits ship operations during the open-water season. Weather conditions also have a serious effect on aerial surveys designed to assess marine mammal distribution and relative abundance, grounding planes during long periods of high wind, persistent fog, and snow.

The use of autonomous platforms is greatly expanding marine observations in the Arctic and elsewhere because of the ability to operate continuously regardless of weather conditions. Each platform or vehicle collects observations on particular time and space scales; thus, each is appropriate for specific applications. For example, buoys allow observations for weeks to months at a time in a single location, and they have the capability to relay data to shore via satellite communications, but buoys cannot overwinter in Arctic sea ice and therefore must be deployed and recovered in a single open-water season. Subsurface moorings allow year-round observations in a single location, but they have no capability to relay data to shore in near real time. Ocean gliders, including Slocum, Spray, and Seagliders (Rudnick et al., 2004; Griffiths et al., 2007; Smith et al., 2011), are mobile underwater autonomous vehicles that can remain at sea for weeks to months at a time surveying over spatial scales from ones to hundreds of kilometers. Shoreside researchers provide gliders with waypoints using two-way satellite communications, and the vehicle navigates between those waypoints autonomously. Although recent advances have been made in navigating Seagliders under ice (Curry et al., 2013), sea ice precludes the transmission of data via satellite in near real time; therefore, most Arctic applications require gliders to be deployed, operated, and recovered during periods of open water.

Significant advancements have been made in the last few decades to record, detect, classify, and remotely report the sounds produced by marine mammals from autonomous platforms (Moore et al., 2007; Baumgartner & Fratantoni, 2008; Van Parijs et al., 2009; Klinck et al., 2012a; Matsumoto et al., 2013; Baumgartner et al., 2013). Passive acoustic recordings have been collected routinely from subsurface moorings since the mid-1990s (e.g., Stafford et al., 1999), and with the rapid expansion of storage capacity and availability of relatively low-cost instruments, the volume of acoustic data collected at sea has grown exponentially with time. The Arctic is no exception to this, as passive acoustic recordings have been one of the primary means of assessing changes in bowhead whale occurrence, distribution, and behavior in response to oil and gas exploration and development (Greene et al., 2004; Blackwell et al., 2007; Thode et al., 2012). Over the past decade, instruments and algorithms have been developed to detect and classify marine mammal sounds *in situ* and to relay that information to shoreside researchers. One of the most successful near real-time detection applications in recent years is the system of buoys that monitor the shipping lanes approaching Boston for the presence of North Atlantic right whales to help mitigate ship strikes for this seriously endangered species (Van Parijs et al., 2009). More recently, Klinck et al. (2012a) and Matsumoto et al. (2013) developed near-real-time detection and reporting systems for beaked whale clicks aboard Seagliders and profiling floats, respectively. Baumgartner et al. (2013) implemented a detection, classification, and near-real-time reporting system for the calls of several baleen whale species from a Slocum ocean glider. These systems have shown great promise for providing persistent real-time monitoring for marine mammals that can be used for both science and conservation applications. We seek here to demonstrate their particular utility for use in the Arctic.

Marine mammals are an integral and iconic part of the Arctic ecosystem. They are of particular importance in the diet and culture of native communities in the United States (Alaska), Canada, Russia, and Greenland. The Pacific Arctic is inhabited year-round by bowhead whales (*Balaena mysticetus*), beluga whales (*Delphinapterus leucas*), Pacific walrus (*Odobenus rosmarus divergens*), bearded seals (*Erignathus barbatus*), ringed seals (*Pusa hispida*), spotted seals (*Phoca largha*), and ribbon seals (*Histriophoca fasciata*) and is visited seasonally by sub-Arctic species such as gray (*Eschrichtius robustus*), fin (*Balaenoptera physalus*), humpback (*Megaptera novaeangliae*), and killer whales (*Orcinus orca*). Little is known about the factors that influence the spatial distribution and occurrence of these species on seasonal or shorter time scales, but there is recent evidence to suggest that ocean fronts and other physical oceanographic features (both persistent and dynamic) may play an important role in governing marine mammal distribution in shallow Arctic seas (Stafford et al., 2013). In 2013, we initiated a program using Slocum ocean gliders equipped with passive acoustic monitoring instrumentation to examine how oceanographic processes in the Chukchi Sea influence the distribution of several Arctic marine mammal species. We describe here the technology, its application during a pilot study in the Chukchi Sea during 2013, and our vision for how this system can be used for both marine mammal and ocean noise monitoring studies in the Arctic.

Methods

We adapted the system described by Baumgartner et al. (2013) to conduct glider-based autonomous surveys for marine mammals in the Chukchi Sea off the northwestern coast of Alaska during a pilot study in September 2013. Passive acoustic monitoring was accomplished with the digital acoustic monitoring (DMON) instrument housed inside a Slocum glider ("shallow" 200-m version) and a hull-mounted faired hydrophone capable of monitoring frequencies between 10 and 7,500 Hz; the hydrophone was attached to the science payload at the midpoint of the glider. The DMON had a 36 dB re μPa/√Hz noise floor at 2 kHz and a sensitivity of −169 dB re V/μPa at 2 kHz. The DMON features (1) a programmable digital signal processor upon which detection, classification, and recording software can be developed and run; (2) 32 MB of flash memory; and (3) serial output lines that allow data to be passed between the DMON and the glider's science computer in real time. For the pilot study, audio was recorded to flash memory continuously at 5 kHz sampling rate and processed in real time on the DMON with the low-frequency detection and classification system (LFDCS; Baumgartner & Mussoline, 2011; Baumgartner et al., 2013). Briefly, the LFDCS detects sounds above a specified threshold and characterizes the frequency and amplitude modulations of those sounds using pitch tracks, compact representations of sound analogous to notes on a page of sheet music. Attributes of each sound are extracted from the pitch tracks (e.g., minimum frequency, maximum frequency, duration) and classified using quadratic discriminant function analysis. Classification relies on a call library of known call types developed from archival recordings (see below); discriminant function analysis matches each new sound with a call type in the call library and reports a statistic, the Mahalanobis distance, that quantifies the quality of that match (Johnson, 1998). Sounds that do not match any call in the call library are considered unknown to the real-time detection system, but their pitch tracks are retained in flash memory so that they can be later compared to the recorded audio for identification by an analyst after recovery of the glider.

The DMON/LFDCS relayed a subset of all pitch tracks (detected sounds) and their associated classification information to the glider's science computer (up to 8 kilobytes of pitch track data per hour) for transmission to shore in near real time via the glider's Iridium satellite modem. A summary consisting of tallies for all calls in each call type contained in the call library was relayed to the glider's science computer every 15 min, and status information (e.g., DMON battery voltage, processing status, error conditions) was relayed from the DMON/LFDCS to the glider science computer every 20 min. The DMON/LFDCS continuously monitored background noise as part of the sound detection algorithm (Baumgartner & Mussoline, 2011), and an exponentially weighted mean background noise spectrum with a time constant of 60 s was relayed to the glider's science computer once every hour. In total, the DMON/LFDCS relayed to the glider approximately 12 kilobytes of data per hour. The glider typically surfaced every 2 h and transmitted to shore via Iridium satellite these DMON/LFDCS data as well as other sensor data such as temperature, conductivity, and position derived from a global positioning satellite (GPS) receiver. A shore-side computer received these data, and information from the DMON/LFDCS was immediately posted to a public website in both tabular and graphical formats.

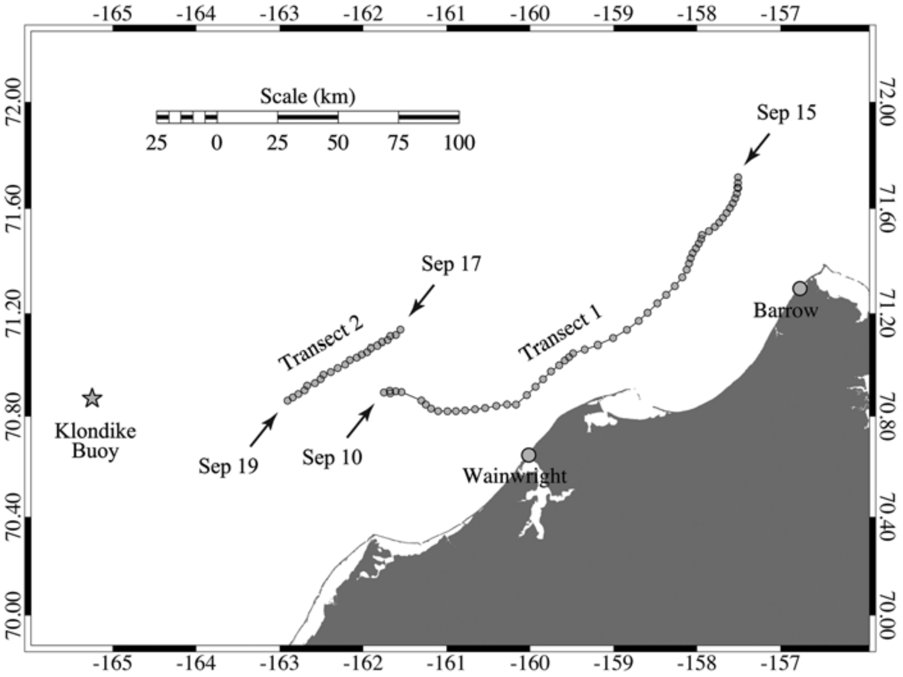
For Arctic applications, we have begun to develop a call library containing call types from a variety of both Arctic and sub-Arctic species. The pitch-tracking algorithm used by the LFDCS works best with species-specific, stereotypical, tonal, whistle-like calls. The frequency modulated tonal calls of bowhead, beluga, killer, humpback, and fin whales as well as bearded and ribbon seals are well suited for this sound characterization approach. Repetitive pulsive sounds, such as those produced by minke whales, walrus, and many fish, are not amenable to pitch tracking and are therefore not as easily characterized, detected, and classified by the LFDCS. However, because all audio are recorded by the DMON/LFDCS, an analyst can manually detect these signals during post-processing after glider recovery. For our pilot study, we developed a preliminary call library with 32 call types for bowhead (various), right (upsweeps), humpback (various), fin (20-Hz call), killer (various), and beluga (various) whales, as well as bearded seals (downsweeps) and walrus (bell calls). With the exception of right whales, audio recordings from the Bering Strait (Stafford, unpublished data) were used to compile exemplars of species-specific call types. Right whale upsweep call types were imported from a North Atlantic call library described in Baumgartner and Mussoline (2011) and were used to detect similar upsweep calls produced by North Pacific right whales. A median of 88 and an average of 113 exemplars were used to characterize each of the 32 call types.

We deployed a single glider equipped with a DMON/LFDCS and temperature and conductivity sensors in the northeastern Chukchi Sea on 10 September 2013 from the M/V *Norseman II* (Figure 1). The glider was navigated east-northeast for 201 km along the coast of Alaska between Wainwright and Barrow (Figure 1) but was recovered on 15 September to avoid interfering with an at-sea subsistence hunt operating off the northern coast of Alaska (as agreed upon prior to commencement of our study). The glider was redeployed northwest of Wainwright on 17 September, navigated to the southwest for 57 km, and recovered on 19 September.

An experienced analyst (KMS) identified marine mammal and human-made sounds in the DMON/LFDCS recorded audio. Evaluation of the real-time DMON/LFDCS detections

FIGURE 1

Glider track in the Chukchi Sea off the northwest coast of Alaska (filled circles indicate the glider's surfacing locations). The glider was recovered at the end of transect 1 on 15 September 2013 and redeployed at the start of transect 2 on 17 September 2013. The location of the Shell Klondike buoy is shown (filled star); wind speed measurements from this buoy are shown in Figure 6.



was conducted by comparing the number of automated detections in each summary tally period (i.e., every 15 min) to the occurrence (presence/absence) of species-specific vocalizations identified by the analyst in the same 15-min periods using logistic regression (after Baumgartner et al., 2013). Relationships between analyst-detected call rates and near-surface temperature and salinity (measured at 3 m) were examined using Poisson regression. Prior to analysis, both call counts and environmental conditions were averaged over 10-km transect segments; this length scale corresponds to the typical range at which low-frequency bowhead whale calls can be reliably detected (Blackwell et al., 2007). Univariate and bivariate models with and without interaction terms were fit to the data, and the best bivariate model was selected based on the Akaike information criterion (AIC). Logistic and Poisson regression models were fitted with the R statistical package (version 3.0.3).

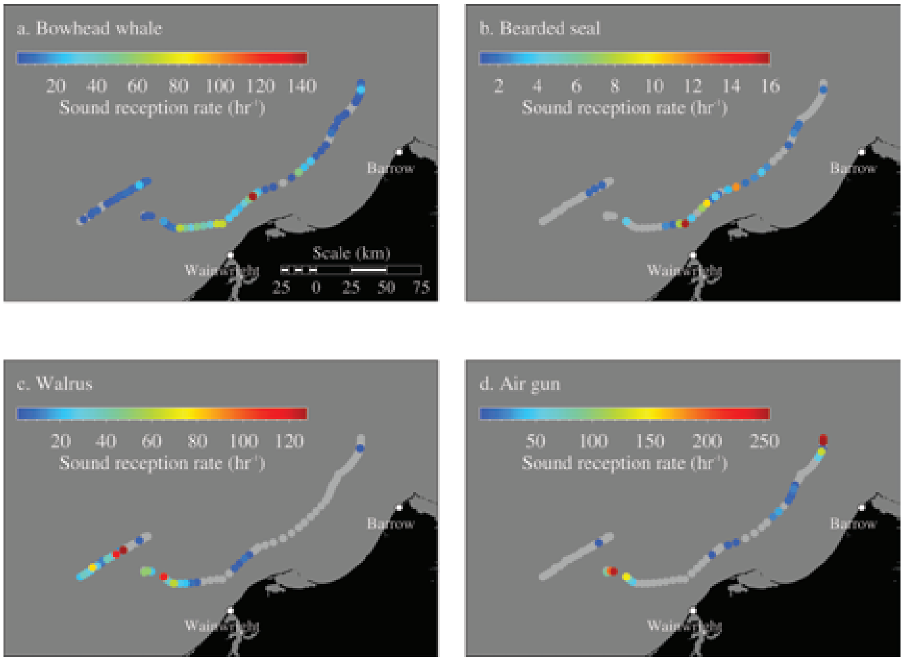
Results

Distribution and Habitat

Upon manual review of the DMON/LFDCS audio recordings, many calls of bowhead whales (*n* = 2,262), walrus (*n* = 2,633), and bearded seals (*n* = 183) were detected, as well as a few calls of gray (*n* = 14) and beluga (*n* = 3) whales. The most numerous sound detected was that of air guns used for geophysical exploration (*n* = 3,980). Call rates of both bowhead whales and bearded seals were highest along the southern inshore section of transect 1 (Figures 2a and 2b), whereas walrus call rates were highest in the southern offshore region of the study

FIGURE 2

Analyst-determined call rates from DMON/LFDCS recorded audio for (a) bowhead whales, (b) bearded seals, and (c) walrus as well as reception rates for (d) air guns. (Color versions of figures available online at: http://www.ingentaconnect.com/content/mts/mtsj/2014/00000048/00000005.)

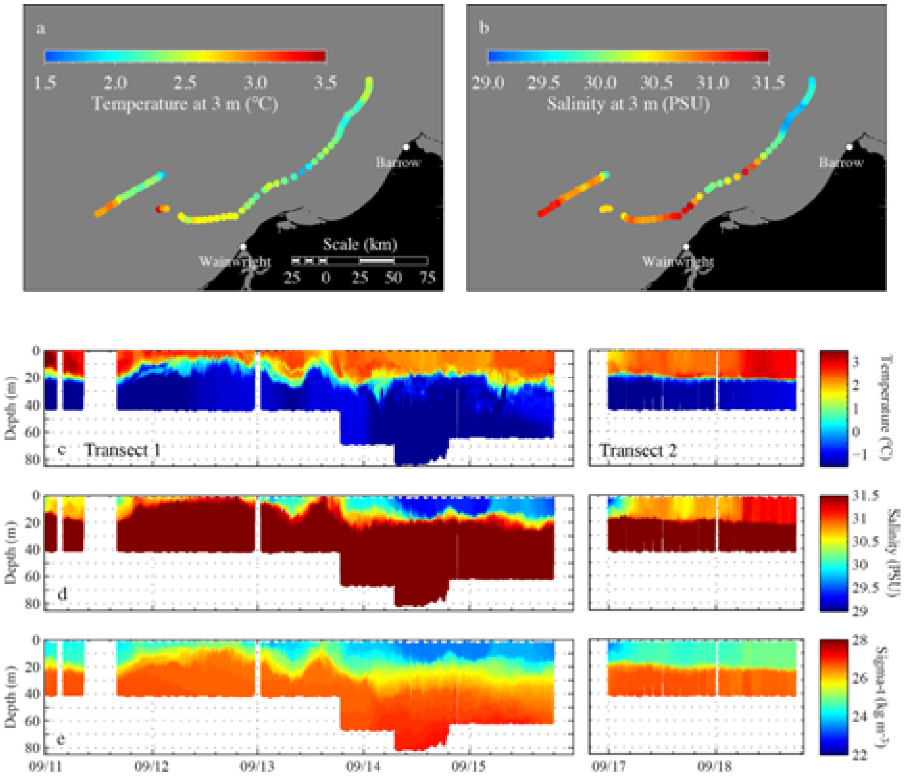


area at the beginning of transect 1 (consistent with walrus sightings at that time from the M/V *Norseman II*) and along transect 2 (Figure 2c). Air guns were detected at high rates at the beginning and end of transect 1 and sporadically at lower rates along the middle of transect 1 and near the beginning of transect 2 (Figure 2d).

We observed a large north-south gradient in glider-measured surface hydrographic properties owing to warmer and saltier waters of Bering Sea origin (Weingartner et al., 1998) occurring at the southern ends of transects 1 and 2 and colder and fresher waters of Arctic origin at the northern end of transect 1 (Figure 3). The call rates of bowhead whales, bearded seals, and walrus were all positively correlated with surface salinity ($p < 0.0001$; Table 1). Bowhead whale call rates were only weakly associated with surface temperature. While calls were detected in both the Bering Sea and Arctic surface water masses, bowhead call rates were higher in the Bering Sea water mass (Figure 4a). No relationship was observed between bearded seal call rates and temperature ($p = 0.45$, Table 1); in fact, all of the models with temperature terms had higher AIC and drop-in-deviance values than the model with only the salinity term (Table 1; Figure 4b). Walrus call rates were strongly associated with temperature as well as salinity ($p < 0.0001$; Table 1), and the fitted Poisson regression model for walrus indicated that call rates increased significantly within the Bering Sea water mass (Figure 4c). Very few walrus calls were detected in the Arctic water mass (Figure 4c).

FIGURE 3

Map of average (a) temperature and (b) salinity measured by the glider at 3 m depth and water column sections of (c) temperature, (d) salinity, and (e) density (sigma-t units) along the glider track. (Color versions of figures available online at: http://www.ingentaconnect.com/content/mts/mtsj/2014/00000048/00000005.)



Near-Real-Time Detection and Classification

Detailed information (pitch tracks and associated classification data) for all detected sounds were archived by the DMON/LFDCS, and a subset of these was transmitted from the glider to a shore-side computer via Iridium satellite and was thus available for review by shore-side researchers in near real time (i.e., within approximately 2 h of a sound being produced). The tonal frequency-modulated sounds of bowhead whales and bearded seals were accurately represented by the DMON/LFDCS pitch tracks (Figures 5a and 5c), as were the downswept low-frequency pulses produced by air guns (Figure 5e). Patterning in bouts of pitch tracks was assessed in near real time to unambiguously identify bowhead whale sounds (Figures 5a and 5b) and repetitive production of air gun sounds (Figures 5e and 5f) irrespective of the classification data.

Although the calls of bowheads and bearded seals were well characterized by the DMON/LFDCS pitch tracks, real-time classification results for these two species were mixed using the preliminary call library. The analyst-determined occurrence of vocally active bearded seals during each 15-min summary period was strongly associated with the number of bearded seal downsweep calls identified by the DMON/LFDCS for the same 15-min summary periods ($p = 0.0001$ for logistic regression of $n = 505$ 15-min periods, 68 of which had one or more vocally active bearded seals present). The rate of missed occurrence during these 15-min periods was very high (85%), though, because many calls were too faint to

TABLE 1

Akaike information criterion (AIC), drop in deviance, and p-value (p) for Poisson regression models relating call rates to temperature (T) and salinity (S) measured at 3-m depth. Asterisks denote the significance of each drop in deviance statistic (***$p < 0.0001$, **$0.001 > p \geq 0.0001$). Regression models included data from $n = 26$ transect segments. Fitted models with the lowest AIC values are shown in Figure 4.

Model	AIC	Drop in Deviance	p
Bowhead whale			
T	663.9	16.91***	<0.0001
S	616.2	64.57***	<0.0001
$T + S$	613.1	69.68***	<0.0001
$T + S + T \times S$	612.5	72.33***	<0.0001
Bearded seal			
T	109.0	0.01	0.9359
S	98.1	10.87***	0.0010
$T + S$	99.7	11.26**	0.0036
$T + S + T \times S$	101.3	11.69**	0.0085
Walrus			
T	705.4	203.34***	<0.0001
S	858.0	50.83***	<0.0001
$T + S$	701.2	209.59***	<0.0001
$T + S + T \times S$	659.9	252.91***	<0.0001

be accurately pitch tracked by the DMON/LFDCS. There was no association between the analyst-determined occurrence of vocally active bowhead whales during each 15-min summary period and the number of bowhead whale calls identified by the DMON/LFDCS for the same 15-min summary periods ($p = 0.13$ for logistic regression of $n = 505$ 15-min periods, 259 of which had one or more vocally active bowhead whales present). Broadband noise produced by movements of the glider's rudder during dives were regularly and falsely detected as walrus bell calls (the DMON/LFDCS used broadband transient noise rejection that successfully prevented many of the louder rudder noises from being pitch tracked, but the adjustable threshold for transient broadband noise detection was set too high to exclude quieter rudder noise).

Background Noise

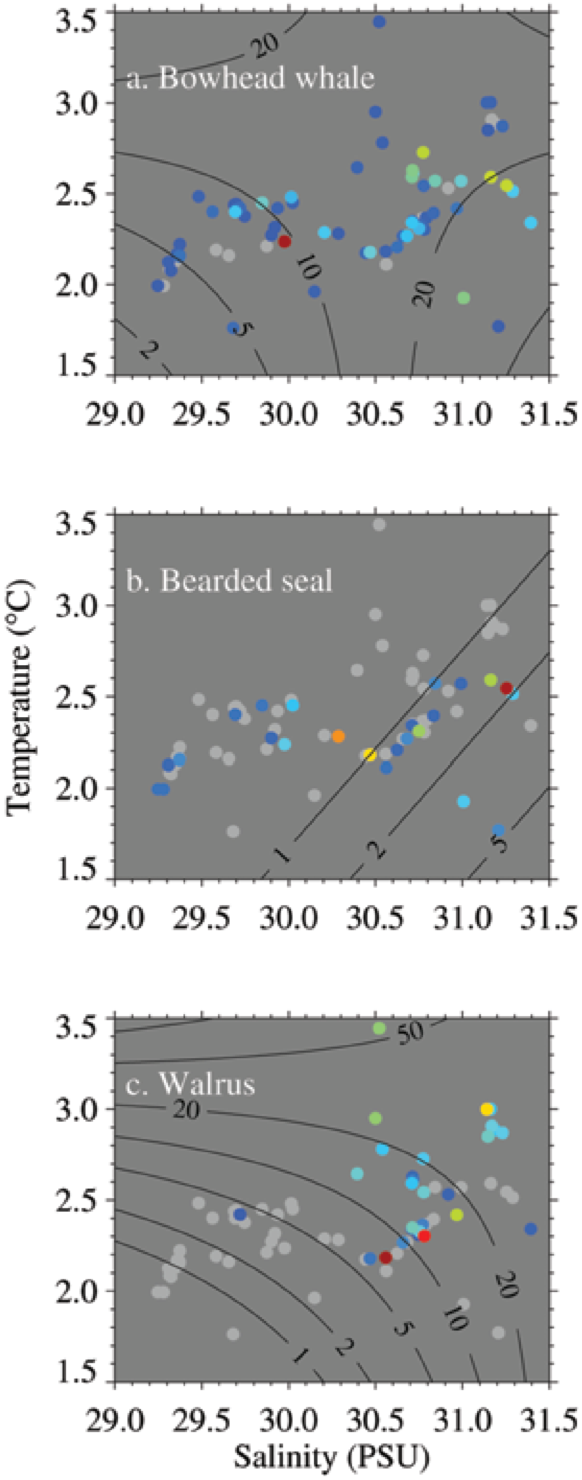
In addition to transmitting detailed and summary sound detection information, the DMON/LFDCS transmitted hourly uncalibrated background noise spectra in near real time (Figure 6a). Ship noise associated with deployment and recovery of the glider from the M/V *Norseman II* was evident in the background noise spectra, as was the passage of a different ship during the pre-dawn hours of 13 September (Figure 6a). Ambient noise when ships were not present was strongly related to wind speed (Figures 6b and 6c). Wind speed was measured within 12.5 km of the glider's location with the Advanced Scatterometer (ASCAT) sensor carried aboard the MetOp-A and MetOp-B satellites (Level 2 coastal ocean surface wind vector product available at http://podaac.jpl.nasa.gov; Verhoef & Stoffelen, 2013). These wind speed observations were qualitatively similar to wind speeds measured at the Shell Klondike buoy at 70.871°N, 165.246°W (see Figure 1), particularly when the glider was close to the buoy at the beginning and end of the mission (Figure 6b). Background noise was significantly correlated with wind speed after excluding observations contaminated by ship noise (Figure 6c; $n = 33$, $r = 0.964$, $p < 0.0001$).

Discussion

The glider successfully recorded continuous audio and collected hydrographic data within and offshore of the Alaska Coastal Current, and we used these data to investigate relationships between the distribution of vocalizing animals and oceanographic conditions. The glider also relayed passive acoustic detection information to shore in near real-time via satellite, including both pitch tracks and classification data. Real-time review of pitch tracks by analysts on shore allowed the unambiguous identification of several sounds, including bowhead whale calls and air gun pulses. On-board classification of detected sounds using the preliminary call library was less successful, but this was not unexpected. The development of our Arctic call library had only just begun at the time of the glider deployment, and we included call types that were exploratory and not fully vetted. We are currently refining the call library using the glider's recorded audio as well as other Arctic acoustic recordings to improve classification performance. We anticipate that classification performance will

FIGURE 4

Distribution of average surface temperature and salinity measured at 3-m depth between each glider surfacing (filled circles). Colors indicate call rates of (a) bowhead whales, (b) bearded seals, and (c) walrus (see Figure 2 for species-specific color scales). Contour lines indicate fitted call rates from the Poisson regression with the lowest AIC value that related call rates to temperature (T) and/or salinity (S) (Table 1; models are $T + S + T \times S$ for bowhead whales and walrus, and S only for bearded seals). (Color versions of figures available online at: http://www.ingentaconnect.com/content/mts/mtsj/2014/00000048/00000005.)

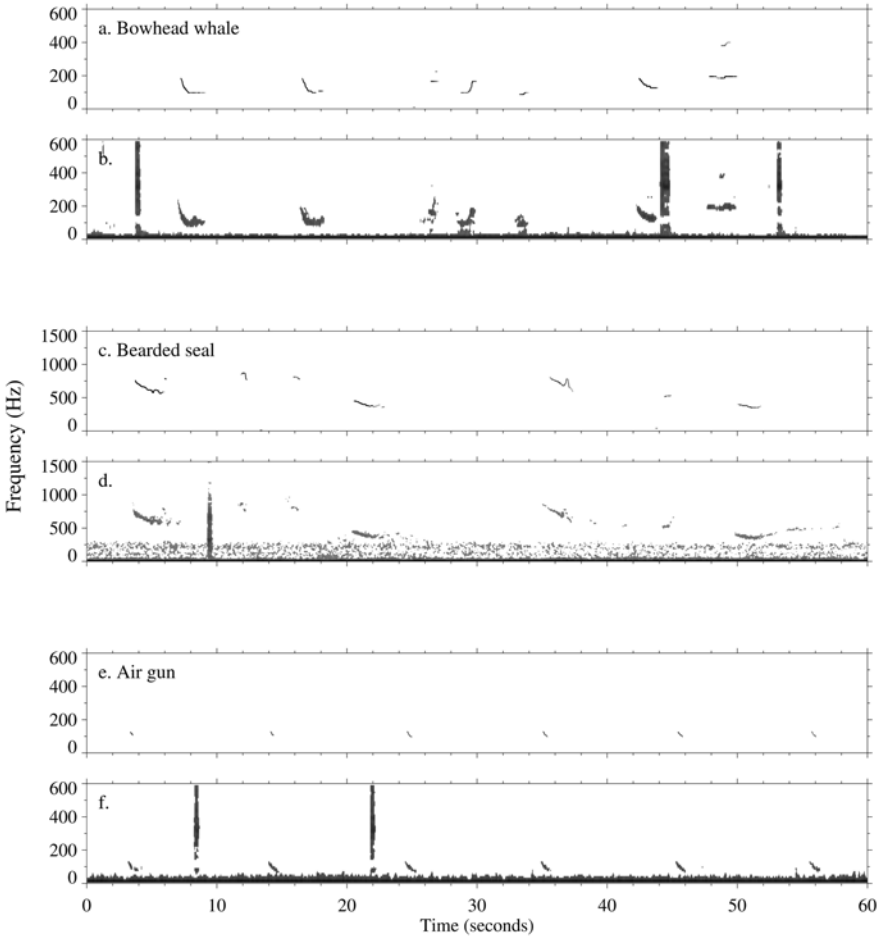


improve significantly with this continued effort, as it has for baleen whale species in the northwest Atlantic Ocean (Baumgartner et al., 2013).

Call rates for the three most commonly detected species, bowhead whales, bearded seals, and walrus, were all positively correlated with surface salinity, which reflected the more southerly distribution of these species in the study area where surface salinities were highest (Figures 2 and 3). Bowhead whales were detected throughout the study area (Figure 2a), but call rates were particularly high just offshore of Wainwright, Alaska. Walrus exhibited the strongest association with surface oceanographic conditions; this is a curious result considering that walrus are benthic feeders (Sheffield & Grebmeier, 2009) whose distribution perhaps should be less tightly coupled with oceanographic conditions than a pelagic feeder like the bowhead whale (Lowry et al., 2004). However, the injection of nutrients and biomass (including meroplankton) from the Bering Sea via the Alaska Coastal Current (Winsor & Chapman, 2004; Grebmeier et al., 2006) likely governs the distribution and abundance of the walrus' benthic prey in the Chukchi Sea. Based on an admittedly small set of observations, we speculate that walruses prefer water masses of Bering Sea origin during the summer because they may be associated with higher abundance of benthic prey. Sea ice has been an important feature of walrus habitat in previous decades because it provided an at-sea substrate for hauling out, but the recent disappearance of summer sea ice has likely had a profound effect on walrus distribution (Jay et al., 2012). Our pilot project has demonstrated that gliders can be an effective tool to study such changes

FIGURE 5

DMON/LFDCS-generated pitch tracks of (a) bowhead whale calls, (c) bearded seal calls, and (e) air gun signals and (b,d,f) spectrograms of simultaneously recorded audio (5 kHz sampling rate, 512 sample frame, 50% overlap, 9.77 Hz frequency resolution, 0.0512 s time step). Broadband sounds in (b), (d), and (f) were caused by the glider rudder.



in the distribution and habitat preferences of walrus as well as other Arctic marine mammals.

Vision for Use

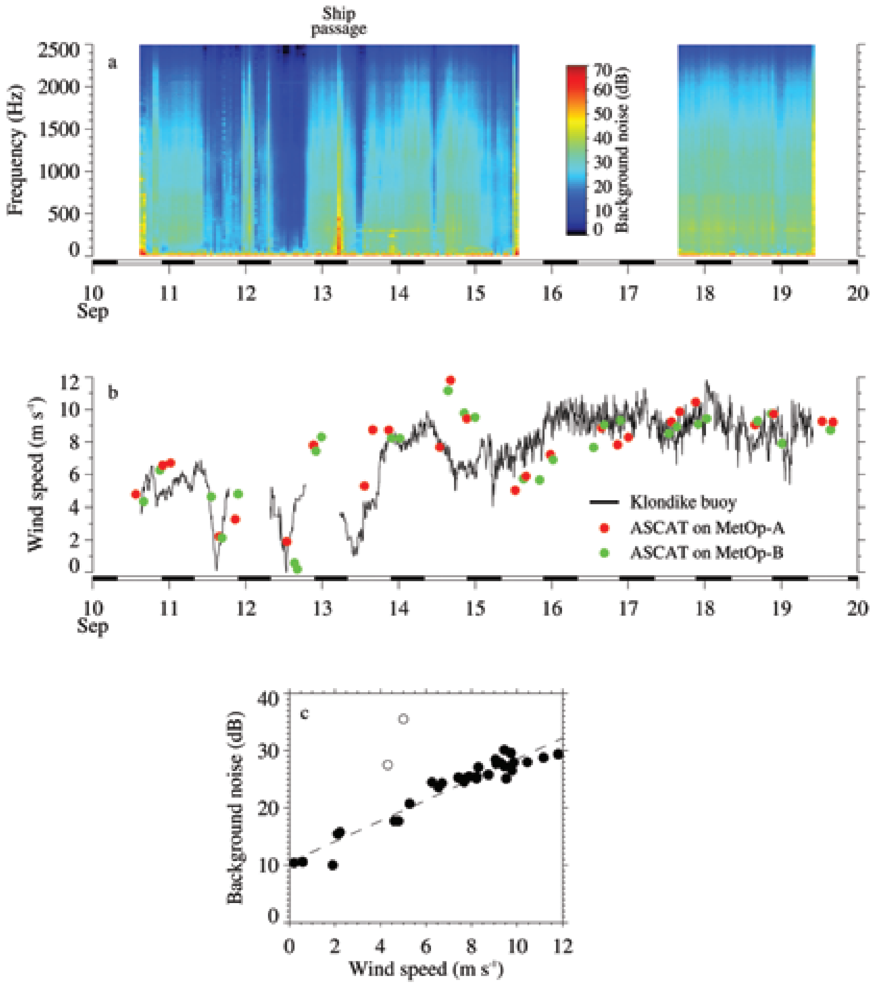
A mobile real-time detection, classification, and reporting capability for marine mammals has numerous applications for both science and conservation, and we envision gliders becoming a regular part of systematic marine mammal monitoring programs. Monitoring in the Arctic (and elsewhere) is conducted primarily with visual observers from aircraft or ships. Aerial surveys have been sustained over three decades in the Beaufort and Chukchi Seas (e.g., Clarke et al., 2013), because information about the distribution and relative abundance of Arctic marine mammals is critical to the environmental assessment process involved in issuing permits for oil and gas exploration. However, Arctic weather is often harsh, and aerial surveys are routinely grounded because of persistently poor viewing conditions (e.g., rough seas, fog, snow). With the availability of autonomous platforms that can remotely report marine mammal occurrence regardless of weather conditions, the limited survey time afforded by short weather windows can be used more efficiently by searching in areas where acoustic observations suggest the presence of marine mammals. Using the autonomous platforms for reconnaissance will significantly improve detection probabilities for aerial surveys and can provide more time on scene with animals to conduct photo identification or collect behavioral observations.

Although there is currently no persistent marine mammal monitoring program in the Arctic that regularly uses shipboard observers, scientists often have projects that require locating and studying individual animals. In our own experience, simply locating marine mammals in the Arctic can consume the majority of time, effort, and funding for these projects, with little left over for actual scientific study when animals are found. Just as gliders can provide reconnaissance for aerial surveys, gliders with a real-time passive acoustic detection, classification, and reporting capability can greatly improve the efficiency of shipboard studies that require close contact with animals, such as for photo identification, tagging, or *in situ* proximate oceanographic or prey sampling.

Some of the most fundamental questions about marine mammal ecology (and arguably the most pressing in marine mammal conservation) concern the dynamic distribution of marine mammals. However, characterizing marine mammal distribution and how oceanographic features or processes cause animal distributions to change over time is challenging to study in the Arctic because the space and time scales of oceanographic variability are quite small and short, respectively (Weingartner et al., 1998, 2013). On shallow Arctic shelves, the Rossby radius, a length scale that determines the width of buoyancy-forced

FIGURE 6

(a) Background noise spectra sampled once every hour and transmitted to shore in real time from the glider. Since the DMON was not accurately calibrated prior to deployment, sound levels are reported in decibels relative to the quietest spectrum element observed during the entire deployment. (b) Wind speed measured at the Shell Klondike buoy (line; location shown in Figure 1). Wind speeds from the Advanced Scatterometer (ASCAT) sensor carried aboard the MetOp-A (filled red circles) and MetOp-B (filled green circles) satellites are also shown. Satellite-derived wind speeds were measured within 12.5 km of the glider's location. (c) Relationship between spectrally averaged background noise and satellite-derived wind speed. The dashed line indicates a simple linear regression of all data except observations collected just after deployment and just before recovery when the M/V *Norseman II* was near the glider (open circles). (Color versions of figures available online at: http://www.ingentaconnect.com/content/mts/mtsj/2014/00000048/00000005.)



coastal currents such as the Alaska Coastal Current, is only 5–10 km (e.g., Carmack et al., submitted). Local ice melt and flow convergence create multiple horizontal density fronts in the Chukchi Sea that are just 1–3 km across (Timmermans & Winsor, 2012). These small-scale features can change on surprisingly short time scales. Winsor and Chapman (2004) determined that winds blowing at speeds in excess of 7 m s^{-1} and in opposition to the normal direction of flow can reverse the direction of the Alaska Coastal Current over time scales of 2–3 days (as observed in sub-surface mooring data by Okkonen et al., 2009, and in high-frequency radar data by Weingartner et al., 2013). Observing marine mammal distribution over these small space and short time scales is nearly impossible using traditional methods in the Arctic. Weather constraints limit the persistence of dedicated aerial or shipboard surveys, making them poorly suited for investigating the response of marine mammals to oceanographic variability on daily time scales. Gliders, however, are adept at surveying over these time scales and are regularly used by physical oceanographers to do so. Although slow moving, gliders operate continuously and can survey over tens of kilometers on daily time scales. With the capability to remotely report both oceanographic measurements and marine mammal occurrence, scientists can also alter the survey design in real time to adapt to rapidly changing environmental conditions.

Concern over short- and long-term impacts of ocean noise on marine mammals has increased substantially over the past decade (National Research Council, 2000, 2003, 2005). Air guns for oil and gas exploration and the propulsion systems of large ships can make substantial contributions to the ocean noise budget over short and long time scales, respectively (Andrew et al., 2011; Guerra et al., 2011; Klinck et al., 2012b; McKenna et al., 2012). The first step in managing this noise is characterizing it, but few contemporary studies of open water Arctic background noise exist (Roth et al., 2012, 2013). Although many marine mammal passive acoustic studies collect observations of background noise, they rarely do so with calibrated hydrophones. A glider equipped with a DMON/LFDCS can provide measurements of background noise in near real time, and with calibration, these measurements can be used to study temporal and spatial patterns in ocean noise. The glider's reporting capability can also be used to initiate management action in near real time if ocean noise levels related to industrial use exceed specified thresholds.

The ability to provide near real-time reports of marine mammal occurrence is of growing interest to marine industries, government agencies, and conservationists alike as a tool to help mitigate interactions between human activities and marine mammals. Gliders equipped with the DMON/LFDCS provide the capability to report detections of a wide variety of marine mammal species from mobile autonomous platforms. For weeks to months at a time, gliders can survey shipping lanes, fishing grounds, oil and gas lease blocks, wind farms, marine construction sites, and naval training grounds to help industries and government agencies manage the impact of their activities on marine mammals. Such large-scale use of the technology will depend heavily on the confidence users have in the accuracy of real-time reports of marine mammal occurrence; it is therefore critical that the accuracy of autonomous real-time systems continue to be rigorously evaluated.

The Future of the Technology

With our pilot study, we have demonstrated a promising capability to conduct marine mammal habitat surveys, assess spatial and temporal variability in background noise, and report marine mammal detections in near real time from a single autonomous vehicle in the Arctic. However, more work is required to improve the call library, further evaluate the system, assess classification accuracy, and determine its ultimate role in monitoring programs and industrial and naval mitigation applications. In the short term, we will use this novel capability for science applications, particularly to study relationships between marine mammal distribution and oceanographic features and processes in Arctic shelf seas, while simultaneously improving and evaluating the accuracy of real-time detections and classifications. Our long-term goal is to build confidence in the system and its various applications so that it becomes a routine tool for marine mammal and ocean noise monitoring in the Arctic.

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